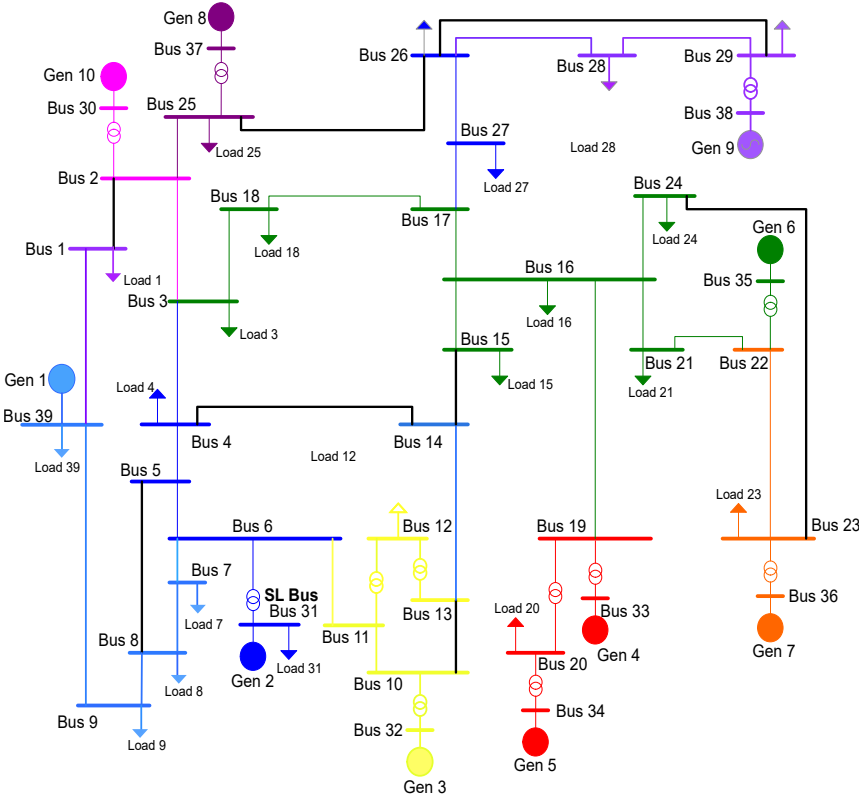
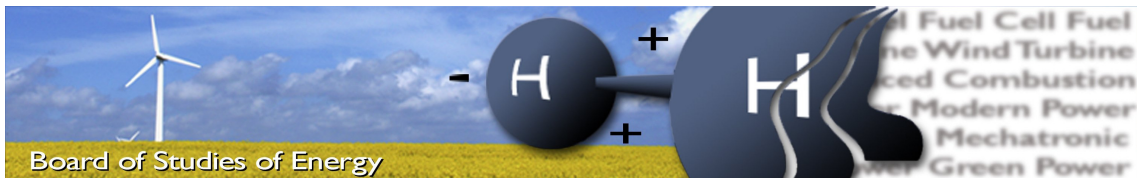


A Simulation Platform for Power System Restoration



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SYNOPSIS:

This paper deals with the concept restoration process. It develops a flexible simulation platform as a decision-support tool for power system restoration. This platform adopts a path searching algorithm based on electric distances to find the direct path from the black-start unit or current energized buses to the bus with shortest electric distance, and then closes the switches to boost its voltage within the operating limit. During the restoration, the grid regulations regarding frequency and voltage at each substation will be iterative checked by time-domain simulations, i.e. either in the root mean square (RMS). A flexible close-loop decision-support tool will be implemented to recalculate the path of energization when necessary, e.g. unavailability of components or violation of grid regulations. The effect of automatic on load tap changer (OLTC) of transformers will also be examined during the restoration process. This flexible simulation platform is developed using DIg-SILENT Programming Language (DPL) in PowerFactory with any selected black-start unit.

Pages, total: 63
 Appendix: A and B
 Supplements: PowerFactory models

Abstract

Power system restoration is the process of restoring a part of or a total electric power grid into normal operation after a wide-area outage. This paper deals with the concept restoration process. It develops a flexible simulation platform as a decision-support tool for power system restoration. This platform adopts a path searching algorithm based on electric distances to find the direct path from the black-start unit or current energized buses to the bus with shortest electric distance, and then closes the switches to boost its voltage within the operating limit. During the restoration, the grid regulations regarding frequency and voltage at each substation will be iterative checked by time-domain simulations, i.e. either in the root mean square (RMS). A flexible close-loop decision-support tool will be implemented to recalculate the path of energization when necessary, e.g. unavailability of components or violation of grid regulations. The effect of automatic on load tap changer (OLTC) of transformers will also be examined during the restoration process. This flexible simulation platform is developed using DIg-SILENT Programming Language (DPL) in PowerFactory with any selected black-start unit. This platform can adapt to different power systems and various grid operating conditions. The IEEE 39-bus New England power system is selected as the test system to validate this plat-form with different black-start paths

Keywords:Power system restoration,Decision support tool, Black start units, Blackout

Preface

This project is the result of a 4th semester master project, carried out by an electrical engineering student from the Department of Electrical Energy Technology at Aalborg University. The theme of the semester is "Power System and High Voltage Systems", and the project mainly concerns about the hybrid simulation platform for power system restoration. The project content, both theoretical and simulations has been carried out in collaboration with the supervisor Associate Professor Chengxi Liu.

Reading Guide

All sections, tables, equations and figures, are in chronological order according to the chapter number. For example, the first section, figure, table, or equation in chapter 4 is numbered 4.1, the second 4.2 and so on. Each figure and table contains a caption with a description of the figure or table. The reference system used in this report is the IEEE Method. The IEEE Method shows the references with the label [Number of Reference]. If the reference is placed before a full stop, the reference is for the specific sentence. If the reference is placed after a full stop, the reference is for the entire section. The complete list with the references is placed in the section called Bibliography, where the Author, Title and Year are shown. Internet websites are labelled as the other references, but they will also include the [URL].

Each chapter is introduced and concluded by a short paragraph written in italic form. These paragraphs are introductions and partial conclusions for the given chapters.

Some of the figures in the report are touched up versions of figures found in different literature. When such a figure appears it will be noted in the caption of the figure what literature inspired the remade figure.

Acknowledgement

The 5 years study period has been full of joy yet challenging. The intense academic life in AAU have made me to always put my best effort and push myself to the limit and I am and will always be grateful for the given opportunities. I am sure that the experience have I gained during my education will be helpful in the next phase of my life. Since this master thesis marks the completion of my journey as a student at AAU I would like to express my sincerest gratitude to those who made it possible.

To my supervisor for the master thesis Chengxi Liu: for all his help and shared knowledge during the period of the master thesis. He was an excellent super visor in all aspects and I will always be thankful.

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To God: I can not finish without thanking the Almighty God for being there for me all the time.

Nomenclature List

Special Symbols and Denotations

Symbol	Description	Derived unit	Unit
C	Capacitance	Farad	F
f	Frequency	Hertz	Hz
H	Inertia	Kilogram metre squared	kg·m ²
I	Current	Ampere	A
L	Inductance	Henry	H
R	Resistance	Ohm	Ω
X	Reactance	Ohm	Ω
P	Active power	Watt	W
Q	Reactive power	Volt-ampere reactive	VA _r
S	Apparent power	Volt-ampere	VA
t	Time	Seconds	s
V	Voltage	Volt	V
Z	Impedance	Ohm	Ω

Acronyms

Acronym	Abbreviation of:
AC	Alternating current
BSU	Black start unit
CB	Circuit breaker
DC	Direct current
DG	Diesel generator
DSO	Distribution system operator
EN	European standard
Gen	Generator
HVDC	High-voltage direct current
HV	High voltage
RMS	Electromechanical transient
MV	Medium voltage
Min	Minutes
p.u.	Per unit
PSR	Power system restoration
TSO	Transmission system operator
URL	Uniform Resource Locator
VSC	Voltage source converter

Contents

Abstract	v
Preface	vii
Acknowledgement	ix
1 Introduction	1
1.1 General background	1
1.2 Goals and steps in restoration	2
1.3 Grid regulations during restoration	3
1.3.1 The active power balance and frequency response	3
1.3.2 The reactive power balance and voltage response	3
1.4 Blackout	3
1.5 Thesis Motivation and Objective	5
1.6 Limitations and Assumptions	5
1.7 Thesis Outline	6
2 Start of the Art on Restoration	9
2.1 Overview of Restoration Process	9
2.2 Generation units with black start capability	10
2.2.1 Hydroelectric generating units	11
2.2.2 Diesel generating units	11
2.2.3 Gas turbine generating units	11
2.2.4 Behaviour of generator during black start	11
2.3 VSV-HVDC in Black Start	12
2.3.1 Advantage of VSC-HVDC in Black start	13
2.4 Coordination of Wind Power and Energy storage System in System Restoration	13
2.4.1 Coordination of Pumped Storage Hydro Units and Wind Power in Restoration	14
2.4.2 Coordination of Battery Energy Storage System and Wind Power in Restoration	14
2.5 Micro-grid in Restoration	16
2.6 Electric Vehicles in Power Restoration	17
2.7 Effects of FACTS devices in Power System Restoration	17
2.7.1 Oscillation stability:	17
2.7.2 Voltage stability:	18
2.7.3 Standing phase angle control:	18
2.7.4 Reactive power control:	18
2.7.5 Sustained over-voltage:	18
2.7.6 Transient over-voltage:	19

2.7.7	Smooth cold load pickup:	19
3	Restoration by Island sectionalisation	21
3.1	The Heuristic Technique	21
3.2	Parallel restoration constraints	22
3.3	Graph theory	23
3.3.1	Expanding the initial sub-islands	29
3.4	Complete restoration sequence for sub-islands	31
3.4.1	Sequence paths for island 1	31
3.4.2	Sequence paths for island 2	32
3.4.3	Sequence paths for island 3	32
3.4.4	Complete restoration time for the whole grid	33
4	A Flexible Simulation Platform for Black Start	35
4.1	Path searching algorithm	35
4.2	Closed-loop decision support tool for detour	37
4.3	The black start process	39
4.3.1	Step by step black start sequence starting from generator 4	42
5	Simulation Result	53
5.1	Result for the flexible simulation platform for black start	53
5.1.1	Case A: Sequence energisation	53
5.1.2	Case B: Black start with detour	55
5.1.3	Case C: Black start with tap changer control	56
5.2	Results for the parallel restoration	58
6	Conclusion	61
7	Future Work	63
	Bibliography	65
A	DPL Scripts for the Flexible simulation platform for PSR	69
A.1	Scripts for black start	69
B	Simulation Model Data	73
B.1	Line parameter	73
B.2	Loads size	74
B.3	Generation input data	75
B.4	Parameters of OLTC	75

Introduction 1

This chapter introduces this thesis. The importance of restoration, steps and constraints in restoration process are discussed. The objective of the thesis is highlighted after the analysis of the problem. The limitations and assumption taken during simulation are highlighted. The chapter is concluded by the short descriptions of the chapters in this thesis

1.1 General background

An electric power system has five operating states namely the normal state, alert state, emergency, in extremis state and the restorative state. During the normal operation the power system is in the preventive state, meaning that all system variables are within the normal range, and all the system equipments are not experiencing any over-loading condition. In this state the system can withstand a contingency without violating the system security. In the alert operating state the level of the security is decreased, but the constraints are still maintained. The occurrence of a disturbance in the system might lead to an emergency state, and if the the disturbance is large then the state will shift to in exetremis. In the emergency state the constraints are violated due to a low operating frequency and abnormal voltages, the constraints can also be violated with the overloading of the system components. The system can shift from one operating state to an other, for example, after the system has entered the emergency state due to disturbance, the emergency control will take action against the disturbance, which will result in the system shift back to alert state. If the emergency control actions can not offer remedy to disturbance, the state will shift to in extremis, in this case all the constraints are violated. In the case of a large disturbance, the system will shift into the restorative state. All the system operating states are shown in Figure 1.1 [18].

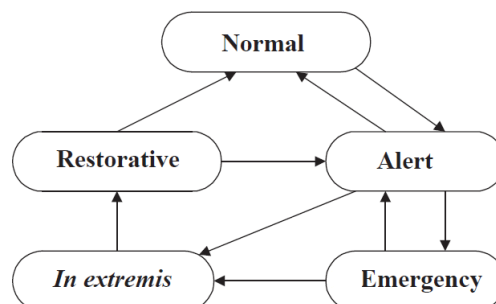


Figure 1.1. Power system operating states

A large disturbance will lead to blackout and is the extreme case a power system can experience. There can be a partial blackout, here a part of the network is out of service or

a total blackout, in this case the whole grid is shut down. Most of blackout events result due to cascading failures [28], the disturbances that can mostly cause blackouts are natural disasters[38],[8].

In both types of blackout the dispatchers will try to re-energise the area where the power is out of service, a process known as restoration, the process has to be take as quickly as possible and by paying a great attention to grid regulations.

1.2 Goals and steps in restoration

There are different restoration strategies, but all of them have common objectives and procedure, the goals in the restoration process involve all aspects of power system operation and planning as shown in Figure 1.2 [2], [16].

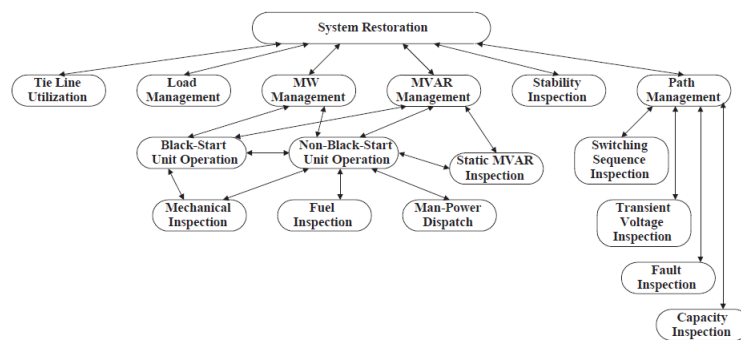


Figure 1.2. Power system restoration goals

The steps that are involved in the restoration process are: the determination of system status, black start of large thermal power plants, energisation of sub-systems and interconnection of sub-systems.

The determination of system status: In this state the boundaries of the energised areas are found, thereafter the level of voltages and frequency is checked. It is checked where there is a possibility of getting the power from neighbouring system, if this is not a possibility to help in the restoration process, then black start units are identified and critical loads are also located.

Black start of large thermal power plants: These large units in the system have to be restarted within a certain period of time. This will help to the restoration efficiency and time when the cranking power is sent to these units from the black start unit. Great attention should be payed to this step as mistakes can lead to unwanted tripping of generators and load shedding due to extensive frequency and voltage deviations.

Energisation of sub-systems: The sub-stations are most of the time prioritised in the restoration process. This reduces the recovering time. In most cases, when there is a total blackout and there is no access to neighbouring network, the restoration is done by sectioning the power system into sub-systems in order to allow parallel restoration of islands, by doing so, reduction of the overall restoration time is achieved. The restoration of sub-islands is done by energising the skeleton of bulk power, where the power reference

is the black start unit. There must be identified paths to non black start units and to other major system components such as loads. After the sub-islands have been successfully restored they can be synchronised to restore the whole network[12]. The eventual remaining lines and loads are restored to bring the system to normal operating state.

1.3 Grid regulations during restoration

During the restoration process different phenomena and abnormal conditions may occur. The problems that result in the process can be divided into two, namely, the active power balance and frequency response as well as the reactive power balance and the voltage response.

1.3.1 The active power balance and frequency response

During the restoration two different aspects of these types of problems are identified: The black start of large thermal power plants, the restoration of this type of generation units will require the same amount of loads to be picked up, otherwise it will result in large frequency excursions, which may lead to the activation of under frequency load shedding relays. Furthermore when the network is extended more generation units are restored and loads are picked up, it is necessary to preserve a balance between active load and generation. In the case this balance is disturbed, the system frequency will be violated, which will lead to the activation of unwanted load shedding schemes. This may lead to newly restored loads being disconnected again. The allowable frequency limit for a 50 Hz system, according to standards, is $\pm 3\%$ of nominal value, meaning a minimum of $47Hz$ and a maximum of $53Hz$ [1],[26].

1.3.2 The reactive power balance and voltage response

Due to the fact that the reactive power contribute to the system voltage, the balance in reactive power should be maintained in order to maintain the system voltage within allowable limits. High charging currents, originating from lightly loaded transmission lines, can lead to the violation of generator reactive capability limits and to the occurrence of sustained over-voltages. The energisation of transmission line may result in transient over-voltage. According to standards during transient events the voltage should remain in the range of $\pm 20\%$ of the rated voltage meaning a voltage minimum of $0.8p.u$ and maximum of $1.2p.u$ must be obeyed. Though, in the steady state events, the bus voltage is allowable to swing in the range of $\pm 10\%$ of nominal voltage, meaning a minimum of $0.9p.u$ and a maximum of $1.1p.u$ [1],[26].

1.4 Blackout

The historical background for blackouts around the world is underlined in this section, where the focus will be on the most major blackout events, meaning some of the events that caused a total blackout.

The northeast blackout in America: On the 13th August 2003 the power system network located between the cities of Ohio, Michigan, Pennsylvania, New York, Vermont,

Massachusetts, Connecticut, New Jersey and a part of Canada, Ontario were hit by the power blackout, where a total of 61 800MW power was not available for a period of 4 to 7 days. Due to the large area of blackout, more people were affected by the event, a total of approximately 50 millions consumers in all the regions were affected. The events cause was the cascading failure, the state estimator (SE) and contingency analysis of the midwest ISO's (MISO) which solves the line loading automatically were not working accordingly, which lead to the cascade of the loading to other part of the system. This affected the control of balance between generation and demand leading to the whole system blackout. Since then the power system in America has been upgraded to smart grid technology, where the system control and data acquisition (SCADA) play a role in the control system[6].

India blackout: On July 30th and 31st These two blackout event in India occurred on two different following days, the time for the power system to be restored to normal operation is said to be several hours on that day. Around 620 and 700 million had no access to electricity. The overloading on the 400 kV double transmission line located in Gwalior-Bina is said to be the reason for the blackout on the 30th, one of the double line was under maintenance and this caused the overloading on the other transmission line causing cascading failure in the system. The over-loading caused low voltage on the system buses causing system components to be tripped by the protection system leaving a generation shortage of 32 GW. The whole high voltage transmission grid was blackout. The network was restored after several hours, however, the imbalance between generation and demand caused the system to collapse again on the next day. The control system and monitoring equipments in India power grid was poor and could not realise the overloading in the system. The system parameters was measured by the remote terminal units (RTU), which did not give accurate information on the current situation in the system, since then the phasor measurement unit (PMU) are utilised[33].

Ukraine blackout: On 23rd December 2015 Ukraine power system had a blackout that left around 225 000 consumers without power for several hours. The system blackout was caused by cyber-attack which hijacked the SCADA network and started to inject false data into the SCADA, the meter measurements units sent wrong data information, the network topology was changed by the attackers and modified system electrical parameters eventual this lead to the collapse of the whole network. The solution to cyber attack is to strengthen the defensive system against the cyber-attack[3].

San Diego blackout: On the 8th September 2011 the Pacific southwest had an outage caused by the tripping of a line during the peak load causing overloading, with insufficient load shedding, the overload propagated to other part of the system components to cause cascading blackout, the power loss lasted for 12 hours and affected approximately 4.2 million customers[9].

Italy blackout: On 28th September 2003, Italy was hit by a blackout where the whole country was left without power, due to the loss of a line between Italy and Switzerland which was hit by a tree contact, causing overloading to the system components. The components were tripped by the protection relay, and there were shortage of generation in the system which lead to the fall in system frequency this lead to the loss of synchronise between Italy and the rest of Europe where 58 million people were affected by the event[36].

European blackout: On 4th November 2006 the European power system was hit by a blackout due the loss of a line in the German power system. An over head line was planned to be disconnected to allow a ship to pass, however the disconnection of the line and a poor communication between TSOs, caused overloading to other system parameters which caused a cascading failure in the European power system. The European interconnected grid was divided into three islands with different frequencies. The attempt to solve the frequency problem was the automatic load shedding which resulted in blackout. More than 15 million were left without electricity, transport such as trains and elevators were trapped with people involved for almost 2 hours[21].

South Australia blackout: On 28th November 2016, the power system network in the south Australia was shut down. The cause for the blackout was a heavy storm that collapsed several transmission towers in the system. The loss of overhead lines resulted in many wind turbines being shut down, making the grid lose about 52 % of the generation, this led to the fall in frequency and voltage. For the emergency solution to the problem, the power was imported from the neighbouring grid (Victoria state), unfortunately the exported power was beyond the interconnection capacity which led to overloading in the system. The south network was then separated from the southeast grid without power supply, approximately 1,7 million people were affected by the event[32].

1.5 Thesis Motivation and Objective

It can be concluded from the previous sections, that a number of complex and serious problems need to be resolved during power system restoration. Hence, a detailed analysis during both the system planing stage and during the restoration stage is necessary. As it will be shown in chapter 2 many researches have been done on power system restoration, but all of them have share the same final solution, which is to develop energisation paths for black start while obeying the grid regulations.

The objective of this thesis is to give simple and approximate rules to assess the feasibility of restoration steps. A flexible simulation platform for power system restoration is developed to guide the operators finding paths for energisation. The restoration scheme can limit the number of time consuming simulations based on trial and error. The platform adopts a path searching algorithm, which is based on finding the shortest path based on shortest electrical distance, the path can be from the black start unit to another generation units or from the currently energized bus to the bus with shortest electrical distance. Using the RMS time domain simulation tool, the grid code requirement for voltage and frequency are checked for each energized path. Regardless of the electric shortest distance, the voltage mitigation during the restoration is examined with the detour process and on load tap changer (ONTTC).

1.6 Limitations and Assumptions

- For the multi-island restoration strategy the black start units are chosen according to the structure of the grid, meaning the exactly placement of the black start in the original new England grid.

