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Source Node Expansion Algorithm for Coherency Based Islanding of Power Systems

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SOURCE NODE EXPANSION ALGORITHM FOR COHERENCY BASED ISLANDING OF POWER SYSTEMS

by

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ABSTRACT

The electric power system is an exposed man-made structure susceptible to wide arrays of disturbance. If not cleared, a lingering disturbance can plunge the system into the unstable mode in a fairly short time frame.

In distributed generation, a drawn-out perturbation can cause system components to operate under unacceptable conditions. When restoration controls fail to revive the troubled system, generators may lose synchronism causing them to swing haphazardly in groups. This crisis separates the power system into unbalanced regions called unintentional islands.

In this thesis, Source Node Expansion Algorithm based on Slow Coherency has been proposed to resolve unintentional islanding. The algorithm initiates expansion from source node, engulfs connected loads until desired power mismatch is met. It then terminates and optimal cutsets deduced from the Adjacency Matrix.

The proposed technique is tested on 14 and 37-bus systems to endorse its potency. The experimentation is carried out in the PowerWorld platform.

Index Terms: Unintentional islanding, Source Node Expansion, Coherency, Adjacency Matrix.

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CHAPTER 1

INTRODUCTION

1.1. Electric Power System (EPS)

The electric power system was initially developed in the late 1800s and is considered the most significant engineering accomplishment of the 20th century. In 1878, Thomas A. Edison began work on the electric light. His epoch-making invention of the dc generators, then called the dynamos, driven by steam engines to supply an initial load of 30KW for 110V incandescent lighting to 59 customers in a 1-square-mile area at Pearl Street in New York City, marked the beginning of the electricity industry [1].

A typical electric power system structure can be divided into four (4) basic subsystems.

a. Generation
b. Transmission
c. Distribution
d. Utilization (Load)

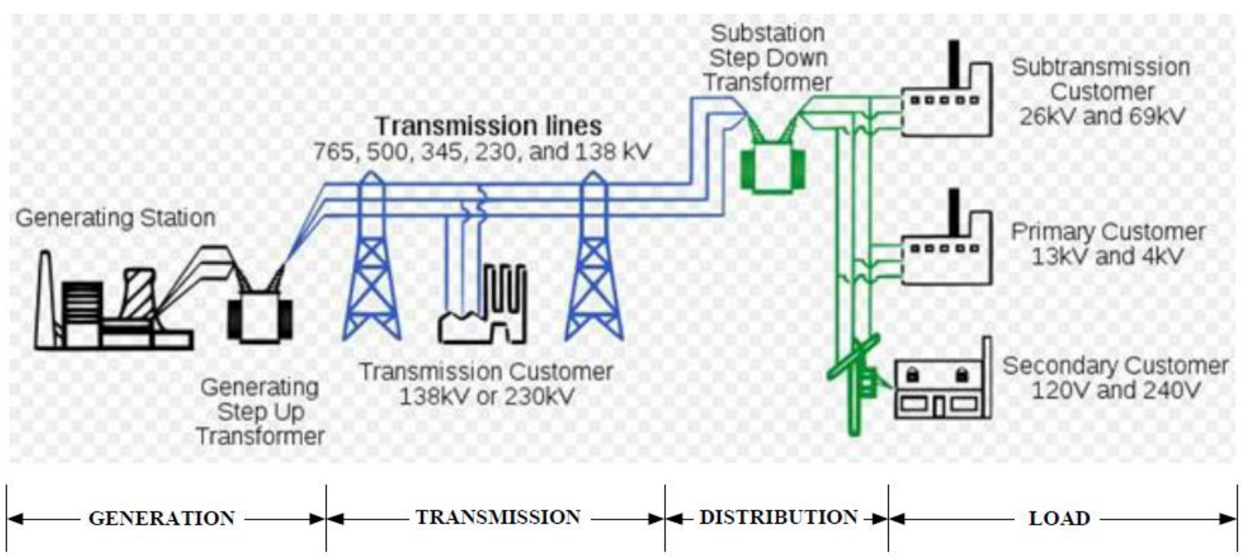


Fig. 1.1 Electric power system

In addition, there is usually an intermediate network, connecting the transmission and distribution systems, and this is called the 'Sub-Transmission System'. These sub-systems operate at different voltage levels. Power transmittability increases and transmission losses decrease with increasing voltage level. The larger the blocks of power to be transmitted and the greater the distance over which they must be wheeled, the higher operating voltage must be chosen. The U.S standard operating voltages are given in Table 1.1.

TABLE 1.1
VOLTAGE HIERARCHY

VOLTAGE CLASS	NOMINAL LINE VOLTAGE
Low	120V 208V 240V 600V
Medium	2.4kV 4.16kV 6.9kV 12.47kV 13.2kV 13.8kV 23.0kV 34.5kV 69.0kV
High	115kV 138kV 161kV 230kV
Extra High	345kV 500kV 765kV

1.1.1. Transmission System

The transmission system is distinctly different, in both its operation and characteristics, from the distribution and sub-transmission systems. Whereas the latter two in most cases draw energy from a single source and transmit it to individual loads, the function of the transmission system is quite different. Not only does it handle the largest blocks of power, it also interconnects all the generator stations and all the major loading points in the system. The energy can be routed, generally, in any desired direction on the various links of the transmission system in a way that corresponds to best overall operating economy.

The transmission circuit, unlike the sub-transmission and distribution systems, tends to obtain a loop structure with voltage levels ranging from 115kV to about 765kV. The two general types of power transmission medium are:

a. Overhead Line
b. Underground Cable

The most common type of AC power transmission is by overhead conductors suspended from metal towers.

1.1.2. Sub-Transmission Level

The sub-transmission circuit distributes energy to a number of distribution sub-stations in a certain geographical area at a voltage level that typically varies between 23 and 138 kV. It receives the energy directly from the generator bus in a generator station or via bulk power substations. Large customers are served directly from those substations.

The role of a sub-transmission system is mainly the same as that of a distribution system, except that it serves a larger geographical area and distributes energy in larger blocks at higher voltage levels. It should be pointed out that in many systems there are no clear demarcation lines between sub-transmission and transmission circuits. Increased load density makes it necessary and economical to superimpose a new and higher voltage grid on the existing one. In this way yesterday's transmission network becomes part of tomorrow's sub-transmission network.

1.1.3. Distribution System

The distribution circuits constitute the finest meshes in the overall network. These lines carry limited amounts of power over shorter distances and operate at lower voltages as well. Usually, two distribution voltage levels are used:

1. The Primary or feeder voltage (for instance 23kV)
2. The secondary or consumer voltage (for instance 120/240 V)

The distribution circuits, fed from the distribution substations (transformer stations), supply energy to the small (domestic) or medium-sized (small industrial and commercial) customers.

1.1.4. Utilization

Loads of power systems are divided into industrial, commercial and residential. Very large industrial loads may be served from the transmission system. Large industrial loads are served directly from the sub-transmission network, and small industrial loads are served from the primary distribution network. The industrial loads are composite loads, and induction motors form a high proportion of these load.

1.2. Electric Power System Representation

Power systems are extremely complicated electrical networks that are geographically spread over very large areas. For most part, they are also three phase networks – each power circuit consists of three conductors and all devices such as generators, transformers, breakers, disconnects etc. are installed in all three phases. In fact, the power systems are so complex that a complete conventional diagram showing all the connections is impractical. Yet, it is desirable, that there is some concise way of communicating the basic arrangement of power system components. This is done by using Single Line Diagrams (SLD). SLDs are also called One Line Diagrams.

Single Line Diagrams do not show the exact electrical connections of the circuits. As the name suggests, SLDs use a single line to represent all three phases. They show the relative electrical interconnections of generators, transformers, transmission and distribution lines, loads, circuit breakers, etc., used in assembling the power system. The amount of information included in an SLD depends on the purpose for which the diagram is used. For example, if the SLD is used in initial stages of designing a substation, then all major equipment will be included in the diagram – major equipment being transformers, breakers, disconnects and buses. There is no need to include instrument transformers or protection and metering devices. However, if the purpose is to design a protection scheme for the equipment in the substation, then instrument transformers and relays are also included.

There is no universally accepted set of symbols used for single line diagrams. Often used symbols are shown in Table 1.2.

TABLE 1.2
COMPONENT & SYMBOLS

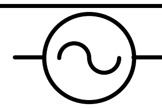
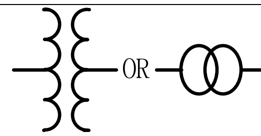
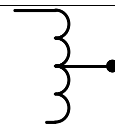
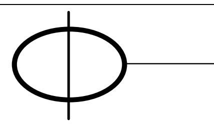
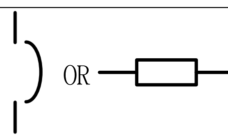
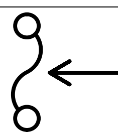
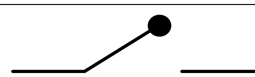
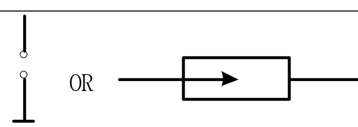
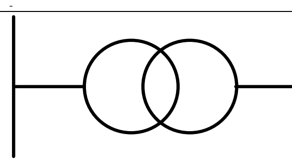
NO	COMPONENT	SYMBOL
1	Generator (Power Station)	
2	Transformer (Two winding)	
3	Auto-Transformer	
4	Current Transformer	
5	Circuit Breaker	
6	Fuse	
7	Disconnect switch	
8	Lightning Arrester	
9	Voltage/Potential Transformer	

Figure 1.2 shows a small power system. Any information that is required is added to the SLD. In this case connections of generator and transformer windings, as well as the method of grounding the neutral are indicated. This type of SLD has often also specified the size of the equipment in MVAs, voltage levels, and any other relevant information.

Figure 1.2 Single line diagram

1.3. Forms of Electric Power System

The electric utility industry's outlook has been greatly influenced by the increasing demand for electricity and the emergence of new generation technologies. This has led to continued restructuring and modification of the conventional EPS structure. The two major forms of EPS are discussed in section 1.3.1 and section 1.3.2 respectively.

1.3.1. Centralized Generation System

The centralized generation paradigm has become the cornerstone of the electricity industry for some time now. It is often referred to as the 'archetype' of all electric power system structures.

Under this paradigm, electricity is mainly produced at large generation facilities (power plants), shipped through the transmission and distribution grids to load centers. Thomas A. Edison formulated the concept of a centrally located power station in the late 1800's.

For decades, the centralized generation paradigm has been the dominant standard in North America and other parts of the world. In spite of its global acceptance, it has suffered serious construction, structural and operational drawbacks. The major issues bedeviling the centralized generation system are discussed below.

1. **Blackouts**:

In power systems, a blackout refers to the total loss of electricity to an area and it is the most severe form of power outage that can occur. Power outages may last from a few seconds to weeks depending on the nature and severity of the blackout and the configuration of the electrical network.

The study of the process of blackouts falls outside the purview of this thesis, but the main cause of their occurrence is major dynamic instabilities following big disturbances. Poor system design, human error, sudden changes to system and many more factors can also play a role.

The centralized generation architecture in most parts is radial in nature. Therefore, any part of the system downstream of a major fault will suffer serious power outages. A historic data of the major blackouts worldwide are tabulated below.

TABLE 1.3

Historic Blackouts Data [3]

No:	LOCATION	DATE	LOST MW	AFFECTED PEOPLE	COLLAPSE TIME	RESTORATION TIME
1	North-eastern US	12/09/65	20,000	30 million	13 mins	13hrs
2	France	12/19/78	29,000	------	26 mins	5hrs
3	US Western	12/22/82	12,350	5 million	-------	------
4	Sweden	12/27/83	67% (Total load)	------	53secs	About 5hrs
5	Tokyo	07/23/87	8,200	2.8 million	20mins	About 75hrs
6	Ghana	08/02/97	80%(total Load)	20 million	>1hr	20 days
7	Brazil	04/11/99	25,000	75 million	30 secs	30min to 4hrs
8	North-eastern US	08/14/03	61,800	50 million	>1hr	Up to 4 days

2. **Transmission and Distribution (T&D) Cost**

Transmission and distribution costs amount for up to 30% of the cost of delivered electricity on average (IEA 2002). The high price for transmission and distribution results mainly from losses made up of the following:

a. Line losses: electricity is lost when flowing into the transmission and distribution lines. Prominent causes are corona, radiation, induction losses, copper losses and sometimes skin effects.
b. Unaccounted for electricity consumption.
c. Conversion losses: when the characteristics of the power flow is changed to fit the specifications of the network e.g. changing the voltage while flowing from the transmission network to the distribution network (EIA, 2009).

The total amount of the losses is significant as shown in Table 1.4.

TABLE 1.4

T&D losses &unaccounted for electricity in the US [4]

DATE	NET GENERATION KWH	T&D LOSS & UNACCOUNTED	(%)
1995	3353	229	6.8
1996	3444	231	6.7
1997	3492	224	6.4
1998	3620	221	6.1
1999	3695	240	6.5
2000	3803	244	6.4
2001	3737	202	5.4
2002	3858	248	6.4
2003	3883	228	5.9
2004	3971	266	6.7
2005	4055	269	6.6
2006	4065	266	6.5
2007	4157	264	6.4
2008	4115	241	5.9

1.3.2. Distributed Generation System

Recent quest for energy efficiency, reliability and the reduction of greenhouse gas emissions led to exploring possible alternatives to supersede the current generation paradigm. It is in this regard that the idea of 'distributed' generation was conceived.

Distributed generation, also known as the 'Decentralized Energy' is an approach that employs small-scale technologies to produce electricity close to the end users of power. As per IEEE STD 1547-2003 [17], distributed generation is defined as electric generation facilities connected to power systems through a point of common coupling (PCC). It has since maintained its position as the best candidate to complement or even supplant the centralized energy system.

Distributed generation entered the electricity market solely because they provided solutions to overcome the shortfalls of the centralized generation paradigm. Figure 1.3 shows a 54-bus distributed energy system.

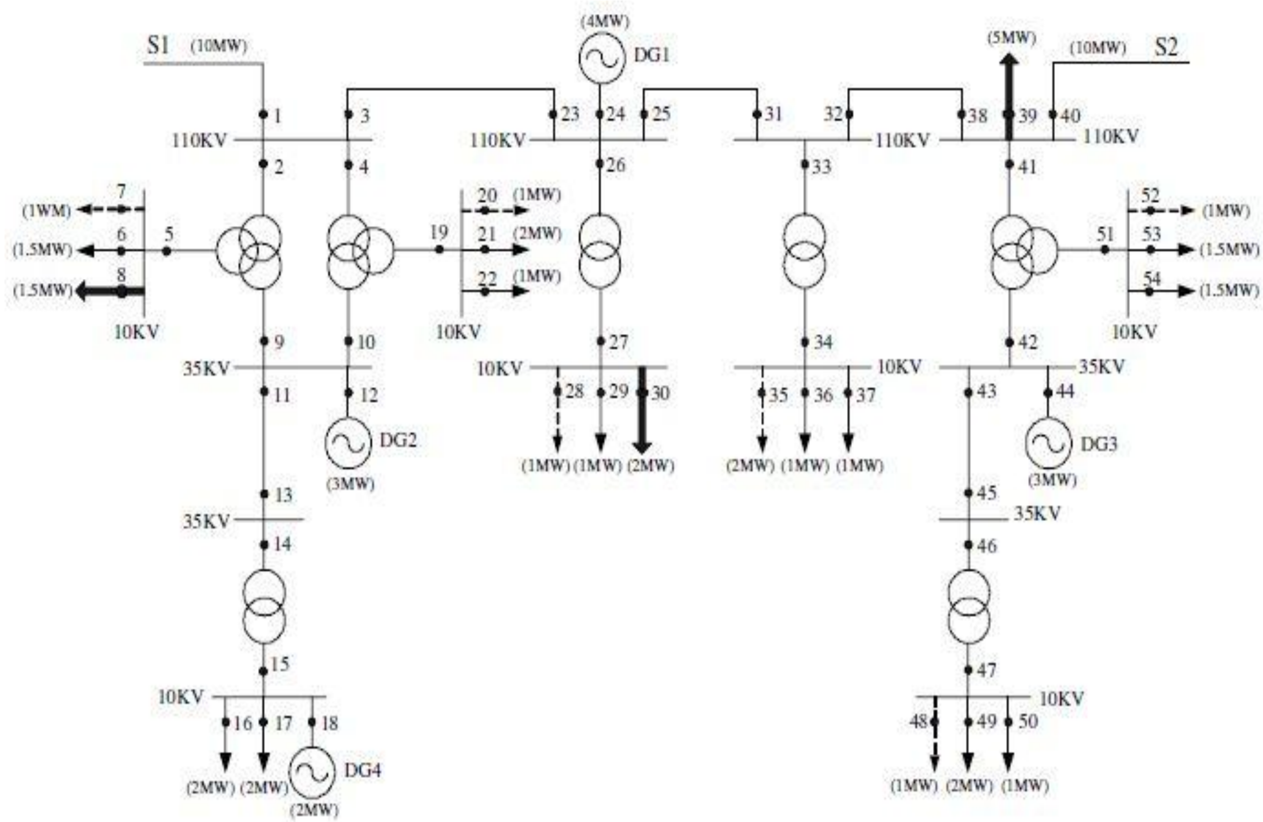


Fig. 1.3 One line diagram of a distributed generation system [5]

A ‘bus bar’ is a high voltage or low voltage common collecting point for receiving and redistributing power. The utility sources are S1 & S2 and the distributed sources are DG1, DG2, DG3 & DG4 connected to the 110KV, 35KV, 35KV and 10KV voltage level busbars respectively as shown in figure above.

1.3.3. Technologies Used For Distributed Generation

According to the International Energy Agency, IEA (2002), the range of technologies for distributed generation can be categorized as follows [4]:

1. **Reciprocating Engines**:

This technology uses compressed air and fuel. The mixture is ignited by a spark to move a piston. The mechanical energy is then converted into electrical energy. Most reciprocating engines run either on fuel or natural gas with an increasing number of engines running on biogas produced from biomass and waste.

2. **Gas Turbines:**

They are widely used for electricity generation thanks to the regulatory incentives included to favour fuel diversification towards natural gas and their low emission levels. Gas turbines are widely used for cogeneration.

3. **Micro turbines:**

Micro turbines have the same characteristics as the gas turbines. But, the only differences that they have are lower capacities and higher operating speed.

4. **Fuel Cells**

Fuel cells are electrochemical devices. Unlike the other technologies, they are built to convert the chemical energy of a fuel into electrical energy. The fuel used is generally natural gas or hydrogen. Phosphoric acid fuel cells are becoming popular these days.

5. **Renewable Resources:**

Renewal technologies have also been deployed to produce distributed energy. Renewal sources range from photovoltaic, wind energy, thermal energy etc. These sources qualify as distributed generation only if they meet the criteria of the definition which is not always the case.

1.3.4. Benefits of Distributed Generation

The distributed generation system has myriads of advantages over the centralized generation paradigm. The major benefits of decentralizing the electric power system are discussed below.

a. **Reduction In T&D Losses**

One of the key advantages of distributed energy is that it helps reduce transmission and distribution losses as distributed generators are not connected to the transmission grid. Some of them might even choose to operate as captive plant for a client with thus limited use of the distribution grid.

b. **Reduction In T&D Distance**

Since power is produced next to its point of use, transmission and distribution distance is greatly reduced. This explicitly affects the cost of installing transmission and distribution lines.

c. **Quality of Power**

Distributed generators can help improve the quality of services provided through voltage control (connecting a distributed generator to a low voltage network makes it possible to reduce the drop in voltage over the distance), providing additional peaking capacities.

d. **Increase Power Capacity**

Adding distributed generators at the distribution level can significantly impact the output power. This enables the network to tolerate more loads.

e. **Reliability**

Unlike the centralized energy system, several electricity production facilities are connected to the distribution grid. Customers on the network no longer have to depend on a particular generating source. Hence, the pooling of resources to augment power supply ensures system reliability.

1.3.5. Challenges of Distributed Generation

a. **Installation Issues**

In the decentralized energy system, whenever a new generator is introduced reinforcement works will have to be undertaken. At times part or the whole system will have to be redesigned to cope with the changes. Besides, we have to incorporate control and protection software and hardware to coordinate with the distributed generators.

b. **Voltage and Current Transients**

Short term abnormal voltage or current oscillation may occur as distributed generators are switched on or off. The result of these oscillations can have a destabilizing effect on the network.

c. **Reverse Power Flow**

When the rotor speed of a distributed generator dips below the synchronous speed normally due to transient faults, the generator begins to behave like motor [37]. At this point, the machine loses its sense of purpose and instead of injecting power onto the grid; it turns into an ‘electrical vampire’ and sucks power from the grid. This phenomenon seldom happens, but the possibility of its occurrence cannot be ruled out.

d. **Harmonics**

A ‘harmonic’ is a sinusoidal component of a periodic wave or quantity having a frequency that is an integer multiple of the fundamental frequency.

Non-linear loads such as rectifiers, computers, UPS, variable speed drive and industrial electronic equipment which contain power semiconductors such as Thyristor converters, inverters etc. are some of the sources of harmonics.

