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Automatic Reactor Hunting Avoidance during Power System Restoration

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ABSTRACT

Modern society is a complex system that combines a lot of variables and one of the most important is electric power supply. Nowadays, our society extremely depends on the secure and consistent electricity supplies, being the main support of current industrial, economical, social and information activity. Furthermore, this dependence is becoming stricter as the society progresses.

However, power systems are very complex systems, which are vulnerable to faults of different nature due to high number of variables. The frequent danger that threats the complete availability of electric power are the large scale blackouts, occurred in case of lightning, natural disasters, operator's errors, technical faults and so on. A large scale blackout has a critic impact on society, since electrical energy is inaccessible in the electric power grid and thus the economy is forced to stop.

As far as Swedish power system is concerned, it is characterized by long high voltage transmission lines connecting North of Sweden, which has the large percentage of the power generation of the country, to central and southern parts of Sweden where the power consumption is concentrated. In consequence, due to this system topology, the risk of voltage collapse at the central or southern parts of the country is an inherent feature of the Swedish system.

The ideal situation for a reliable power supply would be to prevent the system from any blackout. However, blackouts may occur and it is impossible to predict when. Hence, power system restoration must be considered as a critic issue for Transmission System Operators (TSOs). The main objective of TSOs is to perform a power system restoration as fast and safely as possible, in order to minimize the duration of the blackout.

During the restoration after the blackout in Sweden and Denmark on 23 September 2003, a particular problem appeared and increased the restoration time, known as reactor hunting. This project is focused on studying this fault: its causes and its effect, and also ways of avoiding it in order to reduce the restoration process.

In Sweden, the restoration strategy starts with long transmission lines from North to central part, being energized. This leads to high voltage at the end of transmission lines due to the Ferranti effect. In order to reduce the voltage, shunt reactors are connected to the system. Shunt reactors are devices that are used to control the voltage in transmission lines and are controlled by what is called Extreme Voltage Automatics (EVAs).

The EVAs have a tolerance band which defines the behaviour of the shunt reactor. The tolerance band has an upper and lower voltage limits and the objective is to maintain the voltage level within these limits. If the voltage is above the upper limit of the tolerance band, the EVAs connect the device; and on the other hand disconnect it if the voltage level is below the lower limit.

It is important to note that, during restoration, the power system is weak. Thus, connecting the reactors will probably produce critic low voltage (below the lower limit), then the EVAs will turn off the reactor again, returning the voltage to the high level. The reactor will therefore cyclically connect and again disconnect.

This phenomenon is called reactor hunting, which produces large voltage fluctuations between high and low voltages outside the tolerance band. Thus it has a negative effect on the power system and needs to be handled as quickly as possible in order to prevent this fluctuations and possible damages.

The conventional procedure for TSOs to avoid reactor hunting is to deactivate the automatics during restoration time. This leaves the shunts in manual operation, which leads to longer restoration process.

It is almost straightforward to imagine that an automatic method for reactor hunting avoidance will be faster than manual operation and the restoration time will suffer an important decrease, which will be beneficial in blackout restoration.

This project presents a proposal for real time automatic reactor hunting avoidance founded on the “Adaptive tolerance band” concept, which adapts the EVAs behaviour based on the network strength. This new control scheme uses short circuit capacity to predict the voltage drop after shunt reactor connection and then adjusts the lower limit of the tolerance band in order to maintain the voltage within the limits and prevent reactor hunting from happening.

The important thing of this methodology is that it predicts the decrease in voltage after shunt connection. If the prediction is accurate, the lower limit will be adjusted precisely so any other external alteration of the voltage still can be detected by the automatics. If the adjustment is not accurate, an unexpected voltage drop may be ignored. It also needs to set a value for the lower limit that can not be reached to prevent extreme low voltages.

Consequently, the voltage drop prediction allows to detect when the extreme low voltage will be encountered after shunt reactor connection, so it can be decided if carry on with the restoration, take other path or take additional measures to control the voltage.

The core of the project is to implement this technique in a program which is able to perform a restoration process from an initial blackout scenario avoiding reactor hunting in real time with the automatic adaptive tolerance band method. This program allows the user to select any restoration path possible.

Since the adaptive tolerance band is based on the network strength, the program is designed to calculate the Short circuit power from the Thevenin impedance of the specific point of the network for each restoration stage. This Thevenin impedance is calculated from the bus impedance matrix. In consequence, computer methods for network matrices are implemented in this project in order to construct and modify the bus impedance matrix representing the situation of the power system at each moment.

The bus impedance matrix represents the actual strength of every point of the system for any particular time, so it is useful for the purposes of this project and also for other applications, such as short circuit faults, protection device design, etc.

In order to test the viability of the idea presented, this project is done in computer and simulation environments. The NORDIC32 system, which is a simplified model of the Nordic electric power system is used for this project as the test model.

The software used for power system simulation is ARISTO. The real-time program for Reactor Hunting avoidance is developed in MATLAB programming environment and the communication between both is done by AMCX communication tool.

Simulations with two different restoration paths, starting at the same initial southern blackout scenario of the NORDIC32 system, will show the effectiveness of the method proposed in the project for reactor hunting avoidance and will show the reactor hunting phenomenon before and after avoidance.

To sum up, this project, by studying one particular problem during system restoration (reactor hunting), makes a great view of the actual understanding of what an electric power system is, the importance of blackouts and system restoration; and also, some of the computer methods used in power systems such as power system simulators or algorithms for network matrices. This topic is known as Energy Management Systems (EMS) which has an extreme importance for TSOs around the world.

Keywords: Power system restoration - Reactor hunting – Adaptive tolerance band – Real time simulations – Voltage control – Power system modelling – Network matrices – Short circuit power - ARISTO.

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I also want to thank Lars Lingren, who was sharing the office with me. His experience and knowledge in ARISTO simulator and AMCX communication tool helped me to learn how to start working with this environment. He also was extremely helpful when problems appeared during simulations. Finally, he was the responsible for configuring my user and installing my working environment and software tools necessary for my project.

Moreover, I am thankful to all the people and friends in IEA department and Lund University. They have allowed me to experience a great exchange year and I have always felt welcome. I had a great working and personal environment that have made this work possible.

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TERMINOLOGY AND ABBREVIATIONS

ARISTO. Advanced Real Time Interactive Simulator for Training and Operation.

ATB. Adaptive Tolerance Band method for Reactor Hunting.

Circuit breaker. A mechanical switch that can operate fast and is able to interrupt fault current at short-circuits without being damaged.

EVA. Extreme Voltage Automatics that are used to control shunt reactors behaviour.

Ferranti Effect. An increase in voltage occurring at the receiving end of a long transmission line, above the voltage at the sending end. This occurs when the line is energized, but there is very light load or the load is disconnected.

Generation unit. A power plant can have one or more generation units, each mainly consisting of a turbine and a generator.

Ssc. Short circuit power.

Switchyard. Also called substation, is a part of an electrical generation, transmission, and distribution system. Switchyard transforms voltage from high level to low level, or vice versa, and they have switches, disconnectors and circuit breakers to control the different connections of a power system.

EVA Tolerance band. Definition of upper and lower voltage limits that control the behaviour of the automatics in order to maintain the value within the limits. If the voltage is above the upper limit of the tolerance band, the EVAs connect the device and disconnect it if the voltage is below the lower limit.

Transmission System. The high voltage part of a power system that transmits power over long distances.

Z_{BUS}. Bus impedance matrix.

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CHAPTER 1. INTRODUCTION

1.1. Background

Nowadays, our society is based on electrical energy. All economical, social and industrial activity is founded on electricity supply. Furthermore, this dependence is becoming stricter as the society progresses. Consequently, it is highly desirable to ensure power supply.

An electrical power system has a massive number of variables, which makes it susceptible to faults of any kind. In case of events of natural disasters, technical faults or human mistakes, any power system is sensitive to suffer a blackout. A large scale blackout has a critic impact on society, since electrical energy is inaccessible in the electric power grid and thus the economy is forced to stop.

The ideal situation for a reliable power supply would be to prevent the system from any blackout. However, blackouts may occur and it is impossible to predict when. Hence, it is also important to perform a power system restoration as fast and safely as feasible, in order to minimize the duration of the blackout.

As far as Swedish power system is concerned, it is designed with long high voltage transmission lines which connect generation areas in northern Sweden to the central and southern parts of the country. This configuration makes south of Sweden susceptible to blackouts.

During the restoration after the blackout in Sweden and Denmark on 23 September 2003, a particular problem appeared and increased the restoration time, known as reactor hunting.

The restoration strategy starts with long transmission lines being energized. This leads to high voltage at the end of transmission lines. In order to reduce the voltage, shunt reactors are connected to the system. It is important to note that, during restoration, the power system is weak. Thus, connecting the reactors will probably produce critical low voltage (below the lower limit), then the automatic will turn off the reactor again, returning the voltage to the high level. The reactor will therefore cyclically connect and again disconnect. This phenomenon is called reactor hunting.

Reactor hunting produces large voltage fluctuations between high and low voltages outside the tolerance band. The conventional procedure to avoid reactor hunting is to deactivate the automatics and proceed with a manual restoration, which increases the restoration time.

For these reasons, reactor hunting issue must be studied in order to reduce restoration time as much as possible.

1.2. Scope

This thesis is focused in the study of Reactor Hunting avoidance based on the use of shunt reactors which are automatically controlled and are usually installed in convectional electric power systems for voltage regulation.

The idea used to avoid reactor hunting is to let the control parameter depend on the strength of the network (Short Circuit Capacity). The short circuit capacity is used to set the change of the tolerance band of the automatics of the reactive component in order to avoid the hunting phenomenon.

In consequence, it is important to study the relation between the short circuit capacity and the reactor hunting phenomenon. This relation is bases in the network matrix, which represent the state of the system: the arrangement of the different components that are part of the system and how they are interconnected.

This idea has been proved in previous project [1] and is the starting point of this project. More specifically, this thesis will develop an automatic implementation of the reactor hunting avoidance method based on the “adaptive tolerance band”.

1.3. Previous Work

As it was said above, there have been other studies on automatic shunt switching and reactor hunting. In [1,2], it has been studied the control of reactive shunts and how they affect the voltage stability or voltage regulation during restoration. It had been explained the reactor hunting phenomenon and how to be avoided.

However, there is no previous work studying the actual implementation of an automatic reactor hunting avoidance. All the studies that are been carried out were focused on reactor hunting phenomenon and simulation were made manually through electric power system simulators.

On the other hand, the network topology and its influence on the network strength has been studied commonly. The main ideas around this topic that are important to this project are: computer methods in power system analysis, matrix algebra, network matrices, algorithms of formation of network matrices, etc.

1.4. Aims

The starting point of the project is the avoidance of the reactor hunting phenomenon. The method has been conceptually demonstrated by combining simulations and manual intervention [1].

The main purpose of this thesis is to first implement this method for real-time operation. After a large system blackout, the software implemented must allow the user to carry out the restoration, connecting the different buses as the user select, but the software must detect reactor hunting phenomenon and change automatically the reactor shunt automatics in order to prevent reactor hunting from happening.

The software developed is intended to be designed in a general way, in order to make it possible to export the algorithm to any system and to adjust it to the characteristics of any situation, or blackout.

Moreover, to make the results of the research as real as possible, all the process will be developed in top end software simulator ARISTO [1] (Advanced Real Time Interactive Simulator for Training and Operation).

Consequently, the second objective of the thesis is to develop a MATLAB program that simulate the automatic reactor hunting management and communicates with ARISTO.

The communication between ARISTO and MATLAB is possible due to AMCX interface, a software designed to create this bidirectional communication. Consequently, this thesis will involve a period to familiarize with this kind of software.

In conclusion, the main objectives of this project can be summarize in:

- Program that implement "Automatic Adaptive Tolerance band method" for Reactor Hunting phenomenon.
- The Program must allow the user to select any restoration path.
- The Program must be exportable and adjustable to any system and any situation after a blackout.

In addition, there are other objectives:

- Get acquainted with the software involving electric power system simulators.
- Study the Reactor Hunting phenomenon: its causes and effects.
- Study the basic theory behind power system blackouts and restoration process
- Study the influence of network topology on reactor hunting.
- Study computer methods in electric power system.
- Study the formation and modification of network matrices.
- Improve in programming skills and communication protocols between different operating systems.

1.5. Contribution

The main contributions of the project are presented as follows:

- The Adaptive tolerance band method is proposed as a method for reactor hunting avoidance.
- The algorithms used in computer simulation for network matrix construction and modification are presented.
- The influence of the network strength on the reactor hunting, and how the bus impedance matrix is important for an automatic reactor hunting avoidance.
- The program that implements the Automatic Adaptive Tolerance band method for use in real-time simulator (ARISTO).

- The results of this work can be used to evaluate the viability of implementing the method for an automatic avoidance of reactor hunting. This methodology represents a simple concept which easily can be implemented in any real electric power system to speed up the restoration process.

1.6. Outline of Thesis

As far as project outline is concerned, the frame of this project has a straight structure, starting from the basics and finishing with the conclusions arose from the investigation. The core of the project is developed through eight chapters: from chapter 2 to chapter 9.

To begin with, ***chapter 2*** is focused on describing the theoretical aspects that set the base for a complete understanding of the goal of the project, which is reactor hunting; and explaining the critic aspects which are necessary to comprehend the singularity.

On one hand, electric power systems are presented, highlighting the singularities of the Swedish electric power system. Furthermore, it is explained how voltage behaves along a transmission line and why the voltage profile is dependent on the loading of the line at each moment.

Moreover, the blackouts in electric power systems and the subsequent restoration process will be described. It has been explained why Sweden has a special topology which makes the Swedish electric power system particularly susceptible to reactor hunting phenomenon.

In addition, some actuators used to control voltage in the power systems are presented in order to see the differences between them and why are significant. Moreover, shunt reactors are the most important actuators to this project because they are one of the causes of reactor hunting.

Chapter 3 focuses on the reactor hunting phenomenon: its causes and its effects. It is explained that, during restoration, Reactor hunting is a critic problem that causes voltage fluctuation between overvoltages and extreme low voltage. It is also described the method for reactor hunting avoidance: the adaptive tolerance band method.

The method is based on changing the automatics settings (tolerance band), which is an economic and fast solution because it consists on software implementation, instead of hardware investment. This method consists in decrease the lower limit as mas as needed to avoid the reactor disconnection and thus, avoiding reactor hunting.

To study this phenomenon, which is associated with blackouts and restoration process of an electric power system, it is important to have a suitable software. This software is presented in ***Chapter 4.***

As far as implementation is concerned, this project is based in the use of three different software programs that will allow to study the possibilities of these adaptive tolerance band method.

Chapter 4 describes these three modules: the training simulator ARISTO, MATLAB and AMCX. This chapter also presents the main aspects and characteristics of the electric power system model used: NORDIC32.

Chapter 5 will present the Adaptive tolerance band implementation. First, the relation between the bus admittance matrix Z_{BUS} and the short circuit capacity S_{sc} is explained, in order to state the importance of the Z_{BUS} in the implementation of the adaptive tolerance band method.

The main part of the ***Chapter 5*** describes the structure, considerations and operation of the program designed to implement the adaptive tolerance band method, taking in to account all the aspects explained in the project: software limitation, Z_{BUS}, reactor hunting, etc.

Finally, the chapter defined the original scenario that the project will consider, and the different restoration paths that will be followed in the simulation, in order to analyse the result and the performance of the program and the reactor hunting avoidance effectiveness.

Chapter 6 will present the different simulations and analyse the performance of the program, the communication with the ARISTO simulation and the behaviour of the system, starting at the initial system and following restoration path (Chapter 5).

First off all, data verification and bus connections will be carried out for the program. To conclude, final simulations with the fully operative program are done. The results will be analysed in order to evaluate the efficiency of the Automatic Adaptive tolerance band method in Reactor Hunting avoidance and the program overall performance during system restoration.

Chapter 7 will cover the discussion and conclusions of the general project and the final results and software performance

Chapter 8 will discuss the possible future work that can be studied taking as starting point this project, of the possible advantages and improvements that this topic could bring to the actual electric power system field.

CHAPTER 2. THEORY

In order to understand the central objective of this thesis, which is avoiding Reactor Hunting, it is necessary to explain and stablish the theoretical foundations on which it is based.

As it has been said above, Reactor Hunting is a phenomenon which is involved in the Electric Power Systems (EPS) field. Consequently, it will be necessary to present the basics of what an EPS is and, from there, explain how voltage behaves in transmission lines.

Furthermore, it is interesting to explain briefly the blackout process, why and how it occurs. Then, restoration process will be described.

2.1. Electric Power Systems

Nowadays, society is based in power consumption: from small end consumers (houses, restaurant, electric cars, etc.) to big end consumers (Industries or factories). Therefore, an infrastructure is needed to transfer all of this power from the points where power is generated to the consumption points. This structure is known as electric power systems.

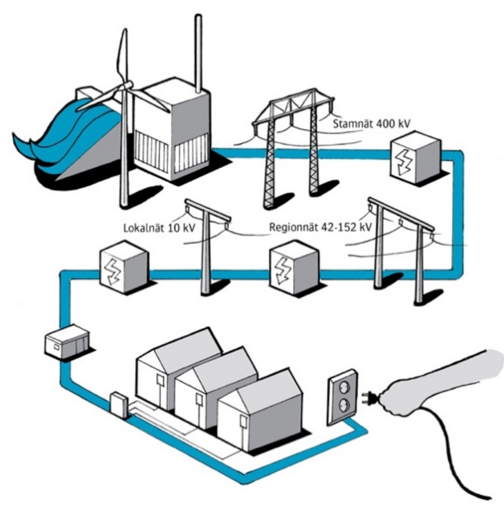


Figure 2.1. Electric Power System structure [6].

Consequently, an electric power system comprises generation sources, end users (loads) and the power lines which connect generation to consumption. A basic structure of a conventional Electric Power System is represented in figure 2.1.

The network topology varies extremely, but the power systems have a common division between generation units and end consumers:

- Transmission network (High Voltage). Connects the main power sources and transmits a large amount of electric energy long distances. To reduce transmission energy losses, transformers are used at power plants to increase voltage and decrease current. The transmission system consists of a network of three-phase transmission lines and transmission substations. The typical transmission voltages range from 230 to 765 kV [3].

Obviously, the main objective for the transmission system is to transmit the energy from the generation areas. However, a transmission system needs other aspects that ensure a high degree of efficiency and reliability. On one hand, the transmission system needs to be able to optimize the generation within the country for every case and also support trading electricity with adjacent countries.
Moreover, it is necessary to withstand different disturbances or faults such as transmission lines outages, lightning storms, outage of power plant, unexpected growth on demand or faults such as shortcircuits. All of these situations need to be handled without reducing the quality of the electricity supply. These are the reasons why the actual electric power systems are designed meshed transmission systems, i.e. the transmission system consists in a number of closed loops instead of straight line. With this structure, there are multiple paths to reach different points in case a fault occurs and a line becomes out of service.

- Sub-transmission network (Medium Voltage). The subtransmission system consists of step-down transformers, substations and subtransmission lines that connect transmission substations to distributions substations. In some cases, a subtransmission line may be tapped to supply a single-costumer load, which needs higher voltage than the available at distribution level, such as a large Industrial plant. Typical subtransmission voltages range from 69 to 138 kV.

- Distribution network, (Low Voltage). Distribution systems comprise step-down transformers that decrease subtransmission voltages to distribution voltages. Distribution of electric energy from distribution substations has two parts to met costumer's premises:
    - Primary distribution, which distributes energy in the 2.2 – 46 kV range.
    - Secondary distribution, which distributes energy at costumer utilization voltages of 120 to 480 V.

2.1.1. The Swedish Energy System

The Swedish electric power system consists of 538,000 km of conductors, of which 40% are overhead lines and the other 60% are underground cables [1]. As other electric power systems, the Swedish electric power system is divided in 3 parts, which are represented in figure 2.2. [6]:

- The National network (Transmission network). The Swedish transmission system consists of approximately 15327 km of power lines, and there are 16 interconnections to other countries [4,7]. The voltage levels of the transmission network are 400 – 200 kV. In Figure 2.4, a general map of the transmission system in Sweden and neighbouring countries is given.
  A state utility, Svenska Kraftnät, manages the national transmission system and foreign links in operation. Svenska Kraftnät owns all 400 kV lines, all transformers between 400 and 220 kV and the major part of the 220 kV Swedish lines [7].

- The regional network (Sub-transmission network). This network has in each load region the same or partly the same purpose as the transmission network. The amount of energy transmitted and the transmission distance are smaller compared with the previous network. Regional networks are usually connected to the transmission network at wo locations, and work with voltages around 130 – 40 kV.

- The local network (distribution network). This network transmits and distributes the electric power that is taken from the substations in the sub-transmission network and delivers it to the end users. There are two different parts at the local network: primary part, working at 40 – 10 kV; and secondary part (low voltage), working at 230/400 V.

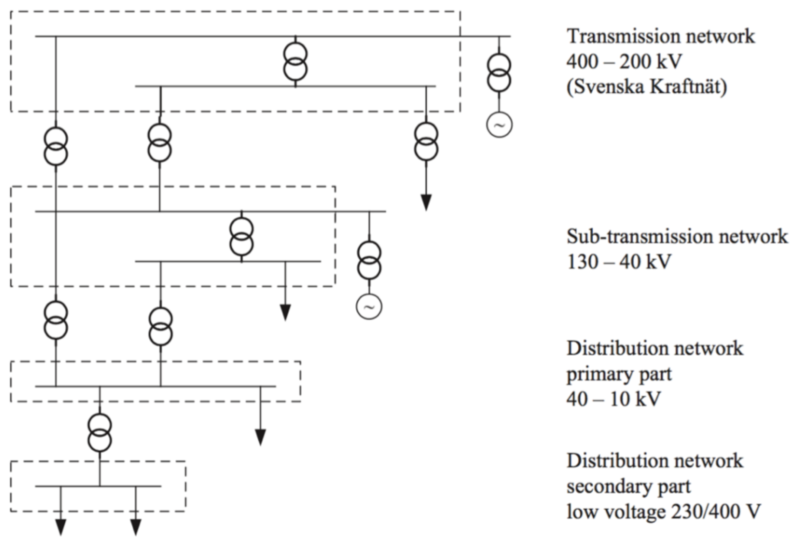


Figure 2.2. Single line representation of the structure of Swedish electric power system [4].

The Swedish national transmission system, is originally built to transfer hydro power and nuclear power (figure 2.3) from the northern part of Sweden, which is mainly a generation area towards the southern and central areas, where most population is concentrated and thus are the main load areas.

Consequently, Swedish transmission system has long transmission lines (400 kV) connecting northern and central areas. This topology is an inherent weakness of the system, and is the main reason for voltage collapse at the central or southern parts of Sweden and critical for blackouts occurred in 1983 and 2003 [1].

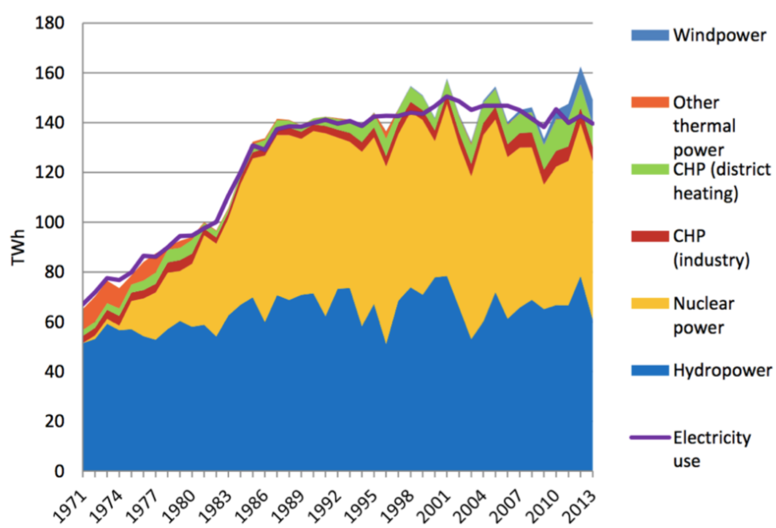


Figure 2.3.Net electricity production in Sweden, 1971 - 2013, TWh [Swedish Agency and Statistics Sweden].

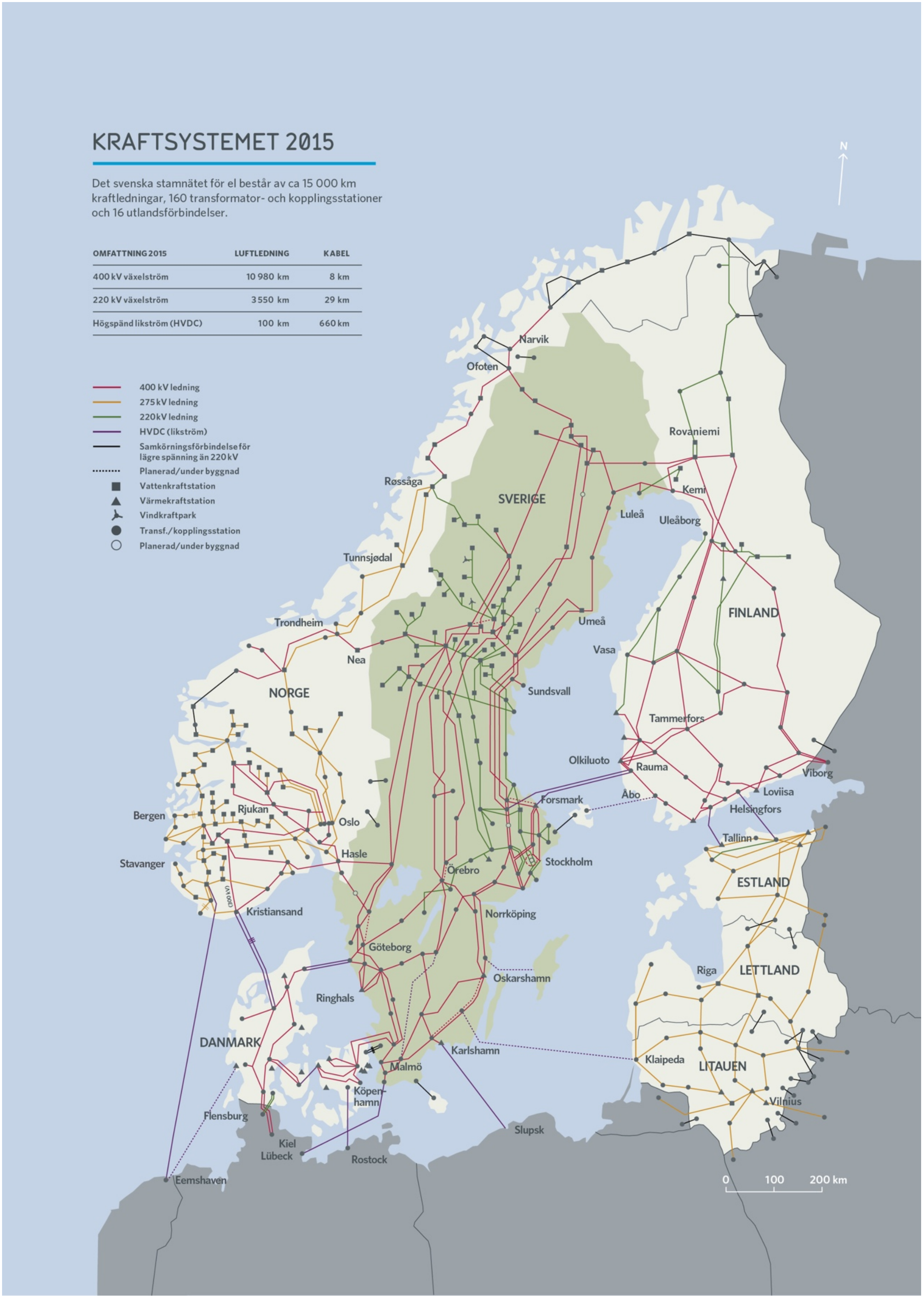


Figure 2.4.Nordic Transmission system [7].

2.2. Voltage Profile

The main focus of this project is to study Reactor Hunting phenomenon, which is directly related with the voltage along transmission line. Thus, it is important to explain how voltage behaves along transmission lines to understand why Reactor Hunting occurs.

2.2.1. Transmission-line Differential Equations

Transmission lines are components of the electric power system that consists in a combination of line constants resistance R, inductance L, and capacitance C. These constants depend on line configuration (geometric factors, number of circuits, etc.) and of the line length. Their units are Ω, H, and F respectively.

Instead of being concentrated, the line constants are uniformly distributed along the length of the line. It can be described as a cascade of identical cells with infinitesimal length as shown in figure 2.5 [8].

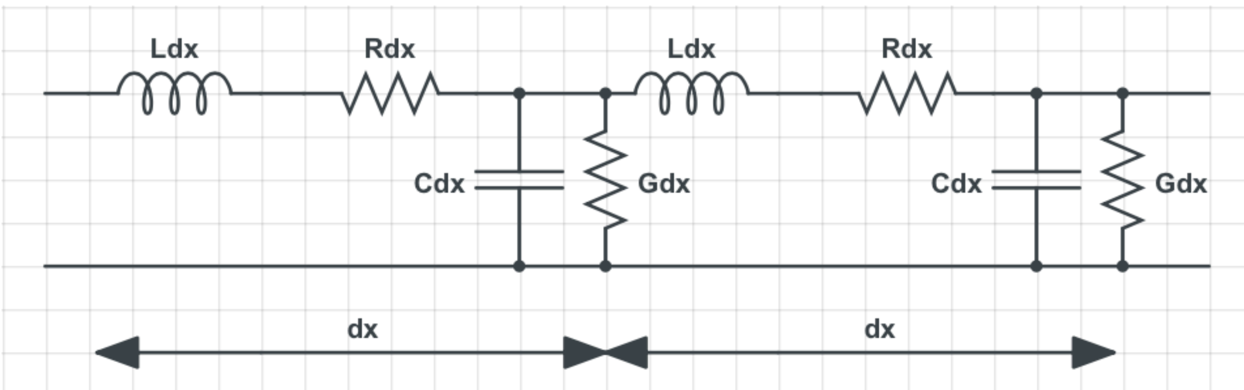


Figure 2.5. Transmission line section of length two times dx.