- For the backbone build up restoration, it is assumed that each generating unit in the system can act as black start unit. Hence, the restoration can take place from whichever generator.
- In this thesis where total blackout scenario is considered, it is assumed that the fault that caused the blackout has been cleared and no harm is done to the system components as well as the major infrastructure.
- It is assumed that convectional black start units are readily available to contribute to system restoration.
- The parallel power system is one of the methods adopted in this report, where the sectionilized islands must be synchronised after they have been successfully restored. It is therefore assumed that the cut set lines that interconnects the sub-islands are equipped with synchronisation equipment, in order for the sub-islands to be synchronised for full network restoration.
- The cost of the black start service is not considered in this project, meaning the raping of generators is not taken into consideration. Only the topology and internal security constraints is taken into consideration.

1.7 Thesis Outline

The total chapters in this thesis are seven. An overview of the contents in all the chapters are given bellow:

1. **Chapter 1: Introduction:** This chapter provides an introduction to the thesis, which includes an overview of the current knowledge withing the blackout and power system restoration. The chapter also gives the objective of the thesis as well as the short description of the thesis contents.
2. **Chapter 2: State of the art on power system restoration:** In this chapter the concept of restoring the power system after blackout is discussed. The chapter starts by highlighting the overview on restoration, followed by the discussion of generating units with black start capabilities. Then a discussion of the technologies that are utilised in restoration are discussed. The chapter is concluded by how the FACTS devices are utilises in restoration.
3. **Chapter 3: Restoration by island sectionalisation:** This chapter present the restoration process by sectionalising the blackout area into sub-islands, to allow parallel restoration. The graph theory is utilised to find the sub-islands, then the energisation paths are found by first prioritising the critical loads as well as the NBSU
4. **Chapter 4: A flexible simulation platform for black start:** In this chapter a simulation platform for power system restoration is developed using DPL scripts. The scripts finds the energisation paths starting from the black start unit. A total blackout scenario out is assumed with only the availability of one black start unit. The BSU unit can be placed any where in the system. Voltage mitigation is done a detour process, in this case if a line is not available due to the grid code violation of a fault still existing the scripts finds a new path for restoration.
5. **Chapter 5: Simulation results:** In this chapter the simulation results for the two form of restoration, namely the restoration by island sectionalisation and the

flexible simulation platform for PSR is presented. The frequency response and voltage response during the black start are checked.

6. **Conclusion:** This chapter concludes the work in this thesis. The main results during the restoration process are concluded.

7. **Future Work:** In this chapter the task that can be carried out with regards to this thesis' topic are identified and highlighted.

This chapter has presented an overall description of the blackout and restoration in electrical power system. It is shown that the blackout concept is a serious matter which can lead to economical losses and system instability. Hence, a restoration plan has to be made in advance in order to minimise the restoration time.

Start of the Art on Restoration 2

This chapter gives a literature survey that provides an overview of the relevant areas in restoration. It is subdivided into three topics. The first topic provides a general overview of the restoration process. It is followed by a discussion of generation units with black start capability. Then, the technologies that can be used in black starts process are highlighted and discussed. The chapter is finished by discussing the impact of FACTS devices in restoration, as support tools to regulate the system voltage and frequency.

2.1 Overview of Restoration Process

Power system restoration is the process where generation, load consumption and system components, e.g. substations, transformers, lines and cables, are restored to normal operation after the power grid has been affected by a total or a partial blackout. Power system blackouts are rare, but depending on the duration of the restoration process, the blackouts may have great impact on the stability of the power system, economy and society. Hence, a fast and reliable restoration scheme is of great importance to minimise the losses. The goal of restoration is to accelerate the restoration process and to reduce the impacts of power outages. However, power system restorations become more and more challenging since power resources migrate to distributed generation and intermittent generation based on RES [34],[10].

The restoration is done by identifying the path of energisation for de-energised buses. Various methods are suggested by different authors, which gives rules to find the paths. In [35] a knowledge based system was developed, which contains rules to follow in identifying the paths of energisation, after the path were identified, a power flow was conducted to verify the feasibility of the restoration plan. In [40] an advanced method to guide for system restoration was developed. During the restoration the method provides the guidance in switching actions and load dispatching. A similar model but more advanced to the previous case was tagged prototype model and is developed in [39], after the blackout the model will perform a fault analysis to identify the location of the fault, thereafter it will generate a targeted configurations and restoration procedure. The loads and generations are restored while the faulted portion of the system is isolated from the restoration paths.

The restoration process is implemented by maintaining the grid code for voltage and frequency, as re-energizing the power system components may make the power grid appear with different characteristics as compared to the initial condition [37]. In addition the system must be restored as quickly as possible, in order to avoid of the surging economic

lost [23]. The restoration of the power system components can be initialised in different ways, such as the use of RES and generators with black start capabilities. The RES can be either a black-start source or supportive black-start units in the whole restoration process, for example a combined system of wind power (WP) and battery energy storage system (BESS) is proposed in for restoration process [19]. The WP supplies the initial active power to crank the synchronous generators in the system and the BESS is used to maintain the system stability by supplying the stored energy to balance the system during the process. Wind power can also be utilised as an independent supportive black-start unit for system restoration. In this case voltage source converters (VSCs) technology is used to connect the wind farm to the grid [29]. The VSC-HVDC based offshore WF are capable of controlling the frequency and voltage of the islanded network during the whole restoration process [30],[31].

Other distributed generation (DG) units such as wind turbines and combined heat and power generators can also be used to restore an islanded grid. The units are coordinately controlled during the restoration process in order to keep the grid in a stable operating condition during the restoration. For example in the case when the wind turbines are not able to supply enough active power, due to unavailable wind then signals should be given to an available DG to support the power grid [11],[24]. Microgrids connected at the point of common coupling to the main grid, contain DG units and energy storage systems, hence can also black-start the network after blackouts [41], [42]. For all the restoration strategies, critical loads are considered to have the first priority to be picked up, meaning that these loads must be restored first.

The restoration process is also done by sectionalizing the blackout grid into small sub-islands, where every sub-island is assigned with black-start units to start the restoration process, each island must meet the stability requirements such as the voltage and frequency regulations and each sub-island must have enough generation to meet the demand. This restoration strategy is known as the parallel restoration, because the divided sub-islands can be restored in parallel. For every sub-island a black-start unit is energized first to send cranking power to another generation units[5], [27].

The objective of all the restoration methods aim on searching for energising paths, after the restoration plan is developed a feasibility check is done with a load flow program such as PowerFactory DIgSILENT.

The transmission system dispatchers (TSO) are responsible for the restoration of the transmission level, while restoration on the distribution level is done by the distribution operators (DSO). However, there must be coordination between the two system operators, meaning that data communication must be allowed between the parts.

2.2 Generation units with black start capability

The black start units (BSUs) are the power units that have the capability of self start, meaning that they do not need power from out side source to start, furthermore these units must be able to be synchronised to the grid, in order to start the black start process. They are utilised in the build up restoration process where sub-islands are formed. These units must be prepared in advance in order to make the restoration process faster, this because

some unit needs more time than others, for example a small diesel generator can be fast started in order to start up other big generators, while a steam turbine generator require station service power of up to 10% of their capacity for boiler feed water pumps. Normally the small BSU are put in stand by for black start, because it is expensive to standby a big BSU though they can be beneficial during black start as they can be used in the restoration process, comparing to small diesel generators which only starts the big NBSU. The BSU that are mostly utilised in the restoration process are: a hydroelectric generating units, diesel generating units and gas turbine generating units.

2.2.1 Hydroelectric generating units

The hydroelectric generators can be utilised to crank power to NBSU during the build up restoration strategy. These types of generators has the capability of self start without the need of outside power. They have a fast primary frequency response characteristic, meaning that they can also contribute to the system frequency regulations when restarting the NBSU. The operation principle for this generator is based on the Bryton cycle as it is demonstrated is section 2.2.3 [12][15].

2.2.2 Diesel generating units

The diesel generators are also used as black start units. The generators have the capability to start on their own with the use of a battery, their starting time is within milliseconds, which means that they can start at any time required by the operators. This advantage of immediately self start make the units very usable in emergency situation such as during the restoration process, where the out of service generators need to be restarted in order to start supplying generation to the grid. These generators are found in small size, therefore they have advantage in terms of transportation from one station to an other if required. Because of thier sizes, these units can not be used to pick up major transmission elements during the restoration process. Their operation is done by converting the mechanical power from the rotating shaft into electrical power needed by the system generator, in general thier operation is based on Bryton cycle discussed later in section 2.2.3 [12][15].

2.2.3 Gas turbine generating units

The gas turbine generator sets used to black start the grid does not have the capability to accomplish the work required for PSR alone, in addition these units are coupled with the on-site diesel generator sets, or batteries to help them start. The gas turbines are large in size, hence they have the capability of participating in the restoration process by picking up loads. The time it takes to start and available ramping capability of these generators depends on how long the units have been offline[12][15].

2.2.4 Behaviour of generator during black start

The generator start up curve 2.1 explains the working principle of the generator during the restoration process, it is based on the available active power and the assigned black start unit.

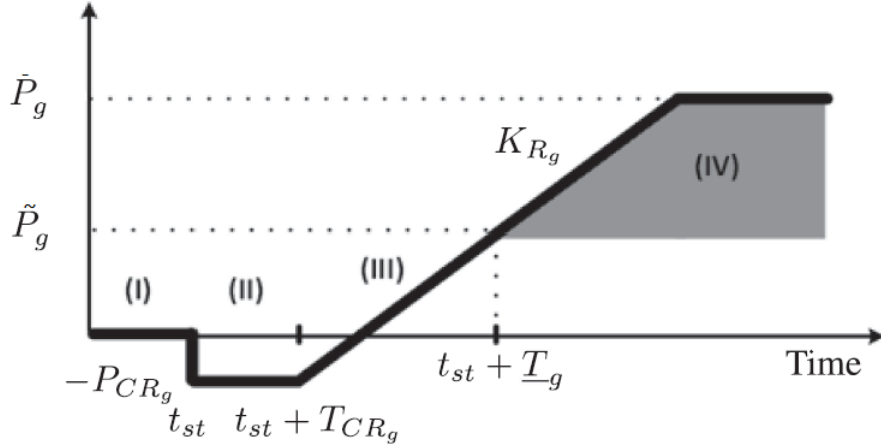


Figure 2.1. Typical generator active power curve[14]

In the Figure 2.1 above which shows the four stages of the generator during the restoration \bar{P}_g is the maximum active power generation, \tilde{P}_g is the minimum power generation, T_{CR_g} is the time between the generator being energised and the time until it can increase its active power from zero, K_{CR_g} is the ramping rate of the generator. The four phase in the curve illustrates the generator which has been disconnected and gets energised at time t_{st} , it takes sometime T_{CR} to be cranked as shown by phase II, its is shown that during the cranking period the generator absorbs the cranking power P_{CR_g} , after the generator is cranked it starts to ramp up to its technical minimum power generation indicated by phase III, then the generation can be supplied within its maximum and minimum range.

2.3 VSV-HVDC in Black Start

The voltage source converter HVDC technology is used as black start during restoration due to the fact that the technology can interconnect two grids. The VSC topology can both inject reactive power and absorb reactive power, this means that it can contribute to the voltage regulation during system restoration. The configuration of VSC-HVDC during black start is shown in Figure 2.2.

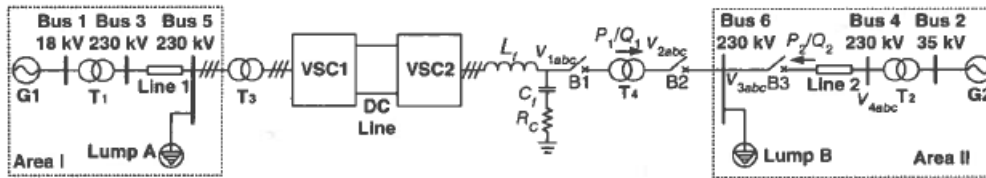


Figure 2.2. Configuration of VSC-HVDC system during restoration[17]

Figure 2.2 shows the major components of the VSC-HVDC transmission system during the black start process. The system has two VSCs, the sending known as the rectifier and the receiving VSC known as the inverter. These converters are indicated as VSC1 and VSC2 in the Figure 2.2, and each one can act as a rectifier or an inverter depending on the direction of the power flow. In the case when the grid is hit by a blackout the rectifier will

be connected to the health network and the inverter connected to the dead grid, suppose that the network in area II experience a blackout, then VSC1 in the figure will act as a rectifier and VSC2 as an inverter. During the black start process the rectifier (VSC1) which energises the DC link capacitors will be operating in DC voltage control mode, this is done by controlling the VSC1 side AC voltage to rated voltage, when the area I grid has reached the synchronous it can be synchronised, connected to the blackout area II via VSC2 which is used for black start and load pick up in area II.

When a blackout event occurs in area II the energy storage system such as a battery will keep the control and the protection system in operation, few seconds later the control and protection system detects that a blackout has occurred, this will cause the inverter (VSC2) to be blocked, the circuit breakers named as $B1$, $B2$ and $B3$ on the receiving station side in Figure 2.2 will be disconnected to allow VSC2 to be automatically controlled in black start mode. As it can be seen from the configuration, the switch $B1$ connect VSC2 to the grid in area II, hence, therefore by the instant $B1$ opens, VSC2 will be automatically be ordered to deblock, causing the AC voltage to gradually ramp up to its reference value, once the AC voltage in area II is built up, the restoration of components can proceed in step wise process, this is done by considering the energisation path where the balance between generation and demand is satisfied, meaning that the load picked up must be less than the available generation[17].

2.3.1 Advantage of VSC-HVDC in Black start

- Due to black start capability of VSC-HVDC, it can provide the initial energy resource needed to crank power to the deenergised power components.
- The VSC-HVDC has the capability of controlling the voltage by injecting or absorbing the reactive power during the restoration process. In the traditional strategy for system restoration, the voltage control is provided by the excitation system of the generator and the reactive power compensation devices such as a reactor connected at a bus.
- The system frequency can be controlled to its allowable limits by the VSC-HVDC during restoration this is done by managing the load pick up during the process.
- Due to the good control of VSC during the black start, the over-voltage issues which arise when system components are energised as a result of electromagnetic transients can be avoided.

2.4 Coordination of Wind Power and Energy storage System in System Restoration

The integration of wind power in modern power system has given the advantage in terms of power system restoration. But, there is concern of using wind power in system restoration due to the fact that wind fluctuates, this characteristics of wind can hinder the restoration process, as during the restoration with wind farm as black start if there is not enough available wind to crank power, the restoration would fail and a new blackout would occur as a result. But the coordination of wind power and energy storage system has brought the assurance of using wind power in black start. Energy storage system posses flexible

characteristics, meaning that they have advantage to the fact that they can store energy when there is excess from wind power and can release the energy to support the grid during unstable condition, the energy storage system can accommodate the uncertainty and variability of wind energy. Among the energy storage system utilises together with wind power are the battery energy storage system (BESS) and pumped storage hydro (PSH)[20].

2.4.1 Coordination of Pumped Storage Hydro Units and Wind Power in Restoration

The energy storage system known as the pumped storage hydro (PSH) units is discussed to be the energy storage system that can be used in coordination with the wind power to provide a reliable system for restoration process. The HSH system stores the energy by using the surplus energy to pump water from a lower reservoir to a high reservoir and generate power in the reverse process, hence in the event of excess wind power the energy can be stored. The system can provide a fast response with large scale, therefore it can be a good energy storage system to be coordinated with the wind power to provide a faster and reliable system for restoration. The PSH can be used to crank power to NBSU or load pick up, or it can also be utilised to compensate the power in the event or wind ramping up[17].

2.4.2 Coordination of Battery Energy Storage System and Wind Power in Restoration

The combination of BESS and the WF has been utilised in restoration process, there are two ways where the BESS and the WF are implemented: the parallel connection at the PCC and the BESS implemented in the DC link of the type 3 wind turbine.

BESS connected in Parallel with the WF at PCC for Black Start

The schematic of the coordination of wind farm and energy storage system is shown in Figure 2.3 where the two system are installed in parallel to the main grid at the point of common coupling(PCC). The WF-BESS hybrid restoration system is done in order to support the deficiency and surplus of generation during load pick up, which have imbalance effect between generation and consumption, this would affect the system frequency and voltage stability during the restoration process.

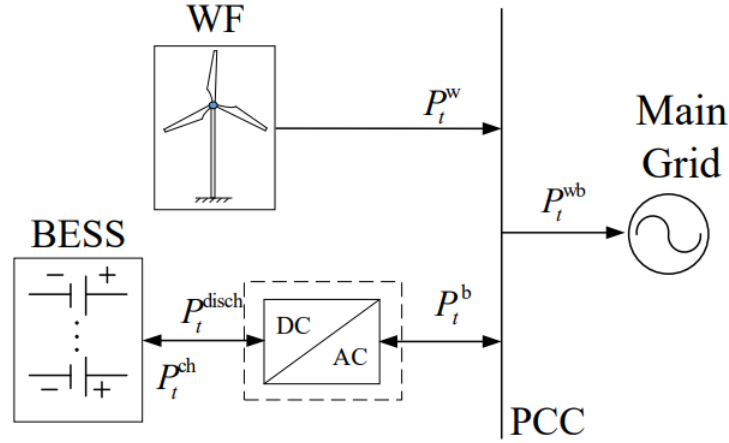


Figure 2.3. Schematic of a typical intergrated wind farm and BESS[20]

Figure 2.3 shows the WF and a battery dispatching strategy as hybrid system for power restoration. The BESS has advantage because, they can act as load and as a generation during the process, meaning that in the case when there is imbalance between load and generation, for example if there is surplus generation, the BESS will act as a load by storing the excess energy to bring balance to the system and when there is less generation comparing to the available load, the BESS will release the stored energy supporting the grid. In the initial stage of the restoration with WF-BESS where generation from wind power begin to ramp up the batteries will be operating in the discharging mode (behaving like a BSU) to crank power to NBSU or load pick up, when there is available power from wind the battery will operate in charging mode storing the surplus energy. This switch of operation will continue during the restoration process until the grid is fully recovered[20]. The out put power of the BESS at time t is expressed as in Equation 2.1

$$P_t^b = P_t^{desch} - P_t^{ch} \quad (2.1)$$

Equation 2.1 shows the working principle of the BESS, for short generation supply from WF P_t^b will be positive indicating the discharging state, hence BESS acting as generation unit to supply power, otherwise P_t^b will be negative for storing the surplus energy. The combined power from WF and BESS is the power sum from the two system as shown in Equation 2.2.

$$P_t^{wb} = P_t^b + P_t^w \quad (2.2)$$

BESS installed in DC link of type 3 wind turbine for black start

The BESS is also some times implemented in the DC link of the type 3 wind turbine, namely, the doubly fed induction generation (DFIG) type wind turbine, for black start the configuration is as shown in Figure 2.4.

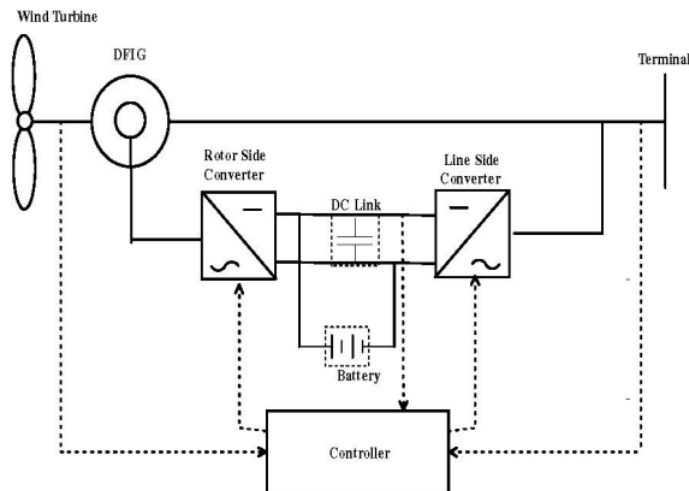


Figure 2.4. Schematic of a typical intergrated DFIG and BESS[22]

The DFIG wind turbine as seen in Figure 2.4 has two VSC converters, the grid side converter (GSC) and the rotor side converter (RSC). The RSC generates the excitation current, this is achieved by maintaining the speed of the rotor at a constant value, thus keeping the DC link voltage constant. During the black start process where the grid is not available, the AC voltage reference is created by the phase lock loop (PLL) and the control of RSC, hence the $P - f$ and $Q - V$ relationship needed in the restoration process is achieved. The BESS generate DC power, therefore it is implemented in the DC link of the DFIG to make sure that the DC voltage is as smooth as possible during the restoration process. The BESS discharges when there is a shortage and charges when there is surplus of power. By installing the BESS and wind turbine in this way an extra AC/DC converter is not needed.

2.5 Micro-grid in Restoration

A micro-grid (MG) is local energy grid which has the control capability of its own, it is powered by local energy sources such as wind turbine, PVs and mobile energy resources (MER) (distribution generation and batteries). The independent control ability means the MG can operate in island mode, meaning that there is no connection from the main grid, therefore in the case of blackout the MG is separated from the main grid to serve local loads. Since the MG have connection to the main grid at the PCC, where the voltage of the main grid and MG are synchronised, the MG can contribute in the system restoration to pick up loads and crank power to NBSU. Since the MG contains MER, it can be used to serve critical loads, in this case the matching between MER and critical loads is conducted in order to guide the dispatch of the MER, where the duration of the outage and the travelling time from the MER to the critical load is taken into consideration. The critical loads normal has reserve power source to support the load in the case of emergence, therefore the MER has to arrive at the particular critical load in time[17].

2.6 Electric Vehicles in Power Restoration

Electric vehicles (EVs) can be used in system restoration, the plug-in hybrid (PHEV) has the capability of charging and discharging, the car has a rechargeable battery that can be charged by connecting to an external power source. Since the the car system can charge and recharge it is considered as an energy storage system, therefore it can be considered as a load when it is charging and as a generation unit when it is discharging to the grid. It can therefore be used as a support system in the restoration process to absorb power in the event of excess power and inject power when there is a shortage of power, in this way the grid stability can be maintained during the restoration process[4].