The above loads draw non-sinusoidal currents from the supply (generators) and lead to voltage distortions. This deviation from a perfect sine wave can be represented by harmonic components having a frequency that is an integral multiple of the fundamental frequency [8].

e. **Formation of Islands**

Transient faults can cause portions of the distribution system to become electrically isolated from the remainder of the power system, yet continues to be energized by an embedded generator or multiple generators connected to the isolated subsystem [9]. This condition is referred to as 'unintentional islanding'. Utility engineers are seriously concerned about unintentional formation of islands. This is because the generators swing waywardly and the utility loses control of the voltage and the frequency during the islanding condition.

CHAPTER 2

ISLANDING CONCEPT

Electric power distribution systems have traditionally been designed assuming that the primary substation is the sole source of power. But, the advent of distributed generation has invalidated this assumption by placing power sources onto the distribution system. As a result, DG interconnection results in operating conditions which do not occur in a conventional system without generation directly connected at the distribution level. These operating situations present engineering challenges unique to distributed generation integration.

One of the new technical issues created by distributed generation interconnection is islanding. It could be intentional (when system is shut down for maintenance) or unintentional (when it happens as a result of an unanticipated fault). As per IEEE STD 1547-2003 [17], an island is a condition where a portion of a grid is energized solely by DGs while that portion of the grid is electrically separated from the rest of the power system. Therefore, we can say that intentional or unintentional island according to the above standard, is a planned or an unplanned island respectively. Figure 2.1 shows the pictorial illustration of islanding operation.

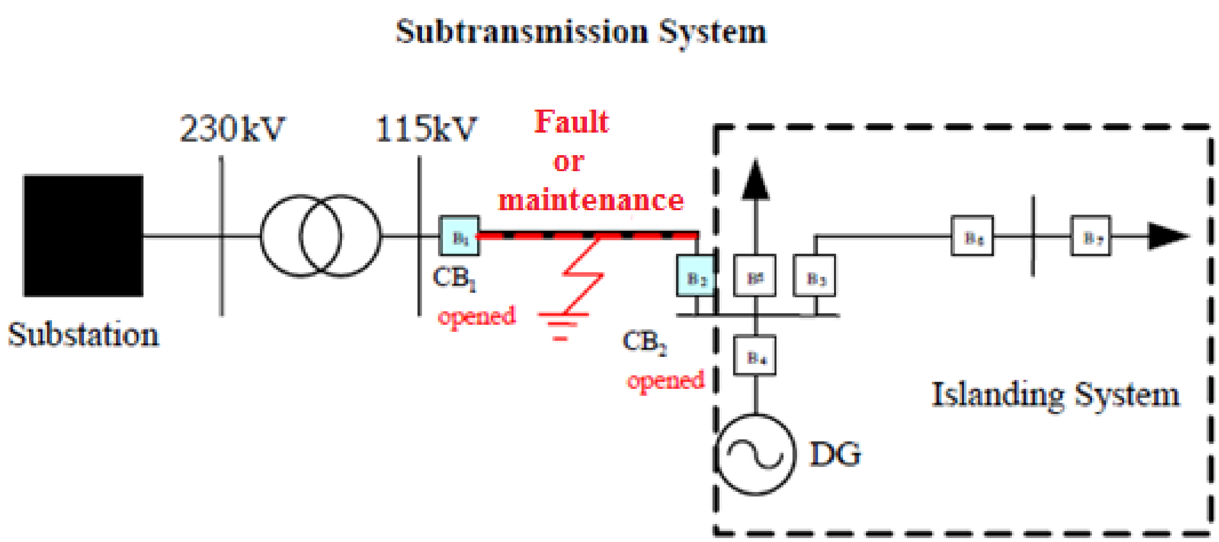


Fig. 2.1 islanding operation

2.1. **How Islands are Formed**

The DG grid under normal operating conditions, maintain voltage and frequency within their standard permissible levels. Also, synchronism exists amongst all DGs on the distribution network and they operate together in unison with constant rotor speed.

When the system is driven into the unstable mode, DG protection system detects the fault and affected tie line is tripped. This action breaks the equilibrium that exists amongst the generators causing them to move out of step. The DGs swing haphazardly due to the deviations in their rotor angles. Interestingly, those generators with rotor angle deviations falling within a specific value will stick together in a group and operate as one entity supplying power to the local loads within its near vicinity. Two or more of such groups (coherent group) may result in a single or multiple swings.

The coherent groups of generators supplying power to local loads in their vicinity bring about an automatic partitioning of the power system into smaller sections called islands. The service in these islands is degraded and system components operate under extremely unacceptable conditions. This can be seen from the dynamic performance of the system at fault. In figures 2.2 and 2.3, a 15,549 bus system showing signs of islanding operations are illustrated [18].

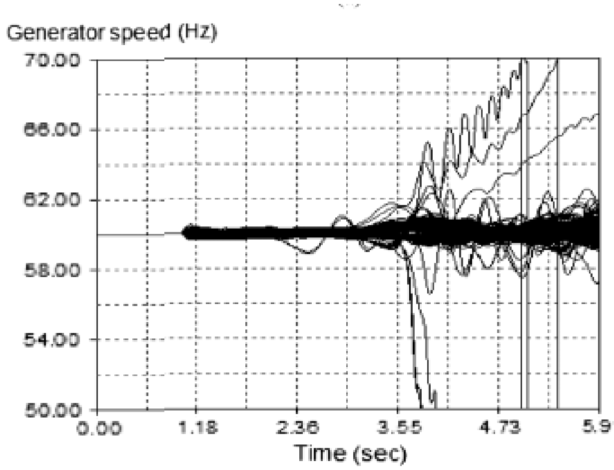


Fig. 2.2 Generator speed after contingency

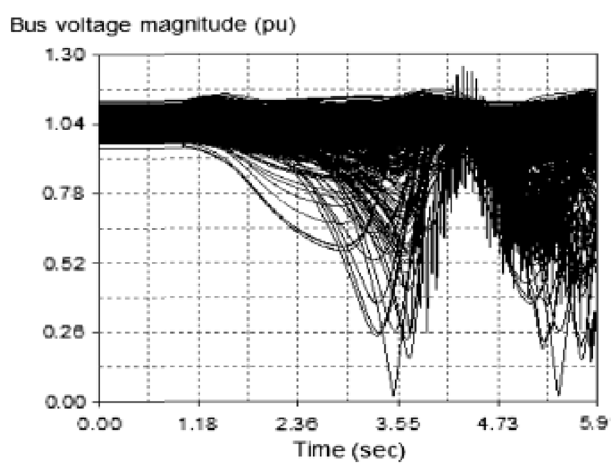


Fig. 2.3 Bus voltage magnitude after contingency

2.2. **Issues Related To Islanding**

Islanding of distributed networks does present a number of safety, commercial, power quality, and system integrity problem. In summary, the major issues are [19]:

1. Islanding may create hazards for utility line workers or the public by causing a line to remain energized that may be assumed to be disconnected from all energy sources.

2. The distributed generators in the island could be damaged when the island is reconnected to the supply system. This is because the generators are likely to be out of synchronism with the system at the instant of reconnection. Such out-of-phase re-closing could result in large starter currents and damages to the generator shaft. It may also result in re-tripping in the supply system.

3. Unintentional islanding may interfere with the manual or automatic restoration of normal service for the neighboring customers.

4. Other major problems may be the isolated DG could cause abnormal voltage and frequency to the utility loads, which could be detrimental to the utility customers.

Due to these reasons, it is very important to detect the islanding quickly and accurately before the situation exacerbates.

2.3. **Islanding Detection Techniques**

Since islands pose a significant risk to safety and equipment, the ability to quickly detect and eliminate a power island is a critical requirement for both the DG owners and utilities. This is reflected in IEEE Std. 1547™ 2003 [20] and IEEE Std. 929-2000 [21] which specify that a DG should cease to energize the EPS within a specified time once an island occurs.

Anti-islanding detection techniques can be categorized under two broad headings. They are Local and Remote detection schemes [19]. The classifications are shown in figure 2.4.

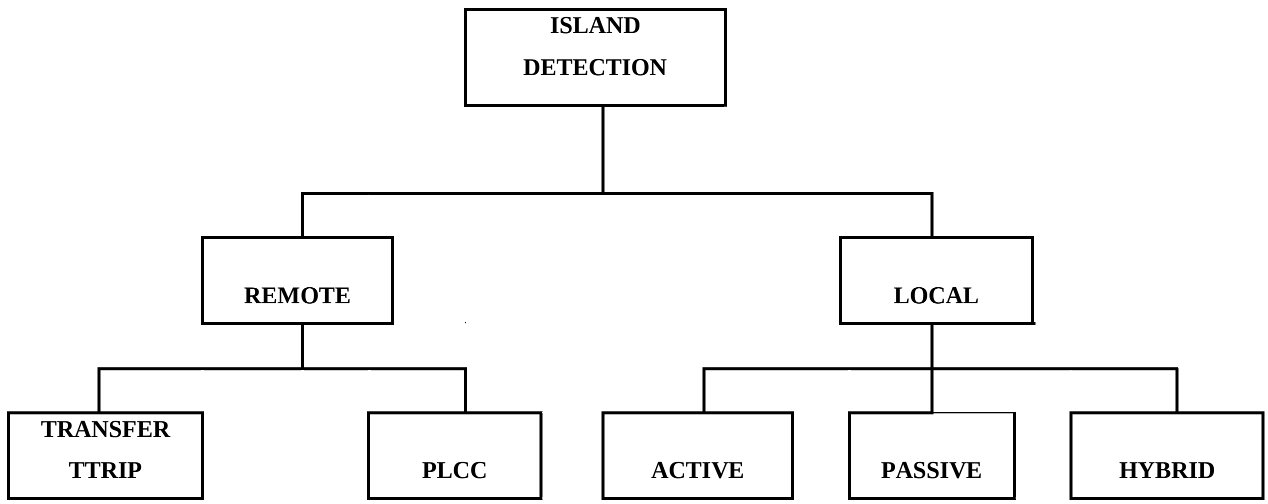


Fig. 2.4 Islanding detection techniques [19]

2.3.1. **Remote Detection Technique**

Most remote techniques for detection of islands are based on communication between the utility and the DGs. Usually remote detection schemes do not have a non-detection zone and are therefore very sound approaches for anti-islanding. However, remote techniques tend to be expensive to implement for small DG systems that do not otherwise require communication within the utility. Two popular detection methods are used under the remote and they are:

1. **Transfer Trip (TT) Scheme:**

The basic idea behind this detection scheme is to monitor the status of all the circuit breakers and reclosers that could island a distribution system. Supervisory Control and Data Acquisition (SCADA) systems can be used for this [22]. This method requires a very tight interaction between the utility and the DGs. This tends to increase the cost dramatically for both the utility and the DG owners. Monitoring a large number of circuit breakers on the DG site also increases the complexity of the system considerably.

2. **Power Line Carrier Communication (PLCC) Scheme:**

Here, a signal generator at the transmission system continuously sends a low-energy communication signal along the power line through a transmitter on the grid site [23]. The receiver, at the DG side can detect an islanding condition based on whether or not the receiver detects the presence of the PLCC signal. The use of PLCC for the detections of islanding does not degrade the quality of the generating power of the DG. It is also effective in multi-DG systems. Existing PLCC signals on the utility not originally intended for anti-islanding may be used to detect islands without interfering with their normal functions. Figure 2.5 shows a PLCC scheme.

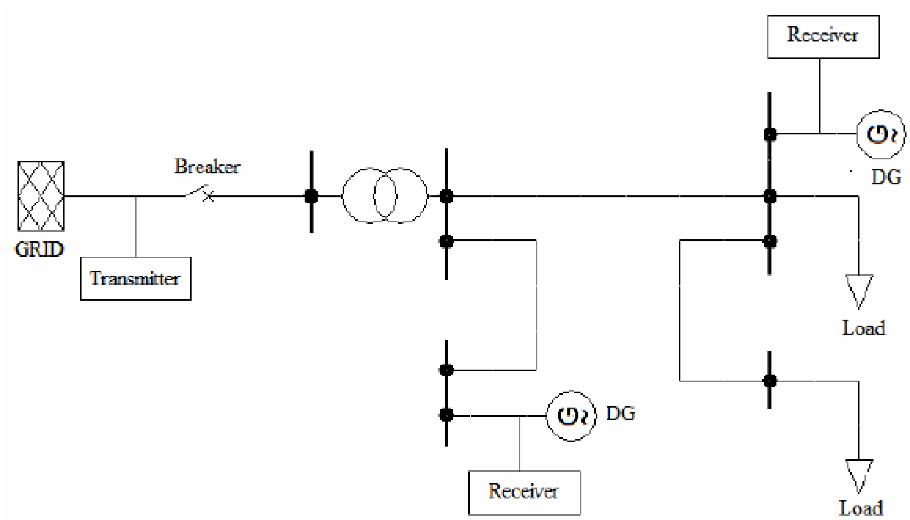


Fig. 2.5 Power line carrier communication

2.3.2. **Local Detection Technique**

Local techniques are based on the information and data available at the DG site, like voltage, frequency etc. This information is normally available as part of the DG control system, so additional sensors and components are not required. Local techniques may be further classified as passive, active, and hybrid.

1. **Passive Detection Techniques**

Passive methods work on measuring system parameters such as variations in voltage, frequency, harmonic distortion etc. These parameters vary greatly when the system is islanded. Differentiation between an islanding and grid connected condition is based upon the threshold set for these parameters. Passive techniques are fast and they do not introduce disturbance in the system but they have a large non detectable zone (NDZ) where they fail to detect the islanding condition.

2. **Active Detection Techniques**

With active methods, islanding can be detected even under the perfect match of generation and load, which is not possible in case of the passive detection schemes. Active methods directly interact with the power system operation by introducing perturbations. The idea behind an active detection method is that this small perturbation will result in a significant change in system parameters when the DG is islanded, whereas the change will be negligible when the DG is connected to the grid.

3. **Hybrid Detection Schemes**

Hybrid methods employ both the active and passive detection techniques. The active technique is implemented only when the islanding is suspected by the passive technique.

CHAPTER 3

LITERATURE REVIEW

The phenomenal growth in load demand in recent times has emerged as a potential challenge to the power system planners and operators. Fortunately, the advent of distributed generation system provided the solutions to the growing demand for electricity consumption. However, the installed DGs in the distribution system have introduced new issues in operational and planning levels. As discussed in previous chapters, uncontrolled islanding has become a major issue associated with distributed generation systems. The ravaging effects of this phenomena make it a huge concern to the utility industry.

In order to contain the impact of uncontrolled islanding when it happens without detection, research into finding the best candidates to counteract such undesirable conditions are far advanced. Some papers have studied controlled system islanding [11-18, 31-33], which means that the dispatch center actively trips some lines to split the power network into several maintainable islands according to asynchronous groups of generators and other requirements. System splitting has been widely acclaimed to be the last line of action to preventing blackout and maintain electricity supply for most customers, albeit the power network will be separated into asynchronous islands.

In islanding, it is not easy in real-time to determine the splitting strategy, namely which lines should be tripped (where to island), and when system splitting is imperative (when to island). However, though 'where' and 'when' to island are two mutually exclusive issues, the latter is beyond the scope of this thesis. References [34-36] have made some effort to solve these problems. Its main difficulties lie in the following aspects.

First, real-time decision-making requires extremely short strategy-search time, but the strategy space will explode exponentially with the increasing of size and complexity of the power network [35].

Secondly, the splitting strategy should satisfy necessary steady-state constraints, e.g. the following three constraints proposed in [35]:

a. constraint that asynchronous groups of generators must be separated,

b. generation-load imbalance in each island must be less than a prescribed limit,
c. all lines in each island must be loaded below their steady-state transmission capacity limits.

Therefore, identifying the appropriate cutsets to satisfy the above constraints is a strenuous challenge that requires exhaustive search technique. Many research efforts have consciously addressed these issues. The pre-determined boundary method had been used in the past. But this approach has become unfashionable because splitting the system along pre-defined cutsets had coherency issues [16].

In literatures [11-16], slow-coherency approach is used. Real-time computer search programs based on descriptive algorithms are developed to find the set of lines to trip. An analytical approach to automatically determine the islands from the identified slowly coherent groups of generators using an exhaustive cutset approach was developed in [12]. Paper [33] is also based on slow-coherency but further refined the islanding determination scheme using a max-flow min-cut, graph theoretic approach with capabilities to merge adjoining slowly coherent groups, or break coherent groups based on the location of the disturbance.

A new splitting scheme based on controlling group identification of generators other than slow-coherency is presented in [32]. A decision-making algorithm is used to find the optimal cutsets under different operational scenarios.

In [31], conjecture is used as a tool for cutset identification. The entire power system architecture together with its instability history is studied. The analysis is then used to surmise suitable splitting spots in future disturbance.

Reference [35] proposed a graph-model to represent a power network by which graph theory and Boolean algebra can be applied to represent and analyze splitting strategies. Based on ordered binary decision diagram (OBDD) representation [7], which is a high-efficiency technique for solving complicated Boolean algebra problems, [34] proposed a three-phase method to find the splitting strategies satisfying all constraints enumerated above in real-time.

In this thesis, a novel offline graph partitioning search algorithm based on slow coherency and graph theory is proposed. The algorithm initiates expansion from a source node and expands its frontiers until generation-load imbalance falls within the prescribed limit. The cutsets are identified from an adjacency matrix and the system is severed.

3.1. **Controlled Islanding**

Power system splitting is the final remedial action against inadvertent formation of islands following a severe disturbance. The main idea behind controlled islanding is to determine the proper splitting points for separating the entire power networks into smaller islands with their power mismatches falling within the permissible range. These islands are autonomous with their own power sources to sustain them. It is therefore the most desirable alternative to resolving uncontrolled system separations in power systems.

If a system disturbance causes zones A and B to separate from the system resulting in electrically unbalanced islands, the methodology for system splitting will have to address two major decision-making issues:

a) When to island
b) Where to island

Many research contributions have addressed these pertinent issues [11]. In some literature, when to island starts right after the detection schemes have identified the uncontrolled islanding phenomena. However, where to island has been the spotlight of most research works.

Several methods have been proposed. Apart from the pre-determined boundaries approach, the rest make use of exhaustive searching strategies to locate the appropriate splitting spots that meet generation-load balance requirements. The most popular ones make use of genetic algorithms, artificial intelligence, conjecture and other heuristic algorithms.

Since the concept of controlled islanding forbids co-habitation amongst generators of different coherent groups, the issues of coherency needs to be considered before performing system splitting.

3.2. **Coherency Identification of Generators**

The concept of coherency is very intuitive. Two machines are said to be coherent if after some disturbance, they present similar dynamical behavior, that is, their rotor angles and frequencies keep very similar along the system trajectories. Mathematically, one has:

Definition 3.2.1: *Two machines are said to be ε-coherent or coherent with precision ε if*

$$\lim_{t\to\infty} \mathrm{Sup}\,|\delta_i (t)-\delta_j (t)| < \varepsilon$$

Where $\boldsymbol{\delta_i}$ and $\boldsymbol{\delta_j}$ are respectively the rotor angles of machines i and **j**. As a limit case of the previous definition, one can say that two machines are perfectly coherent if **ε**=**0** [6].

Coherency analysis in power systems is an important task which can supply very important information about the behavior of power systems. As, in general, the dimensions of the power system is very large, coherency analysis have been extensively used, in stability studies, to reduce the computational effort by aggregating coherent generators into a unique equivalent generator.

Under normal operating conditions, the rotor angles of all the generators swing together in the synchronous frame of reference prior to the occurrence of disturbance. This means the angular difference between any two generators is approximately constant over a period of time. The disturbance on the system causes drift in the rotor angle of some generators and hence these generators move away from the rest of the generators in the system and form different groups. The generators in each group are known as coherent generators. After the removal of the disturbance, the affected generators will again swing back to the rest of the generators. Formation of different coherent groups depends upon the nature of the disturbance occurring on the system.

Many methods have been proposed to identify coherent machines. Basically they are divided into three methods. Classically, the coherent generators are identified through a time simulation for some specific contingency. Then the rotor angles are directly compared and those which are very similar are classified as coherent [12, 13, 14, 15, 16, 18]. The second approach identifies coherent generators by analyzing directly the state matrix of the linearized system. Another method comprises analyzing the eigenvectors associated with the system oscillation modes.

With the exception of the classical approach, the rest are unsuitable for online applications. Therefore, it has given it the necessary impetus for extensive research. A number of contributions have appeared on the classical approach of identifying coherency in power systems with slow-coherency being the widely used method amongst the lots.

3.2.1. **Slow Coherency Method**

Slow coherency is increasingly becoming the most popular time-domain approach for identifying coherency amongst a pool of generators in power systems. This is because it provides a potential method for capturing the movement of generators between groups by analyzing their swing curves under disturbance. We define generators to be coherent if the waveforms of the rotor-angle trajectories are identical. In practice, however, they may be very close but not identical. Figure 3.1 shows the swing curves of some generators in a power system.