Where,

$$L \equiv series\ inductance\ per\ unit\ length$$

$$R \equiv series\ resistance\ per\ unit\ length$$

$$C \equiv shunt\ capacitance\ per\ unit\ length$$

$$G \equiv shunt\ conductance\ per\ unit\ length$$

The shunt conductance is used in order to simplify the adding of parallel elements.

A new circuit is defined for the transmission line with new constants combining the series and shunt parameters together.

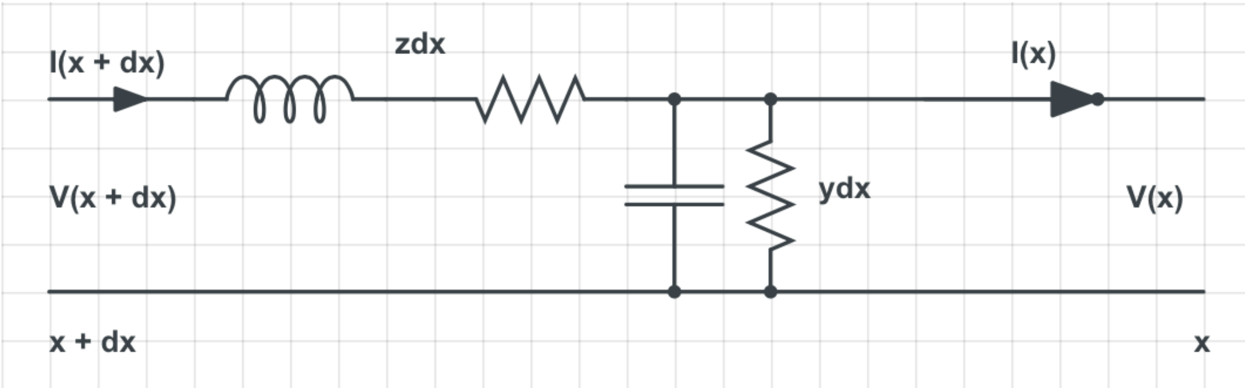


Figure 2.6. Transmission line section of length dx.

Where z is the series impedance per unit length and y is the shunt impedance per unit length:

$$z = R + j\omega L \quad \Omega/m \tag{2.1}$$

$$y = G + j\omega C \quad S/m \tag{2.2}$$

It is important to note that G is usually neglected for overhead lines. Applying Kirchhoff's Voltage Law (KVL) to the circuit represented in figure 2.6 [3]

$$V(x+dx) = V(x) + (zdx)I(x+dx) \tag{2.3}$$

Rearranging (2.3) and taking the limit as dx approaches to zero,

$$\frac{V(x+dx) - V(x)}{dx} = zI(x) \tag{2.4}$$

$$\frac{dV(x)}{dx} = zI(x) \tag{2.5}$$

Operating the same way with the current and the Kirchhoff's Current Law (KCL) [3],

$$I(x+dx) = I(x) + (ydx)V(x+dx) \tag{2.6}$$

$$\frac{I(x+dx) - I(x)}{dx} = yV(x+dx) \tag{2.7}$$

$$\frac{dI(x)}{dx} = yV(x) \tag{2.8}$$

Equations (2.5) and (2.8) are two linear, first order, homogeneous differential equations with two unknowns, $V(x)$ and $I(x)$. First $V(x)$ will be solved eliminating $I(x)$ from equation:

$$\frac{d^2V(x)}{dx^2} = z\frac{dI(x)}{dx} = zyV(x) \rightarrow \frac{d^2V(x)}{dx^2} - zyV(x) = 0 \tag{2.9}$$

The solution to differential equation (2.9) is,

$$V(x) = C_1e^{\gamma x} + C_2e^{-\gamma x} \tag{2.10}$$

Where C_1 and $C_2$are integration constants and γ is called propagation constant,

$$\gamma = \sqrt{zy} \quad m^{-1} \tag{2.11}$$

Solving now for I(x),

$$I(x) = \frac{C_1e^{\gamma x} - C_2e^{-\gamma x}}{Z_c} \tag{2.12}$$

Where Z_c is known as characteristic impedance,

$$Z_c = \sqrt{\frac{z}{y}} \quad \Omega \tag{2.13}$$

With the constants $Z_c$and γ defined, it is needed to determine the constants C_1 and C_2, that are obtained from the boundary conditions of the voltage V_0 and current I_0 at the receiving end of the line x=0,

$$V_0 = V(0) \tag{2.14}$$

$$I_0 = I(0) \tag{2.15}$$

Solving (2.10) and (2.12) at x=0 for C_1 and C_2, the result is

$$C_1 = \frac{V_0 + Z_cI_0}{2} \tag{2.16}$$

$$C_2 = \frac{V_0 - Z_cI_0}{2} \tag{2.17}$$

Substituting C_1 and C_2, in (2.10) and (2.12) and rearranging the terms, the transmission line equations are obtained, and are function of just the parameters of the line and the voltage and current at the receiving end of the line,

$$V(x) = \left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right) V_0 + Z_c \left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right) I_0 \tag{2.18}$$

$$I(x) = \frac{1}{Z_c}\left(\frac{e^{\gamma x} - e^{-\gamma x}}{2}\right) V_0 + \left(\frac{e^{\gamma x} + e^{-\gamma x}}{2}\right) I_0 \tag{2.19}$$

It is easy to recognize the hyperbolic functions $cosh$ and $sinh$, which makes (2.18) and (2.19) more simple,

$$V(x) = \cosh{(\gamma x)} V_0 + Z_c \sinh{(\gamma x)} I_0 \tag{2.20}$$

$$I(x) = \frac{1}{Z_c} \sinh{(\gamma x)} V_0 + cosh(\gamma x) I_0 \tag{2.21}$$

2.2.2. Lossless Lines

Since transmission lines and distribution lines in real electric power systems are designed to have as low losses as possible, it is interesting to simplify the model of transmission line presented above neglecting the losses. This simplified model is known as lossless line model, and without losses, the expressions are simpler for the line parameters.

For a lossless line, $R = G = 0$, Thus, the characteristic impedance is,

$$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{R + jwL}{G + jwC}} = \sqrt{\frac{jwL}{jwC}} == \sqrt{\frac{L}{C}} \quad \Omega \tag{2.22}$$

And the propagation constant

$$\gamma = \sqrt{zy} = \sqrt{(jwL)(jwC)} = j\beta \quad m^{-1} \tag{2.23}$$

Where β is

$$\beta = w\sqrt{LC} \;\; m^{-1} \tag{2.24}$$

In the light of the foregoing, the characteristic impedance Z_c is pure real (resistive) and is called surge impedance [3]. Moreover, the propagation constant γ is pure imaginary.

Taking into account this simplification with the values of Z_c and γ, the hyperbolic functions $cosh$ and $sinh$ of expressions (2.20) and (2.21) can be simplified as follows:

$$\cosh(j\beta x) = \frac{e^{j\beta x} + e^{-j\beta x}}{2} = \frac{\cos(\beta x) + jsin(\beta x) + \cos(\beta x) - jsin(\beta x)}{2} = \cos(\beta x) \tag{2.25}$$

$$\sinh(j\beta x) = \frac{e^{j\beta x} - e^{-j\beta x}}{2} = \frac{\cos(\beta x) + jsin(\beta x) - \cos(\beta x) + jsin(\beta x)}{2} = \text{jsin}(\beta x) \tag{2.26}$$

Consequently, in a lossless line, the transmission equations are:

$$V(x) = \cosh(\gamma x)\, V_0 + Z_c \sinh(\gamma x)\, I_0 = \cos(\beta x) V_0 + j\sqrt{\frac{L}{C}} \sin(\beta x) I_0 \tag{2.27}$$

$$I(x) = \frac{1}{Z_c} \sinh(\gamma x)\, V_0 + cosh(\gamma x) I_0 = j\sqrt{\frac{C}{L}} \sin(\beta x) V_0 + \cos(\beta x) I_0 \tag{2.28}$$

2.2.3. Surge Impedance Loading

Surge Impedance Loading (SIL) is the power delivered by a lossless line to a load resistance equal to the surge impedance Z_c [3]. A simple circuit with SIL connected at the end of the line is represented in figure 2.7.

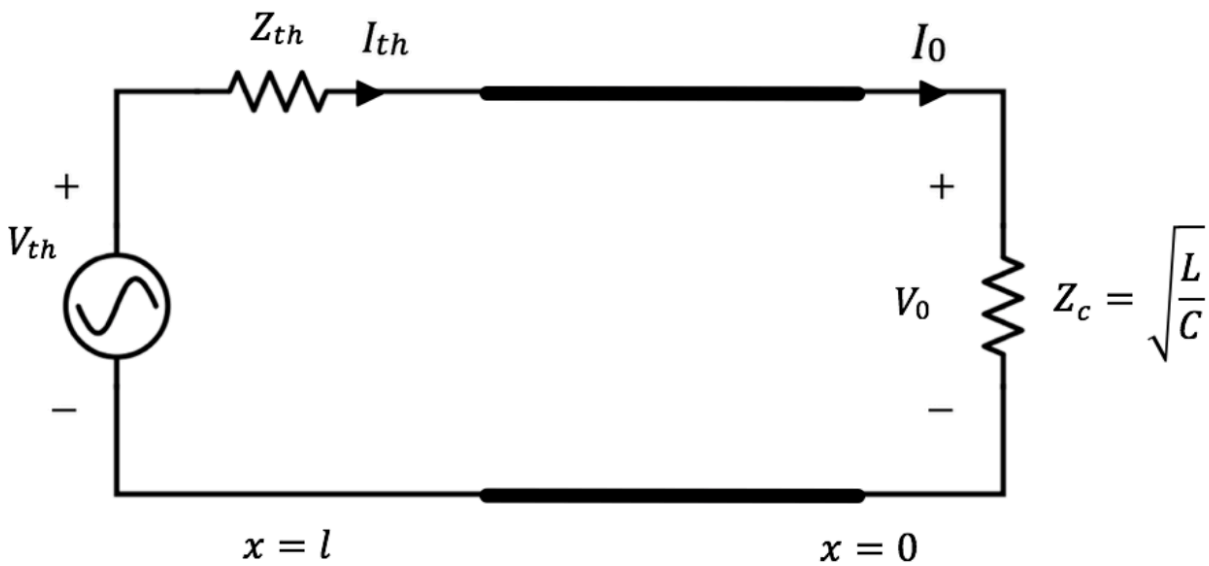


Figure 2.7. Simple circuit with SIL connected at the end of the line.

$$V_0 = Z_c I_0 \tag{2.29}$$

Therefore, the voltage along the transmission line is

$$\mathrm{V(x)} = \cos(\beta x) V_0 + jZ_c \sin(\beta x) \frac{V_0}{Z_c} = \big(\cos(\beta x) + j\sin(\beta x)\big) V_0 = e^{j\beta x} V_0 \tag{2.30}$$

Where

$$|\mathrm{V(x)}| = |V_0| \tag{2.31}$$

Thus, the voltage at any point along a lossless transmission line at SIL is constant. That means the voltage profile is flat.

It is easy to obtain the equivalent expression for the current at SIL with (2.28) and (2.29):

$$|\mathrm{I}(\mathrm{x})| = \left|\frac{V_0}{Z_c}\right| \tag{2.32}$$

Another approach to explain the behaviour of a transmission line at SIL is focusing on Reactive Power [2]. The shunt capacitance presented in the line model is charged during line operation. Thus, Reactive Power is produced and is dependent on the reactance of the line X_c and the voltage at which the line is energized V, as following.

$$\mathrm{Q}_c = \frac{V^2}{X_c} \tag{2.33}$$

On the other hand, transmission lines also have inductance and consume reactive power to support their magnetic field. The amount of reactive power consumed is related to the load of the line (current I) and the reactance of the line X_l, as following:

$$\mathrm{Q}_l = \mathrm{X}_l I^2 \tag{2.34}$$

With this approach, SIL is reached when the amount of reactive power generated equals the amount of reactive power consumed. Taking into account that $\omega = 2\pi f$, where f is the frequency, and the values of the reactance depend on capacitance C and inductance L, SIL is reached when

$$\mathrm{Q}_c = \mathrm{Q}_l \rightarrow \frac{V^2}{X_c} = \mathrm{X}_l I^2 \rightarrow \left(\frac{V}{I}\right)^2 = X_c X_l = \frac{\omega L}{\omega C} = \frac{L}{C} \rightarrow Z = Z_c = \frac{V}{I} = \sqrt{\frac{L}{C}} \tag{2.35}$$

Consequently, SIL can be determined with the voltage level of the line and the surge impedance:

$$\mathrm{SIL} = \frac{V^2}{Z_c} \tag{2.36}$$

In practice, common transmission lines are not operating at SIL. Thus, there are difference in voltage along the transmission line. If a line is loaded above SIL will act as a shunt reactor and absorb reactive power. Instead, if the line is loaded below SIL, it will act as a shunt capacitor and produce reactive power. That is why it is interesting to study the voltage profiles of the line at different loads.

2.2.4. Voltage Profiles

If a line is not terminated by SIL at the receiving end, the voltage profile is consequently not flat.

Figure 2.8. represents the voltage profile of different lines or different loading conditions with fixed sending end voltage V_s and same length l. It is considered four loading conditions:

a) No load. This condition implies that $I_0 = 0$. Taking (2.27), the voltage profile is

$$\mathrm{V}_{No\ load}(\mathrm{x}) = \cos(\beta x) V_0 \tag{2.37}$$

b) SIL. The voltage profile is flat as explained above.
c) Short circuit. In the event of a short circuit, the voltage at the receiving end is $V_0 = 0$. Thus, the voltage profile is:

$$\mathrm{V}_{Shot\ circuit}(\mathrm{x}) = Z_c \sin{(\beta x)} I_0 \tag{2.38}$$

d) Full load. Depending of the specifications of the line, the voltage profile at full load condition is somewhere in between SIL and short circuit conditions.

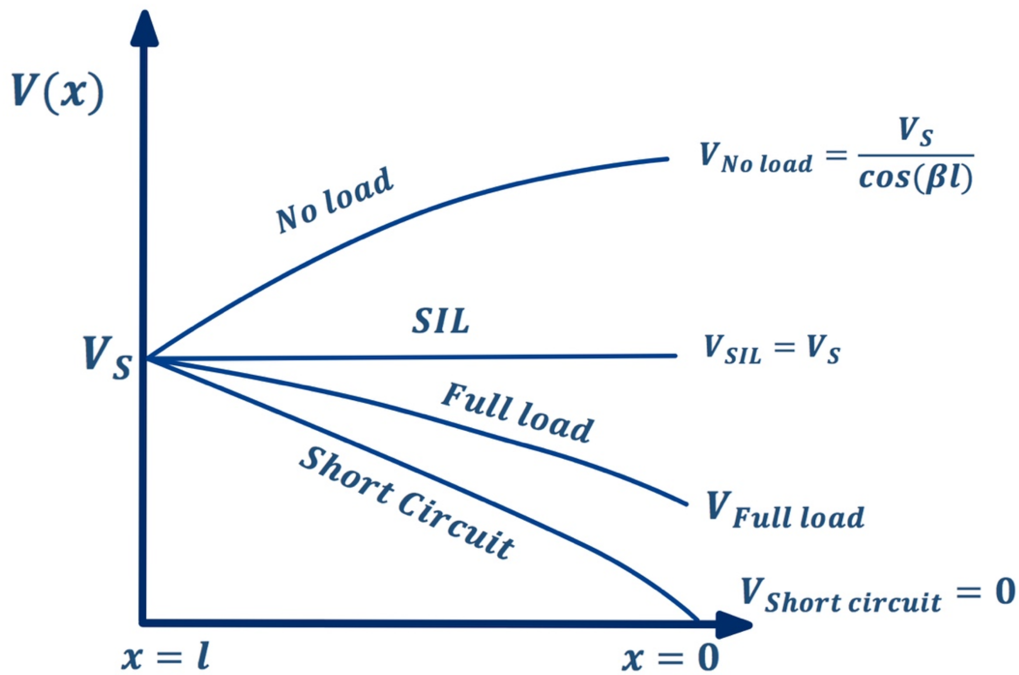


Figure 2.8. Voltage profile of a line with different loading conditions.

As it can be concluded from the explanation, the behaviour of the voltage in transmission lines is extremely dependent on the characteristics of the transmission line.

The important conclusion for this particular project is that the voltage of the line can increase in relation to the voltage at the sending point if there is light load or no load (lower than SIL). This effect is known as Ferranti effect, and has been explained by determining the transmission equations of the line.

2.2.5. Ferranti effect

The Ferranti effect is caused by the natural line capacitance and inductance. As it can be seen in figure 2.5, in a long transmission line there is a high amount of capacitance and inductance distributed across the line. Ferranti effect occurs when current drawn by the capacitance of the line is greater than the current associated with the load at the receiving end of the line (light load).

This capacitor charging current leads to voltage drop across the line inductor of the transmission system which is in phase with the sending end voltages. This voltage drop keeps on increasing additively as we move towards the load end of the line and, consequently, the receiving end voltage tends to get higher than the applied voltage at the sending point [9].

In conclusion, both line inductance and capacitance are responsible for this phenomenon, not just capacitance as it can be thought at first.

The Ferranti effect will be more pronounced the longer the line and can be neglected in short transmission lines. Precisely, the length of the line has a quadratic effect on the voltage rise.

This effect is critical for Reactor Hunting phenomenon because, is the reason it happens. During restoration process of a power system, long transmission lines are energized without load, so is the perfect situation for Ferranti effect to happen.

2.3. Voltage Regulation

As it has been described in the previous section, the voltage along the transmission line is dependent on numerous parameters and is susceptible to vary. During normal operation, loads can change with time, making the voltage profile increase or decrease depending on the load characteristics. Consequently, it needs to be controlled.

This section aims to present a brief description of the actuators or methods used in transmission line operation to control the voltage level [1] in order to improve voltage stability and prevent voltage collapse in power systems. Each actuator is designed and used for different purposes, and this description will show which actuator is more suitable for controlling the voltage rise of the line during restoration.

2.3.1. Transformer Tap Changer

A tap changer is a device along a power transformer winding that allows a variable number of turns to be selected in discrete steps, enabling stepped voltage regulation output. The tap selection may be made via an automatic or manual tap changer mechanism. [3]. Tap changers restore the voltage for the sub-transmission and distribution levels. The restoration process usually takes several minutes.

2.3.2. Synchronous Generator

Another possibility to control voltage in an electric power system is to adjust the voltage of the generators in order to set the transmission voltage level. Most of generators nowadays are synchronous generators, which have the characteristic of the excitation circuit to create the magnetic field. Instead of have fixed excitation as most cheap portable generators, big power generators have Automatic Voltage Regulator (AVR).

An AVR is a device installed on the synchronous generator excitation system to regulate the terminal voltage based on local measurements. AVR controls the output by sensing the voltage at a power-generating coil and comparing it to a stable reference. The error signal is then used to adjust the average value of the field current [10].

2.3.3. Load Shedding

Load shedding is not an actuator, but it can be used as a method to control voltage. It is based on the possibility of disconnecting some loads that are not critical in order to maintain the system operation as much stable as possible. Thus, when a disturbance occurs and it leads to a voltage drop to unacceptable values, some loads are shed in the system to recover the loading and the voltage to acceptable levels.

2.3.4. Static Var Compensator (SVC)

The SVC is a solid-state reactive power compensation device based on high power thyristor technology. In order to obtain overall control of the reactive power of the network, SVC consists on thyristors controlled reactors or thyristor switched capacitors combined with mechanically switched shunt reactors and capacitors, all controlled by the SVC control system [11].

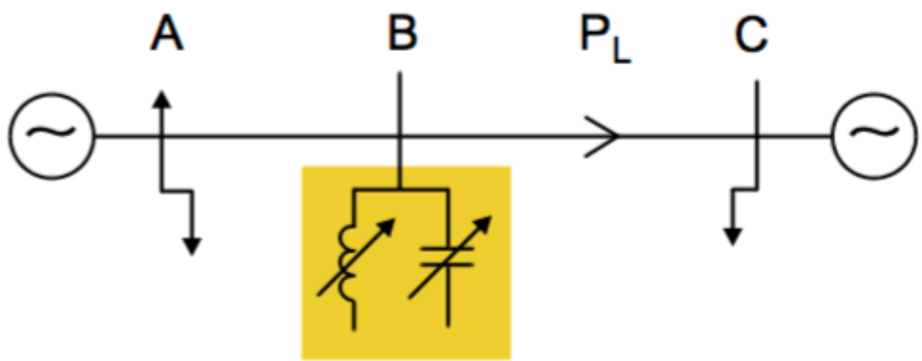


Figure 2.9. Static Var Compensator. ABB [11].

Consequently, SVC can provide rapidly reactive power control and thus great control of the bus voltage. SVC is placed at either the midpoint or end of the transmission lines to improve the short-term voltage stability [1].

2.3.5. Shunt Capacitor

One of the most used actuators in voltage regulation are shunt capacitors. In electric power systems where the amount of power managed is high, it is used what it is known as Shunt Capacitor Banks (SCBs), instead of using a single unit of capacitor per system phase.

Shunt capacitors have several uses in the electric power systems; they are relatively economical and require easy installation and they are used at all voltage levels, distribution and transmission levels [1]. Shunt capacitors are utilized as sources of reactive power. One of the possible utilities is to connect capacitors in series with long lines in order to reduce the line impedance. But the main utility of capacitors is shunt connection.

Shunt capacitors are used to correct the power factor, control the feeder voltage and compensate reactive losses.

Figure 2.10. Shunt Capacitors. [Energe Capacitors]

Shunt capacitors are usually called “power factor correction capacitors”, and they are widely used in distribution systems to correct the power factor and also to control the feeder voltage. Capacitor banks provide reactive power near inductive loads.

Consequently, the total current of the feeder decreases, improving the voltage profile along the feeder, freeing additional feeder capacity and reducing losses. In result, the power factor correction provides reactive power locally instead of supplying it from remote sources [12].

As far as transmission systems are concerned, shunt capacitors are used to compensate the reactive losses of the lines and keep the voltage within the limits, since shunt capacitors slightly increase the operating voltages. As the transmission voltage increases, less current is necessary to supply the load, so transmission losses decrease.

Moreover, shunt capacitors increase the power transfer capability of a transmission line. Since they produce reactive power, generators no longer need to produce so much reactive power, enabling the generator to work at operating points with higher power factors and active power.

2.3.6. Shunt Reactor

Shunt Reactors are commonly used in electric power systems as reactive power consumers in order to carry out three main tasks [13]:

- Compensate the effect of the line capacitance.
- Improve the stability and efficiency of the energy transmission.
- Limit the overvoltage of the lines.

Figure 2.11. Siemens Shunt Reactor [13].

The last utility is the main use of the shunt reactor as far as this project is concerned. As it was explained in section 2.2.4 – 2.2.5, the Ferranti effect describes the phenomenon in which the voltage rises in the receiving end of a long transmission line when there is light or no load. Shunt reactors are used to control this overvoltages.

Shunt reactors are equipped with automatics which connect and disconnect the reactors when the voltage exceeds certain limits of a security band, also known as tolerance band. These automatics are known as Extreme Voltage Actuators (EVA).

These automatics are commonly situated at the transmission voltage level (400 and 220 kV), and work on an on/off local scheme. This means that the EVAs switch once the local bus voltage is outside the tolerance band. The behaviour of the EVA is presented in the figure 2.12.

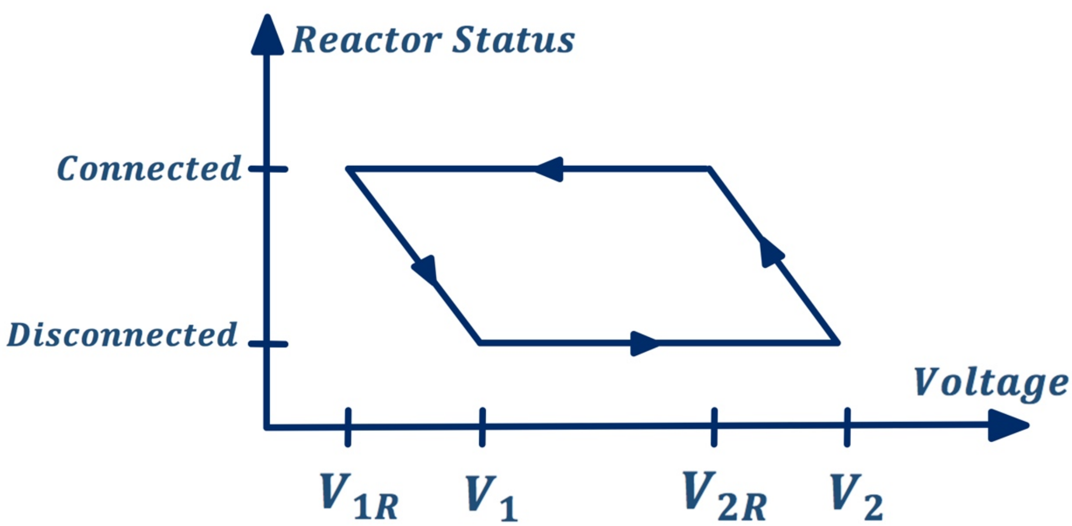


Figure 2.12. Hysteresis curve for the EVA in shunt reactors.

It is important to note that this automatic functionality works sometimes with capacitors. Some of the shunt capacitors which are installed in the regional and distribution networks have EVA but they connect and disconnect capacitors when the voltage is below or above a certain limit, respectively.

Traditional shunt reactors have a fixed rating, i.e. the shunt reactor is either connected to the network or not connected to the network depending on the load and EVAs. However, there are new technologies that allow the reactor shunt to change the reactive power consumption. These are known as Variable Shunt Reactor (VSR), which have a variable rating that can be changed in steps [14].

VSR are considered as technically advance products, so they are not in widespread use. In consequence, this project focuses on traditional shunt reactor with fixed rating and EVAs to control them.

2.4. Blackouts

Nowadays, the society dependence on the electric power systems to fulfill the demand of the different sectors in terms of energy consumption has made the electric power systems become very reliable systems that secure the supply.

However, it is practically impossible and economically unfeasible to prevent all possible faults on the system. Thus, there is a possibility of minor faults and major faults which may compromise the service.

As far as major faults are concerned, the most critic failure of an electric power system is a blackout, also known as power outage. A blackout is a short or long-term loss of the electric power to an area, which causes interruption of the service and all the consequences implicit in economy and society.

In the past, systems were small and less interconnected. In addition, the power industries were dedicated as service oriented and commonly managed by the Government. This situation made the power systems more secure.

However, actual power systems are much large, complex and interconnected with neighbouring systems and countries. The power industries are forced to be operated by a competitive market, which makes the system utilization increase and be more efficient, but on the other hand, it also increases the risk of operation by stressing the power system and reducing the predictability of operations [15].

In addition, large interconnected systems are stronger and thus less susceptible to failures. However, large systems cover big areas. This implies that the number of possible external disturbances increases, as well as the possibility of having multiple disturbances at the same time. Consequently, Power systems are high controlled and monitored, but still power blackouts may occur.

Due to the importance of power blackouts impact, even if they are rare events, there are a lot of articles that study the phenomenon in depth. These studies have revealed that these outages were caused by a cascading sequence of events starting with initial disturbances such as: line tripping, protection system malfunction, line overloading, lightning, operator's errors, shot-circuit of transmission lines. Each blackout has its own origin, evolution and behaviour. However, there are common characteristics among the different major blackouts, such as large-scale blackouts in the U.S (1996), Italy (2003), Sweden (2003) or Europe (2006) [16].

Since this project focuses on Swedish electric power system, it is interesting to describe the 2003 blackout in Denmark and Sweden. With this description it will be possible to understand in a simple manner the behaviour of a blackout.

2.4.1. Blackout in Southern Sweden and Eastern Denmark – September 23, 2003

As it was explained in section 2.1.1, the Swedish electric power system is characterized by a centralized generation area in the northern part of Sweden, mainly hydropower and nuclear power, and long transmission lines connecting it to the southern part of Sweden where the majority of power consumption is concentrated. These long transmission lines are an inherent weakness of the system and voltage collapse has lead to major blackouts in 1983 and 2003 [1].

Figure 2.13. Sweden Map. Principal faults during 2003 blackout [Google Maps].

The power outage of 2003 occurred on September 23. Prior to the fault, the system was moderately loaded but several system components, including two 400-kV lines and HVDC links connecting the Nordel system (Denmark, Finland, Iceland, Norway and Sweden) with continental Europe, were out of service due to maintenance. Maintenance procedures are carried out during this period of the year in order to prepare the system before the peak load period during the winter. [17].

The first contingency was the loss of a 1250 MW nuclear unit in southern Sweden, in the nuclear plant (Kärnkraftverk) of Oskarshamn (Blue marker in figure 2.13) due to problems with a steam valve. This resulted in an increase of power transfer from the north.

System security was still acceptable after this contingency, because this amount of power is considered as a disturbance to be handled normally in Swedish power system designing process based on the N-1 security criterion, i.e. after any single contingency the system is stable without undervoltages, overvoltages or overloads.

Five minutes after this incidents a fault occurred on the western coast of Sweden: loss of two generation units (1750 MW) at Ringhals nuclear power plant (red marker in figure 2.13) due to a fault in the double bus bar at the Horred substation (green marker in figure 2.13).

This resulted in the loss of a number of lines and two 900 MW nuclear units, and as a consequence a very high power transfer north to south on the remaining 400 kV line. Consequently, the system experienced voltage collapse leading to the separation of a region of the Southern Swedish and Eastern Denmark system. In a matter of seconds, this islanded system collapsed in both voltage and frequency and thus resulted in a blackout.

The isolated system had only a total generation to cover some 30% of its demand, which was far from sufficient to allow islanded operation. A total of 4700 MW of load was lost in Sweden (1.6 million people affected) and 1850 MW in Denmark (2.4 million people affected) [17].

2.5. Restoration

As it has been explained, power blackouts are rare events that can be caused by different disturbances, such as disasters, line overloads, etc. that create a cascade of sequence of events that result in a power outage.

Even though each blackout is different in cause and impact, all outage situations need to be restored. There is an increasing interest in designing systematic restoration strategy that makes restoration processes fast, effective, and structured and reliable in order to reduce as much as possible the impact of blackouts on economy and society and to reduce the equipment damage because of the outage [18].