2.7 Effects of FACTS devices in Power System Restoration

The restoration process threatens the stability of the grid as more generations, lines and loads are out of serve, which cause the imbalance of voltage and frequency, therefore the Flexible AC transmission system devices (FACTS) such as static var compensator (SVC), thyristor-controlled series capacitor (TCSC), static synchronous compensate (STATCOM) and unified power flow controller (UPFC) are considered in the restoration process, in order to assure a faster and a smooth restoration process. The SVC and TCSC are based on variable reactances, meaning that they can contribute to voltage regulation, the STATCOM and UPFC devices are based on voltage source converter, therefore has the ability of absorbing or injecting reactive power for voltage support also the control of power flow[13]. The issues that may occur during the restoration process, and which can lead the introduction of a FACTS device are oscillation stability, voltage stability, transient stability, standing phase angle control, reactive power control, sustained over-voltage, transient over-voltage reduction in stored energy for circuit breaker, and smooth load pickup[25]. The discussion of this issues and possible solution in terms of which FACTS device can be implemented for the matter is addressed in the following subsections:

2.7.1 Oscillation stability:

As discussed in chapter 1, one of the causes of the blackout is the low frequency oscillation in the voltage magnitude. The issue can still occur during the restoration process, due to interconnection of the transmission lines or if there is no devices to damp the oscillations. The device that can be used to mitigate the power system oscillations during the restoration is the STATCOM, the SSSC and UPFC. The STATCOM with its VSC has the ability for reactive power compensation, meaning it can absorb or generate reactive power in order to damp the voltage oscillations. The SSSC can also be used to damp the oscillations, this is done by regulating the difference of both angle and phase between the sending end and receiving end buses. UPFC is a combination of SSSC and STATCOM, therefore it can also be utilised to damp the voltage oscillations. The generators contain the power system stabilizer (PSS) which is used to damp the power oscillations, however, since there generation unit is not installed at every bus, it may be a more practical to have a FACTS device which can be installed at a particular bus when necessary.

2.7.2 Voltage stability:

Under normal condition and during dynamics, the voltage stability is a concern, which can be described as the ability of the power system to maintain the voltage within a pre-described grid limits. Factors that can lead to voltage instability during the restoration is the loadability margin. The components loadings, such as transmission line loading can be reduced by reducing the line reactance. When transmission lines are not energised for a while there will be generated loading, hence during the restoration process where lines are being energised the reactance of the some lines may be large compared to the initial condition. FACTS devices such as SVC, STATCOM, TCSC can be installed to adjust the line reactance thereby improving the voltage profile. When the system is in steady state the voltage should be maintained within $\pm 10\%$ of the nominal value, while a $\pm 20\%$ of the rated value is acceptable for during dynamic analysis[26].

2.7.3 Standing phase angle control:

After the sub-islands have been successfully restored, they have to be synchronised, during the synchronization the system dispatcher may face an excessive standing phase angle (SPA) at the sending and receiving nodes of the tie lines. When standing phase angle is large synchronising the sub-islands in this condition may lead to cascading events and system outage, the instability of the sub-island synchronization can also lead to the damage on the system components. The generators are the most affected components in the system due to large SPA, to avoid this relays are normally installed at the transmission lines or transformer in order to avoid the switching on a large SPA. To reduce the SPA the output of the generating units in the system is adjusted, this can be done by the tap changer of the transformers. But FACTS devices can be implemented to help the adjustment of the SPA.

2.7.4 Reactive power control:

When HV transmission lines are out of service for a while there will be an increase in reactive power during the energisation due to line charging current, this will cause an increase in system reactive power, which will sustain over-voltage. A solution to this matter can be to pick up some positive reactive loads to avoid the reactive power imbalance, however the pick up of extra loads may cause the system frequency to drop, because of the imbalance in active power. The alternative solution is to use a FACTS device like the one with a negative reactive power compensator and which can contribute zero active power. The SVC has the capability of absorbing reactive power, hence it is used in system restoration where it can be connected at the bus bar.

2.7.5 Sustained over-voltage:

The sustained over-voltage is caused by the line charging currents of lightly loaded HV transmission lines, the phenomena can cause damage to transformers due to over heating, it can also cause over-excitation on the transformer, over and under excitation on the generators and harmonic distortion, overall the stability of the system is greatly affected, a STATCOM or an SVC can be used in such matters.

2.7.6 Transient over-voltage:

Transmission line are energised by closing circuit breakers (CB) installed at the ends. energising a large section of lines causes transient over-voltage. The phenomenon can also result when the capacitive components in the system are energised. Transient over-voltage can lead to the failure of relays, this is because, the phenomenon result is a current that is a bit above the nominal value and the relays have difficulties in detecting such currents. The closure time point of the CB is of important, for example closing the CB when source instantaneous voltage is at peak result in zero missing phenomena. Controllable FACTS devices can be used to avoid such problem, where they can be utilised to find the optimal closure time point to avoid switching transient.

2.7.7 Smooth cold load pickup:

The capacity of loads in the initial period after pick up is often higher than the steady state load. The reason for load capacity increase is the losing of asynchrony of the constant power temperature controlled loads. During the restoration process, the system's constant temperature controlled loads such as refrigerator, electric heater and other consumer appliances will be energised simultaneously, which will result in the load power increase in a short time, at this time the load demand can be increased up to 10 times compering to the steady state value, however during the final stage of load pick up the load is larger for 4-5 times. This rapid increase in load will cause overloading and a large fluctuations in system frequency will take place, therefore the voltage and frequency will be large at this stage. By controlling the voltage and frequency during restoration FACTS devices can help to smooth the power flow during the load pick up to maintain frequency and voltage within the allowable grid code limitations.

The chapter has presented the technologies used in power system restoring restoration. It is seen that the electrical power system can be restored efficiently and successfully, and there are different ways utilised in restoration, though it can be summarised in two categories, namely, the build up and build down. It is seen that in order to restore the system efficiently, optimisation techniques are utilised in order to minimise the restoration time. The VSC–HVDC transmission, wind power and energy storage system has been used in black start process, it is shown that these technology are useful for black start, due to thier contribution in achieving a more stable system. Finally is shown that FACTS devices such as STATOM and SVC can also contribute to power restoration, since they can help to regulate the system voltage and frequency

Restoration by Island sectionalisation 3

This chapter presents the restoration process based on the build up strategy, where the blackout network is sectionalized in small islands depending on the available black start units, in order for the islands to be restored individually. The heuristic technique is adopted in this process to find the balanced islands for restoration, based on the availability of black start units, voltages limit and frequency limitation. The method defines the energising time and find the final cut set lines as the objectives, in order to maximise the possibility of finding the optimal sub-islands in short time. After the sub-islands are found, the energising path is selected by prioritising the critical loads and non black start units. The developed restoration plan is implemented in DIg SILENT PowerFactory.

3.1 The Heuristic Technique

The Heuristic method is adopted in this thesis to find the optimal islands when a total blackout scenario is considered. The Heuristic approaches a technique of solving a problem based on experts knowledge, meaning that the restoration constraints and procedures must be known as well as experts experience plays also a role in the technique, this is done in order to explore the search space in a practical way[7]. Figure 3.1 shows the all the steps adopted by Heuristic in order to sectionalise the sub-islands taking into account on the sub-islands minimum energising time. The constraints, knowledge in restoration procedure and the energising time determine the initial cut set, this gives an overview of the initial divided sub-islands, which are considered to be the close optimal solution. After find the initial optimal solution, the search space continues by reducing the number of cut set lines, as the lines which are not to be restored before sub-islands are parallel restored are reduced, the probability to obtain an optimal solution is higher, as the cut set lines can not be reduced any more an optimal solution has been achieved.

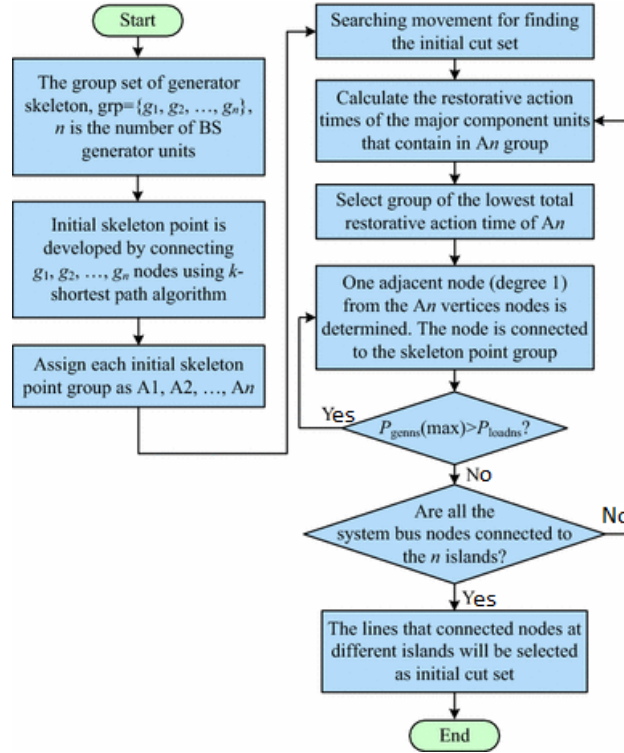


Figure 3.1. The Heuristic initialization technique[7]

The Heuristic technique by Figure 3.1 is basically composed of two main steps: the first step is to group the generators in the system according to the number of black start units (BSUs) available, then create the generator skeleton, the generators are grouped in accordance to the total active power generation balance between the the islands as in equation 2.7.7. The second step is to search for initial cut set lines referencing to solution in step one and according to Heuristic algorithm. In step two, the total restorative time for major system components in each group is taken into consideration.

3.2 Parallel restoration constraints

In sectionalising the islands several constraints must be fulfilled, this done as to maintain the reliability of the sub-islands in order to be restored in parallel, by doing so the stability of the sub-islands is obtained. The constraints to be obeyed during the sectionalising and synchronizing are the following.

- **Black start unit constraint:** As there is no power available in the network, each sub-island must have a black start unit (BSU) as the main cranking power to non black start unit (NBSU)[12].
- **Frequency constraint:** The total maximum power generated in each island must be higher than the total power consumed by the loads in each island. This is done in order to main the system frequency withing prescribed range. The frequency is affected by the imbalance between generation and demand and according to standards it must be maintained in the range of $\pm 3\%$ of nominal value, meaning a minimum of $47Hz$ and $53Hz$ according to standards [1],[26].

- **Voltage constraints:** Each island must have sufficient voltage control capabilities in order to maintain the bus voltage within prescribed limits. According to standards during transient events the voltage should remain in the range of $\pm 20\%$ of the rated voltage meaning a voltage minimum of $0.8p.u$ and maximum of $1.2p.u$ must be obeyed. Though, in the steady state events, the bus voltage is allowable to swing in the range of $\pm 10\%$ of nominal voltage, meaning a minimum of $0.9p.u$ and a maximum of $1.1p.u$ [1],[26].
- **Synchronisation constraints:** It is recommended that the cut set lines must contain synchronisation equipment to allow the sub-islands synchronisation to take place. It is assumed in this thesis that each cut set is equipped with synchronous meter to measure the sub-islands frequency and voltage before they can be synchronised.

3.3 Graph theory

The steps in Heuristic technique is applied to the grid in Figure 4.5 for a total blackout scenario. In order to find the generator skeleton, the system is modelled using graph theory method according to Equation 3.1.

$$G = (V, E, W) \tag{3.1}$$

where V stands for major electrical components (bus, generator, loads), E is the transmission lines (edges) and W is weight factor of the transmission line in terms of electric distance, all the system components are represented as a node as seen in Figure3.2.

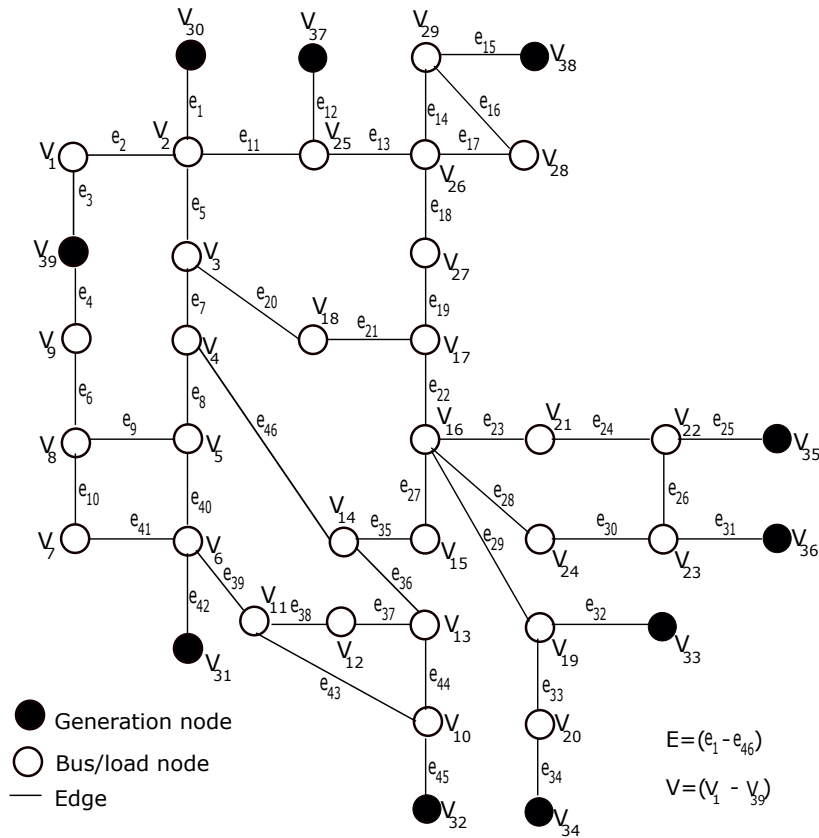


Figure 3.2. The 39-Bus system represented as a graph

Figure 3.2 show the reference system represented as an undirected graph using the graph theory method, where each bus is represented as nodes according to equation 3.1. The black nodes are generators located at 30, 31, 32, 33, 34, 35, 36, 37, 38 and 39 respectively, where the black start unit location is node 37, 31 and 34, this leads to the three number of generator groups to be created $n = 3$. There are 29 load nodes as indicated by the white nodes. The critical loads are located at node 7, 18, 21, 23 and 26, these are the loads that must be prioritised during the restoration paths in the sub-islands. In order to find the restoration paths, where the generation and loads will be restored by restoring the transmission lines interconnecting them, sets of generators groups must be created. This is achieved by fulfilling the total power generation balance as well as the gap of the skeleton size, which is accomplished by applying the k-shortest path algorithm. The method searches for the three shortest paths between each generation unit in the system as shown in Figure 3.3.

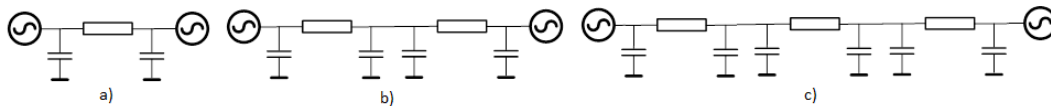


Figure 3.3. The k-shortest method: a) short-distance with two-side power source c) long-distance with two-side power source

Figure 3.3 shows the energisation sequence according to k-shortest paths, this means that a) will be energised before b) and c). The identification of generator skeleton is performed by searching for the three shortest path lines between the generating units,

the searched paths are ranked according to the weight of edges' connection number and electrical distance, in order to allocate the best path for restoration. The result from the k-shortest path is shown in Figures 3.4-3.10. It must be noted that each generating unit is being considered once in terms of being considered as reference when searching for the paths, and if the generating unit has been taken as reference can not be included in the searching paths.