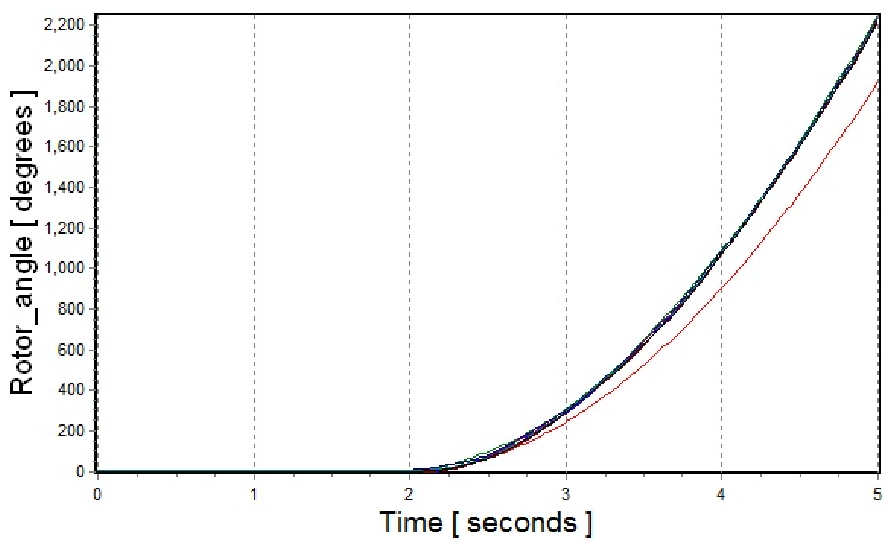


Fig. 3.1 Swing curve of a 56 bus system

In Figure 3.1 above, the system comprises 10 generators in the power network. When transient stability analysis was performed during fault condition, two coherent groups were identified from slow-coherency. The thick curve atop the thin one represents 9 generators in one coherent group.

However, in very complex power systems (e.g. 25,000 buses), just analyzing the swing trajectories becomes a quixotic challenge. Fortunately, many power research labs have developed software packages based on slow coherency principle to identify coherency amongst a large number of generators in the power system network. One typical example is the 'Dynamic Reduction Program', DYNRED, developed by the Electric Power Research Institute, EPRI, based in California, USA [24]. In [18], DYNRED was deployed into a 15,549 bus system in which 2385 generators were identified as belonging to two slowly coherent groups. There are 959 generators that belong to the North group and 1426 that belong to the south group. This is shown in figure 3.2 below.

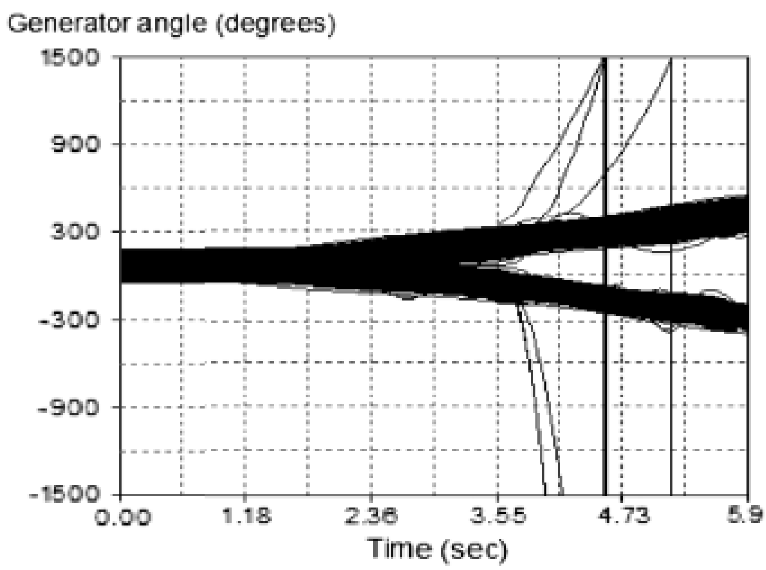


Fig. 3.2 Swing trajectories of 15,549-bus system

3.3. **Graph Theory**

In complex power systems with thousands of buses and branches, say 20,000 buses and 37,000 branches, system analysis becomes an arduous challenge. To demystify the cumbersomeness of this mechanism for stability studies, the graph theory is used. The graph theory, however, remains a vital reduction tool in power systems. Any power grid, regardless of its complexity, can be translated into a simple two-dimensional graph eliminating lots of redundant information [18]. The application of graph theory in power system islanding involves three operational parts:

a. Graph generation
b. Graph simplification
c. Graph partitioning

3.3.1. Graph Generation

The power grid is converted into a graph, G= (V, E). The inputs to the graph are nodes (v) and branches (e). In a real power system, nodes denote buses and branches represent transmission lined and at times transformers. Buses with generators are called generator nodes ($\mathbf{v^g}$) and those carrying loads are called load nodes ($\mathbf{v^l}$). So, for all $\mathbf{v^g} \in \mathbf{V^G}$ and $\mathbf{v^l} \in \mathbf{V^L}$, we obtain the equation below.

$$\mathbf{V = V^G \cup V^L}$$

The terminologies used to better understand graph theory are given below.

a) Degree

The degree of a node is the number of branches connected to this node. It could be any non-negative integer. Zero degree means the node has no branch or connection.

b) Weight

The weight, w, is the active power flowing out of the node. It is positive if the node is converted from a generator bus and negative otherwise.

c) Domain

A generator node and the load nodes distributed to it form the domain of that generator node. A load node only belongs to a particular generator node, and there is no load node that does not belong to any generator node. Therefore, the number of domains of the graph model is equal to the number of generator nodes.

3.3.2. **Graph Simplification**

This operation is performed on the complex power system to trim or reduce its size to the desired form. However, simplifying the graph without losing too much useful information is also paramount. The following rules are employed in simplifying the graph.

a) Removal of degree one node

This rule could reduce both the size of nodes and branches of a graph.

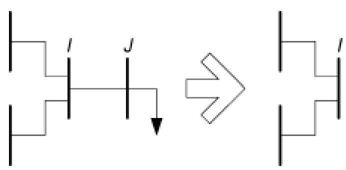


Fig. 3.3 Removal of degree-one node

As shown above, node J can be removed from the graph without changing the total vertex weights by adjusting the weight of vertex I connected to them [18].

b) Removal of degree two node

For buses at which no loads and generators are connected, the power flow into the buses should equal the power flow out of the buses if power loss along the transmission lines is ignored. In figure 3.4 below, since no active power is injected at bus J, $\mathbf{P_1}=\mathbf{P_2}=\mathbf{P}$. Hence, node J can be removed.

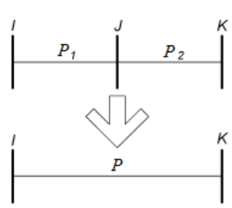
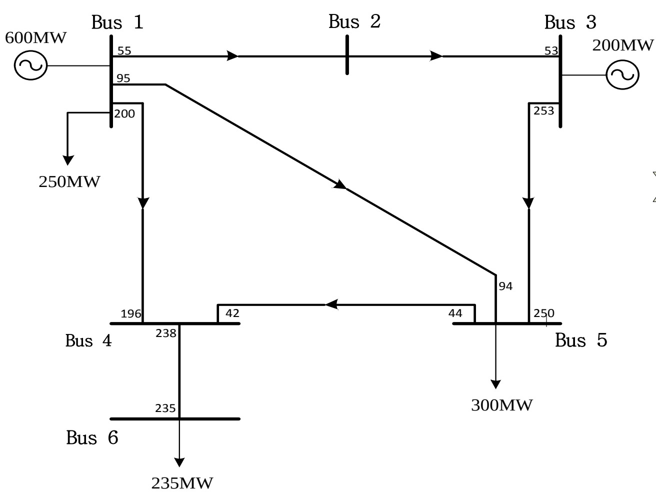


Fig. 3.4 Removal of degree-two node

c) Removal of Transformers

Step-up transformers are removed by merging the two or three buses that the transformer connects. Combining two or three buses at different voltage levels and making them one is not a problem because in graph theory associated two or three nodes have no significant difference.

Figure 3.5 is a typical power system consisting of six buses and seven branches. After graph simplification, the 6-bus system is reduced to four buses and five branches. This is shown in figure 3.6.



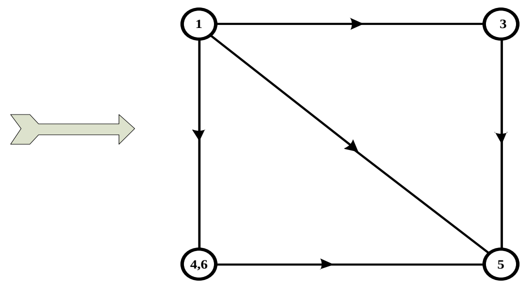


Fig. 3.5 A 6-bus system

Fig. 3.6 A 4-bus graph model

In [14], the power system comprises 37,839 edges and 26,552 vertices. After graph simplification, a significant amount of edges and vertices of the graph were eliminated and the computational cost for graph partitioning was reduced. This is shown in the figure below.

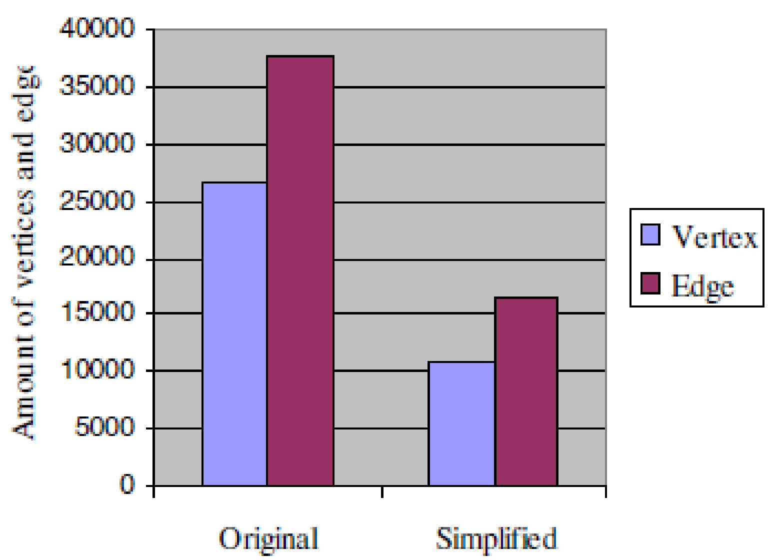


Fig. 3.7 Graph size before and after reduction

3.3.3. **Graph Partitioning**

Graph partitioning is the most crucial aspect of graph theory in power system islanding. Search algorithms are deployed to identify the appropriate splitting branches or cutsets after which the system is finally partitioned desirably to meet generation-load balance requirement. This is where our proposed partitioning algorithm is introduced.

3.4. **Graph Searching Algorithms**

Graph searching is a common approach to solving problems that are able to be modeled as a graph, G. since the power system can also be modeled as a graph through graph theory, knowledge of graph searching methods will be very useful. The most common ones are Dijkstra's algorithm, breadth-first-search (BFS), Depth-first-search (DFS), and Bellman-Ford-Moore's algorithm. In this section, the algorithm of Dijkstra's method will be discussed

3.4.1. **Classical Dijkstra Algorithm**

Dijkstra's algorithm, conceived by Dutch computer scientist Edsger Dijkstra in 1959, is a graph search algorithm that solves the single-source shortest path problem for a graph with nonnegative edge path costs, producing a shortest path tree. This algorithm is often used in routing, especially for transport, communication, routing protocols etc. For a given source vertex (node) in the graph, the algorithm finds the path with lowest cost (i.e. the shortest path) between that vertex and every other vertex. It can also be used for finding costs of paths from a single vertex to a single destination vertex by stopping the algorithm once the path to the destination vertex has been determined. For example, if the vertices of the graph represent cities and edge path costs represent driving distances between pairs of cities connected by a direct road, Dijkstra's algorithm can be used to find the shortest route between one city and all other cities.

In figure 3.8, a directed graph *G* having four vertices and five edges is used to illustrate Dijkstra's algorithm.

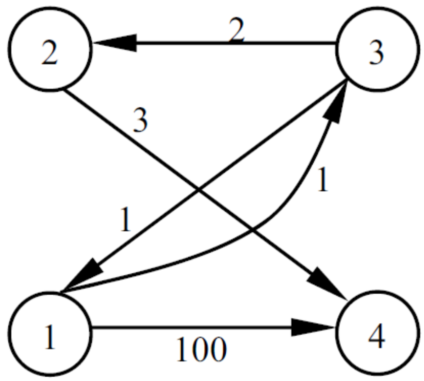


Fig. 3.8 A directed graph

The results from Dijkstra are giveng below.

D[2, 3] = 0	D[3, 2] = 2	D[1, 3] = 1	D[1, 2] = 3	D[4, 2] = 0
D[2, 4] = 3	D[3, 1] = 1	D[1, 4] = 100	D[3, 4] = 5	D[3, 4] = 101

CHAPTER 4

SOURCE NODE EXPANSION ALGORITHM (SNE)

Source Node Expansion (SNE) for slow coherency based islanding is a novel graph searching algorithm to determine optimal cutsets when splitting the power system into electrically balanced islands at post-fault. Canonically, when the power system is severely disturbed causing loss in synchronism, initial unbalanced islands are formed due to coherent grouping of generators.

The SNE initiates graph search for optimal cutsets from within each coherent group by starting source node expansion amongst individual generator nodes in each coherent group until cutsets are collectively found for the entire coherent group. This is achieved through a systematic frontier expansion across an Adjacency Matrix axis until generation-load balance is met. Once expansion terminates, for a particular coherent group, optimal cutsets can be found from matrix. This can be done by tracing up or down columns of locked load nodes during expansion. All entries, $A_{ij}=1$, whose i remained unlocked during row expansion becomes the splitting spot. Hence, $e_{i\text{-}j}$ becomes the splitting edge or the cutset. Fig. 4.1 illustrates SNE.

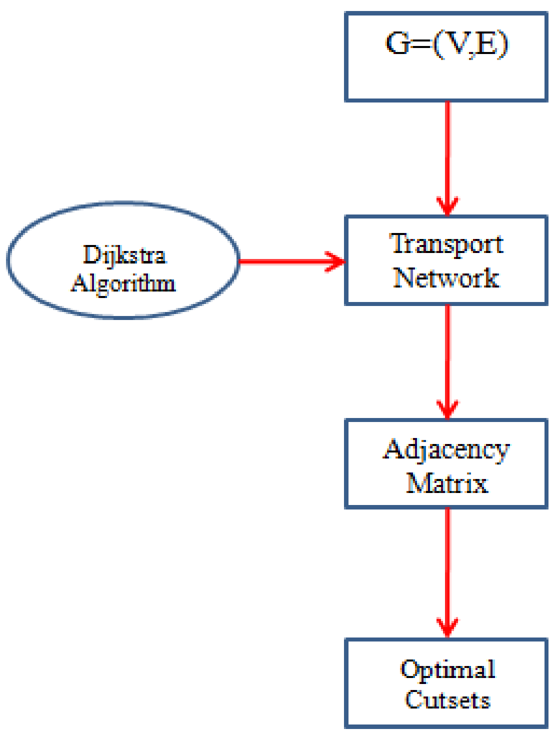


Fig. 4.1 SNE Flow Chart

4.1. **How the Algorithm Works**

4.1.1 **Generator Grouping**

Slow-coherency based generator grouping is the basis of Source Node Expansion Algorithm. A knowledge of the grouping information is imperative for setting the initial Islanding boundaries before graph search expansion is initiated from each coherent group. Slow coherency is discussed in detail in section 3.2.1 of Chapter 3.

4.1.2 **Transport Network**

After graph simplification and power flow tracing on the tie lines, a transport network is assembled, which is a directed graph, $G = (V, E)$ where V is the set of vertices and the edge set E, represents the total number of tie lines interconnecting the nodes. Fig. 4.2 shows a 16-node transport network with nodes 1, 5, 12 and 15 as generation or source nodes and the net power generation/consumption indicated next to each node; a positive number denotes total generated power of a source node and a negative value specifies the total power consumption of a load node. The units of these values are of no significance for the purpose of this algorithm.

Assume that a fault occurs on the network and studying rotor-angle response curves identifies 3 coherent groups of generators: generator nodes 1 and 5 form one group and nodes 12 and 15 each form their individual coherent group. The coherent grouping of generators is shown in Table 4.1. For complex systems, a software packaged called DYNRED developed by the Electric Power Research Institute (EPRI) can be used to categorize generators on the basis of coherency [24].

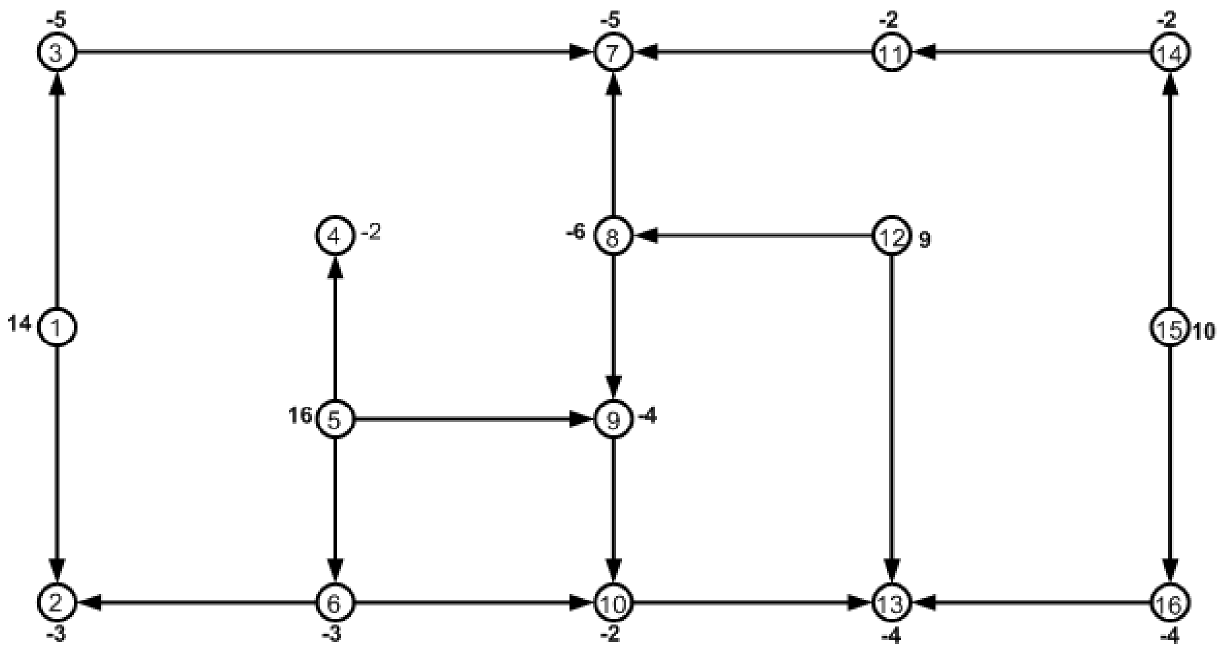


Fig. 4.2 16-node Transport Network

TABLE 4.1
GROUPING DATA

GROUP NAME	**GROUP MEMBER**	**TOTAL POWER (PU)**
A	1,5	30
B	12	9
C	15	10

4.1.3 **Dijkstra Implementation**

After having transformed the post-disturbance power system into a transport network based on flow tracing, a modified Dijkstra algorithm is used. This algorithm solves the single-source, shortest-path problem for a graph where all edges have nonnegative weights [26].

The Dijkstra algorithm considers the source node as the origin and the visiting node as the destination. This algorithm records the distance it travels from all origins (source nodes) to destinations it visits based on the flow tracing pattern of the network.

The distance from one node to the other is translated into a *cost*, C. The source node is always used as the cost reference. A source node is called the *root*. In Fig. 4.3, the Dijkstra algorithm has been applied to source node 5. For this node, destinations 4, 6, and 9 are called *parents* and nodes 2 and 10 become are the *children*. Any node with an out-going degree of zero (no child) is called a *leaf* [27]. Destination 13 is a leaf. Node **i** is a *brother* of node **j** (**i**≠**j**) if nodes **i** and **j** have the same parent. Nodes 2 and 10 can be said to be brothers. Node **i** is an *ancestor* of node **j** (**i** ≠ **j**) if node **i** lies on the path from the root to node **j**. Nodes 6, 10 and 13 are the ancestors of node 5 figure below.