Consequently, there is a common strategy in order to design a restoration process. Each restoration procedure must start with the determination of the System Status [19]. In this first step, an analysis of the situation of the system after the outage is carried out with the objective of:

- Determining which parts of the system are still working. The boundaries of the still energized areas are identified. These areas enable a considerably faster restoration process because these areas are supplying power (just the necessary to keep the area operating), so the connection is easier than a generator which is stopped completely. Voltages and frequencies within these areas must be monitored.

- In case of total blackout, or areas without connection to neighbouring systems, available black start resources are identified.

- It must be identified all the equipment damaged during the blackout: lines, protections, breakers, and so on, in order to repair or replace them.

Once the first stage of the restoration process is finished and the system status is known, operators have prepared restoration plans and guidelines to handle the blackout restoration. In figure 2.14, an example is shown, representing the sequence of operations in a restoration process. It is important to note, that public health and safety facilities have priority.

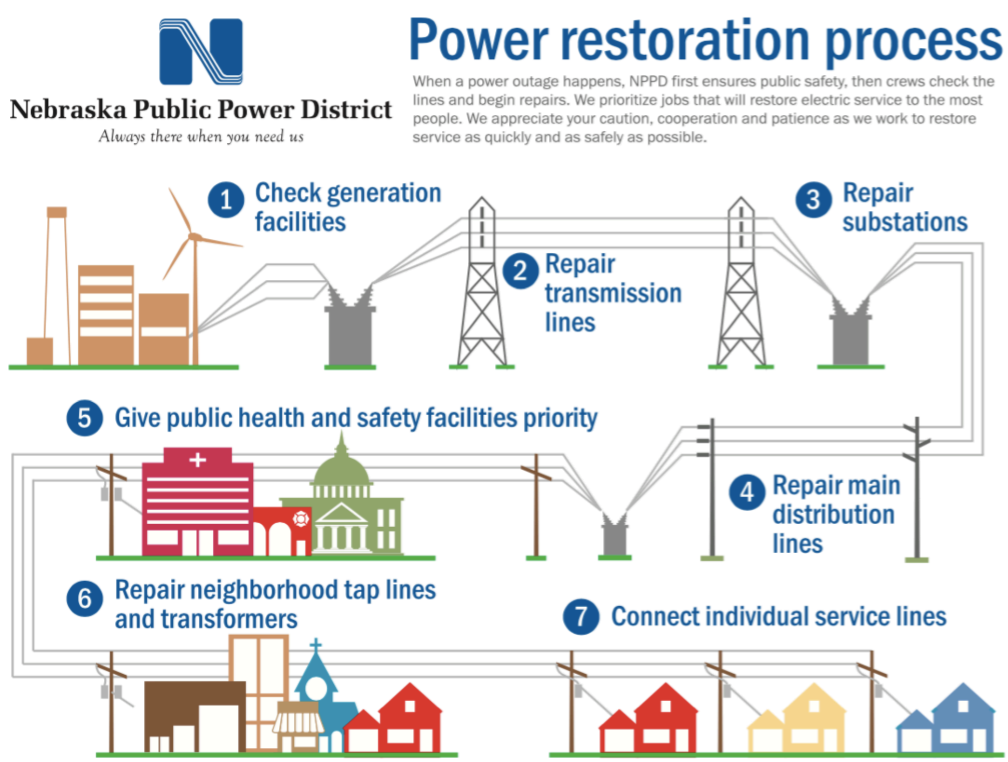


Figure 2.14. Power System Restoration process in Nebraska. [Nebraska Public Power District NPPD]

Apart from the illustrative example, there are two main strategies that are used in the restoration process of electric power systems: the" build-up" and "build-down" strategies [19].

2.5.1. Build-up Strategy

To begin with, the “build-up” strategy means that the entire power system is divided into different electrically isolated subsystems, called islands, where voltage and frequency are monitored. Then, this strategy restores the defined islands in parallel, i.e. generation units are connected gradually and also the required loads in order to keep the voltage and frequency within the limits. When all islands are completely stable, then they are synchronized and the entire network is finally restored.

This strategy has important advantages: first, the restoration time is significantly reduced compared to other strategies. Moreover, the “build-up” strategy, in case of a large disturbance in an island, a recurrent blackout would only occur in the affected area, reducing the impact.

However, regarding disadvantages, as the network is divided in smaller subsystems, the stability margins of the different islands are narrower and are an important aspect to consider during the restoration process [20].

2.5.2. Build-down Strategy

On the other hand, the “build-down” strategy means that the transmission system energizes first the high voltage grid and all the lower voltage levels are then energized, while the whole energized power system is kept synchronized.

During “build-down” strategy, the main part of the system must be energized first, before reconnecting the loads or synchronizing the generators, just connecting transmission lines to other stations in order to supply the emergency power necessary to start them. Once, the high voltage level is energized, loads and generation should be energised in parallel.

The main advantage of this strategy is that the stability margins are substantial. Thus, the reliability and probability of effective restoration are significant. The main drawback of this strategy is the restoration time compared with the previous strategy [20].

Since the restoration process duration is significantly reduced with the “build-up” strategy compared with the “build-down” strategy, the former strategy is the one predominantly used in most countries and the “build-down” strategy is usually used for partial blackouts [19].

2.5.3. The Swedish Strategy

However, Sweden uses the “build-down” strategy due to the characteristic topology of the Swedish electric power system. In Sweden, the general plan is to restore the system from the North to southern parts of the country, which is an example of “Build-down” strategy.

The reason behind this strategy in Sweden is that the hydropower in the North is normally much easier to use during restoration and faster to start [18]. In addition, since the main loads are the central and southern part of the system, the blackouts mainly happen in this areas. Thus, it is natural to apply a “build-down” strategy, where the restoration process starts with energizing the long transmission lines between North and central areas.

This last statement is critic to start explaining the importance of the reactor hunting phenomenon in Sweden during system restoration, because of the early connection of the long transmission lines.

2.6. Summary

This chapter had the main purpose of introducing the background behind Reactor Hunting, and explaining the critic aspects which are necessary to comprehend the singularity of Reactor Hunting, its causes, impacts and how it can be avoided.

On one hand, the blackouts in electric power systems and the subsequent restoration process have been described. It has been explained why Sweden has a special topology which makes reactor hunting a possible problem.

In addition, some actuators used to control voltage in the power systems have been presented in order to see the differences between them and why are significant. Moreover, shunt reactors are the most important actuators to this project because they are one of the causes of reactor hunting.

On the other hand, with all the theory at the start of the previous chapter explained, it is understood how voltage behaves along a transmission line and why the voltage profile is dependent on the loading of the line at each moment.

CHAPTER 3. REACTOR HUNTING

This chapter is intended to present the problem that this project is trying to study, once all the basic theory aspects have been presented, and to develop an automatic system to avoid it. In consequence, chapter three will describe reactor hunting phenomenon and possible methods of avoidance.

On one hand, the Reactor hunting phenomenon is described: its principal causes and effects, starting at the Ferranti effect and presenting the way automatics cause this phenomenon. A small mathematical demonstration will be presented in order to clarify the concepts.

On the other hand, different methods used for reactor hunting avoidance will be studied: the conventional one, which consists in disconnecting the automatics; and the "Adaptive tolerance band method".

This last method will be described in depth, because it will be used in this project to avoid Reactor hunting phenomenon.

3.1. Reactor Hunting during Restoration

As described in chapter 2, there are a number of long 400 kV transmission lines connecting the northern part of Sweden with the centre and south of the country. As far as restoration process is concerned, following the "build-down" strategy, these lines are energised in the first stage of the restoration.

Regarding the line equations presented in the previous chapter or the Ferranti effect, in this conditions, the lines have low or no-load. Consequently, this energization initially results in excess of reactive power and overvoltage as it can be seen in figures 3.1 and 3.2 as an example.

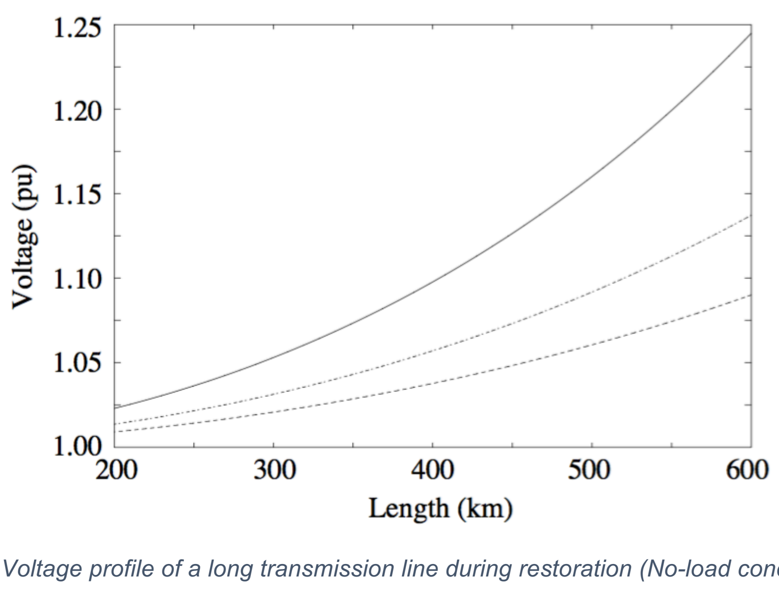


Figure 3.1. Voltage profile of a long transmission line during restoration (No-load conditions) [21]

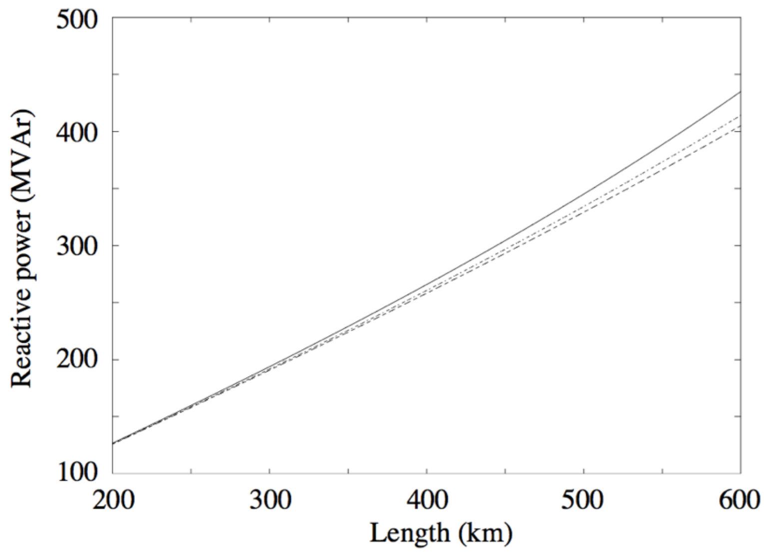


Figure 3.2. Reactive Power of a long transmission line during restoration (No-load conditions) [21]

For instance, during the restoration in the 2003 Swedish blackout, the voltage rose up to 476.5 kV in the southern part of the system. Regarding normal operation, the working voltage level used in Svenska Kraftnät (Swedish TSO) is 415 kV, thus the overvoltage reached is near 15% [7].

3.1.1. The phenomenon

As it was explained previously in chapter 2, the actuators used to regulate the voltage level on the bulk power system on the transmission level are the shunt reactors. These actuators are equipped with automatics (EVAs) which connect and disconnect the reactors when the voltage exceeds certain limits (tolerance band). The shunt reactor and EVAs are usually installed and used in the transmission level (400 kV and 220 kV).

As far as voltage limits are concerned, the tolerance band of the EVA at 400 kV is 420-425 kV on the high level and 380-385 kV for the lower level. Respectively, on the 220 kV level, the high level is around 230 kV and low level is 210 kV. The connection of a reactor is delayed by 0.4 s whereas disconnection is postponed by 2 s [21].

During the restoration process, the system is almost down and thus the power system is weak. In the stage of energizing the long transmission lines with almost no-load, the overvoltage produced at the receiving end of the line makes the EVAs to turn on and connect the shunt reactors to reduce the voltage.

Since the power system is weak, connecting the shunt reactors might lead to an extreme low voltage. The weaker the system, the greater the decrease. Consequently, the voltage might get below the lower limit of the tolerance band, which is set for normal operation and normal network strength.

If the voltage gets below this limits, the EVAs will turn off again. This results in disconnection of the shunt reactors, which brings back the original situation with overvoltage. Consequently, the EVA will turn on again and this leads to a repetitive process of connection and disconnection of the shunt reactors. This phenomenon is known as Reactor Hunting [21].

Reactor Hunting may cause severe problems as the voltage will strongly fluctuate. The repetitive process has a time cycle governed by the delay times of the EVAs in combination with the response time of circuit-breaker (around 2 seconds).

Figure 3.3 symbolizes a simple scheme of the Reactor Hunting phenomenon, representing the fluctuations of the voltage around the tolerance band.

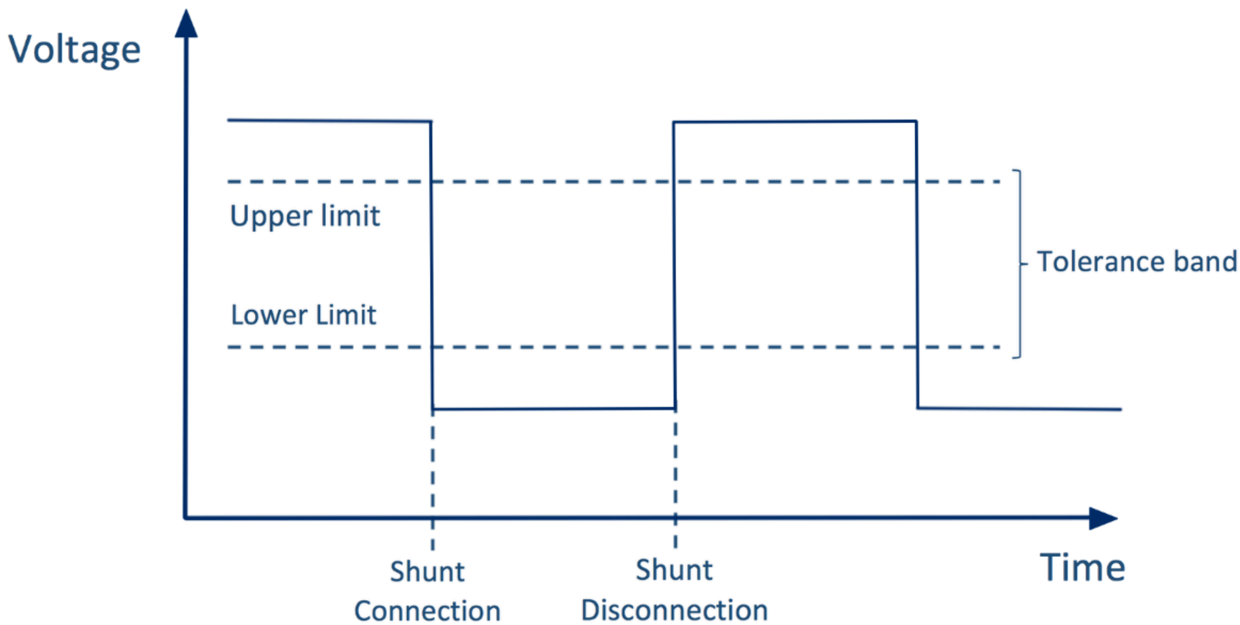


Figure 3.3. Reactor Hunting phenomenon during power system restoration.

3.1.2. Demonstration

In order to get a deeper understanding of the reactor hunting, a simple demonstration of the phenomenon is explained as follows, considering a simple circuit represented in figure 3.4. This circuit symbolizes a simplification of an electric power system. This basic network topology can represent the simplified situation where the power system in north of Sweden is intact while the central and southern areas have suffered a power outage [1].

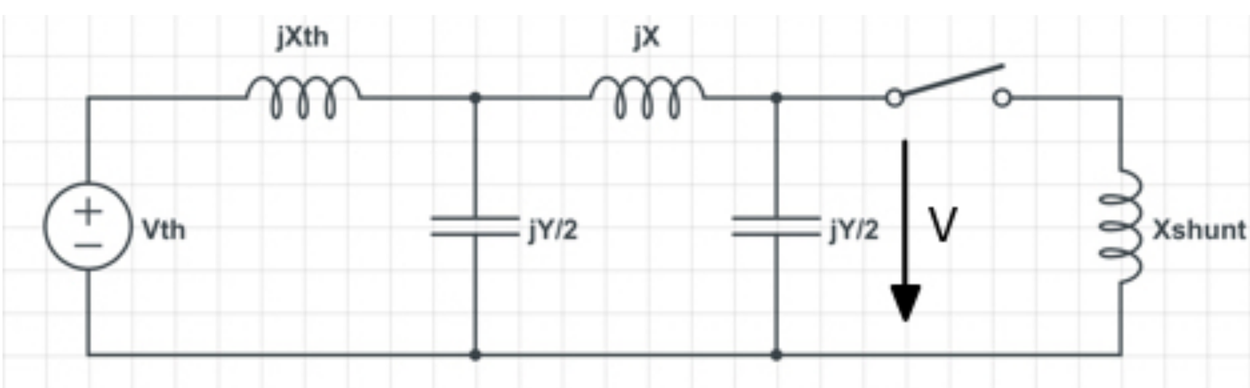


Figure 3.4. Simplification of an electric power system with shunt reactor.

First, there is a Thévenin equivalent to represent the system with the Thévenin voltage V_{th} and Thévenin reactance X_{th}. Then a lossless transmission line (PI model where Y and X are the transmission line admittance and reactance) is connected to the network, and finally, a shunt reactor X_{shunt} is connected to the remote end of the line, through a switch.

In order to study the influence of the network strength on the reactor hunting phenomenon, three different cases are considered:

- Case A: One transmission line is energized from a weak network.
- Case B: One transmission line is energized from a strong network.
- Case C: Two parallel transmission lines are energized from a strong network.

The values of the parameters defined above are presented in the following table.

Circuit parameters	
Network	$V_{th} = 400\ kV$
	$X_{th} = 8\ \Omega\ (Strong)$
	$X_{th} = 80\ \Omega\ (Weak)$
Transmission Line	$X = 120\ \Omega$
	$Y = 0.000819\ S$
	$Length = 400\ km$
Shunt Reactor	$Q = 200\ MVar$
	$X_{shunt} = 800\ \Omega$
	$Tolerance\ Band = [380 - 420] kV$

Table 3.1. Circuit parameters for demonstration of Reactor Hunting phenomenon.

The demonstration consists in determining the voltage V of the transmission line end point. This voltage is calculated for the three cases presented above, considering two different situations: with the shunt reactor connected, or disconnected. The main difference between both cases is that the reactance X_{shunt} is not considered in the second situation (shunt disconnected) [1].

To begin with, it is considered that the shunt reactor is disconnected. Consequently, it is easy to determine that the voltage $V_{disconnected}$ is:

$$V_{disconnected} = \left[\frac{-j\,{}^{2}/_{Y}}{-j\,{}^{2}/_{Y} + jX}\right]\left[\frac{\dfrac{-j\,{}^{2}/_{Y}\,(X - {}^{2}/_{Y})}{-\,{}^{2}/_{Y} + (X - {}^{2}/_{Y})}}{\dfrac{-j\,{}^{2}/_{Y}\,(X - {}^{2}/_{Y})}{-\,{}^{2}/_{Y} + (X - {}^{2}/_{Y})} + jX_{th}}\right]V_{th} \tag{3.1}$$

On the other hand, in the situation where the shunt reactor is connected, the reactance X_{shunt} is taken into account. Thus, the voltage is: $V_{connected}$

$$V_{connected} = \left[\frac{-j\,{}^{2}/_{Y}}{-j\,{}^{2}/_{Y} + jX}\right]\left[\frac{Z}{Z + jX_{th}}\right]V_{th} \tag{3.2}$$

Where,

$$Z = j\left[\frac{X\left({}^{Y}/_{2} - {}^{1}/_{X_{shunt}}\right) - 1}{X\,{}^{Y}/_{2}\left({}^{1}/_{X_{shunt}} - {}^{Y}/_{2}\right) + Y - {}^{1}/_{Xshunt}}\right] \tag{3.3}$$

The results are presented in figure 3.5, where the voltage V at the end of the transmission line is calculated before (grey colour) and after (red colour) reactor connection in the three cases.

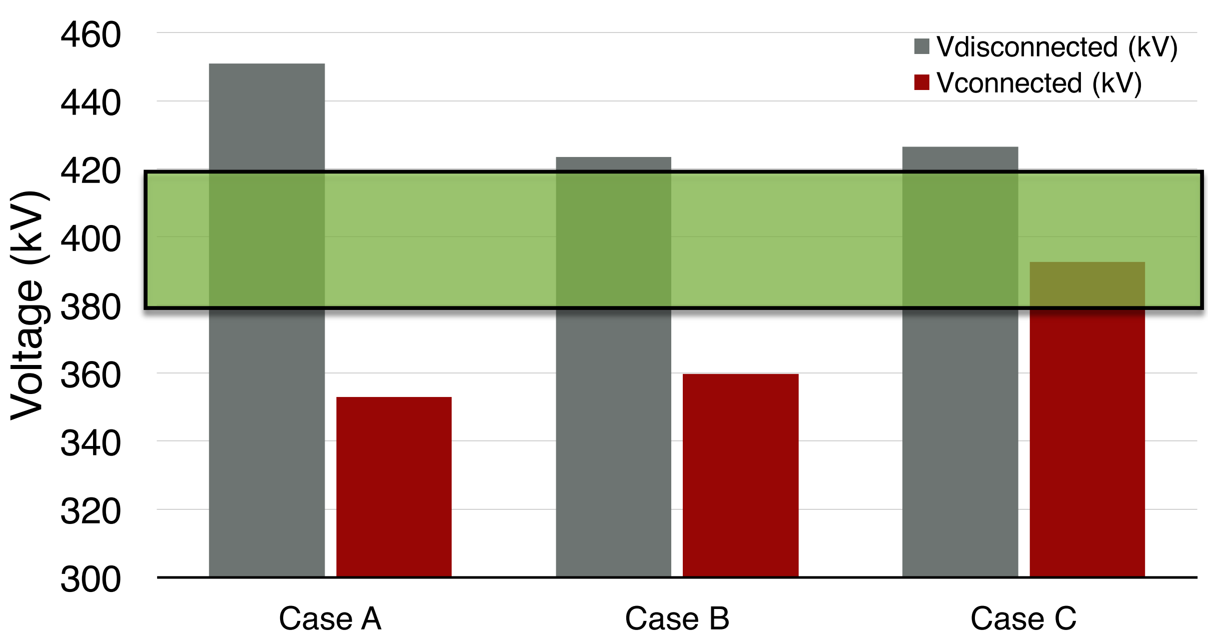


Figure 3.5. Voltage at the end point of the transmission line before (Grey) and after (Red) the shunt reactor connection.

In cases A and B, the voltage drop is too high and the voltage decreases below the lower limit of the tolerance band, and then Reactor Hunting phenomenon starts. When two lines are energized from a strong network (case C), Reactor hunting does not happen, because the voltage drop is lower and the voltage after shunt reactor connection stays within the limits of the tolerance band.

Once the voltage behaviour has been demonstrated, it is necessary to see how the Network strength influences this phenomenon. In order to see this relation, the short circuit power S_{sc} is determined, as a measure of the network strength.

The short circuit power is calculated based on the short circuit current I_{sc}, and the ending point voltage of the transmission line V_{sc} before the shunt reactor connection (No load voltage). The expression for S_{sc} is:

$$S_{sc} = V_{sc} I_{sc} \tag{3.4}$$

Where short circuit current is:

$$I_{sc} = \left[\frac{V_{th}}{jX_{th} + \frac{-j(2/_Y)X}{X - 2/_Y}} \right] \left[\frac{2/_Y}{(2/_Y) - X} \right] \tag{3.5}$$

With expression 3.4 and 3.5, and the parameters of table 3.1, the short circuit power can be obtained. The results for the three cases is presented in table 3.2.

Case A	Case B	Case C
$S_{sc1} = 920,1\ MVA$	$S_{sc2} = 1327,6\ MVA$	$S_{sc3} = 2522,8\ MVA$

Table 3.2. Short circuit power of the shunt reactor bus.

The main results of the demonstration are presented in figure 3.5 and table 3.2. In the light of the results, each case has different short circuit power. Consequently, there is an inversely proportional relation between voltage change (connection of reactor shunt) and short circuit power: the lower short circuit power (Weaker network), the higher change in voltage (Case A).

In conclusion, short circuit capacity is a good indication to determine if reactor hunting will occur or not. In consequence, this parameter needs to be determined to stablish the level of risk of reactor hunting in each bus of the network during restoration process in order to design a plan for avoiding the phenomenon.

3.2. Reactor Hunting Avoidance Methods

As it has been explained, Reactor Hunting is a phenomenon that makes a negative impact in the electric power system during restoration, producing large voltage fluctuations. These oscillations are not acceptable and need to be avoided in order to make a secure, effective and fast restoration process.

3.2.1. Traditional Method

To attack the problem, the common practice to avoid Reactor Hunting and speed up the restoration process for TSOs around the world is turning off the EVAs during restoration time. This strategy leaves the reactor shunt in manual operation and the Reactor Hunting is avoided. However, the restoration process is not as fast as preferably would be, and this avoidance method leads to slow down restoration process.

Consequently, an alternative method to avoid Reactor Hunting and also speed up the restoration process is needed. This method is known as Adaptive Tolerance Band [1].

3.2.2. Adaptive Tolerance Band

As it has been shown above, disconnecting the EVAs and make the restoration process with the reactor shunts in manual operation is not an effective solution. The Adaptive tolerance band method for the EVAs to avoid Reactor Hunting proposes another approach to the problem.

Instead of having a fixed tolerance band, the EVAs setting will change based on the network strength, and the tolerance band will be adjusted. Thus, this method proposes an adaptive tolerance band based on the operating conditions. By implementing this technique, the automatic operation of the shunt reactors can continue during restoration time, which speeds up the restoration process [1].

It has been stated above that short circuit power is an indicator for the network strength: the lower the short circuit capacity, the weaker the node. In consequence, it is needed to stablish a formula to relate the short circuit capacity of the operating conditions of the network, based on measurable data., with the voltage sensitivity. To derive the approximate formula, circuit of figure 3.4 is considered with the following assumptions [1]:

- The shunt reactor is disconnected at the remote end of the transmission line, in order to analyse the system without external actuators.
- The Thévenin reactance is neglected since it is assumed that the voltage at the sending point of the transmission line is fixed ($E \angle 0$).
- The transmission line admittances are disregarded since they do not affect excessively the shot circuit power at the remote end of the line.

The simplified circuit from figure 3.4, taking into account the assumptions stated above is represented in figure 3.6.

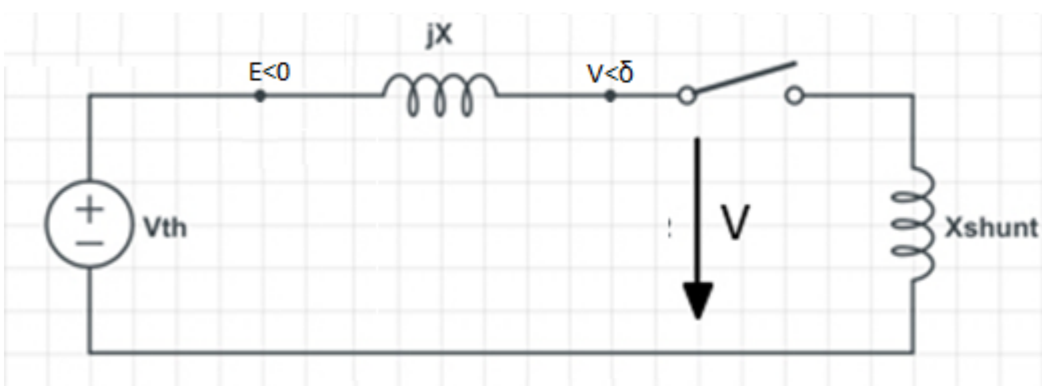


Figure 3.6. Simplified Circuit.

With this considerations, the expression for determining the reactive power Q received at the remote end of the transmission line is [8]:

$$Q = \frac{EV}{X} cos\delta - \frac{V^2}{X} \tag{3.6}$$

From this equation, it can be obtained the equation which represents the voltage sensitivity with respect to the reactive power:

$$\frac{\partial V}{\partial Q} = \left(\frac{\partial Q}{\partial V}\right)^{-1} = \left(\frac{E}{X} cos\delta - \frac{2V}{X}\right)^{-1} \tag{3.7}$$

If the equivalent system is unloaded, then $\delta = 0$ and it is considered that the voltage along the transmission line does not change, i.e. the voltage level at the sending point is equal to the voltage level of the receiving end of the transmission line: $E = V = 1$. Then, the expression 3.7 is reduced to:

$$\frac{\partial V}{\partial Q} = \left(\frac{E}{X} - \frac{2E}{X}\right)^{-1} = \left(\frac{-E}{X}\right)^{-1} = \frac{X}{E} = -X(pu) \tag{3.8}$$

This last consideration will be discussed at the end of the chapter, where the influence of the Ferranti effect (chapter 2) will modified this simplification.

On the other hand, with the definition of short circuit power (equation 3.4), it can be obtained a relation between X and S_{sc}:

$$S_{sc}(p.u.) = V_{th} I_{sc} = \frac{V_{th}^2}{Z_{th}} = \frac{E^2}{X(p.u.)} \approx \frac{1}{X(p.u.)} \tag{3.9}$$

Therefore, since the per unit short circuit capacity is inversely proportional to the reactance, the final expression for voltage sensitivity with respect to reactive power received at the end of the transmission line is approximately:

$$\frac{\partial V}{\partial Q} = -X(pu) \approx -\frac{1}{S_{sc}(p.u.)} \tag{3.10}$$

In the light of the results, it has been demonstrated that if a certain node of the system at some stage of the restoration process has low short circuit capacity, i.e., it is a weak bus; then the voltage sensitivity to the injection or consumption of reactive power is high and the voltage fluctuation with the connection and disconnection of reactor shunts might lead to reactor hunting.