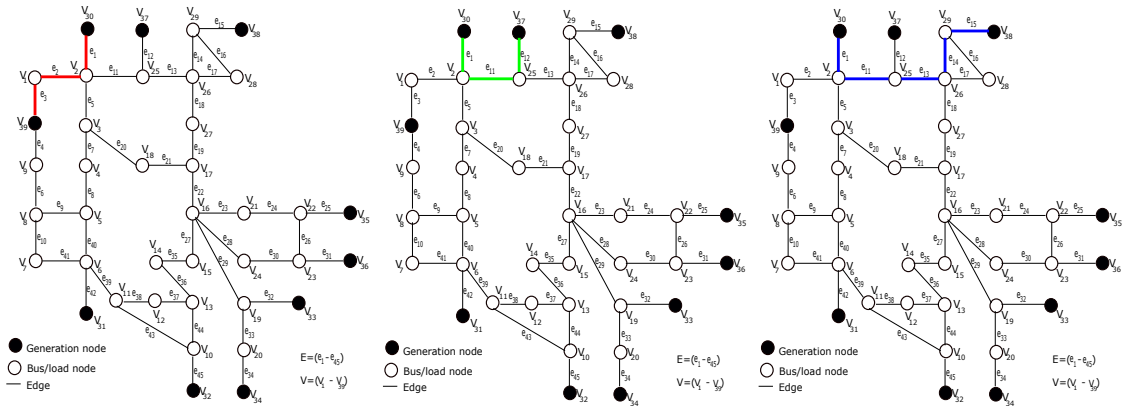


Figure 3.4. Generator skeleton from bus 30

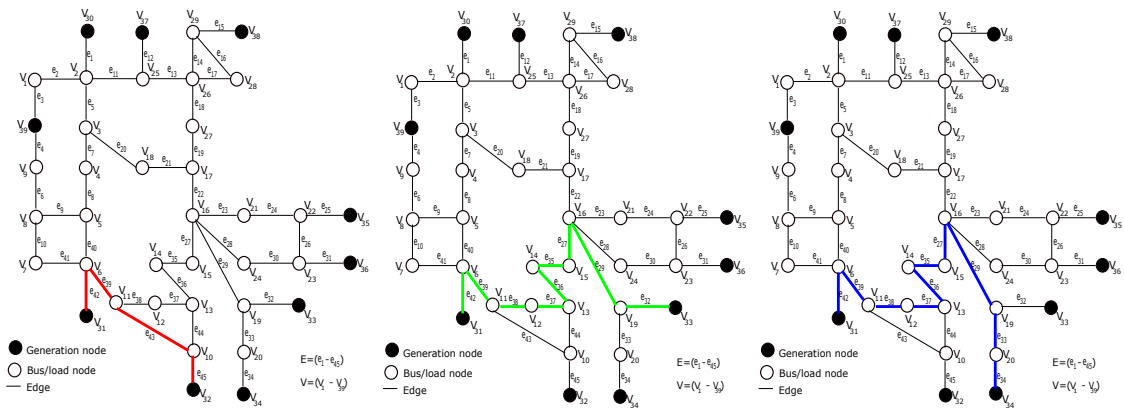


Figure 3.5. Generator skeleton from bus 31

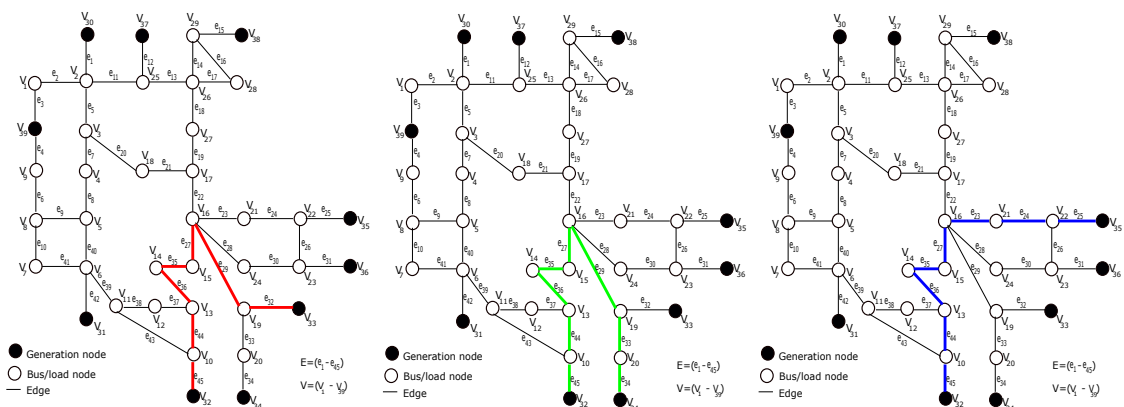


Figure 3.6. Generator skeleton from bus 32

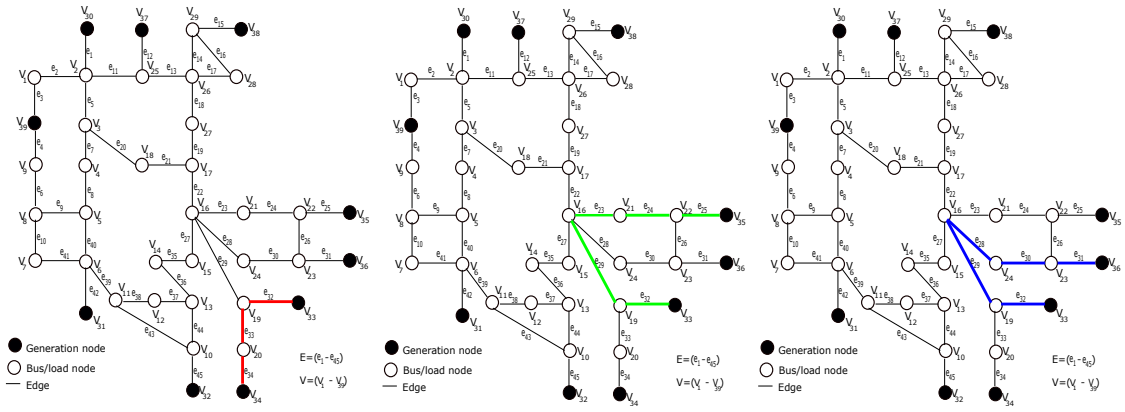


Figure 3.7. Generator skeleton from bus 33

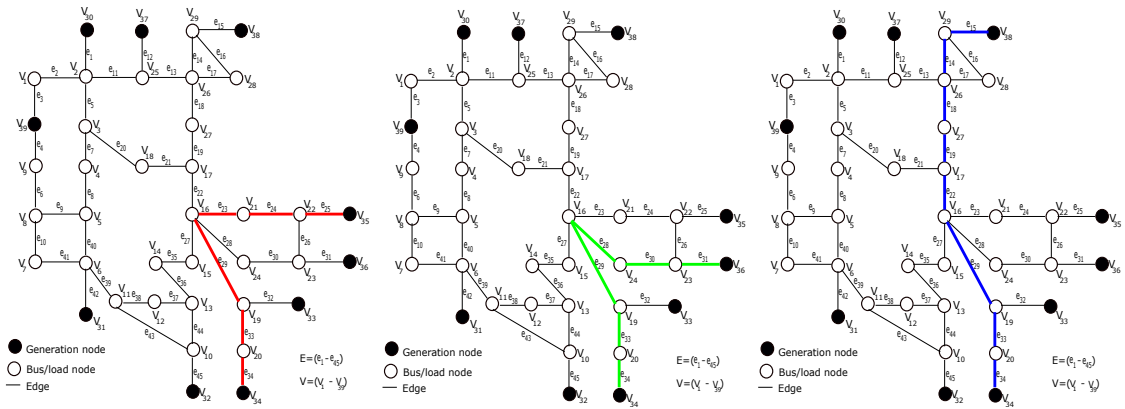


Figure 3.8. Generator skeleton from bus 34

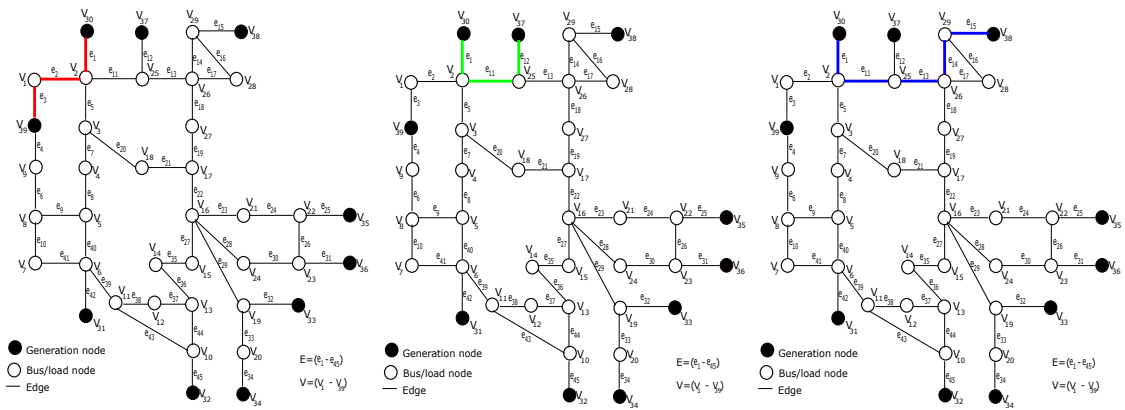


Figure 3.9. Generator skeleton from bus 37

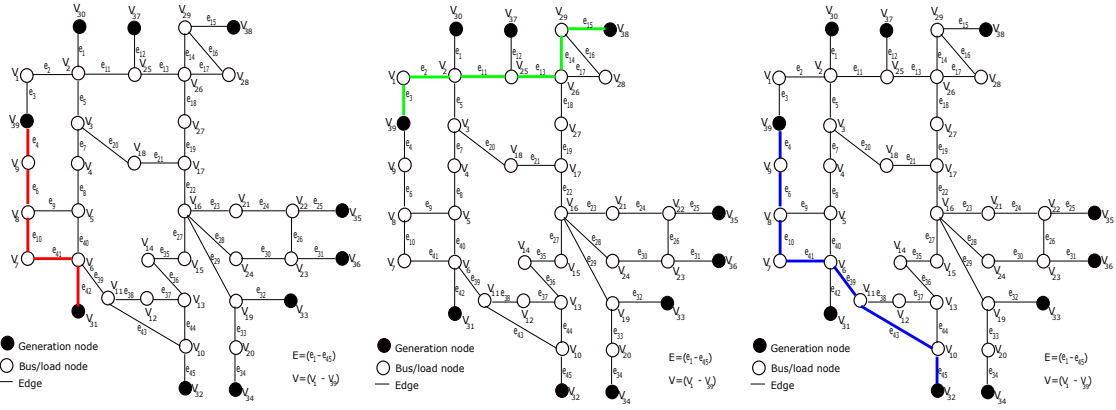


Figure 3.10. Generator skeleton from bus 39

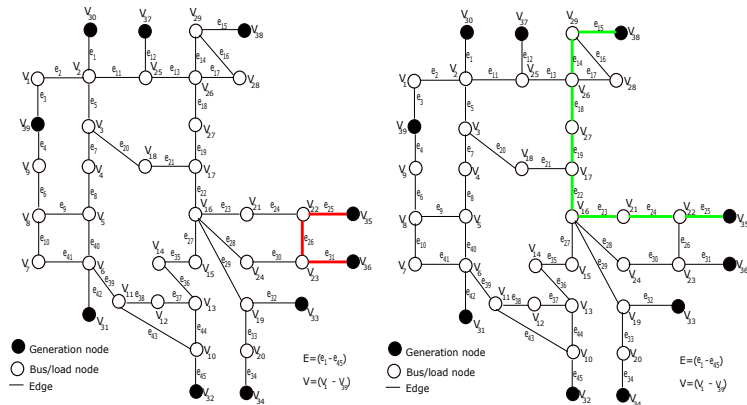


Figure 3.11. Generator skeleton from bus 35

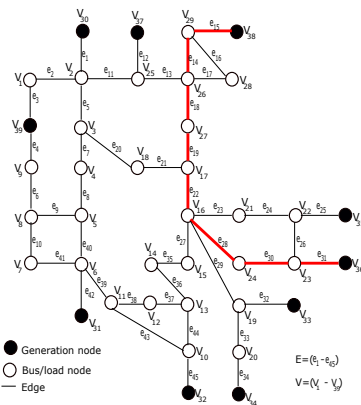


Figure 3.12. Generator skeleton from bus 36

The three shortest paths shown in the above figures are the three shortest distance in terms of edges (lines) from a generating unit to the three closed units. The found three shortest paths will now be ranked according to their electric distance, in order to find the best shortest path. The electric distance is the total reactance of the shortest paths, meaning the reactance sum of transformer and line as indicated by graph models. The ranking is shown in Table 3.1.

PV bus	Shortest path	No of lines	Electric distance [p.u]
30	30,2,25,37	3	0,0499
	30,2,1,39	3	0,0842
	30,2,25,26,29,38	5	0,1371
37	37,25,2,1,39	4	0,0979
	37,25,26,29,38	4	0,1336
	37,25,2,3,4,5,6,31	7	0,1086
39	39,9,8,7,6,31	5	0,1001
	39,1,2,25,26,29,38	6	0,1851
	39,9,8,7,6,11,10,32	7	0,1076
31	31,6,11,10,32	4	0,0575
	31,6,5,4,14,5,16,19,34	8	0,1181
	31,6,5,4,14,5,16,19,33	9	0,1357
32	32,10,13,14,15,16,19,34	7	0,0992
	32,10,13,14,15,16,20,33	8	0,1168
	32,10,13,14,15,16,21,22,335	8	0,1268
33	33,19,20,33	3	0,046
	33,19,16,21,22,35	5	0,0755
	33,19,16,24,23,36	5	0,1018
34	34,20,19,16,21,22,35	6	0,0931
	34,20,19,16,24,23,36	6	0,1194
	34,20,19,16,17,27,26,29,38	8	0,1703
35	35,22,23,36	3	0,0511
	35,22,21,16,17,27,26,29,38	8	0,1608
36	36,23,24,16,17,27,26,29,38	8	0,1871

Table 3.1. The rankings of the three shortest paths

Table 3.1 shows the sequence of the three shortest path from each generating unit according to the electrical distance of the edges. From the table the generators can be arranged according to the sequence of thier first shortest path, and no generating unit will be repeated in the process, the generator grouping sequence are as follow: 30, 37, 39, 31, 32, 33, 34, 35, 36, and 38 respectively.

From the above result the sub-islands can be estimated. There are three generations with black start capabilities in the system, they are located at bus 37, bus 32 and bus 33. Hence, three sub-islands can be estimated. Based on the location of the black start units, the three possible islands are : island 1 with generating units (Gen 10, Gen 8 and Gen 9), island 2 with generating units (Gen 1, Gen 2 and Gen 3) and island 3 with generating units (Gen 4, Gen 5, Gen 6 and Gen 7). The generator skeleton according to the initial islands can be seen is Figure

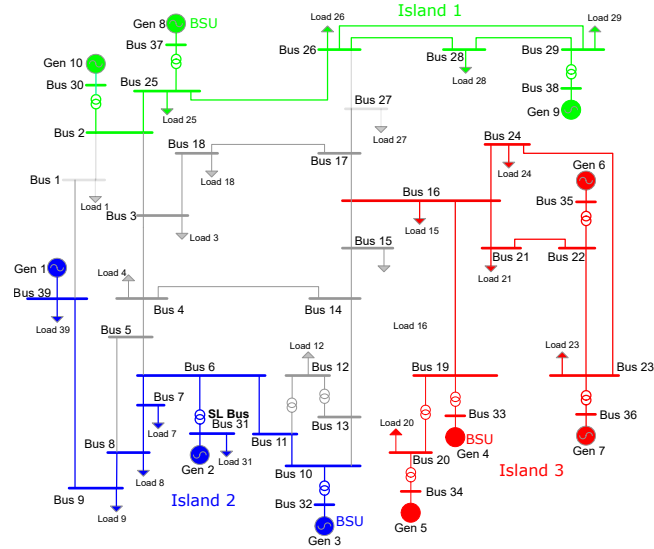


Figure 3.13. The initial skeleton bus points for sub-islands

Figure 3.13 shows the generator skeleton for the three suggested sub-islands, the buses that connect the generator are allocated in the same group together with the loads connected at those buses. The sub-islands are expended in order to accommodate the remaining lines and loads. This done by following the load-generation balance, meaning that the generation in each sub-island must be greater than the consumption. To decide which sub-island must be allowed to expand first the restorative time for generator and loads is used, meaning that the sub-island with less sum restorative time will be expanded first. The restorative time for each components are shown in Table 3.2.

Action	Time [min]
(A1) Restart BSU	15
(A2) Energise bus from BSU	5
(A3) Connect tie line	25
(A4) Crank power to NBSU from a bus	15
(A5) Synchronise sub-islands	20
(A6) Pick up load	10

Table 3.2. Time to complete an action during restoration

3.3.1 Expending the initial sub-islands

The initial sub-islands are expended by first considering their respective restoration time, in order to decide which sub-island must be allowed to expend first.

The restoration time for the islands are calculated by finding the energization path starting from the black start unit. The energisation paths and the calculated restoration time is explained using the island 1, then the other islands restoration path will be shown in a table. In island 1 the BSU is located at bus 37, therefore the black start must take this node as the reference to start the black start process. Hence, the BSU Gen 8 is in operation after 15 min (A1) the number of connection between the energised components (generating unit) and the next component to be energised (load or generating unit) is two, unless that path is not available. It can be seen from Figure 3.13 that the number of

connection from BSU to load 25 is 1, hence this load is picked up after 15 min (A2+A6). In parallel restoration critical loads are of first priority, there is a critical load at bus 26 after 15 min (A2+A6) this load is picked up from the already energised bus 25. The NBSU Gen 10 at bus 30 is considered to be next to receive the cranking power from the already energised bus 25, this is accomplished after 25 min (A2+A2+A4). The NBSU Gen 9 at bus 38 is restored next, and it requires two connections from the already energised bus 26, it can be noticed that by restoring this NBSU the load 29 is picked up in the process, therefore it takes 35 min (A2+A6+A2+A4) to restore this path. The load 28 is restored after 15 min (A2+A6) and the total restoration time for the initial sub-island 1 is 120 min.

The sequence for restoring the initial island 2 and 3 to get the restorative time is shown in Table 3.3

Path	Restored elements	Actions	Time [min]
-	BSU Gen 3	A1	15
$(v_{32}, v_{10}, v_{11}, v_6, v_{31})$	Load 31, NBSU Gen 2	A2+A2+A2+A2+A6+A4	45
(v_6, v_7)	CL at v_7	A2+A6	15
(v_7, v_8, v_9, v_{39})	Load 8, 9, 39 , NBSU Gen 1	A2+A6+A2+A6+A2+A4+A6	60

Table 3.3. Initial restoration time for island 2

It can be seen from Table 3.3 which shows the energisation sequence for the initial island 2 that the time to restore the island is 135 min.

Path	Restored elements	Actions	Time [min]
-	BSU Gen 4	A1	15
$(v_{33}, v_{19}, v_{20}, v_{34})$	Load 20, NBSU Gen 5	A2+A2+A6+A2+A4	40
(v_{19}, v_{16}, v_{21})	Load 16, CL at v_{21}	A2+A6+A2+A6	30
(v_{21}, v_{22}, v_{35})	NBSU Gen 6	A2+A2+A4	25
(v_{22}, v_{23}, v_{36})	CL at v_{23} , NBSU Gen 7	A2+A6+A2+A4	35

Table 3.4. Initial restoration time for island 3

It can be seen from Table 3.4 which shows the energisation sequence for the initial island 3 that the time to restore the island is 145 min.

From the calculated restoration time the island 1 has a lower restorative time, therefore it is selected to expend first, this done by connecting the buses that are adjacent to the that island. From Figure 3.13 it can be noticed that the buses 1, 3 and 27 are adjacent to islands 1, therefore are connected to expend that island. All the 3 islands are expended by checking their load generation balance, meaning that in each achieved island the total active power generated must be higher than the total active power consumed. The final sectionalized islands can be seen in Figure 3.14.

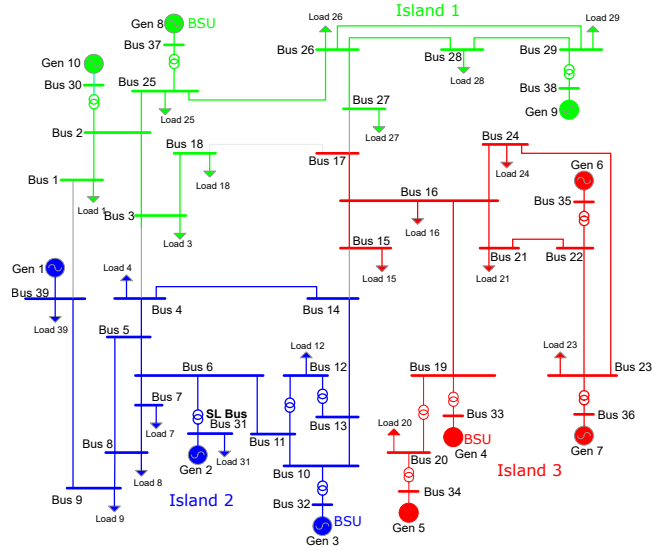


Figure 3.14. Three islands for parallel restoration

Figure 3.14 shows the sub divided islands to be restored in parallel, it can be seen that after the load-generation balance has been calculated for each island, there are 5 lines de-energised separating the islands, after the islands has been successfully restored they can be synchronised. The total power generated and consumption in each island can be seen in Table 3.5.

Island	P_{max}^{load} [MW]	P_{max}^G [MW]	Critical load	NBSU [PV bus]	BSU [PV bus]
1	1613.500	1620,000	L18, L26	30, 38	37
2	1854.500	2248.329	L7	31, 39	32
3	2107.100	2096.000	L21, L23	34, 35, 36	33

Table 3.5. Generation and demand in each island, and the critical loads

3.4 Complete restoration sequence for sub-islands

After the sub-islands have been found the energisation paths for each island and their total restoration time are determined. It must be noted that the main focus in graph theory method is to make the energisation paths in the way that the sub-islands will be restored in approximately same time and the buses with zero injection are not considered in the total restoration time, meaning that the restoration will be focusing on the restoration of generation nodes as well as the loads nodes with non zero consumption. Further more the graph theory based method focuses on prioritising the restoration of critical loads before the non critical loads.

3.4.1 Sequence paths for island 1

The complete restoration sequence for island 1 together with their respective restoration time is shown in Table 3.6.

Sequence path	Restored elements	Actions	Time [min]
-	BSU Gen 8	A1	15
(v_{25})	Load 25	A2+A6	15
(v_{26})	CL at v_{26}	A2+A6	15
(v_2, v_{30})	NBSU Gen 10	A2+A2+A4	25
(v_{29}, v_{238})	Load 29, NBSU Gen 9	A2+A6+A2+A4	35
(v_3, v_{18})	Load 3, CL at v_{18}	A2+A6+A2+A6	30
(v_{27}, v_{28})	Load 27, Load 28	A2+A6+A2+A6	30
(v_1)	Line (e_2, e_{16})	A2	5

Table 3.6. Restoration sequence for island 1

It can be noticed in Table 3.6 that the total time it will take to recover island 1 is estimated to 170 minutes.

3.4.2 Sequence paths for island 2

The complete restoration sequence and thier respective restoration path is shown in Table 3.7.

Sequence path	Restored elements	Actions	Time [min]
-	BSU Gen 3	A1	15
($v_{32}, v_{10}, v_{11}, v_6, v_{31}$)	NBSU Gen 2	A2+A2+A2+A2+A4	35
(v_6, v_7)	CL at v_7	A2+A6	15
($v_7, v_8, v_9, v_{\{39\}}$)	Load 8, 9, 39, NBSU Gen 1	A2+A6+A2+A6+A2+A4+A6	60
(v_{11}, v_{12})	Load 12	A2+A6	15
(v_6, v_5, v_4)	Load 4	A2+A2+A6	20
(v_{13}, v_{14})	Line ($e_9, e_{37}, e_{36}, e_{46}$)	A2+A2	10

Table 3.7. Restoration sequence for island2

From Table 3.7 it can be seen that the total restoration time for island 2 is estimated to 170 minutes.

3.4.3 Sequence paths for island 3

The complete sequence path for the restoration of island 3 with the total restoration time is shown in Table 3.8.

Sequence path	Restored elements	Actions	Time [min]
-	BSU Gen 4	A1	15
($v_{33}, v_{19}, v_{20}, v_{34}$)	Load 20, NBSU Gen 5	A2+A2+A6+A2+A4	40
(v_{19}, v_{16}, v_{21})	Load 16, CL at v_{21}	A2+A6+A2+A6	30
(v_{21}, v_{22}, v_{35})	NBSU Gen 6	A2+A2+A4	25
(v_{22}, v_{23}, v_{36})	CL at v_{23} , NBSU Gen 7	A2+A6+A2+A4	35
(v_{23}, v_{24})	Load 24	A2+A6	15
(v_{16}, v_{15})	Load 15	A2+A6	15

Table 3.8. Restoration sequence for island3

Table 3.8 shows the sequence path to restore the island 3, the calculated restoration shows that it will take approximately 175 minutes to restore the island.

3.4.4 Complete restoration time for the whole grid

The total restoration time, as well as the sequence to recover the 39 bus new England system in divided islands is shown Tables 3.9.

Island No.	1	2	3
Sequence Energisation	Gen 8	Gen 3	Gen 4
	Trf 37-25	Trf 32-10	Trf 33-19
	Lne 25-26	Lne 10-11	Trf 19-20
	Lne 25-2	Lne 6-11	Trf 20-34
	Trf 2-30	Trf 6-31	Lne 16-19
	Gen 10	Lne 6-7	Lne 16-21
	Lne 26-29	Lne 7-8	Lne 21-22
	Trf 29-38	Lne 8-9	Trf 22-35
	Lne 2-3	Lne 9-39	Lne 22-23
	Lne 3-18	Gen 1	Trf 23-36
	Lne 28-29	Trf 11-12	Lne 23-24
	Lne 26-27	Lne 5-6	Lne 15-16
	Lne 1-2	Lne 4-5	Lne 16-24
		Trf 12-13	Lne 16-17
Lne 26-28	Lne 13-14		
	Lne 4-14		
	Lne 5-8		
	Lne 10-13		
Total restoration time [Min]	170	170	175
Synchronise islands	Lne 17-18		
	Lne 17-27		
	Lne 3-4		
	Lne 14-15		
	Lne 1-39		

Table 3.9. Sequence of restoration for three islands

From Table 3.9 shows that it will take a total of 515 minutes to restore the complete network. It must be noted that the time required for the generators to be able to inject power to the grid as well as the time to synchronise the islands is not taken into consideration. It can be see that after the sub-islands have been restored in their respective time, the lines 1-39, 3-4, 17-18, 17-27 and line 14-15 that separate the three islands are still de-energised, these lines are energised to restore the whole network. In restoring the cut set lines it is assumed that the synchronisation equipment are available at the cut set lines.

This chapter has discussed the build up restoration process. The grid was discretized in three islands which gives them a good timing in terms of restoration, this also enables the island to be restored in stable condition, hence enabling them to be interconnected without the concern of stability issues. The energisation of line, transformer and load were tested

in both normal EMT simulation mode and in hybrid mode, it is shown that when the hybrid mode is utilised to switch on elements in order to analyse the transient phenomena there less transient resulting after the event which makes it easy to analyse the behaviour of the components after the event.

-

A Flexible Simulation Platform for Black Start 4

This chapter discusses the developed simulation platform for power system restoration. The algorithm considers the total blackout scenario, where every generator in the system can be considered to act as a black start unit. The shortest line path from the generator to an other generator is searched for energisation, and the search sequence continues from the already energised bus. The grid regulations for frequency and voltage is taken into consideration during the process. To minimise the violation of grid regulations two cases are proposed: 1) the detouring process, in this case when the energisation path is not available due to the fact that the voltage limit is violated the search continues to the next shortest available path. 2) By considering the tap changer to regulate the system voltage, in this case when the voltage limit is violated transformer on load tap changer (OLTC) will be activated to try to regulate the voltage. The path search algorithm is developed with PDL scripts in PowerFactor.