When we move from root node 5 to leaf node 13, a cost of *C* = 3 is assigned. This is done for all the nodes involved and the results are tabulated. This is shown in Table 4.2

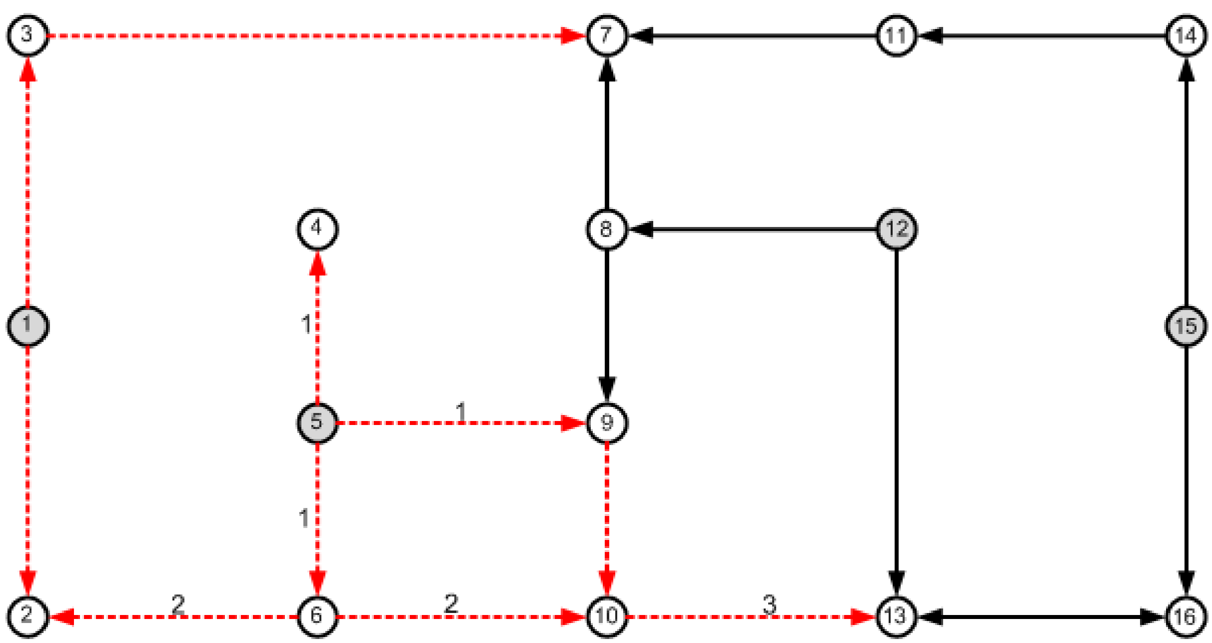


Fig. 4.3 Dijkstra algorithm on 16-node transport network

TABLE 4.2
DIJKSTRA OUPUT

PATH		TRAVEL COST(C)
A	B	
1	2	1
1	3	1
1	4	0
.	.	.
.	.	.
.	.	.
5	9	1
5	10	2
5	11	0
	.	
	.	
	.	
16	14	0
16	15	0
16	16	0

4.1.4 **Adjacency Matrix Formation**

The output of the Dijkstra algorithm on the directed graph is now used to construct a matrix called the adjacency matrix. For a power system represented by a simplified graph containing N vertices, an $N \times N$ matrix will be formed. Fig. 4.4 shows the adjacency matrix for the 16-node graph presented in Fig. 4.2. This matrix is a sparse matrix with its non-zero elements representing the flow of power between two vertices. In other words, $A_{ij} = k$ corresponds to power flow from node i to node j where k is the cost of travel between these nodes. It can be observed that in general, $A_{ij} \neq A_{ji}$. That is to say, if $A_{ij} = k$, then $A_{ji} = 0$. Furthermore, $A_{ij} = 1$ represents a direct connection between nodes i and j. These connections will be given priority during the source node expansion.

Power out-flow node

Power in-flow node

A =

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	1	0	1	0	0	1	2	0	0	3	0	0	0
6	0	1	0	0	0	0	0	0	0	1	0	0	2	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1	0	1	2	0	0	3	0	0	0
9	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
11	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	2	1	2	0	1	0	1	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0
15	0	0	0	0	0	0	3	0	0	0	2	0	2	1	0	1
16	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Fig. 4.4. Adjacency matrix of the 16-node transport network

The rows of the adjacency matrix can be viewed as node power outflow and the columns as node power inflow. This will be evident when considering a node with power only flowing out (i.e. a source node), the column corresponding to this node will be all zeros.

4.1.5 Source Node Expansion Using Adjacency Matrix

The SNE algorithm considers the rows in the adjacency matrix corresponding to each source node. Before the start of expansion, all load nodes are considered to be *unlocked*. This means that they can be included or moved into any island provided that there is a tie-line connection. A node that is moved in one row will then be considered *locked* and cannot be moved in subsequent rows. This will eliminate *thrashing*, or repeated locking of the same node [28].

The expansion algorithm for each group of coherent source nodes will go as follows: the entries in the row representing a source node are regarded. First, any load node with direct connection to this source (i.e. any $A_{ij} = 1$) is considered. If the source generates enough power to feed that load, its node will be moved into the island. This expansion and inclusion of loads will continue until the generation/load balance is reached or all the row elements with the value of 1 are moved. In the latter case, if the source can still provide more power, the same criteria is applied to all the nodes in its row with $A_{ij} = 2$, then $A_{ij} = 3$ and so on. The stopping criterion for the algorithm in each row is when the power balance condition is satisfied or all the nodes with $A_{ij} \neq 0$ are moved.

The next row to be studied is the next generator node in the same coherency group. The same expansion process is applied to this source followed by all the sources in this coherency group.

The next step is to establish the cutsets for this group of coherent generators. These can be determined by searching the columns related to all the locked nodes. Any $A_{ij} = 1$ in the column representing an unlocked node will be one of the cutsets.

The final stopping criterion for the algorithm is when all the sources are expanded. This procedure can be illustrated using the adjacency matrix of Fig. 4.5 as an example:

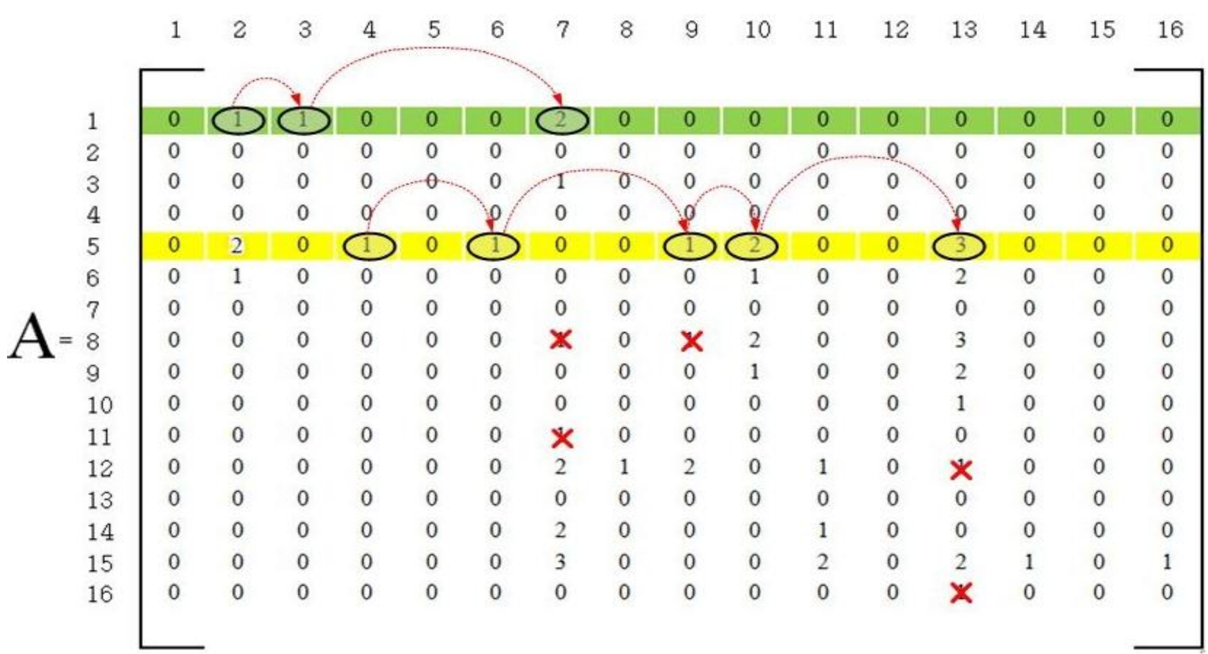


Fig. 4.5 SNE of Adjacency Matrix and Cutsets

The first row is considered corresponding to source node 1. At this node, SNE initiates at $C = 1$. The first entry, A_{12} representing a connection to load node 2 is moved and locked. This source node still has ample power generation so the next entry, A_{13} is visited and locked. Since the source node 1 has room to accommodate more loads and there are no more branches with $C = 1$ in this row, $C = 2$ is set. Expansion continues in a similar manner and A_{17} is locked which will satisfy generation-load mismatch for power balance requirement. The algorithm terminates for this row and C is set back to 1 for the next source node expansion, which is node 5 in the same coherency group as node 1. At $C = 1$, load nodes 4, 6 and 9 will be included and locked. Then at $C = 2$, node 10 is moved (note that node 2 was already locked in the expansion of row 1 and hence not considered in this row). Since generator 5 can still accommodate more load, setting $C = 3$, load 13 is included in this expansion, which will stop the algorithm for this row. At this point, by tracing the columns corresponding to the locked nodes 2, 3, 4, 6, 7, 9, 10 and 13, searching for all the 1's associated with an unlocked node, the cutting edges of , $e_{8\text{-}7}$, $e_{8\text{-}9}$, $e_{12\text{-}13}$ and $e_{16\text{-}13}$ are determined. The algorithm continues for all the source nodes and the final cutset is found to be $E_{final} = \{e_{8\text{-}7}, e_{8\text{-}9}, e_{11\text{-}7}, e_{12\text{-}13}, e_{16\text{-}13}\}$. The islands now can be formed as shown in Fig. 4.6. It is clear that generation-load mismatch is satisfied in each island.

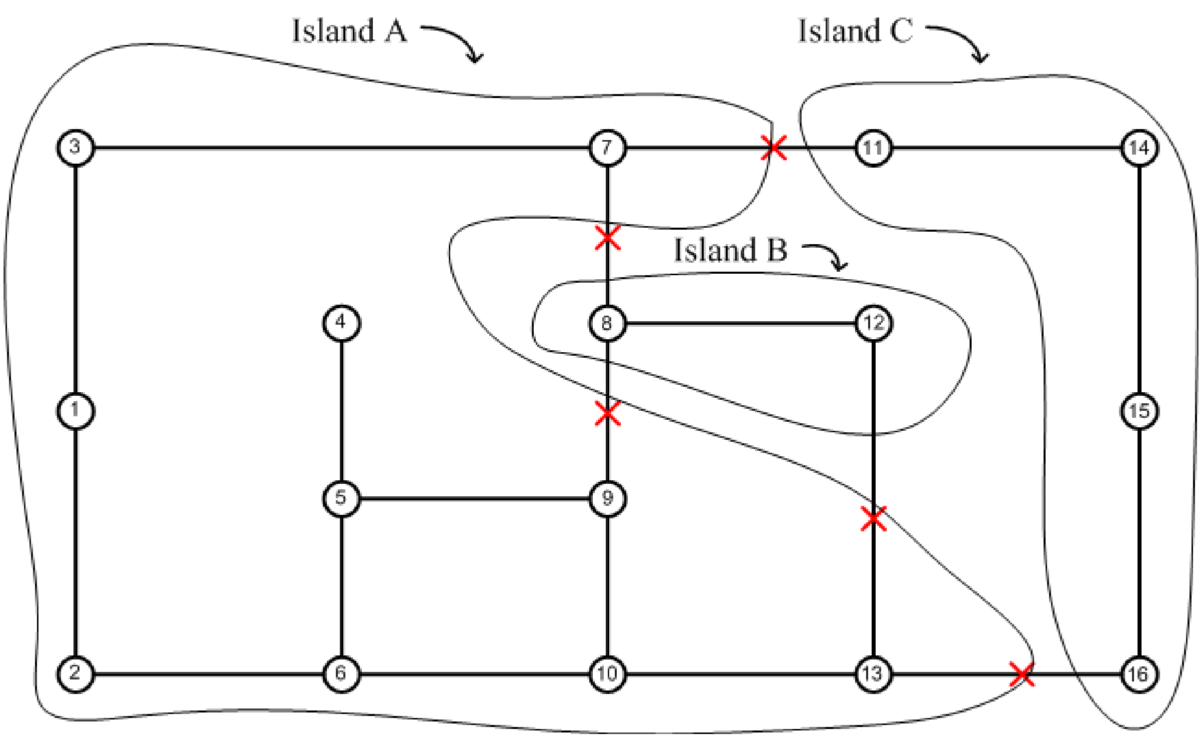


Fig. 4.6 Balanced islands in the 16-node transport network

This algorithm is also able to reduce the number of loads that need to be shed in order to provide system stability and maintain dynamic performance.

4.1.6 Final Separation

The final system splitting is shown in Fig. 4.7. Table 4.3 shows that acceptable power mismatch exists amongst the three balanced islands.

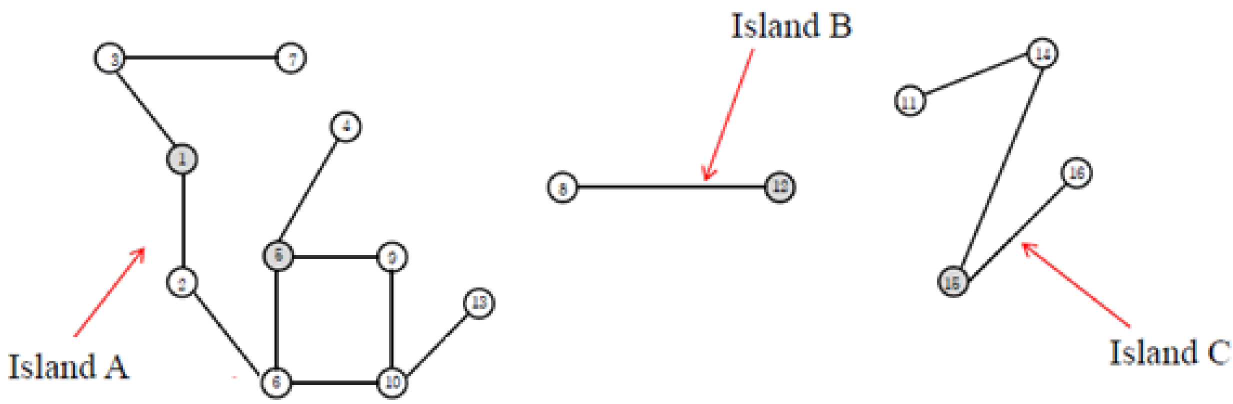


Fig. 4.7 Balanced Islands

TABLE 4.3
GENERATION-LOAD MISMATCH DATA

ISLAND	TOTAL GENERATION (PU)	TOTAL LOAD (PU)
A	30	28
B	9	6
C	10	8

CHAPTER 5

CASE STUDY

This chapter covers the testing of the algorithm in a simulated environment. A 3 phase-to-ground fault is considered. A 14-bus system and a 37-bus system are tested to verify the SNE algorithm. The PowerWorld Simulator software is used to display the implications of the SNE algorithm.

5.1. The 14-Bus System

5.1.1. System Design

Figure 5.1 shows a 14-bus system with 5 generators and 10 loads. This system can be an example of a distribution network with several DG sources with varying production capabilities

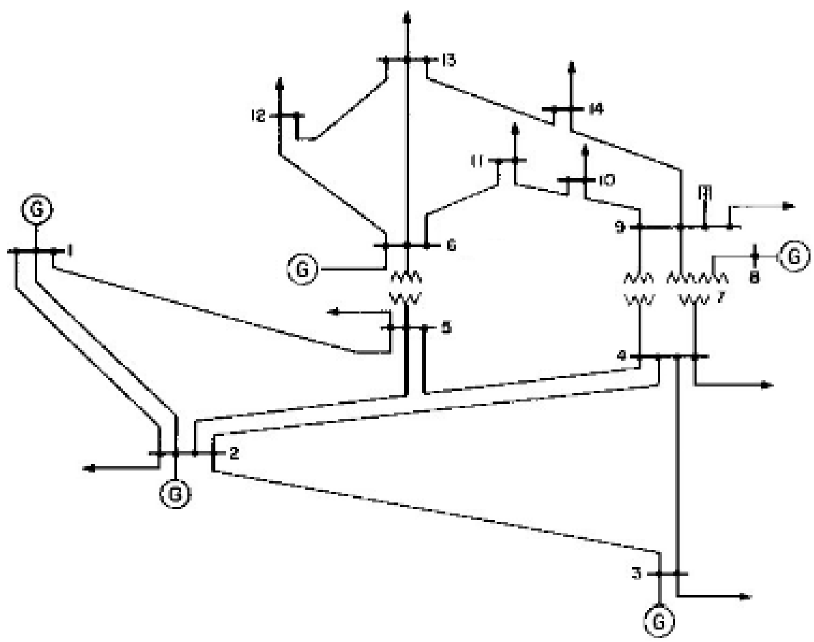


Fig. 5.1 14-Bus system

5.1.2. The 14-Bus Graph Model

Fig. 5.2 is the corresponding simplified graph for this system. It can be seen that the original system with 14 buses and 21 branches is trimmed to a graph with 13 nodes and 18 edges. The load and generation data can be found in Table and Table, respectively.

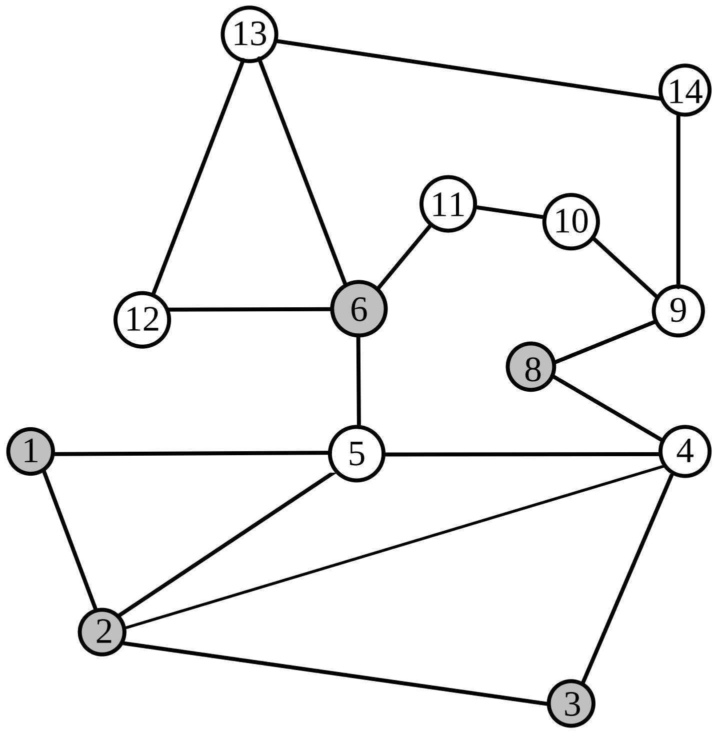


Fig. 5.2 Simplified graph of 14-Bus System

TABLE 5.1
LOAD INFORMATION

BUS NO.	2	3	4	5	6	7
POWER	21.7	94.2	47.8	7.6	0	0
BUS NO.	9	10	11	12	13	14
POWER	29.5	9	3.5	6.1	13.5	14.5

TABLE 5.2
GENERATOR INFORMATION

BUS NO.	1	2	3	6	8
POWER	232.4	42.4	23.4	12.2	17.4

5.1.3. **Fault Analysis**

a. Contingency 1

A three phase to ground fault takes place on line 5-6 at 2 seconds. 0.04 seconds later, another fault occurs on line 6-13. Both lines are tripped by protective relays after 0.5 seconds. If no other action is taken, uncontrolled islanding will occur and generators will lose synchronization. In this case, Fig. 5.3 shows the generator angles, Fig. 5.9 is the generator rotor deviations from synchronous speed and Fig. 5.10 displays the bus voltage magnitudes. Significant voltage oscillation as well as system instability is observed. It is evident that the dynamic performance of the system is completely unacceptable and a complete halt of operation is the only way to deal with this situation.

5.1.4. **Simulation Results**

a. **14-Bus Swing Curve**

Fig. 5.3 shows the generator rotor-angle trajectories of the 14-bus system. From the graph, two coherent groups could be identified. Generator node 6 exists on its own as a coherent group and the rest (generator nodes 1, 2, 3 and 8) belong one coherent group.

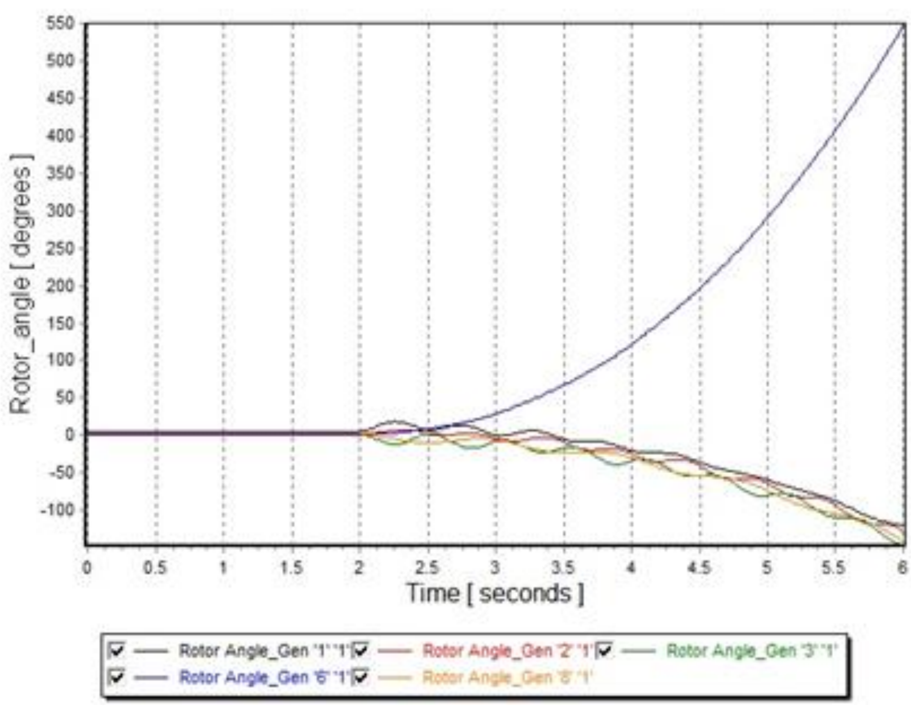


Fig. 5.3 Generator angles after contingency

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The graphs below shows the detailed rotor-angle response curves of all the five generators on the fourteen-bus system.