This last assumption states the base for the avoidance method of the adaptive tolerance band. As it has been described before, the main variables that affect Reactor hunting and possible ways to avoid reactor hunting with each of them are presented in table 3.3. These four parameters presented are critical to reactor hunting phenomenon.

From table 3.3, it is concluded that the first three parameters are difficult or impossible to modified during restoration. In consequence, the parameter which is more convenient to modified during restoration process is the tolerance band of the automatics, and that is the reason why this project focuses on this method for reactor hunting phenomenon avoidance. The main advantage of this method is that, given the short circuit capacity of the system, it is easy to adjust the tolerance band through software and send it to the automatics.

The adaptive tolerance band method is based on equation 3.11, which shows that the voltage change at a specified node can be predicted if the short circuit power of the node and the amount of reactive power change are known.

$$\partial V \approx -\frac{\partial Q}{S_{sc}(p.u.)} \tag{3.11}$$

The adaptive tolerance band method for reactor hunting phenomenon uses equation 3.11 to predict the bus voltage after shunt reactor connection when a specified transmission line is energized, during restoration process. In consequence, before the reactor connection, EVAs settings of the shunt reactor are adjusted, decreasing the lower limit of the tolerance band in order to avoid reactor hunting.

To illustrate this method, the adaptive tolerance band is applied for cases A and B of the demonstration [1]. (section 3.1.2.). Taking into account that the nominal value of the shunt reactor is 200 Mvar and the short circuit capacity presented in table 3.2., equation 3.11 predicts a voltage drop of:

- Case A: Voltage drops to 352 kV, which is a decrease of around 22%.

- Case B: Voltage drops to 360 kV, which is a decrease of around 15%, lower than case A because of higher short circuit power.

In consequence, EVAs settings are set to a new lower limit of the tolerance band: below 352 kV for case A, and below 360 kV for case B. Then, reactor hunting is completely avoided. This change in the tolerance band is presented in figure 3.7.

The reason to adjust the lower limit instead of the upper limit of the tolerance band is easy to describe. If the upper limit is incremented in order to prevent the shunt reactor from connecting and avoid reactor hunting, then overvoltages are permitted. Therefore, if a new transmission line is energized the voltage will rise even more due to Ferranti effect, making the situation more problematic.

Reactor Hunting parameters		
Variables	**Description**	**Actions**
The overvoltage	The overvoltage produced at the receiving end of a transmission line during the restoration process depends on the line (length, reactance, etc.) and system characteristics (voltage at the sending point)	This parameter is difficult to be modified since it depends on the physic characteristics of the electric power systems.
The reactor shunts rating	Reactor shunts stablish the amount of reactive power that will be consumed, which affects the voltage drop after the connection of the shunt.	Variable Shunt Reactors (VSR) [14], can manage the voltage drop by adjusting the rating of the reactor and making the voltage drop stay within the limits of the tolerance band. However, VSR are not in widespread use, and traditional shunt reactor with fixed rating are more commonly installed.
The Short circuit capacity S_{sc}	As it has been demonstrated above, S_{sc} affects the voltage drop after the connection of the reactor shunt. The weaker the node, the higher the decrease after connection of the shunt reactor.	Short circuit capacity is an inherent characteristic of the electric power system and the actual state of the network: which buses are connected, which lines, transformers, etc. In consequence, it is not a parameter that can be modified in order to avoid reactor hunting phenomenon during the restoration process.
The Automatics	EVAs have a tolerance band that stablish the behaviour of the connection and disconnection of reactor shunts and determine the range in which reactor hunting can take place. They stablish an upper limit to trigger the connection of the reactor shunt in order to decrease the over voltage and a lower limit to disconnect the reactor shunt.	Changing the tolerance band is an easy task, which can avoid reactor hunting. If the tolerance band is adjusted in order to decrease the lower limit of the band enough to cover the voltage drop after shunt reactor connection, then the reactor hunting phenomenon is avoided.

Table 3.3. Parameters that influence Reactor Hunting phenomenon.

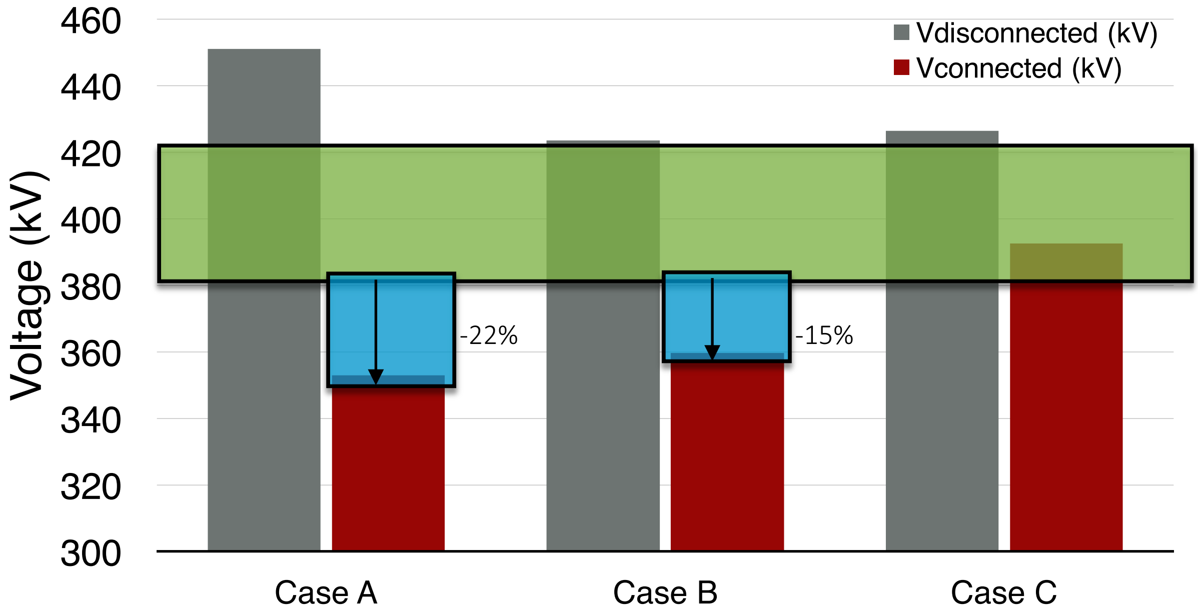


Figure 3.7. Adaptive tolerance band.

As it is represented in figure 3.7, decreasing the lower limit of the tolerance band will include the voltage after shunt reactor connection within the tolerance band, preventing the EVAs from triggering the disconnection again and thus, avoiding reactor hunting phenomenon.

It is important to note that the result of this control scheme is a new lower limit for the tolerance band. In consequence, it needs to be set also limits for this new lower limit in order to prevent extreme low voltages.

The important thing of this methodology is that it predicts the decrease in voltage after shunt connection. If the prediction is accurate, the lower limit will be adjusted precisely so any other external alteration of the voltage can be still detected by the automatics. If the adjustment is not accurate, an unexpected voltage drop may be ignored.

In addition, the voltage drop prediction allows to detect when the extreme low voltage will be encountered after shunt reactor connection, so it can be decided if carry on with the restoration or take additional measures to control the voltage.

To conclude, the adaptive tolerance band method restores the original tolerance band with the default values (440 – 380 kV) after the restoration process is finished in order to control the voltage of the power system for normal operation.

Ferranti effect consideration.

The adaptive tolerance band method described until this point (from equations 3.6 to 3.11), had the assumption that the voltage at the receiving end of the transmission line was the same as the voltage level at the sending point, i.e. $E = V = 1$.

However, it is known that the voltage at the receiving end of the transmission line is different, and, if there is no load, higher due to the Ferranti effect explained in chapter 2. In consequence, the previous assumption is not accurate, and both voltages need to be considered differently $E \neq V$.

This new assumption must be taken into account in order to make more accurate the expression 3.11, and thus the adaptive tolerance band method. All the assumptions stated in the previous section and the circuit of figure 3.6 as reference are considered.

Starting from equation 3.7, which represents the voltage sensitivity with respect to the reactive power:

$$\frac{\partial V}{\partial Q} = \left(\frac{\partial Q}{\partial V}\right)^{-1} = \left(\frac{E}{X}cos\delta - \frac{2V}{X}\right)^{-1} \tag{3.7}$$

It is assumed that the sending point voltage is fixed at $E = 1$ and the transmission line is unloaded ($\delta = 0$). In addition, because of Ferranti effect, the voltage at the receiving end of the line V is higher than the voltage at the sending point of the transmission line.

The voltage V is defined as a percentage of the voltage at the sending point E:

$$V = \alpha E \tag{3.12}$$

Where α is a constant value bigger than 1.

By applying the above considerations, equation 3.7 is then:

$$\frac{\partial V}{\partial Q} = \left(\frac{\partial Q}{\partial V}\right)^{-1} = \left(\frac{E}{X} - \frac{2V}{X}\right)^{-1} = \frac{X}{1 - 2\alpha} \tag{3.13}$$

The short circuit power at the receiving end of the transmission line is calculated as follows:

$$S_{sc} = \frac{V^2}{X} = \frac{\alpha^2 E^2}{X} = \frac{\alpha^2}{X} \tag{3.14}$$

Adding S_{sc} to 3.13, the following expression can be obtained:

$$\frac{\partial V}{\partial Q} = \left(\frac{\alpha^2}{1 - 2\alpha}\right)\frac{1}{S_{sc}(p.u.)} \tag{3.15}$$

In conclusion, the adaptive tolerance band is based on equation 3.16, which is similar to the expression 3.11, but adding the influence of the Ferranti effect α.

$$\partial V = \left(\frac{\alpha^2}{1 - 2\alpha}\right)\frac{\partial Q}{S_{sc}(p.u.)} \tag{3.16}$$

The last thing that needs to be discussed is the value for the parameter α. The 2003 Swedish blackout case is taken as reference and use the same α ($\alpha = 1.14$) [17].

3.3. Summary

This chapter has presented the reactor hunting phenomenon: its causes and its effects. It is concluded that, during restoration, Reactor hunting is a critical problem that causes voltage fluctuation between overvoltages and extreme low voltages. Thus, this problem needs to be avoided.

It has also been stated that the actual method to avoid reactor hunting is to switch off the EVAs and make the restoration process with the connection of reactor shunt in manual mode. Therefore, the restoration time increases significantly.

This is the main reason why it is important to study an automatic method for reactor hunting in order to speed up the restoration process, which is the goal of this thesis. In order to fulfil this objective, the adaptive tolerance band method is presented.

The reason to study this method is mainly because it is based on changing the automatics settings (tolerance band), which is an economic and fast solution because it is based on software implementation.

This method consists of decreasing the lower limit as much as needed to avoid the reactor disconnection and thus, avoiding reactor hunting. The expression for the adaptive tolerance band was determined considering the simplification of flat voltage profile along the transmission line.

To finish, this simplified expression was completed with the Ferranti effect consideration, which state that the voltage at the receiving end of the line is higher. The equation 3.16 is the final expression that defines the adaptive tolerance band method.

CHAPTER 4. PROGRAMS AND MODELS

In the previous chapters, the main aspects of theory needed in order to understand the Reactor Hunting phenomenon has been described. In addition, it has also been proposed the adaptive tolerance band method to avoid reactor hunting.

To study this phenomenon, which is associated with blackouts and restoration process of an electric power system, it is important to have a suitable software. The software needs to be able to manage long and short term dynamics. The main systems that provide this sort of functionalities are training simulators for operators of power systems, which also provides an interactive user interface.

Currently, there are an important number of training simulators available. They are mainly used to educate in normal network operation and handling small disturbances. However, there are some simulators that are useful to study some phenomenon, such as reactor hunting, during blackout and restoration scenarios.

As far as implementation is concerned, this project is based in the use of three different software programs that will allow to study the possibilities of the adaptive tolerance band method. These three modules are:

1. The power system simulator ARISTO version 4.5. [22]. It is an electric power system simulator which provides the environment in which a realistic electric power system is simulated and reactor hunting studies can take place.
   It is a tool for training operators and education or research analysis. It is able to run large systems with large number of components and automatics models. The simulations are fully interactive with a friendly user interface and include dynamic analysis at real time operation with a 20 ms time step speed.
   NORDIC32 is the system considered in this project. It is a CIGRE test system which can be considered as a simplification of the Swedish electric power system with similar characteristics [23].

2. MATLAB 2012a. (MathWorks). [24]. It is a programing language environment software, developed by MathWorks, which is used to implement the software of the automatic adaptive tolerance band method for reactor hunting avoidance in real-time operation.

3. AMCX version 1.0 [25]. AMCX offers an environment for communication between ARISTO and MATLAB which allows the implementation of the algorithm and study the results in the NORDIC32 test system during restoration.

This chapter presents the main aspects and characteristics of these modules and the NORDIC32 test system.

4.1. ARISTO

The real time power system simulator ARISTO is a fast, interactive simulator with real-time capabilities (20 ms time step), which offers high performance calculations and efficient models. This allows large power systems to be studied.

Consequently, it combines the advantages of an analysis tool and a dispatch training simulator. The simulator is, in consequence, a suitable tool for training operators, but it is also useful for research analysis in depth.

The following dynamic phenomena can be simulated [22]:

- Transient stability, with short circuits, line switchings, etc.
- Long term dynamics, with frequency control, etc.
- Voltage collapse phenomena.
- Restoration process.

4.1.1. History

The idea of the ARISTO simulator arose from the experience learnt on the Swedish power outage in December 1983. The ARISTO project development started, and the first version of the simulator was completed by Svenska Kraftnät in 1993. Further development has continued ever since [26].

Nowadays, ARISTO is a simulator used in Svenska Kraftnät for training operators: understanding systems behaviour, disturbance and fault analysis and control, routine maintenance control, etc. Statnett, Vattenfall, E.ON and Fortum also use ARISTO for the same purposes [27].

On the other hand, ARISTO is also used for educational and research purposes in Swedish technical universities in Lund (LTH), Stockholm (KTH) or Göteborg (Chalmers University).

4.1.2. Structure

The ARISTO system is executed on a standard multiprocessor workstation from Sun Microsystems, Inc. The graphic user interface utilizes three screens. It is made for Solaris operating system, and runs on X86 and Sperc processors. It is developed in C/C++ and it uses Data views graphical library [22].

The simulator may be divided into three main subsystems: The “User Interface”, “Run-Time System” and “Data Preparation”. In figure 4.1., it is represented the working environment of ARISTO simulator.

The features, options, capabilities and tasks of the three subsystems are presented in table 4.1.

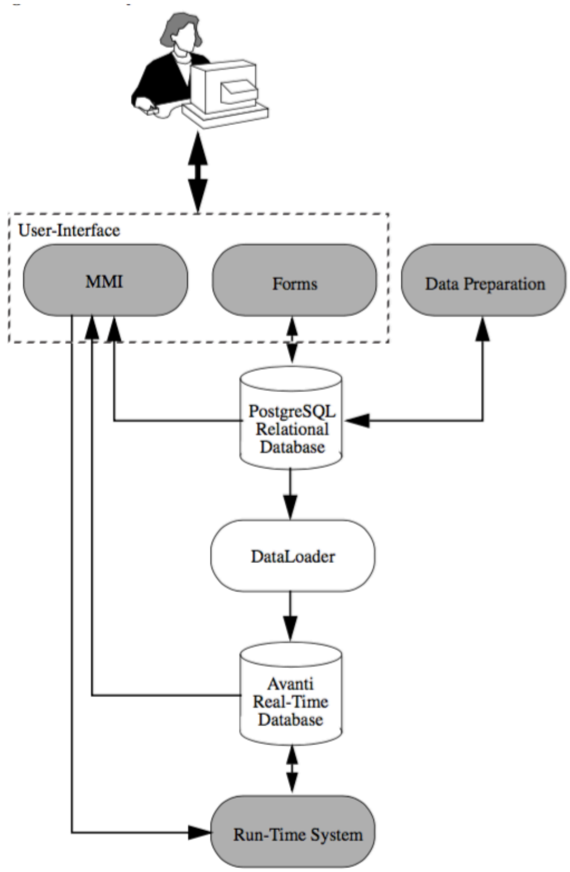


Figure 4.1. ARISTO power system simulator environment [22].

Subsystem	Description
User Interface	The ARISTO power system simulator is controlled through its user interface, or MMI (man-machine-interface). The user interface is divided into a number of applications (ControlPanel, EventBrowser, etc.). Using the MMI, it is possible to change simulation parameters; prepare data previous to the simulation, and control the electric power system during simulation (open circuit breakers, measure voltage, set generator operating point, etc.)
Run-Time system	The run-time system is the part of the ARISTO power system simulator in which the actual real time calculations are performed. It consists of the power system model and the real time database.
Data preparation	In the data preparation subsystem, the network data is stored. The work in this mode is made off-line and when all necessary data are available, a load flow is carried out, to calculate an initial state. All the data may then be loaded from the relational database to the real time database in the Run-time system.

Table 4.1. ARISTO Subsystems

4.1.3. Modelling

In order to understand how ARISTO works, it is important to know the model structure it has. In ARISTO, the total amount of data describing a power system is called the Power System Model (PSM), which is stored in a relational database and in a file system [28].

Every single component is the PSM is defined as an object, from a port of a transmission line to a regulator or circuit breaker. Each object must have its own identity, and they can be arranged in a hierarchical geographical order (Areas and Zones), as it is presented in figure 4.2.

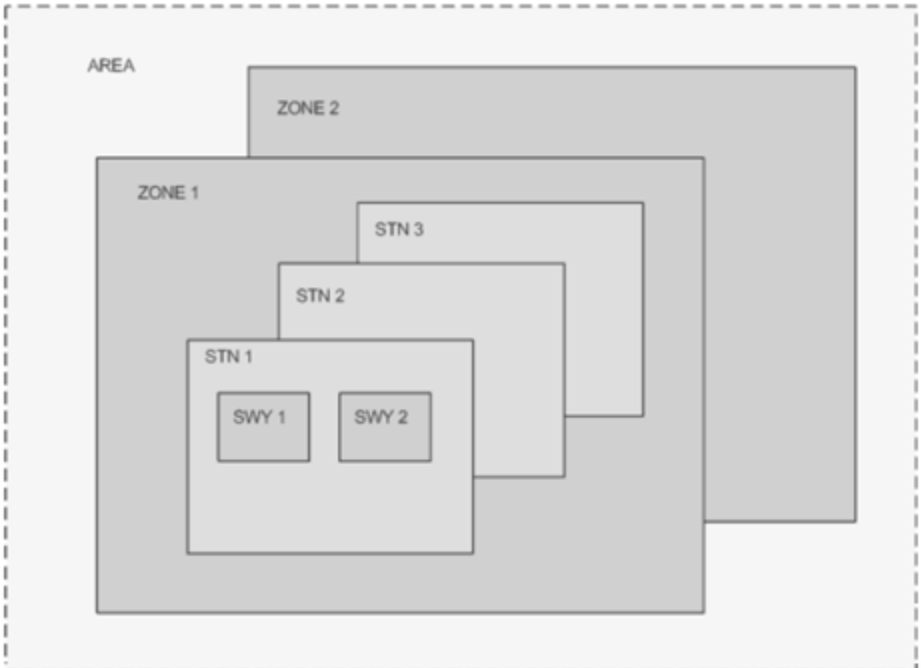


Figure 4.2. Hierarchical Model Structure of PSM in ARISTO [28].

The lower level in the PSM structure is the Switchyard (SWY), which is characterized by the corresponding voltage level, which cannot change inside it. Each switchyard may contain the different objects that form an electric power system: busbars, shunts, loads, generators, breakers and disconnectors. Line and transformers connect switchyards, so these components are part of both switchyards.

All the network components are stored in the ARISTO database and are characterized by their main parameters that can change in order to adjust them to the value required for each particular PSM. The ARISTO models are divided into the following main groups [29]:

- Network object models. Connections, switches, lines, transformers, shunt and series compensators, etc.
- Load models.
- Generation (Synchronous machines). General parameters, excitation system, etc.
- Protection.
- Automatics.

The stations (STN) contain one or more switchyards. In addition, every station, together with other stations belong to a geographical zone (ZONE), which is part of the higher level of the model structure of PSM, known as geographical area (AREA).

4.1.4. User Interface

The ARISTO power system simulator is controlled via its user interface (MMI), which is divided into a number of applications. Using the MMI, it is possible to change simulator properties, prepare data for the simulation and control the simulated power system process during simulation.

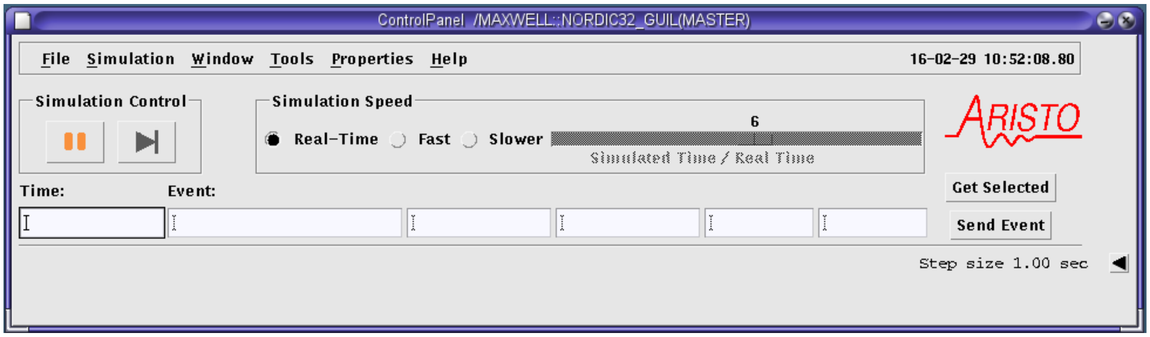


Figure 4.3. Control Panel Application [ARISTO].

All the simulator system is controlled via the *Control Panel* application (Figure 4.3.), which is the main application. Starting ARISTO implies opening the *Control Panel,* from where it can be chosen a PSM, and initiate or conclude simulation. From *Control Panel,* the different applications can be open.

The ARISTO user interface is divided into a number of applications, each of which is controlled in its own window. Each application is designed for a specific activity or purpose, e.g. displaying the network diagram, plotting different diagrams, etc.

The main applications are: *Network Diagram, Curve Diagram, Event Browser and Panel, Unit Panel [22]*.

- The *Network Diagram* application displays overviews of the system state of the network. It is shown important information of voltage, current or power levels of the different switchyards, lines and transformer. In addition, warning and alarms may be connected in order to highlight overloads or overcurrents with a change in colour of the object. By using pop-up menus more information about specific objects can be obtain and it is also possible to perform connection and disconnection operations.
  There are different interactive views, which can be used to arrange the different objects of the system in different ways, and to open the station diagram for a particular station of the system. In figure 4.5 it is presented an example of a station diagram (VATTENDRAGET AT111)

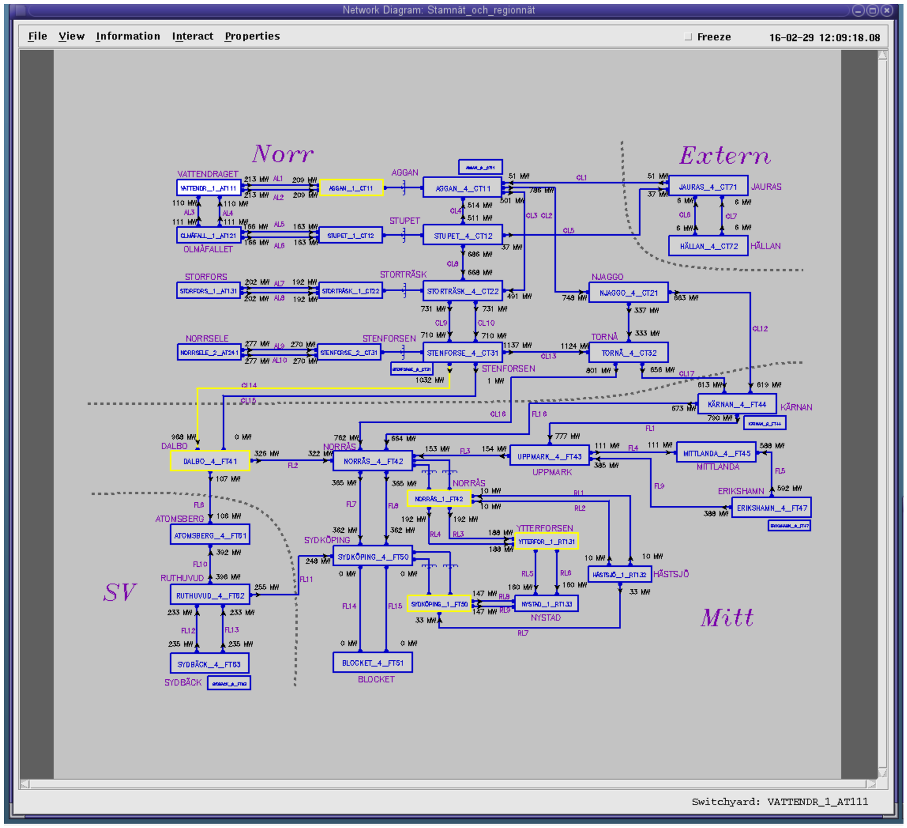


Figure 4.4. Network Diagram Application [ARISTO]

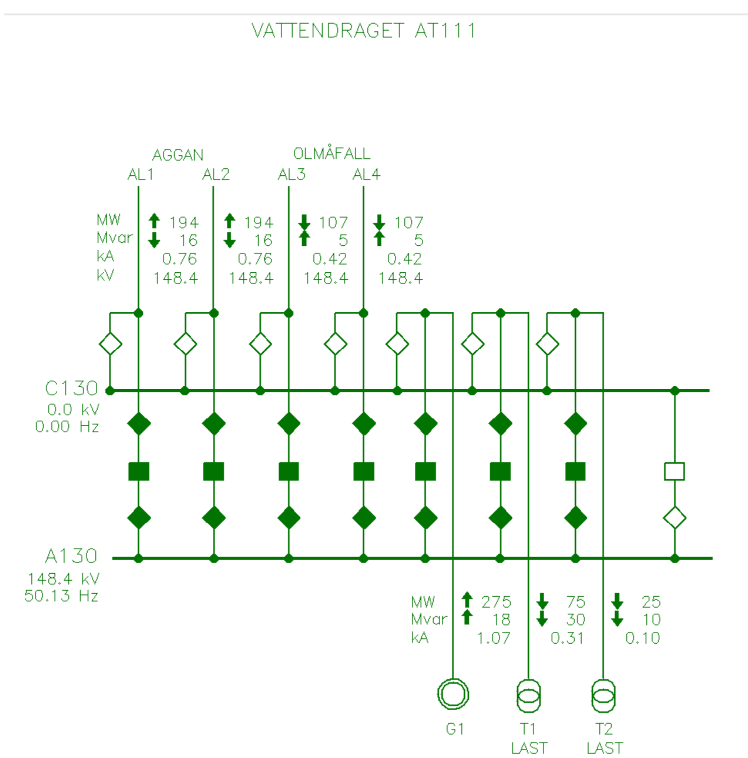


Figure 4.5. Station Diagram [ARISTO].

- The *Curve Diagram* application is used to display results during simulation. Network parameters are plotted in different diagrams, e.g. graphs or bar charts.

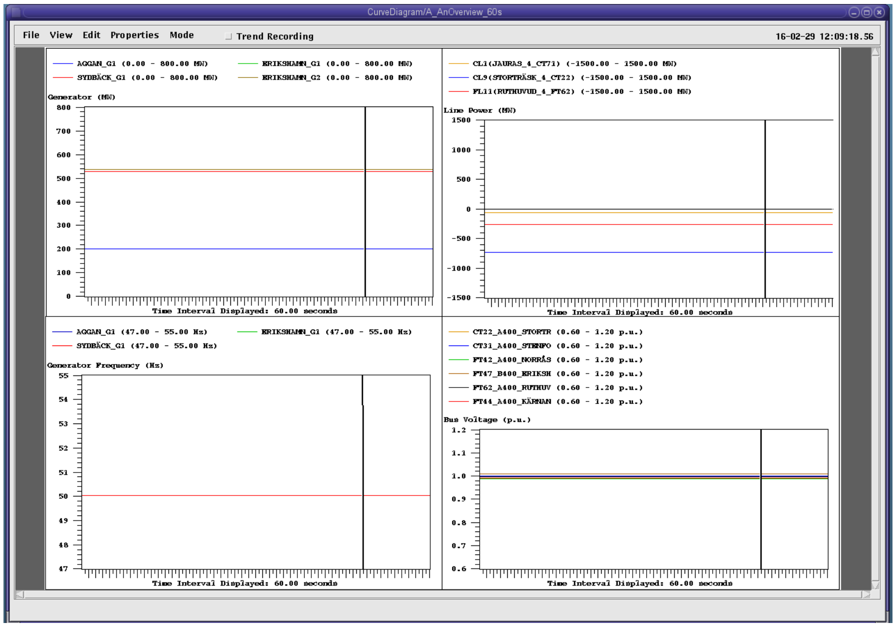


Figure 4.6. Curve Diagram Application [ARISTO].

- The *Unit Panel* application is used to monitor and control a specific generation unit. The set-point values for voltage or active and reactive power can be changed. In addition, start, stop or tripping of the unit is also performed in the *Unit Panel.*

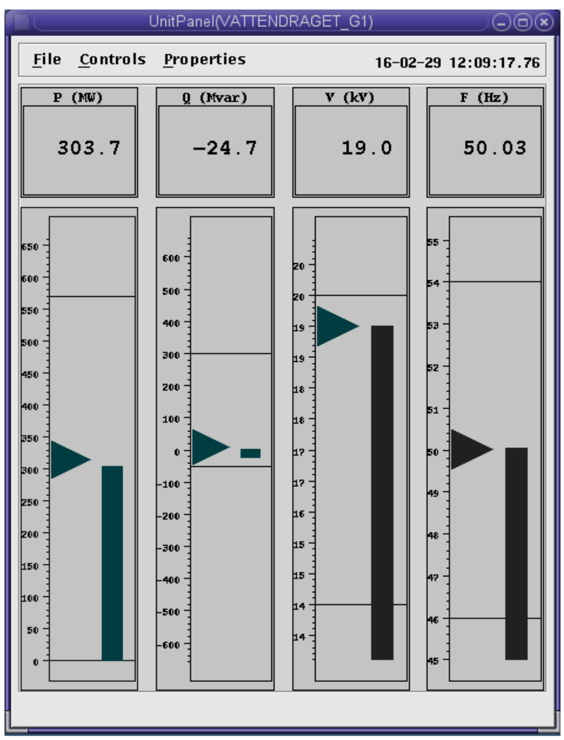


Figure 4.7. Unit Panel [ARISTO].

