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Power System Security Analysis: Applications for Wind Power Allocations and Smart Islanding

Master of Science Thesis in Electric Power Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2010

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Chalmers Reproservice
Göteborg, Sweden 2010

‘‘The key to success is persistence’’

To all people I love

Acknowledgements

This work has been carried out at the Division of Electric Power Engineering, Department of Energy and Environment at Chalmers University of Technology.

First of all, I would like to express my deep and sincere gratitude to my supervisor and examiner Dr. Tuan A. Le for his excellent supervision during the work as well as giving the opportunity for me to explore in depth the area of self-healing of smart grid.

I really appreciate my classmate Yifan Jia and for providing valuable comments and suggestions. My gratitude also goes to all the master students in Room 2528 for they provide a good study circumstance for me to focus on my thesis work. I would like to thank Dr. Bin Ma for his patience every time I asked questions.

My ultimate gratitude goes to my aunt Yenlin Chou and her husband Jeffry. It is because of their endless concerns that I can accomplish this work eventually.

Also thanks a lot to those people I met who helped me in different ways without being aware of that.

Natually, the most heartfelt thanks to my parents, Jianling Hou and Xueping Li to encourage me every day that I was far away from them.

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Abstract

Power system reliability is the overall objective in power system design and operation. It includes two main aspects: adequacy and security. During the last decades, outages and blackout emerged more and more frequently which affected the normal consumption of consumers. In order to meet the increase the power system security, a self-healing grid is needed to monitor and response to the change within the whole network in time. Smart islanding is considered as an effective way to prevent small outages in the system from propagating into big blackout.

In this paper, two common methods used to find the islands are introduced and the formation of islands was conducted by a C++ minimal cutset algorithm based program which was implemented on the platform of Dev cpp in the simulation part, moreover the proposed approach was applied to a Nordic 32-bus test system and was used to save the network from voltage collapse. On the other hand, since the large amounts of sustainable resources are being widely used by taking into account of the ever-increasing load demand throughout the world, people are exploring new resources to replace the existing non-renewable resources. As one of the renewable energy, wind power, draws people's attentions more and more. Renewable resource generation connected to the existing network will incur plenty of problems which will decrease the power system reliability. The wind energy injection will probably induce transmission overloaded problem which reduce the power system adequacy. It is critical to allocate the wind energy optimally. In order to find good locations to set up large-scale wind power projects, a Weighted Transmission Loading Relief (WTLR) / Equal Transmission Loading Relief (ETLR) sensitivity was introduced in this work to help find the positions of injecting the wind power so that the increasingly load demand can be satisfied as well as reduce the contingency overloads within the system to enhance the power system reliability.

Keywords: Smart islanding, self-healing grid, power system security, minimal cutset, a C++ minimal cutset algorithm program, renewable energy, power system reliability, large-scale wind power projects, WTLR/ETLR sensitivity

Table of Contents

List of figures

List of tables

List of Terms

Acronyms:

NERC	North American Electric Reliability Council
EPRI	Electric Power Research Institute
OPF	Optimal Power Flow
WWEA	World Wind Energy Association
TLR	Transmission Loading Relief
WTLR	Weighted Transmission Loading Relief
ETLR	Equal Transmission Loading Relief
SCADA	Supervisory Control and Data Acquisition system
HMI	Human–Machine Interface
MTU	Master Terminal Unit
RTU	Remote Terminal Unit
DG	Distributed Generation
APCO	Average Percentage Contingency Overload
AMWCO	Aggregate MW Contingency Overload (AMWCO)
SC	Synchronous Condenser
MCs	Minimal Cutsets
DAG	Directed Acyclic Graph
SS	System Splitting
BP	Balanced Partition
$\|V_t\|$	Voltage Magnitude
δ	Power Factor
P_i	Net active power injected at bus i,
Q_i	Net reactive power injected at bus i,
G_{ij}	Real part of the element in the line admittance between bus i and j,
B_{ij}	Imaginary part of the element in the line admittance between bus i and

Chapter 1

Introduction

In this chapter, a general description of the emergence of smart grid that meet the increasing growth rate of load demand and consumer's requirement is provided. Due to the fact that outages and blackouts occurred more frequently during the latest years, the need for an intelligent strategy to control the electricity network is emphasized by more people throughout the world. In addition, one important issue, optimal allocation of wind energy, which is related to the connection of renewable resource to the existing network, is introduced. Finally, the framework of this thesis is pointed out.

1.1 Self-healing grid: Smart islanding

The statistic report from the North American Electric Reliability Council (NERC) and analyses from the Electric Power Research Institute (EPRI) tell us such a fact that average outages from 1984 to now have affected approximately 700,000 customers per event annually. Outages and large blackout occurred more and more frequently than before during the last 40 year which spotlighted our requirement to realize the complex phenomena related to power systems and the development of emergency controls and restoration. The statistic of outages occurred during 2001-2005 in North America can be seen in Figure 1.1[1] :

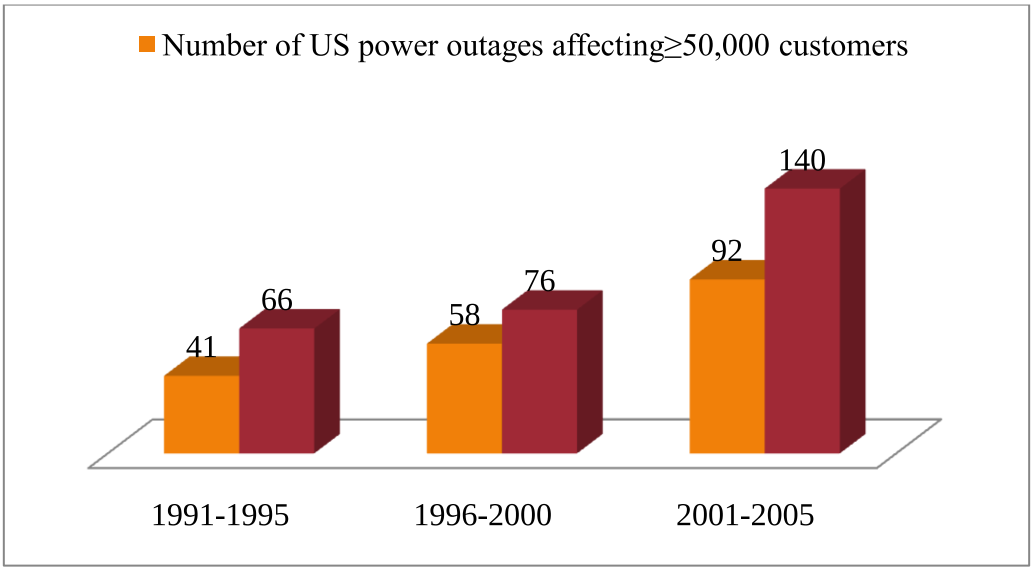

Figure 1.1: Historical analysis of U.S. outages (1991-2005)

In the past 30 years, the information and communication technology has undergone enormous changes, but the aging America network does not keep up with the pace of technological evaluation. The consumers proposed higher standards for the power supply requirements than before, national security, various environmental protection policies also asked for a power grid with higher standard construction and management level [66]. The 2003 Canada-U.S.A blackout is a motivation for the American electric power industry to decide to create a robust grid which is safe and reliable, cost-effective, clean and environmentally friendly, transparent and open, that is, the smart grid.

Actually, the situation in America is not particular. The big blackout around the world in recent years which are explicated in [3] [4] [5] highlight the requirement for such a self-healing system with the function of adaptive protection which can minimize the impact on the whole system performance when there is an emergence of contingency. The critical step of creating a self-healing grid, it's to build a processor into each component of a substation. It means that each component in the network, namely the breaker, switch, transformer, busbar, so on, needs to be armed with a processor so that the devices can communicate with each other. Thus, the infrastructure of the system will be changed. The transmission line must be accompanied with a parallel information line. The information on device parameters and device status and analog measurements is recorded in the processors. Once such system is built up, the updated data will be reported to the central control computers immediately instead of waiting for the database generated by central control personnel. The system will therefore be more sensitive to the rapid changes within the system. The emergence of smart grid provides the possibility for the operators to monitor the system and optimize the mitigation scheme.

In fact, there are a lot of preventive ways can be applied to avoid total voltage collapse. In smart grid, the self-healing function can be carried out very well by the smart islanding approach which has the main goal of splitting the whole system into isolated 'islands' when there are failures occurred somewhere within the system. After the formation of the 'islands', each of which must then be self-sustaining. The components in each island act as independent agents with the intelligent distribution. It is capable of reorganizing themselves and makes best use of available local resources to remove the failure that occurs within the network until they are able to reconnect to the network. A network of local controllers can act as a parallel, distributed computer, communicating via microwaves, optical cables, or the power lines themselves, and intelligently limiting their messages to only that information necessary to achieve global optimization and facilitate recovery after failure [6] .

Generally speaking, smart islanding is a corrective control strategy that separates the system into self-sustaining islands after contingency. There are two methods that are commonly used to form the islands, as slow coherency method and minimal cutset method. The formation of the islands can be beneficial since it can keep the rest system work normally which prevents the small outages from evolving into big blackout. The emergence of the self-healing grid changes the present network into a more robust interactive electric network. This is of great significance for the optimization of allocation of resources as well as increasing the efficiency and reliability of power system. Besides, some new technologies' research and development, for instance, wind power, solar power, electric vehicles produces a rapid growth demand for the development of Smart Grid technology. By integrating the smart islanding method, the present grid can be transformed into an intelligent self-healing system enhance power system security and reliability [7] [8] [9] .

1.2 Big wind generation project: One trend of the generation development

Energy and environment is the impending problem that should be solved for the survival and development of human beings. Due to the depleting of fossil fuels, people highlight the use of sustainable resources which push the prosperity of the rapid development of environment-friendly products. Wind power, to be one of the renewable resources, has many advantages as no green gas emission, widely distributed and high potential development which draw people's attention more and more. With the scientific and technological progress, electric power generation technology, especially wind power generation technology, has made great advances and steps into maturity by and by. This gives us the opportunity to replay the present generations with the wind generation and connect it into the existing grid

From the year 2009 statistic report of the World Wind Energy Association (WWEA), we get to know that all wind turbines installed by the end of 2009 worldwide are generating 340 TWh annum which is the total electricity demand of Italy, the seventh largest economy of the world, and equals to 2 % of global electricity consumption. The trend of the augmentation of wind generation worldwide can be seen in Fig 1.2 [10] [11] :

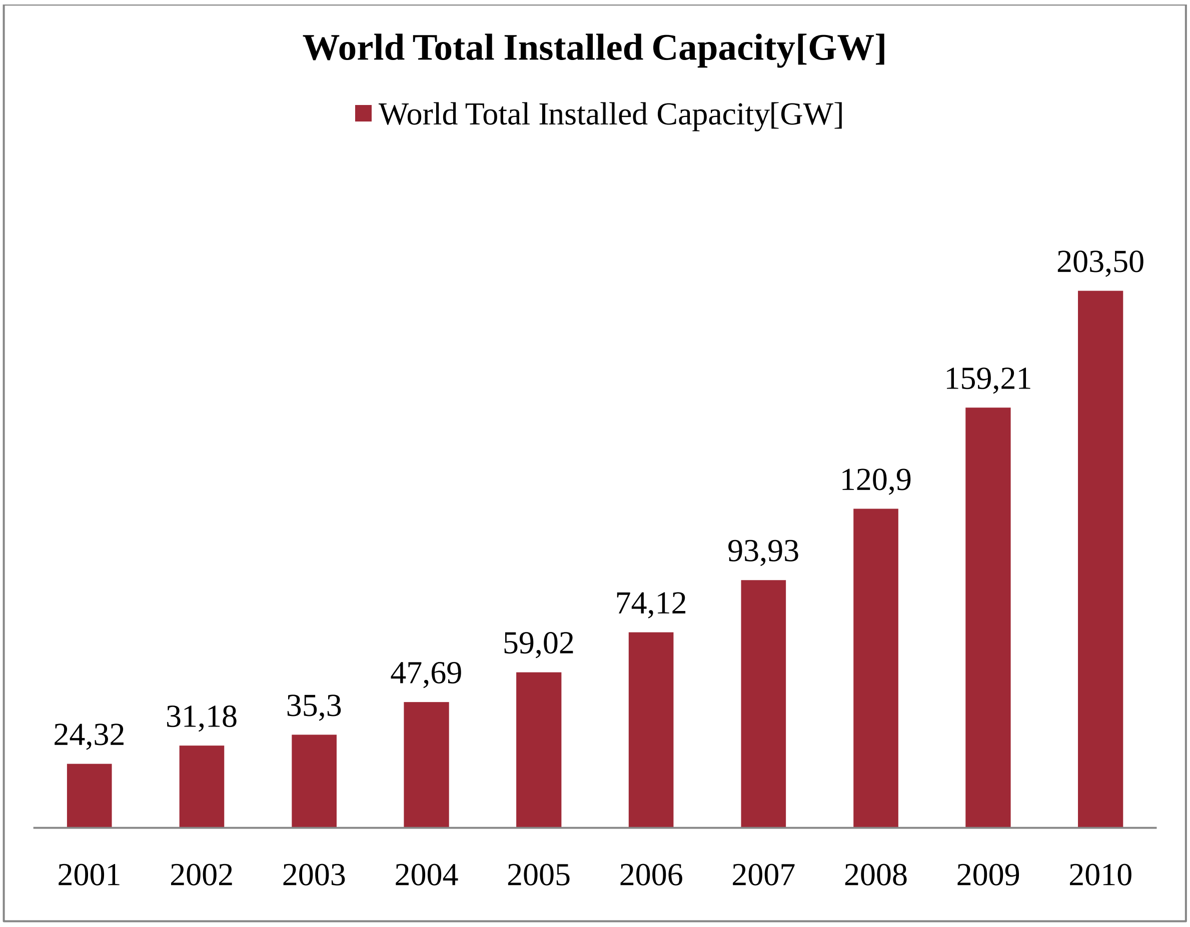

Figure 1.2: The wind generation capacity worldwide per year from 2001 to 2010

Figure 1.2 shows that the increase of wind generation is over 30% per year with the highest growth-rate in year 2010. In virtue of the rapid development of the world wind generation, more and more wind farms are being set up to meet the local demand and mitigate the burden of transmission instead of long line transmission [12] [13] . [13] This results in the issue of large-scale integration of wind power generation into the present system. To be different from the small wind generation farm, the large wind farms are usually connected into the power grid directly. Hence, more requirements are brought out as the transient stability; recover ability from accidents, frequency and voltage control as well as automatic dispatch [14] .

New injections would have an impact on the other transmission lines which results in the problem of contingency overload. As we know, the transmission overload will decrease the adequacy of the transmission line which is just one important factor for system reliability. In order to meet the reliability requirement as well as satisfying the increasing load demand by using wind generation. The integration of wind projects should be planned by consideration of problems:

1) The determination of locations of the wind project.

2) The size of the wind project and the strength of the wind output across time.

3) The different injections that incur the overloaded branches which is required to be expanded.

According to the recommendation of North American Electric Reliability Council, the system should be designed and operated to withstand N-1 and N-2 contingencies namely indentifying weak transmission branches by simulating forced transmission and generation outages and develop a metric to assess the weakness of each existing transmission branch. In order to satisfy these requirements, the Weighted Transmission Loading Relief (WTLR)/ Equal Transmission Loading Relief (ETLR) sensitivity methodology is used to evaluate the new wind generations' effect on the system [15] .The WTLR means 1 MW new injection at the specific bus will reduce 0.5 MW contingency overload in transmission branches if we get a WTLR of 0.5 at that bus while the Equal Transmission Loading Relief (ETLR) signifies the total expected MW contingency overload reduction, in all transmission lines and under all contingencies, if 1 MW is injected at that prescribed bus. Positive ETLR and WTLR sensitivities show that new injection will tend to increase overloads and reduce overall system security and vice verse [16] . The method gives us the insights into the exploration of the influence of new injections on the whole system. More details of ETLR/WTLR methodology will be depicted in Chapter 2.

This thesis describes work on finding methods to improve power system security. The work includes two parts: the optimal connection of wind power in transmission grids using sensitivity method as well as development of preventive way, namely controlled partition or called smart islanding method, for power system blackouts. The main goal of this work is firstly on a simulation of determining the optimal locations of wind generation project. Several scenarios are set up to show the results. As we know, more generations on buses will probably incur the contingency overload. The problem was assumed to be solved by using the WTLR/ETLR sensitivity method. A study case which is based on Nordic 32 test system is presented to demonstrate the availability of the sensitivity methodology under the help of Powerworld Simulator Software package. Thereafter, more work is done by implementing the smart islanding approach into the same test system by using the Powerworld software. As a self-healing grid, smart islanding should be able to prevent the small outages from evolving into big blackouts and keep the rest part work normally. The method of forming the 'islands' was demonstrated by a C++ minimal cutset algorithm based program. Finally, a case study of applying smart islanding to prevent blackout is demonstrated and presented at last by using Powerworld software as well.

1.3 Thesis outline

Chapter 2 introduces three important concepts related to the power system operation issues which are power system stability, security and reliability. The power system reliability includes two aspects: security and adequacy. A reliable system could sometimes be insecure. In other words, it could be also operated in the emergency state or went to insecure condition when it is subjected to a certain disturbance and a stable system can also be insecure when we compared it with another system. The criteria of system reliability and security are enacted by different organizations according to different situations. It is the standards for the electrical engineers to design the network which is presented in this chapter. Moreover, the concept of power system stability and the interconnection among these three concepts are presented at last.

In Chapter 3, one issue involved in meeting the continuous grow-up of load demand is introduced. A WTLR/ETLR sensitivity method is utilized to determine the good locations to set up wind farms which can satisfy the load increase as well as mitigate the contingency overload. A case study of Nordic 32 system is presented to see the impact of the new injection on the whole system. Several scenarios are presented to demonstrate the practicability of this new methodology. In this section, Powerworld Simulator is used to carry out the simulations and represent the results graphically.

In Chapter 4, several common methods that are used to find the weak connected areas during the implement of smart islanding are introduced, moreover, a C++ minimal cutset algorithm based program is presented to show the results and the process of finding the "islands" along with the codes are explicated as well, what's more, a study case of using smart islanding approach to protect the power system is shown under the help of Powerworld simulator.

Main conclusions drawn from this work are summarized in Chapter 5 and different directions of future researches are also given in this Chapter.

Chapter 2

Power System Security and Reliability

Power system reliability is the general purpose in the power system design and operation. If the system is considered to be reliable, it must be secure most of the time while power system stability belongs to one aspect of power system secure. To be secure, the system have to be stable, however, more considerations should be done on the preventions of contingencies which are not included in the stability problems. Thus, it is critical to understand these concepts and interconnections among them and construct power system correspond to standards and criteria which are derived from these concepts to enhance the reliability of the system as well as satisfy the requirement of the customers.

2.1 Power System Security

2.1.1 Power system operation security

With the increasing electric power demand, electric power system are operates closer to its stability limit [17] , the operation of power system becomes more complicated and will become less secure. What's more, as a result of restructuring, the problem of power system security has become one overriding factor in the operation of the electric power system in deregulated power industry [18] . As it is defined in North American Electric Reliability Corporation (NERC) (1997), the term 'Security' has the meaning of the ability of the electric systems to withstand sudden disturbances such as electric short-circuits or unanticipated loss of system element, without affecting delivering power to the customers [19] . The objective of security analysis is to enhance the power system's ability to run safely and operate economically. As described in [20] , it relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances.

As detailed in [21] [[22] , power system is said to be operated in the normal state if the following conditions are met:

1. There is a perfect balance between power generation and load demand; consequently, the load flow equations are satisfied.
2. The frequency f is constant throughout the system.

3. The bus voltage magnitude $|V_t|$ is within the prescribed limit, i.e.

$$|V_t|_{min} \ll V_t \ll |V_t|_{max} \tag{2.1}$$

4. No power system component is to be overloaded.

In the power system, the equipments are usually protected by automatic devices which can make the equipments quit the system immediately once it operates out of its limits. The event maybe followed by a series of further actions that cause other equipments disconnected from the system. This is what we called cascading failures. If this process of cascading failures continues, then the system will suffer from blackout which means the whole network or most part of it may completely collapse. Thus, it is not sufficient to merely maintain a system in the normal operating state. We need to specify a security for each system to withstand the disturbance under distinct conditions.

2.1.2 Security criteria

Assuming that we give a set of disturbances to a power system one at a time. If the system can also operate in the normal operating state, then the system is said to be secure. In practice, all power systems cannot avoid being affected by unpredictable faults and failures such as lightning strikes on transmission lines, mechanical failures in power plants, or fires in substations. In virtue that this nature phenomenon are unavoidable and happens relatively frequently, all power systems should be designated to withstand them without emergency. In order to avoid blackouts and wide scale consumer disconnections, the system should be operated with a sufficient margin which can be explained in terms of two elements: reserve generation and transmission capacity.

- Reserve generation: Leaving enough reserve generation capacity in case of the loss of a generating unit.

- Transmission capacity: Keeping enough transmission capacity to take up the flow that was flowing on the outage line.

We also need to know that the system is impossible to be 100% secure since a system which can be against all contingencies is obviously incredible. The fundamental principle only requires the system to defend against credible contingencies, that are so called ‘N-1 contingency’ as well as ‘N-2 contingency’. When the system is subjected to disturbance as losing any one of its N components and continues to operate normally, it is said to be ‘‘N-1 secure’’ while the ‘‘N-2 secure’’ means no consumer would be disconnected even if two components were suddenly disconnected [23] . In engineering, the N-1 contingency secure are usually a metric for the operators to measure the security of the power system.