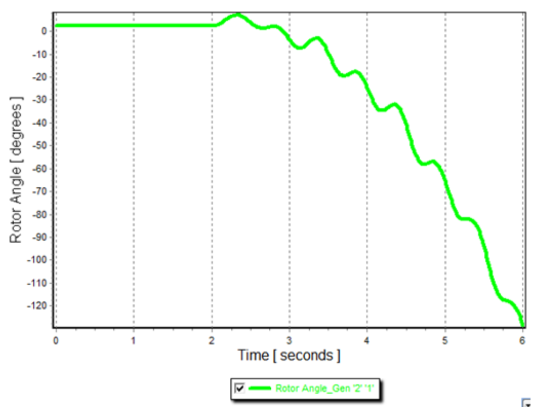


Fig. 5.4 Generator 1 rotor angle

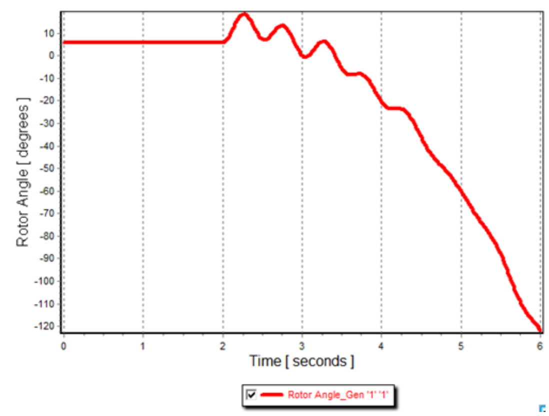


Fig. 5.5 Generator 2 rotor angle

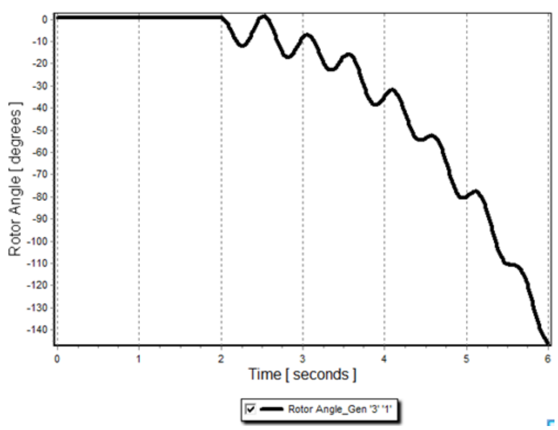


Fig. 5.6 Generator 3 rotor angle

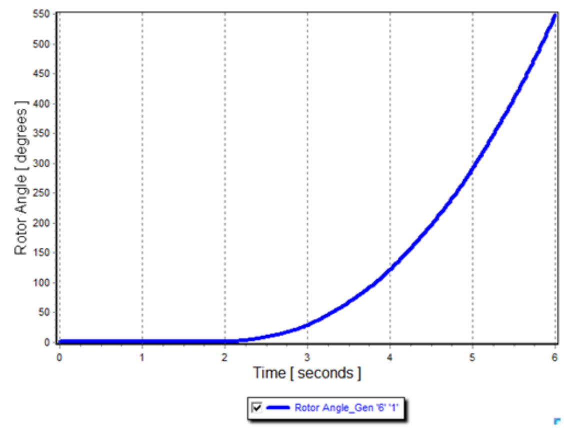


Fig. 5.7 Generator 6 rotor angle

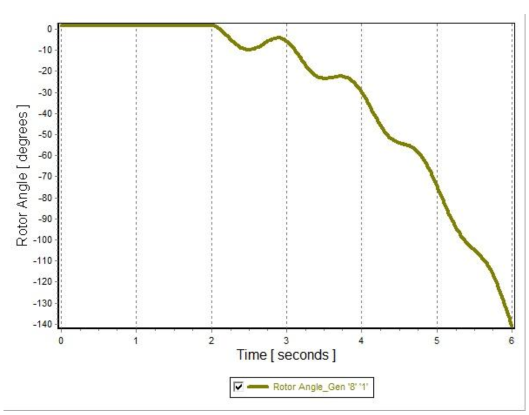


Fig. 5.8 Generator 8 rotor angle

b. **Rotor Speed Deviation**

Figure 5.10 is the generator rotor deviations from synchronous speed. Speed deviation is constant before contingency. Unstable speed deviations are observed after contingency.

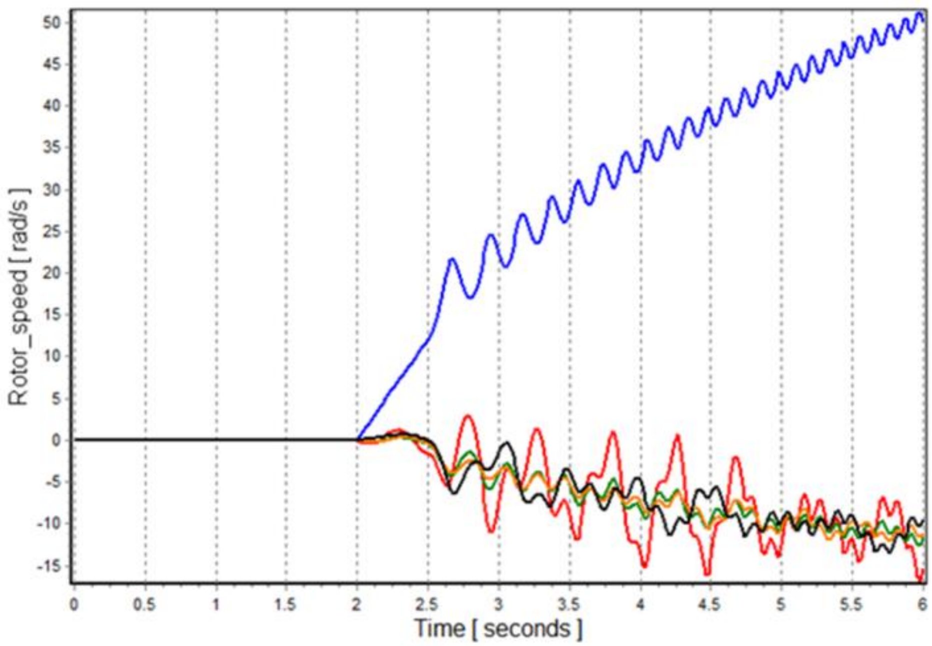


Fig. 5.9 Generator speed deviations after contingency

c. **Bus Voltages**

Fig. 5.10 displays the bus voltage magnitudes. Significant voltage oscillation as well as system instability is observed. It is evident that the dynamic performance of the system is completely unacceptable and a complete halt of operation is the only way to deal with this situation.

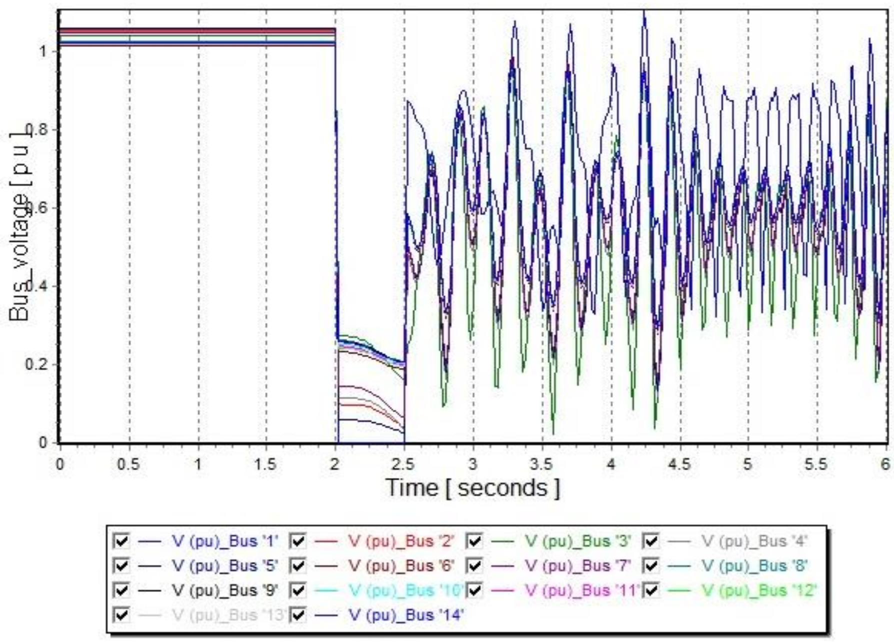


Fig. 5.10 Bus voltage magnitudes after contingency

5.1.5. **Cutset Search**

a. Transport Network

A MATLAB program in Appendix A.1 is used to convert the graph in Fig. 5.2 into a transport network. This is displayed in Fig. 5.11.

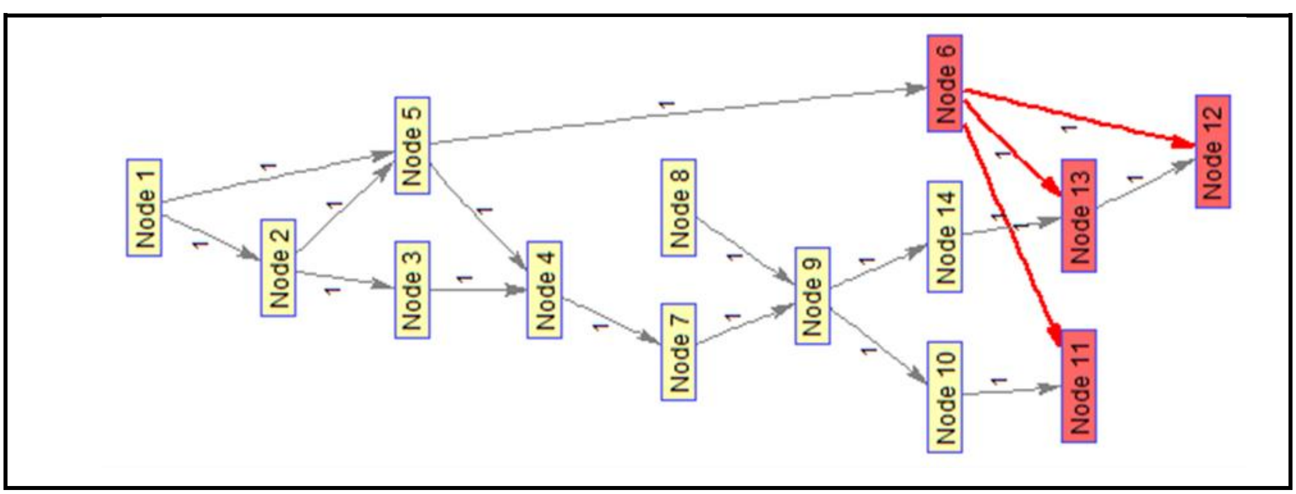


Fig. 5.11 MATLAB graph

b. Dijkstra's Algorithm

The transport network is used as input to Dijkstra algorithm to compute the cost, *C*. Table 4.4 shows the output results from Dijkstra algorithm.

TABLE 5.3
DIJKSTRA RESULTS

PATH		TRAVEL COST
A	B	
1	2	1
1	3	2
1	4	3
.	.	.
.	.	.
.	.	.
6	10	0
6	11	1
6	12	1
.	.	.
.	.	.
.	.	.
14	12	2
14	13	1
14	14	0

c. Adjacency Matrix Formation

The data shown in Table 5.3 is used to form the Adjacency Matrix to deduce the optimal cutsets. The final Adjacent Matrix formed is displayed in Table 5.4.

TABLE 5.4
ADJACENCY MATRIX

A =

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0													0
2		0											0	
3			0									0		
4				0							0			
5					0					0				
6	0	0	0	0	0	0	0	0	0	0	1	1	0	0
7							0	0						
8							0	0						
9	0	0	0	0	0	0	0	0	0	1	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	1	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	1	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Cutsets

The optimal splitting branches were identified after row expansions. The red-circled entries denote the cutsets. Therefore, $\mathbf{E}_{final} = \{e_{5\text{-}6}, e_{6\text{-}13}, e_{13\text{-}16}, e_{7\text{-}8}, e_{7\text{-}11}, e_{12\text{-}13}, e_{8\text{-}9}\}$.

5.1.6. **Final Separation**

The figures below illustrate the formation of two electrically balanced islands after SNE algorithm is implemented.

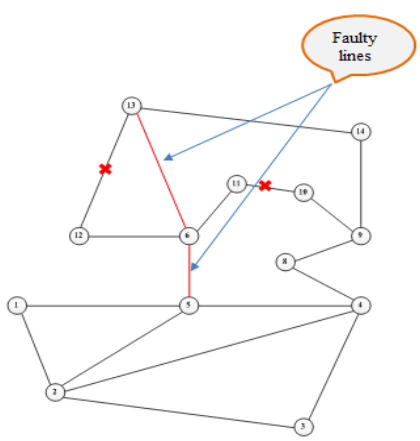


Fig. 5.12 Marking cutsets

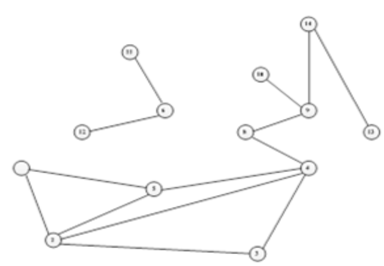


Fig. 5.13 Removing cutsets

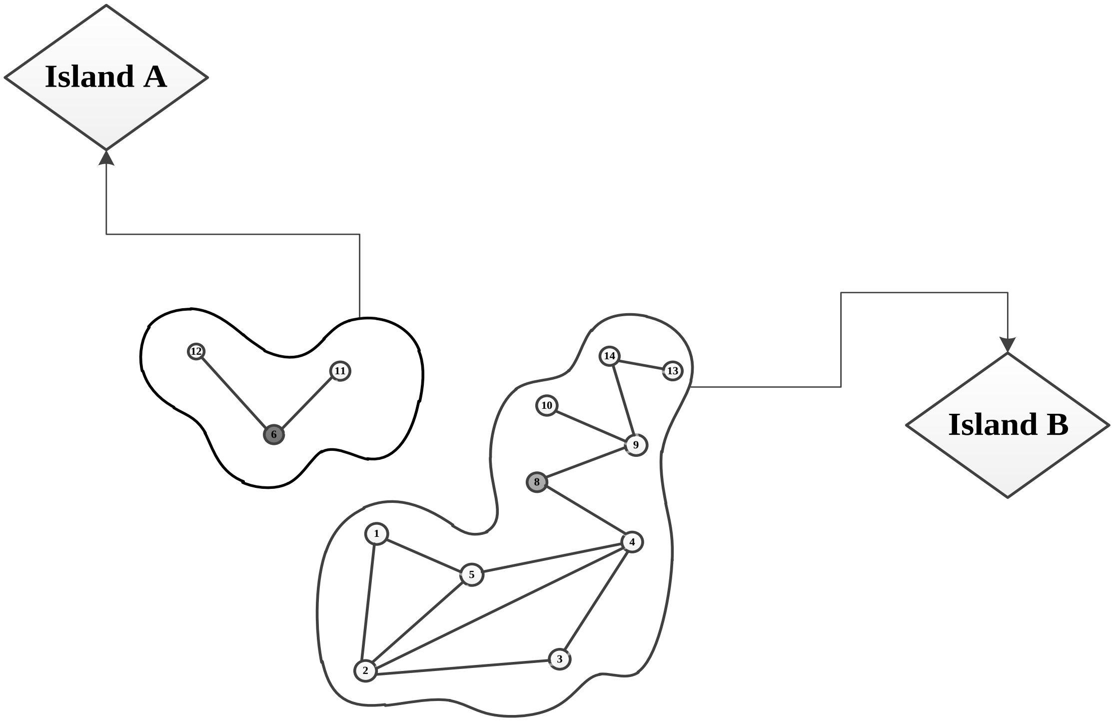


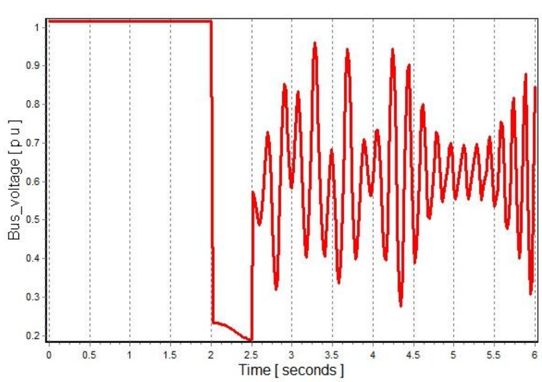
Fig. 5.14 Balanced islands

5.1.7. **Bus Voltage Comparison**

Table 5.5, shows the bus-to-bus voltage comparisons for scenarios *a* and *b*.

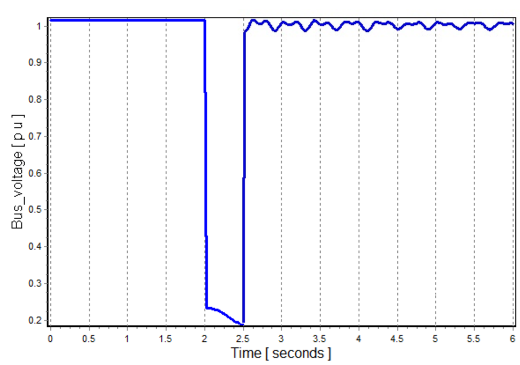
TABLE 5.5
BUS VOLTAGES

a. Bus Voltage after contingency

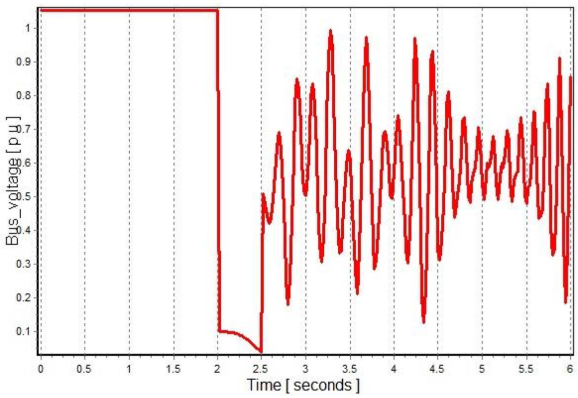


Bus 1 voltage after contingency

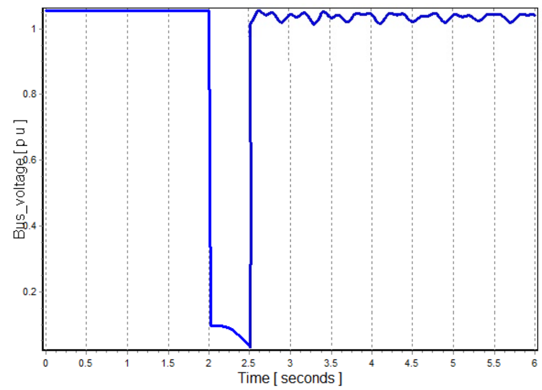
b. Bus Voltage after Islanding



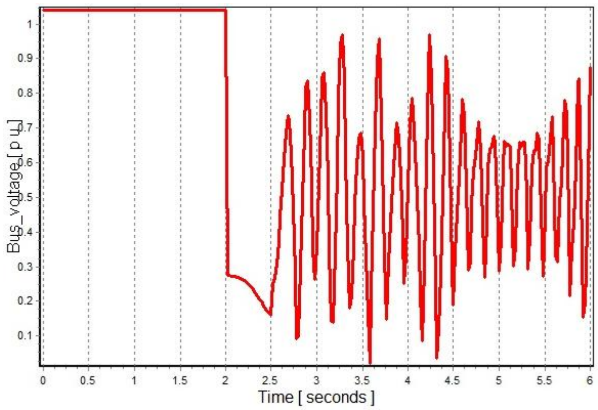
Bus 1 voltage after islanding



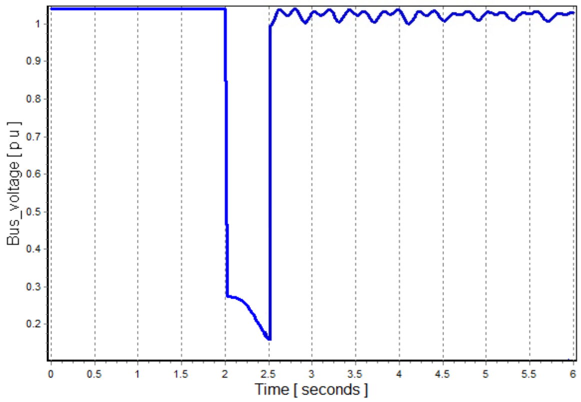
Bus 2 voltage after contingency



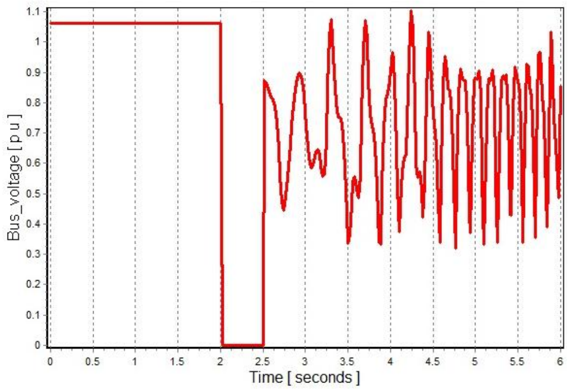
Bus 2 voltage after Islanding



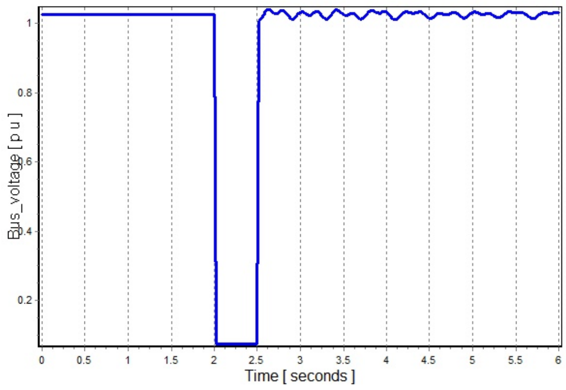
Bus 3 voltage after contingency



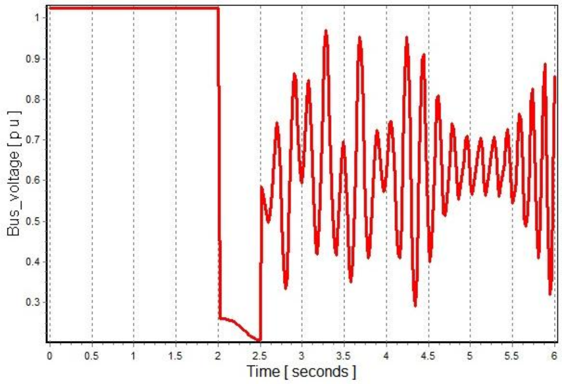
Bus 3 voltage after islanding



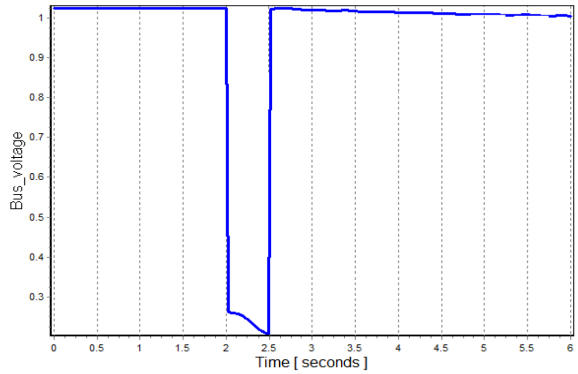
Bus 6 voltage after contingency



Bus 6 voltage after islanding



Bus 8 voltage after contingency



Bus 8 voltage after islanding

At bust 6, the voltage took a nosedive from 1.06pu to zero after 2seconds. After tie lines were tripped to clear fault, voltage at bus flickers. Voltage flickering is terribly harmful for sensitive equipment drawing active power from this bus. But, intentional islanding benefits the bus by raising the voltage magnitude from zero back to 1.06 where it stabilized after some few seconds.