- The *Event Browser* and *Event Panel* applications are used to manage events. In ARISTO, all commands and actions to the simulator are referred to as events. Events can be sent via user interaction with MMI, e.g. when changing the voltage set-point of a generation unit in the *Unit Panel*. However, every action is registered as an event and is managed by the *Event Browser* and *Event Panel* applications (Figure 4.8).
  On one hand, the *Event Browser* is used to display the event log during simulation. Each event is registered in it. On the other hand, the *Event Panel* is used to send events and create event sequences. All the events that are not sent via the user interface are sent via the *Event Panel.*

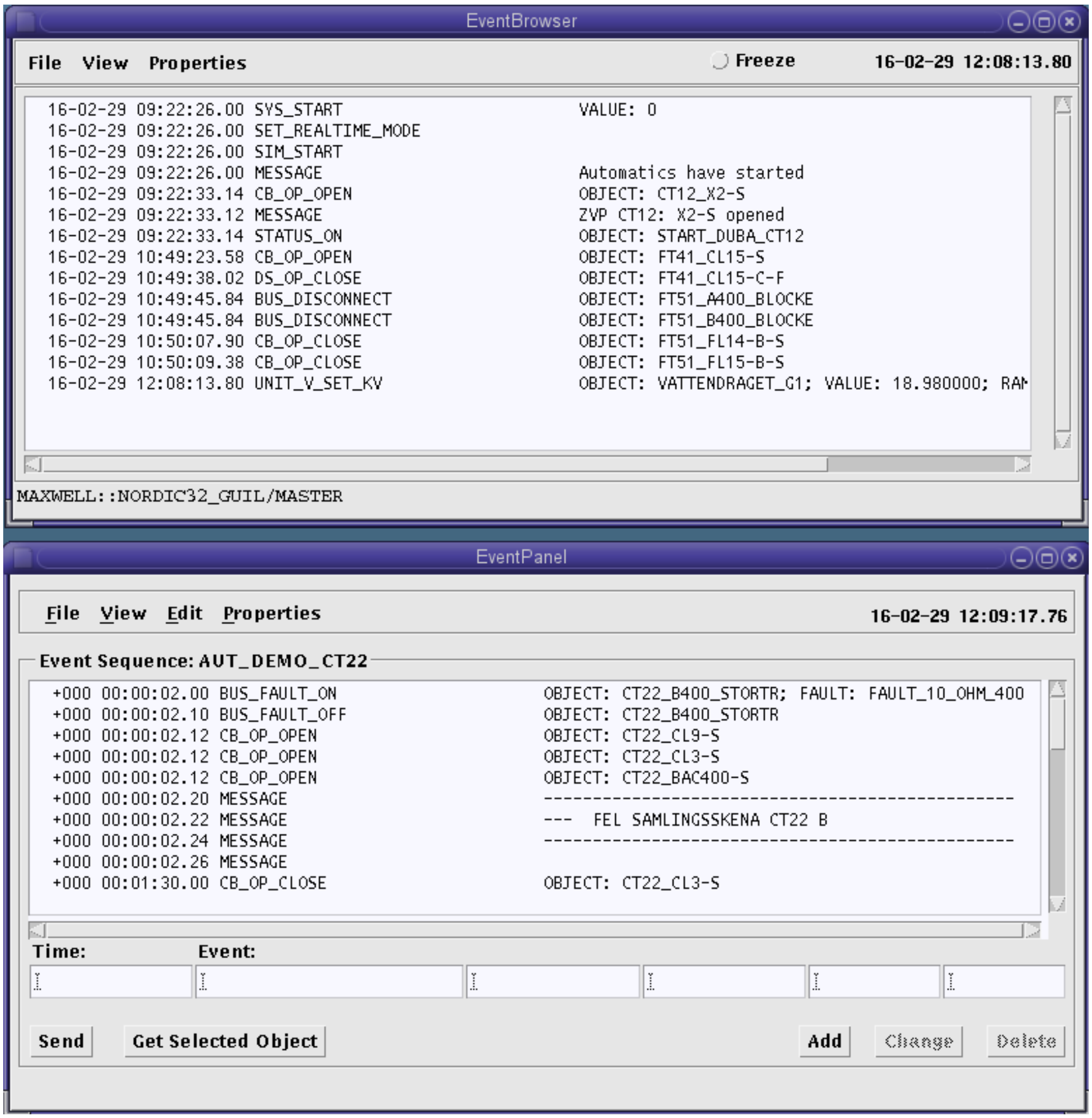


Figure 4.8. Event Browser (upper) and Event Panel (lower) applications [ARISTO].

In figure 4.9, it is presented a possible view of the ARISTO during simulation at Lund University office. The user interface consists in three screens working in the simulation in order to make space to display different applications at the same time.

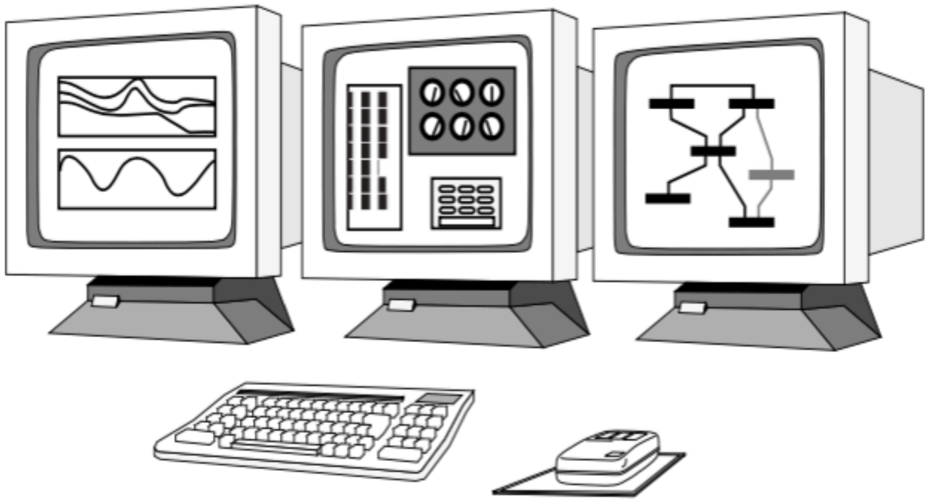


Figure 4.9. ARISTO User Interface [22].

4.2. MATLAB

Since ARISTO is a power system simulator for operator training, its main objective is not research and electric power system design. In consequence, it is limited in programming tools. In ARISTO, it is possible to: change and create new systems, change the automatics configuration, add new components, etc.

However, it is not possible to change parameters or automatics during simulation in real time in automatic mode. As a consequence, another software solution needs to be considered, if research is carried out, for example, for implementation of the adaptive tolerance band method for reactor hunting avoidance. The solution considered for this project is MATLAB [24].

MATLAB is a widespread solution, that offers a high-level language and interactive environment. In addition, MATLAB offers Simulink tool, which provides a graphical programming interface that it is very suitable for simulation.

By using MATLAB and Simulink, it is possible to write the necessary code in order to implement real-time simulation, where computation, data gathering, plotting graphs and making decisions can be done at the same time.

In consequence, MATLAB and Simulink are suitable for the purpose of this project, which is implementation of the automatic adaptive tolerance band method for reactor hunting avoidance during restoration in real-time simulation

However, MATLAB and ARISTO are not compatible by default, and MATLAB can not obtain the system data automatically. Therefore, another tool needs to be considered in order to stablish real-time communication between MATLAB and ARISTO. This solution is AMCX [25].

4.3. AMCX

AMCX is a tool that establishes communication between ARISTO and MATLAB. In figure 4.10 it is presented the typical setup for the use of AMCX between 2 computers, where in orange is presented the AMCX system.

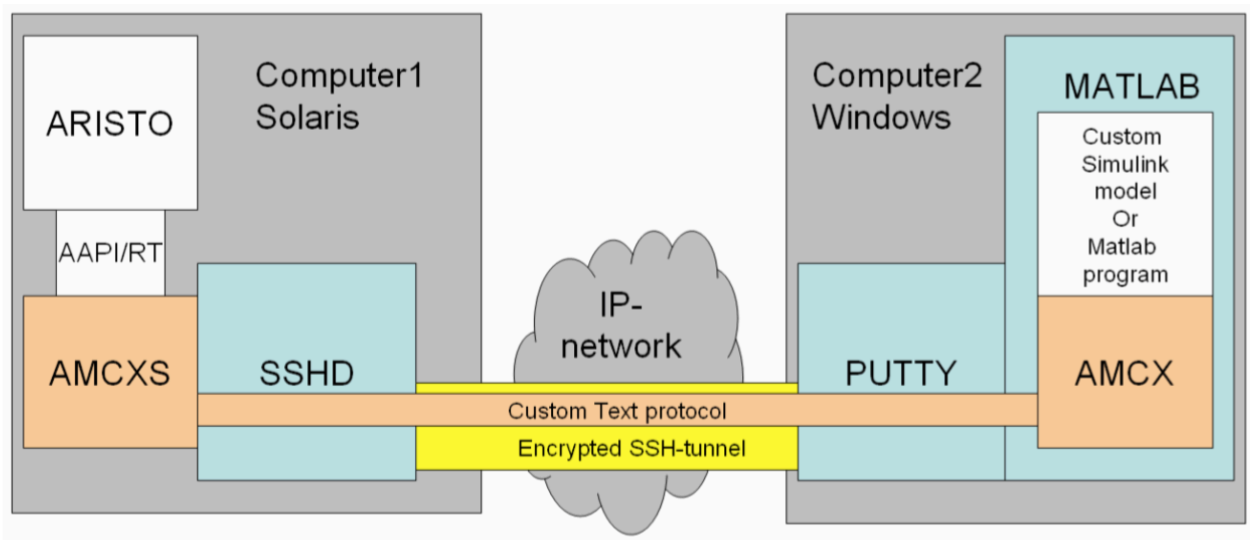


Figure 4.10. AMCX Setup between ARISTO and MATLAB [25].

As it can be seen in figure 4.10., the configuration of ARISTO and MATLAB through MATLAB comprises [25]:

- ARISTO power system simulator, which runs on Solaris operating system.
- AAPI/RT, C++ programming interface of ARISTO.
- SSHD the SSH-server, included in Solaris, for authentication, encryption and network communication.
- MATLAB, which runs on Windows operating system.
- PUTTY, a free SSH client for Windows operating system.
- AMCX, with AMCXS server implemented in C++ for Computer 1(Solaris) and AMCX client implemented in MATLAB (Computer 2).

As it has been explained above, ARISTO power simulator is designed for simulation of traditional power systems, and make difficult of unfeasible to use new models or control structures that are often motivated by research. However, general purpose tools, such as MATLAB, give the possibility of implementing this solution in a direct way.

AMCX provides the environment for combining ARISTO and MATLAB, and thus allows a range of activities that are not possible in ARISTO simulator alone. Some of the possible uses of this combination are [25]:

- Implementation of distance protection with visualization of the impedance plane.
- Control system for damping of power system oscillations with braking resistors.
- Modelling of wind power plants.
- Dynamic map colouring due to voltages or voltage angle.
- Convenient data recording for plotting figures in MATLAB.

In conclusion, in the working place at Lund university, AMCX is installed in an alternative computer with Windows operating system; and the communication with ARISTO computer is stablished in order to carry out the research of this project.

4.4. NORDIC32

As it was stated before, an electric power system model is needed in order to carry out simulations and obtain relevant results in the study. Thus, the test system considered is NORDIC32, developed by CIGRE [23]. This system has the main characteristics of the Swedish power system, but it is a reduced order network. This makes the system more convenient to the purposes of this project than a full representation the power system which is difficult or even impossible to develop.

The NORDIC32 system consists of four geographical areas with different production and consumption characteristics [30]:

- North. This area has high levels of Hydro generation and low level of consumption.
- Central. This area has Thermal generation and high level of consumption.
- Southwest. This area has low Thermal generation and some consumption.
- External. This area has moderate levels of hydro generation and consumption.

As far as transmission system is concerned, the NORDIC32 system consists of the main 400 kV transmission network (19 nodes) and two regional systems: one operating at 130 kV (11 nodes) and a second working at a voltage level of 220 kV (2 nodes). The transmission system thus contains 32 nodes.

Concerning generation, The NORDIC 32 system is modelled with 23 synchronous generators, of which 10 are Thermal power plants generators (round rotor), 12 are Hydro power plant generators (salient pole) and 1 salient pole synchronous compensator.

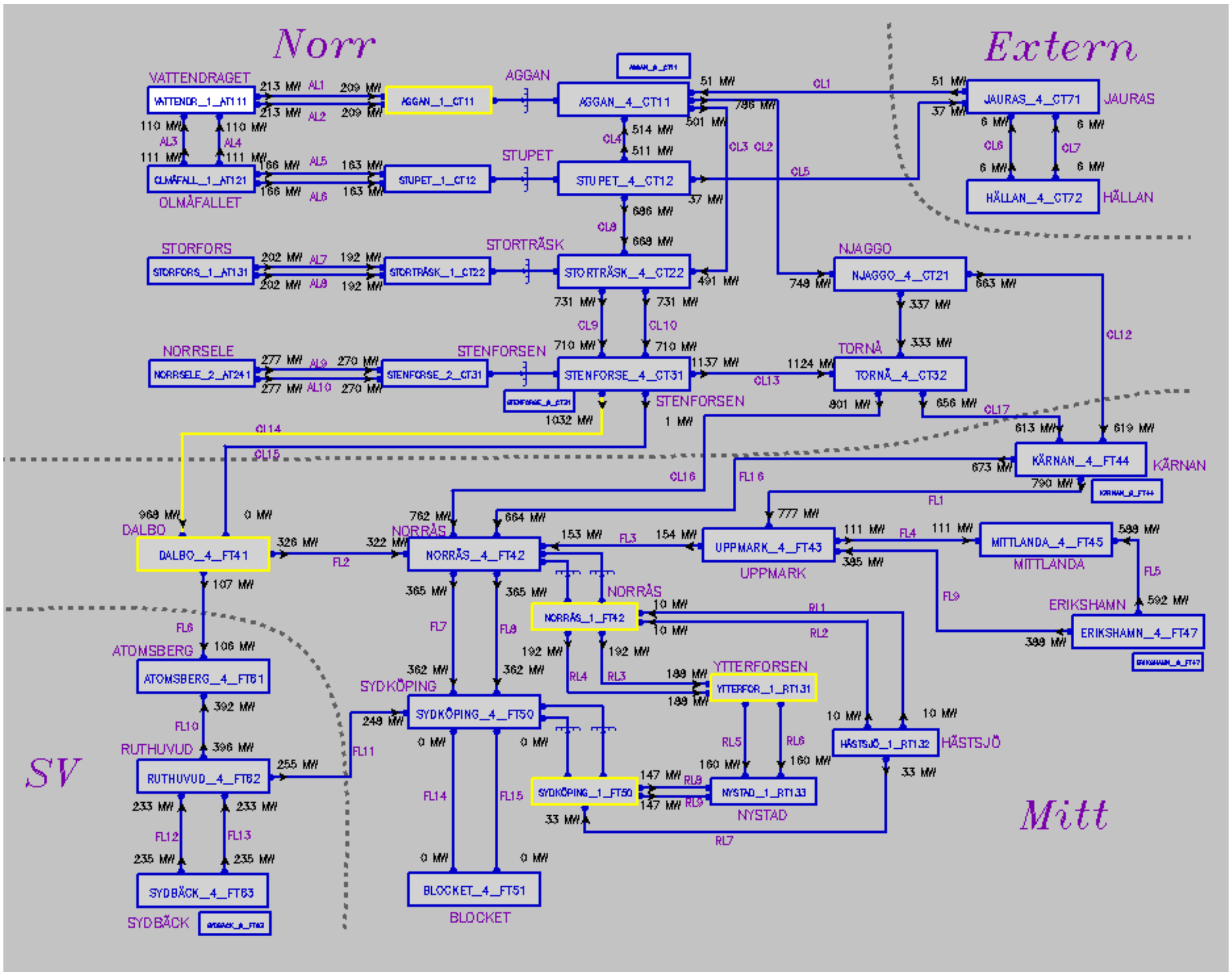


Figure 4.11. NORDIC32 System in ARISTO.

In figure 4.11 it is presented the NORDIC32 system common representation in ARISTO simulator, with the 32 nodes (Switchyards). In addition, it is interesting to see a geographical representation of the system, available in ARISTO (Figure 4.12).

The main characteristic of the NORDIC32, as in the Swedish electric power system, is the long distances between the main production area (North) and the core consumption area (Central). Both areas are connected by long transmission lines (400 kV) where series capacitance compensation is used in order to reduce the high electrical distance.

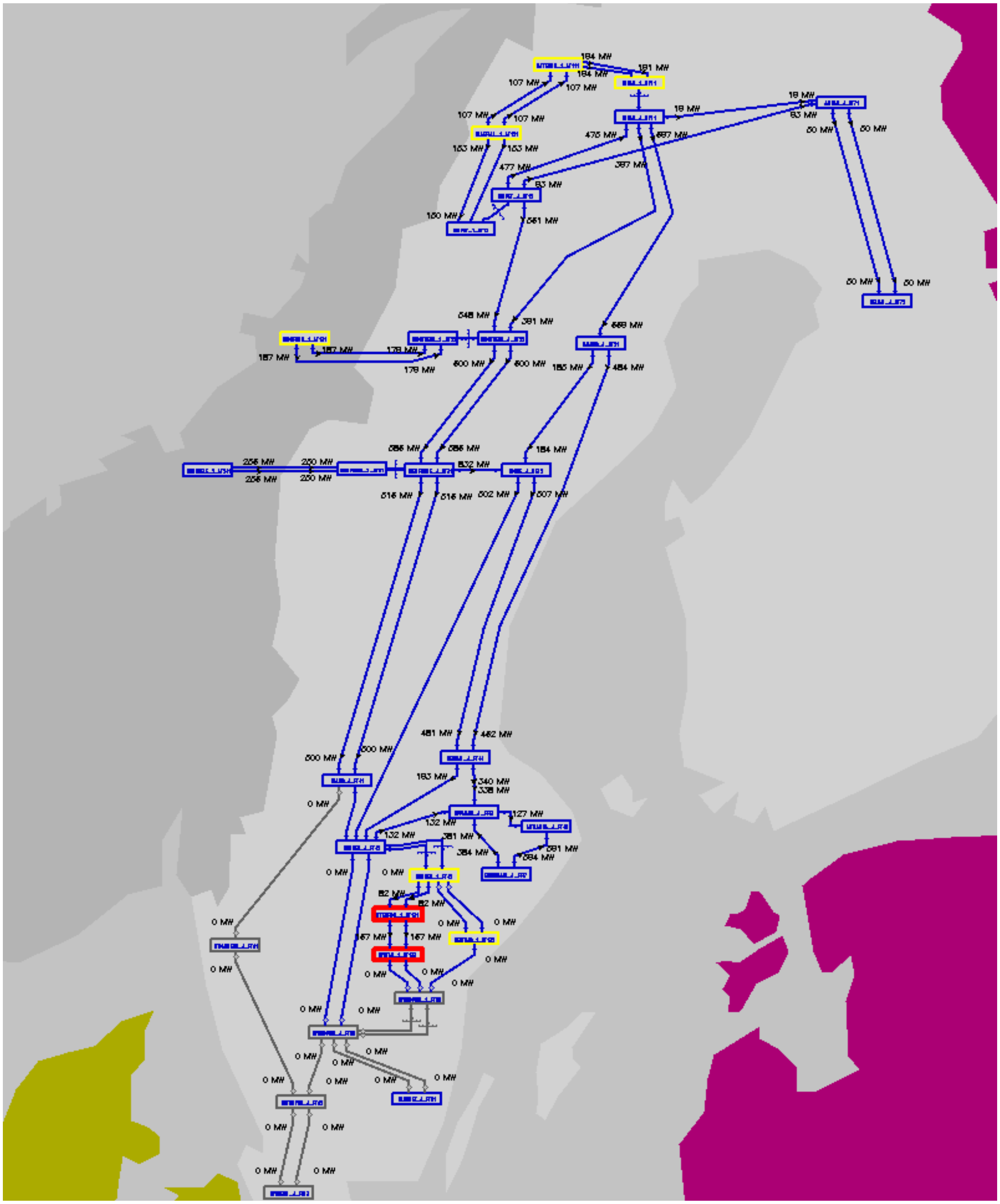


Figure 4.12. NORDIC32 system in Geographical view in ARISTO

4.5. Summary

With the description of the NORDIC32 system, all the aspects regarding programs and models for this project purpose are presented in this chapter: The ARISTO power system simulator, the MATLAB programming environment and the AMCX communication tool; as well as the NORDIC32 test system.

On one hand, ARISTO will provide the environment in which a realistic electric power system, such as NORDIC32 system, can be simulated in real-time simulation. On the other hand, MATLAB allows the possibility of implementing the software needed for this project in order to automatically avoid reactor hunting in a straightforward way, which could be very difficult or even impossible with just ARISTO simulator. Finally, AMCX makes these two programs work together to accomplish the project purposes.

At this point, all the aspects concerning the presentation of the basic theory and instruments needed for the project have been explained: The chapter 2 focused on the theory basics; chapter 3 on reactor hunting phenomenon and chapter 4 in programs and models that will be used for demonstrating the possibility of the method studied in this project.

In conclusion, the next chapters will cover the core of the project: the automatic adaptive tolerance band method for reactor hunting avoidance during restoration process after a blackout in NORDIC32 system: the development of the method, the simulation and the result analysis.

CHAPTER 5. ADAPTIVE TOLERANCE BAND METHOD IMPLEMENTATION

This chapter will describe the methodology used to implement the solution presented for Reactor hunting avoidance. As it was described in the previous chapter, the software environment used in this project will be MATLAB where all the program will be written.

Moreover, the communication tool AMCX is used to stablish the communication between the program, written in MATLAB, and the ARISTO simulator, both located in different computers with different operating systems.

To begin with, the first step to undertake the development of the program is to implement the method for determining the short circuit power S_{sc}. As it was explained in Chapter 3, and represented in expression (3.10), the S_{sc} is inversely proportional to the voltage decrease of the bus after shunt reactor connection. Thus, this parameter is needed in each bus that is going to be connected in order to prevent Reactor Hunting.

Consequently, this chapter will present the method for obtaining S_{sc} for each bus during system restoration, which is based on the bus impedance matrix Z_{BUS}. Then, the algorithm used to carry out the restoration process with Reactor Hunting avoidance based on the adaptive tolerance method will be explained.

To finish the chapter, the scenarios that will be used in simulation for the restoration process are presented.

5.1. Relation between S_{sc}, Z_{Th} and Z_{BUS}

The main expression on which the adaptive tolerance band method is based in order to avoid Reactor Hunting is:

$$\frac{\partial V}{\partial Q} \approx -\frac{1}{S_{sc}(p.u.)} \tag{5.1}$$

In consequence, the short circuit power S_{sc} for each bus is needed. One of the most interesting method to determine S_{sc} is by using the Bus impedance Matrix Z_{BUS}, which is related to the value of the Short circuit power. It is especially convenient to use Z_{BUS} in large systems because it is easily obtained or changed with computer aid.

The bus impedance matrix Z_{BUS} is an important instrument in electric power system analysis, especially in studies which involve system faults or short circuits and, as it is intended to present in this project, to restoration process studies.

In electric power systems, the bus admittance matrix Y_{BUS} is more used, because it is easily constructed branch by branch from primitive admittances. Z_{BUS} is straightforwardly formed by inverting Y_{BUS}:

$$Z_{BUS} = {Y_{BUS}}^{-1} \tag{5.2}$$

Since Y_{BUS} is symmetrical around the principal diagonal, Z_{BUS} must also be symmetrical. The Z_{BUS} matrix for a system with n buses

$$Z_{BUS} = \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{1n} \\ Z_{21} & \ddots & \ddots & Z_{2n} \\ \vdots & \ddots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \dots & Z_{nn} \end{bmatrix} \tag{5.3}$$

In order to understand the physical significance of the various impedances in the matrix, the equations of the bus admittance matrix are used to obtain the equation for the bus impedance matrix:

$$I = Y_{BUS}\, V \;\rightarrow V = Z_{BUS}\, I \tag{5.4}$$

Where $V$and I are the voltage and current vectors of all the buses of the system, where I_i is the current at the bus i, defined as the current injecting to the bus. The equations can be expanded as follows, for each bus:

$$\begin{gathered} V_1 = Z_{11}I_1 + Z_{12}I_2 + Z_{13}I_3 \\ \vdots \\ \vdots \\ V_n = Z_{n1}I_1 + Z_{n2}I_2 + Z_{n3}I_3 \end{gathered} \tag{5.5}$$

The bus impedance matrix provides important information regarding the electric power system network. One of the most important characteristics of Z_{BUS}, specially for this project is the relationship between the diagonal elements of Z_{BUS} and the Thévenin impedance presented by the network at each of its buses [8].

The Thévenin impedance Z_{Th}at a representative bus i of the system is given by

$$Z_{Th} = Z_{ii} \tag{5.6}$$

Finally, as it was presented in chapter 3, the short circuit power S_{sc} is related to the Thévenin impedance (3.9). The short circuit power of bus $i, S_{sc,i}$ is

$$S_{sc,i}(p.u) \approx \frac{1}{Z_{Th,i}(p.u)} = \frac{1}{Z_{ii}(p.u)} \tag{5.7}$$

In conclusion, it has been stated the relation between S_{sc} and Z_{BUS} and thus the importance of obtaining and accurate bus impedance matrix of the NORDIC32 system during the restoration process and being able to update the matrix as fast as possible during each new connection to the grid.

5.2. Formation of Bus Impedance Matrix

Generally, in simple systems, the Z_{BUS} matrix is obtained straightforwardly by inverting the bus admittance matrix, because Y_{BUS} is easily constructed branch by branch from primitive admittances of the elements that form the system.

However, the bus admittance matrix of a large-scale interconnected power system is typically very sparse with mainly zero elements, so the inversion of Y_{BUS} is rarely employed in large power systems of thousands of nodes.

Instead, the bus impedance matrix can be directly constructed element by element using simple algorithms to incorporate one element at a time into the system representation. These algorithms consist of different ways of updating the matrix when a new element (line, generator, bus) is connected to the system [8].

The work entailed in constructing Z_{BUS} is much greater that the required to construct Y_{BUS} in small systems. In large system this work is done by computers so the algorithm provides a fast an accurate way of constructing Z_{BUS} avoiding the inversion of a sparse Y_{BUS}.

As far as NORDIC32 system is concerned, this project will take both methods to handle the network matrices. On one hand, the system is not large enough to consider constructing Z_{BUS} from the start. In addition, the original scenario will be a southern blackout, so the system will be smaller at first.

Thus, the first Z_{BUS} of the original scenario will be obtained through the construction of Y_{BUS}, but with the Incidence matrix method [31], which is a systematic method for Y_{BUS} determination, which needs a few operations to get Z_{BUS}.

On the other hand, during the system restoration, the program that controls the restoration must update the Z_{BUS} automatically with the new bus, whichever it is. Regarding the matrix update, the methods described for constructing Z_{BUS} will be used, but starting from the matrix of the original scenario and including new buses, one by one, as the restoration process progresses. This method eliminates the necessity of inverting the Z_{BUS} and adding a new branch on Y_{BUS}, to inverting back again to get the updated Z_{BUS}.

In conclusion, by following this strategy, the project covers both methods of handling network matrixes, exploiting the advantages of each one. All the calculations are done in per unit system. The two methods are described below: formation and update of Z_{BUS}.

5.2.1. Formation of Z_{bus}

As it was stated above, the formation of the Z_{BUS} is done by first obtaining the Y_{BUS} and then inverting it. The method used to constructing the Y_{BUS} uses the incidence matrix.

Incidence matrix.

The first step in the Y_{BUS} construction is the definition of the element-node incidence matrix A, which shows how elements are connected to the different buses of the system. The elements of the matrix are as follows:

$$a_{ij} = \;\; 1 \; if \; the \; i \; element \; is \; incident \; to \; and \; oriented \; away \; from \; the \; j \; bus.$$

$$a_{ij} = -1 \; if \; the \; i \; element \; is \; incident \; to \; and \; oriented \; toward \; the \; j \; bus.$$

$$a_{ij} = \;\; 0 \; if \; the \; i \; element \; is \; not \; connect \; to \; the \; j \; bus.$$

The orientation of the elements can be stated arbitrarily at first, but it must be fixed during the A formation. The dimension of the matrix is $e \times n$, where e is the number of elements and n is the number of buses of the system. The different elements that are part of the system are generators, transformers and lines.

The generators are elements that are connected to the ground and thus their admittance is added to the diagonal element of Y_{BUS}. Accordingly, they are represented in A with just one $a_{ij} = 1$, where i will be the number given to the generator and j the bus to which the generator is connected. This one element different to zero in the row will affect just to the diagonal element of the Y_{BUS}, as it will be seen after.

The transformers, in per unit systems, are treated as impedances so they are similar to lines. Both elements are then connected to two buses so they have one $a_{ij} = 1$ and one $a_{ij} = -1$. In addition, the lines are represented as the π-model in ARISTO simulator as it can be seen in figure 5.1.

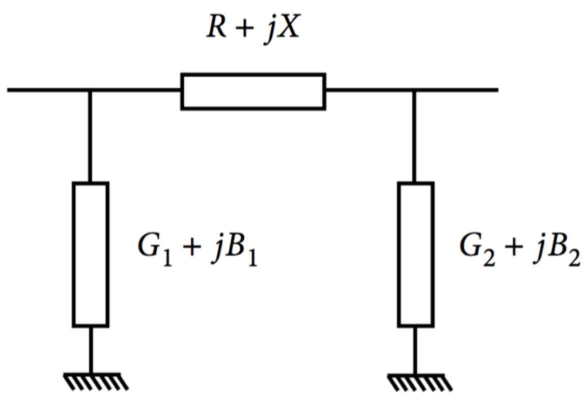


Figure 5.1. Line model in ARISTO simulator [28].