2.1.3 System security function

Power system security may be divided into three modes, namely [24] :

1. Steady state security which is created under the steady state condition of a power system.

2. Transient security which copes with the transient state of a system when it is subjected to a disturbance.

3. Dynamic security which concerns the system response of the order of few minutes

In security evaluation, it is recommendable to find an indicator for each mode of security which can be revealed by various decision standards and the so called security function is brought out if the indicator is represented by mathematical functions. Usually, the security function concerns three major aspects and is carried on in an operations center [28] :

1. System monitoring.

2. Contingency analysis.

3. Security-constrained optimal flow.

The continuous updating information on the conditions of the power system is given to the operators through system monitoring. Based on this, some quantities such as, voltage, currents, power flows, and the status of electric equipments as circuit breakers, and switches in every substation in a power system transmission network can be measured and monitored. In addition, further information on frequency, generator unit outputs and transformer tap positions can be also gathered and transmitted back to the control center. By account of the complexity and arduousness of the task, the data will be processed by digital computers and then be arranged in a database which gives the chance for the operators to display the information on large display monitors. What's more, the computer can also identify the overload condition or voltage violations by comparing the incoming information with the given limits and remind the operators of reacting in time. In practice, supervisory control systems, a system which allow operators to control circuit breakers and disconnect switches and transformer taps remotely, are always combined with such systems to create an new kind of systems. This is what we called supervisory control and data acquisition （SCADA） system. The SCADA system makes the real time monitoring and correction of overloads or out-of-limit voltages available. A simplified structure of SCADA can be seen in Figure 2.1:

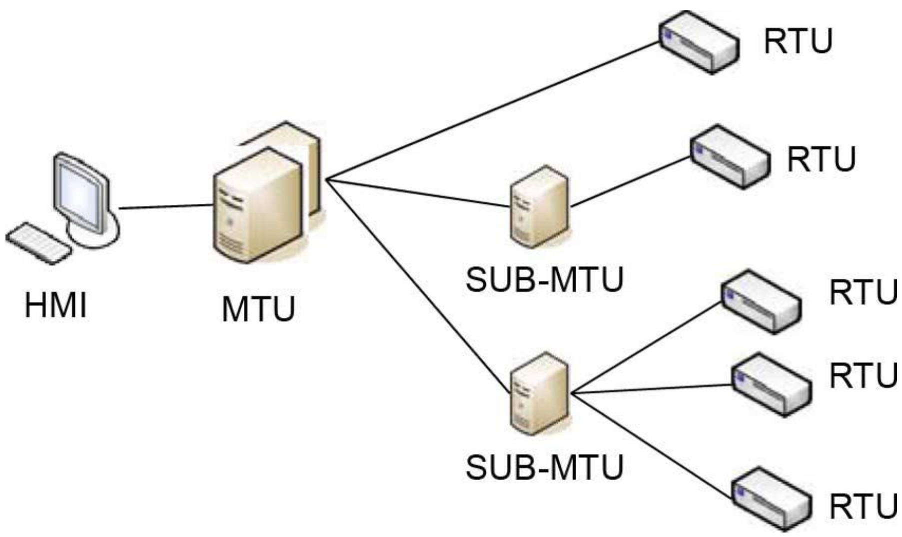

Figure 2.1: SCADA system

Commonly, a SCADA system is composed of three types of communication equipment: human–machine interface (HMI), master terminal unit (MTU), and the remote terminal unit (RTU). The function of each part is explicated in [25] . More pertinent information on SCADA is explained at length in [26] [27] .

The function of contingency analysis is aimed at dealing with the problems that happens within a short duration. Since it occurs so quickly that no operator could take action in time. This is often how the cascading failures come out. In order to refrain from this, we need to implement the contingency analysis programs into our operation computers to eliminate the troubles before they arise as much as possible. The position of contingency analysis in the security analysis is shown in Figure 2.2 [28] :

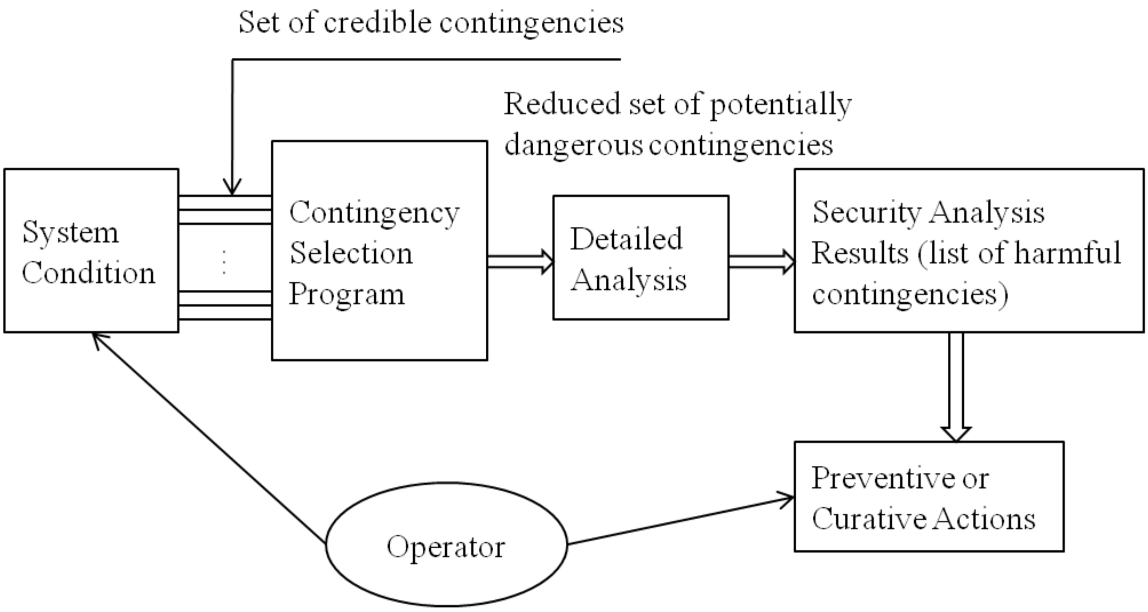

Figure 2.2: Contingency analysis procedure

Actually, the last major function, Security-constrained optimal flow, is generated based on the second function. It concludes contingency analysis as well as an optimal power flow (OPF) method. With the implement of OPF, we can find the best solution to the optimal dispatch generation as well as other adjustment according to the given objective function, so that when a security is sun, no contingencies would incur violations [29] . A real case of the application of the third security function, Security-constrained optimal flow is presented in [30] .

2.1.4 On-line security analysis

The power system security analysis has three main goals as[31] :

1. Determination of the most probable time of contingency
2. Prediction of the impact on the whole system
3. Identification of proper control actions to reduce the risk of failures

In reality, the power system security analysis is usually performed according to N-1 contingency criteria. Some works have already been done on the power system security analysis technologies as can be known in [32] [33] .

The on-line security analysis and control includes three aspects: monitoring, assessment and control. The connection among them can be seen in Figure 2.3:

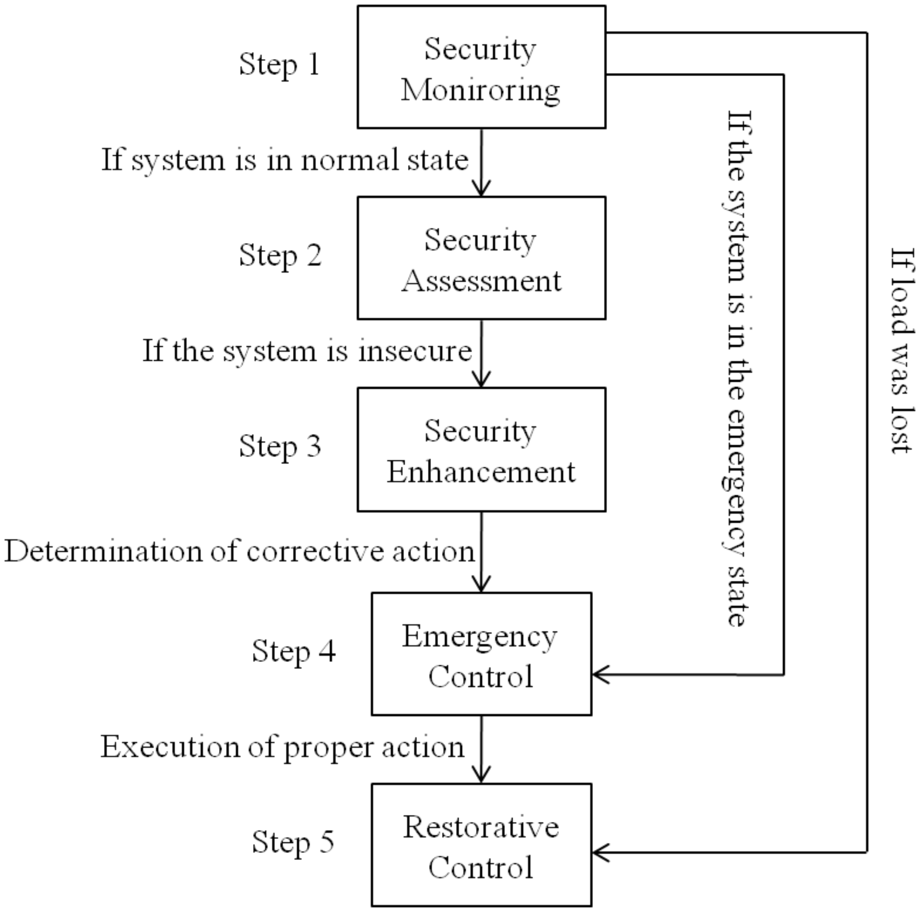

Figure 2.3: On-line security analysis framework

In step 1, we use real-time system to recognize whether the system is operating normally or not. If it is in normal state, then we move to the step 2 in which the system is subjected to a series of contingencies to see if it is secure or insecure. When we find the system is insecure, we will continue to conduct the step 3 to decide what action could be used to make the system in normal state. The execution of remedial action which means use appropriate corrective action to bring the system back to its normal state and the last step is used to restore service to system loads [34] .

2.2 Power System Reliability

2.2.1 The concept of reliability

The term 'reliability' is the ability of the system to pertain secure state when it is subjected to a set of contingencies. A more precise definition can be found in [35] , in which reliability of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period. According to the definition of NERC, the reliability is composing of two aspects: security as well as adequacy. On one hand, adequacy is the ability of systems to supply energy to their customers with satisfying the load demand. On the other hand, security is the ability of the systems to withstand sudden disturbances such as short circuit or unanticipated loss of system elements [36] .

In fact, the understanding of the reliability from the operators' view is that any consequence of a credible disturbance that requires a limit. From their eyes, it can also be called 'security', if we give more content to redefine it. The redefined 'security' can be catalogued into three aspects as can be seen in Figure 2.4:

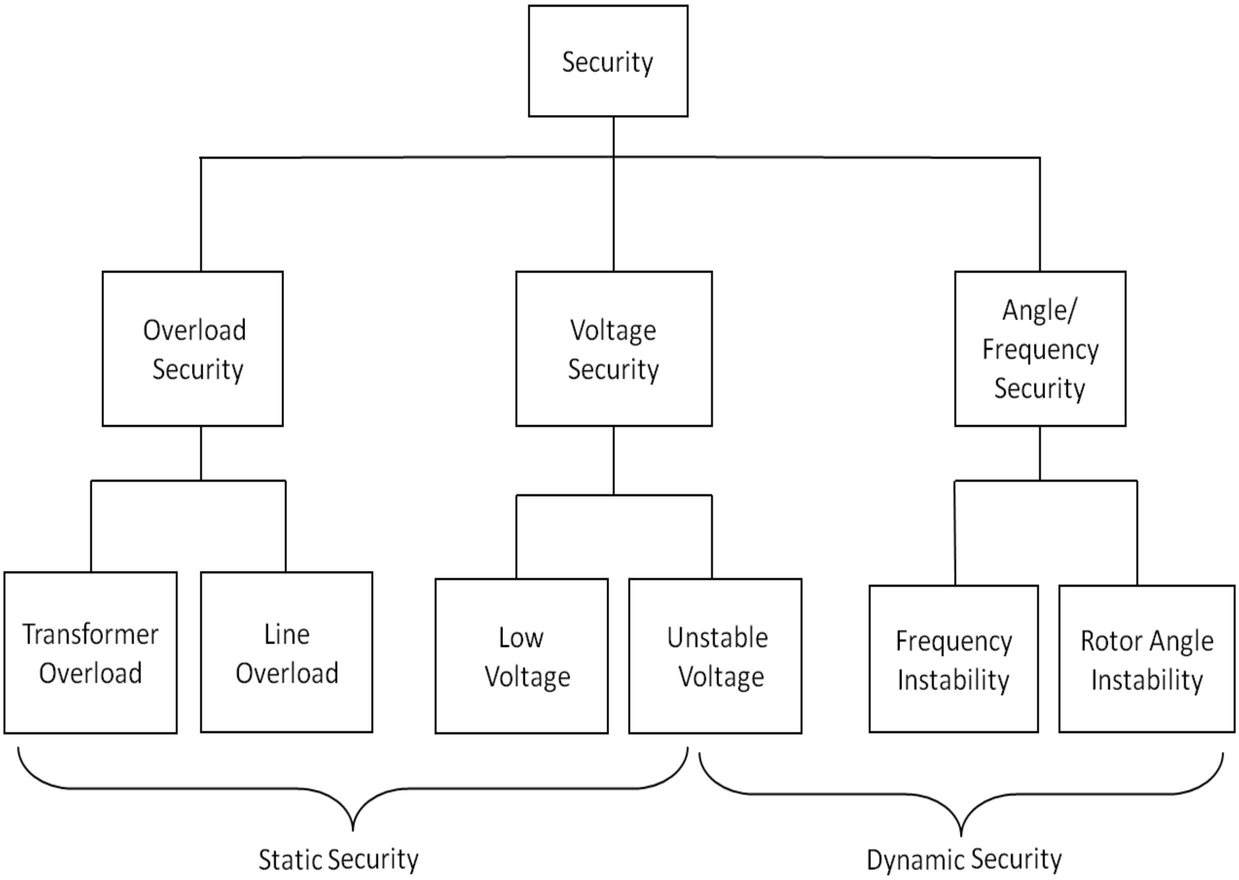

Figure 2.4: The meaning of security in the eyes of electric power system operators

Based on the statements above, it is not difficult to know that the two branches of reliability can be then given a new definition as security corresponds to dynamic security while adequacy concerns static security.

2.2.2 Reliability criteria

To be different from the security criteria, reliability criteria are rules by which the performance of a power system with respect to emergence of component failures can be judged acceptable or unacceptable. The reliability criteria defined by NERC [37] and used by individual North American reliability councils [38] [39] [40] [41] [42] [43] [44] [45] [46] gives us a critical standard for system planning and operations. This standard is articulated as a higher level of performance is required for disturbances generally having a higher frequency of occurrence and it is often embedded in the so-called disturbance-performance criteria, which specify different classes of allowable performance for different classes of disturbances [47] .

2.3 Power System Stability

As one aspect of system security, power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact [35] .

According to the physical feature of power system instability, the size of disturbance as well as by taking into account of time span, process and devices those are included in the research of power system stability problem. We can divide the power system as three main types which can be seen in Figure 2.5:

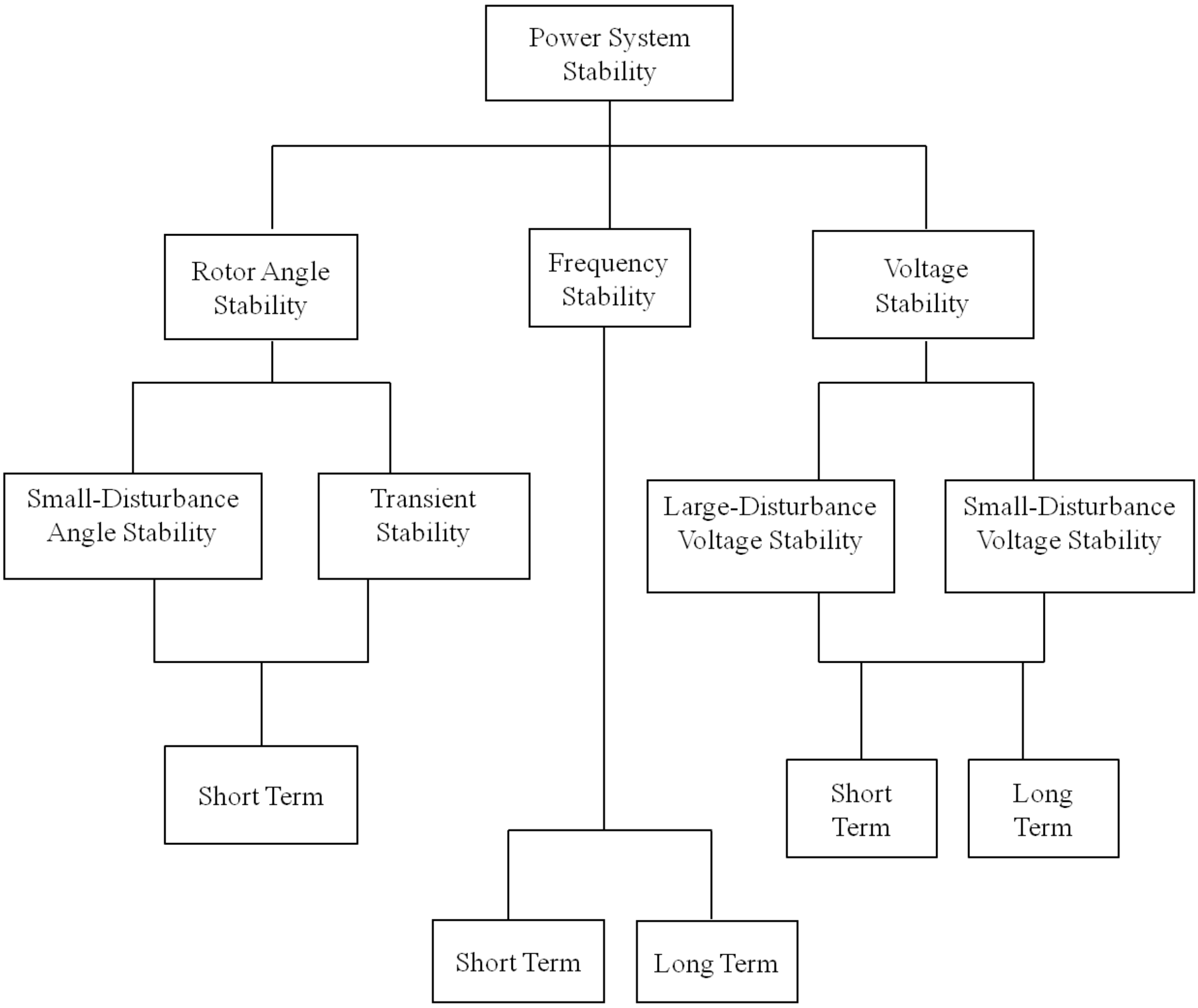

Figure 2.5: Classification of power system stability

The classification of system stability into proper categories is beneficial for us to indentify critical factors that incur instability and invent philosophies of improving operating in normal state. Moreover, it contributes to the proper selection and simplification of devices’ models and analysis technologies so that the reasonable operation mode as well as the control strategy of improving system security level can be arranged scientifically [48] .

2.3.1 Power System Stability Standardization

In [49] , the standardization of steady-state stability requirements and transient stability requirements are articulated. Based on this, the actual power system stability regulations are created. The requirements of stability are listed in Table 2.1 as follow [50] :

Table 2.1: Power system Stability Requirements

	Normal Design Contingencies			**Extreme Contingencies**
	I	**II**	**III**	Extreme contingencies exceeding its severity normal design contingencies.
Security Criterion	N-1	N-2	N-3	N-k
Acceptable Consequences	Stable operation without protection system intervention	Stable operation with protection system intervention		Instability is acceptable. Power system integrity is ensured by protection system and operator intervention.
Normal Conditions	**During design contingencies** power system stability must be maintained for the maximum permissible transmitted active power added on random power flow variations. • The maximum permissible transmitted active power must satisfy the standard stead-state stability margin under normal conditions • The maximum permissible transmitted active power must not exceed the transient stability limits appropriate to all design contingencies with due regard to protection system intervention			During and after extreme contingencies protection system and operator intervention must not lead to cascade outages and loss of a significant amount of consumption.

Post-fault Conditions	**After design contingencies** • Transmitted active power must satisfy the standard steady-state stability margin under post-fault conditions • Transmitted active power must satisfy the thermal limit	

2.3.2 Comparisons of power system stability, security and reliability

Power system stability, security and reliability are three aspects that are widely used to describe the ability of systems to survive from the unexpected events which can destroy the equilibrium state of the operation. They are sometimes related to each other, however, there are still some differences among them [35] :

1. Reliability is the overall objective in power system design and operation. To be reliable, the power system must be secure most of the time. To be secure, the system must be stable but must also be secure against other contingencies that would not be classified as stability problems, for instance, damage to equipment such as an explosive failure of a cable, fall of transmission towers due to ice loading or sabotage. As well, a system may be stable following a contingency, yet insecure due to post-fault system conditions resulting in equipment overloads or voltage violations.

2. System security may be further distinguished from stability in terms of the resulting consequences. For example, two systems may both be stable with equal stability margins, but one may be relatively more secure because the consequences of instability are less severe.

3. Security and stability are time-varying attributes which can be judged by studying the performance of the power system under a particular set of conditions. Reliability, on the other hand, is a function of the time-average performance of the power system; it can only be judged by consideration of the system’s behavior over an appreciable period of time.

4. Security and reliability could be considered as the same issue sometimes, however, we can also distinguish them by adequacy. But we should not overlook such a fact that even the most reliable systems will not avoid to undertake periods of severe insecurity.

2.4 New technologies for improving system reliability and security

2.4.1 The improvement of reliability by Smart Grid

As has been mentioned in Chapter 1, smart grid is the new product that was generated in the 20th century to satisfy the requirement of customers and replace the aging electric grid gradually. It has many contributions to the increase of the system reliability as [51] :

1. Better situational awareness and operator assistance.
2. Autonomous control actions to enhance reliability by increasing resiliency against component failures and natural disasters, and by eliminating or minimizing frequency and magnitude of power outages subject to regulatory policies, operating requirements, equipment limitations and customer preferences. Such control actions can be more responsive than human operator actions.
3. Efficiency enhancement by maximizing asset utilization
4. Resiliency against malicious attacks by virtue of better physical and IT security protocols.
5. Integration of renewable resources including solar, wind, and various types of energy storage. Such integration may occur at any location in the grid ranging from the retail consumer premises to centralized plants. This will help in addressing environmental concerns and offer a genuine path toward global sustainability by adopting "green" technologies including electric transportation.
6. Real-time communication between the consumer and utility so that end-users can actively participate and tailor their energy consumption based on individual preferences (price, environmental concerns, etc.).
7. Improved market efficiency through innovative solutions for product types (energy, ancillary services, risks, etc.) available to market participants of all types and sizes.
8. Higher quality of service–free of voltage sags and spikes as well as other disturbances and interruptions – to power an increasingly digital economy.

2.4.2 The contribution of Distributed Generation (DG) to the system security

The distributed generation (DG) is defined by CIGRE(International Coucil on Large Electric Systems) Working Group 37-23 [52] as a generation not centrally planned by the utility, not centrally dispatched, normally smaller than 50-100 MW and usually connected to distribution power systems (networks to which customers are connected, typically ranging from 230 V/400 V to 145 kV). The increasing demand of DG can be relied on its financial value which is discussed in [53] .

Presently, there are several renewable resources which are concerned by most of people as, wind power, cogeneration, photovoltaic (PV), small hydro and waste/biomass. Those resources can all be considered as DGs. Different forms of DGs have been installed in Europe and wind energy posses the fastest rates of development with 75GW to be installed in Europe in 2010 [54] and still keeps the increasing rate of growth in some countries. The explanation of this phenomenon can be quite comprehensive, however, there is no doubt that the application of DGs should be due to its economic benefits as well as its contribution to the system reliability.