5.2. The 37-Bus System

5.2.1. System Design

This case models a 37-bus system with 8 generators and 24 loads. It also contains three different voltage levels (345kV, 138kV, and 69kV) and 57 transmission lines. Fig. 5.15 shows the single line diagram of the 37-bus system.

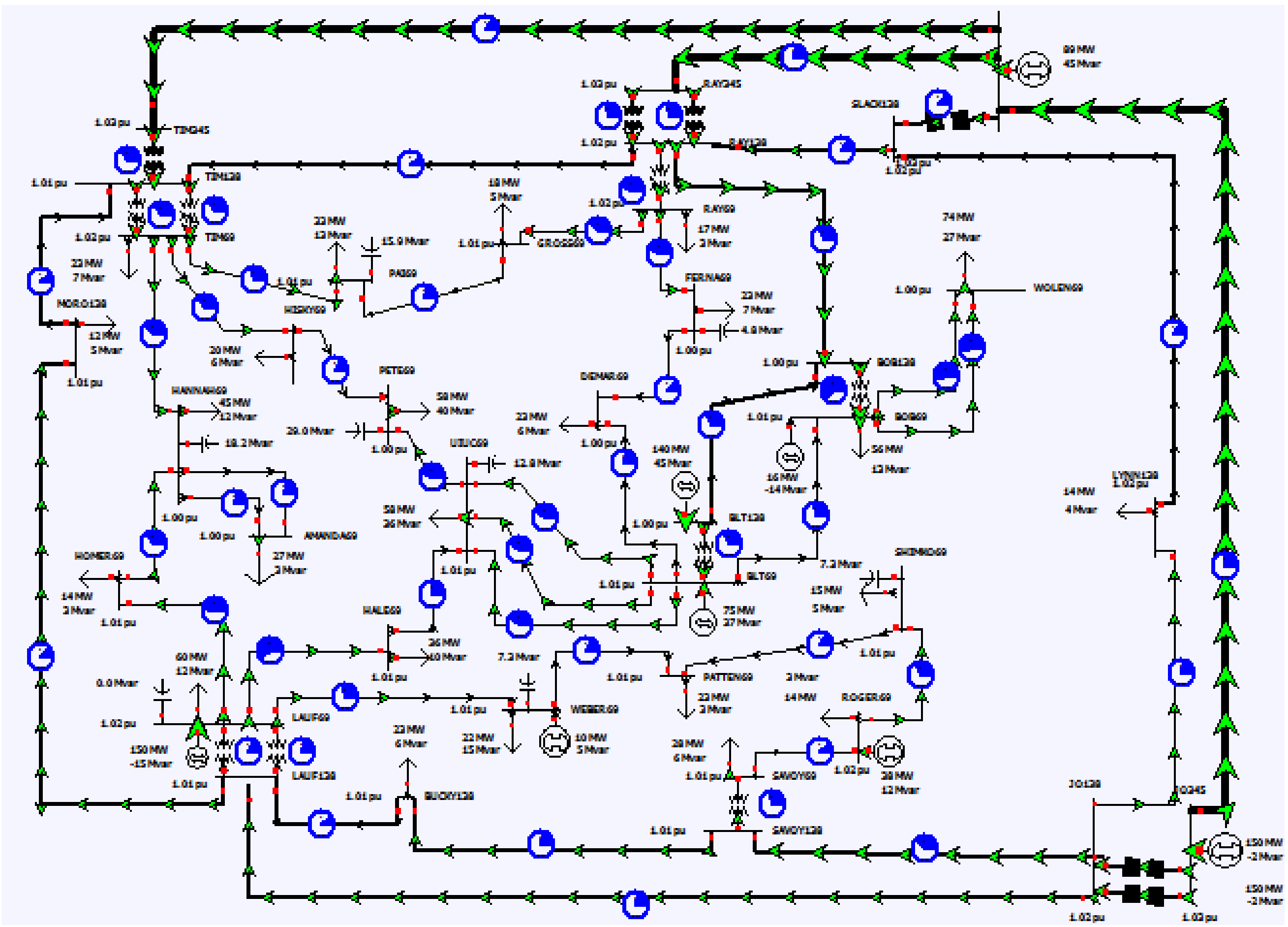


Fig. 5.15 37-Bus system [1]

5.2.2. **The 37-Bus Graph Model**

Fig. 5.16 displays the simplified graph model of the 37-bus system. After graph simplification, system complexity is reduced. The branches are downsized to 46. Table 5.6 contains bus names and their corresponding bus numbers information.

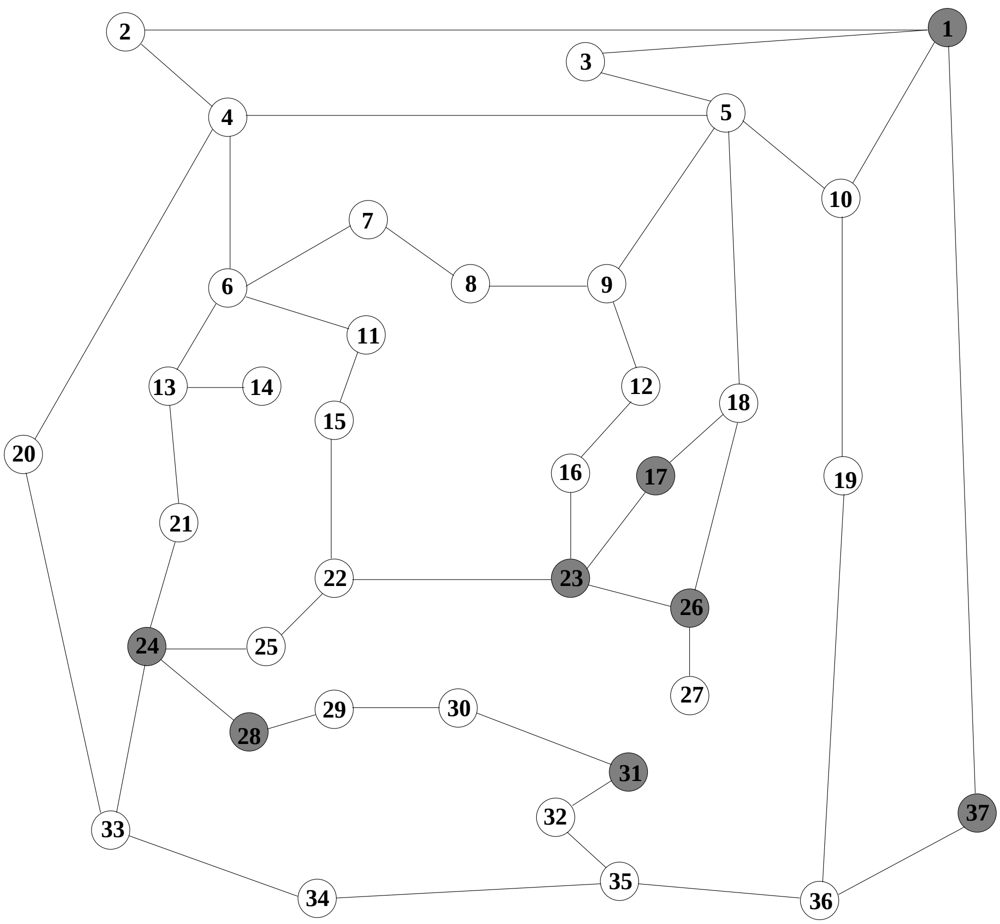


Fig. 5.16 Simplified graph of the 37-bus system

TABLE 5.6
BUS INFORMATION

BUS NAME	**BUS NUMBER**
SLACK345	1
TIM345	2
RAY345	3
SLACK138	10
RAY138	5
TIM138	4
TIM69	6
PAI9	7
GROSS69	8
RAY69	9
MORO138	20
HISKY9	11
PETE69	15
DEMAR69	16
BOB138	18
WOLEN69	27
HANNAH69	13
UIUC69	22
BLT138	17
BOB69	26
AMANDA69	14
SHIMKO69	30
HOMERS69	21
HALE69	25
WEBER69	14
PATTEN69	29
ROGER69	31
LAUF69	24
LAUF138	33
BUCKY138	34
SAVOY69	32
SAVOY138	35
JO138	36
LYNN138	19
JO345	37
FERNA69	12
BLTI69	23

5.3. Fault Analysis

Two contingencies are studied: contingency 1 which showed remarkable system resiliency and contingency 2 with prevalence of uncontrolled islanding.

5.3.1. Contingency I

A 3-phase-to-ground fault occurs on the line from **SLACK345 (Slack** bus) to **RAY345** (bus 3) circuit 1. The fault was cleared 0.52sec later. Fig. 5.17 illustrates the location of fault on the 37-bus system.

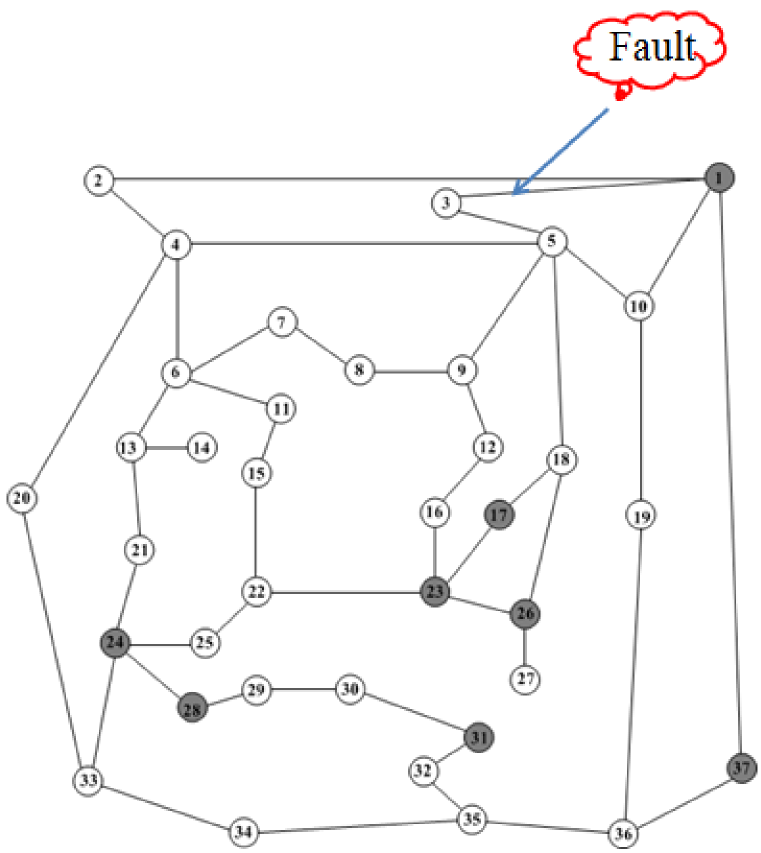


Fig. 5.17 Fault location on 37-bus system

5.3.2. **Simulation results**

a. Generator rotor angle

Figure 5.18 illustrates the generator angles trajectory after contingency. All 8 generators belonged to one big coherent family.

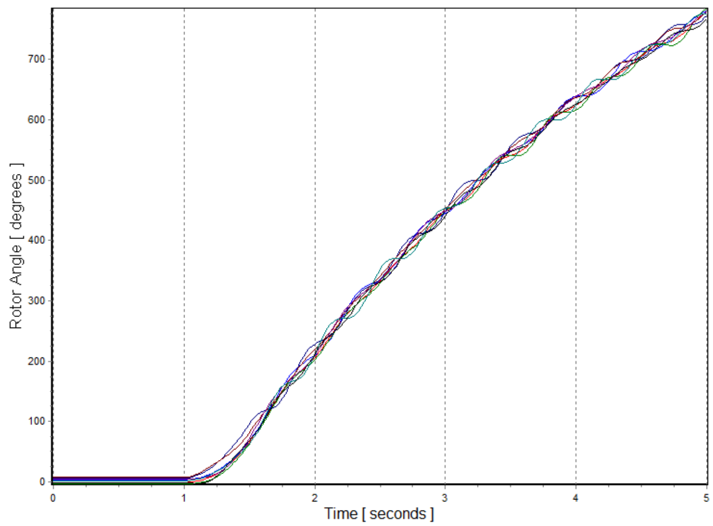


Fig. 5.18 Generator rotor angle after contingency

b. Bus speed deviation

Fig. 5.19 is the bus speed deviation of the 37-bus system after contingency.

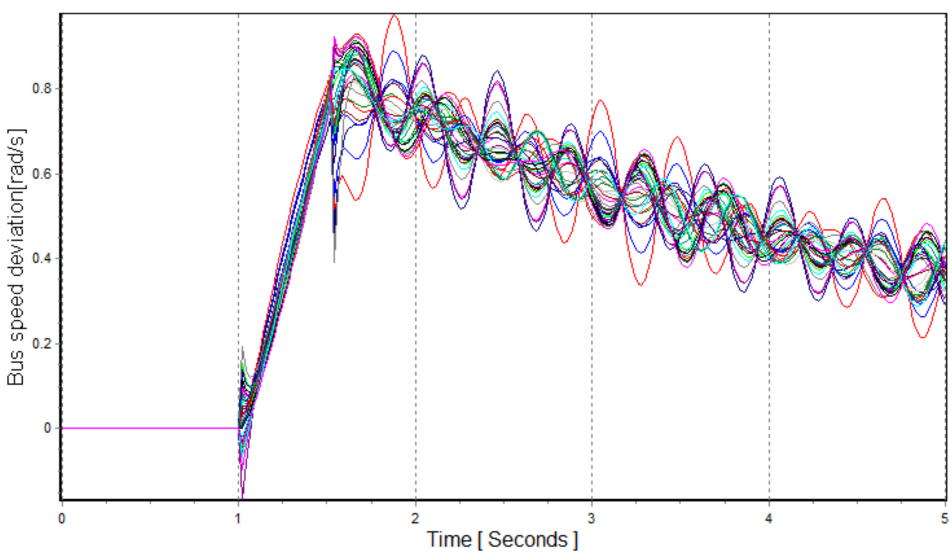


Fig.5.19 Bus Speed deviation after contingency

c. Generator speed deviation

Fig. 5.20 is the generator rotor deviations from synchronous speed.

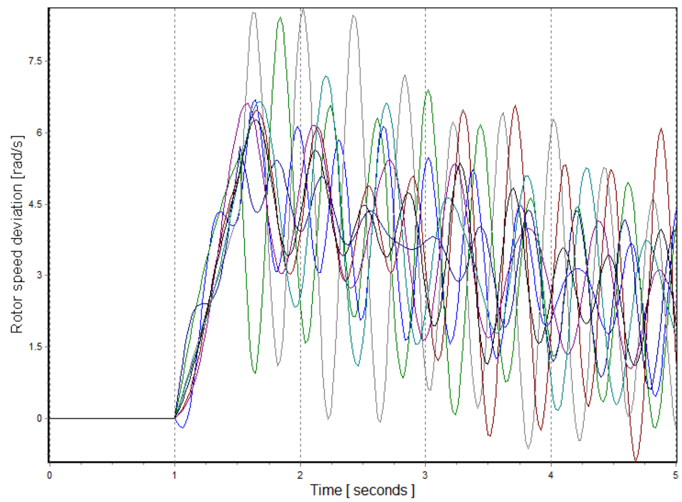


Fig. 5.20 Generator speed deviations after contingency

d. Bus voltages

Fig. 5.21 displays the bus voltage magnitudes.

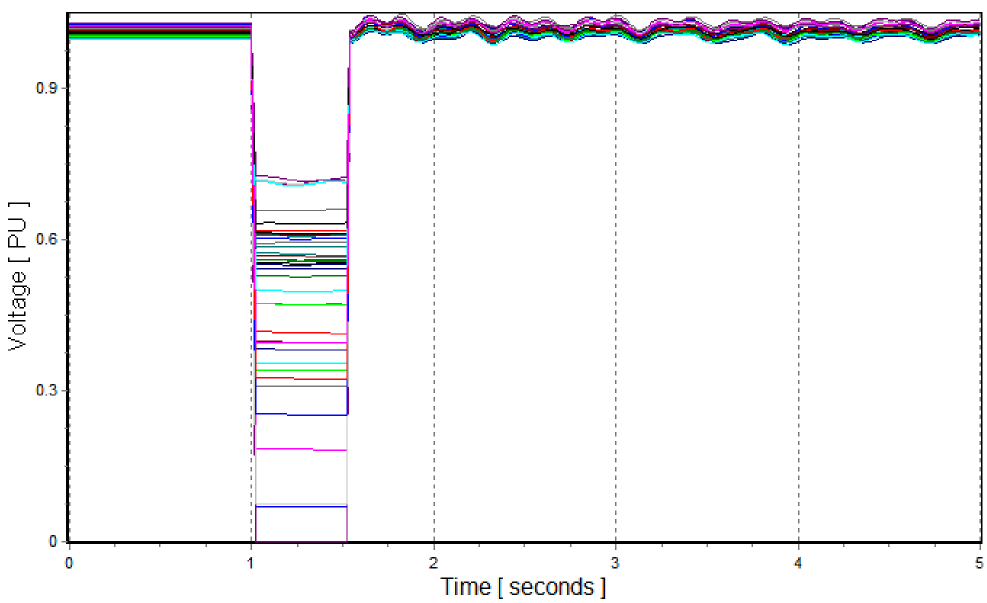


Fig. 5.21 Bus voltage magnitudes after contingency

Since the dynamic performance of system after contingency falls within the permissible range, as evidenced in all simulation results, no islanding issues existed.

5.3.3. **Contingency II**

A three phase to ground fault happens on the line between **SLACK345** and **TIM345** and very close to **SLACK345**. After 0.01sec, another fault occurs on line between **JO345** and **SLACK345** near **JO345**. Both lines are tripped by protective relays in 0.5sec and 0.7sec later respectively to clear fault.