The shunt conductances G_1 and G_2 are considered zero. In consequence, the shunt susceptances B_1 and B_2 are the only shunt elements in the π-model of the line. They are connected to the ground, so they are defined in A the same way as the generators for the buses to which the line is connected.

Example.

As an example for incidence matrix formation, it is presented the circuit of figure 5.2. This circuit is a single line diagram of a 5 bus system, with 6 lines and 3 generators with 3 transformers connecting the generators to buses. The data for each element is presented in table 5.1.

It is also represented the arbitrary orientation of the lines connecting the different buses with arrows. As it was explained before, this orientation is random, but once it is stablished, it must be followed in the calculations for constructing the different matrices.

The generator and the transformer connected to the bus are considered one single element, because the generator impedance is in series with the transformer impedance (transformer in per unit system). In consequence there are 9 elements and 5 buses, so the incidence matrix A is a 9×5 matrix.

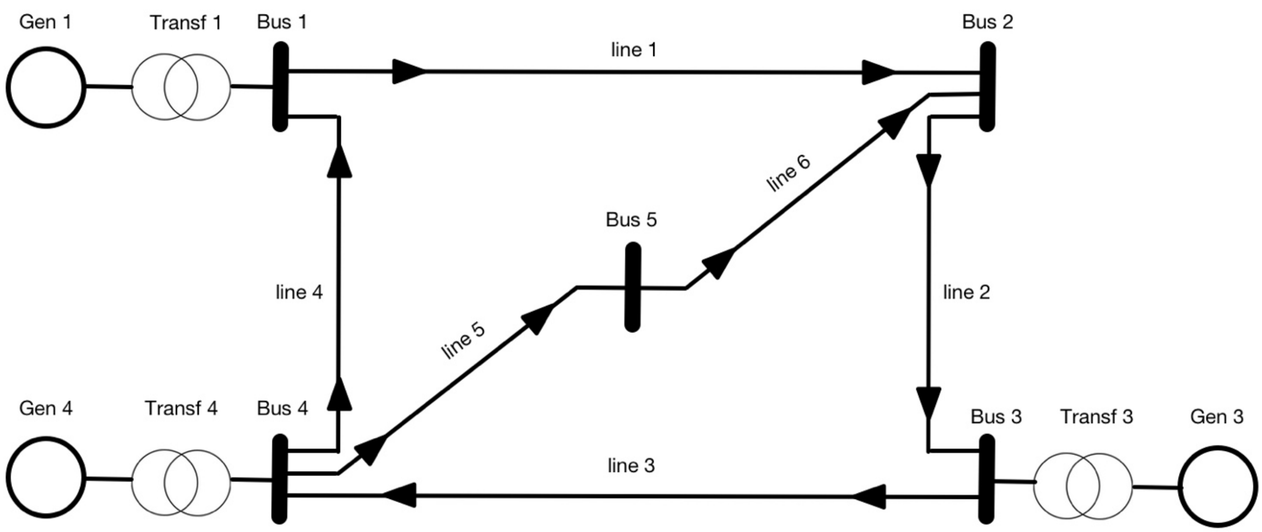


Figure 5.2. Circuit for incidence matrix example.

Element	$Z = R + jX$ [p.u.]
Line 1	$Z_{l1} = 0.1 + 0.7j$
Line 2	$Z_{l2} = 0.14 + 0.9j$
Line 3	$Z_{l3} = 0.1 + 0.7j$
Line 4	$Z_{l4} = 0.14 + 0.9j$
Line 5	$Z_{l5} = 0.05 + 0.5j$
Line 6	$Z_{l6} = 0.05 + 0.5j$
Gen/transf 1	$Z_{g1} = 0.06j$
Gen/transf 3	$Z_{g3} = 0.09j$
Gen/transf 4	$Z_{g4} = 0.15j$

Table 5.1. Data parameters.

The element-node incidence matrix for the graph represented in figure 5.2 is

$e \setminus n$	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
Line 1	1	-1	0	0	0
Line 2	0	1	-1	0	0
Line 3	0	0	1	-1	0
Line 4	-1	0	0	1	0
Line 5	0	0	0	1	-1
Line 6	0	-1	0	0	1
Gen/transf 1	1	0	0	0	0
Gen/transf 3	0	0	1	0	0
Gen/transf 4	0	0	0	1	0

Table 5.2. Incidence matrix A for the 5 bus system.

Where the lines have two elements of the matrix different to 0 (1, -1) and the generator and transformers just one element (1), because they are just connected to one bus.

Bus admittance matrix and Bus impedance matrix.

Once the incidence matrix A is set, the construction of the bus impedance matrix Y_{BUS} is one operation:

$$Y_{BUS} = A^t[y]A \tag{5.8}$$

Where $[y]$ is the primitive admittance matrix which is diagonal square matrix (considering not mutual coupling), where each element y_{ii} is the admittance of the element i. Finally, the bus impedance matrix Z_{BUS} can by obtain by inverting Y_{BUS}

$$Z_{BUS} = {Y_{BUS}}^{-1} = (A^t[y]A)^{-1} \tag{5.9}$$

Example continuation.

Following the example of the circuit presented in figure 5.2, the next step to construct the bus impedance matrix Z_{BUS} is arrange the primitive admittance matrix $[y]$. The $[y]$ matrix is formed with the data of table 5.1, where $Y_x = \frac{1}{Z_x}$:

$[y]$	*Line 1*	*Line 2*	*Line 3*	*Line 4*	*Line 5*	*Line 6*	*G/T 1*	*G/T 3*	*G/T 4*
Line 1	Y_{l1}	0	0	0	0	0	0	0	0
Line 2	0	Y_{l2}	0	0	0	0	0	0	0
Line 3	0	0	Y_{l3}	0	0	0	0	0	0
Line 4	0	0	0	Y_{l4}	0	0	0	0	0
Line 5	0	0	0	0	Y_{l5}	0	0	0	0
Line 6	0	0	0	0	0	Y_{l6}	0	0	0
Gen/transf 1	0	0	0	0	0	0	Y_{g1}	0	0
Gen/transf 3	0	0	0	0	0	0	0	Y_{g3}	0
Gen/transf 4	0	0	0	0	0	0	0	0	Y_{g4}

Table 5.3. Primitive impedance matrix fro the 5 bus system.

Finally, the bus impedance matrix Z_{BUS} can be obtained with expression 5.9

$$Z_{BUS} = {Y_{BUS}}^{-1} = (A^t[y]A)^{-1} \tag{5.9}$$

$\boldsymbol{Z_{BUS}} = (\boldsymbol{A^t}[\boldsymbol{y}]\boldsymbol{A})^{-1}$	*Bus 1*	*Bus 2*	*Bus 3*	*Bus 4*	*Bus 5*
Bus 1	$0.0007 + 0.0544j$	$-0.0002 + 0.0249j$	$-0.0007 + 0.0061j$	$-0.0006 + 0.0039j$	$-0.0005 + 0.0155j$
Bus 2	$-0.0002 + 0.0249j$	$0.0379 + 0.3136j$	$0.0004 + 0.0274j$	$-0.0001 + 0.0421j$	$0.0192 + 0.1705j$
Bus 3	$-0.0007 + 0.0061j$	$0.0004 + 0.0274j$	$0.0017 + 0.0722j$	$-0.0012 + 0.0144j$	$0.0011 + 0.0498j$
Bus 4	$-0.0006 + 0.0039j$	$-0.0001 + 0.0421j$	$-0.0012 + 0.0144j$	$0.0034 + 0.1163j$	$-0.0007 + 0.0282j$
Bus 5	$-0.0005 + 0.0155j$	$0.0192 + 0.1705j$	$0.0011 + 0.0498j$	$-0.0007 + 0.0282j$	$0.0351 + 0.3602j$

Table 5.4. Bus impedance matrix for the 5 bus system.

5.2.2. Update of Z_{bus}

In order to conduct the restoration process, the bus impedance matrix needs to be updated with the new buses that are connected. In order to make this operation efficiently, algorithms for modification of an existing Z_{BUS}, including the addition of a new bus or the connection of a new line are used in this project [8]. It is obvious that is possible to construct the new Z_{BUS} by creating a new Y_{BUS} and invert it.

However, direct methods of modifying Z_{BUS} are simpler and faster with computers than matrix inversion, even for an electric power system with small number of buses, because the inversion is skipped.

There are several types of modifications in which a branch having impedance Z_l is added to a network with known Z_{BUS}. The new branch can be connected to the reference bus (ground); it can connect two exiting buses or it can connect the system to a new bus. The original matrix is identified as $Z_{original}$, an $n \times n$ matrix representing a system of n buses.

As far as system restoration is concerned, this project will cover the connection of new buses to the system. In consequence, the modification that is used is the addition of Z_l from a new bus q to an existing bus p, as it is presented in figure 5.3.

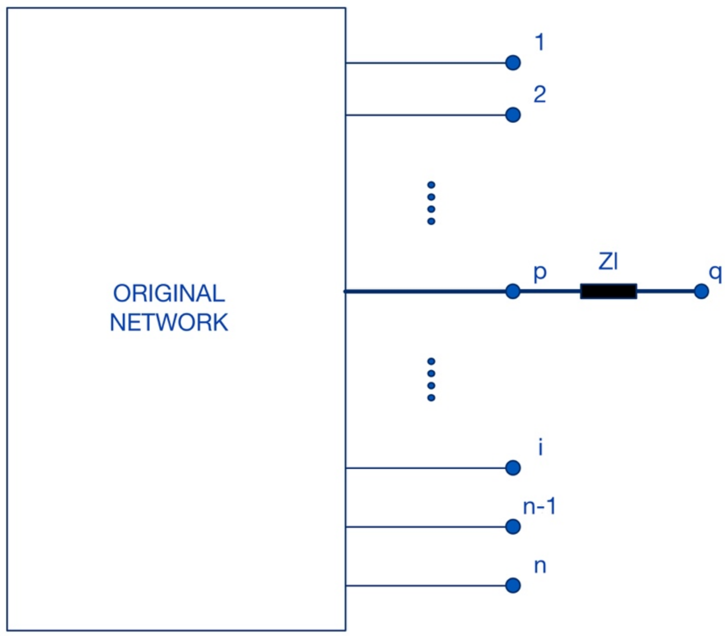


Figure 5.3. Representation of Z_l connecting new bus q to existing bus p.

Since a new bus is added to the network, the new Z_{BUS} will be an $(n+1)\times(n+1)$; because Z_{BUS} must be a square matrix around the principal diagonal. The matrix equation for the new Z_{BUS} is

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \\ \hline V_q \end{bmatrix} = \left[\begin{array}{cccc|c} & & & & Z_{1p} \\ & Z_{original} & & & Z_{2p} \\ & & & & \vdots \\ & & & & Z_{np} \\ \hline Z_{p1} & Z_{p2} & \cdots & Z_{pn} & Z_{pp} + Z_{l1} \end{array}\right] \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \\ \hline I_q \end{bmatrix} \tag{5.10}$$

Since Z_{BUS} is a symmetrical matrix, the expression for the new row and column are

$$Z_{qi} = Z_{iq} = Z_{pi} \;\; for\; i = 1,2, \dots, n\; and\; i \neq q$$
$$Z_{qq} = Z_{pq} + Z_l \tag{5.11}$$

These equations have a straightforward implementation in programming language.

Once, the methods for constructing and updating the bus impedance matrix are explained, it is time to develop the program that controls the restoration process of the NORDIC32 system from an original southern blackout, implementing the Adaptive tolerance band for Reactor Hunting avoidance.

Example.

In order to show how this algorithm works, a new bus is added to the circuit used in the example of the previous section (Figure 5.2). The bus 6 is added to bus 2 with line 7 ($Z_{l7} = 0.1 + 0.1j$), as it is presented in figure 5.4.

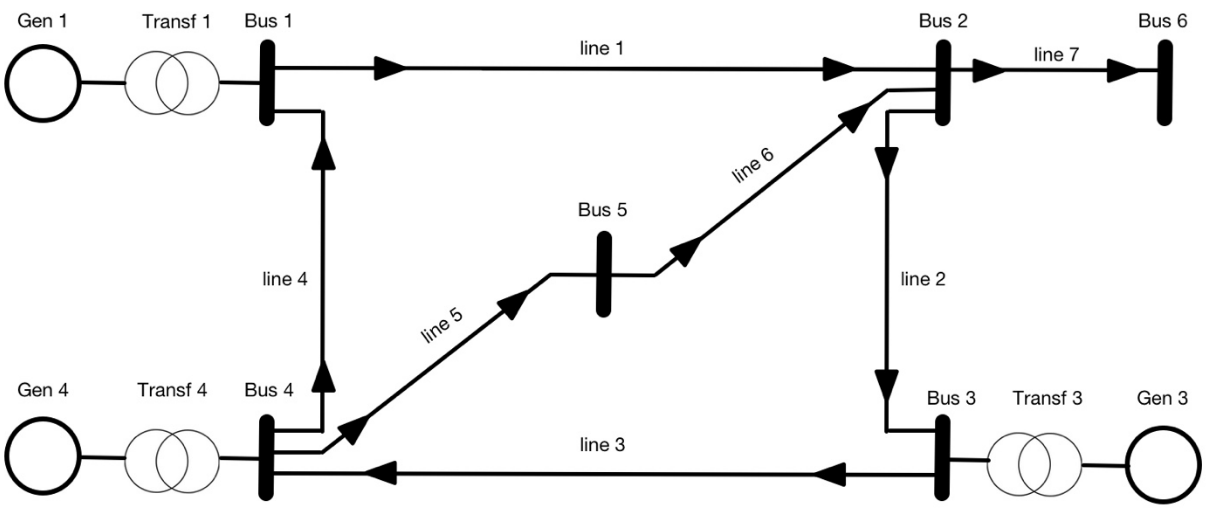


Figure 5.4. Circuit with new bus 6 connected to bus 2.

This new bus 6 needs to be added to the bus impedance matrix. Consequently, the algorithm presented in equation 5.11 is used for updating Z_{BUS} from a 5×5 to 6×6. Bus 6 is connected to bus 2 through line 7. Following the notation of 5.11, bus p is $p = 2$ and bus q is $q = 6$. The new matrix is presented in table 5.5.

As it can be seen, the update of the matrix when a new bus is connected consists in adding the row of the bus from where the new bus is connected and the line impedance of the new line is added to the diagonal element q, q (6,6 in this case).

Z_{BUS}	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6
Bus 1	$0.0007 + 0.0544j$	$-0.0002 + 0.0249j$	$-0.0007 + 0.0061j$	$-0.0006 + 0.0039j$	$-0.0005 + 0.0155j$	$-0.0002 + 0.0249j$
Bus 2	$-0.0002 + 0.0249j$	$0.0379 + 0.3136j$	$0.0004 + 0.0274j$	$-0.0001 + 0.0421j$	$0.0192 + 0.1705j$	$0.0379 + 0.3136j$
Bus 3	$-0.0007 + 0.0061j$	$0.0004 + 0.0274j$	$0.0017 + 0.0722j$	$-0.0012 + 0.0144j$	$0.0011 + 0.0498j$	$0.0004 + 0.0274j$
Bus 4	$-0.0006 + 0.0039j$	$-0.0001 + 0.0421j$	$-0.0012 + 0.0144j$	$0.0034 + 0.1163j$	$-0.0007 + 0.0282j$	$-0.0001 + 0.0421j$
Bus 5	$-0.0005 + 0.0155j$	$0.0192 + 0.1705j$	$0.0011 + 0.0498j$	$-0.0007 + 0.0282j$	$0.0351 + 0.3602j$	$0.0192 + 0.1705j$
Bus 6	$-0.0002 + 0.0249j$	$0.0379 + 0.3136j$	$0.0004 + 0.0274j$	$-0.0001 + 0.0421j$	$0.0192 + 0.1705j$	$0.1379 + 0.4136j$

Table 5.5. Updated Z_{bus} with bus 6

5.3. Program Considerations

In order to develop the program in MATLAB, it is important to study the characteristics, data or limitations of the NORDIC32 test system, the ARISTO simulator and the AMCX communication tool. In consequence, an analysis of the main considerations is done in order to develop the program, which will be represented by a flow diagram.

Apart from Z_{BUS} calculations, there are other considerations that are important in order to implement the software: Database, Automatics, Adaptive tolerance band implementation and AMCX communication.

5.3.1. Database

There are a great number of components in every electric power system. NORDIC32 system is not as large as a real power system with thousands of elements, but it has a great number of variables that need to be managed in an efficient way: the solution proposed is database.

ARISTO simulator has all the data to simulate the system stored in databases: lines, switchyards, transformers, circuit breakers, automatics, generation units, etc. This information is critical in order to create an accurate Z_{BUS}, and thus S_{sc}.

In addition, the information of the different elements is important to allow a correct communication through AMCX tool. From MATLAB environment, the program must be able to send a correct command (open, close, measure, trip, set, etc.) to the correct element with a unique identification code (ID code).

In order to make the program performance efficient, a new database is created in MATLAB environment with all the information needed for the correct operation. This new database skips the communication with ARISTO to get the values needed, making the program faster because it has to search the information in its own database.

To create the MATLAB database, all the information stored in ARISTO database is exported to a .txt file and transferred to the windows OS. The information is stored in an Microsoft Excel file and then imported into MATLAB workspace. The databases created in MATLAB uses the "Cell Array" data type.

However, there are some kind of information that can not be obtained through AMCX tool (line connections, automatics, circuit breakers). Thus, this database is created manually in the MATLAB environment.

The most relevant information stored in the program database is summarize in table 5.6, dividing the information in four groups: elements data, switchyards ID, connections and incidence matrix A. The information of the whole system is stored, but some data must be changed for each different scenario: the incidence matrix A, and the switchyards that are connected at first.

5.3.2. Adaptive Tolerance Band Implementation

In chapter 3, the Adaptive tolerance band method was explained. In order to make the calculations efficiently it is important to define an algorithm to calculate the new tolerance band for each new connection systematically.

To begin with, it has to be known the line l that is going to be connected next, in order to know the already connected switchyard p and the new switchyard q. With this information Z_{BUS} can be updated in the following expression (5.11).

Once the new switchyard is added to the bus impedance matrix, the short circuit power S_{sc} at that switchyard is determined as follows in per unit system:

$$S_{sc}(p.u.) = \frac{1}{Z_{Th,q}} = \frac{1}{Z_{qq}} = \frac{1}{Z_{pq} + Z_l} \tag{5.12}$$

With S_{sc}, it is possible to determine the decrease expected in voltage of the switchyard q after shunt reactor ∂Q (Mvar) connection (equation 3.16). The power base of the system is $S_{base} = 1000\ MVA$.

$$\partial V \approx \frac{\alpha^2}{1-2\alpha}\frac{\partial Q(p.u)}{S_{sc}(p.u)} = \frac{\alpha^2}{1-2\alpha}\frac{\partial Q(Mvar)}{S_{sc}(MVA)} \tag{5.13}$$

Based on the 2003 Swedish blackout [7], α is calculated and it is found that $\alpha = 1.14$ In consequence, the expression is

$$\partial V = -1.0153 \cdot \frac{\partial Q(Mvar)}{S_{sc}(MVA)} \tag{5.14}$$

The value of the shunt reactor Q must be known before hand. Thus, this information is also stored in the database "Element connection" in order to have quick access to it during simulation. Finally, the lower limit of the tolerance band V_{low} of the EVAs must be set to

$$V_{low} = \partial V \cdot V_{before} \tag{5.15}$$

Where V_{before} is the voltage at the busbar before connecting the shunt reactor. These calculations are repeated for every new connection during restoration process.

Data	Description
Elements Data	The information of each element that is part of the NORDIC32 system is stored in this database. The information stored is: the identification code of the element in order to differentiate it to the others The elements stored and their information are: - Lines. The ID code (for example "CL16"), the values of the line impedance and the switchyards ID that each line connects. - Transformers. The transformers are treated as impedances in per unit system, so the information is similar to the lines: ID code, values and connected switchyards ID. - Generators. The ID code, the values of reactance, and the only switchyard ID to which the generator is connected. The information stored in this database is used to Z_{BUS} calculations.
Switchyard ID	The switchyard ID is stored. The order of the switchyards is selected arbitrarily but, once it is set, it must be followed in the rest of the program (incidence matrix, Z_{BUS}, etc.). Instead of creating one single database for the 32 switchyards of the NORDIC32 system, three different databases are created: - ID for the 32 switchyards of the NORDIC32 system. - ID of the switchyards that are already connected. - ID of the switchyards that are not connected. The last two databases are updated during the restoration process and are important to know the actual state of the system: which switchyards and which not are connected.
Incidence Matrix A	The incidence matrix A is stored as a numeric matrix with three different values (0, 1, -1). It represents the elements that are connected and how they are connected in the original system. In consequence, A is different for each original scenario, and it only represents the switchyards and lines that are connected after the blackout. The matrix needs to follow the order selected in advance for the different elements and switchyards
Element connection	This database is used to store the information needed to connect each line and send the correct command to ARISTO simulator through AMXC communication tool. For each line the information stored is: - Circuit breaker ID of each switchyard that is connected by the line. - Busbar ID of the switchyars to measure the voltage. - Shunt Reactor circuit breakers of each switchyard to control the automatics.

Table 5.6. Database for NORDIC32 system

5.3.3. Automatics during Restoration

The Adaptive tolerance band method is based on a continuous change in the tolerance band of the automatics. However, the ARISTO simulator only allows manual changes in the EVAs behaviours. Thus, there are no commands and EVAs can not be modified from MATLAB during simulation.

As a consequence, the automatics of the ARISTO simulator are disconnected and new automatics must be created in the program in order to simulate the same behaviour, but in the MATLAB environment the tolerance band can change automatically.

In chapter 2, the automatics for shunt reactor were described and the most important values were the response time and the tolerance band. In our system, the response time is 2 seconds; this means that the changes between connection and disconnection of the shunt reactor are 2 seconds.

Moreover, the tolerance band is adjustable. The higher limit is fixed to $V_{high} = 440\ kV$ to create a safer margin for avoiding hunting, but the lower limit, which is generally $V_{low} = 380\ kV$, is the value that is going to change in the adaptive tolerance band method.

The behaviour of the EVAs with the adaptive tolerance band is presented in figure 5.5.

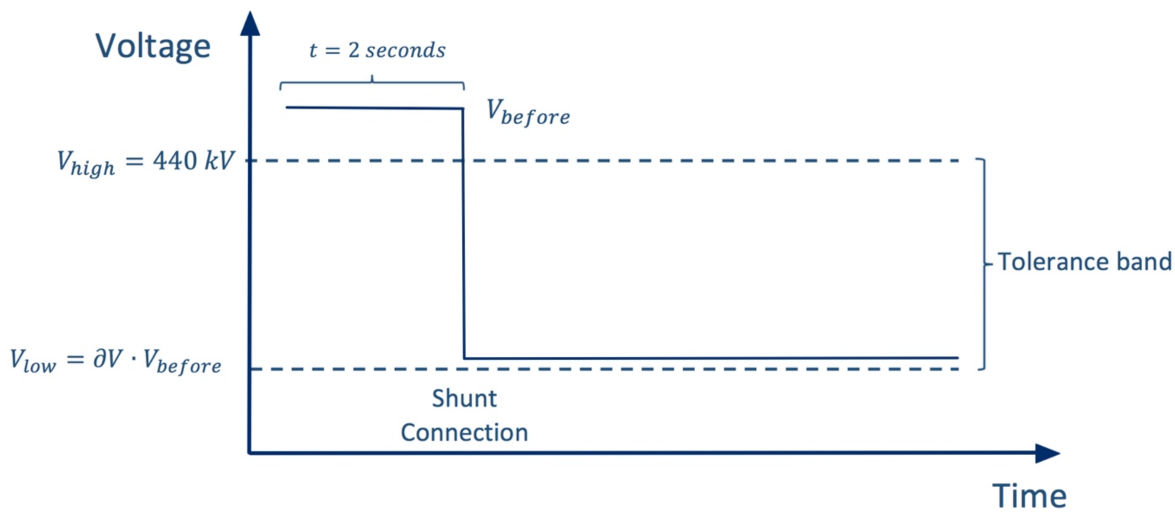


Figure 5.5. EVAs behaviour with adaptive tolerance band.

In comparison with figure 3.3, where Reactor hunting is represented, figure 5.5 shows that the reactor hunting is avoided after adjusting the lower limit of the tolerance band V_{low}, with the operations described in the previous section (equation 5.12 – 5.15). The time with overvoltage (over 440 kV) is 2 seconds, which is the time for the EVAs to actuate.

5.3.4. AMCX Communication

The last important thing to consider is the options and limitations that the AMCX communication tool offers, in order to make the communication between ARISTO simulator and MATLAB as much efficient as possible.

On one hand, AMCX basically allows to send commands to the ARISTO event browser (chapter 4) and to read values of variables (voltage, current, power, state of a circuit breaker, etc.). As far as the Adaptive tolerance band method is concerned, the critical value that needs to be measured and controlled is the voltage of the switchyards (busbar).

On the other hand, the commands that are used for this program are the connection and disconnection of lines and shunt reactors. This implies to open or close the correct circuit breaker at each switchyard. The IDs for the circuit breakers are stored in the databases (presented in table 5.6)

In order to get a value (voltage) from ARISTO or send a command (open a circuit breaker), the identification code of the busbar (where the voltage want to be measured) or the circuit breaker (that wants to be opened or closed) needs to be known and used in the AMCX code in order to make ARISTO understand the command.

In consequence, all this information needs to be accessible from the MATLAB environment. As it was described in a previous section (table 5.6), this information is stored in the database "Element connection".

5.4. Flow Diagram

All the considerations stated above, and the theory behind the construction and update of the bus impedance matrix Z_{BUS}, are used to design the program that will implement the automatic adaptive tolerance band method for reactor hunting avoidance during system restoration of the NORDIC32 test system.

One of the main objectives of this program is to, once the initial system is defined, make it capable of connecting whichever switchyard needed, in order to make the restoration process adjustable, making any restoration path possible.

To begin with, the program is structured in blocks, and there is the Main program which includes 4 subprograms that have different tasks. The main characteristics of each of the parts is presented below. The Flow diagram of the program is presented in figure 5.6.

5.4.1. Main Program

The main program is the core of the program and it is the one that needs to be started. The main program will be executed once and will be finished when the restoration process is concluded or the user wants to exit the program. It will execute the different subprograms in order automatically.

The structure of the main program is divided in two blocks: the first block, which is run once and the second, which is a while loop that is continuously executed until the user wants. The main characteristics of both blocks are described below.

First block.

Once the main program is executed, the first block starts. The main tasks carried out in this part of the program are:

- Load data from the different databases saved in the program files. These databases are described in table 5.6. an have different purposes. The databases are characteristic of the initial system, so they need some changes (incidence matrix and connected and disconnected switchyards) if the initial system is different.

- Creation of Z_{BUS} following the steps described in section 5.2.1.

When the Z_{BUS} is created, the first block is finished and it is not executed until the main program is restarted. A message is send when this block is executed successfully and the second block can start.

Second block.

The second block of the main program consists in a while loop that is repeated continuously until the user orders to stop. The while is again divided into two blocks: dialog protocol and subprogram execution.

- Dialog protocol. The aim of this part is to know which is the next step of the restoration process; i.e., ask the user which is the line that is going to be connected next. It is the only part of the program where there is communication user-system. The rest of the program is executed automatically. The process is divided in three steps or questions:

    - *"Which switchyard do you want to connect next?"*. The switchyard ID that is intended to be connected must be stated. It is only possible to select a switchyard that is not already connected, in order to prevent wrong connections and continue the restoration process with new switchyards.
    - *"From which switchyard do you want to connect it?".* The switchyard ID from which the previous switchyard is intended to be connected must be stated. It is only possible to select connected switchyards that have line connecting both switchyards.
    - *"Which line do you want to connect?".* If there is just one line available connecting both switchyards, it is automatically selected. However, if there is more than one, then the program asks to select one between the possibilities.

    If no command is stated or a wrong command is sent, a message error appears on the console describing which is the error ("No command stated", "This switchyard is already connected", "This switchyard does not exist, etc.).
    The end of this section is reached when it is stated in the program (creation of variables) which are the sending switchyard, the receiving switchyard and the line connecting both ends. This is represented in the flow diagram (Figure 5.6), as switchyard X, Y and line Z.
    There are two other possible commands to enter at this stage: REPEAT and EXIT:

    - *"REPEAT*". Whenever this command is stated, the process of getting the next connection of the restoration process is restarted with the first question (switchyard X).
    - *"EXIT*". This is the command used to stop the program execution. It can be entered in each of the three questions, and the program finishes.

- Subprogram execution. Once the user has entered the three variables, the program will start the last part of the execution. This part is executed automatically. All the connections and calculations are carried out in this part using different subprograms that are explained below.

Once the different subprograms are finished and the connection is completed successfully avoiding reactor hunting, the next stage begins. The program will start at the first question of the dialog protocol (start of the while loop). In consequence, subsequent stages will be executed until the restoration process is done or until the user enters the exit command.

5.4.2. Subprograms

As it was described in the previous section, the main calculations, measurements and connections for the adaptive tolerance band method are carried out in different subprograms designed for different purposes. The subprograms are general for any switchyard and they just need as entry which switchyard is going to be connected and from where (entered by the user).

There are four subprograms, each one with a different task: Update of the Z_{BUS}; Search connection data; switchyard connection and adaptive tolerance method. The main characteristics are described below.

Update of the Z_{BUS}.

This subprogram updates the Z_{BUS} with a new switchyard (switchyard X). First of all, an algorithm searches the position in the previous Z_{BUS} of the switchyard from where the new one is going to be connected (switchyard Y), in order to give the p variable to that switchyard. Then, the steps described in equation 5.11 are followed to update the matrix.

In addition, an update in the databases is done: the new bus is added to the connected switchyards and eliminated from the disconnected switchyards database.

Search connection data.

This subprogram is the previous step before AMCX communication. The objective of this subprogram is to load, from the "element connection" database, the ID codes of the circuit breakers that are going to be connected in each stage, depending on the switchyard X, Y and line Z. The data loaded is

- Circuit breakers ID for the line connection on both switchyards.
- Circuit breakers ID for the shunt reactors in the new switchyard.
- Busbar ID to measure the voltage of both switchyards.