As has been articulated in [55] , the large-scale penetration of DG will change the power flows in the distribution network. The change in real and reactive power flows caused by DG has its meaning in both technical and economic aspects. Besides, DG can increase the power system security by ensuring a frequency control which can be proved by the case of wind farms that are asked to contribute to frequency control in Ireland and Denmark. In sum, the penetration of DGs will contribute to the enhancement of electric grid security and the development of DG technology is far-reaching.

Chapter 3

Optimal Allocation of Wind Power in Transmission Grids using Sensitivity Method

The purpose of this chapter is to show how the WTLR/ETLR sensitivity method is used in determination of optimal allocation of wind power. Firstly, some concepts are introduced, which include Aggregate MW Contingency Overload (AMWCO), the aggregate percent contingency overload(APCO), Transmission Loading Relief (TLR), equivalent TLR (ETLR) and Weighted Transmission Loading Relief (WTLR), then a case study which is based on Nordic 32 test system is presented to demonstrate the results. The Powerworld Simulator is used to set up the model and solve the problems of getting the good locations as well as the amounts of injection on each location. Finally, several scenarios are studied to see the practical value of using sensitivity methodology. The models for different scenarios are also set up by the Powerworld Simulator and the results are obtained based on the method mentioned above.

3.1 Introduction

Nowadays, two impending problems confine the survival and development of human beings, namely energy and environment. In virtue of the increasing depletion of fossil fuel and increasing concerns on the global environment from people all over the world, governments and international organizations have invested on the exploration of renewable energy in succession from 70s of last century to dig out a resource and environment coordinated path which corresponds to the socio-economic progress as well as sustainable development. As one kind of renewable resources, wind power plays an importance role for its development potential and outstanding advantages. The wind generation has the most mature technology, largest development and commercialization prospects which draw attentions of various countries and results in the widely utilization and exploration throughout the world [56] .

Under the support from the governments, the research of wind generation undertakes a great progress. Many countries as Sweden, Germany, Denmark and U.S.A has begun the projects of large-scale integration of wind generation due to its own advantages of short construction period, flexible installed capability, saving fossil energy, relieving contradictions in power supply and adjusting the energy structure as well as non-consume of fuel, on-pollution influence to the surroundings during operation which has a profound function in maintaining ecological balance.

The work of connecting large-scale wind generation into the power network will generate several problems, such as voltage deviation, voltage fluctuation, flicker and harmonics while more studies have to be done before this. The construction of large wind farms usually come out with the problem of determination of good positions to inject. Where and how much energy should we inject would be a problem for the current electrical engineers [57] [58] [59] .

3.1 Measuring network security

3.1.1 Aggregate MW Contingency Overload (AMWCO)

System security always means the network operates without loss of loads, voltage violations, transmission branches flows within the thermal limits as well as enough safe margins from the collapse point. The strategy for designating a traditional power system is usually done by strictly following the criteria which are set up by different organizations. Usually, the system is designed and planned by taking the N-1 and N-2 contingency analysis which is according to the recommendation of the NERC. In order to show the severity of contingencies as well as the emergency of multiple violations, an indicator is introduced, that is, the aggregate percent contingency overload (APCO) [60] , which can be defined as follow:

$$\mathrm{APCO}_{\mathrm{BRANCH,jk}} = \sum_{\substack{\text{Contingencies that} \\ \text{overload branch jk}}} (\text{loading\%} - 100) \tag{3.1}$$

APCO is the total percent overload flow shown on a certain transmission line during a series of contingencies. We also have the interest to define another quantity to change the overload expression from percentage form into the real value. This is so called Aggregate megawatt contingency overload (AMWCO) which is expressed as,

$$AMWCO_{BRANCH,jk} = APCO_{BRANCH,jk} \times MVARating_{BRANCH\ jk} \tag{3.2}$$

From the expression, we can see that the AMWCO is actually calculated by using MVA rating instead of MW. It is necessary to be in accordance with the definition of transmissions loading relief (TLR) which will be explained later.

Based on these two quantities, we can easily point out the weak elements[1]. The higher the value is, the weaker the transmission element is. While zero means no overload contingency happens on this line. In spite that both two quantities are able to rank the weakness, we prefer to use AMWCO in most case since it can give the real value information [61] .

[1] It means when there is contingency on other transmission line this line will undertake serous overloading.

3.1.2 Weighted Transmission Loading Relief (WTLR)

To meet the increasing load demand, it is necessary to increase the generation. However, the transmission lines would be overloaded without proper regulation. A common way to solve this problem is to use DG which can be seen in Figure 3.1 [62] :

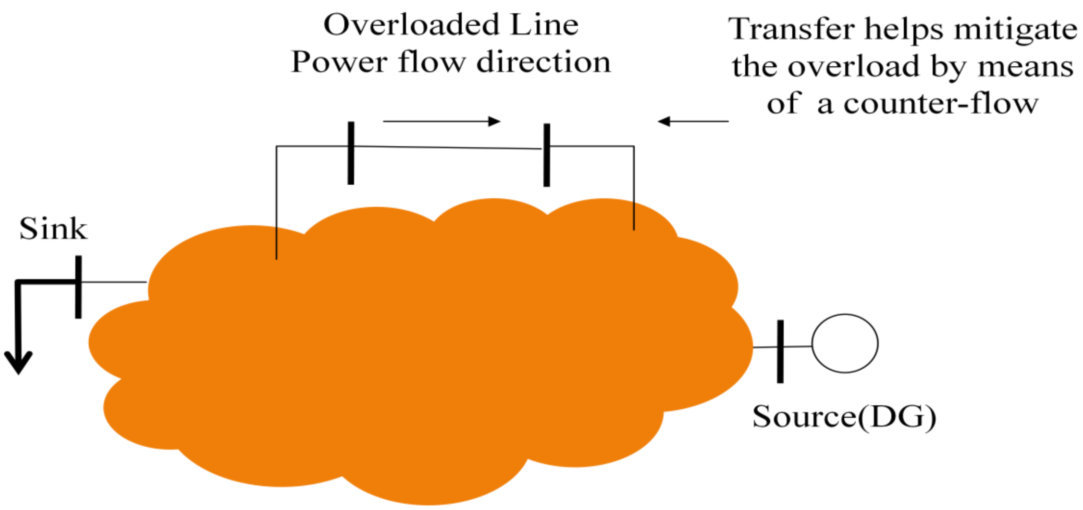

Figure 3.1: Source and Sink

The graph indicates that DG can be injected locally to produce counter-flows that help reduce contingency overloads. Wind power generation can be used as one kind of DG, however, there will be an opposite impact on the transmission line if the power flow direction in Fig 3.1 is reversed. Hence, the determination of locations is dominant for wind generation planning [63] .

When we plan to install a wind project at a certain place, the new generation at that bus will certainly influent the flows in the transmission element. The emergence of TLR gives us the chance to know the impact of the new injection before contingencies.

- Post-contingencies TLR

$$TLR_{BUS\ i,BRANCH\ jk} = \frac{\Delta MWFlow_{BRANCH\ jk}}{\Delta MWInjection_{BUS\ i}} \tag{3.3}$$

In the case of contingency analysis, it is necessary to calculate TLR Sensitivity, which represents the MW increase in an element per MW transfer Contingency TLR.

- Contingencies TLR

$$TLR_{BUS\ i,BRANCH\ jk,CONT\ c} = \frac{\Delta ContMWFlow_{BRANCH\ jk,CONT\ C}}{\Delta MWInjection_{BUS\ i}} \tag{3.4}$$

Once a wind farm is built up in one location, it will certainly influence some other branches concurrently which incur the change in the angle under distinct contingency conditions. Therefore, an equivalent TLR (ETLR) sensitivity is nominated to catch the entire variation of flows during contingencies after injection.

$$ETLR_{BUS} = \sum_{\substack{jk \in Overloaded \\ Elements}} \sum_{\substack{Contingencies\ that \\ overloaded\ branch\ jk}} TLR_{BUS,i,BRANCH,jk,CONT\ C} \quad (3.5)$$

Despite that the ETLR remarks the simultaneous effect of Injection, it does not consider the severity of the contingency overloads which is the base to mitigate overload at times. This is overcome by WTLR which has the general formation as follow:

$$WTLR_{BUS,i} = \frac{N_{CONT}}{AMWCO_{Sys}} \times \sum_{jk \in Branches} \begin{pmatrix} COD_{ir_{BRANCH}jk} \\ \times TLR_{BUS\ i.BRANCH,jk} \\ \times AMWCO_{BRANCH,jk} \end{pmatrix} \quad (3.6)$$

COD_{ir}: The overload direction, if the line is overloaded in the forward direction during all the contingencies, then the value will be 1 while the value will be minus 1, if it is always overloaded in the reverse direction during all contingencies [64] .

N_{CONT}: The number of contingencies,

In general, the ETLR and WTLR sensitivity are two good indicators to help decide the good locations to inject. The ETLR signifies the total expected MW contingency overload reduction, in all transmission lines and under all contingencies, if 1 MW is injected at that prescribed bus. Positive ETLR and WTLR sensitivities point that new injection will tend to increase overloads and reduce overall system security and vice verse. While 1MW of new injection at the particular bus has a great possibility to reduce 0.5 MW of overload in transmission branches during contingencies, if a WTLR value of 0.5 is seen at that bus. Based on this, we can continue to determination of good locations. A flow chart can be seen below in Figure 3.2, where GIS means Geographic information system [65] [66] .

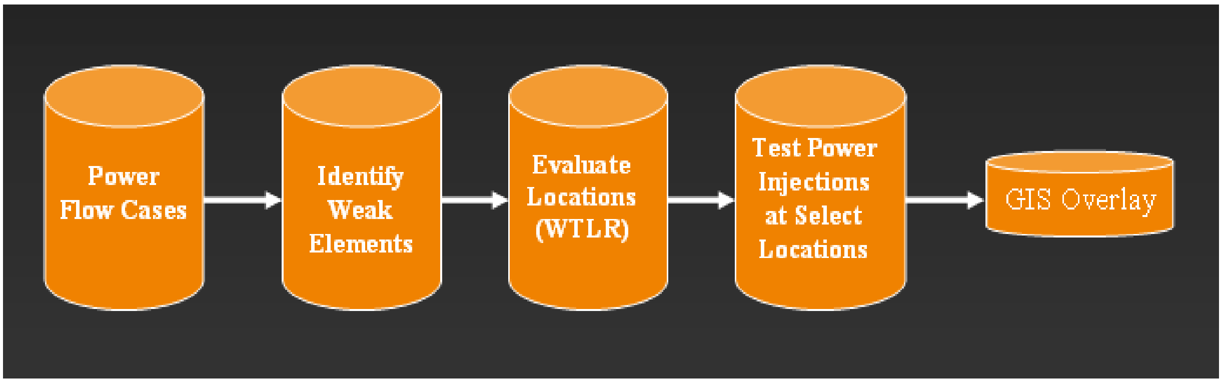

Figure 3.2: The process for determination of good locations

In engineering, we prefer to use WTLR sensitivity instead of ETLR sensitivity to determine the optimal locations to inject. The reason is based on the fact that the contingency information of a weak element can be captured.

3.2 Simulation part

The previous concepts have been demonstrated using Powerworld Simulator and a 32-bus test system. What more, the ETLR/WTLR methodology is performed in order to obtain optimal allocation of wind generation.

3.2.1 System description

For this study, a modified Nordic 32 bus system was utilized. The single line diagram of the original Nordic 32 bus system is shown in Figure 3.3. As we can see, it consists of four major areas [67] :

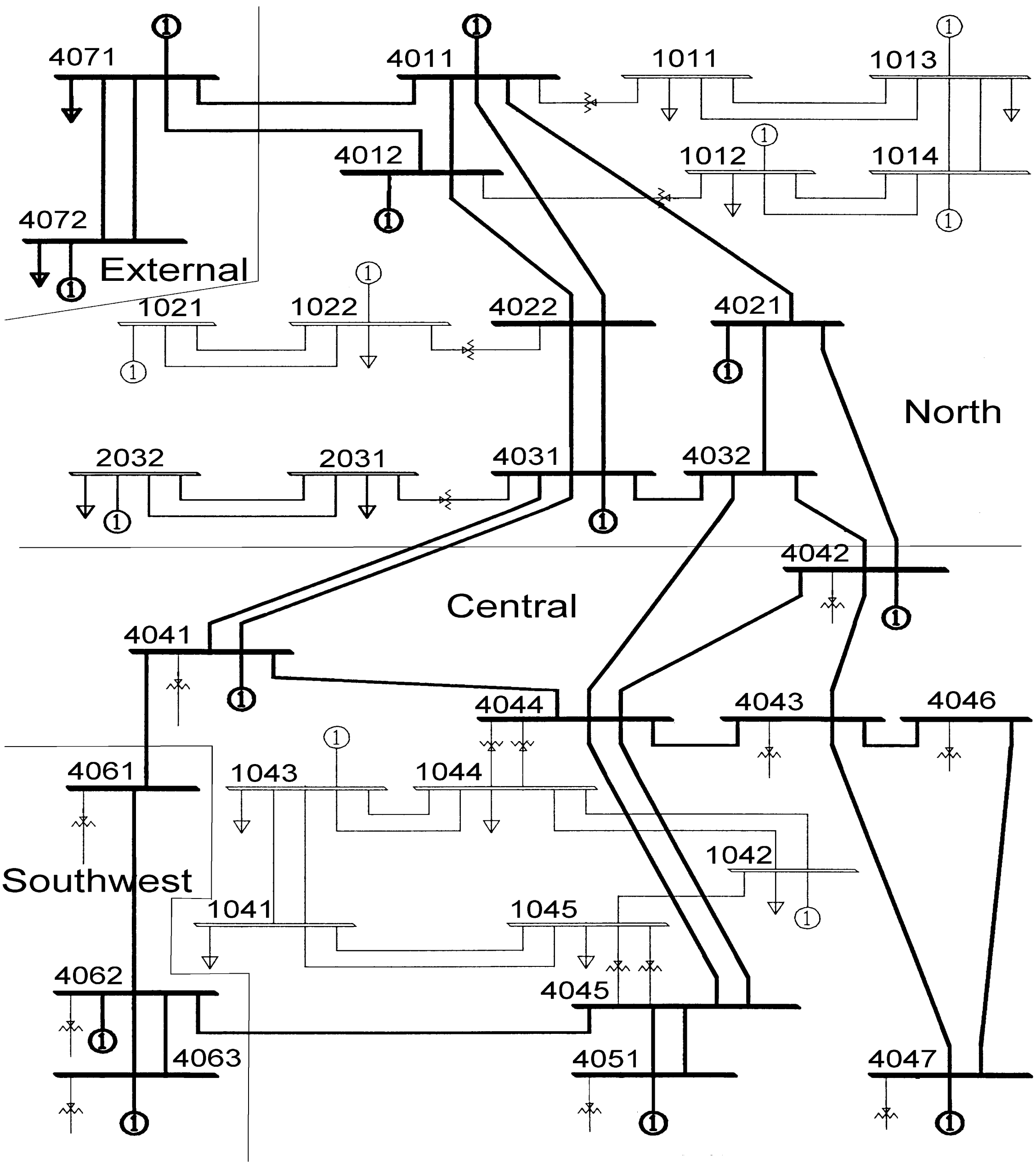

Figure 3.3: Nordic 32-Bus System Single Line Diagram

- External: connected to the North. It has a mix of generation and load.
- North: with basically hydro generation and some load.
- Central: with a large amount of load and rather large thermal power generation.
- Southwest: with a few thermal units and some loads.

The power is basically transferred from the "North" area to the "Central" area. The system has its main transmission system designed for 400 kV, with some other regional systems at 130kV and 220kV. There are total 19 generators and shunt compensation is considered in case of voltage violation. Bus 4011 is selected as the slack bus, moreover, Bus 4071 and 4072 is chosen as the external part which can be regarded as the foreign country power supply.

3.2.2 Optimal allocation of wind power

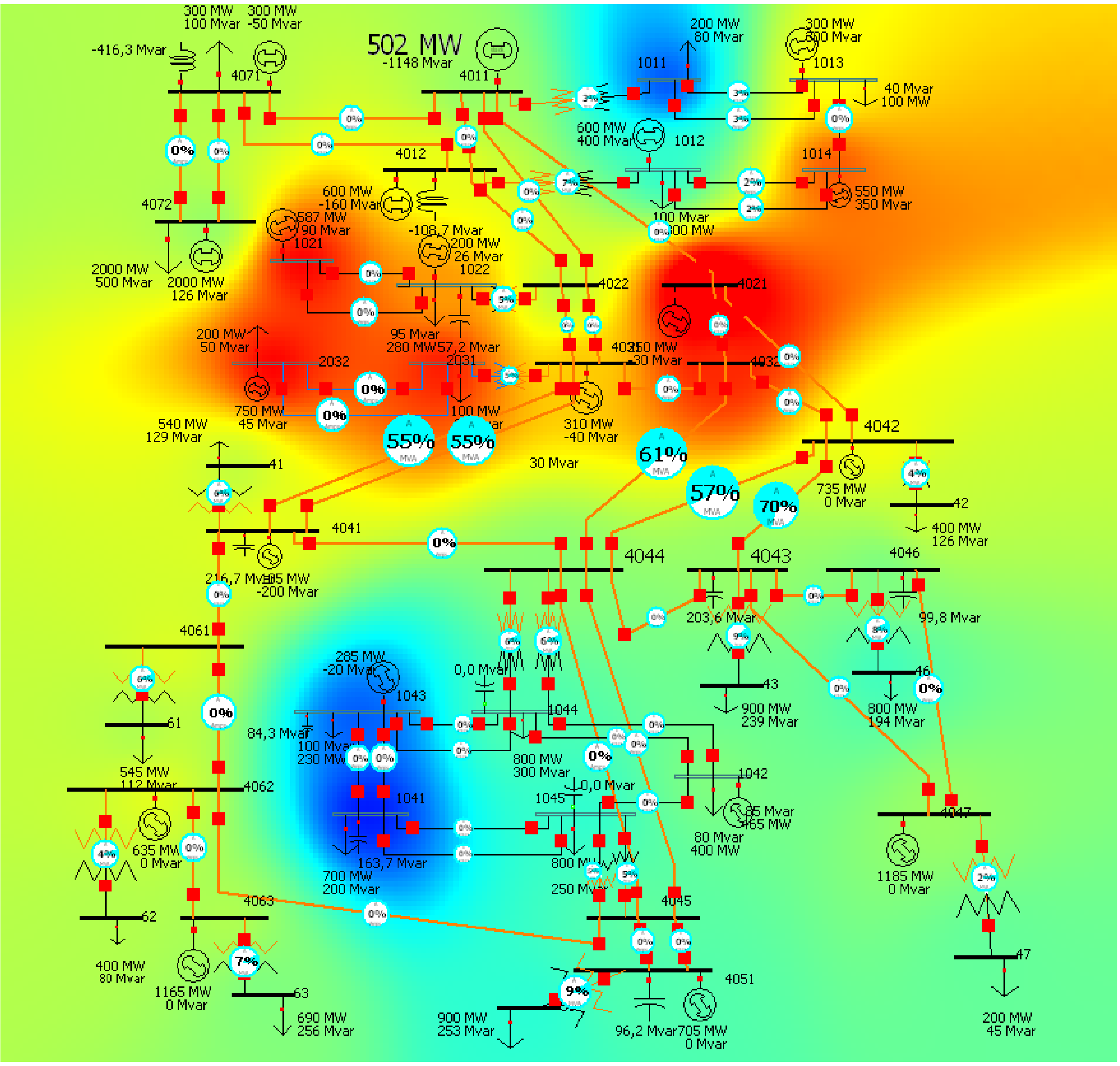

Figure 3.4: Voltage profile of scenario 2010

From the base case, we can see that the five main lines which transport power from north to south are undergoing more loading than the other lines. Hence, we can predict that there will be overloading problems occurred on these lines when we increase the load demand. Originally, we have a Nordic 32 test system with a total 10940MW loads demand. According to the statistic report of Nordel, the electricity consumption in Nordic power market is assumed to grow 1.5% per year [68] . Based on this, we give a 1.5% load increase per year to the Nordic 32 test system and increase the load demand to 11785 MW after 5 years load augment and this is considered to be the base case which can be seen in Figure 3.4:

We give the name scenario 2010 to the base case for further use. Also we set up another two scenarios, namely scenarios 2015 and scenarios 2020 to present the results and analysis. The creations of these two scenarios are based on the above statement. We give a 1.5% load increase every year and the load demand for scenario 2015 and 2020 are 12696MW and 13678MW respectively. We emphasized the existence of the slack bus generator and the five main lines because the slack bus generator will support the whole system once there is load-generation imbalance while the five main lines are undertaking the highest power transmission burden. The colored background shows the voltage difference among the system. The red means the highest voltage and blue means the lowest voltage. The simulation steps are exhibited in Figure 3.5:

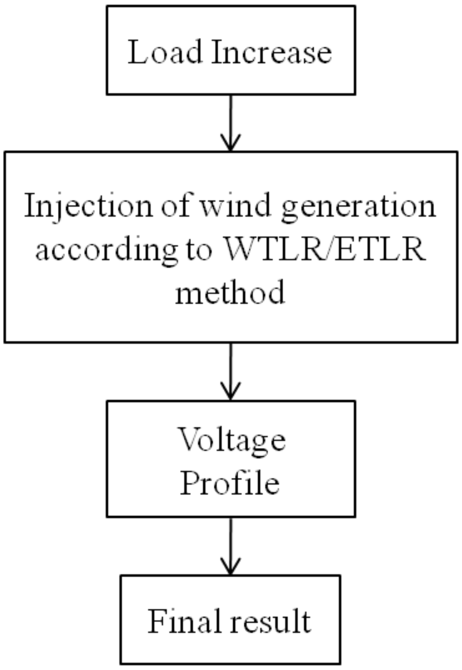

Figure 3.5: Simulation phases

Consider the test system described in section 3.2.1, we run the N-1 contingency to analysis the security of this system. In Figure 3.6, the arrows refer to the active flows' direction and the proportion of line loading is shown through a pie chart. The red area represents the weak elements while the blue means there is no violations on these branches. The weak branches were selected by AMWCO values which are shown in Table 3.1. Information about the number of contingency violations, the aggregate percentage overload (APCO), the aggregate MW contingency overload (AMWCO) as well as the from bus and to bus names are included in this tablet. The contingency overloaded lines are ranked based on AMWCO. Obviously, line 4042 to 4043 and 4042 to 4044 are the weakest elements in this system, what's more, as can be seen from Table 3.1, line 4042 to 4044 suffered more serious condition than what line 4042 to 4043 did.