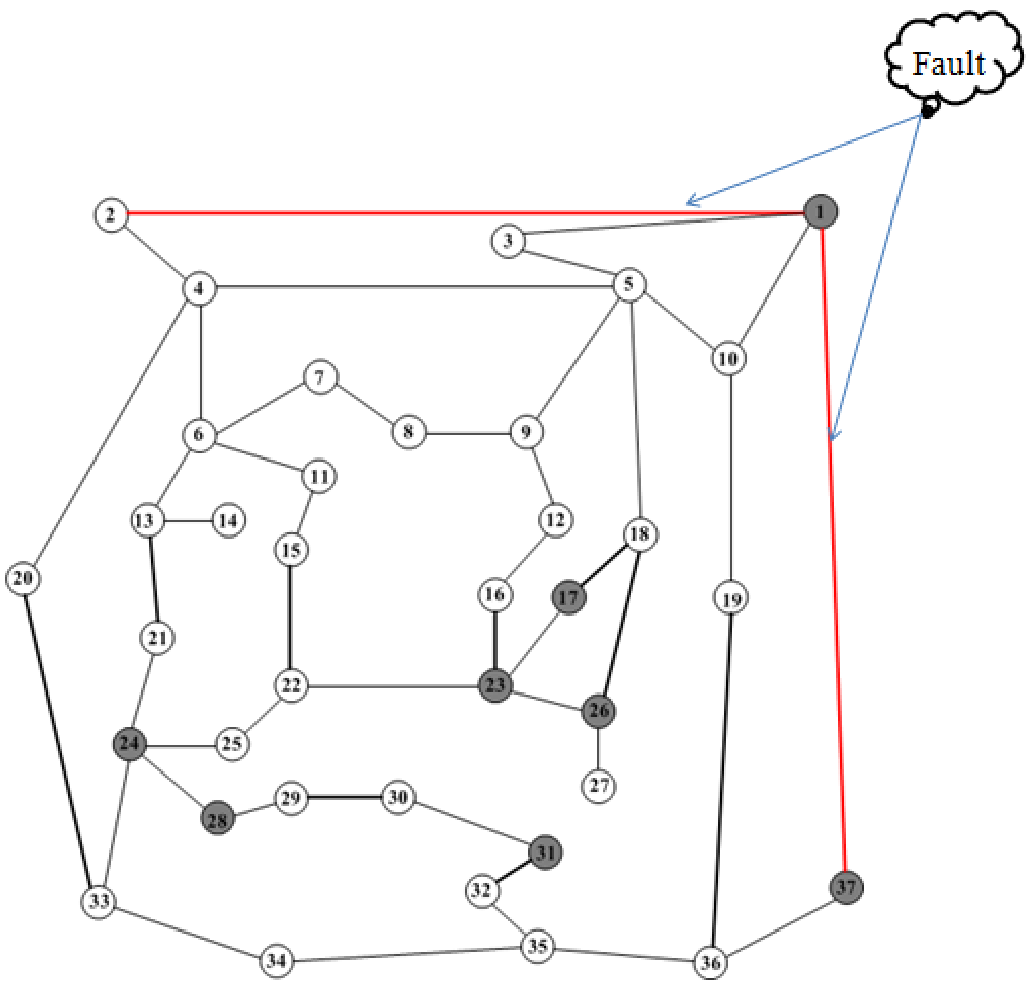


Fig. 5.22 Three phase Fault

5.3.4. **Simulation results**

a. Generator rotor angle

Fig. 5.23 is the generator rotor angle swing curves.

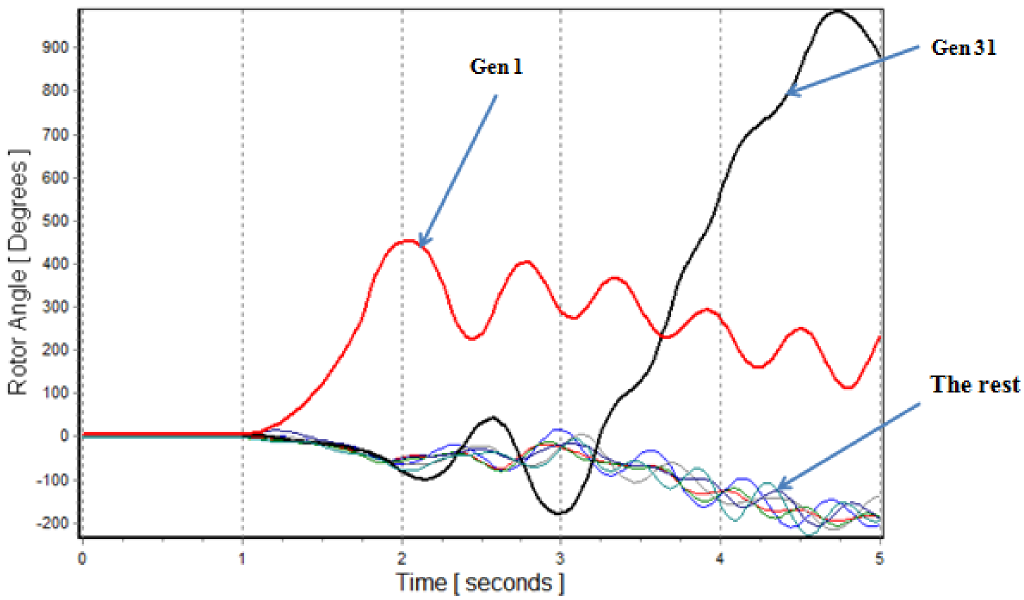


Fig. 5.23 Generator rotor angles after contingency

b. Bus speed deviation

Fig. 5.24 shows the bus speed deviation of the 37-bus system.

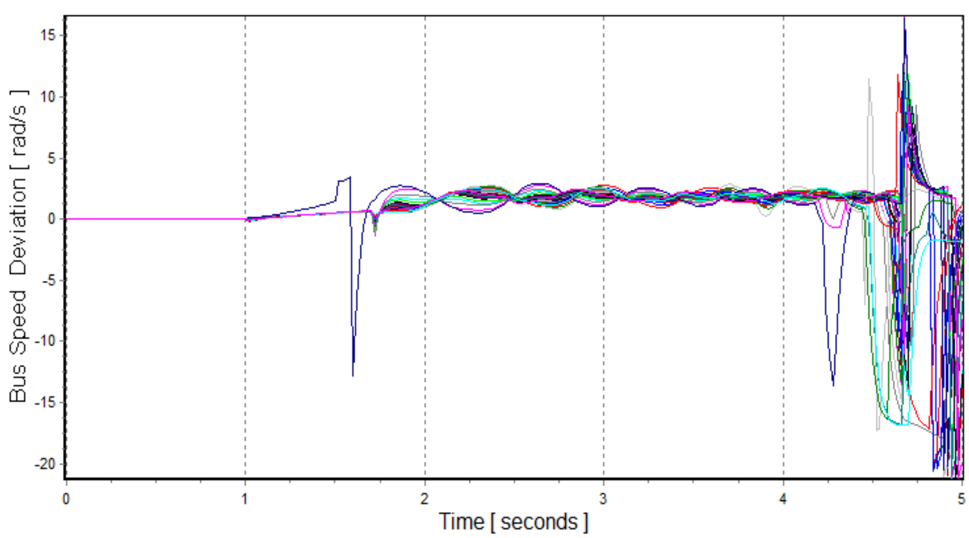


Fig. 5.24 Bus speed deviations after contingency

c. **Bus Voltages**

Fig. 5.25 displays the bus voltage magnitudes.

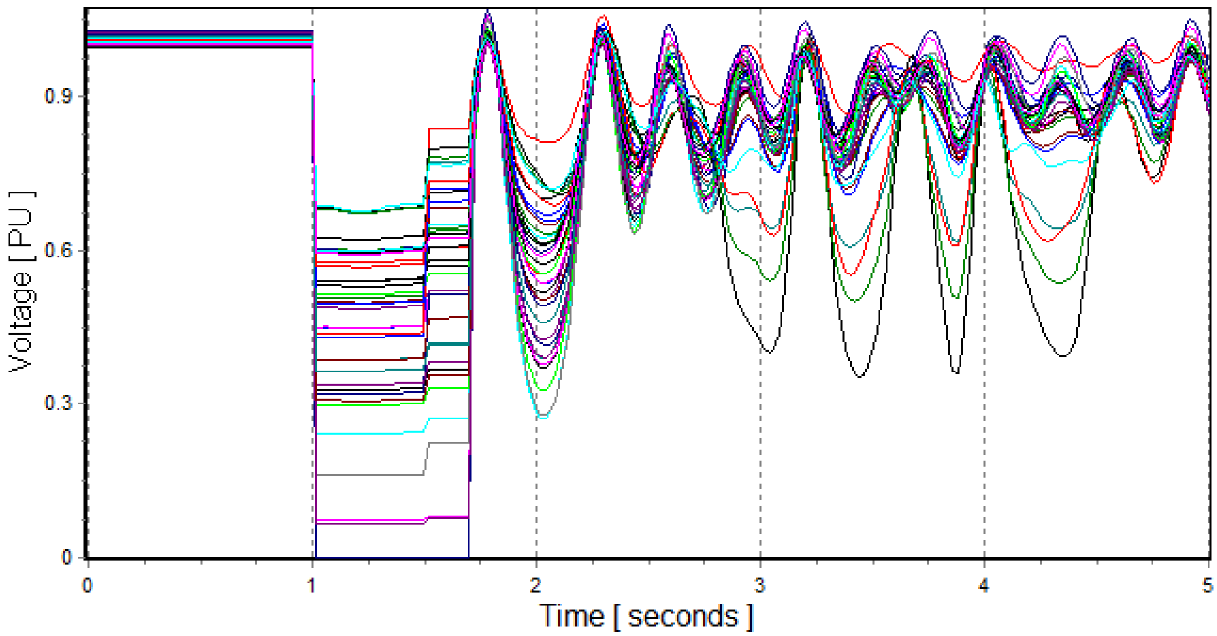


Fig. 5.25 Bus voltage magnitudes after contingency

In Fig. 5.23 slow coherency identified three coherent families hinting a possible occurrence of islanding. Also, significant voltage flicker is observed in Fig. 5.25 which is terribly harmful for sensitive equipment and system components. So, from the dynamic performance of the system we can conclude that an islanding situation has occurred in contingency 2.

5.3.5. **Contingency Resolution**

a. **Coherency Identification**

In order to implement SNE algorithm, the first step is to distinguish the three coherency groups in the system: generators 1 and 31 belong to two different groups and the rest (generators 17, 23, 24, 26, 28, and 37) form another group.

b. Transport network

A MATLAB program in Appendix A.4 is used to direct the graph model in figure 5.22. The result is shown in Fig. 5.26.

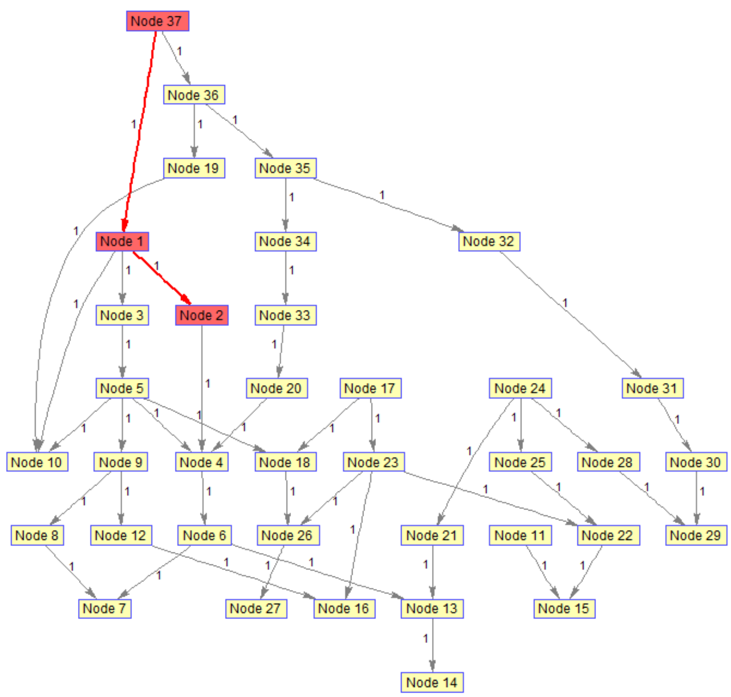


Fig. 5.26 A MATLAB graph

c. Dijkstra Algorithm

Dijkstra is implemented on the graph in Fig. 5.26 to find cost, *C*. Details of the algorithm can be found in Appendix A.2. The results are tabulated for next step.

d. Adjacency matrix formation

Tabulated results are used to construct the adjacency matrix for source node expansion. Table 5.7 is the Adjacency Matrix formed.

TABLE 5.7
ADJACENCY MATRIX

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
1	0	0	1	3	2	4	5	4	3	1	5	4	5	6	6	5	0	3	2	4	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
2	1	0	0	1	0	2	3	0	0	0	3	0	3	4	4	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	2	1	3	4	3	2	2	4	3	4	5	4	4	0	2	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	1	0	0	0	1	2	0	0	0	2	0	2	3	3	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	2	3	2	1	1	3	2	3	4	4	3	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	2	0	0	0	0	1	0	0	0	0	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	(1)	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	(1)	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(1)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	(1)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	2	3	3	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	(1)	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(1)	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	3	2	(1)	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	3	4	4	0	0	0	0	(1)	2	0	0	1	2	0	0	2	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0	4	5	5	0	0	0	0	2	3	0	0	2	3	0	0	3	0	0	0	0	1	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	0	0	0	0	3	4	0	0	3	4	0	0	4	4	3	2	1	2	1	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0	6	7	7	0	0	0	(1)	4	5	0	0	4	5	0	0	5	5	4	3	2	3	2	1	0	0
37	1	0	0	0	0	0	0	0	0	0	0	0	7	8	8	0	0	0	2	5	7	0	0	5	6	0	0	6	6	5	4	3	4	3	2	1	0

○ = Cutset

The final cutset is found as: $\boldsymbol{E}_{final} = \{ e_{13\text{-}21}, e_{17\text{-}18}, e_{15\text{-}22}, e_{16\text{-}23}, e_{18\text{-}26}, e_{29\text{-}30}, e_{31\text{-}32}, e_{20\text{-}33}, e_{19\text{-}36} \}$. Note that edges $e_{1\text{-}2}$ and $e_{1\text{-}37}$ were already cut by the protection relays. Fig. 5.27 shows the cutset locations.

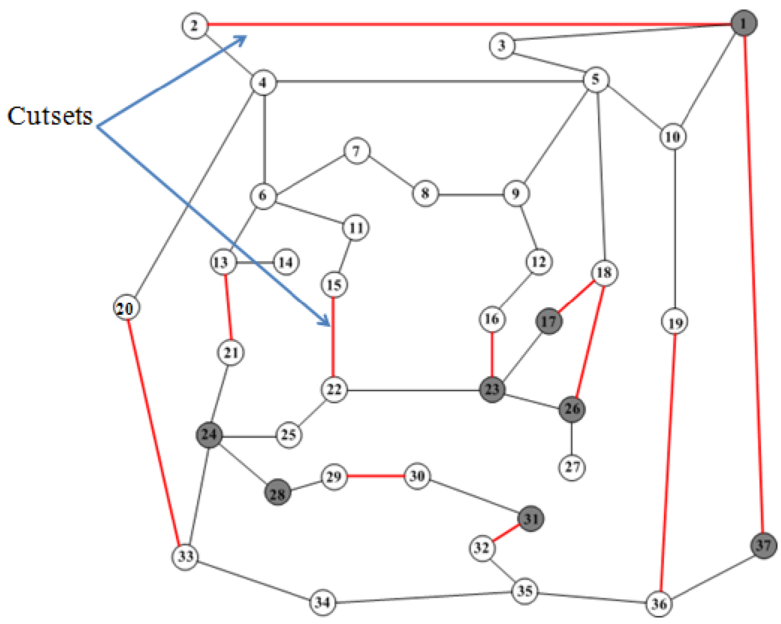


Fig. 5.27 Cutset locations

5.3.6. **Final Separation**

The new islands are shown in Fig. 5.28. The formed islands have power balance without any need for load shedding.

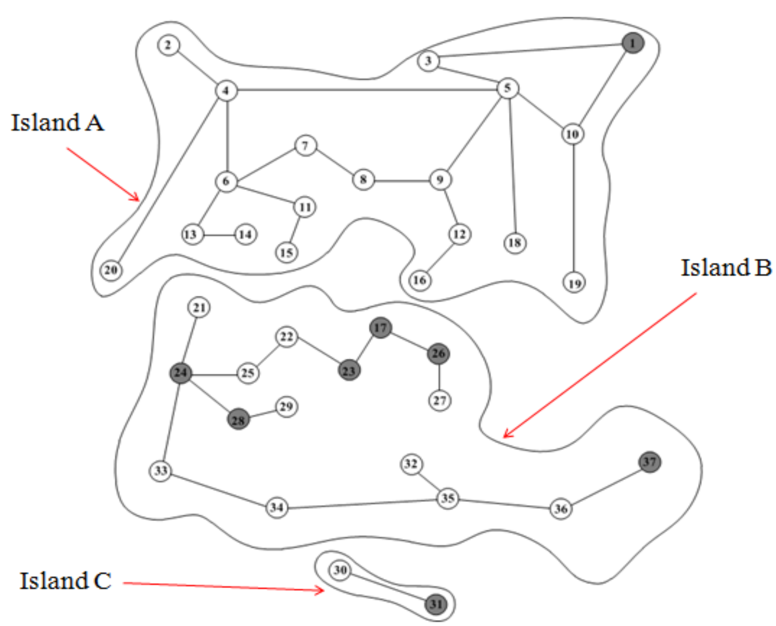


Fig. 5.28 balanced islands

5.3.7. **Simulation results**

a. **Generator rotor angle**

Fig. 5.29 shows the generator rotor angle swing trajectory after islanding is performed.

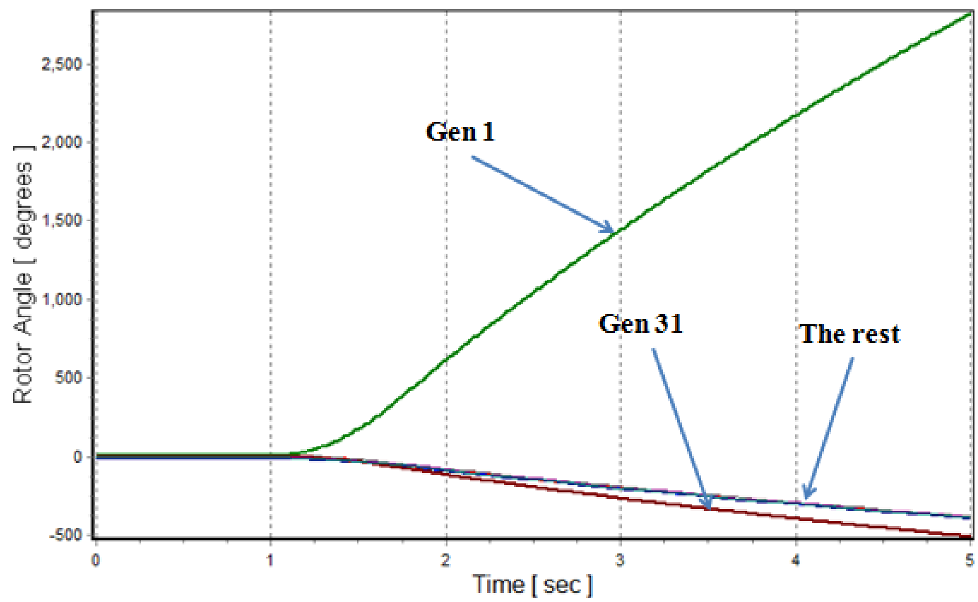


Fig. 5.29 Generator rotor angles after islanding

b. **Rotor speed deviation**

Fig. 5.30 shows the generator rotor speed deviations from synchronous speed.

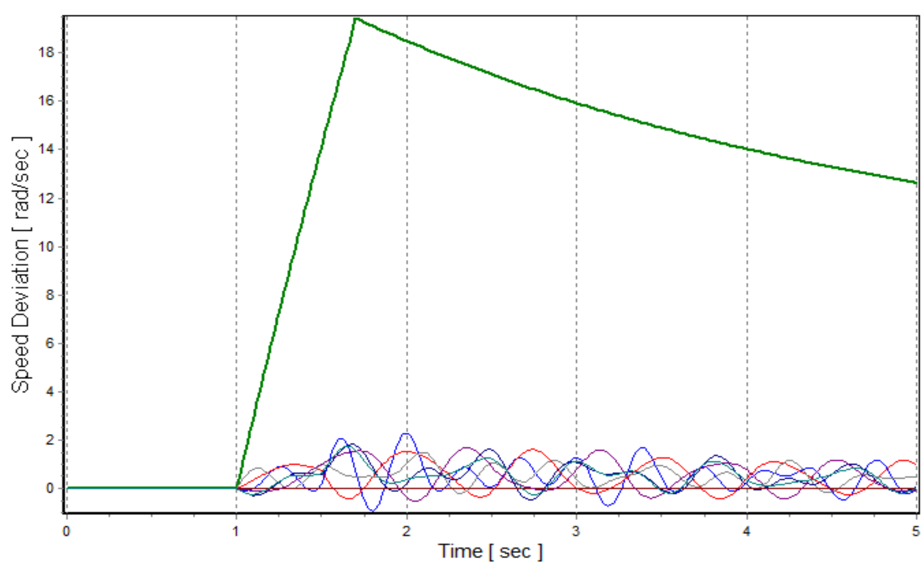


Fig. 5.30 Generator speed deviations after islanding

c. **Voltage at buses**

Fig. 5.31 shows the bus voltage magnitudes after islanding is done.