4.1 Path searching algorithm

The path search algorithm is explained in a flow chart diagram in Figure 4.1, where B represent the sets of black-start units, E for energized substations, D for de-energized substations, U for unavailable branches and L for de-energized branches.

The first step in the black start process according is to assess the extent of blackout, this is done by checking the status of all switches, generators, substations, transformers, cables and transmission lines. The generating units with black start capabilities are considered to crank power to non-black start units.

The second step is to find the sequence of generation units starting from the black-start unit, then the path searching algorithm Figure 4.1 is implemented to find the transmission path to implement the sequence. All the switches and breakers along the path are searched out. Then the actions of closing switches and breakers will be arranged in sequence as switch events. For each switch event, the grid regulations, which includes the criteria of voltage and frequency, will be checked by time-domain (T-D) simulation. After all the substations are energized, the final step is to restore the remaining de-energized branches from the one with the shortest electric distance. In this thesis, at each step of the searching path algorithm, e.g. Step m , the branch connecting one energized substation $i \in E$ and one de-energized substation $j \in D$ with the shortest electric distance, i.e. $d_{ij,m} = d_{min,m}$, has highest priority to be connected. This is because the energization of long-distance branches, especially long under-ground cables, may result in large charging current when the grid

is weak. In other words, it is better to energize the branches that have larger charging current when the grid is stronger.

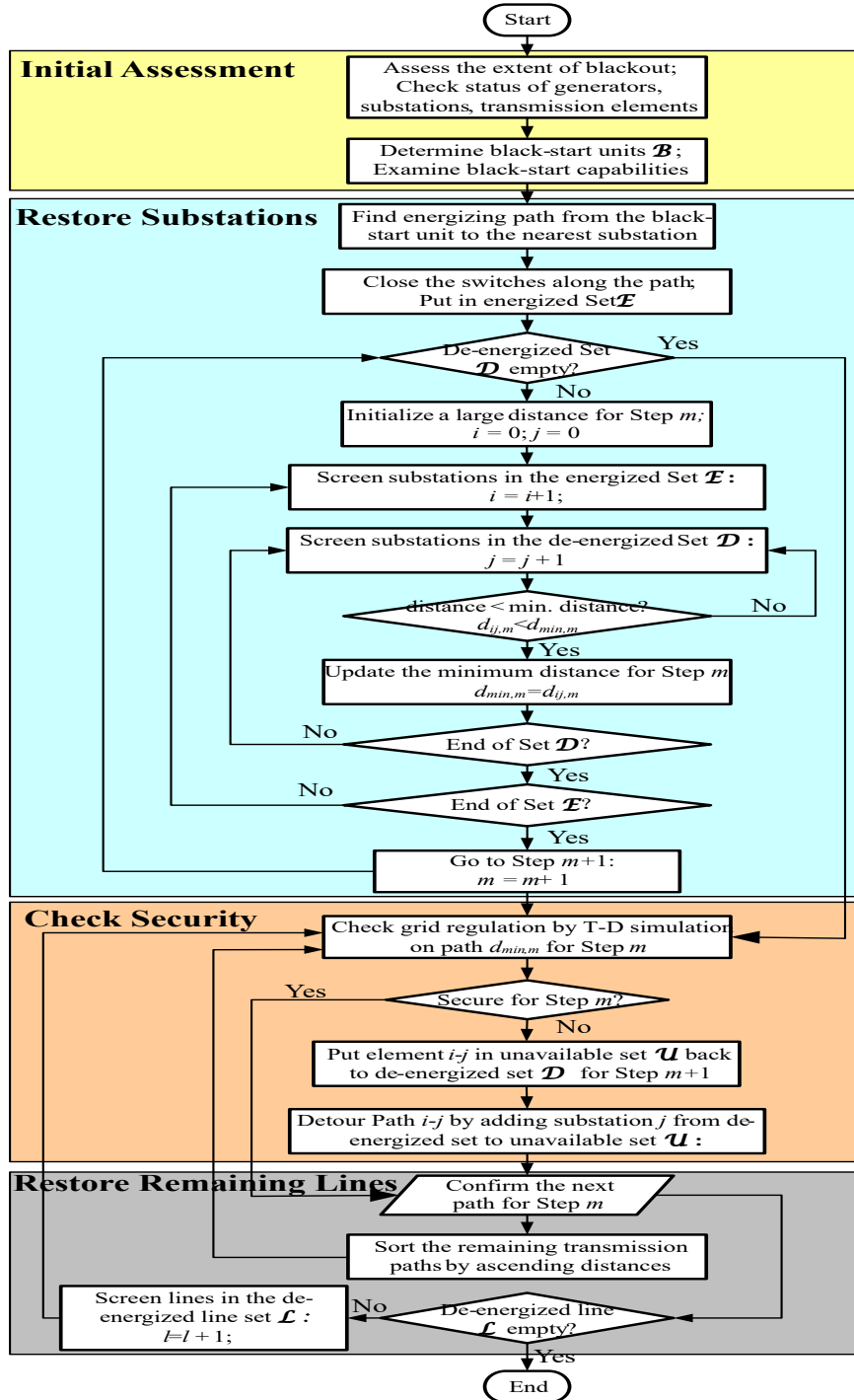


Figure 4.1. Flow diagram of path searching algorithm

The strategy for the shortest path to energize the transmission branches such transformers and transmission line in order to crank power to non black start unit and load pick up is explained by :1) Figure 4.2, in the case of deciding between two paths when a generation unit is to crank power to two different generators and 2) by Figure 4.3 the priority when a generating unit is to supply power to two different loads.

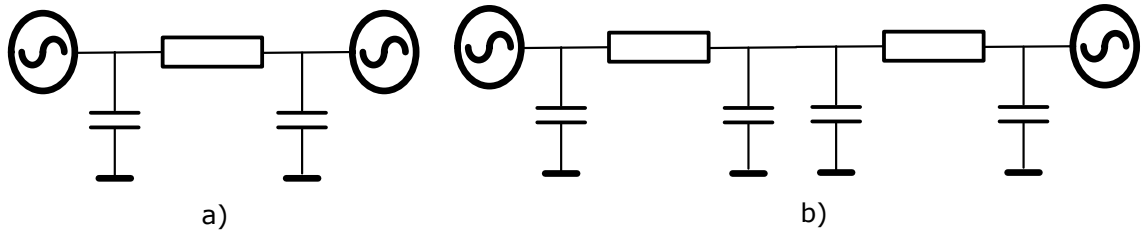


Figure 4.2. Sequence of energization with two generation

Figure 4.2a) and b) shows two ways of energisation, the short distance is expressed as a single transmission line and the long distance is expressed as two transmission lines as indicated by a Π model. a) shows a short distance with two side power source and b) a long distance with two side power source. In the case for energisation the path searching algorithm will connect a) first as the shortest path.

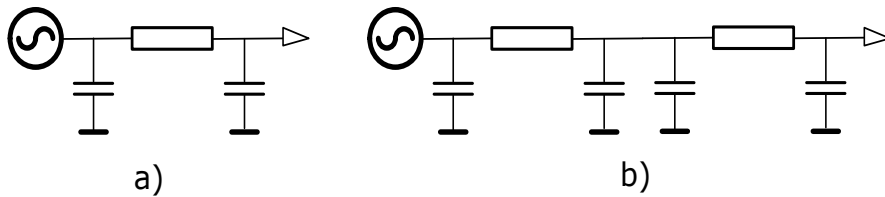


Figure 4.3. Sequence of energization with a generator and a load

Figure 4.3a) and b) shows two ways of energisation, the expression for short distance and long distance is the same as explained for Figure 4.2. a) show the short-distance with one-side power source and a load and b) long-distance with one-side power source and a load, in the case for energisation the path searching algorithm will connect a) first as the shortest path.

In terms of higher security, it is advantageous to first connect the shorter electric distance branches with both sides energized, for example cranking power to NBSU is the first priority during the black start, meaning the connection of 4.2 a) would be first priority for energisation comparing to the connection in Figure 4.2 b), and the energisation configuration in Figure 4.3 will be last.

4.2 Closed-loop decision support tool for detour

In order to reduce the risk of violating the voltage limits during the path searching process a closed-loop decision support tool named detour is proposed as shown in Figure 4.4. The detour process will search for the next possible shortest path to be energised if the path that was supposed to be energised threatens to violate the system voltage.

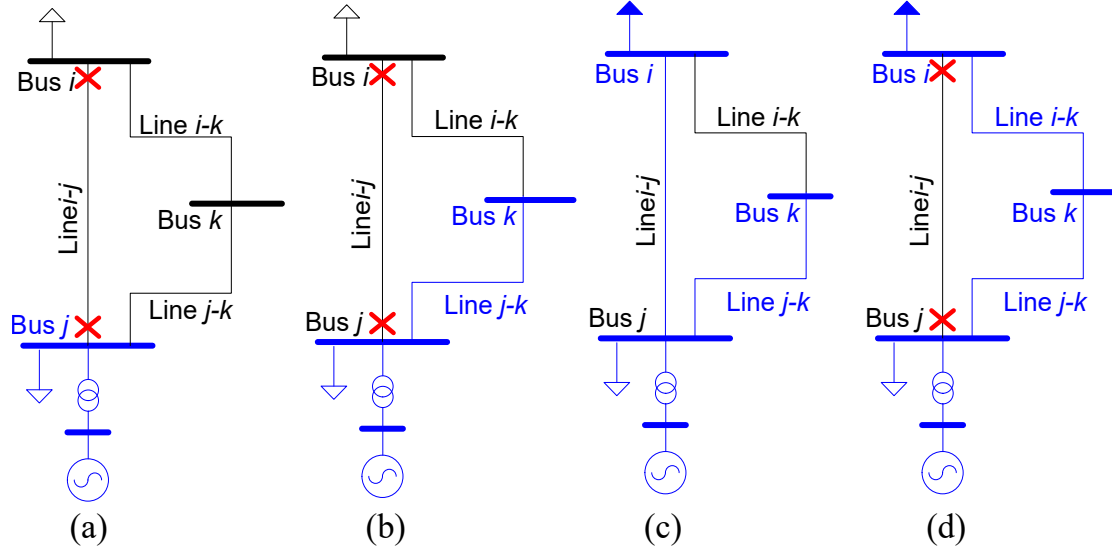


Figure 4.4. Illustration of energization path for detour line $i-j$

The detour process as shown by Figure 4.4 a)-d). Figure a) shows the process in the case when the line $i-j$ is not available for switch, then the line $i-j$ will be excluded from the set of de-energized lines L . After the unavailability of this line, the detour process is then to find the detour path, i.e. along line $j-k$ and Line $i-k$, shown in Figure 4.4 b) and 4.4 c), if Line $i-j$ is checked out of violations of grid regulations by T-D simulations, shown as 4.4 a), the detour algorithm will find Line $j-k$ as the next branch to be energized shown in Figure 4.4 b). Then the line $i-j$ which was removed from the set will be put back into the set of de-energized lines L . Figure 4.4 c) shows the next step after the line $i-j$ is put back in the de-energised set L , namely $i-j$ and line $i-k$ which is the line that was supposed to be energised after the energisation if line $j-k$ will be compared according to their electric distance. If the electric distance of line $i-j$ is the shortest compared to line $i-k$, i.e.

To maintain the stability of the network, and the reliability of the black start process the voltage and frequency grid requirements must be maintained. According to the standards [1],[26] the voltage and frequency limits during the restoration process are as follow:

- **Frequency constraint:** The total maximum power generated in each restoration process must be high than the total power demand. Hence, the system frequency is maintained within the prescribed range. The frequency must be maintained in the range of $\pm 3\%$ of nominal value, meaning a minimum of $47Hz$ and $53Hz$ must be obeyed.
- **Voltage constraint:** Before the black start process, it must be ensured the capabilities of voltage control, meaning that reactive power compensation such as FACTS devices must be available, to avoid the system voltage to violate the allowable limits. According to standards during transient situation the voltage should remain in the range of $\pm 20\%$ of the rated voltage meaning a voltage minimum of $0.8p.u$ and maximum of $1.2p.u$ must be obeyed. But, in the steady state events, the system voltage is allowed to swing in the range of $\pm 10\%$ of nominal voltage, meaning a minimum of $0.9p.u$ and a maximum of $1.1p.u$.

4.3 The black start process

The grid adopted in this thesis is the IEEE 39-Bus New England system. It is a reduced system from the structure of 1960 New England grid and contains only the transmission voltage level. A single line diagram of the network is shown in Figure 4.5. The grid has 10 synchronous machines periods, it has a total active power of 6250 MW and a total reactive power of 1390 MVar. The network has 46 transmission lines and 12 transformers, the generators are connected to the grid via step up transformers.

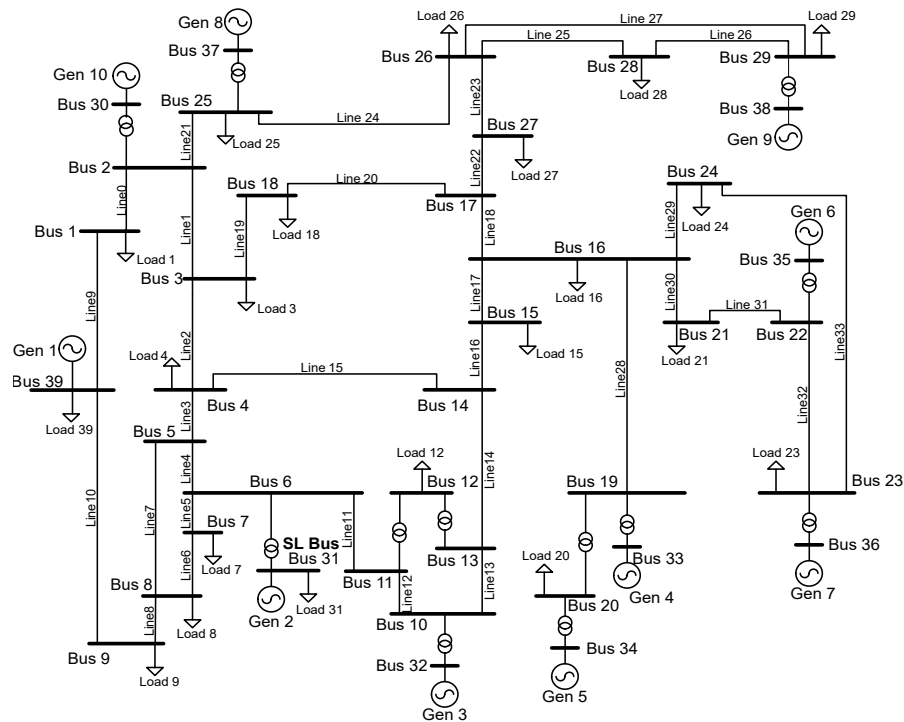


Figure 4.5. The single line diagram of the 39 Bus New England System

The searching path algorithm is applied on the network in Figure 4.5 to find the sequence of energisation. The whole planned energisation sequence of power restoration from all generation units (G1-G10) is shown in Tables 4.1 and 4.2 respectively.

BSU	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5
Restore Substation	Lne 01-39	Trf 06-31	Trf 10-32	Trf 19-33	Trf 20-34
	Lne 09-39	Lne 05-06	Lne 10-11	Trf 19-20	Trf 19-20
	Lne 08-09	Lne 06-11	Trf 11-12	Trf 20-34	Trf 19-33
	Lne 07-08	Trf 11-12	Trf 13-12	Gen 05	Gen 04
	Lne 06-07	Trf 13-12	Lne 06-11	Lne 16-19	Lne 16-19
	Trf 06-31	Lne 10-11	Trf 06-31	Lne 16-24	Lne 16-24
	Gen 02	Trf 10-32	Gen 02	Lne 16-17	Lne 16-17
	Lne 05-06	Gen 03	Lne 05-06	Lne 17-18	Lne 17-18
	Lne 06-11	Lne 06-07	Lne 06-07	Lne 15-16	Lne 15-16
	Trf 11-12	Lne 07-08	Lne 07-08	Lne 03-18	Lne 03-18
	Trf 13-12	Lne 13-14	Lne 13-14	Lne 16-21	Lne 16-21
	Lne 10-11	Lne 04-05	Lne 04-05	Lne 21-22	Lne 21-22
	Trf 10-32	Lne 03-04	Lne 03-04	Trf 22-35	Trf 22-35
	Gen 03	Lne 03-18	Lne 03-18	Gen 06	Gen 06
	Lne 13-14	Lne 17-18	Lne 17-18	Lne 22-23	Lne 22-23
	Lne 04-05	Lne 16-17	Lne 16-17	Trf 23-36	Trf 23-36
	Lne 03-04	Lne 16-24	Lne 16-24	Gen 07	Gen 07
	Lne 03-18	Lne 15-16	Lne 15-16	Lne 02-03	Lne 02-03
	Lne 17-18	Lne 16-21	Lne 16-21	Trf 02-30	Trf 02-30
	Lne 16-17	Lne 21-22	Lne 21-22	Gen 10	Gen 10
	Lne 16-24	Trf 22-35	Trf 22-35	Lne 02-25	Lne 02-25
	Lne 15-16	Gen 06	Gen 06	Trf 25-37	Trf 25-37
	Lne 16-21	Lne 22-23	Lne 22-23	Gen 08	Gen 08
	Lne 21-22	Trf 23-36	Trf 23-36	Lne 17-27	Lne 17-27
	Trf 22-35	Gen 07	Gen 07	Lne 26-27	Lne 26-27
	Gen 06	Lne 02-03	Lne 02-03	Lne 03-04	Lne 03-04
	Lne 22-23	Trf 02-30	Trf 02-30	Lne 04-05	Lne 04-05
	Trf 23-36	Gen 10	Gen 10	Lne 05-06	Lne 05-06
	Gen 07	Lne 02-25	Lne 02-25	Trf 06-31	Trf 06-31
	Lne 02-03	Trf 25-37	Trf 25-37	Gen 02	Gen 02
	Trf 02-30	Gen 08	Gen 08	Lne 06-11	Lne 06-11
	Gen 10	Lne 17-27	Lne 17-27	Trf 11-12	Trf 11-12
	Lne 02-25	Lne 26-27	Lne 26-27	Trf 13-12	Trf 13-12
	Trf 25-37	Lne 16-19	Lne 16-19	Lne 10-11	Lne 10-11
	Gen 08	Trf 19-20	Trf 19-20	Trf 10-32	Trf 10-32
	Lne 17-27	Trf 19-33	Trf 19-33	Gen 03	Gen 03
	Lne 26-27	Gen 04	Gen 04	Lne 06-07	Lne 06-07
	Lne 16-19	Trf 20-34	Trf 20-34	Lne 07-08	Lne 07-08
	Trf 19-20	Gen 05	Gen 05	Lne 13-14	Lne 13-14
	Trf 19-33	Lne 08-09	Lne 08-09	Lne 08-09	Lne 08-09
Gen 04	Lne 09-39	Lne 09-39	Lne 09-39	Lne 09-39	
Trf 20-34	Gen 01	Gen 01	Gen 01	Gen 01	
Gen 05	Lne 01-39	Lne 01-39	Lne 01-39	Lne 01-39	
Lne 26-28	Lne 26-28	Lne 26-28	Lne 26-28	Lne 26-28	
Lne 28-29	Lne 28-29	Lne 28-29	Lne 28-29	Lne 28-29	
Trf 29-38	Trf 29-38	Trf 29-38	Trf 29-38	Trf 29-38	
Gen 09	Gen 09	Gen 09	Gen 09	Gen 09	

Restore Remaining Lines	Lne 10-13	Lne 10-13	Lne 10-13	Lne 10-13	Lne 10-13
	Lne 5-8	Lne 5-8	Lne 5-8	Lne 5-8	Lne 5-8
	Lne 4-14	Lne 4-14	Lne 4-14	Lne 4-14	Lne 4-14
	Lne 14-15	Lne 14-15	Lne 14-15	Lne 14-15	Lne 14-15
	Lne 25-26	Lne 25-26	Lne 25-26	Lne 25-26	Lne 25-26
	Lne 23-24	Lne 23-24	Lne 23-24	Lne 23-24	Lne 23-24
	Lne1-2	Lne 1-2	Lne 1-2	Lne 1-2	Lne 1-2
	Lne 26-29	Lne 26-29	Lne 26-29	Lne 26-29	Lne 26-29

Table 4.1. Sequence of restoration with different black start units from Gen 1 to Gen 5