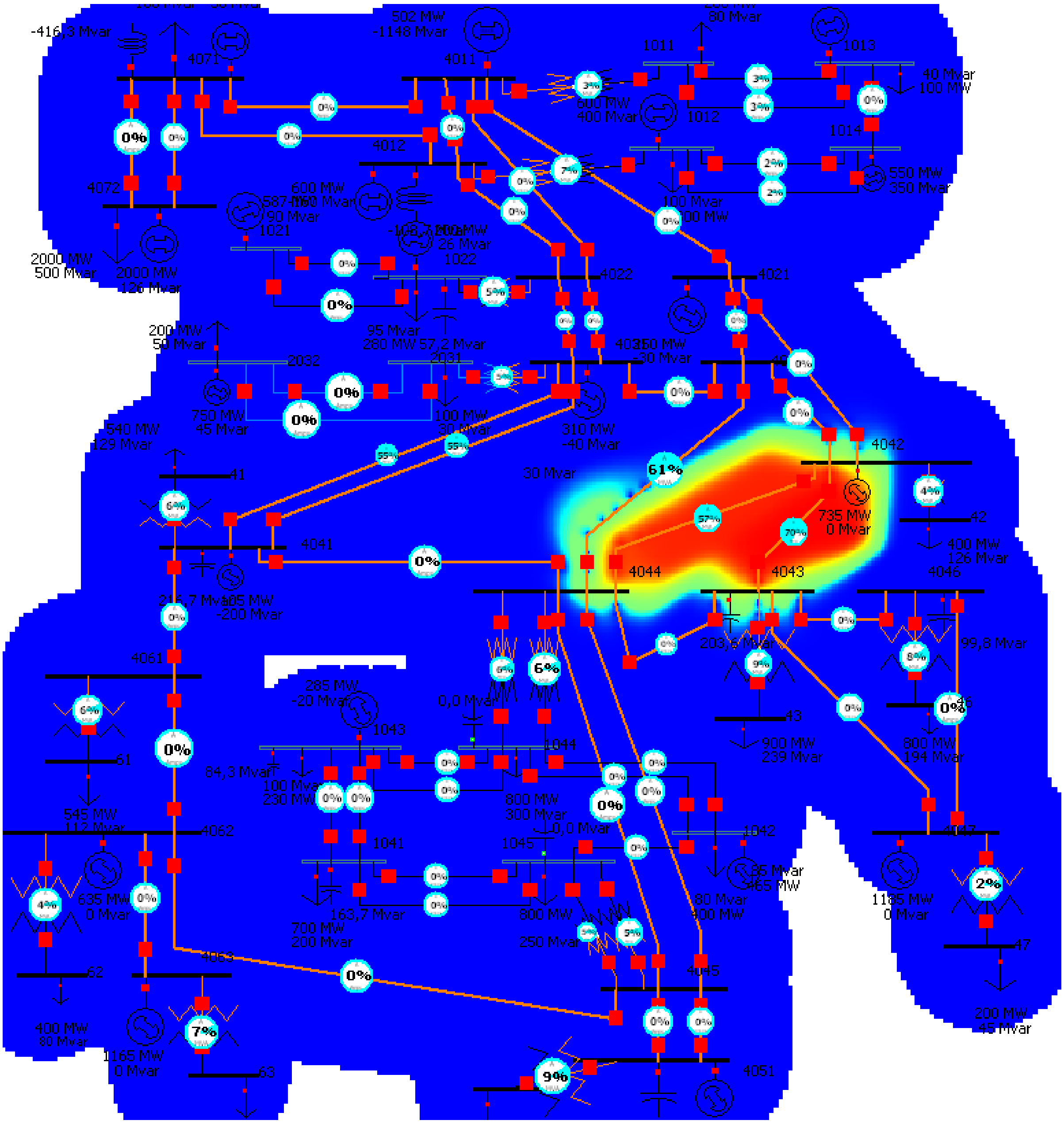

Figure 3.6: Visualized Weak elements

Table 3.1 shows that there is one violation on each weak branch with an AMWCO of 156.1 MVA-overload and 146.3MVA-overload respectively which is responded to what we presumed previously.

Table 3.1: Weak elements selected by AMWCO

From BUS	To BUS	Lim MVA	APCO(MVA)	AMWCO(MVA)	Violations
4042	**4043**	1200.00	13.00	156.10	1
4042	**4044**	1200.00	12.20	146.30	1

For the purpose of increasing system security, new injection should be located properly to generate counter-flow in the overloaded branches to help fulfill the mitigation. Therefore, we need to calculate the ETLR and WTLR sensitivity to go on with the selection work. The ETLR as well as WTLR results for each branch are listed in Table 3.2:

Table 3.2: WTLE&ETLR sensitivity

				Multiple Bus TLR Sensitivities
Number	**ETLR**	**WTLR**	**4042 to 4043**	**4042 to 4044**
41	-0.11	-0.11	-0.04	-0.07
42	0.55	0.55	0.26	0.29
43	-0.36	-0.38	-0.38	0.01
46	-0.36	-0.37	-0.38	0.01
47	-0.36	-0.37	-0.37	0.01
51	-0.31	-0.31	-0.13	-0.18
61	-0.17	-0.17	-0.06	-0.10
62	-0.18	-0.18	-0.07	-0.11
63	-0.17	-0.17	-0.07	-0.11
1011	0.12	0.12	0.06	0.06
1012	0.12	0.12	0.07	0.05
1013	0.12	0.12	0.07	0.05
1014	0.12	0.12	0.06	0.05
1021	0.10	0.10	0.06	0.04
1022	0.09	0.09	0.05	0.04
1041	-0.34	-0.33	-0.14	-0.19
1042	-0.29	-0.29	-0.12	-0.17
1043	-0.32	-0.32	-0.14	-0.19
1044	-0.30	-0.30	-0.12	-0.18
1045	-0.30	-0.30	-0.13	-0.18
2031	0.06	0.06	0.04	0.02
2032	0.07	0.07	0.04	0.03
4011	0.12	0.12	0.06	0.06
4012	0.11	0.11	0.06	0.05
4021	0.23	0.23	0.11	0.11
4022	0.09	0.09	0.05	0.04
4031	0.06	0.06	0.04	0.02
4032	0.11	0.11	0.06	0.05
4041	-0.11	-0.11	-0.04	-0.07
4042	0.55	0.55	0.26	0.29
4043	-0.37	-0.38	-0.38	0.01
4044	-0.30	-0.30	-0.12	-0.18
4045	-0.30	-0.30	-0.12	-0.18
4046	-0.37	-0.38	-0.38	0.01
4047	-0.36	-0.38	-0.38	0.01
4051	-0.31	-0.30	-0.13	-0.18
4061	-0.16	-0.16	-0.07	-0.10
4062	-0.18	-0.17	-0.07	-0.11
4063	-0.17	-0.17	-0.06	-0.11

4071	0.12	0.12	0.06	0.05
4072	0.12	0.12	0.06	0.05

The data we obtained is based on the scenario 2010. From the table above, we can get information of the impact of new injections on the system. It is evident that injecting power at bus 4046, 4043, 43, 4047, 46, 47 and 1041 would be most effective since it has the lowest value which means that injecting at these buses would have the greatest contributions to the mitigation of contingency overload. BUS 1043, 62, 4062, 63, 4063, 61and 1042 can be saved as backup for their relatively lower negative value, however, we also get the information of poor injection's positions, which are BUS1011, 1013, 1014, 4071 and 4072. Once wind project is launched at these locations, it will certainly increase the contingency overloads. The last two columns is the TLR sensitivity with respect to different contingency lines. As we knew, the TLR shows the change in the flow of a line due to an injection at a bus under a contingency condition. The negative sign of TLR means the injection at the specific bus will give a reduction to the contingency line while the positive sign has the reverse meaning.

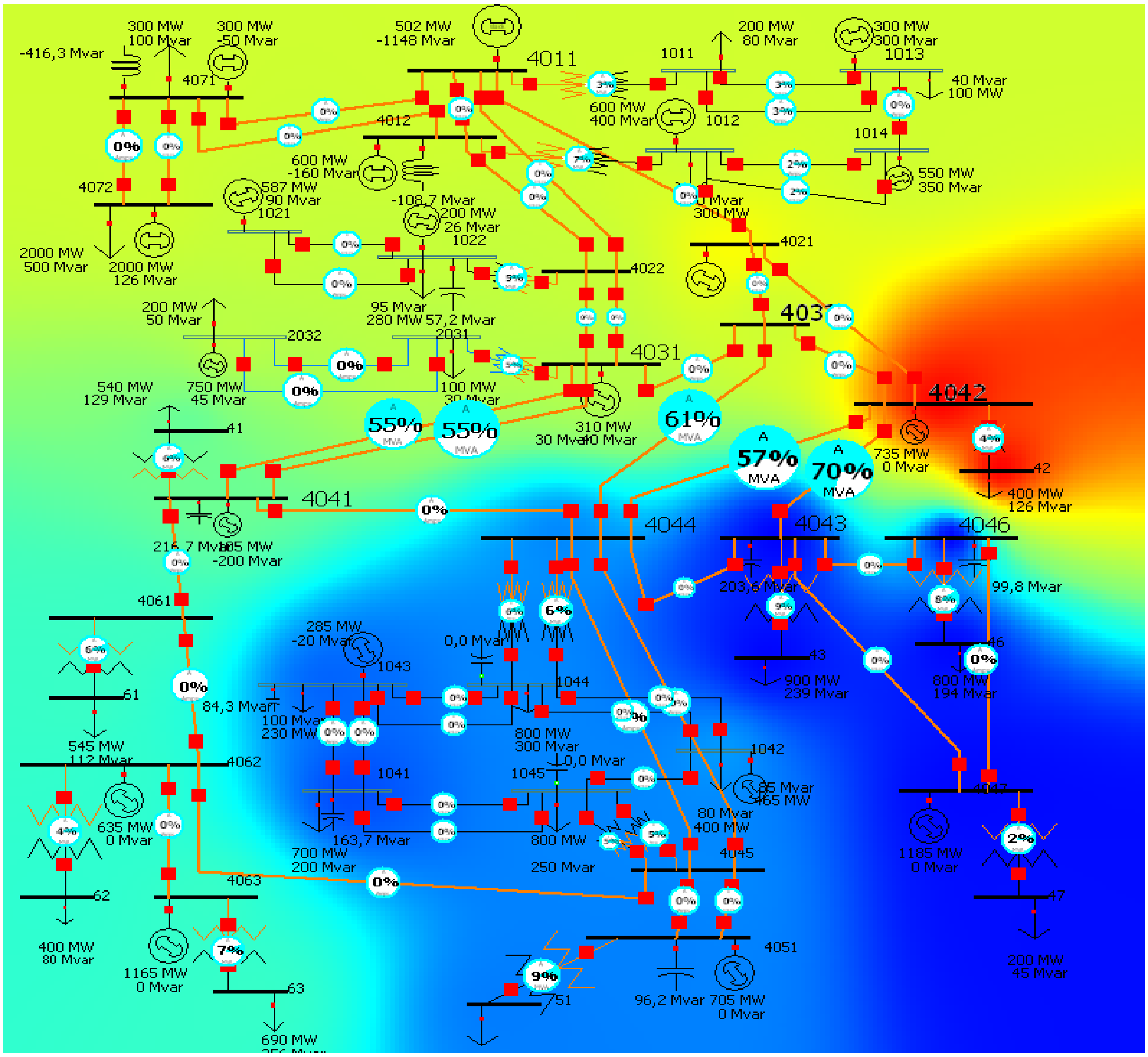

Figure 3.7: Visualization of WTLR sensitivity

In Figure 3.7, a visualization of the WTLR sensitivity is shown. The blue area indicates the best locations for new generation while the red zone indicates the poor locations. We also show interests on some areas which is painted with orange color. This area seems to be insensitive to the new injection. Injections at these places would have insignificant effect. We can prove our assumption by looking it up in Table 3.2. In which we can see that the WTLR sensitivities of these buses are close to zero.

Another conclusion can be drawn by comparing the Figure 3.6 with Figure 3.7, namely, the positive values of WTLR always come out at the sending end of the weak branches, and the flipside of this is that negative values are always found at the receiving end. This has the practical meaning as in a power market, we usually gives a higher price at the receiving end and a lower price at the sending end in order to call the market participants' attentions on generating more at these locations. The simulation result is just in accord with this strategy [69] .

3.2.3 Case study

According to the report of Nordel, the electricity consumption in Nordic power market is assumed to grow 1.5% per year. Based on the scenario 2010 which is modified from the Nordic 32 system with a total load demand of 11785MW which has been described previously, we simulate the load increase for year 2015 and 2020. We give 1.5% increase consumption annually and inject wind energy to compensate for the imbalance between load and generation respectively. Commonly, the load increase problems can be solved by generation dispatch method. But if the generators in the system has already reached its limits, that is to say, the generators cannot dispatch more active power any more. In the case of this, the generators in the system could not change its output to compensate for the load increase automatically and maintain the generation-load balance if we apply the dispatch generation method. Thus, some other approach is calling for to handle this issue. As one form of DGs, wind injection can be selected to meet the requirement. The optimal allocation of wind injection is conducted by using the WTLR/ETLR sensitivity methodology which will be presented in the following statement.

In all scenarios, we increase the load on southern part with uniformly amount of augment. Shunt devices are installed to get a better voltage profile. During the simulation, we use a Synchronous Condenser (SC) to control the voltage at the beginning and then substitute it with shunt devices. This is due to the fact that we should not have so many synchronous condensers in the system in reality, however, shunt devices are usually installed on every substation for the sake of compensation or absorption. Hence, we use the SC just for the consideration of finding a more precise value for shunt devices. In Powerworld Simulator, a SC is generated by setting the active power output to zero in the control panel of generator. As well, we use a negative load to simulate the effects of wind power injections. The utilization of negative loads instead of generators is by considerations of its convenience. Usually, the power factor of wind turbines can be set as 0.85, however, we did not inject any reactive power in these two scenarios, in other words, our wind turbines are assumed to be with a 1.0 power factor. This is due to the reason that the WTLR/ETLR sensitivity is actually active power sensitivity. If we inject the reactive power in each bus, it will influence the loading of each line and give us the obstacle to analyze the final result.

3.2.3.1 Case analysis for scenario 2015

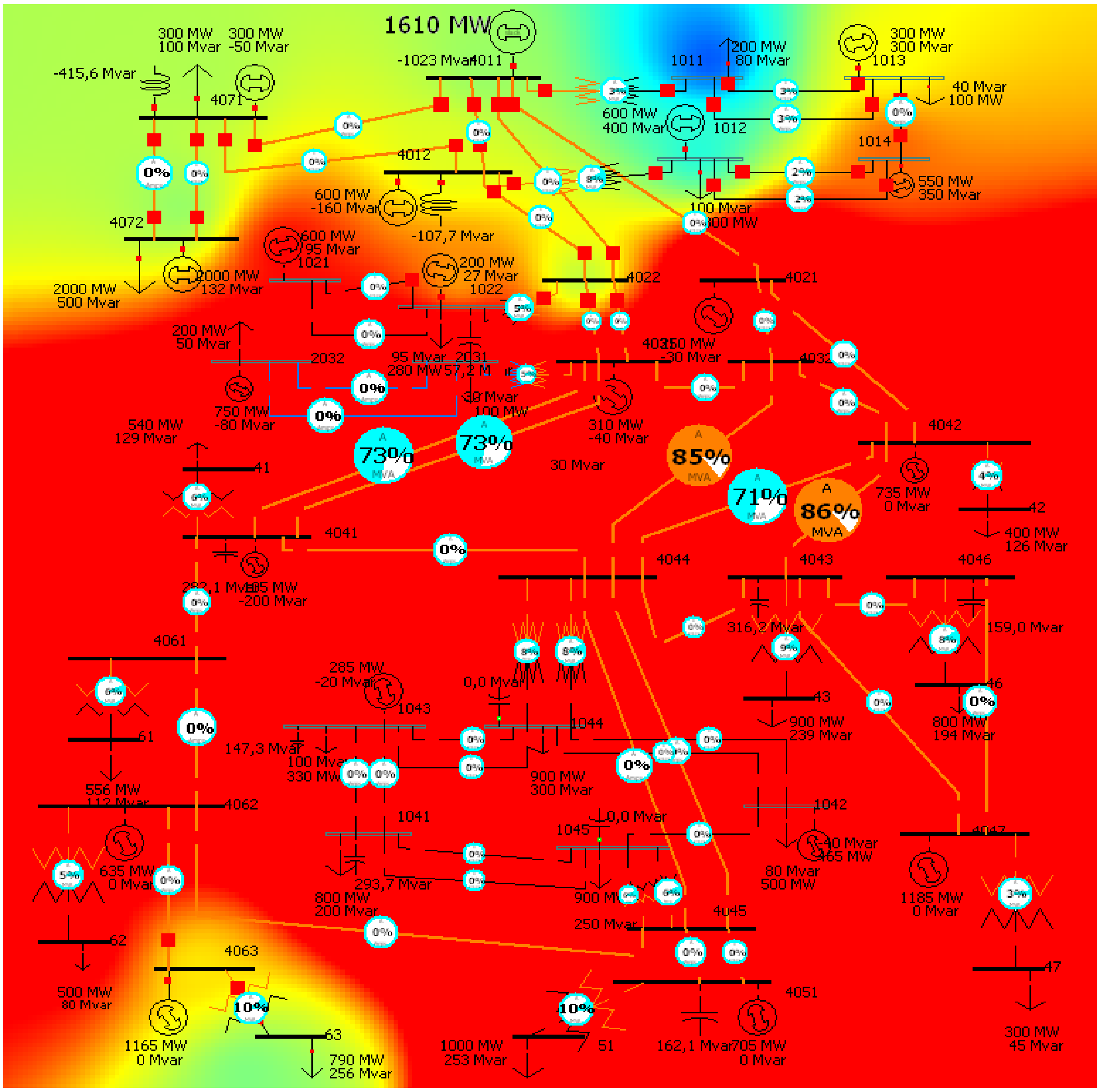

Figure 3.8: The voltage contour of scenario 2015 without any active power compensation

Figure 3.8 shows the condition after load increase without any new injection. It visualized the voltage distribution of scenario 2015. The red color means the voltage was already over 1.15 per unit. In order to support the system and compensate for the imbalance between generation and load, the slack bus generator would support the network by producing more active power. As can be seen, the active power output of the slack bus generator has already reached 1610MW which is far away from its limit of 1000MW while the five main lines which deliver powers from North to south are suffering from high loading contingencies as well. If there is a disturbance happened somewhere within the system, the system would collapse. We need a method to increase the security of this system.

The pie charts of the five main lines show the loading of the present line. It is the critical parts to prove our assumption that is the optimal allocation of wind energy will help mitigate the contingency overload. According to the theory mentioned above, we found the

weak elements at first and then generated the WTLR/ETLR sensitivities by Powerworld Simulator. The data can be seen in Appendix B, Table B.1 and Table B.2 respectively. The data in these tables gives us several selections to choose where to inject. It is obviously that BUS1041, BUS1043 and BUS4051 are the optimal locations. We inject 1200MW power into these buses uniformly. The amount of injection is selected by consideration of two aspects: slack bus generator output and loading of five main lines. We intercept part of Table B.2 to analyze, as follow:

Table 3.3: WTLR/ETLR sensitivities of selected buses

Bus Name	**ETLR**	**WTLR**	**TLR 4031 to 4041**	**TLR 4031 to 4041**	**TLR 4032 to 4044**	**TLR 4042 to 4043**	**TLR 4042 to 4044**
1041	-0.69	-0.78	-0.09	-0.09	-0.19	-0.13	-0.19
4051	-0.67	-0.75	-0.09	-0.09	-0.18	-0.13	-0.18
1043	-0.68	-0.77	-0.09	-0.09	-0.19	-0.13	-0.18

From the theory we mentioned in section 3.1.1, we get to know that a WTLR of 0.5 at a bus means that 1MW of new generation injected at the specific bus is likely to reduce 0.5 MW of overload in transmission elements during contingencies while a ETLR of 1 represents the expected MW contingency overload reduction, in all branches and under all contingencies when we inject 1MW at that particular bus. Based on these, we can draw the conclusion that the new injection at Bus1041 is likely to reduce 156MW, 0.78 multiply by 400MW and divided by two, of overload in transmission elements during contingencies while it also contributes to 276MW, 0.69 multiply by 400MW, contingencies overload reduction.

Moreover, the effects of new injection on line 4031 to 404, 4032 to 404, 4012 to 4043 and 4042 to 4044 can be analyzed by the TLR sensitivities which show the power flow change of a line due to the new injection at the specific bus. In our case, the injection at Bus1041 helps mitigate these five lines by a power flow reduction of 36MW, 36MW, 76MW, 52MW and 76MW respectively. The results of influence of the other injections on other lines can be obtained by similar process. The visualization of voltage profile after wind injection and the loading information of five main lines in this case can be seen in Figure 3.9:

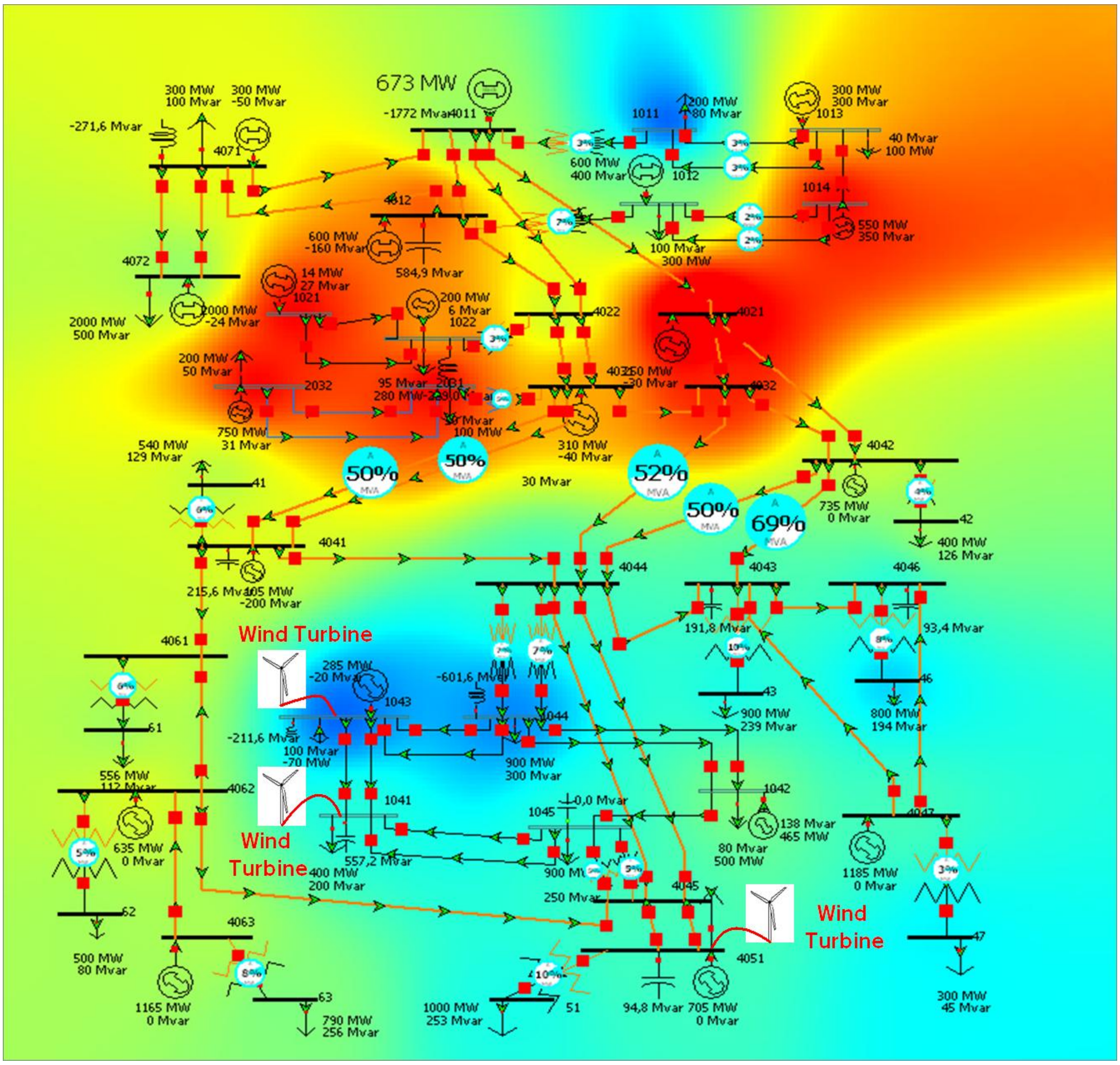

Figure 3.9: The voltage profile of 2015 after wind injection

The slack bus generator outputs 673MW active power to the system which is within the limit and the loading of the five main lines has been reduced significantly which can be known by comparing Figure 3.8 with Figure 3.9.