Switchyard connection (AMCX).

With the correct ID for the circuit breakers at both sides of the line, and the busbar, the communication between MATLAB and ARISTO simulator can be executed through AMCX tool. This subprogram orders ARISTO to close the circuit breakers and measure the voltage of both switchyards.

Adaptive tolerance band (AMCX).

This subprogram implements the Adaptive tolerance band method for reactor hunting avoidance. First of all, it determines the new lower limit of the tolerance band, taking the diagonal element of the Z_{BUS} of the new switchyard. The formulas used are 5.12 – 5.15. The upper limit of the tolerance band is set to 440 kV during all the restoration process.

With the new tolerance band stablished, the simulation of the EVAs is executed with these new limits. As it was explained previously, the automatics behaviour must be simulated in MATLAB environment because it is not possible to change the tolerance band of the ARISTO automatics using AMCX tool. With the ID for the shunt reactor of the switchyard, and busbar ID for measuring the voltage, it is possible to create a model of the EVAs behaviour in MATLAB.

The subprogram is designed to use one shunt reactor at first. If after the shunt reactor connection, the voltage is still above the upper limit of the tolerance band, then another shunt reactor is activated. When the reactor hunting is avoided and the voltage is within the tolerance band limits, the subprogram finishes and a new restoration stage can start for a new switchyard.

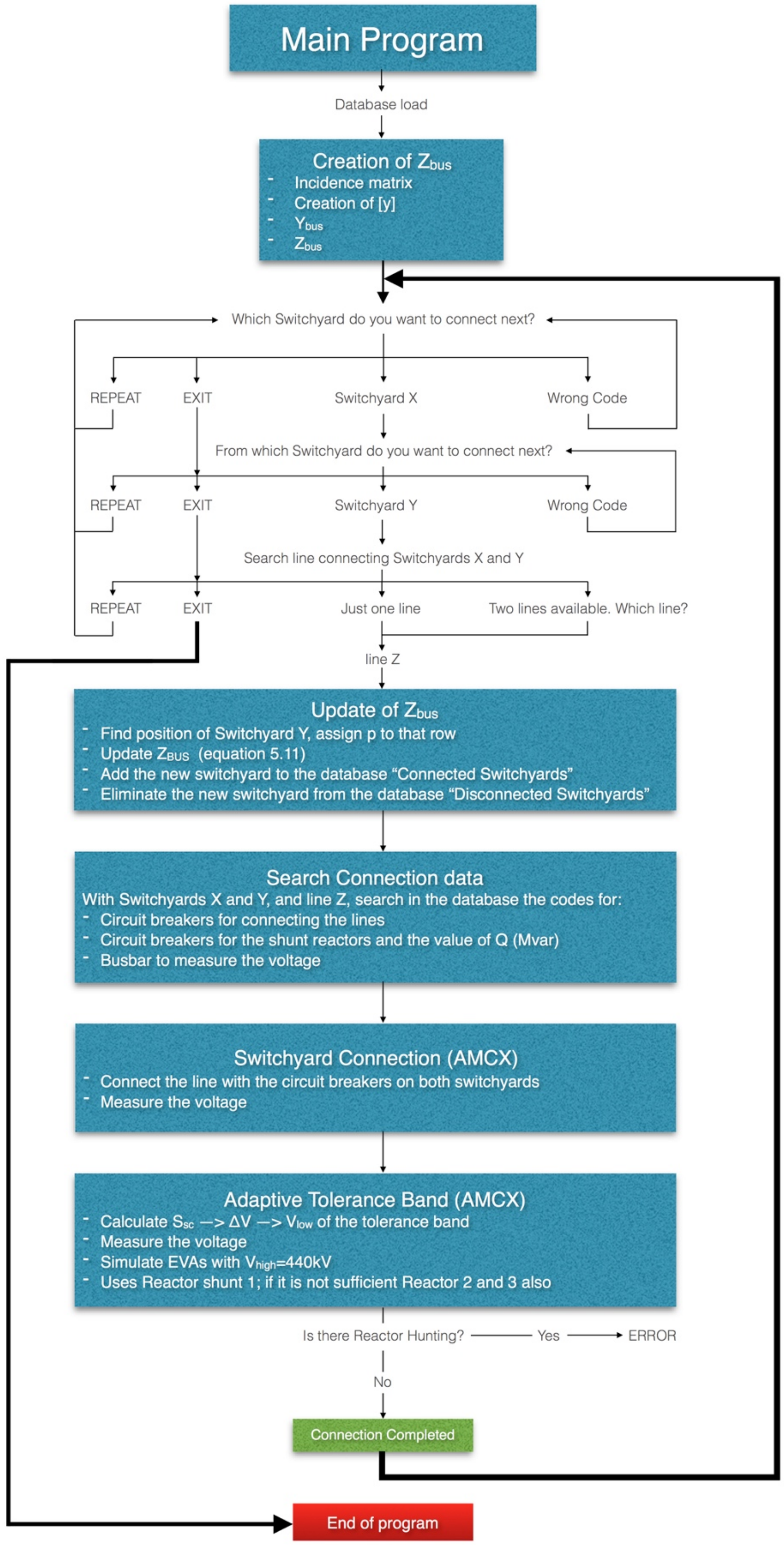


Figure 5.6. Flow diagram

5.5. Strategy

As it was presented, the program has been designed in a general way in order to make it adjustable to different systems and scenarios, with just simple modifications in the database. For the purpose of proving the performance of the program and to be able to study the impact of the adaptive tolerance band method for Reactor Hunting avoidance, it is necessary to establish some scenarios for the NORDIC32 test system, with different restoration paths in which Reactor Hunting occurs.

In consequence, the original system after the southern blackout must be defined and the different paths that will be carried out. Simulation for these different cases will be studied to analyse the results and make conclusions.

5.5.1. Original System

To begin with, an initial system must be defined. As it has been explained before in chapter 2, the scenario that is intended to be analysed is the southern blackout system of Sweden, because this is the most common blackout in the Swedish electric power system due to its topology (power generation at the north connected to power consumption at the south through long transmission lines) and because reactor hunting may appear in the restoration of long transmission lines.

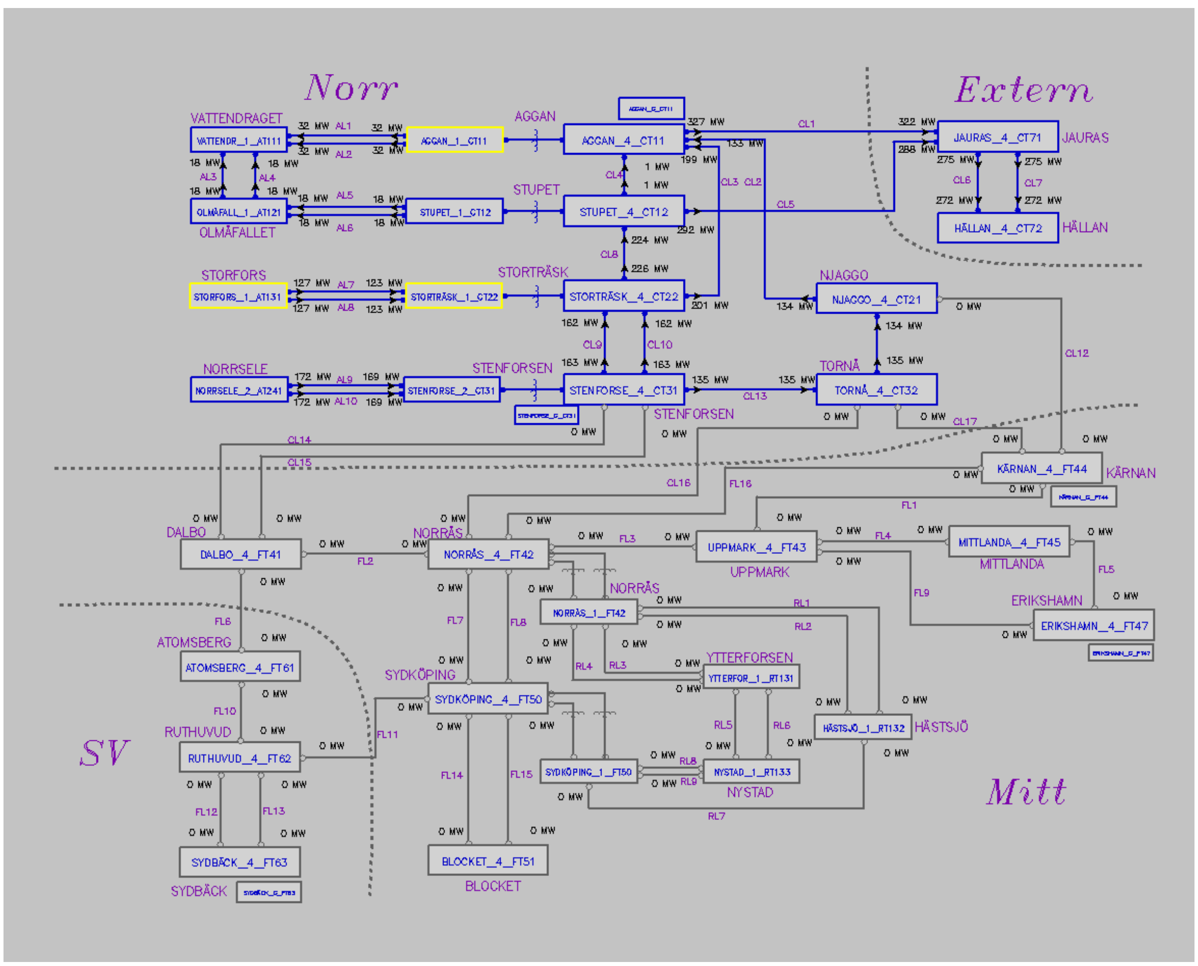


Figure 5.7. Initial System

In terms of NORDIC32 system, which is a simplification of the Swedish system, the southern blackout scenario is defined as it can be observed in figure 5.7. There are 16 connected switchyards (*Norr* and *Extern* areas) representing the North of Sweden with mainly generation; and 16 disconnected switchyards (*SV* and *Mitt*), representing the South of Sweden where the main power consumption is concentrated.

The connected switchyards, transformers and lines are represented with coloured outline in figure 5.7 and grey colour means that the element is disconnected In consequence, the initial Z_{BUS} will be a 16×16 matrix. In addition to switchyards, lines and transformers, 14 generators are connected in the initial system.

The database "Switchyard ID" and the incidence matrix are created based on this initial system, the other databases are general for the NORDIC32 system.

5.5.2. Restoration Paths

Once the initial system is defined, the program allows the user to carry out all restoration paths available. In order to analyse the performance of the program, and the results of the adaptive tolerance band method, some restoration paths must be defined.

This restoration paths must have reactor hunting phenomenon in a switchyard in order to verify the effectiveness of the program. The weaker the bus, the higher the probability for reactor hunting. Therefore, the paths selected have at least three switchyard connection, in order to make the last switchyard weaker.

Several paths have been tested. Finally, 2 different paths were selected. These paths have the characteristic of Reactor Hunting occurring at the last same switchyard of the connection sequence: "*SYDKOPING_4_FT50"*. The restoration sequence of both paths is represented in figure 5.8.

Path 1.

This path consists in 3 stages or switchyard connections. It starts at "*NJAGGO_4_CT21*", and the following connections are

- Stage 1: "*KARNAN_4_FT44*" through line "*CL12*".
- Stage 2: "*NORRAS_4_FT42*" through line "*FL16*".
- Stage 3: "*SYDKOPING_4_FT50*" through line "*FL8*".

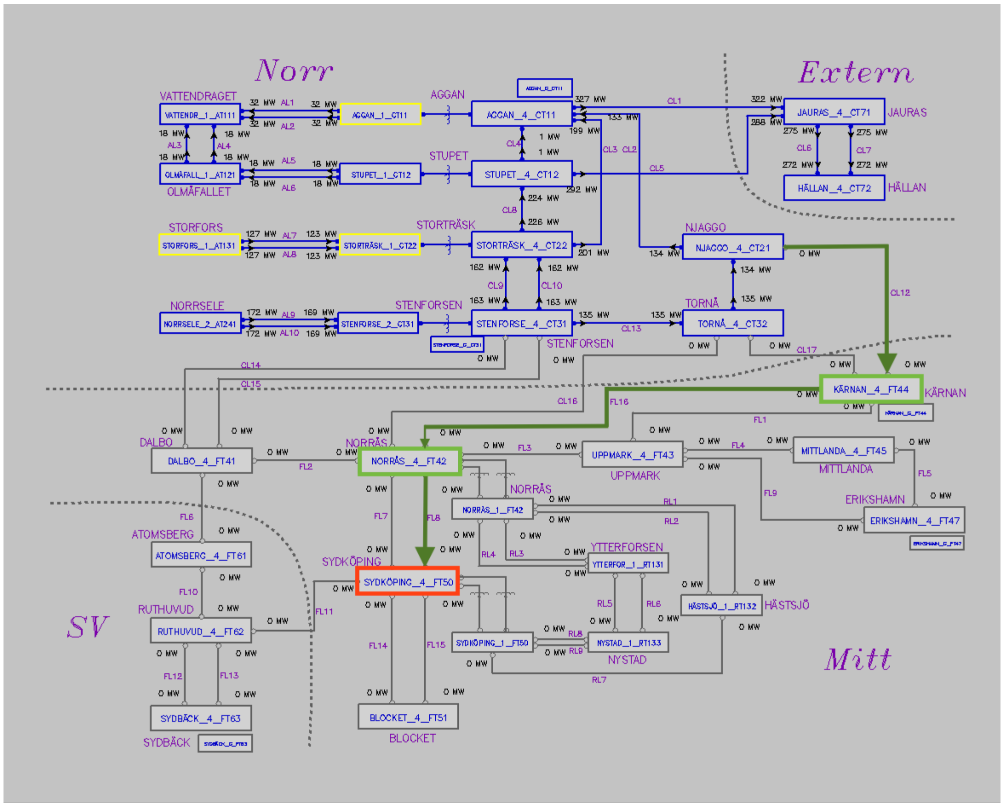
Reactor hunting appears at *SYDKOPING_4_FT50.* The sequence is represented in the upper figure of figure 5.8.

Path 2.

This path consists in 4 stages or switchyard connections. It starts at "*STENFORSE_4_CT31*", and the following connections are

- Stage 1: "*DALBO_4_FT41*" through line "*CL14*".
- Stage 2: "*ATOMSBERG_4_FT61*" through line "*FL6*".
- Stage 3: "*RUTHUVUD_4_FT62*" through line "*FL10*".
- Stage 4: "*SYDKOPING_4_FT50*" through line "*FL11*".

Reactor hunting appears at *SYDKOPING_4_FT50.* The sequence is represented in the lower figure of figure 5.8.



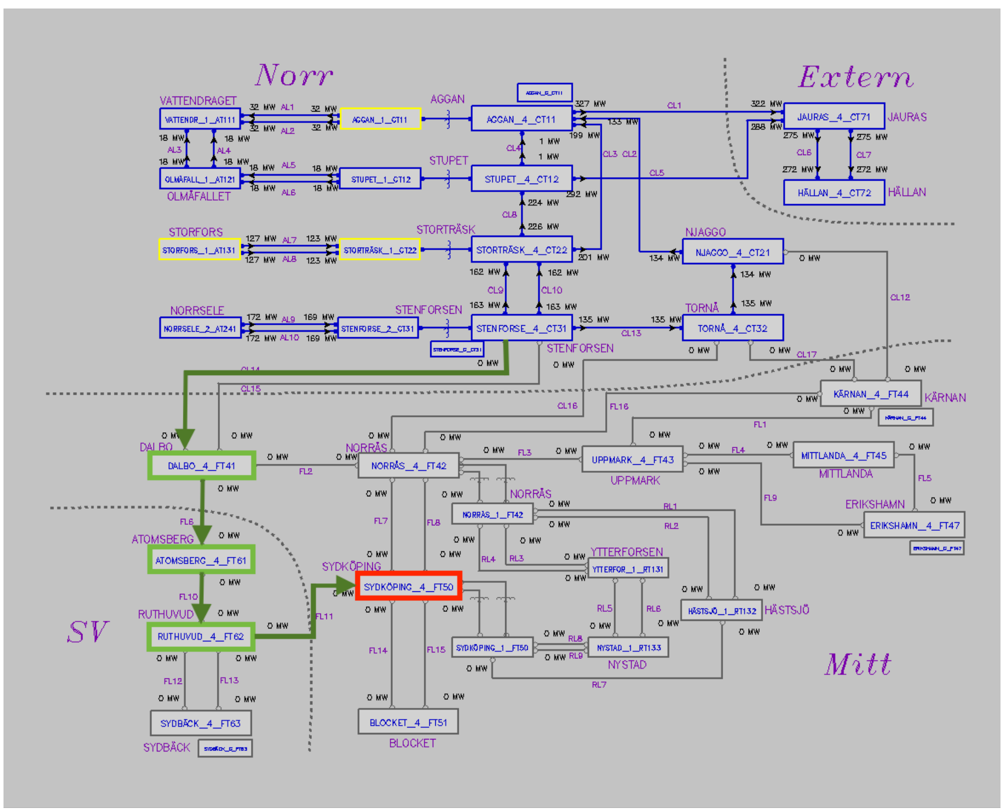


Figure 5.8. Restoration paths: path 1 (upper figure); path 2 (lower figure).

5.6. Summary

Once these two paths are presented and their connection sequence defined, all the considerations concerning the Adaptive tolerance band method implementation, which is the main purpose of the chapter, are presented.

First, the relation between the bus admittance matrix Z_{BUS} and the short circuit capacity S_{sc} is explained, in order to state the importance of the Z_{BUS} in the implementation of the adaptive tolerance band method.

Since Z_{BUS} is the key factor in this method, the theory behind the formation of the matrix is explained, using the incidence matrix method; and the algorithm to update the matrix after the connection of a new switchyard.

The main part of the chapter describes the structure, considerations and operation of the program designed to implement the adaptive tolerance band method, taking into account all the aspects explained in the project: software limitations, Z_{BUS}, reactor hunting, etc.

Finally, the chapter defined the original scenario that the project will consider, and the different restoration paths that will be followed in the simulation, in order to analyse the results, the performance of the program and the reactor hunting avoidance effectiveness.

CHAPTER 6. SIMULATIONS

Chapter 5 presented the methodology used for Reactor hunting avoidance and the program that will perform the restoration process in the NORDIC32 test system, starting at a southern power outage as the initial system. Once the program works properly, it is time to analyse the efficiency of the method studied in this project and the effectiveness of Reactor Hunting avoidance.

As far as simulations are concerned, chapter 6 will present the different simulations and analyse the performance of the program, the communication with the ARISTO simulator and the behaviour of the system, starting at the initial system and following restoration paths 1 and 2 (presented in Chapter 5).

To begin with, data verification will be done. The databases will be created as it was explained in chapter 5. Then, the bus impedance matrix Z_{BUS} of the initial NORDIC32 test system is created, and checked the values of the short circuit capacity S_{sc}, and voltage drop ΔV, with the values obtained in ARSITO simulator. The Z_{BUS} update accuracy will also be checked.

Once the verifications are done, simulation of the different restoration paths are done with the final program, but with a fixed tolerance band in order to detect the reactor hunting phenomenon and to prove that the program works properly in terms of receiving orders of which switchyard is going to be connected next.

To conclude, final simulations with the fully operative program are done. The results will be analysed in order to evaluate the efficiency of the Automatic Adaptive tolerance band method in Reactor Hunting avoidance and the program overall performance during system restoration.

6.1. Data Verification

Previous to simulations with the program developed and the communication with the ARISTO simulator, it is important to ensure that the data used to describe the NORDIC32 test system, and the calculations that are used in the program (presented in chapter 5) are accurate.

On one hand, the databases must be created correctly in order to obtain the first results and, on the other hand, the calculations explained in this project must be accurate enough in order to implement the program and avoid reactor hunting successfully.

6.1.1. Database Creation

First of all, the database must be created with the correct data, which is stored in the ARISTO simulator database. The per unit values of the different elements (lines, transformers, and generation units) are presented in tables A.1, A.2 and A.3 of Appendix A.

The different databases presented in table 5.6 are configured for the initial NORDIC32 system. Here is the point were the order of the elements is set and a number is assigned to every switchyard ID (table A.4 of Appendix A).

With these equivalences and the order of elements, the incidence matrix A is created (Table A.5 of Appendix A), taking into account the considerations described in chapter 5. This matrix will be critical for the construction of the bus impedance matrix of the initial system.

6.1.2. Short Circuit Capacity

With the databases configured, the program creates the Z_{BUS} for the initial NORDIC32 test system. As it is intended in this project, the Z_{BUS} is used to determine the short circuit power S_{sc}. In order to analyse the accuracy of the matrix in this calculation, some switchyards of the NORDIC32 test system are used to calculate the S_{sc} directly through the simulator.

The ARISTO simulator does not have the option of determining S_{sc} directly. Consequently, the equation in which the Adaptive tolerance band method is based (3.16) will be used inversely in order to obtain the S_{sc}.

$$\partial V = \left(\frac{\alpha^2}{1-2\alpha}\right)\frac{\partial Q(p.u)}{S_{sc}(p.u.)} \rightarrow S_{sc}(p.u.) = \left(\frac{\alpha^2}{1-2\alpha}\right)\frac{\partial Q(p.u)}{\partial V} \quad (6.1)$$

With $\alpha = 1.14$.

Several switchyards are selected in order to compare both S_{sc}. The voltage drop ∂V is calculated directly in ARISTO simulator, disconnecting and connecting manually the different shunt reactors of each switchyard, and measuring the voltage. It is only used one shunt reactor for each voltage drop. The comparison is presented in table 6.1. Note that the Power base is: $S_{BASE} = 1000\ MVA$.

Switchyard ID	Q [Mvar]/[p.u.]	∂V	S_{sc} from ARISTO	S_{sc} from Z_{BUS}	Error [%]
AGGAN_4_CT11	100 / 0.1	0.0029	35.54	38.4	8.05
HALLAN_4_CT72	150 / 0.15	0.005	30.46	30.35	0.36
STENFORSE_4_CT31	150 / 0.15	0.02	7.61	7.77	2.1
NJAGGO_4_CT21	100 / 0.1	0.0334	3.03	2.96	2.3
TORNA_4_CT32	150 / 0.15	0.031	4.91	4.93	0.4

Table 6.1. S_{sc} comparison between Z_{bus} and ARISTO simulator of the initial NORDIC32 system

As it can be seen from the results in table 6.1, the S_{sc} obtained from the Z_{BUS} matrix with the programs is accurate. The error is around 2%, except in "AGGAN_4_CT11", which is the strongest switchyard. It is important to note that a slight error in the voltage drop makes the difference between S_{sc} larger, so the error can reach 8%, but it is still acceptable. Better voltage measures and a more efficient inversion of the matrix will reduce the error.

The important switchyards are the last 3, because they are the switchyards in the exterior of the initial system, and thus these will be the switchyards used for connecting the different restoration paths.

This verifies that the method is valid and can be used in the adaptive tolerance band method, taking advantage of the quick calculation of the matrix once the databases are configured, leading to a faster performance of the program.

On the other hand, it is also important to prove that the Z_{BUS} update algorithm is also accurate. Thus, the same comparison is done with the switchyards of paths 1 and 2. For each step of the path, the Z_{BUS} is updated, the S_{sc} is obtained from the matrix and the voltage drop is measured directly in ARISTO after manually connect the shunt reactor, as it was done with the initial system comparison of table 6.1.

It is important to note that, during restoration of path 2, there is a switchyard with ID: "ATOMSBERG_4_FT61", which does not have shunt reactors. In consequence, the voltage drop ∂V can not be calculated the same way as the rest of the switchyards. This switchyard is not taken into account in the comparison. The results of the comparison of S_{sc} of each path is presented in table 6.2

Switchyard ID	Q [Mvar]/[p.u.]	∂V	S_{sc} from ARISTO [p.u.]	S_{sc} from Z_{BUS} [p.u.]	Error [%]
Path 1					
KARNAN_4_FT44	150 / 0.15	0.148	1.03	1.057	2.6%
NORRAS_4_FT42	100 / 0.1	0.1124	0.903	0.874	3.2%
SYDKOPING_4_FT50	150 / 0.15	0.19	0.8	0.743	7.1%
Path 2					
DALBO_4_FT41	100 / 0.1	0.057	1.78	1.86	4.5%
RUTHUVUD_4_FT62	150 / 0.15	0.1773	0.859	0.842	1.98%
SYDKOPING_4_FT50	150 / 0.15	0.3054	0.499	0.501	0.4%

Table 6.2. S_{sc} comparison between Z_{bus} and ARISTO simulator of path 1 and 2

From the results of table 6.1 and 6.2, it can be concluded that the bus admittance matrix is calculated accurately enough for the project objective. The average error is around 3%, the same as the previous table, which is an acceptable value.

Some of the differences may be consequence of the transitory behaviour of the voltage after shunt reactor connections; the reactive energy absorbed by the reactors may be different to the nominal value or errors in the inversion of the bus impedance matrix.

In conclusion, it has been showed that the methodology used for calculating the short circuit power, and thus the lower limit of the tolerance band is correct and the program can be used for the restoration process simulations of the next section.

6.2. Line Connection Simulations

Once, the data used and the calculations are verified, the program can be tested. To begin with, the program will simulate the restoration process of paths 1 and 2 separately, starting both at the initial system, without reactor hunting avoidance.

This means that the adaptive tolerance band method is deactivated and the tolerance band of the EVAs is set to:

$$V_{low} = 380\ kV\ ;\ V_{high} = 440\ kV \tag{6.2}$$

The main objective of this simulations is to check the behaviour of both restoration paths, to analyse the voltage drop at each new connection and to show that reactor hunting phenomenon occurs at the last switchyards of both paths: “SYDKOPING_4_FT50”.

In addition, the overall performance of the program is verified, except the adaptive tolerance band method: user interface, connections, measurements and results representation. Both paths will be analysed separately.

All the graphs are plotted in MATLAB environment with the use of AMCX communication tool. All the voltages needed are measure during simulation and stored in MATLAB workspace. Then, the plots needed are represented.

6.2.1. Path 1

The first restoration path consists in 3 stages, as it was presented in chapter 5: “*KARNAN_4_FT44*”, “*NORRAS_4_FT42*” and “*SYDKOPING_4_FT50*”. The initial switchyard is “*NJAGGO_4_CT21*”.

Stage 1: “KARNAN_4_FT44”.

The first connection is “*KARNAN_4_FT44*” to “*NJAGGO_4_CT21*”. The voltage evolution of this switchyard is presented in figure 6.1, where the tolerance band of the automatics is presented.

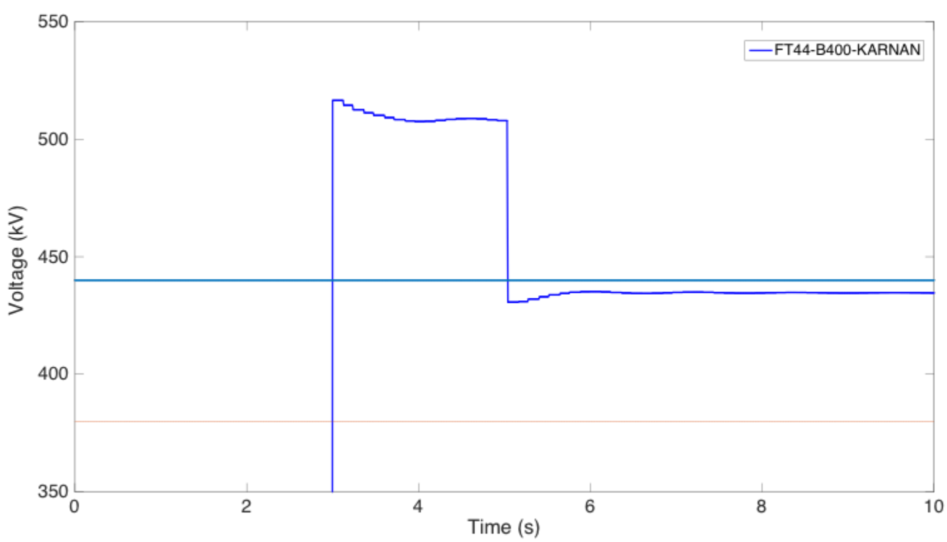


Figure 6.1. Connection of Shunt Reactor in Switchyard: "KARNAN_4_FT44”.

As it can be seen, the voltage at the switchyard after connection of line “*CL12*” is over the tolerance band. In consequence, the EVAs trigger the shunt reactor, which is connected 2 seconds after the connection (Response time).

The connection of the shunt reactor produces a decrease in the voltage as it was expected. In this case, the voltage stays within the limits of the tolerance band after shunt reactor connection. Thus, there is no reactor hunting.

Stage 2: “NORRAS_4_FT42”.

This stage is similar to the previous one. In this step, the switchyard “*NORRAS_4_FT42*” is connected to “*KARNAN_4_FT44”* through line *“FL16”*. The voltage evolution is presented in figure 6.2.

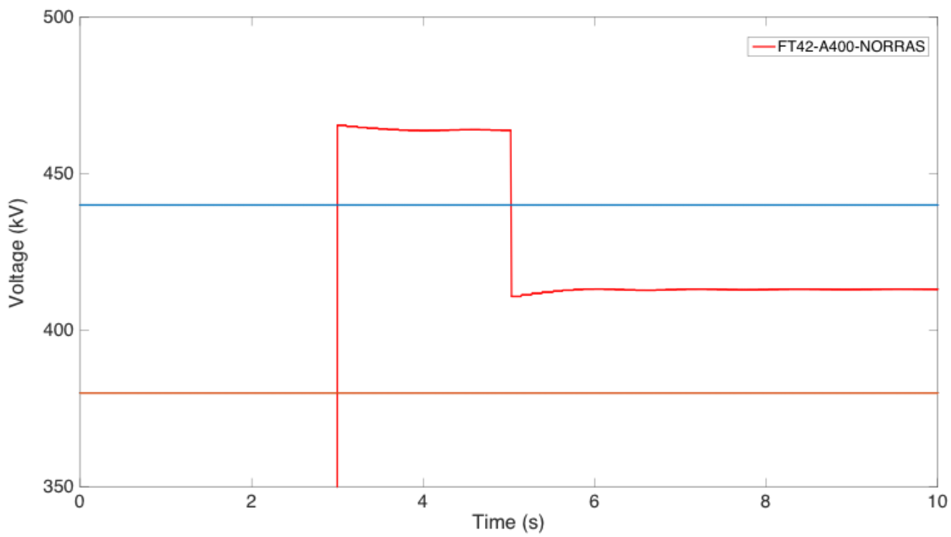


Figure 6.2. Connection of Shunt Reactor in Switchyard: "NORRAS_4_FT42”.