BSU	Gen6	Gen7	Gen8	Gen9	Gen10
Restore Substation	Trf 22-35	Trf 23-26	Trf 25-37	Trf 29-38	Trf 10-30
	Lne 22-23	Lne 22-23	Lne 2-25	Lne 28-29	Lne 2-25
	Trf 23-36	Trf 22-35	Trf 2-30	Lne 26-28	Trf 25-37
	Gen 7	Gen 6	Gen 10	Lne 26-27	Gen 8
	Lne 21-22	Lne 21-22	Lne 2-3	Lne 17-27	Lne 2-3
	Lne 16-21	Lne 16-21	Lne 3-18	Lne 17-18	Lne 3-18
	Lne 16-24	Lne 16-24	Lne 17-18	Lne 16-17	Lne 17-18
	Lne 16-17	Lne 16-17	Lne 16-17	Lne 16-24	Lne 16-17
	Lne 17-18	Lne 17-18	Lne 16-24	Lne 15-16	Lne 16-24
	Lne 15-16	Lne 15-16	Lne 15-16	Lne 3-18	Lne 15-16
	Lne 3-18	Lne 3-18	Lne 16-21	Lne 16-21	Lne 16-21
	Lne 2-3	Lne 2-3	Lne 21-22	Lne 21-22	Lne 21-22
	Trf 2-30	Trf 2-30	Trf 22-35	Trf 22-35	Trf 22-35
	Gen 10	Gen 10	Gen 6	Gen 6	Gen 6
	Lne 2-25	Lne 2-25	Lne 22-23	Lne 22-23	Lne 22-23
	Trf 25-37	Trf 25-37	Trf 23-36	Trf 23-36	Trf 23-36
	Gen 8	Gen 8	Gen 7	Gen 7	Gen 7
	Lne 17-27	Lne 17-27	Lne 17-27	Lne 2-3	Lne 12-27
	Lne 26-27	Lne 26-27	Lne 26-27	Trf 2-30	Lne 26-27
	Lne 16-19	Lne 16-19	Lne 16-19	Gen 10	Lne 16-19
	Trf 19-20	Trf 19-20	Trf 19-20	Lne 2-25	Trf 19-20
	Trf 19-33	Trf 19-33	Trf 19-33	Trf 25-37	Trf 19-33
	Gen 4	Gen 4	Gen 4	Gen 8	Gen 4
	Trf 20-34	Trf 20-34	Trf 20-34	Lne 16-19	Trf 20-34
	Gen 5	Gen 5	Gen 5	Trf 19-20	Gen 5
	Lne 3-4	Lne 3-4	Lne 3-4	Trf 19-33	Lne 3-4
	Lne 4-5	Lne 4-5	Lne 4-5	Gen 4	Lne 4-5
	Lne 5-6	Lne 5-6	Lne 5-6	Trf 20-34	Lne 5-6
	Trf 6-31	Trf 6-31	Trf 6-31	Gen 5	Trf 6-31
	Gen 2	Gen 2	Gen 2	Lne 3-4	Gen 2
	Lne 6-11	Lne 6-11	Lne 6-11	Lne 4-5	Lne 6-11
	Trf 11-12	Trf 11-12	Trf 11-12	Lne 5-6	Trf 11-12
Trf 13-12	Trf 13-12	Trf 13-12	Trf 6-31	Trf 13-12	
Lne 10-11	Lne 10-11	Lne 10-11	Gen 2	Lne 10-11	

BSU	Gen6	Gen7	Gen8	Gen9	Gen10
Restore Substation	Trf 10-32	Trf 10-32	Trf 10-32	Lne 6-11	Trf 10-32
	Gen3	Gen3	Gen3	Trf 11-12	Gen3
	Lne 6-7	Lne 6-7	Lne 6-7	Trf 13-12	Lne 6-7
	Lne 7-8	Lne 7-8	Lne 7-8	Lne 10-11	Lne 7-8
	Lne 13-14	Lne 13-14	Lne 13-14	Trf 10-32	Lne 13-14
	Lne 8-9	Lne 8-9	Lne 8-9	Gen3	Lne 8-9
	Lne 9-39	Lne 9-39	Lne 9-39	Lne 6-7	Lne 9-39
	Lne 1-39	Lne 1-39	Lne 1-39	Lne 7-8	Lne 1-39
	Lne 26-28	Lne 26-28	Lne 26-28	Lne 13-14	Lne 26-38
	Lne 28-29	Lne 28-29	Lne 28-29	Lne 8-9	Lne 28-29
	Trf 29-38	Trf 29-38	Trf 29-38	Lne 9-39	Trf 29-38
	Gen9	Gen9	Gen9	Lne 1-39	Gen9
Restore Remaining Lines	Lne 10-13	Lne 10-13	Lne 10-13	Lne 10-13	Lne 10-13
	Lne 5-8	Lne 5-8	Lne 5-8	Lne 5-8	Lne 5-8
	Lne 4-14	Lne 4-14	Lne 4-14	Lne 4-14	Lne 4-14
	Lne 14-15	Lne 14-15	Lne 14-15	Lne 14-15	Lne 14-15
	Lne 25-26	Lne 25-26	Lne 25-26	Lne 25-26	Lne 25-26
	Lne 23-24	Lne 23-24	Lne 23-24	Lne 23-24	Lne 23-24
	Lne 1-2	Lne 1-2	Lne 1-2	Lne 1-2	Lne 1-2
	Lne 26-29	Lne 26-29	Lne 26-29	Lne 26-29	Lne 26-29

Table 4.2. Black start sequence from generator 6 to generator 10

Tables 4.1 and 4.2 show the planned sequence of power system restoration from different black-start units. Restoring all substations has the highest priority in the restoration process. After this process is complete the remaining lines are energized in the sequence according to the shortest distance. The black start process in this thesis will further be considered as from the generator 4 as the only available black start unit available in the system, the reason for choosing generator 4 to be further examined is that it is a black start unit in the original network for new England system. The step by step energisation paths from G4 as shown in Table 4.1 column 6 is explained.

4.3.1 Step by step black start sequence starting from generator 4

After the energising sequence are searched out as seen in Table 4.1, it is noticed that there are 10 phases to be performed in order to recover the system in Figure 4.5.

Step I: Restoring sub-station Gen 5

The generator with black start capability is considered to be G4 located at bus 33, therefore it is considered as the source generator, meaning the black start process start at this bus. As it is shown in Figure 4.6, the path searching algorithm detects the sub-station at generator 5 to be located at shortest electric distance, hence this sub-station is restored.

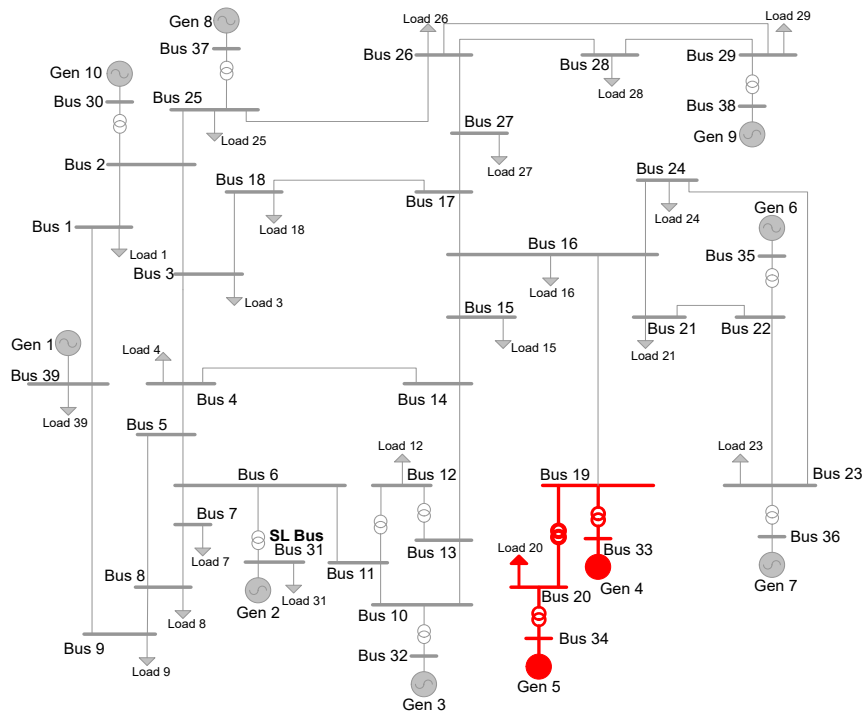


Figure 4.6. The first phase for black start, starting at generator 4

From Figure 4.6 it can be seen that the BSU (Gen 4) sends cranking power to NBSU (Gen 5), this is done by energising transformers at bus 33-19, 19-20 and 20-34 respectively, as shown by the red colour. It can also be noticed that by restoring sub-station *Gen 5*, the load 20 is picked up.

Step 2: Restoring sub-station Gen 6

After the sub-station has been restored, the path searching algorithm detects substation Gen 6 as the shortest electric distance and it restored, the cranking power is sent from the already energised bus 19 as shown by the green colour in Figure 4.7. According to the rule of energisation in Figure 4.2 of energising a single generating source and by obeying the power generation balance rule, the path from *Gen 6* to load 3 can be safely restored.

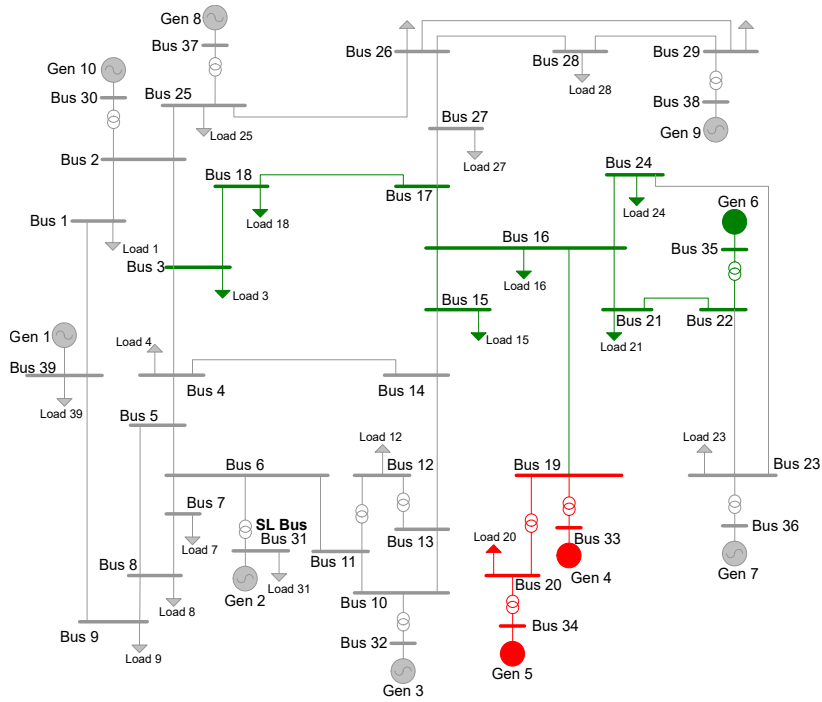


Figure 4.7. The second phase for black start, starting at generator 4

Figure 4.7 shows the restoration of sub-station *Gen6*, the cranking power is transferred from the already energised bus 19 through lines 16-19, 16-24, 16-17, 17-18, 3-18, 16-21, 21-22 and the energization of transformer 22-35. It can be noticed that by energising these lines the loads 21, 16, 15, 18, 3, 21, and 24 are picked up.

Step 3: Restoring sub-station Gen 7

In this phase the sub-station *Gen 7* is restored from the already energised bus 22, by cranking power to this generator it can be seen that the load 23 is also picked up. The process is shown by the orange color in Figure 4.8.

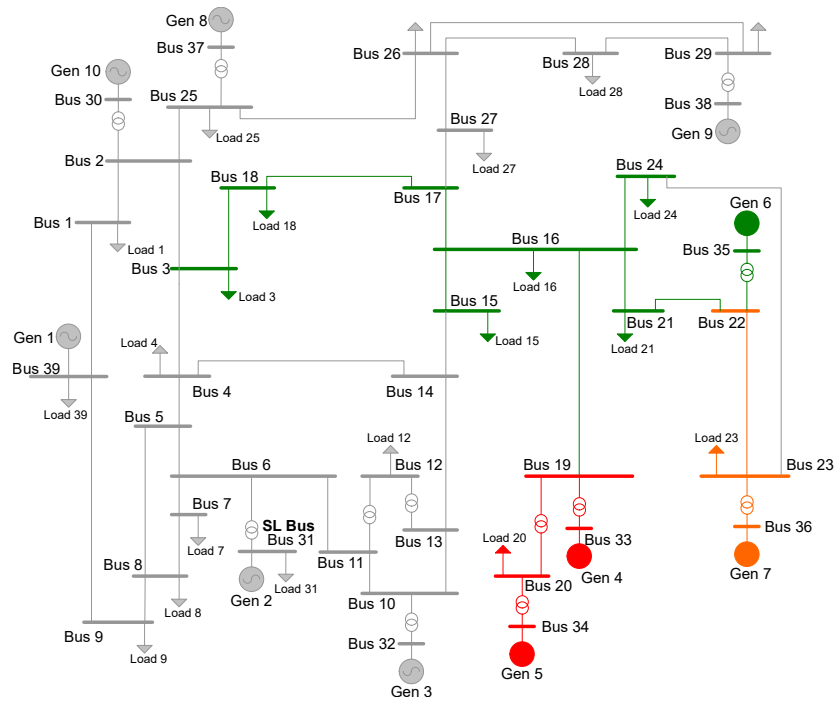


Figure 4.8. The third phase for black start, starting at generator 4

Step 4: Restoring sub-station Gen 10

The fourth phase in the black start of the 39 bus new England system is shown in Figure 4.9 with the magenta color.

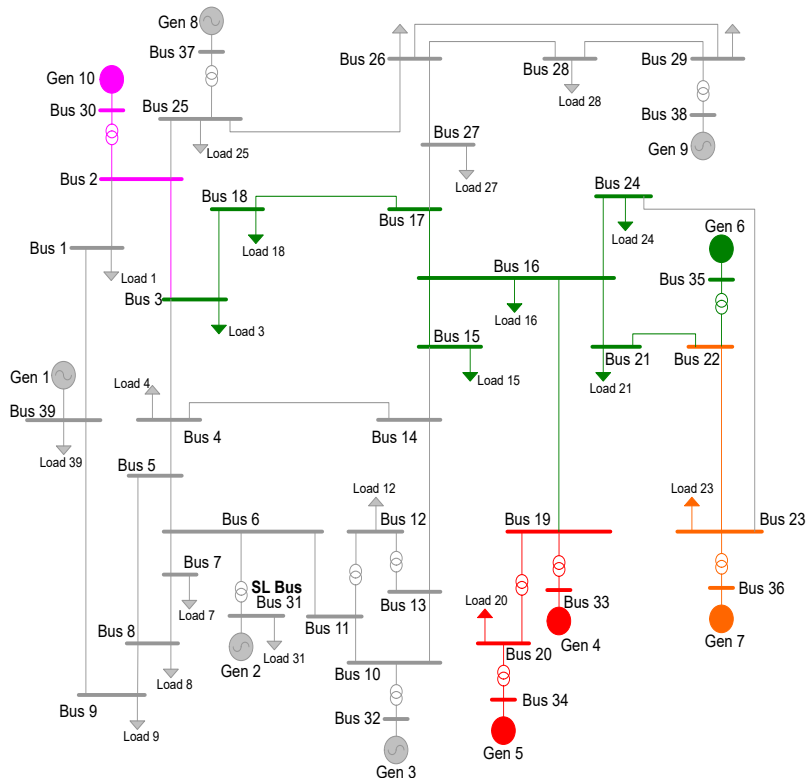


Figure 4.9. The fourth phase for black start, starting at generator 4

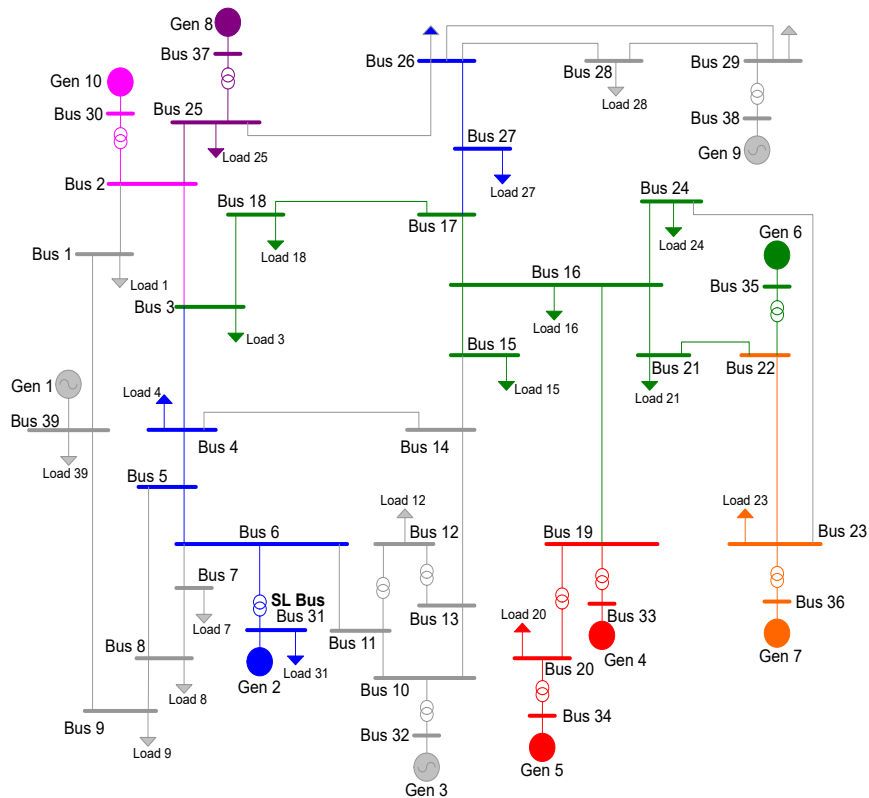


Figure 4.11. The sixth phase for black start, starting at generator 4

Figure 4.11 shows the six phase when Gen 2 is restored via the already energised bus 3, it can be noticed that by sending the cranking power to the substation the loads 4, and 31 are picked up in the process. The load pick up is a priority, hence the system decides that the line 17-27 and 27-26 can be safely energised from the already energised bus 17, by energising these lines the loads 26 and 27 are picked up.

Step 7: Restoring sub-station Gen 3

The restoration of sub-station Gen 3 is shown in the yellow color in Figure 4.12. The cranking power is sent from the already energised bus 6, by following the energisation priority in Figure 4.3 the load 12 can be picked up.

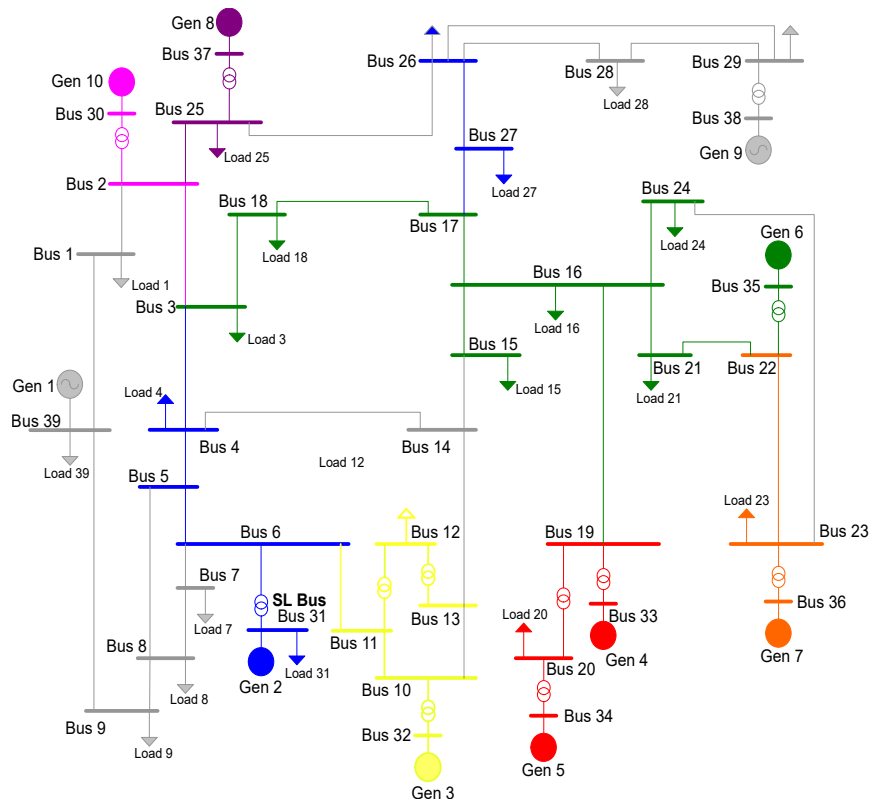


Figure 4.12. The seventh phase for black start, starting at generator 4

Figure 4.12 sequence of sending the cranking power to Gen 3. The phase is accomplished by energising transformer 11-12, 12-13 and 10-32 as well as the energisation of line 11-10.

Step 8: Restoring sub-station Gen 1

This phase restores the sub-station Gen 1 as shown by the color light blue in Figure 4.13, the cranking power to this generator is sent from the already energised bus 6.

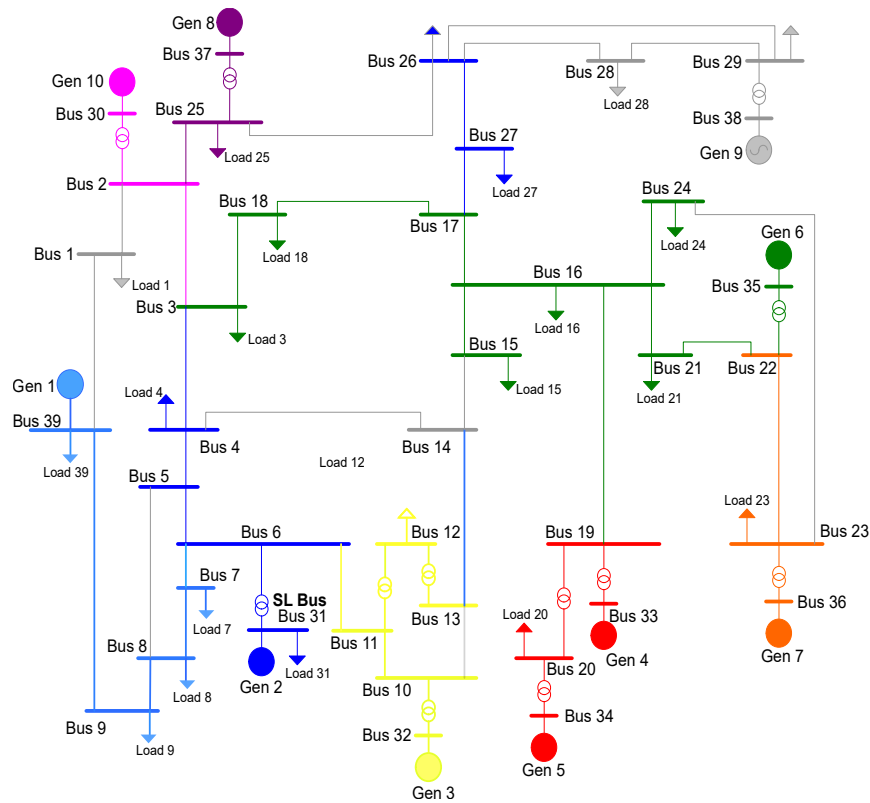


Figure 4.13. The eighth phase for black start, starting at generator 4

Figure 4.13 shows the sequence of cranking power to Gen 1, this is done by energising the lines 6-6, 7-8, 8-9 and line 9.39. It is noticed that by sending the cranking power to this sub-station the loads 7, 8, 9, and 39 are picked up.