In same way, we finished the simulation of scenario 2020. The voltage profile and the optimal locations of wind injection of scenario 2020 can be seen in Appendix A, Figure A.1 and Figure A.2. The comparisons of two scenarios are listed in Table 3.4. The scenario 2020 is set up based on the scenario 2015 by keep the existing wind farm. Since the power flow has been changed after new injection. We need to recalculate the WTLR/ETLR sensitivity to decide where we should inject the wind generation. In this scenario, the best locations for injection could be BUS4046, 4043 and 46. We injected totally 900MW power to meet the requirement according to the same rule this time. The data about the weak element and WTLR/ETLR sensitivity and be seen in Appendix B, Table B.3 and Table B.4 respectively. All information of voltages on each bus in different scenarios can be seen in Appendix A.

3.2.3.2 Comparisons and Discussions

The Voltage Deviation parameter, gives us an idea of how much the bus voltages are deviated from 1.0 per unit. It was calculated with the following formula:

$$\text{Voltage Deviation} = \sqrt{\sum_{i}^{n} \frac{(1 - V_i)^2}{n}},$$

Where:

V_i: The voltage at bus ‘i’ in p.u.

n: The total number of buses

Comparisons of several scenarios

Table 3.4: Comparisons of different scenarios

	Test system	Scenario 2010	Scenario 2015	Scenario 2020
Consumption(MW)	10940.00	11785.00	12696.00	13678.00
Generation(MW)	11391.80	12226.70	13025.90	13902.20
Compensation(Mvar)	961.23	1107.88	1950.18	2073.22
Absorption(Mvar)	308.65	525.00	1313.77	-1469.94
Wind injection(MW)	0.00	0.00	1200.00	900.00
Voltage deviation	0.18	0.05	0.06	0.06

The result of voltage deviation on load buses is derived from 1.00 per unit standard voltage parameter, which shows that the voltage condition in each scenario is almost same.

The final results of optimal locations and the amount of power that should be injected at the selected location for both scenarios is shown in Table 3.5:

Table 3.5: Injection locations and amounts

Scenario	Bus Name	Injection Amount
2015	1041	400.00
	1043	400.00
	4051	400.00
2020	4046	300.00
	4043	300.00
	46	300.00

In summary, it is so apparently that the system is running normally under different scenarios and all the models show its priority in both voltage stability and system losses in comparison with the base case. Hence, the ETLR/WTLR sensitivity is proved to be a useful indicator for us to decide the locations to install wind project at that location. What's more, we also injected wind energy at BUS.4042 at which the WTLR/ERLT sensitivities are positive to demonstrate the theory.

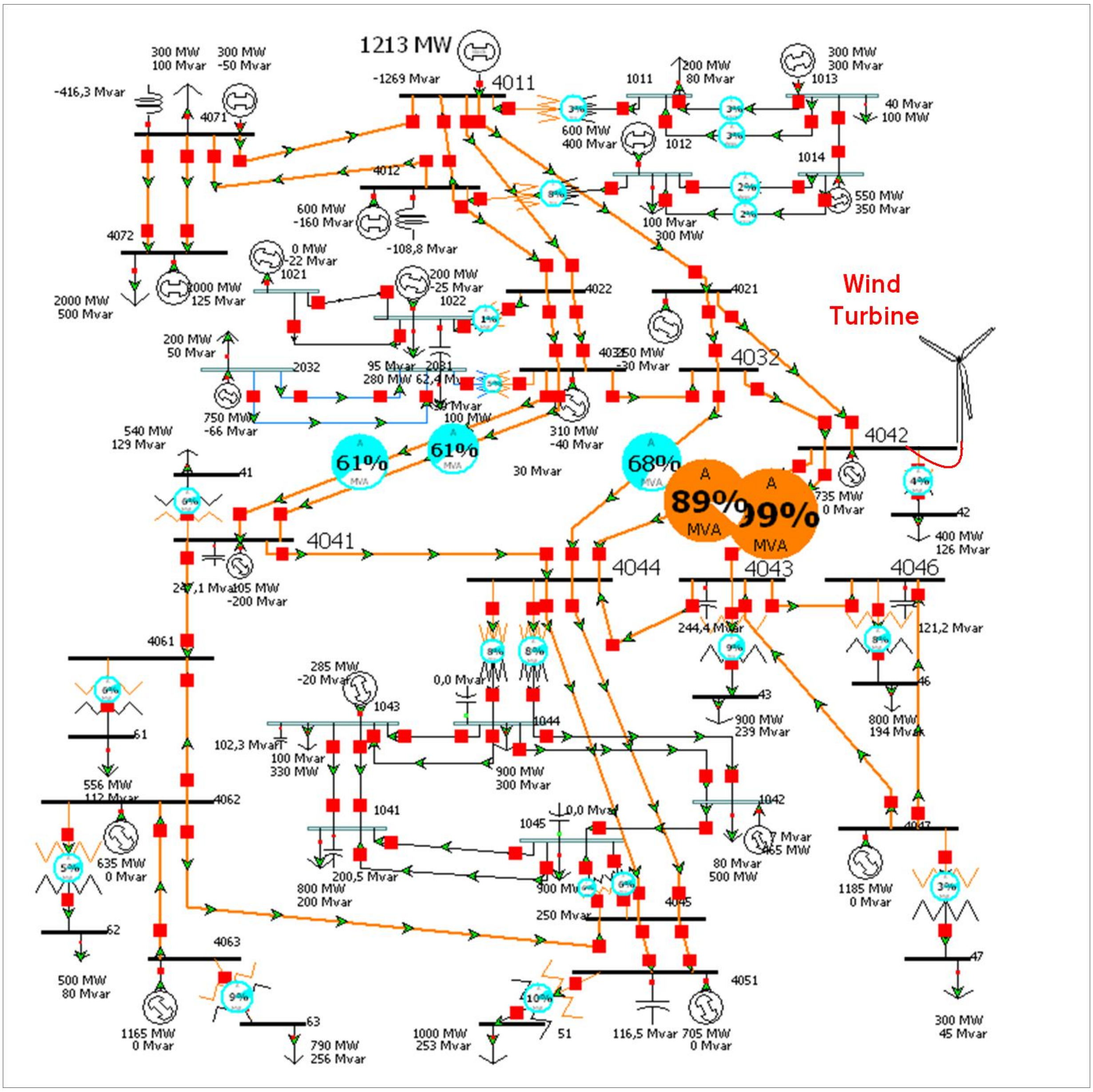

Figure 3.10: The scenario 2015 with wind energy injected to the wrong location

Figure 3.11 shows the result after injecting 800MW active power at BUS4042 at which the ETLR and WTLR sensitivity are positive. By comparing Figure 3.11 with Figure 3.9 and Figure 3.8, we notice that the loading of line 4031 to 4041 and line 4032 to 4044 is reduced while the loading of line 4042 to 4043 and line 4042 to 4044 are increased. The phenomenon can be explained by looking up the Table B.4. In which we notice that the sign of TLR sensitivities for the case injecting at Bus 4042 is not consistent. The line 4032 to 4041 and line 4032 to 4044 has a negative sign which means new injection at Bus 4042 will help mitigate the overloaded contingency on these two lines and the positive sign can be seen on the other two lines shows that the new injection will change the power flow of the two lines and worsen the overload contingency.

In general, injection at unsuitable place will increase contingency overload while the optimal allocation of wind energy can help mitigate the overloaded situation. Different injections can have different effects on different lines during different contingencies.

3.3 Conclusions

In this section, a methodology to determine the good locations of wind energy is presented. Different scenarios are proposed and analyzed to understand the effects of new injections on other branches. The utilization of ETLR/WTLR approach has succeeded in mitigating the problem of contingency overload induced by load enhancement as well as the determination of proper location of wind project and amounts of new injection which proves the practicality of this method. Actually, the reduction of the loading on the contingency lines means the increase of adequacy which is one aspect of power system reliability. The optimal allocation of wind energy is a mitigation scheme which reduces the overload contingency. This action can maintain the power system operate in normal state, that is to say, operate securely. By using the proposed methodology, the power system security and reliability could be increased. Finally, synchronous compensators are used to help find a more accurate value for shunt devices. However, in this case we have a lot of injection points to select instead of choosing it more scientifically we just choose it according to WTLR/ETLR sensitivity without taking into account of the economic factors, such as local generation prices as well as the availability of the wind power. It is a drawback which can be overcame by modifying the model and constrains in future.

Chapter 4

Blackout Prevention by Controlled System Islanding

This chapter presents a method that is widely used in the self-healing part of smart grid to increase power system reliability, so called controlled system islanding or smart islanding. Two methods to find the 'islands' within the system are included, as slow coherency method and minimal cutset method. A 41-bus, 20 generators test system is used to demonstrate the results. A C++ minimal cutset algorithm based program is compiled and implement on the platform of dev cpp to help complete the formation of the islands. After the formation of the islands, we disconnect the lines that connect the islands to simulate the function of smart islanding. Eventually, a modified model of smart islanding is introduced by taking into consideration of the practical issues.

4.1 Introduction

With the application of deregulation and restructuring, power system ,which suffers from the pressure not only from the competition in the market but also some other factors that mainly related to the augmentation both in supply and demand without proper transmission system expansion, are undergoing stressed situation. Since the systems are operated closer to its limits, the systems will not be robust anymore and there is a great opportunity for this kind of weak systems to lose its stability even develop to catastrophic failure. An intelligent strategy for planning and controlling the electric network is asked to solve the existing problems. The emergence of smart grid adapts the needs of the times.

As an advanced technology, smart grid has its own characteristics which are concluded in Figure 4.1, in which the main features of smart grid are presented. The unique characteristic of smart grid is self-healing. Based on this, a smart islanding method is proposed to increase the power system stability [70] .

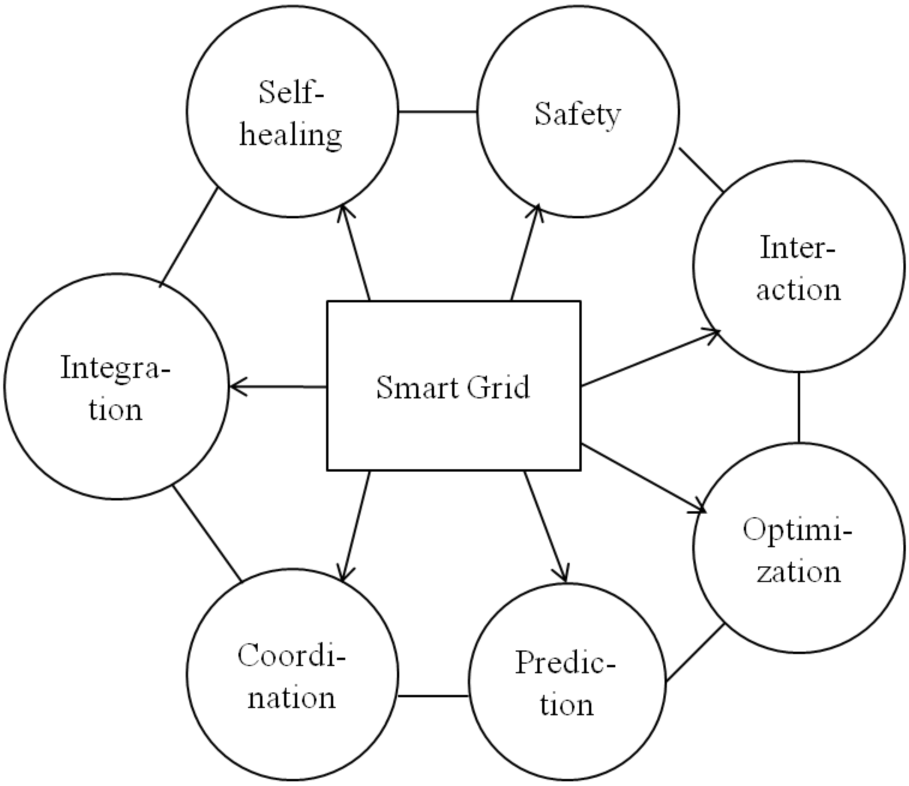

Figure 4.1: Definition of smart grid

Since 1975, plenty of researches have been done to slow the instabilities of large-scale network via decomposition which can be seen in [71] **Error! Reference source not found.**[72] . The idea is that we use Vector Lyapunov method to find out the weak connections between groups of generators in the power system and partition the whole system into small areas, then a load shedding method can be used to help regulate the unbalanced condition between generation and consumption [73] . Slow coherency theory gives us a tool to find out the groups of generators so that the decomposition method or called smart islanding method can be conducted. Once the islands are set up, they will instantaneously exit the system as soon as the outage happens. This prevents the local outage from evolving into big blackout which is what we learned from the August 14, 2003 U.S.A-Canada Power System Outage [74] .

4.2 Blackout prevention using System Islanding

4.2.1 Slow coherency based islanding

The core content of a smart islanding theory is to find the ‘islands’ within the power system for a given contingency. Several approaches can be used to separate the whole network into small systems, that is, the determination of islands. Two-time-scale theory based slow coherency method is one of these, in which the relations among the generators are considered by time variables [75] .Sometimes we are asked to decompose the huge network into small system with more accurate solutions. Then, a modified method is needed to meet the requirement as tolerance based slow coherency which is described in [76] . In reality, we cannot simply decide the islands by time variables. Some factors should be considered during the formation of the islands, such as location of a disturbance as well as the physical constrains [77] . Within these methods, two assumptions are made:

1. The coherent groups of generators are nearly independent of the size of the disturbance.
2. The coherent groups are independent of the level of detail used in modeling the generating unit [78] .

The first assumption is based on the observation that the coherency behavior of a generator is not significantly changed as the clearing time of a specific fault is increased. While the second assumption is to ensure the generator not to change the basic network characteristics entirely [79] .

Slow coherency theory essentially is based on the singular perturbation or two-time-scale method [80] which make it possible for partitioning the system into r weakly connected areas, in which r means the number of slow coherency groups. After finding the weak connections, we can apply an automatic islanding algorithm which is based on the slow coherency method to form the islands [81] [82] [83] [84] [85] .

4.2.2 Smart Islanding using minimal cutsets

The methodology of minimal cutset introduced by Stoer-Wagner [86] has been widely used in solving the contingency analysis problems. The general description can be explained as: in an undirected connected network, if we remove an edge set then it can be changed into two connected components, the edge set is so called cutset, the minimal cutset is the minimal summation of weighted value.

Classical powers systems are usually consist of buses and transmission lines which connect each other. The power flow in transmission lines are with different values and directions. Therefore, we can regard a power system network as a directed graph with different weights at vertices**.**

The most critical function of smart islanding is to minimize the real power imbalance within the islands to benefit the restoration. When an island is created, we can calculate the imbalance between the real power supply and load demand by computing all the generator vertices and load vertices [87] however, it requires much more computation and the calculation process is really time-consuming. The problem can be simplified by taking into account the branches which are connected to this island without considering the vertex inside it.

The power flows in the transmission line also contain information of the distribution of the generators throughout the system. Once the island is formed, the net flow in the tripping lines indicates exactly how different the real generation and load is within the island (The losses is not taking into account here). Therefore, the problem has been converted into searching the minimal cutsets (MCs) to construct the island with the minimal net flow. We can decompose the islanding problem into two stages:

1. Find Minimal Cutsets;

2. Obtain Optimal Minimal Cutset by various criteria [88]

4.2.3 Comparisons of several methods used in finding islands

The slow coherency method and minimal cutset method can both be used to form the islands; the dominant difference is that in slow coherency theory we need to get the information of the machines while it is not really necessary in the minimal cutset method. Besides these two methods, some method can be used in solving the problem as well. The differences among them can be seen as follow:

Table 4.1: Smart islanding methods comparison

Slow coherency smart partition approach	• Slow coherency among the groups of generators does not vary significantly by the change of initial condition and disturbance. • The two-time-scale weak connection form inherently describes the oscillation feature of large-scale power systems: the fast oscillation within a group of machines and the slow oscillation between the groups via weak tie lines. • The slow coherency method also conserves the characteristics of the coherency-based grouping. It will not be influenced by the size of the disturbances as well as detail of the generator model [82] .
Minimum cutset smart partition approach	o We can decompose the islanding problem into two phases: Find Minimal Cutsets and Obtain Optimal Minimal Cutset by various criteria. o Any additional criteria can be used to formulate the optimization procedure under different conditions in the second stage. o The approach is fully compatible with other techniques. o User-specified requirements can also be included during islanding [88] .
Vector Lyapunov method	o Simple numerical algorithm o Widely used in variety applications ,such as economic modeling, electric power systems, queueing networks and computer system o Suitable for stability analysis[89]

ordered binary decision diagrams (OBDDs)	○ A directed acyclic graph (DAG) representation of a Boolean expression. ○ It has many advantages to system splitting (SS) problems or Balanced partition problem (BP) problem [90]
Hierarch islanding	○ Maintaining stable islanding and utilizing the DG contribution to system availability under conditions of major systemdisturbance. ○ Integrated splitting, real-time load shedding and resynchronization ○ Including Mini Island and Substation Island[91]

4.3 Case study

4.3.1 System description

The model was originally developed with the Powerworld simulator software.In order to find the ‘island’to partition, a C++ minimal cutset algorithm program is compiled and conducted on the platform of Dev cpp to find the solutions.

4.3.2 Modelling of transmission lines and power flow in Powerworld

In order to find the ‘island’, we need first get the total power flow of the test system and set up a datebase according to the obtained values. In Powerworld, we use a lumped π-equivalent model to represent the transmission lines, which can be seen in the Fig 4.2 [92]

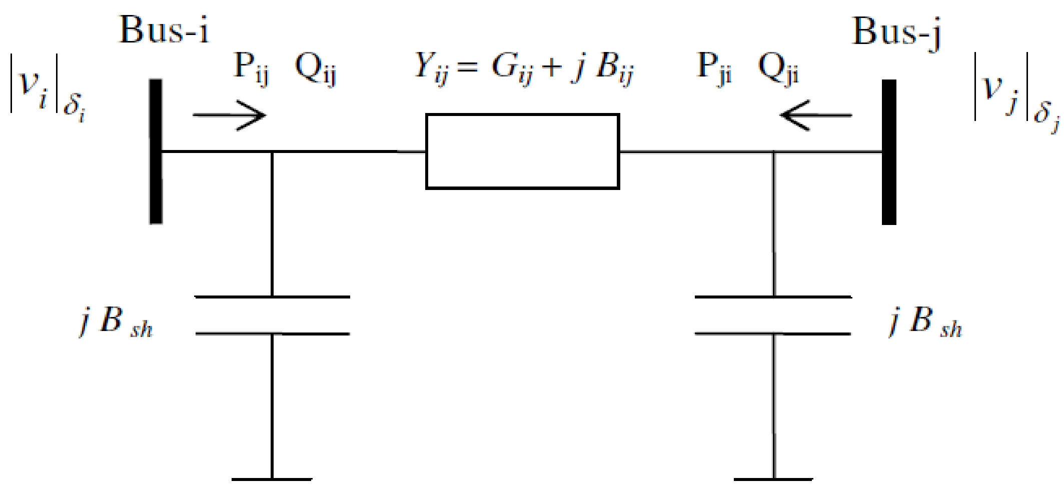

Figure 4.2: Lumped π-equivalent model of a transmission line and power flowing through it

The base model used in this work is specified in section 3.4.1 as follows:

a. Power flow equations

$$P_i = \sum_{j=1}^{n} |V_i||V_j|(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}) \quad (4.1)$$

$$Q_i = \sum_{j=1}^{n} |V_i||V_j|(G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}) \quad (4.2)$$

Where $G_{ij} = \frac{r_{ij}}{r_{ij}^2+x_{ij}^2}$ and $B_{ij} = \frac{-x_{ij}}{r_{ij}^2+x_{ij}^2}$

P_i: the net active power injected at bus i,

Q_i: the net reactive power injected at bus i,

G_{ij}: the real part of the element in the line admittance between bus i and j,

B_{ij}: the imaginary part of the element in the line admittance between bus i and j,

b. Line flow equations

The active and reactive power flow from bus.i to bus.j can be written as :

$$P_{ij} = |V_i|^2 G_{ij} - |V_i||V_j|[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)] \quad (4.3)$$

$$Q_{ij} = -|V_i|^2(B_{ij} + B_{sh}) - |V_i||V_j|[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)] \quad (4.4)$$

While we can get the active and reactive power flow from bus j to bus i in the same way:

$$P_{ji} = |V_i|^2 G_{ij} - |V_i||V_j|[G_{ij}\cos(\delta_i - \delta_j) - B_{ij}\sin(\delta_i - \delta_j)] \quad (4.5)$$

$$Q_{ji} = -|V_i|^2(B_{ij} + B_{sh}) + |V_i||V_j|[G_{ij}\sin(\delta_i - \delta_j) + B_{ij}\cos(\delta_i - \delta_j)] \quad (4.6)$$

What's more, the active and reactive power losses can be computed by using the following equations:

$$P_{loss} = P_{ij} + P_{ji} = G_{ji}(|V_i|^2 + |V_j|^2)G_{ij} - 2|V_i||V_j|G_{ij}\cos(\delta_i - \delta_j) \quad (4.7)$$

$$Q_{loss} = Q_{ij} + Q_{ji} = -\left(|V_i|^2 + |V_j|^2\right)(B_{ij} + B_{sh}) + 2|V_i||V_j|B_{ij}\cos(\delta_i - \delta_j) \quad (4.8)$$

c. Constraints

Generation reactive power limits: $Q_{min} < Q_{gen} < Q_{max}$

Voltage limits: $V_{min} < v < V_{max}$

$$\frac{\pi}{2} \leq \delta \leq \frac{\pi}{2}$$

In Powerworld simulator, we did the simulation by keeping the lower voltage limit to 0.9 p.u and upper voltage limit to 1.1 p.u. The upper limit selection is to avoid insulation failures while the lower limit is selected by considering the safe margins, however, the lower limit selection is not as precise as the higher one [93] . The power flow data from Powerworld can be found in Appendix A.