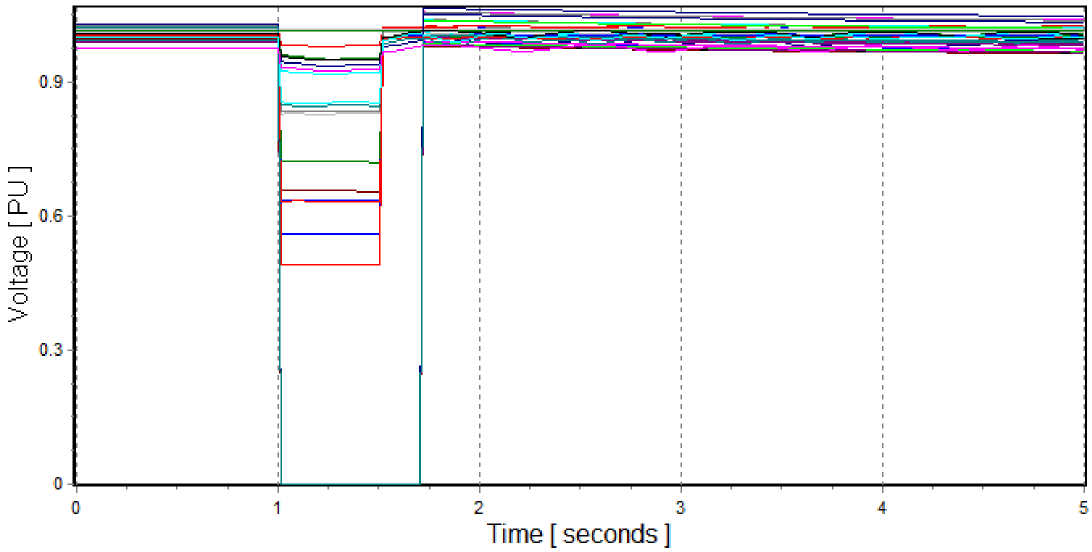


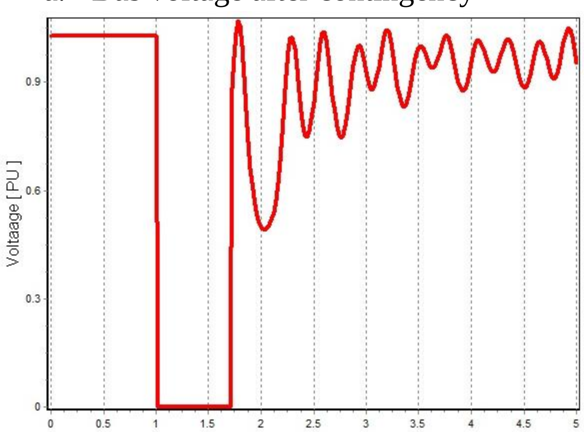
Fig. 5.31 Bus voltage magnitudes after islanding

d. **Voltage comparison**

Table 5.8 compares bus-to-bus voltage magnitudes for two cases *a* and *b*.

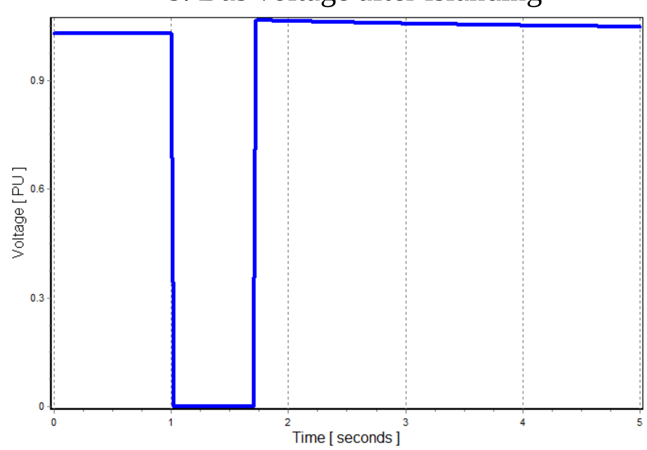
TABLE 5.8
BUS VOLTAGE COMPARISON

a. Bus voltage after contingency

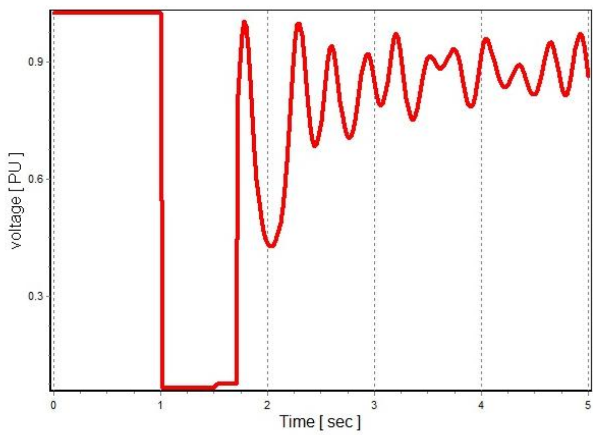


Bus 1 voltage after contingency

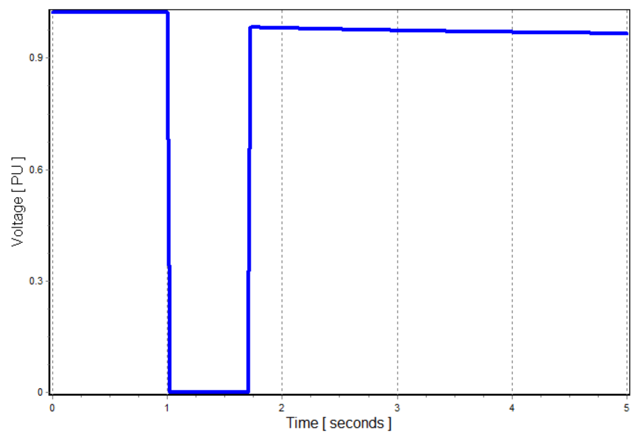
b. Bus voltage after islanding



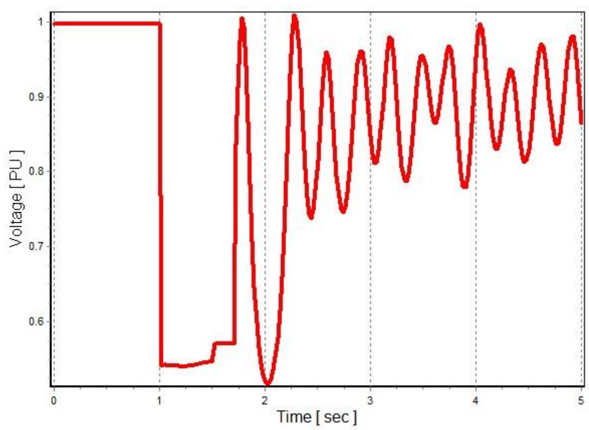
Bus 1 voltage after islanding



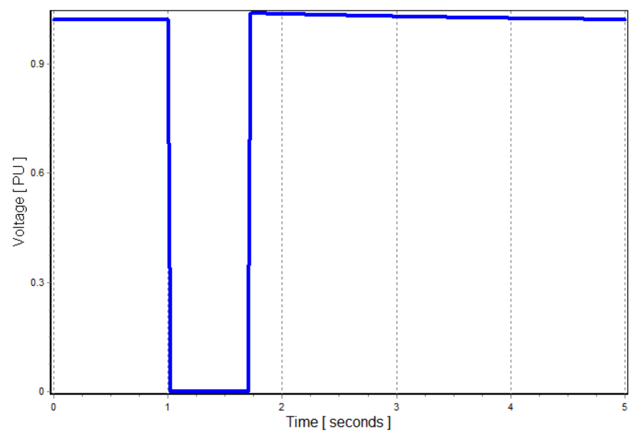
Bus 2 voltage after contingency



Bus 2 voltage after islanding



Bus 18 voltage after contingency



Bus 18 voltage after islanding

It can be shown from simulation results that system's deteriorating stability performance received a massive boost after islanding was performed. In Table 5.8, bus voltage oscillations are stabilized after islanding. Also, no critical oscillation is observed in any of the islands, indicating a good dynamic response.

CHAPTER 6

DISCUSSIONS AND CONCLUSION

This research work presents a novel islanding strategy based on slow coherency and graph theory. Generator groups are identified by slow coherency criterion based on the swinging behavior of generator rotor-angles to disturbance. Graph theory is used to reduce the complexity of power system network to expedite computational time. The topological information of the power system graph is then translated into an adjacency matrix using Dijkstra's algorithm. The entries to this matrix were the distances covered by Dijkstra in moving from one node to the other in a transport network. The optimal cutsets are deduced after row expansion by tracing up or down locked load nodes in the power-inflow columns for A_{i-j}=1 not locked during frontier expansion.

The proposed islanding strategy was tested on a 14-bus and a 37-bus system respectively to verify its efficacy. The simulation results validated the potency of this islanding strategy to solving uncontrolled islanding in power systems.

6.1. **Future work to be done**

Source node expansion algorithm (SNE) solves just a jigsaw piece of the bigger islanding puzzle. It only focuses on the issue of 'where' to initial islanding assuming that uncontrolled islanding conditions already prevail in the power system. Even though its implications on tested systems showed remarkable results, I still believe much can be done to improve its potency.

In my future works, I hope to explore the possibility of testing algorithms in this extensive area of research that seeks to address the issues of 'when' and 'where' to island concurrently without treating them as two mutually exclusive events. The algorithm should be able to undergo some decision-making process to determine when islanding is necessary or must be done before the search for appropriate cutsets is inaugurated.

APPENDICES

1. APPENDIX A1

```
% This Program generates the MATLAB graph for Dijkstra Algorithm
% Let A represent the distance from node i to node j
    A = [ 1  1  1  1  1  1  0  1  0  0  1  0  1  1  1  1  0  1  1  0  1  0  1  0  1  1  1 ];
% Let B be the node and its connecting link with neighboring nodes.
    B = sparse ( [1 2 3 1 5 2 6 5 7 8 4 9 8 7 10 9 11 10 6 12 6 13 13 14 14 9 6 ],
[2 3 4 5 4 5 6 6 7 8 7 9 9 9 10 10 11 1 1 11 12 12 13 12 14 13 14 13] , D );
% This displays the MATLAB graph
    Graph = view ( biograph (B , [ ] , 'ShowWeight' , 'on' ) ),
% This finds the shortest path from i to j on graph
    [ distance, path_1 ] = graphshortestpath ( B, 6, 11 );
    [ distance, path_2 ] = graphshortestpath ( B, 6, 12 );
    [ distance, path_3 ] = graphshortestpath ( B, 6, 13 );
% This highlights the Nodes under investigation
    Set ( Graph.Nodes ( path_1 ), 'Color', [1 0.4 0.4] )
    edges = getedgesbynodeid ( Graph, get ( Graph.Nodes (path_1 ), 'ID' ) );
    set ( edges, 'LineColor' , [1 0 0] )
    set ( edges, 'LineWidth', 1.5 )
    set ( Graph.Nodes (path_2) , 'Color', [1 0.4 0.4] )
    edges = getedgesbynodeid ( Graph, get ( Graph.Nodes ( path_2 ) , 'ID' ) );
    set ( edges , 'LineColor' , [1 0 0] )
    set ( edges , 'LineWidth' , 1.5 )
    set ( Graph.Nodes (path_3 ) , 'Color' , [ 1 0.4 0.4 ] )
    edges = getedgesbynodeid ( Graph , get ( Graph.Nodes ( path_3 ) , 'ID' ) );
    set ( edges , 'LineColor' , [ 1 0 0 ] )
    set ( edges , 'LineWidth' , 1.5 )
% This computes the time taken to execute
    t1=tic;
```

2. APPENDIX A2

```
% The tabulates Path against Cost of travel from node 1 to node 14

   for i=1: n

       [Path, Cost] = Dijkstra (Graph, i);

       Table = [Path; Cost]

       fprintf ('%6.0f     %8.0f\n', Table)

   end

%This calculates the time taken to go through all nodes

toc
```

3. **APPENDIX A3**

```
% This Program generates the MATLAB graph for Analysis

% Let D represent the distance from one node i to node j

D= [0 0 1 0 1 0 1 1 0 1 1 0 1 0 1 0 1 0 0 1 1 1 1 0 1 0 1 1 1 0 1 0 1 0
   1 0 1 0 1 1 0 1 0 1 0 1 0 1 0 1 0 1 1 0 1 0 0 1 1 0 1 0 1 0 1 1 0 1
   0 1 1 0 0 1 1 1 1 1];

% Let DG be the node and its connecting link with neighboring nodes.

DG = sparse ([1 2 1 3 1 5 3 2 6 4 5 7 6 8 8 9 5 10 37 37 20 33 34 35 35
   36 36 37 9 32 35 31 32 30 31 29 30 19 36 19 28 28 24 24 25 24 22 25
   21 24 13 21 6 14 13 11 15 11 22 23 23 16 23 12 12 9 17 17 18 17 5
   26 27 23 18 26 5 1],[1 2 2 3 3 5 5 4 6 6 4 7 7 8 7 9 9 10  37 1 4 20
   33 35 34 36 35 36 8 32 32 31 31 30 30 29 29 19 19 10 28 29 24 28 25
   25 22 22 21 21 13 13 13 14 14 11 15 15 15 23 22 16 16 12 16 12 17 23
   18 18 18 26 27 26 26 27 10 10], D);

% This displays the MATLAB graph

Graph = view (biograph (DG,[ ],'ShowWeight','on'))

% This finds the shortest path from i to j on graph

[ distance, path_1 ] = graphshortestpath (DG, 37, 1);
[ distance, path_2 ] = graphshortestpath (DG, 1, 2);

% This highlights the Nodes under investigation

Set (Graph.Nodes (path_1),'Color', [1 0.4 0.4])
```

```
edges = getedgesbynodeid (Graph, get(Graph.Nodes(path_1),'ID'));
set (edges,'LineColor',[1 0 0])
set (edges,'LineWidth',1.5)
set (Graph.Nodes(path_2),'Color',[1 0.4 0.4])
edges = getedgesbynodeid(Graph, get(Graph.Nodes(path_2),'ID'));
set (edges,'LineColor',[1 0 0])
set (edges,'LineWidth',1.5)

%This computes the time taken to execute

t1=tic;
```

REFERENCES

1. J. Duncan Glover, Mulukutla S. Sarma, Thomas .J. Overbye, “Power System Analysis and Design”, Fourth Edition, Publication Year: 2008.
2. Olle L. Elgerd, “ Electric Energy Systems Theory-An Introduction, Second Edition”, Publication Year: 1982, Page(s): 533
3. Vijay Vittal, Mani V., “Detection, Prevention & Mitigation of Cascading Events”, PSERC Publication Year: 2008, Page(s): 8-18.
4. Dondi P., Bayoumi D., Haederli C., Julian D., Suter M., (2002), “Network Integration of Distributed Power Generation”, Journal of Power Sources 106, pp. 1-9.
5. Yuping Lu, Xin Yi, Ji’an Wu, Xia Lin, “An intelligent islanding technique considering load balance for distribution system with DG’s”, IEE/PES General Meeting, 2006.
6. Shu-Chen W., Pei-Hwa H., “Fuzzy c-means clustering for power system coherency”, Systems, Man and Cybernetics, 2005 IEEE conference, Volume 3, Page(s):2850-2855.
7. Bryan R.E, “Graph-Based Algorithms for Boolean Function Manipulation”, IEEE Transactions on. Computers, Publication Year: 1986, Volume: C-35, pp. 677-691.
8. 12.1 Cividino L, “Power Factor, Harmonic Distortion; Cause, Effects and Considerations“. Telecommunications Energy Conference, 1992, Publication Year: 1992, Page(s): 506-513
9. Walling R.A., Miller N.W., "Distributed Generation Islanding - Implications on Power System Dynamic Performance." Proceedings of the IEEE/PES Summer Meeting, Chicago, July 2002, Vol. 1, Publication Year: 2002, Page(s): 92-96.
10. Pourbeik P., Kundur P.S., Taylor C.W., ‘The Anatomy of a Power Grid Blackout-Root Causes and Dynamics of Recent Major Blackouts,’ IEEE Power and Energy Magazine, Vol. 4, No.5, Publication Year: 2006, pp. 22-29,
11. Senroy N., Heydt G.T., Vijay V., “Decision Tree Assisted Controlled Islanding”, IEEE Trans. Power Systems, Vol. 21, No. 4, Publication Year: 2006, pp. 1790-1797.
12. You H., Vijay Vittal, Wang X., “Slow Coherency-Based Islanding”, IEEE Transaction on Power Systems, Vol. 19, No. 1, pp 483-491, Feb. 2004.
13. Podmore R, “Identification of Coherent Generators for Dynamic Equivalents”, IEEE Transaction on Power Apparatus and Systems, Vol. PAS-97, No. 4, pp. 1344-1354, July/Aug. 1978.

14. Bo Yang, Vittal V, Heydt G.T., Sen A. "A Novel Slow Coherency Based Graph Theoretic Islanding Strategy", IEE/PES General Meeting, 2007, Publication Year: 2007, Page(s): 1-7.
15. Yuanqi Liu, Yutian Liu, " Islanding Cutset Searching Approach Based on Dispatching Area", IPEC, Trans. Power System, 2007, Publication Year: 2007, Page(s): 950-954.
16. Wang C.G, Zhang B.H., Shu J., Li P., Bo Z.Q., "A Fast Method For Power System Splitting Boundary Searching", IEEE Trans. Power System, 2009, Page(s): 1-8.
17. "IEEE 1547 Standard For Interconnecting Distributed Resources with Electric Power Systems", 2003.
18. Guanyue Xu, Vijay Vittal, "Slow Coherency Based Cutset Determination Algorithm for Large Power Systems", IEEE Trans. Power Systems, Vol. 25, No. 2, Publication Year: 2010, Page(s): 877-884.
19. Mahat P., Zhe Chen, Bak-Jensen B., "Review of Islanding Detection Methods for Distributed Generation', IEEE Trans. Power Systems, Publication Year: 2008, Page(s): 2743-2748.
20. IEEE, Standard 15477-2003, Standard for Interconnecting Distributed Resources with Electric Power Systems, June 2003, Page(s): 1-16.
21. IEEE, Standard 929-2000, IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems, 2000.
22. Refern M.A, Usta O., Fielding G., 'Protection against Loss of Utility Grid Supply for a Dispersed Storage and Generation Unit', IEEE Trans. On Power Delivery, Vol. 8, no.3, pp. 948-954, July 1993.
23. Ropp M., K. Aaker, J. Haigh, and N. Sabhah, "Using Power Line Carrier Communications to Prevent Islanding'', in Proc. 28th IEEE Photovoltaic Specialists Conf., 2000, pp. 1675-1678.
24. P Plus Corporation, Release Notes for the Dynamic Reduction Program (DYNRED) V5.3, Electric Power Research Institute (EPRI), Palo Alto, CA.
25. Qifeng Lu, "LU: A Best First Search to Process Single-Origin Multiple-Destination Route Query in a Graph" IEEE Trans. GEOProcessing, Publication Year: 2010, Page(s): 137-142.

26. Tianrui Li, Luole Qi, Da Ruan, " An Efficient algorithm for the Single-Source Shortest Path Problem in Graph Theory", ISKE, 2008, Vol. 1, Publication Year: 2008, Page(s): 152-157.

27. D.S. Parker, "Combinatorial merging and Huffman's algorithm," *IEEE Trans. On Computers*, vol. C-28, pp 365-367, August 2006.

28. G. Karypis, and V. Kumar, "Parallel multilevel k-way partitioning scheme for irregular graphs," *Proc. 1996 ACM/IEEE Conference on Supercomputing*. Page(s): 35

29. IEEE 14cdf.txt [Online]. Available: http://www.ee. washington.edu /research /pstca

30. Bertin, J.,Semiology of Graphics: Diagrams, Networks, Maps. The University of Wisconsin Press, 1984.

31. Adibi, M.M., Kafka, R.J., Maram, S., Mili, L.M., "On Power System Controlled Separation'', IEEE Transactions on Power Systems, Volume: 21, Issue: 4, Publication Year: 2006, Page(s): 1894-1902.

32. Ming Jin, Sidhu, T.S., Kai Sun, " A New System Splitting Scheme based on the Identification of Controlling group", 2005 International Conference on Future Power Systems, Publication Year: 2005, Pages(s): 6 pp.-6.

33. X. Wang and V. Vittal, "System Islanding Using Minimal Cutsets and with Minimum Net Flow,'' Proceedings on IEEE PES Power System Conference & Exposition, New York, October 2004, Vol. 1, Page(s): 379-384.

34. K. Sun, D. Zheng and Q. Lu, " Splitting Strategies for Islanding Operation of Large-scale Power Systems using OBDD-Based Methods'', IEEE Trans. On Power System, Vol. 18, no. 2, pp. 912-923, May 2003.

35. Zhao Q.C, Sun K, and Zheng D.Z, "A Study of System Splitting Strategies for Islanding Operations of Power System: A two-phase method based on OBDDs", IEEE Trans. Power Syst., 2003, Vol. 18, pp. 1556-1565.

36. Sun K. Zheng D.Z, and Lu Q., "A simulated study on OBDD-based proper splitting strategies for Power Systems under consideration of transient stability", IEEE Trans. Power Syst., 2005, Vol. 20, pp.389-399.

37. Kar N, "Lecture Notes on Electrical Machines", University of Windsor, fall 2009.

VITA AUCTORIS

Issah Ibrahim was born in 1983 in Kumasi, Ghana. He had his secondary education at the Mfantsipim School, Cape-Coast, where he graduated with distinction in 2002. From there he went to the Kwame Nkrumah University of Science and Technology (KNUST) where he obtained a B.Sc. (Honors) in Electrical Engineering in 2007.

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