Step 9: Restoring sub-station Gen 9

The only sub-station still de-energised is the Gen 9. The cranking power to this generating unit is sent from bus 26 which is already energised. The energisation sequence is shown by the eggplant color in Figure 4.14.

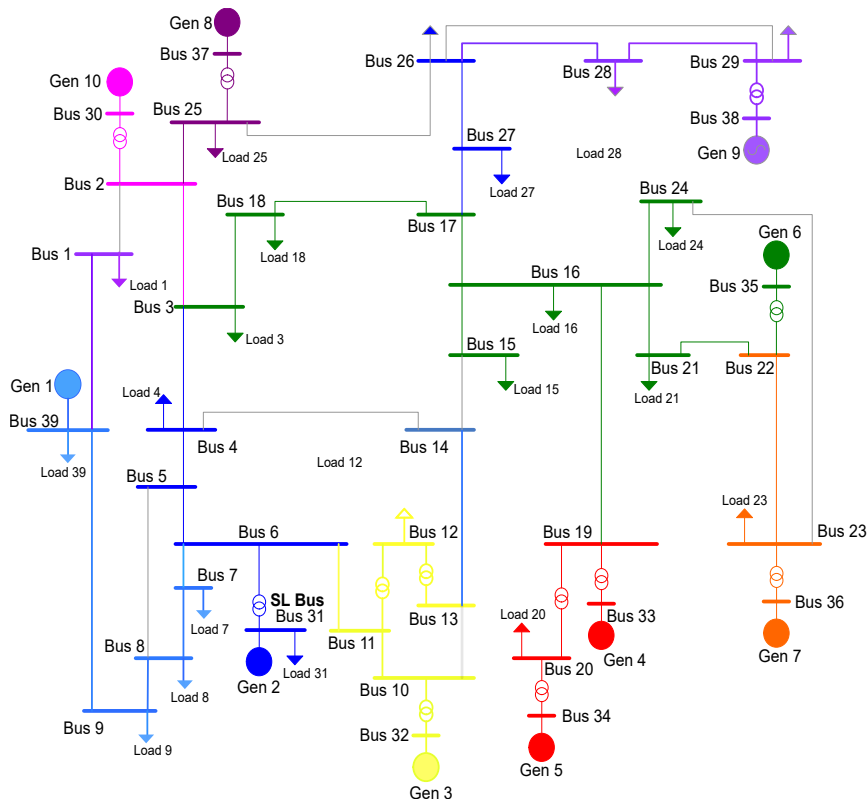


Figure 4.14. The ninth phase for black start, starting at generator 4

Figure 4.14 shows the energisation sequence of Gen 9, this is done by energising lines 26-28, 28-29 and the energisation of transformer 29-38. It can be noted that by energising these lines the loads 28 and 29 are picked up in the process. It is also shown that line 39-1 can be energised together with the Gen 9 substation, by doing so, the load 1 is picked up. This completes the recovery of all the sub-stations in the system as well as the restoration of all loads. It is noted that some lines are still de-energised, these are done in the next and final phase to complete the full restoration for the 39 bus new England.

Step 10: Restoring the remaining de-energised lines

The phase 9 completed the restoration of all sub-stations after the energisation of lines interconnecting the busses, however it is noticed that there are lines that are still not restored as approved by the path searching algorithm that searches all lines that are not energised and restore them following the order of shortest electric distance. The remaining lines highlighted in black colour as can be seen in Figure 4.15.

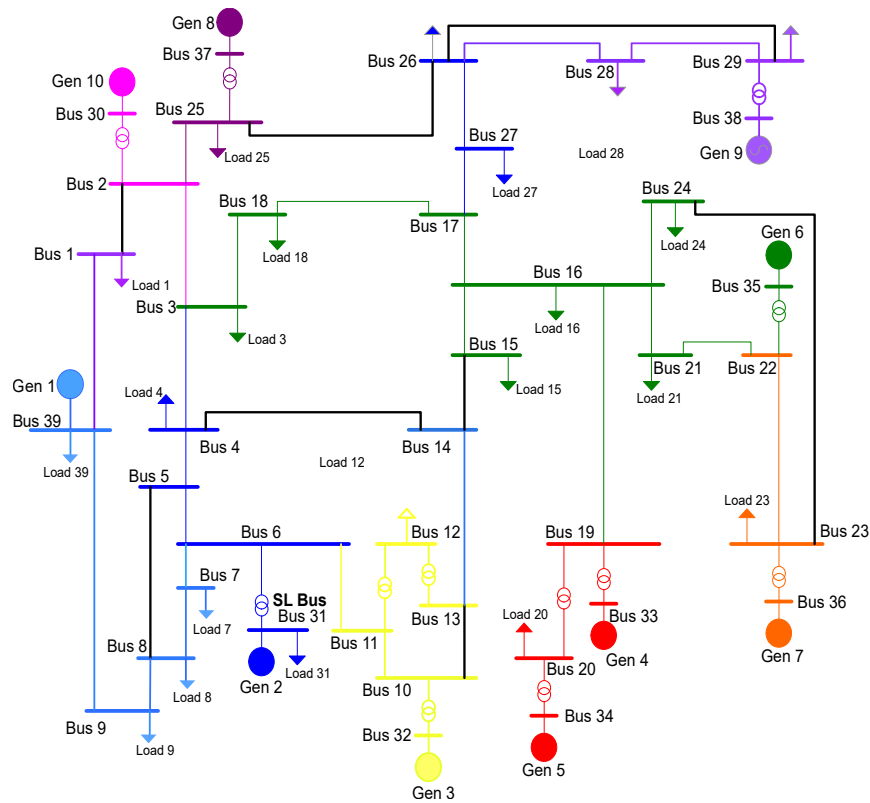


Figure 4.15. The tenth phase for black start, starting at generator 4

The lines that were remaining to be restored are lines 10-13, 5-8, 4-14, 14-15, 25-26, 23-24, 1-2 and 26-29. These lines are restored according to the size of their electric distance. However, the lines can also be restored at the same time to reduce the restoration duration.

This chapter has developed a flexible simulation platform for black start. It has shown that the 39 bus new England system can be successfully restored by placing a generation with black start capability at any sub-station in the system. The detour process is performed in order to increase the reliability of the path searching algorithm in terms of system security which include the system voltage and frequency.

Simulation Result 5

This chapter presents the simulation results for the restoration strategy as developed in the previous chapter, namely the result for the energisation sequence, the result when the detour is considered and the results when the tap changer effect is taken into consideration.

5.1 Result for the flexible simulation platform for black start

The total length of simulation is 2800sec, where three cases are defined:

- **Case A:** The power system restoration following the original sequence, where the shortest paths are considered as shown in Tables 4.1 and 4.2 respectively.
- **Case B:** In this case the power system restoration is performed with the detoured sequence.
- **Case C:** In this case the restoration sequence is the same as in case A with except that automatic on load tap changer (OLTC) is implemented to be activated to regulate the voltage during the black start process, meaning that the transformer tap-changers will be tuned upward or downward if the voltage is out of range of $0.97 - 1.01p.u$ for more than 5 sec.

5.1.1 Case A: Sequence energisation

This section presents the result for energisation sequence for black start from Gen 4 as in case A. It must be noted that the results shown for system frequency are for busses 1-20 in the system 4.5, because it is where the frequency $\pm 3\%$ of rated value is violated, and the bus voltage result shown are for busses 21-39 as the allowed voltage $\pm 20\%$ of rated value limits is violated. The frequency response at bus-bar 1-20 is shown in Figure 5.1.

5.1.

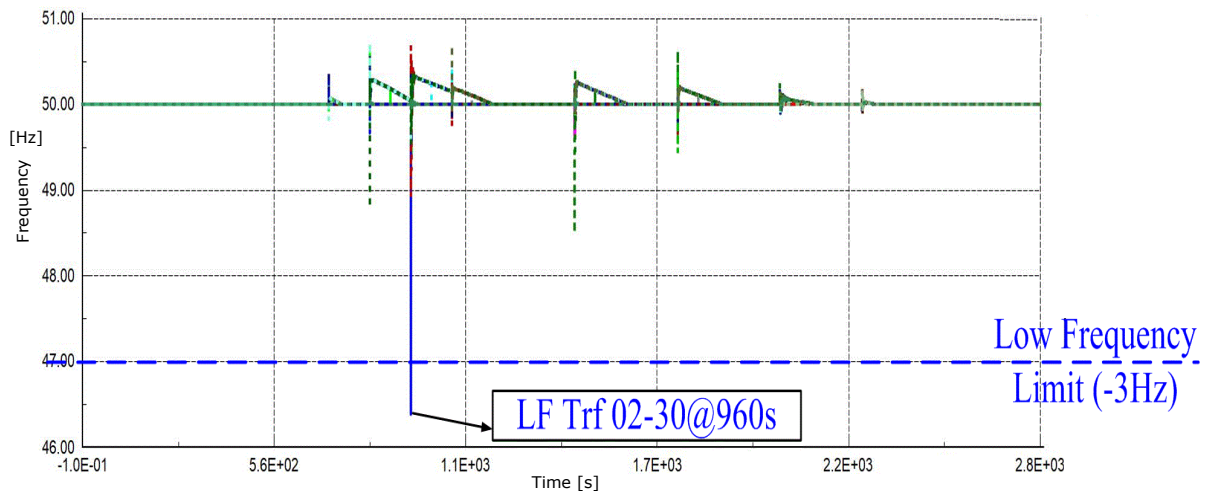


Figure 5.1. T-D simulation frequency response for black start process from Gen 04

From the result in Figure 5.3 it is noted that the frequency regulation is violated as shown by the blue color that the frequency at bus 3 is below the -3% of the 50 Hz nominal value. The frequency violation happens after 960 seconds when energising the sub-station Gen 10, meaning restoring the path in step 4 in Chapter 3 Figure 4.9. The bus voltage response resulting after the black start is shown in Figure 5.2.

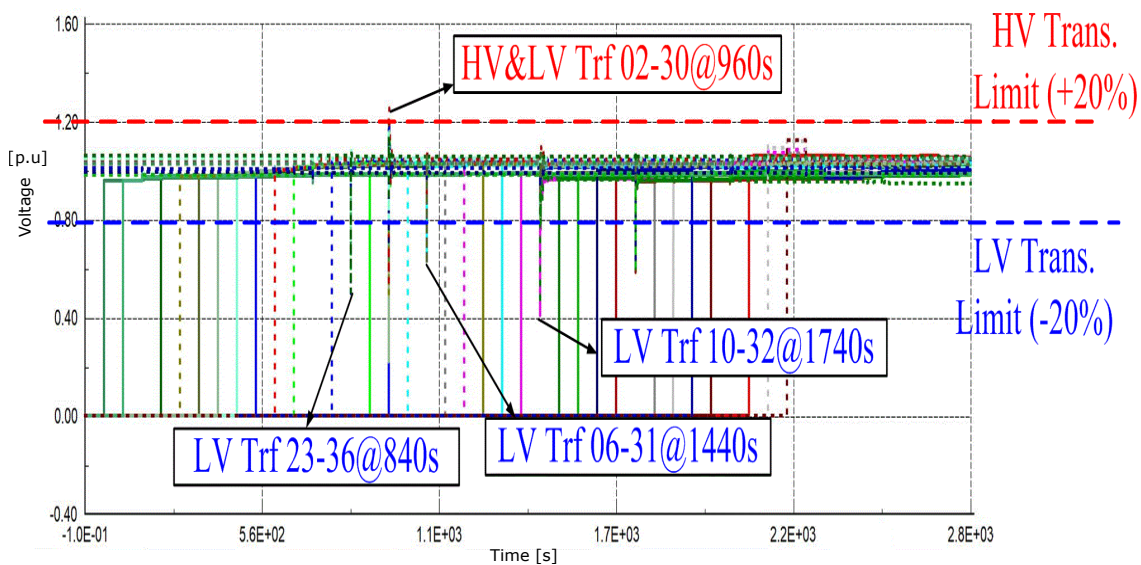


Figure 5.2. T-D simulation voltage response for black start process from Gen 04

Figure 5.2 shows voltage response at bus 21-39. It can be seen that the restoration of some result in the voltage violating the allowable $\pm 20\%$ of rated value limit. The restoration of sub-stations that violated the voltage limit are tagged in the Figure 5.2 as follow: 1) it is noted that the restoration of sub-station Gen 7 as shown in step 3 in Chapter 3 Figure 4.8 resulted in under voltage, this happens after 840 seconds at bus 33 and bus 36. 2) It is also noticed that the restoration sub-station Gen 10, meaning restoring the

path in step 4 in Chapter 3 Figure 4.9 resulted in both over-voltage and under voltage, the violation happens after 960 seconds at busses 24 and 30. 3) The restoration of sub-station Gen 3 as shown in step 7 in Chapter 3 Figure 4.12 resulted in under voltage as tagged in Figure 5.2, the minimum voltage violation happens after 1740 seconds at bus 32.

5.1.2 Case B: Black start with detour

This case presents the result for the black start process from Gen 4 as in case A, but with the detour, meaning the detour process is programmed to act if the voltage limitation is violated as explained in Chapter 3 section 4.4. The frequency response in this case is shown in Figure 5.3.

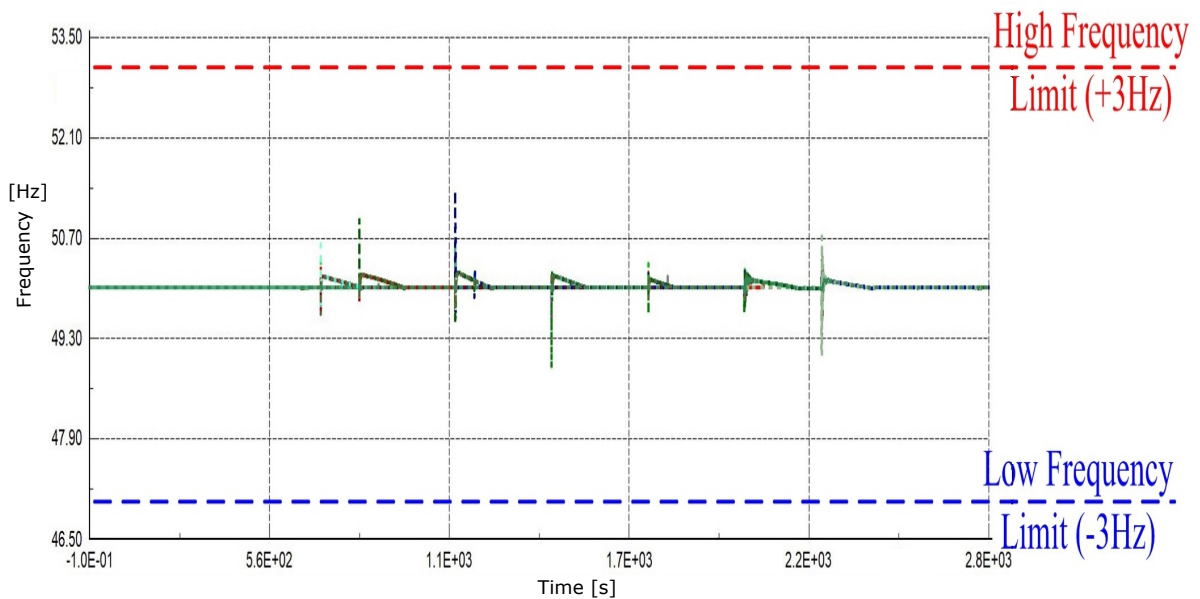


Figure 5.3. T-D simulation frequency response for black start process from Gen 04 with detour

Figure 5.3 shows the frequency response for black start from Gen 4 when the detour algorithm is applied, meaning that there will be a detour if the voltage limits are violated. It is noticed that for the detour the system frequency is maintained in the allowable frequency range of $\pm 3\%$ of rated value for all the system recovery process. The voltage response for the detour is shown in Figure 5.4.

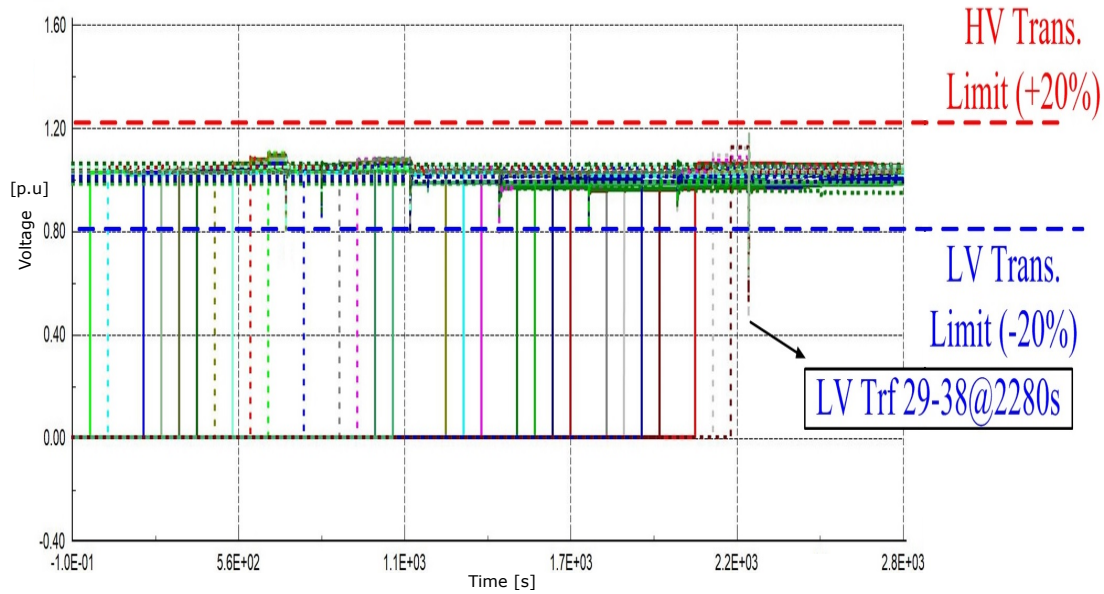


Figure 5.4. T-D simulation voltage response for black start process from Gen 04 with detour

From the voltage response it can be noticed that the energisation sequence is detoured at time 840 seconds this is the first time in case A, when the black start process resulted in voltage violation when the cranking power was sent to sub-station Gen 7. The effect of detour can be noted as after the detour at 840 seconds there is no voltage violation taking place until the restoration of the last sub-station Gen 9, after 2280 seconds which resulted in under voltage as tagged in the figure, because this is the last sub-station to be restored the detour does not take place.

5.1.3 Case C: Black start with tap changer control

This section presents that simulation result for the black start process as in case A with the OLTC controller implemented to regulate the voltage. The frequency response is shown in Figure 5.5.

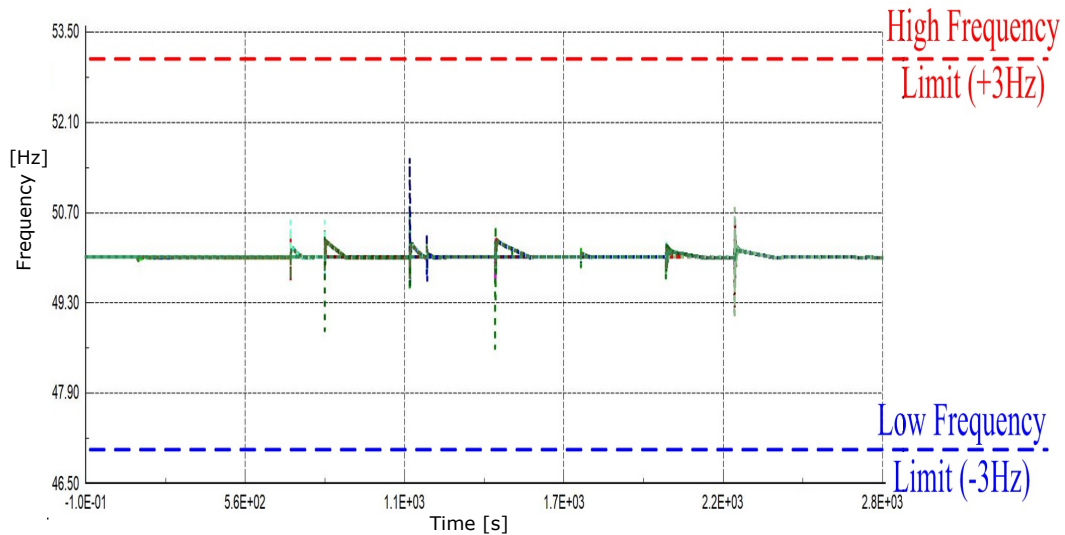


Figure 5.5. T-D simulation frequency response for black start process from Gen 04 with OLTC control

From Figure 5.5 it is noticed that the system frequency is maintained within the allowable range $\pm 3\%$ of rated value is violated. Hence the effect of OLTC is noticed compared to case A, where the frequency regulations was violated. The voltage response due to OLTC is shown in Figure 5.6.