4.3.3 Enumeration method implemented by Dev cpp

During the simulation process, there are totally 4 main phases in order to find the island which can be listed as,

1. Implement the Powerworld software and get the power flow data from it.
2. Set up a database for the C++ by using the power flow data.
3. Code compilation
4. Results collection and selection

There are plenty of approaches can be used to find the islands. In this work, we fulfill the task based on minimal cutset theory.

4.3.3.1 Algorithm and Problem description

The island is formed when the contingency happens. From the analysis in section 3.3.2, we can see line 4042 to 4043 and 4042 to 4044 undertook the highest risk of overloading. Hence,we implement the smart islanding according to this fact. By increasing the load on bus 4042 step by step, we can know that the maximum load point, namely collapse point is 1559MW. If more power is injected at this bus, a blackout will be incurred which can be seen in Figure 4.4. In order to demonstrate the theory of smart islanding, we take the power flow data which is obtained inmmediately before the blackout. The power flow data is shown in Appendix B and the condition just before the blackout can be seen in Figure 4.3:

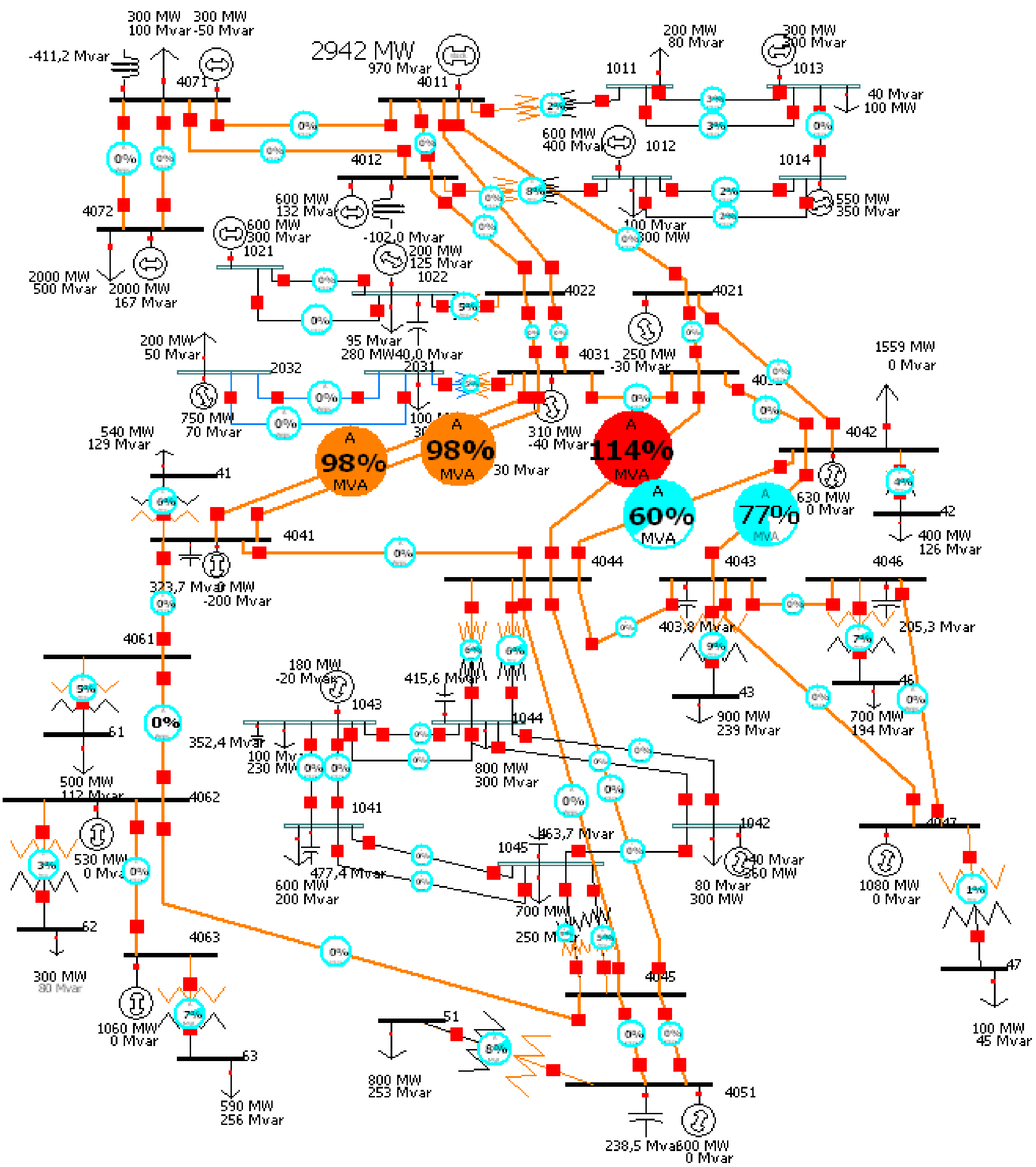

Figure 4.3: Visualization of voltage profile at the point of blackout

From the graph above, we can notice that the line 4032 to 4044 has the loading of 114% due to the increase of 1559 MW load demand on bus 4042. In order to support the whole system, the slack bus generator is forced to generate 2942 MW active power. This is far away from its limit of 1000MW which is not a normal phenomenon in the operation of real power system. If one more MW active power is injected into this bus, then the system will encounter the blackout which can be seen in Figure 4.4. The graphic tells us that the Bus 4042 has already reached its collapse point. If no actions are taken at this time, then the system would turn into total collapse. Thus, a smart islanding method is applied to prevent the accident from developing further,, in other words, prevent the whole system from undertaking big blackout.

The phenomenon of our simulation as to the voltage stability and voltage collapse agree with what has been articulated in [94] .

In this work, the prevention is merely done by static simulation. In fact, the voltage instability problem did occur if we show it in the dynamic simulation.

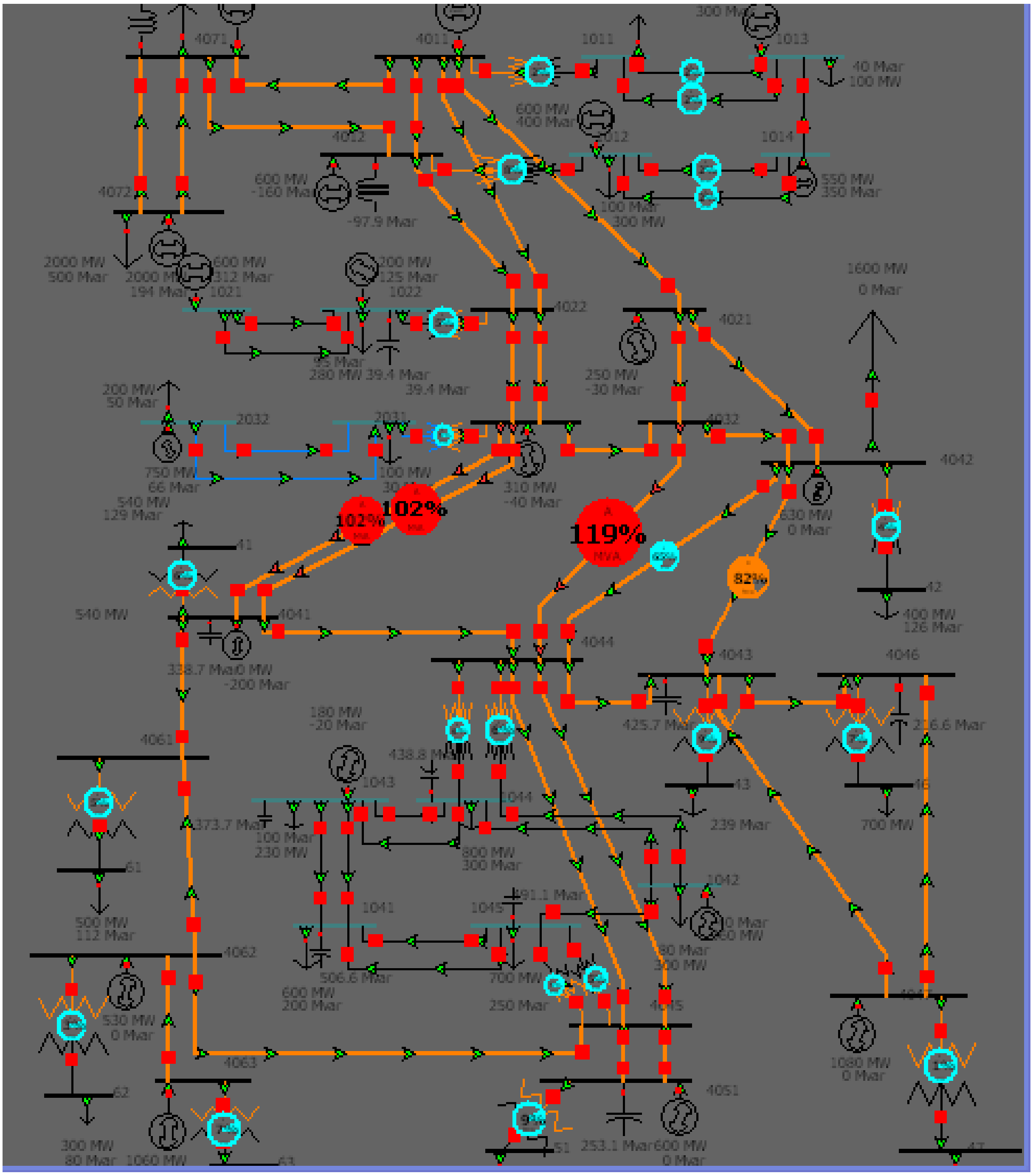

Figure 4.4: The visualization of system blackout with 1600MW power injection

The smart islanding can be implemented by two steps,

- The formation of the islands: Find the areas which has the least power interchange with the others. Hence, it will not affect the other parts a lot when we disconnect this area.
- Disconnet the lines that link the islands: Since the power flow on this lines has no serious impacts on the other lines, we can disconnect them to protect parts of the system to work normally.

4.3.3.2 Formation of the islands

It has been presented in section 3.2.1 that the system contains 41 buses. If we assume that each bus represents a node, then the smart islanding problem can be transferred into a mathematic model. There are totally 42 nodes connecting each other in one graoh. Each side has its weight and direction. The objective is to find connected subgraph which meets the condition that interchange flow among different cutsets is minimum.

As can be seen in Figure 3.3, there are totally 32 buses, namely, 32 nodes within the system. In fact, the system consists of 41 buses, 9 extra buses are not included in the system, which are bus 41, 42, 43, 46, 47, 51, 61, 62 and 63. Since they have no relations with the other buses exvept the buses next to them. We can simplify the model to a 32-node graph instead of 41 which will reduce the computation time by a great extent.

Based on the theory introduced in section 4.2.2, we employ the minimal cutset algorithm to find the islands and the algorithm flowchart can be seen in Figure 4.5.

The formulate of the islands was fulfilled by a C++ minimal cutset algorithm program which is run on the platform of Dev cpp. The program is one citical part of implement the idea of smart islanding. Therefore, we give a name to this program as ‘controlled partition program’.The input file is shown in Appendix B, Table B.6. The visulization of the original senario in the normal operating state is shwon in Figure 4.6.

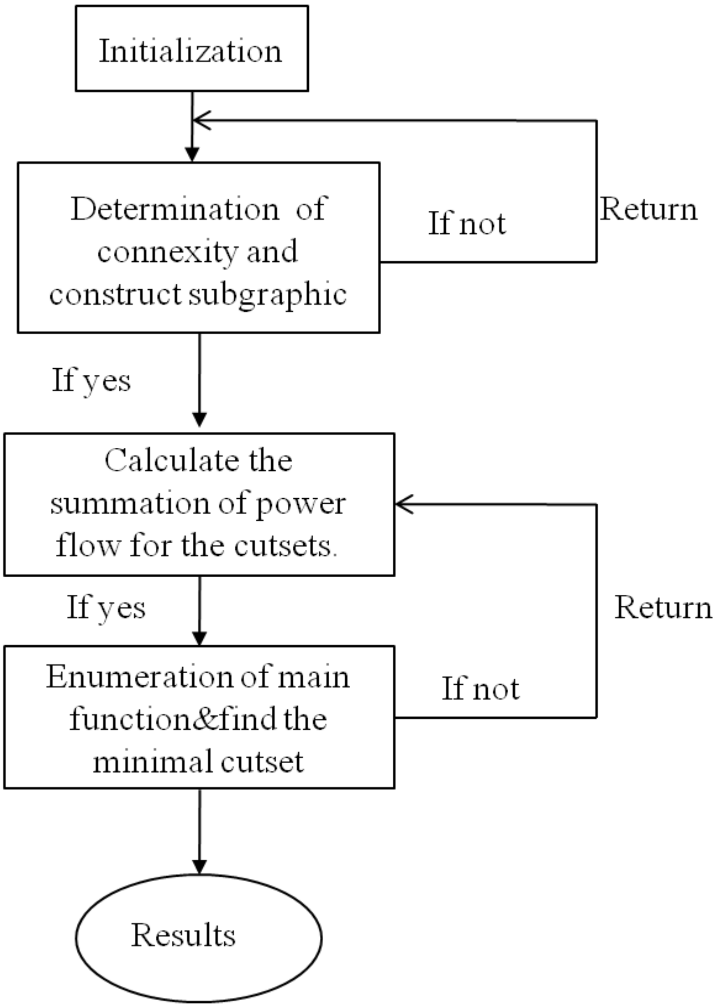

Figure 4.5: The program flow chat

The main phases are explained in details below,

1. Initialization: Since we have already set up a database, a file, which contains the line flow. In this step, the variables are defined and the file contains the line flow data is called.

2. Determination of connectivity and construct sub graphic: Firstly, the program will select some points (buses) randomly. Then a circle is used to judge the points that are selected if the points can compose a connected graph then move to next phase, if not return the beginning of the circle.

3. Calculate the summation of the power flow for the prescribed cutsets: Since we have obtained the entire possible connected sub graph in phase two. In this phase, a Calculation of the power flow that connected to this sub graph is conducted.

4. Enumeration: List all the possible cutsets for this network. Judge the current minimum cutset, if it is smaller than the previous one, and then update the current cutset to the smaller one.

5. Results: Export the results. The island is formed and the buses within the island are selected.

4.3.3.3 Simulation results and discussions

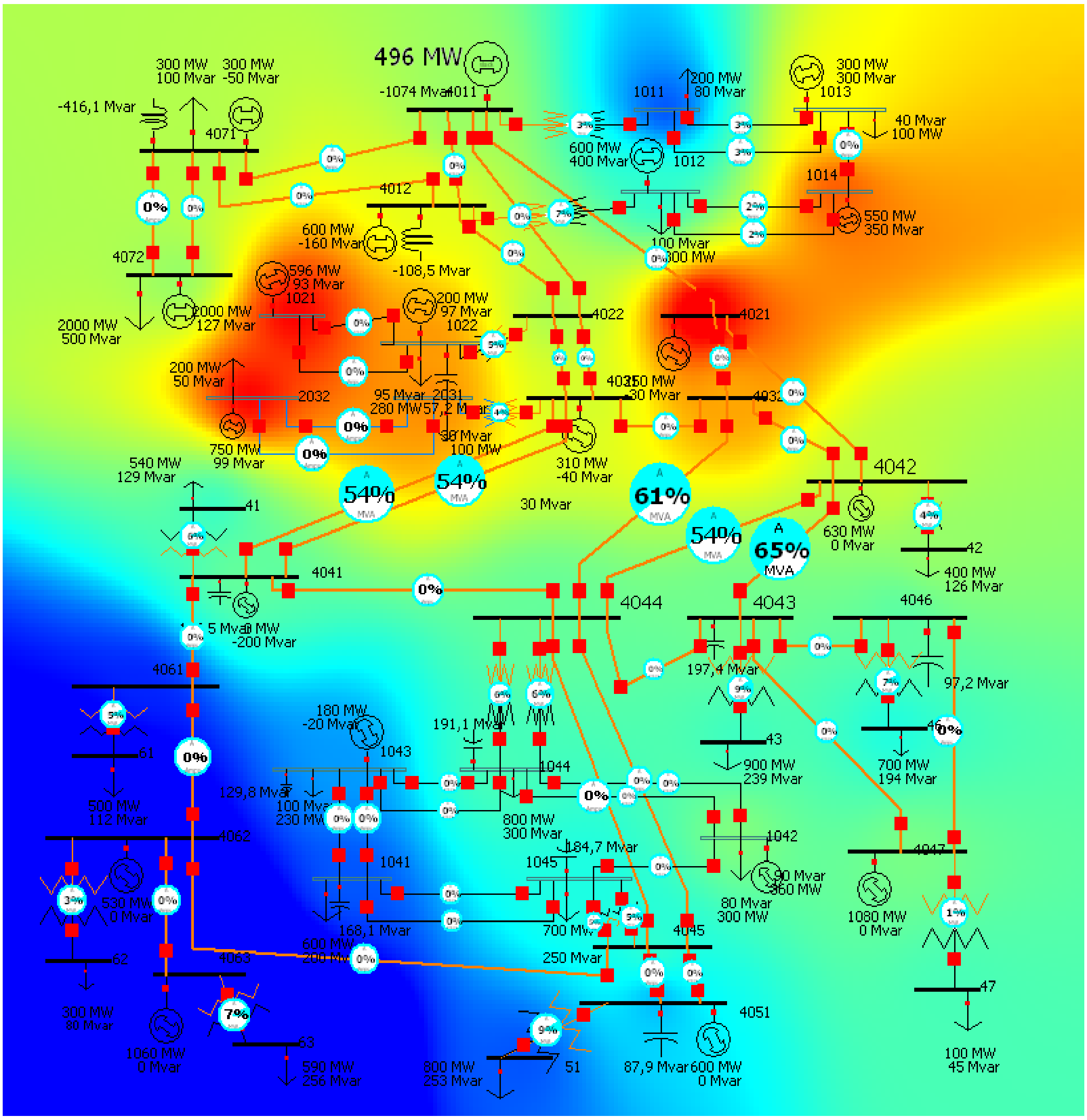

Figure 4.6: The voltage visualization of original scenario

As mentioned before, the program is compiled with the C++ language and run on the platform of Dev cpp and the results are listed in Appendix B, Table B.5. We select result 5 to be the final result randomly. The ‘island ‘that was found by the program can be seen in Figure 4.7:

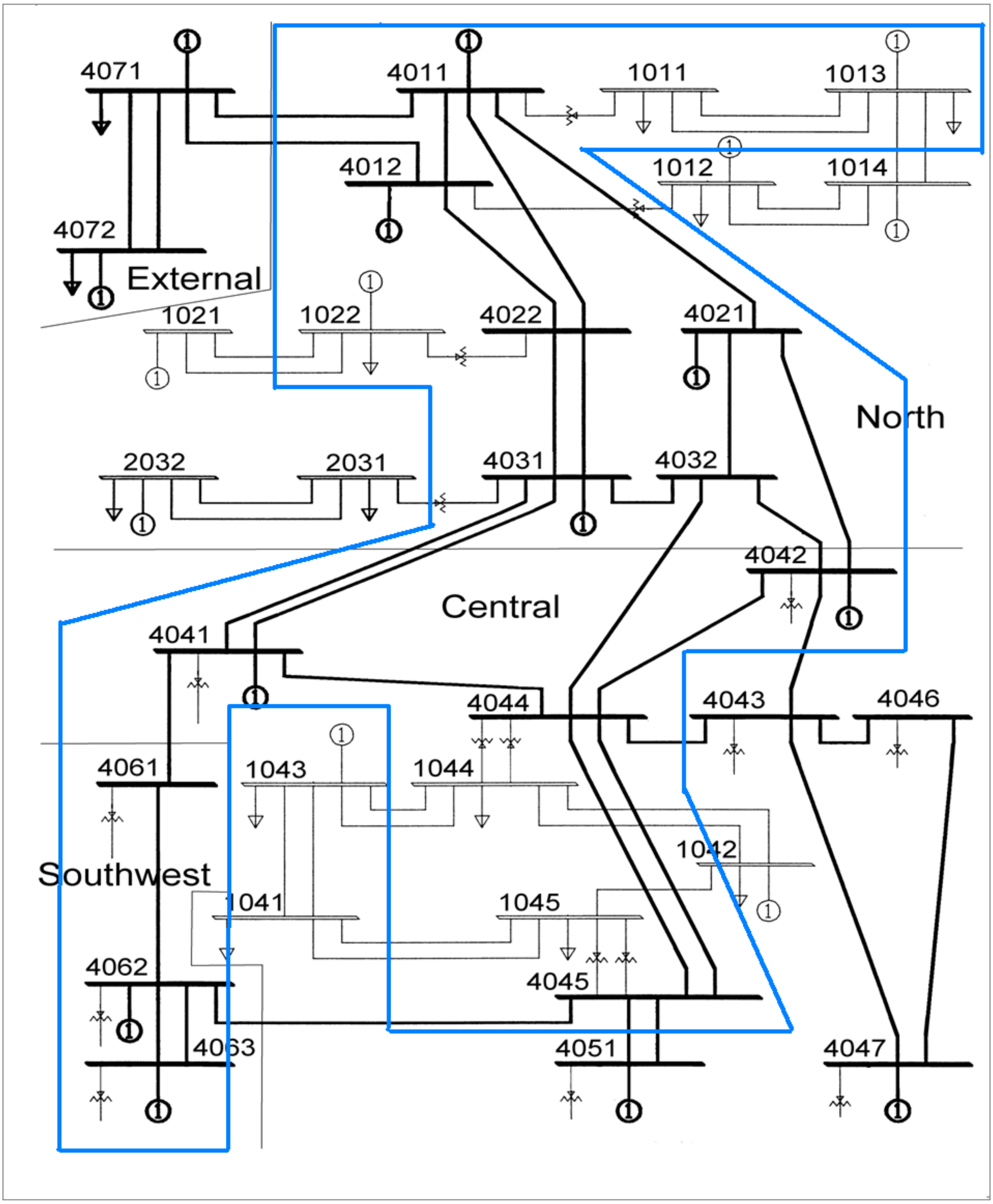

Figure 4.7: The Island found by a controlled partition program

Obviously, there are totally 22 buses that are included in the whole system. In practice, we prefer more areas are operated normally on account that more buses left outside the islands means more areas are working normally so that less restorative actions need to be taken.

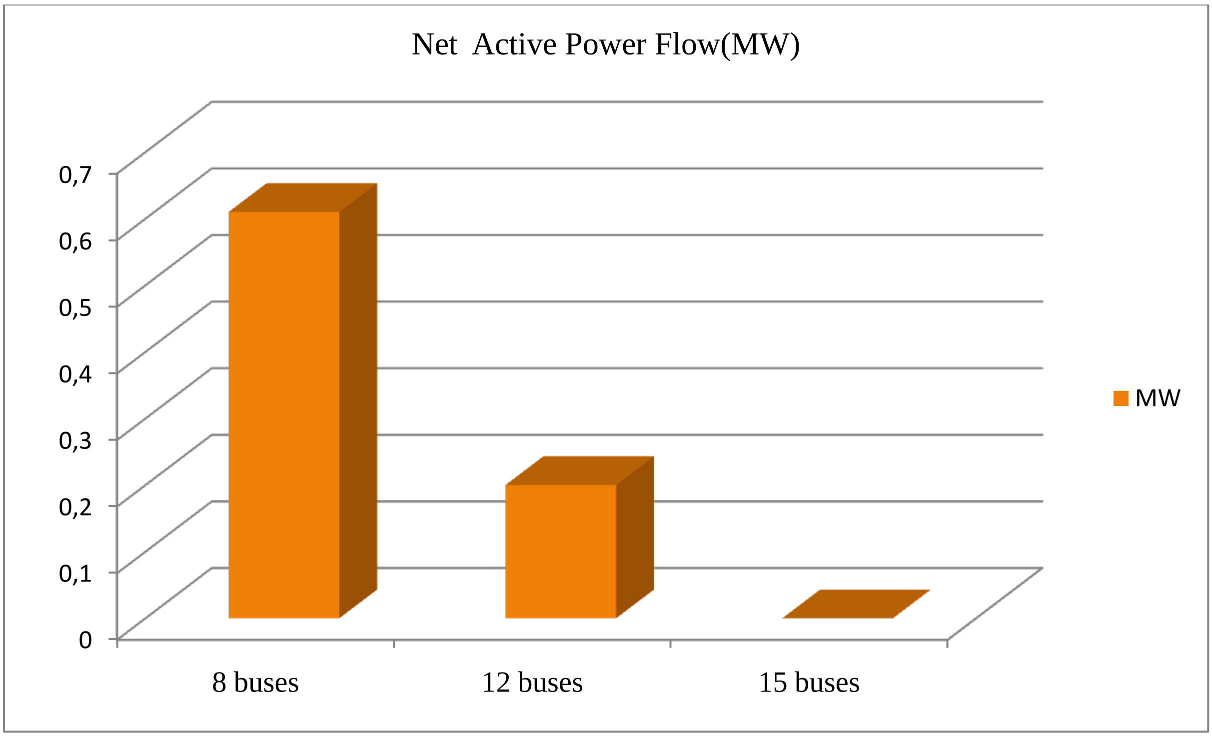

Figure 4.8: Minimal net flow V.S Island's sizes

In order to get an approximately relations between the number of buses included within the islands and the net active power flow. We change the program to find the islands with different sizes which is compared in Figure 4.8. The results of different islands can be seen in Appendix B.

Based on the simulation's results, it is not hard to say that more buses included in the island, less power interchange with the other parts it will be. In other words, more buses in the cutset can keep the imbalance of load and generation to a relative lower value. The objective function of the program is to minimize the net flow while our task is to keep as many as rest power system work normally after the islands are formed. The computer gives us a cutset which meets the requirement that the net power flow is minimal, however, as we knew that there is a trade-off between the number of buses included and the minimum net power flow. One task left for us in practical is to find the optimal solution to satisfy different scenarios under different situations.

4.3.4 Modified islands' model

In order to prevent the total collapse, a modified model is constructed as in Figure 4.9.

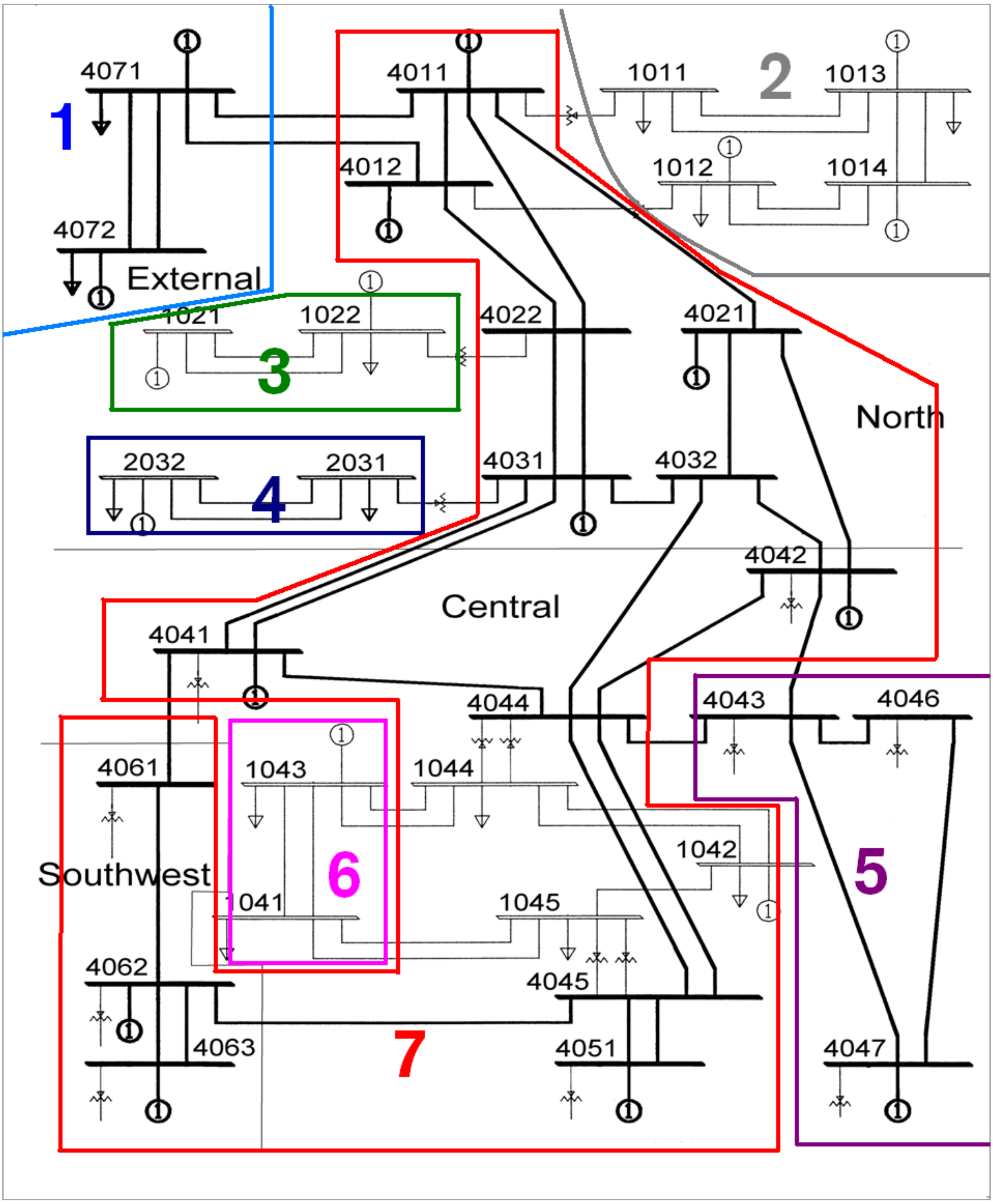

Figure 4.9: The modified formation of islands

Figure 4.9 shows that the whole system has been divided into 7 islands, in which island -7 is the biggest one and it is also where the contingency happened. From the practical point, it is more preferable if we can keep most of the areas working normally; however, we did not expect so many islanding, either. The reason can be referred to the difficulty in controlling of the subsystem after decomposition. Thus, there is a tradeoff existed. The rules should be published according to different situations. The modified model reduces the cutset size from 22 buses to 16 buses. The information of the islands for this scenario is given in Table 4.2.

Table 4.2: Islands' groups

Island Number	Bus Number
1	4071, 4072
2	1011, 1012, 1013, 1014
3	1021, 1022
4	2032, 2031
5	4043, 4046, 4047, 47, 46, 43
6	1043, 1041
7	4051, 51, 4061, 4062, 4063, 61, 62, 63, 4011, 4012, 4022, 4021, 4031, 4032, 4042, 4044, 4041, 4045, 1045, 41, 42

4.3.5 Disconnection from the main grid

Figure 4.10 shows the voltage profile after applying the smart islanding on this unstable system. The green colored lines represent the disconnected lines. The blue area just corresponds to island-7 in Table 4.2. Since there is contingency occurred on bus 4042, we form the island to separate it from the other parts and then more actions can be done to recover the system. From the simulation we can see that the other islands can work normal except island-7. After the formation of the islands, there is a slack bus generator appeared in each island to support its own small system. This means that the system decomposition has been completed successfully. The whole system has been divided into several subsystems.

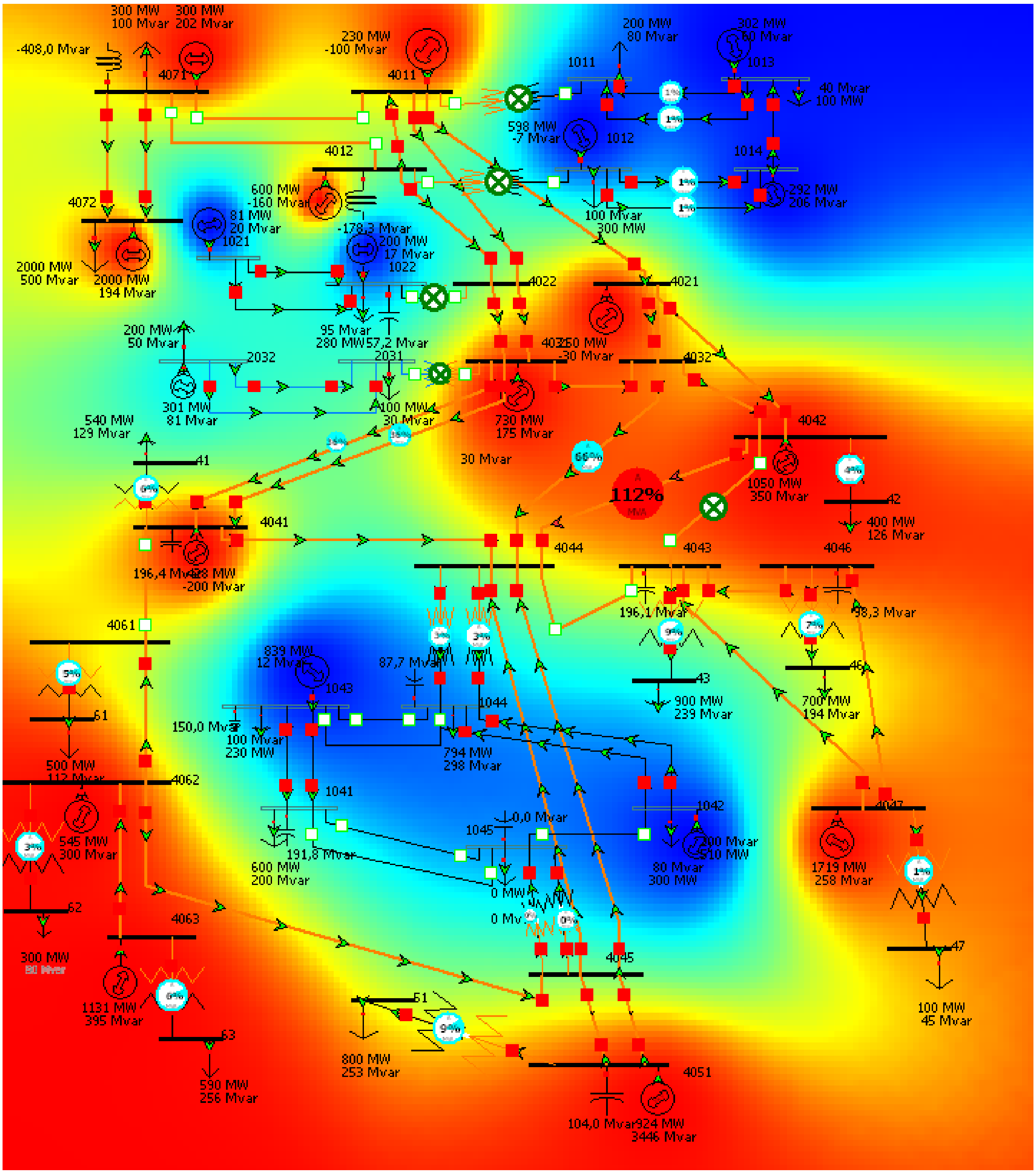

Figure 4.10: The contour of voltage profile after the formation of island

Eventually, a fragment of codes written with C++ language and be implemented in Dev cpp platform is shown as follow:

Controlled Partition Program

```
void initial() //Initialzation,definition of variables
{
    char buf[MAXNUM_BUF];
    char namebuf1[MAXNUM_BUF] , namebuf2[MAXNUM_BUF];
    string name1 , name2;
    int pos1 , pos2;
    double tmp;
    string rstName;
    name2pos.clear();
    for( int i = 0; i < MAXNUM_POINT; ++i )//
           pos2name[i] = "";
     memset( graph , 0 , sizeof( graph ) );
    memset( edge , 0 , sizeof( edge ) );
    nPoint = 0;
    int64 cnt;
priority queue<RESULT>qu;
    const int quSize = 20;


 fIn = fopen( "line_flow_data_32.txt" , "r" );//Input the line flow data which has already         been set up previously
    string fileName;
    time_t currentTime = time(0);
    string timeStr;
    timeStr = (string)(ctime(&currentTime));
    timeStr = timeStr.substr(0,timeStr.length() - 1 );
    for(int i = 0; i < timeStr.length(); ++i)
            if( timeStr[i] == ':' || timeStr[i] == ' ' )
                timeStr[i] = '_';
    fileName = "result_" + timeStr + ".txt
fOut = fopen( fileName.c_str() , "w" );
    while( fgets( buf , MAXNUM_BUF , fIn ) != NULL ){
        sscanf( buf , "%s%s%*d%lf" , namebuf1 , namebuf2 , &tmp );
        name1 = (string)namebuf1;
        name2 = (string)namebuf2;
        if( name2pos.find(name1) == name2pos.end() ){
            name2pos[name1] = nPoint;
 pos1 = nPoint;
            nPoint++;
        }else{
            pos1 = name2pos[name1];
        }
```

```
pos2name[pos1] = name1;
        if( name2pos.find(name2) == name2pos.end() ){
               name2pos[name2] = nPoint;

pos2 = nPoint;
            nPoint++;
        }else{
            pos2 = name2pos[name2];
        }

        pos2name[pos2] = name2;
        graph[pos1][pos2] = graph[pos2][pos1] = 1;
        edge[pos1][pos2] = (int)( tmp * 10000 );
    }
}


void dfs( int u , int64 statei )// searching the points to see if
they are connected or not
{
int i;
    for( i = 0; i < nPoint; ++i )
        if( ( subClr & (1LL<<i) ) == 0 &&
            ( statei & (1LL<<i) ) != 0 &&
            graph[u][i] != 0 ){

            subClr |= 1LL<<i;
            dfs( i , statei );
        }
}

inline bool isConnect( int64 statei )//Judgment of connectivity
{
    subClr = 0;
    int i;
    for( i = 0; i < nPoint; ++i )
        if( ( subClr & (1LL<<i) ) == 0 &&
            ( statei & (1LL<<i) ) != 0 ){
            subClr |= 1LL<<i;
            dfs( i , statei );
            break;
        }
    return statei == subClr;
}
```

```
 void process( int tmpNPoint )//calculation the weight of the summation
of nodes
{
    nPoint = tmpNPoint
;

int i , j;
    memset( value , 0 , sizeof( value ) );

for( i = 0; i < nPoint; ++i )
        for( j = 0; j < nPoint; ++j ){
            value[i] -= edge[i][j];
            value[j] += edge[i][j];
        }
}


inline bool cnt1valid( int64 statei )//calculation the number of nodes
{
    int cnt = 0;
    while( statei ){
        cnt++;
        statei = statei & ( statei - 1 );
    }
return cnt >= 6 && cnt <= 12;
}
int64 cnt;


void findRst()//Enumeration of the main function,find the minimal
cutset
{
    int64 statei;
    int rst , tmpRst;
    int64 rstState;
    priority queue<RESULT>qu;
    const int quSize = 20;

    rst = 0x7fffffff;
    cnt = 0;
    for( statei = 1; statei < ( ( 1LL<<nPoint) - 1 );++statei ){

    if( statei % 10000000LL == 0 ){
            printf( "mission completed : %.2lf%%\n" , ((double)statei /
(double)((1LL<<nPoint)-1) ) * 100.0 );
        }
```

```
 if( cnt1valid(statei) && isConnect( statei ) ){
            tmpRst = 0;
            for( int j = 0; j < nPoint; ++j )

                if( ((statei & (1LL<<j) )) != 0 ){
                    tmpRst += value[j];
                }
            tmpRst = abs( tmpRst );

if( tmpRst < qu.top().rst ){
                qu.push(RESULT(statei,tmpRst));
                if(qu.size() >= 20 )
                    qu.pop();
            }
        }
    }

int rstNum;
    rstNum = 0;
    while( !qu.empty() ){
        rstNum++;
        fprintf( fOut , "the %dth result is %.4lf\n" , rstNum ,
(double)qu.top().rst/10000.0 );
        prtState( qu.top().state , false );
        qu.pop();
    }
}
```

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Since the energy crisis of 1973, people realize that the depletion of non-renewable resource will have significant impact on human beings' life. Hence, more and more concerns are given on the utilization of new sustainable resources to replace the existing ones. As a clean renewable resource, wind power, which has less impact on the environment than the other resources that can be used in electricity generation industry, moreover, the ever-increasing load demand asked for a new form of generation as well. Hence, people shows more interests in the application of wind power generation and governments has begun to increase the proportion of wind generation in the total national generation. However, in order to create more economic benefits to the society, we need to think out the blueprint of a wind power project. One overriding issue to be deliberated is the selection of good locations and the amounts of new injections on each position.

At the beginning, this thesis introduced the WTLR/ETLR sensitivity methodology which gives us good indicators to select the best locations to inject. The results present that the right selection can not only balance the load increase by local generation but also mitigate the contingency overload. The overall loading of the contingency lines are proved to be mitigated by the new injections, however, in some scenario, the loading of certain line is increased though the overall loading is decreased. This is due to the fact that the TLR of each contingency line is not always with the same sign. The positive sign will increase the power flow on that line when inject at a specific bus and vice verse. The reduction of the loading on the contingency lines has two meanings: on one hand, it increase the power system security by making the line transmit power far away from its transmission limit and maintain the system to operate more securely. On the other hand, the reduction of the loading leaves a safe margin for the transmission lines which is the enhancement of the system adequacy. This action increases the power system reliability at some extent. The optimal places are selected according to the value of WTLR/ETLR sensitivity, all places with minus value can be selected as the injection point, however, the decision should be made based on the local climax and local generation price as well. Several scenarios were made up to demonstrate our theory. The results showed that the WTLR/ETLR sensitivity approach is feasible. The new injection succeeded in both reducing the contingency overload as well as balancing the increasing load. Besides, several scenarios tell us that the load increase will generate some problems as overload on transmission lines, the imbalance between the load and generation which can destroy the voltage stability and push the system to operate closer to its limit. This problem has been solved by the new injection successfully. One strange phenomenon that came out during the simulation is that the voltage on certain buses will be increased if we increased the load on these buses. This disobeyed what we expected at all times that the voltage should be decreased when we increase the load. The explanation of this can be relied on the fact that the simulation is done based on a Nordic 32-bus system. In such a meshed network the power flows within the system have changed significantly which would contribute to the emergence of the abnormal phenomenon.

In the next stage of the thesis, we examine the issues related power system security. As explained previously, smart islanding approach is an important solution to the preventive ways of power system big blackout. Several approaches have been carried on to find the islands, such as slow coherency method, minimal cutset method. In this thesis, the smart islanding is conducted based on the minimal cutset theory through which the smallest imbalance area of load and generation is identified. In the simulation, a 32-bus, 20-generators test system is used to demonstrate the feasibility of applying smart islanding method into the power system to construct a self-healing grid. The availability of smart islanding method is proved through a case study. The results demonstrate that it is really a good way to prevent the small outage from evolving into the big blackout. A C++ minimal cutset algorithm based program (Controlled partition program) is set up to find the 'islands'. The Controlled partition program is running on the platform of Dev cpp. The obtained results give us an area that has the least interaction with the rest parts within the system. We also simulate the situation of emergene of contingency, that is, let the island instantaneously quit the system once an outage happened in some place. From the theory, the rest part should be protected if the smart islanding method is useful. This is implemented on the Power simulator. The simulation result is corresponding to what we imaged. The system succeeded in escaping from incurring serious power accidents. The power system is saved by this method and turned into normal operating state instead of emergency state. The power system security and reliability are increased by the application of smart islanding, however, there is one thing that is not very practical during the simulation as the blackout happened after the contingency overload. In practical, the construction of the overhead lines and cables should have been already considered the factors related to the overload condition. Rather, the insulation problems will be happened before the blackout.

5.2 Future work

With the rapid growth of electricity consumption, there will be more wind projects installed. Besides the determination of the good locations to inject, more work can be done by taking into account of the economic benefits. As we know, the prices on each location has a prominent difference, the determination of injection should be planned by thinking of using Optimal Power Flow(OPF)method to find out the optimal power that should be inject at a certain location under a given price. Also local factors should be considered like the regular wind performance. Even if the location is the best place to inject, we cannot install wind turbines in a place which is lack of wind. Besides, the consideration of fault ride through study for wind power after selection of locations should be done as well. Presently, grid codes usually ask the wind turbines to keep connected during grid faults so that it can support the system till the fault is cleared. The wind turbines must be designed to withstand the voltage disturbances. More work should be done after the integration of wind energy into the existing grid in future work.