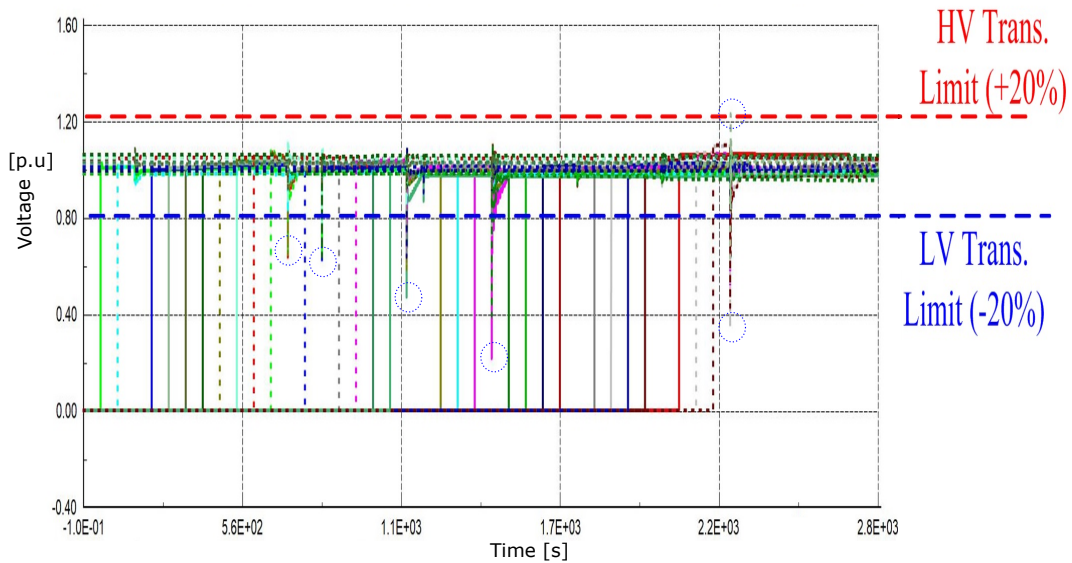


Figure 5.6. T-D simulation voltage response for black start process from Gen 04 with OLTC control

Figure 5.6 shows voltage response at busses when the OLTC controller is considered in regulating the system voltage. As mentioned the tap controller will be activated when the voltage decreases to below 0.97 p.u and when it increases to 1.01 p.u for more than 5 seconds. It is noticed from the result that more transients under-voltages are induced as indicated by the blue circles, meaning that the restoration of more sub-stations resulted in voltage violation. It can also be noticed that the restoration of the last sub-station Gen 9 resulted in both under and over-voltage. The tuning of transformer OLTC may exhaust

the reactive power, which will contribute to the increase in system voltage.

5.2 Results for the parallel restoration

This section presents the simulation results for the parallel restoration, meaning the restoration where the island is divided in three islands and the critical loads are first priority for restoration, as developed in Chapter 4 in table 3.14. The frequency and voltage response for all the three islands are presented on the same graph. The first island is restored first, then the second and the third, the five cut set lines are restored last, the sequence to restore these lines is by their shortest electric distance, meaning the line with the shortest electric distance is restored first.

Frequency response

After the sequence paths for the three sub-islands are simulated, the frequency response during the black start start for each sub-island is checked, the frequency result at each bus in the system is shown in Figure 5.7.

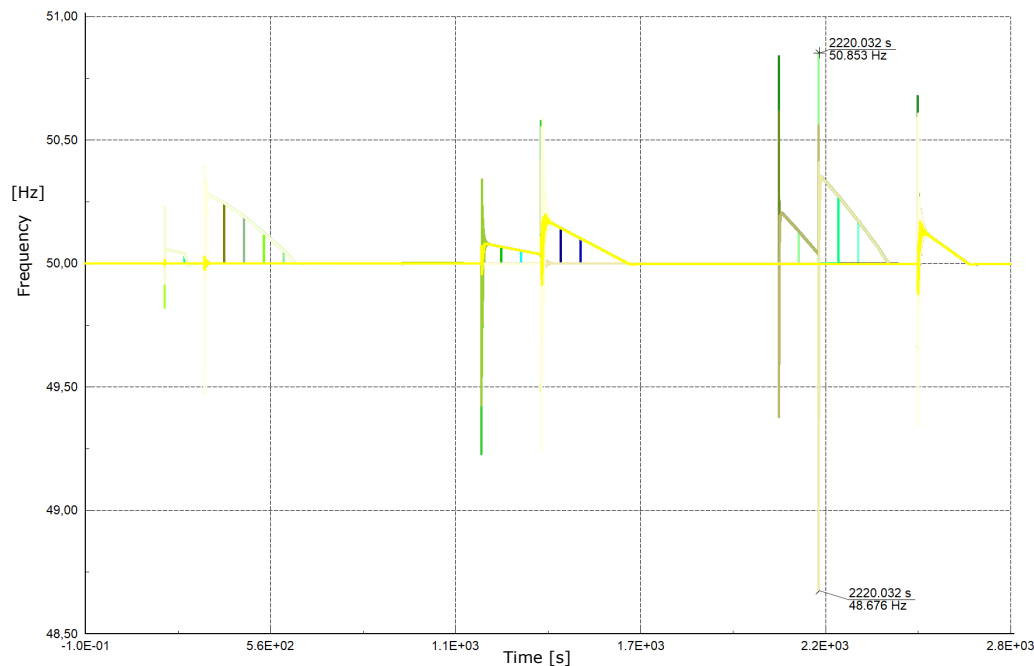


Figure 5.7. T-D simulation frequency response for parallel restoration

As it can be seen from the graph system frequency is maintained within the allowed limits. The lowest frequency is 48.676 Hz which happens at 2220.032 seconds at bus 36, meaning that it was during the restoration of Gen 7 in the sub-island 3. The fall in frequency is due to the imbalance between generation and consumption. The highest frequency is 50.853 Hz taking place at 2220.032 seconds, this is at bus 33 in island 3. It can be noted that the allowed frequency range of [47-53] Hz is maintained.

Voltage response

The voltage response for each sub-island is shown in Figure 5.8.

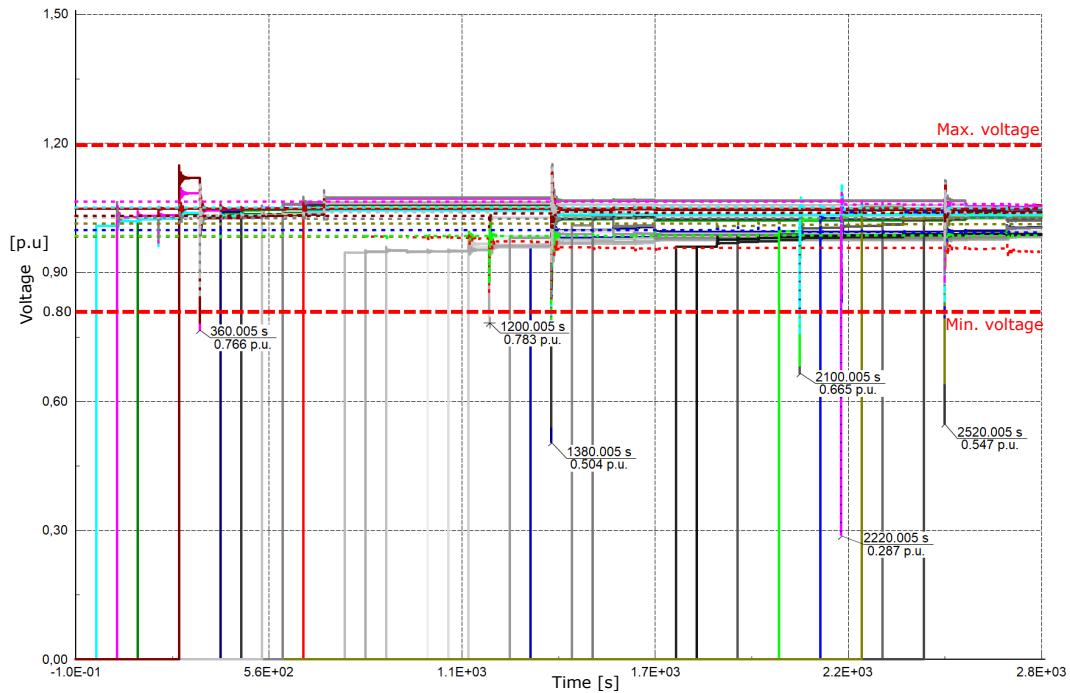


Figure 5.8. T-D simulation voltage response for parallel restoration

Figure 5.8 shows the voltage at each bus in the system for each island. It can be noticed the allowed voltage limitation is violated as five busses has under-voltage during the restoration. The voltage violation happens in the sub-islands, though the island three contains more busses where the voltage limit is violated.

This chapter has presented the simulation result for the scenarios in chapter 3 (Parallel restoration) and in chapter 4 (A flexible simulation platform for PSR). The result shown are the frequency response and the voltage. The parallel restoration is performed successful, but it is noticed that the frequency is maintained within the allowed limits for all sub-islands. However, for the voltage response case the allowed voltage limit is violated. For the case of restoration using the method described in chapter 4, it was shown that the original sequence energisation resulted in under and over-voltage as well as the violation of system frequency. The process of bringing the voltage within the allowed limits, the voltage mitigation is performed, this is achieved by the detour process. The result showed that the voltage at each bus are within the allowed limit, only the energisation of Gen 9 which was energised last resulted in under-voltage. The effect of transformer tap changers to mitigate the voltage seemed to be not the right solution as more over-voltage and under-voltage happened during the black start. Therefore, it can be concluded that the detour process is the right option when utilising the flexible simulation scheme for PSR.

Conclusion 6

This thesis has dealt with power system restoration, meaning finding the energisation paths for restoration of electrical loads and generation. Two way for restoration were tested, the first was the parallel restoration, where the islands was divided into three sub-islands, which can be restored in parallel. The graph theory was utilised for this restoration strategy which focuses on restoring the critical loads before non-critical loads. The sequence energisation paths for each island were restored by focusing on the islands being restored within approximately same time. After the energisation paths have been successfully made, it is shown that the islands 1, 2 and 3 have restoration time of 170 min, 170 min and 175 min respectively. By looking at the system frequency and voltage response at each bus in the sub-island, it is noticed that the frequency is maintained withing the allowed limits for all sub-islands. However, for the voltage response case the allowed voltage limit is violated, this happens in all sub-islands. The sub-island 1 had one bus with under-voltage, the island 2 had one and the island 3 had three busses with under-voltage. A FACTS device can be utilised during the parallel restoration, it an be installed the busses where the voltage is violated, in this case reactive power can be injected to rise the system voltage.

For the case of restoration using the method described in chapter 4 (A flexible simulation platform for PSR), it was shown that the original sequence energisation paths as tagged case A, resulted in under and over-voltage as well as the violation of system frequency. The process of bringing the voltage within the allowed limits, the voltage mitigation is performed, this is achieved by the detour process. The result showed that the voltage at each bus are within the allowed limit, only the energisation of Gen 9 which was energised last resulted in under-voltage. The effect of transformer tap changers to mitigate the voltage seemed to be not the right solution as more over-voltage and under-voltage happened during the black start. Therefore, it can be concluded that the detour process is the right option when utilising the flexible simulation scheme for PSR. The flexible simulation platform for PSR can be utilised in the industry to help reduce the restoration process. This because, after the disturbance has been occurred, the restoration platform can find the energisation paths quickly, where the faulty line can be isolated by the detour proess.

Future Work 7

Based on the work done in this thesis the recommendation to further the topic of hybrid simulation platform are listed below:

- **Include an SVC in the study** The parallel synchronous Var compensate is used for reactive power compensation. Hence, it would be interesting to install one at the busses where the system voltage is violated such as in the parallel restoration.
- **Use different restoration strategies:** The build up restoration strategy was investigated in two main cases, one for sub-islands creation and the other one in the developed restoration platform where the system is considered as having only one black start unit available. Using another strategy, such as the VSC-HVDC which can restore the island without the need for dividing the network, would be of interest.
- **Experiment:** Only simulation was performed in this thesis, it would be interesting to experiment the hybrid strategy on a real network.

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DPL Scripts for the Flexible simulation platform for PSR



This chapter present the scripts developed to perform the finding of energisation paths for black start.

A.1 Scripts for black start

```
!! To get the Active Stage, otherwise error and quit.
sStage = GetActiveStages();
oStage = sStage.First();
if (oStage = NULL) { ! there is no active project
    Error('There is no stage activated, no recording, exit!'); exit(1);
}

!! To clear the Recorded Stage, so as to start from the begining
while(oStage) {
    printf('The activated variation is : %o', oVariationRecord);
    printf('The activated stage is : %o', oStage);
    sContent = oStage.GetContents();
    oContent = sContent.First();
    while (oContent) {
        !oContent.ShowFullName();
        oContent = sContent.Next();
    }
    oVariationRecord.Deactivate();
    Delete(sContent);
    printf('The stage %o is cleared!', oStage);
    oVariationRecord.Activate();
    oStage = sStage.Next();
}
```

```

!!Run a power flow calculation first
pComLdf.Execute();

!!!! TO OBTAIN A BLACK-START PROCESS
sElmTerm = TermFilter.Get(); ! Get all terminals
sElmLne = LneFilter.Get(); ! Get all lines
sElmTermFrom.Add(oBlackStartBus); !the first bus is BS Unit
sElmTermTo = sElmTerm;
sElmTermTo.Remove(oBlackStartBus); ! Remove BS unit from the TO-list
sElmLneDeenergized = sElmLne;

oElmTermTo = sElmTermTo.First(); ! Get the first Term from the TO-list
while(oElmTermTo){ !If the sElmTermTo is not empty
    fDistShortest = 40000;!Initialized with a large distance in km
    oElmTermFrom = sElmTermFrom.First();! OUTER LOOP for FROM-list
    while(oElmTermFrom){
        if(iFlagViolation = 1)    sElmTermTo.Remove(oBranchRemove);

        oElmTermTo = sElmTermTo.First(); ! INNER LOOP for To-list
        while(oElmTermTo){
            oElmTermTo.ShowFullName();
            fDistance = oElmTermFrom.GetMinDistance(oElmTermTo, 0, sPath);
            !printf('Shortest distance: %f - between %o and %o', fDistance, oElmTer
            if(fDistance < fDistShortest) {
                fDistShortest = fDistance;
                sPathShortest = sPath;
                oElmTermNext = oElmTermTo; !Determine next terminal with shortest d
            }
            oElmTermTo = sElmTermTo.Next(); !End of INNER LOOP
        }
        oElmTermFrom = sElmTermFrom.Next(); ! End of OUTER LOOP
    }
}

!!Run a power flow calculation first
pComLdf.Execute();

!!!! TO OBTAIN A BLACK-START PROCESS
sElmTerm = TermFilter.Get(); ! Get all terminals
sElmLne = LneFilter.Get(); ! Get all lines
sElmTermFrom.Add(oBlackStartBus); !the first bus is BS Unit
sElmTermTo = sElmTerm;
sElmTermTo.Remove(oBlackStartBus); ! Remove BS unit from the TO-list
sElmLneDeenergized = sElmLne;

oElmTermTo = sElmTermTo.First(); ! Get the first Term from the TO-list
while(oElmTermTo){ !If the sElmTermTo is not empty
    fDistShortest = 40000;!Initialized with a large distance in km
    oElmTermFrom = sElmTermFrom.First();! OUTER LOOP for FROM-list
    while(oElmTermFrom){
        if(iFlagViolation = 1)    sElmTermTo.Remove(oBranchRemove);

        oElmTermTo = sElmTermTo.First(); ! INNER LOOP for To-list
        while(oElmTermTo){
            oElmTermTo.ShowFullName();
            fDistance = oElmTermFrom.GetMinDistance(oElmTermTo, 0, sPath);
            !printf('Shortest distance: %f - between %o and %o', fDistance, oElmTer
            if(fDistance < fDistShortest) {
                fDistShortest = fDistance;
                sPathShortest = sPath;
                oElmTermNext = oElmTermTo; !Determine next terminal with shortest d
            }
            oElmTermTo = sElmTermTo.Next(); !End of INNER LOOP
        }
        oElmTermFrom = sElmTermFrom.Next(); ! End of OUTER LOOP
    }
}

```

```

oPathElm = sPathShortest.First();
while(oPathElm){
    iFlagElmTerm = oPathElm.IsClass('ElmTerm'); !If path element is NOT a termin
    if(iFlagElmTerm = 0){ sEnergizeSeq.Add(oPathElm); sElmLneDeenergized.Remove(
        oPathElm = sPathShortest.Next();
    }

    sElmTermFrom.Add(oElmTermNext); ! Add next Terminal to FROM-list
    sElmTermTo.Remove(oElmTermNext); ! Remove next Terminal to TO-list
    oElmTermTo = sElmTermTo.First(); !Do this for the outer while-loop
}

sElmLneDeenergized.SortToVar(0,'dline'); !If there is still some deenergized lines
oPathElm = sElmLneDeenergized.First();
while(oPathElm){
    sEnergizeSeq.Add(oPathElm);
    !printf('The length of %o is %f.',oPathElm,oPathElm:dline);
    oPathElm.ShowFullName();
    oPathElm = sElmLneDeenergized.Next();
}
printf('Sequence of Restoring Remaining Lines:');! Can be deleted

! Put In Simulation
pComInc:iopt_sim = 'rms'; !Start with RMS simulations
Delete(pComInc:p_event); !Remove all simulation events
pComInc.Execute(); !Create a new simulation events
fSecTime = iTIME_INTERVAL;
oPathElm = sEnergizeSeq.First();
oSwitchEventPSR:mtime = 0;
oSwitchEventPSR:time = 0;
while(oPathElm){
    oPathElm.ShowFullName();
    oSwitchEventPSR:p_target = oPathElm;
    oSwitchEventPSR:time = fSecTime;
    fSecTime = fSecTime + iTIME_INTERVAL;
    sNameSwitchEvent = sprintf('Switch_%s', oPathElm:loc_name);
    pComInc:p_event.AddCopy(oSwitchEventPSR, sNameSwitchEvent);
    oPathElm = sEnergizeSeq.Next();
}

```

Figure A.1. DPL scripts for finding energisation paths

Simulation Model Data

B

B.1 Line parameter

Line data				
From Bus	To Bus	Resistance [p.u]	Reactance [p.u]	Susceptance [p.u]
1	2	0.0035	0.0411	0.6987
1	39	0.0010	0.0250	0.7500
2	3	0.0013	0.0151	0.2572
2	25	0.0070	0.0086	0.1460
3	4	0.0013	0.0213	0.2214
3	18	0.0011	0.0133	0.2138
4	5	0.0008	0.0128	0.1342
4	14	0.0008	0.0129	0.1382
5	6	0.0002	0.0026	0.0434
5	8	0.0008	0.0112	0.1476
6	7	0.0006	0.0092	0.1130
6	11	0.0007	0.0082	0.1389
7	8	0.0004	0.0046	0.0780
8	9	0.0023	0.0363	0.3804
9	39	0.0010	0.0250	1.2000
10	11	0.0004	0.0043	0.0729
10	13	0.0004	0.0043	0.0729
13	14	0.0009	0.0101	0.1723
14	15	0.0018	0.0217	0.3660
15	16	0.0009	0.0094	0.1710
16	17	0.0007	0.0089	0.1342
16	19	0.0016	0.0195	0.3040
16	21	0.0008	0.0135	0.2548
16	24	0.0003	0.0059	0.0680
17	18	0.0007	0.0082	0.1319
17	27	0.0013	0.0173	0.3216
21	22	0.0008	0.0140	0.2565
22	23	0.0006	0.0096	0.1846

Table B.1. Line parameter for the 39 new England system

Line data				
From Bus	To Bus	Resistance [p.u]	Reactance [p.u]	Susceptance [p.u]
23	24	0.0022	0.0350	0.3610
25	26	0.0032	0.0323	0.5130
26	27	0.0014	0.0147	0.2396
26	28	0.0043	0.0474	0.7802
26	29	0.0057	0.0625	1.0290
28	29	0.0014	0.0151	0.2490
12	11	0.0016	0.0435	0.0000
12	13	0.0016	0.0435	0.0000
6	31	0.0000	0.0250	0.0000
10	32	0.0000	0.0200	0.0000
19	33	0.0007	0.0142	0.0000
20	34	0.0009	0.0180	0.0000
22	35	0.0000	0.0143	0.0000
23	36	0.0005	0.0272	0.0000
25	37	0.0006	0.0232	0.0000
2	30	0.0000	0.0181	0.0000
29	38	0.0008	0.0156	0.0000
19	20	0.0007	0.0138	0.0000

Table B.2. Line parameter for the 39 new England system

B.2 Loads size

Bus	Type	Load	
		Active power [MW]	Reactive power [Mvar]
3	PQ	322.0	2.4
4	PQ	500.0	184.0
7	PQ	233.8	84.0
8	PQ	522.0	176.0
12	PQ	7.5	88.0
15	PQ	320.0	153.0
16	PQ	329.0	32.3
18	PQ	158.0	30.0
20	PQ	628.0	103.0
21	PQ	274.0	115.0
23	PQ	247.5	84.6
24	PQ	308.6	-92.0
25	PQ	224.0	47.2
26	PQ	139.0	17.0
27	PQ	281.0	75.5
28	PQ	206.0	27.6
29	PQ	283.5	26.9

Table B.3. Size of load of the 39 bus new England system

B.3 Generation input data

Bus	Type	Voltage [p.u]	Generator		
			Active power [MW]	Reactive power [Mvar]	Unit no.
30	PV	1.0475	250.0	-	Gen 10
31	PV	0.9820	-	-	Gen 2
32	PV	0.9972	650.0	-	Gen 3
33	PV	0.9972	632.0	-	Gen 4
34	PV	1.0123	508.0	-	Gen 5
35	PV	1.0493	650.0	-	Gen 6
36	PV	1.0635	560.0	-	Gen 7
37	PV	1.0278	540.0	-	Gen 8
38	PV	1.0265	830.0	-	Gen 9
39	PV	1.0300	1000.0	-	Gen 1

Table B.4. Input data for generation units

B.4 Parameters of OLTC

The parameters of the transformer on load tap changer utilised in black start process to regulate the system voltage are shown in Table B.5.

Parameter	Value
OLTC delay time [s]	5
Minimum voltage [p.u]	0.97
Maximum voltage [p.u]	1.01
Minimum tap position [p.u]	-10
Maximum tap position [p.u]	10

Table B.5. OLTC controller parameter

From Table B.5 the tap-changers are tuned upward or downward if the voltage is out of the range $0.97 - 1.01 p.u$ for more than 5 sec.