On the other hand, the smart islanding prevents the emerge of big blackout, however, more attentions should be paid after the formation of the islands. In load-rich islands, a load shedding scheme is usually used while the generation shedding scheme is applied in a generation-rich island. More work can be done in dynamic simulation of the system in combination of islanding algorithm. As showed in the previous work, certain measures can be used to protect the system from a total collapse, as modification of protection setting, smart islanding, circuit-breaker blocking, tap-changers transformers blocking and loading shedding. The loading shedding and circuit-breaker blocking measures have already been done in [94] In future, dynamic simulation of voltage and frequency control during the blackout combing with smart islanding method to prevent total collapse can be done under the help of Advanced real-time Interactive Simulator for Training and Operation (ARISTO) system.

Appendix A

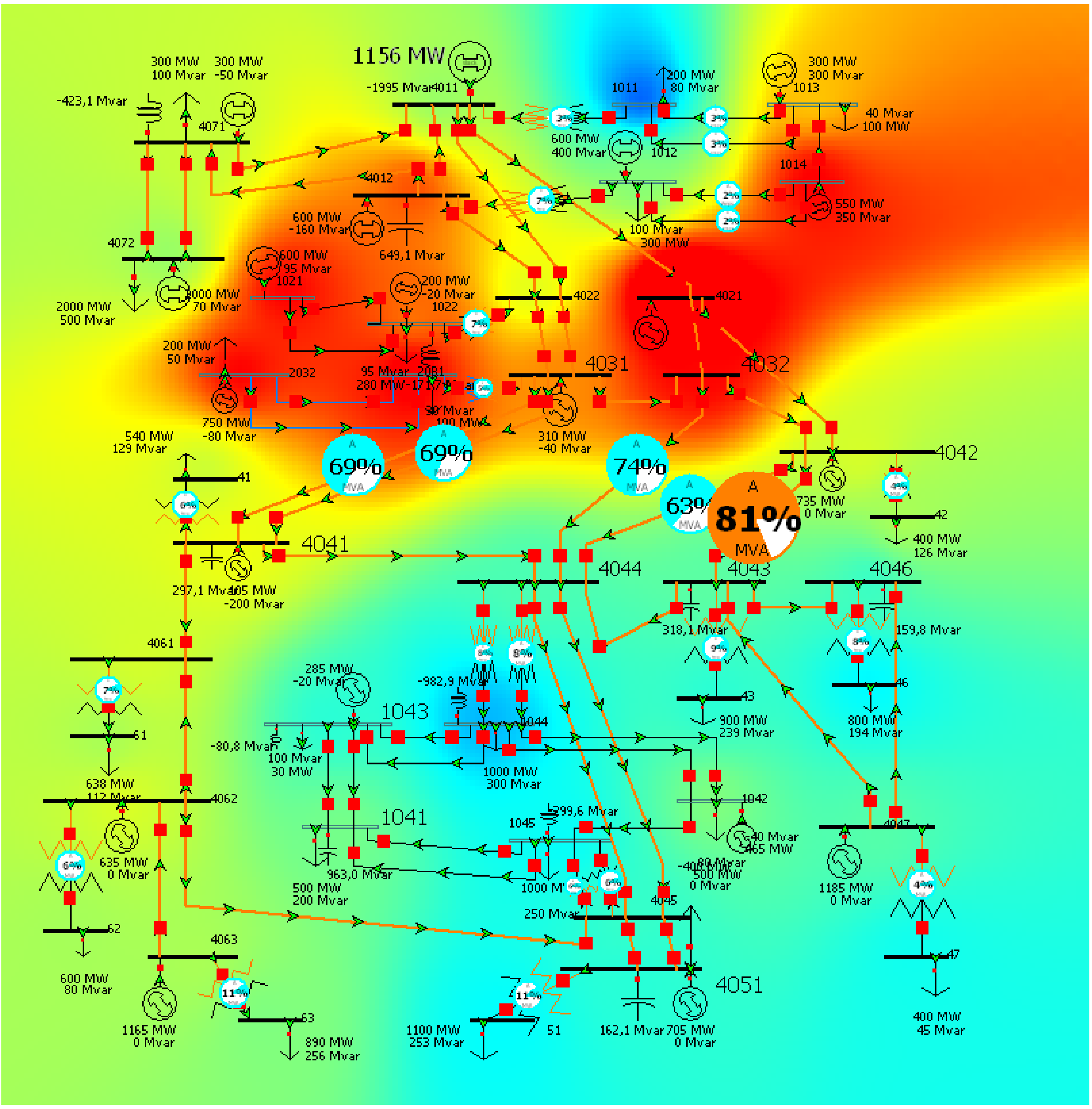

Figure A.1: Scenario 2020 before injecting wind energy

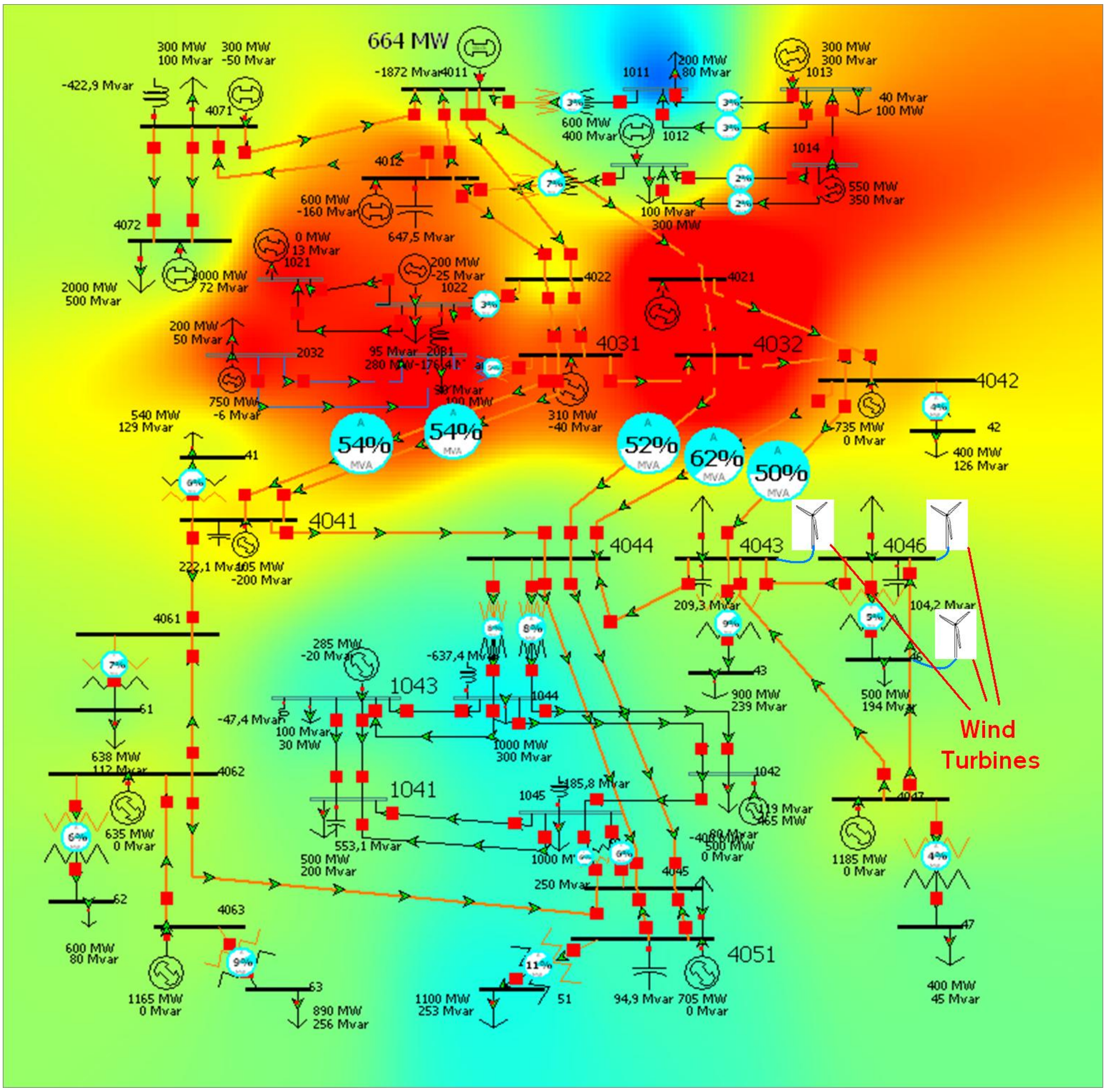

Figure A.2: Scenario 2020 after injecting wind energy

Table A.1: Voltage profile of test system for 2010

Voltage profile							
Bus	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**
41	1.03	**1012**	0.97	**1041**	0.90	**2031**	1.10
42	1.03	**1013**	1.05	**1042**	1.00	**2032**	1.10
43	0.99	**1014**	1.08	**1043**	0.92	**4011**	1.01
46	0.98	**1021**	1.10	**1044**	0.98	**4012**	1.04
47	0.99	**1022**	1.07	**1045**	0.97	**4021**	1.13
51	0.97	**4022**	1.03	**4043**	1.01	**4051**	0.98
61	1.02	**4031**	1.06	**4044**	1.00	**4061**	1.04
62	1.02	**4032**	1.09	**4045**	0.99	**4062**	1.04

63	1.00	**4041**	1.04	**4046**	1.00	**4063**	1.02
1011	0.92	**4042**	1.05	**4047**	1.01	**4071**	1.02
4072	1.01						

Table A.2: Voltage profile of test system for 2015

Voltage profile							
Bus	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**
41	1.02	**1013**	1.05	**2032**	1.10	**4044**	0.98
42	1.01	**1014**	1.08	**4011**	1.01	**4045**	0.97
43	0.96	**1021**	1.10	**4012**	1.04	**4046**	0.97
46	0.94	**1022**	1.10	**4021**	1.12	**4047**	0.98
47	0.95	**1041**	0.93	**4022**	1.03	**4051**	0.95
51	0.94	**1042**	1.00	**4031**	1.06	**4061**	1.02
61	1.01	**1043**	0.90	**4032**	1.08	**4062**	1.03
62	1.01	**1044**	0.95	**4041**	1.03	**4063**	1.01
63	1.00	**1045**	0.95	**4042**	1.02	**4071**	1.02
1011	0.92	**2031**	1.09	**4043**	0.98	**4072**	1.01
1012	0.97						

Table A.3: Voltage profile of test system for 2020

Voltage profile							
Bus	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**	**Bus**	**Voltage (p.u)**
41	0.99	**1013**	1.04	**2032**	1.10	**4044**	0.98
42	0.99	**1014**	1.07	**4011**	1.01	**4045**	0.97
43	0.94	**1021**	1.10	**4012**	1.01	**4046**	0.93
46	0.91	**1022**	1.07	**4021**	1.09	**4047**	0.94
47	0.91	**1041**	1.08	**4022**	1.01	**4051**	0.94
51	0.93	**1042**	1.00	**4031**	1.03	**4061**	1.00
61	0.98	**1043**	1.03	**4032**	1.06	**4062**	1.01
62	0.99	**1044**	0.97	**4041**	1.00	**4063**	1.01
63	1.00	**1045**	0.95	**4042**	1.01	**4071**	1.01
1011	0.92	**2031**	1.07	**4043**	0.96	**4072**	1.01
1012	0.95						

Appendix B

Table B.1: Weak elements selected by AMWCO of scenario 2015

From Bus	To Bus	Limit (MVA)	APCO (MVA)	AMWCO (MVA)	Violations
4031	**4041**	1200.00	11.80	141.20	3
4032	**4044**	1200.00	48.70	584.10	1
4042	**4043**	1200.00	50.60	607.00	1
4042	**4044**	1200.00	36.10	433.10	1

Table B.2: WTLR&ETLR sensitivity of scenario 2015

Multiple Bus TLR Sensitivities							
Bus Name	**ETLR**	**WTLR**	**4031 to 4041**	**4031 to 4041**	**4032 to 4044**	**4042 to 4043**	**4042 to 4044**
41	-0.64	-0.40	-0.24	-0.24	-0.04	-0.04	-0.08
42	0.38	0.59	-0.05	-0.05	-0.10	0.27	0.30
43	-0.64	-0.85	-0.07	-0.07	-0.15	-0.37	0.01
46	-0.64	-0.85	-0.07	-0.07	-0.16	-0.37	0.01
47	-0.64	-0.84	-0.07	-0.07	-0.15	-0.37	0.02
51	-0.66	-0.74	-0.09	-0.09	-0.18	-0.13	-0.18
61	-0.65	-0.52	-0.19	-0.19	-0.09	-0.07	-0.11
62	-0.64	-0.55	-0.17	-0.17	-0.10	-0.08	-0.12
63	-0.64	-0.53	-0.17	-0.17	-0.10	-0.07	-0.12
1011	0.40	0.38	0.09	0.09	0.10	0.06	0.06
1012	0.40	0.38	0.09	0.09	0.10	0.06	0.06
1013	0.40	0.38	0.09	0.09	0.10	0.06	0.06
1014	0.40	0.38	0.09	0.09	0.10	0.06	0.06
1021	0.40	0.36	0.10	0.10	0.10	0.05	0.04
1022	0.40	0.36	0.11	0.11	0.10	0.05	0.04
1041	-0.69	-0.78	-0.09	-0.09	-0.19	-0.13	-0.19
1042	-0.66	-0.74	-0.09	-0.09	-0.18	-0.12	-0.18
1043	-0.68	-0.77	-0.09	-0.09	-0.19	-0.13	-0.18
1044	-0.65	-0.74	-0.08	-0.09	-0.18	-0.12	-0.18
1045	-0.66	-0.74	-0.09	-0.09	-0.18	-0.12	-0.18
2031	0.41	0.33	0.13	0.13	0.10	0.04	0.02
2032	0.41	0.34	0.12	0.12	0.10	0.04	0.03
4011	0.40	0.38	0.09	0.09	0.10	0.06	0.06
4012	0.40	0.38	0.09	0.10	0.10	0.06	0.06
4021	0.39	0.47	0.04	0.04	0.07	0.12	0.13
4022	0.40	0.36	0.11	0.11	0.10	0.05	0.04
4031	0.41	0.32	0.13	0.13	0.10	0.04	0.02
4032	0.40	0.45	0.07	0.06	0.16	0.06	0.05

4041	-0.64	-0.40	-0.24	-0.24	-0.04	-0.04	-0.08
4042	0.38	0.59	-0.05	-0.05	-0.10	0.27	0.30
4043	-0.65	-0.86	-0.07	-0.07	-0.15	-0.37	0.02
4044	-0.65	-0.74	-0.08	-0.08	-0.18	-0.12	-0.18
4045	-0.66	-0.74	-0.10	-0.10	-0.18	-0.12	-0.18
4046	-0.65	-0.86	-0.07	-0.07	-0.15	-0.37	0.01
4047	-0.64	-0.85	-0.07	-0.07	-0.15	-0.37	0.02
4051	-0.67	-0.75	-0.09	-0.09	-0.18	-0.13	-0.18
4061	-0.66	-0.52	-0.20	-0.19	-0.09	-0.07	-0.11
4062	-0.64	-0.54	-0.17	-0.17	-0.10	-0.08	-0.12
4063	-0.64	-0.53	-0.17	-0.17	-0.10	-0.07	-0.12
4071	0.40	0.38	0.09	0.09	0.10	0.06	0.06
4072	0.40	0.38	0.09	0.09	0.10	0.06	0.06

Table B.3: Weak elements selected by AMWCO of scenario 2020

From Bus	**To Bus**	**Limit (MVA)**	**APCO (MVA)**	**AMWCO (MVA)**	**Violations**
4042	**4043**	1200.00	7.10	85,10	1
4042	**4044**	1200.00	5.50	66,30	1

Table B.4 : WTLR&ETLR sensitivity of scenario 2020

Multiple Bus TLR Sensitivities				
Bus Name	**ETLR**	**WTLR**	**4031 to 4041**	**4031 to 4041**
41	-0.11	-0.11	-0.04	-0.07
42	0.54	0.54	0.25	0.29
43	-0.37	-0.42	-0.38	0.01
46	-0.37	-0.42	-0.39	0.01
47	-0.37	-0.42	-0.38	0.01
51	-0.30	-0.30	-0.13	-0.18
61	-0.17	-0.17	-0.07	-0.11
62	-0.19	-0.18	-0.07	-0.12
63	-0.18	-0.18	-0.07	-0.11
1011	0.13	0.13	0.07	0.06
1012	0.12	0.12	0.06	0.06
1013	0.12	0.13	0.07	0.06
1014	0.12	0.12	0.07	0.06
1021	0.10	0.10	0.05	0.04
1022	0.09	0.09	0.05	0.04
1041	-0.31	-0.31	-0.13	-0.18
1042	-0.31	-0.30	-0.13	-0.18
1043	-0.30	-0.30	-0.13	-0.18
1044	-0.31	-0.30	-0.13	-0.18

1045	-0.30	-0.30	-0.13	-0.18
2031	0.06	0.06	0.04	0.02
2032	0.07	0.07	0.04	0.03
4011	0.13	0.13	0.07	0.06
4012	0.12	0.12	0.06	0.06
4021	0.22	0.22	0.11	0.11
4022	0.09	0.09	0.05	0.04
4031	0.06	0.06	0.04	0.02
4032	0.11	0.11	0.06	0.05
4041	-0.11	-0.10	-0.04	-0.07
4042	0.54	0.53	0.25	0.29
4043	-0.37	-0.42	-0.39	0.01
4044	-0.30	-0.30	-0.12	-0.18
4045	-0.30	-0.30	-0.12	-0.18
4046	-0.38	-0.43	-0.39	0.01
4047	-0.37	-0.42	-0.38	0.01
4051	-0.30	-0.30	-0.12	-0.18
4061	-0.17	-0.17	-0.07	-0.11
4062	-0.19	-0.18	-0.07	-0.11
4063	-0.18	-0.17	-0.07	-0.11
4071	0.12	0.12	0.07	0.06
4072	0.12	0.12	0.07	0.06

Table B.5: Final result for islands generated by Dev cpp

Result Number	**Minimal net active power flow**	**Number of buses**	**Bus Name**
First	0.6001	8	BUS4044 BUS4045 BUS4031 BUS4041 BUS4051 BUS4062 BUS4063 BUS2031
Second	0.2000	11	BUS1011 BUS4011 BUS4012 BUS4022 BUS1045 BUS1044 BUS1042 BUS4044 BUS4021 BUS4071 BUS4042
Third	0.0020	12	BUS4011 BUS4022 BUS4044 BUS4045 BUS4031 BUS4041 BUS4021 BUS4043 BUS4046 BUS2031 BUS2032 BUS1044
Fourth	0.0002	15	BUS4011 BUS1012 BUS4012 BUS1043 BUS1041 BUS1045 BUS1042 BUS4044 BUS2031 BUS4031 BUS4021 BUS4032 BUS4041 BUS4043BUS4022
Fifth	0.0000	18	BUS1011 BUS1013 BUS1021

			BUS1022 BUS4022 BUS1041 BUS1045 BUS1043 BUS1044 BUS1042 BUS4045 BUS4031 BUS4011 BUS4041 BUS4044 BUS4061 BUS4062 BUS4032

Table B.6: Line flow created by Powerworld

From Bus	To Bus	Active power (MW)	Reactive power(Mvar)	P_{Loss} (MW)	Q_{Loss} (Mvar)
41	**4041**	-540.00	-12.80	0.00	20.85
4042	**42**	400.00	139.80	0.00	14.12
4043	**43**	900.00	272.70	0.00	33.84
4046	**46**	700.00	222.80	0.00	29.09
4047	**47**	100.00	47.80	0.00	2.61
4051	**51**	800.00	276.90	0.00	23.64
4061	**61**	500.00	129.60	0.00	17.31
4062	**62**	300.00	89.120	0.00	9.01
4063	**63**	590.00	276.10	0.00	19.91
1011	**1013**	-193.90	-125.40	6.33	42.98
1011	**1013**	-193.90	-125.40	6.33	42.98
4012	**1012**	-636.20	-433.40	0.00	58.29
1013	**1014**	-200.60	-76.80	1.48	9.51
1021	**1022**	300.00	132.70	26.80	175.55
1021	**1022**	300.00	132.70	26.80	175.55
1022	**4022**	466.40	-12.90	0.00	34.88
1043	**1041**	168.80	-72.20	0.81	2.30
1043	**1041**	168.80	-72.20	0.81	2.30
1041	**1045**	-132.10	37.00	1.35	5.55
1041	**1045**	-132.10	37.00	1.35	5.55
1044	**1042**	-14.70	17.90	0.16	-9.75
1044	**1042**	-14.70	17.90	0.16	-9.75
1045	**1042**	-29.20	48.30	1.10	-16.39
1043	**1044**	-193.80	168.70	3.19	22.35
1043	**1044**	-193.80	168.70	3.19	22.35
4044	**1044**	582.30	-146.40	0.00	19.56
4044	**1044**	582.30	-146.40	0.00	19.56
1045	**4045**	-468.80	89.50	0.00	10.99
1045	**4045**	-468.80	89.50	0.00	10.99
2031	**2032**	-267.50	38.60	7.53	54.68
2032	**2031**	275.00	16.10	7.53	54.68
2031	**4031**	434.90	-107.20	0.00	22.79
4011	**4012**	0.10	-0.40	0.00	-0.82
4011	**4012**	90.20	-31.30	0.08	-40.16
4011	**4021**	1642.60	614.70	196.08	1589.41
4011	**4022**	1175.70	422.90	65.84	446.17
4012	**1012**	-636.20	-433.40	0.00	58.29
1013	**1014**	-200.60	-76.80	1.48	9.51

1021	**1022**	300.00	132.70	26.80	175.55
1021	**1022**	300.00	132.70	26.80	175.55
4011	**4071**	7.60	-152.00	0.01	-285.66
4012	**4022**	1334.00	488.80	83.68	546.56
4012	**4071**	-7.60	-159.20	0.01	-305.13
4021	**4032**	604.10	-385.30	16.39	-115.03
4021	**4042**	1092.40	-619.50	121.97	-76.35
4022	**4031**	1413.30	-64.40	105.67	946.25
4022	**4031**	1413.30	-64.40	105.67	946.25
4031	**4032**	1512.60	1006.00	29.81	227.18
4031	**4041**	923.80	-592.60	59.03	83.89
4031	**4041**	923.80	-592.60	59.03	83.89
4032	**4042**	1044.10	-758.90	105.05	-163.43
4032	**4044**	1026.40	-744.60	58.43	-257.83
4045	**4062**	-421.90	-470.80	9.55	-939.21
4046	**4047**	-591.30	-122.70	1.89	-156.58
4061	**4062**	-264.60	-507.70	2.20	-228.68
4062	**4063**	-468.20	100.20	1.78	-175.88
4071	**4072**	0.00	-140.80	0.01	-307.18
4071	**4072**	0.00	-140.80	0.01	-307.18
4045	**4062**	-421.90	-470.80	9.55	-939.21

Reference

Reference

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