As it occurred in the previous stage, the voltage at “*NORRAS_4_FT42*” goes higher than the tolerance band, and the EVAs connect the shunt reactor to decrease the voltage after 2 seconds. The voltage decreases to a level within the limits, and thus there is no reactor hunting.

Stage 3: “SYDKOPING_4_FT50”.

The last stage of the restoration process followed in path one is where reactor hunting appears. The switchyard connected is “*SYDKOPING_4_FT50”* from “*NORRAS_4_FT42*” with line *“FL8”*. The line *“FL7”* is also available to connect in this stage.

At this point, the short circuit power is $S_{sc} = 743\ MVA$. This represents that the switchyard is weak. This is because the farther the restoration process goes, the weaker is the new switchyard.

In consequence, the reactor shunt of $Q = 150\ Mvar$ makes the voltage drop to a level lower that the tolerance limit. This is the origin of the reactor hunting. The evolution of the connection of this switchyard is presented in figure 6.3.

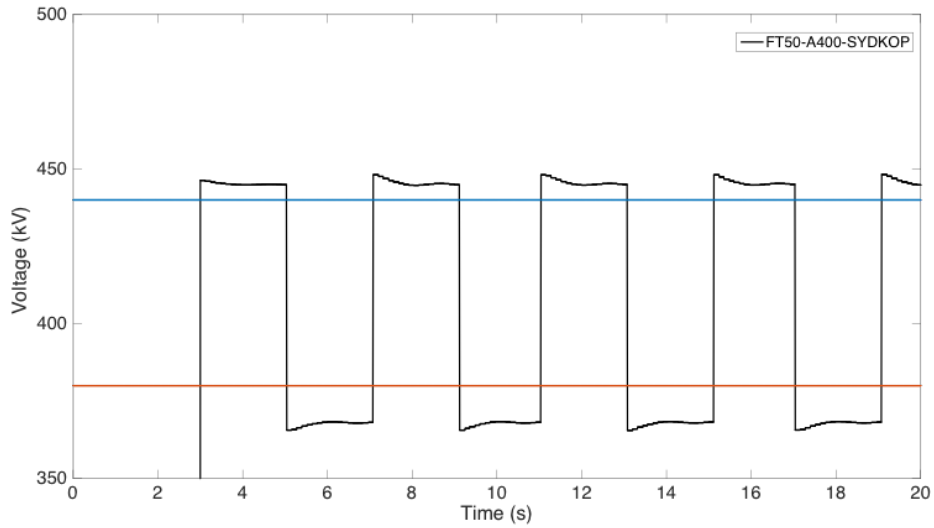


Figure 6.3. Connection of Shunt Reactor in Switchyard: "SYDKOPING_4_FT50"

As it can be seen, the typical behaviour of the reactor hunting phenomenon is represented. Once the switchyard is connected, the voltage rises to a level higher than the tolerance band (440 kV).

In consequence, the EVAs trigger the shunt reactor connection. This process takes 2 seconds and the voltage decreases. However, this time in difference to the previous stages, the voltage drops below the tolerance limit (380 kV). Thus, the EVAs disconnect the reactor shunt after 2 seconds, going to the initial situation. Then continuous connection and disconnection of the shunt reactor every 2 seconds starts.

In conclusion, there is reactor hunting in this path, at the switchyard "*SYDKOPING_4_FT50".* This simulation shows the existence of the phenomenon and can be compared with the adaptive tolerance band method applied later, where the reactor hunting is avoided in the same situation.

Simulation of the whole restoration process: path 1.

To conclude, the whole restoration process is represented in figure 6.4. where the original switchyard voltage and the voltage of the three connected switchyards are represented in the same graph.

In this figure, it can be observed how the switchyard becomes weaker when it is farther from the initial system (north). The weaker the switchyard, the larger the voltage drop, until the drop is large enough to set the voltage below the tolerance band, and then reactor hunting occurs.

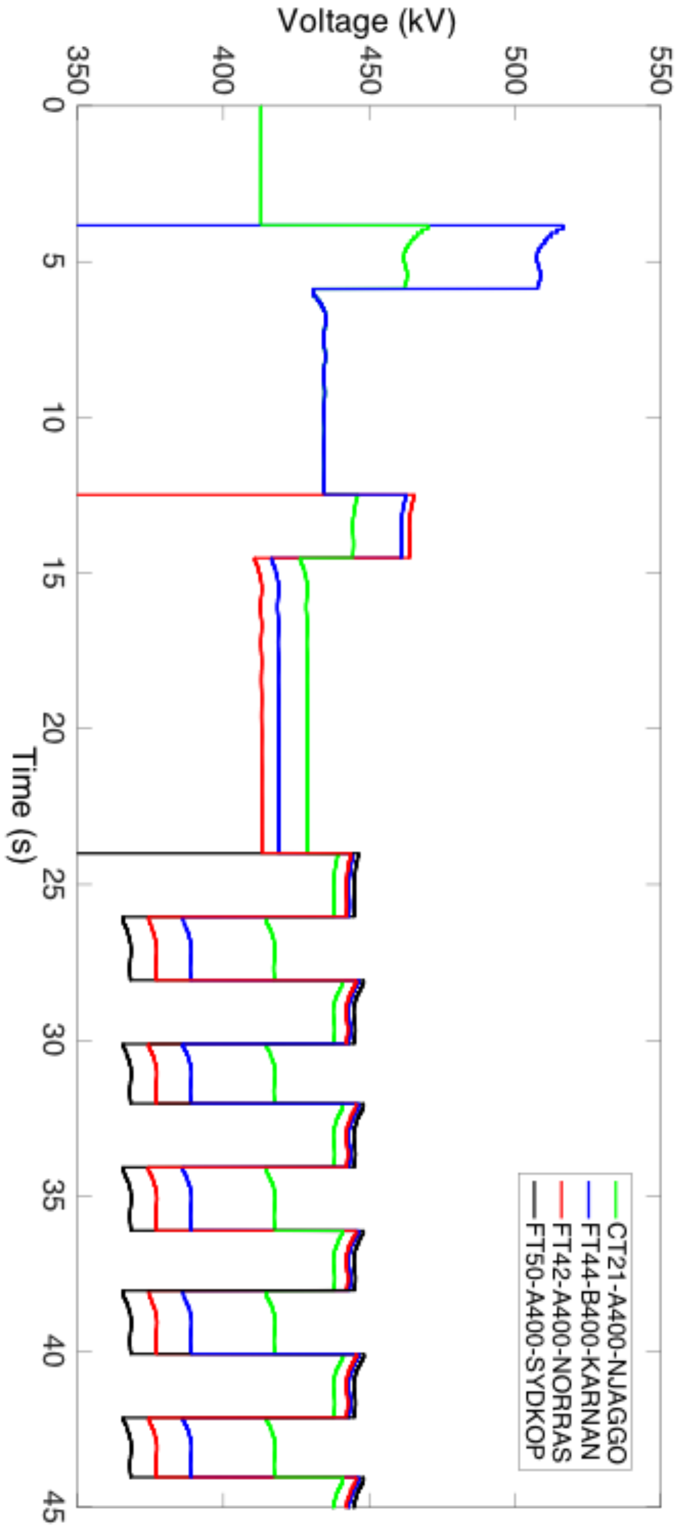


Figure 6.4. Restoration Process, Path 1. With Reactor Hunting.

6.2.2. Path 2

The second restoration path consists in 4 stages, starting at switchyard "STENFORSE_4_CT31", as it was presented in chapter 5: "*DALBO_4_FT41*", "*ATOMSBERG_4_FT61*", *"RUTHUVUD_4_FT62"* and "*SYDKOPING_4_FT50*".

Stage 1: "DALBO_4_FT41".

The first stage of the restoration path 2 is "*DALBO_4_FT41*", which is connected from "STENFORSE_4_CT31" through line "*CL14*" (line "*CL15*" is possible also). The voltage evolution is represented in figure 6.5.

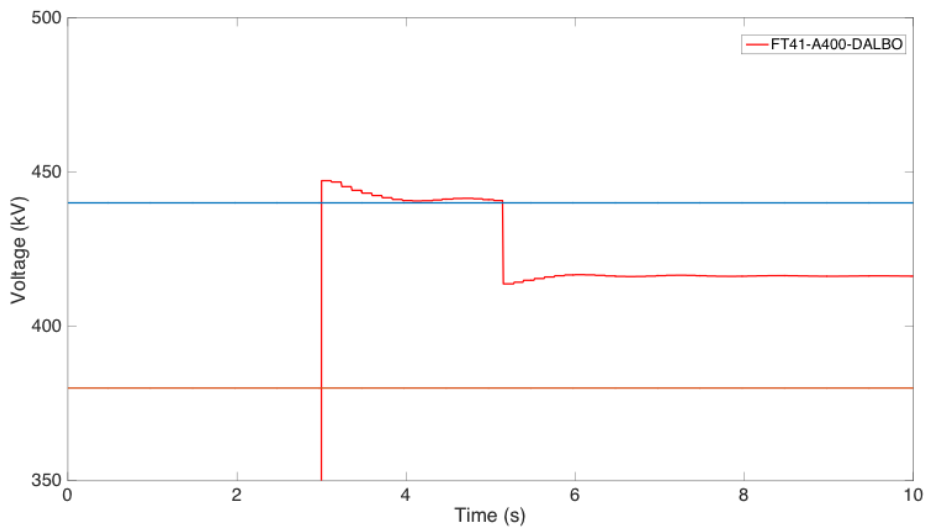


Figure 6.5. Connection of Shunt Reactor in Switchyard: "DALBO_4_FT41".

After connection of the line, the EVAs are activated because the voltage is above the tolerance band. However, the switchyard is strong enough to maintain the voltage within the tolerance band limit after shunt reactor connection.

Stage 2: "ATOMSBERG_4_FT61".

This stage connects the switchyard "*ATOMSBERG_4_FT61*" from "*DALBO_4_FT41*" with line *"FL6".* This switchyard does not have shunt reactor connecter. Therefore, there is no voltage regulation. After the line connection, the voltage stays at the same level, above the upper limit of the tolerance band. This voltage is represented in figure 6.6.

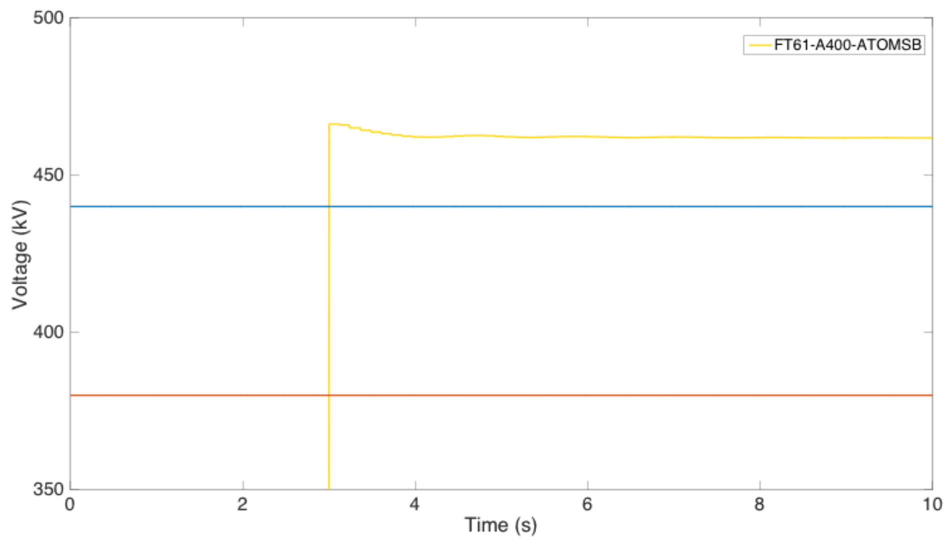


Figure 6.6. Connection of Shunt Reactor in Switchyard: "ATOMSBERG_4_FT61".

Stage 3: "RUTHUVUD_4_FT62".

The third stage of the restoration path 2 is the connection of switchyard *"RUTHUVUD_4_FT62" from* "*ATOMSBERG_4_FT61*" with line "FL10". This voltage evolution is represented in figure 6.7.

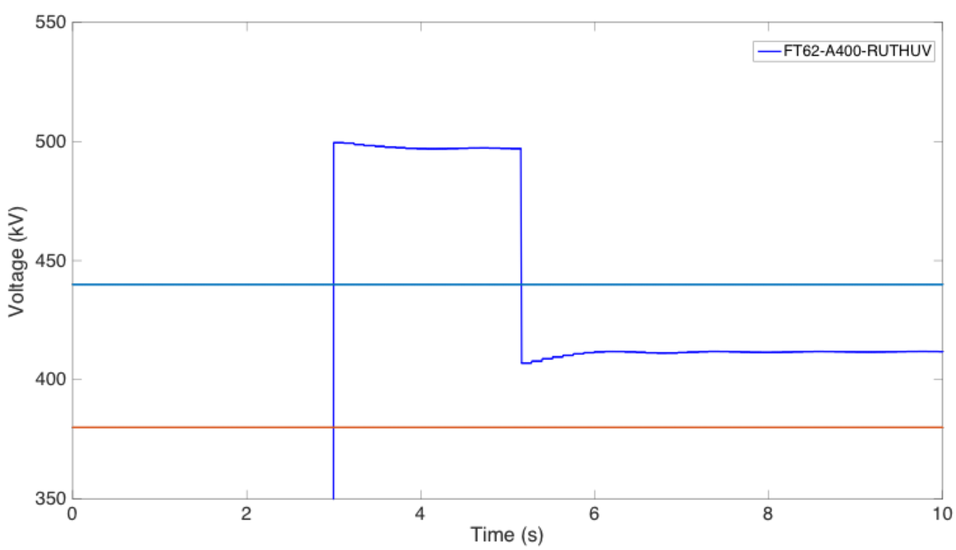


Figure 6.7. Connection of Shunt Reactor in Switchyard: "RUTHUVUD_4_FT62"

The behaviour is the same as the majority of switchyards: the voltage rises above the tolerance band after line connection; but the switchyard is still strong enough, so the voltage remains within the tolerance band after shunt reactor connection.

Stage 4: "SYDKOPING_4_FT50".

The last stage of restoration path 2 is the connection of switchyard "*SYDKOPING_4_FT50*" from *"RUTHUVUD_4_FT62"* with line *"FL11".* The voltage behaviour is different to the previous cases presented.

First of all, the voltage after line connection is much higher (around 650 kV) than the previous cases. This high voltage is not really acceptable and, in a real restoration process, the first shunt reactor should be connected before energizing the line. Therefore, the automatics react after this overvoltage connecting the shunt reactor. The problem is that the voltage drop is not sufficient, and the voltage stays above the tolerance band (450 kV).

In consequence, the shunt reactor 1 (150 Mvar) is not able to control the voltage. Then, the EVAs trigger shunt reactor 2 (100Mvar), with the first one already connected. After 2 seconds, the voltage decreases again. This time, the voltage drop is lower than the previous one because the shunt reactor is smaller. However, the switchyard is weak, so the voltage decreases to a level below the tolerance band. Therefore, reactor hunting phenomenon appears in this switchyard with reactor shunt 2. The reactor shunt 1 does not have reactor hunting and it stays connected. The evolution of the voltage is represented in figure 6.8.

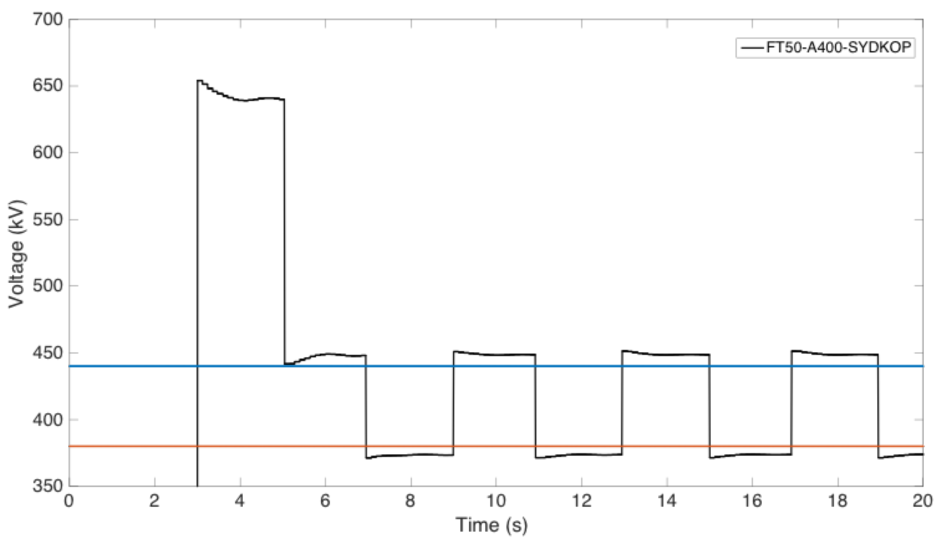


Figure 6.8. Connection of Shunt Reactor in Switchyard: "SYDKOPING_4_FT50"

Simulation of the whole restoration process: path 2.

To conclude, the whole restoration process 2 is shown in figure 6.9. where the original switchyard voltage and the voltage of the four connected switchyards are represented in the same graph.

In this figure, it can be observed how the switchyard becomes weaker when it is farther from the initial system (north). The weaker the switchyard, the larger the voltage drop, until the drop is large enough to set the voltage below the tolerance band, and the reactor hunting occurs.

In this case, in comparison to path 1, the reactor hunting appears with shunt reactor 2, instead of the reactor shunt 1. This is because the first voltage rise after line connection is much larger, so the voltage needs to be decreased from a higher voltage level.

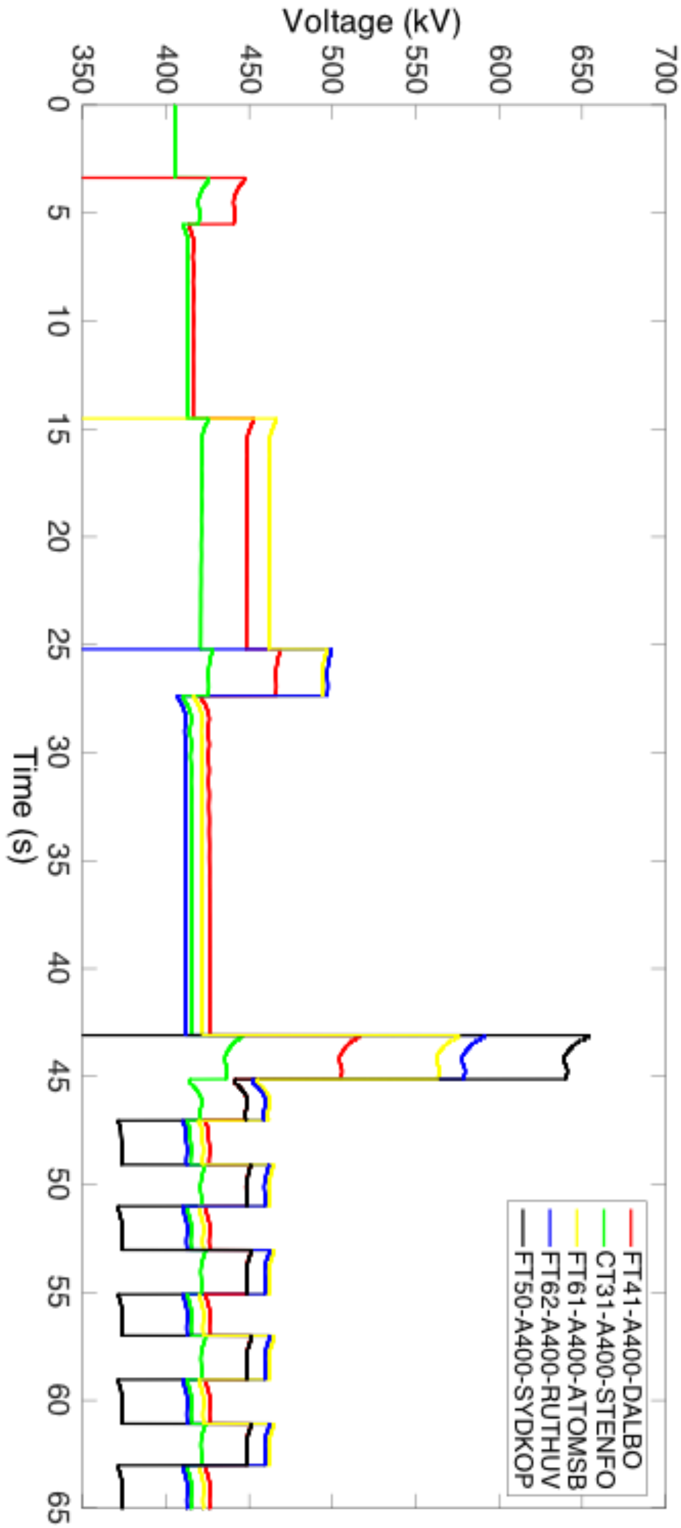


Figure 6.9. Restoration Process, Path 2. With Reactor Hunting.

6.3. Reactor Hunting Avoidance

As it was discussed in the previous section, the restoration process is carried out successfully with the software; and the data and calculations are accurate. Therefore, the adaptive tolerance band method can be applied to the software in order to avoid the reactor hunting phenomenon presented above.

The restoration process carried out is the same as above: paths 1 and 2. In this case, the reactor hunting avoidance is the centre of study. In consequence, only switchyard "*SYDKOPING_4_FT50*" will be discussed in both cases. The rest of switchyards have the same behaviour as previously because there is no reactor hunting, and the voltage stays within the tolerance band after the shunt reactor connection.

As far as Adaptive tolerance band method is concerned, the effectiveness of reactor hunting avoidance will be studied: the accuracy in the calculation for the new lower limit of the tolerance band for each switchyard and the complete avoidance of the fault in the switchyard.

For these simulations, the complete program developed is used. The simulation dialog registered in MATLAB for both restoration paths is presented in Appendix B.

6.3.1. Path 1

Restoration path 1 has three stages starting at "*NJAGGO_4_CT21*". Although the first two switchyards do not have reactor hunting, the adaptive tolerance band method is working in every new connection to the system and the tolerance band is adjusted. Consequently, these switchyards are also useful to calculate the accuracy of the method.

In table 6.3, it is presented the result of the accuracy analysis of the adaptive tolerance band method for restoration path 1. The switchyard voltage before V_{before} and after V_{after} the shunt reactor connection measured in ARISTO simulator is presented and the voltage calculated with the adaptive tolerance band method, V_{low}.

V_{low} represents the prediction of how much the voltage is going to decrease after shunt reactor connection. Thus, the error in the accuracy of the method will be the difference between V_{low} and V_{after}.

Path 1					
Switchyard ID	**S_{sc} from Z_{BUS} [p.u.]**	**V_{before} [kV]**	**V_{after} [kV]**	**$V_{low}(ATB)$**	**Error [%]**
KARNAN_4_FT44	1.057	507.76	432.29	427.2	1.18
NORRAS_4_FT42	0.874	463.81	411.65	409.83	0.44
SYDKOPING_4_FT50	0.743	444.88	366.59	353.6	3.54

Table 6.3. Adaptive tolerance band method (ATB) results. Path 1.

As it can be seen, the results are precise. The adaptive tolerance band predicts accurately the voltage drop of each switchyard. This is expected due to the accuracy of the S_{sc}, discussed above.

The last part of the analysis consists of checking if the system is able to avoid reactor hunting. Since the adaptive tolerance band method calculates the voltage drop prediction, it is able to set the lower limit of the tolerance band just below the voltage after shunt reactor connection.

The evolution of the voltage at "*SYDKOPING_4_FT50*" is represented in figure 6.10. The default lower limit of the tolerance band is presented in red colour and the new adaptive tolerance band for this particular situation is presented in green colour.

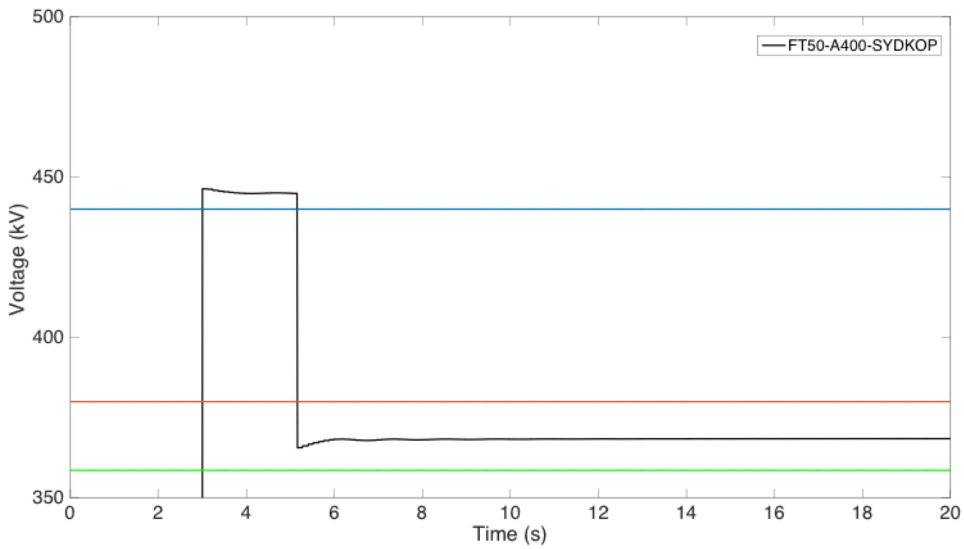


Figure 6.10. Adaptive tolerance band in Switchyard: "SYDKOPING_4_FT50" (path 1).

As it can be seen, the adaptive tolerance band adjust the lower limit just below the voltage after the shunt reactor connection. Then the EVAs detect that the voltage stays within the tolerance band limits and there is no reactor hunting. The objective is reached and the fault is avoided.

To conclude, figure 6.11. represents the complete restoration path 1 with the adaptive tolerance band method. In comparison with figure 6.4, where there was reactor hunting, this time the reactor hunting is avoided and the restoration time is reduced.

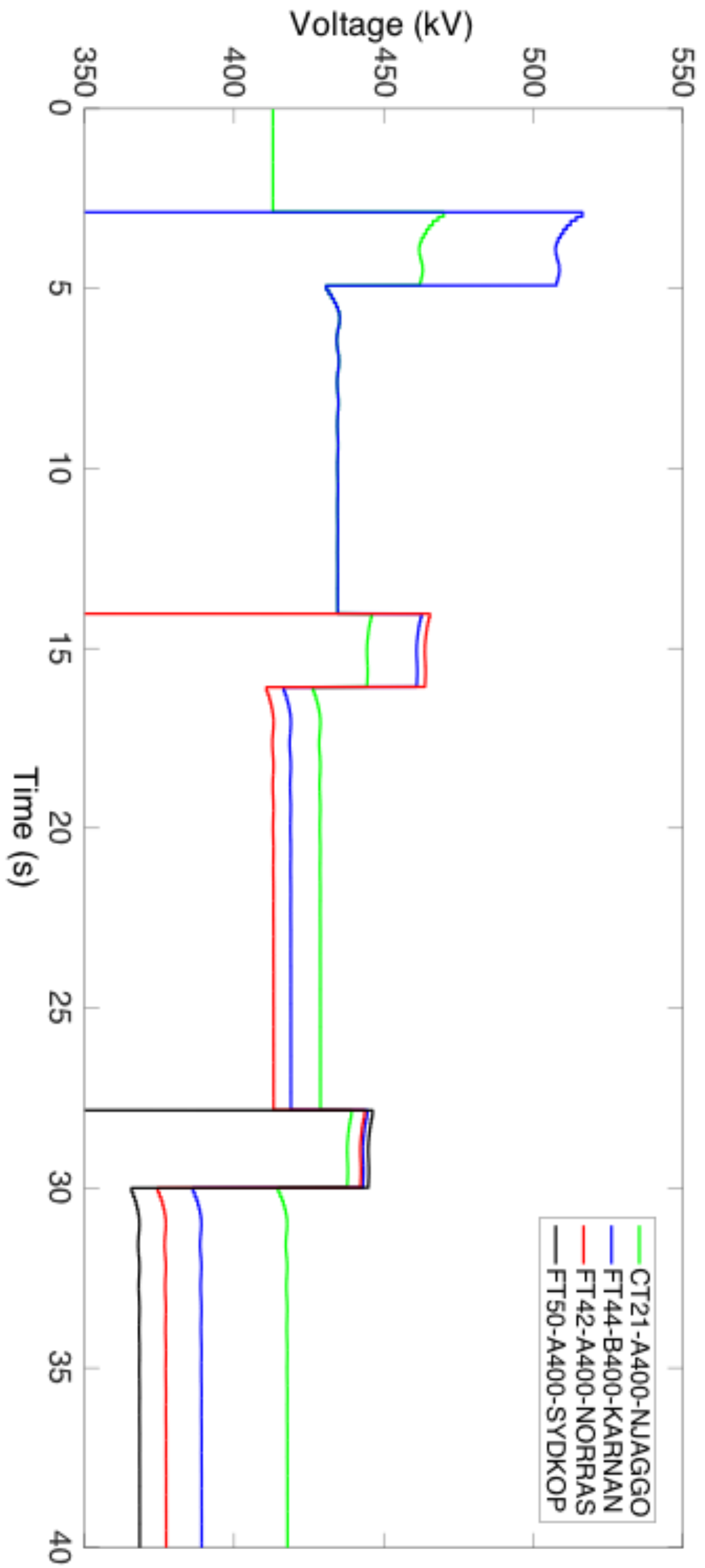


Figure 6.11. Restoration Process, Path 1, by applying the Adaptive tolerance band method.

6.3.2. Path 2

The same strategy is followed with restoration path 2, where the process starts at switchyard "STENFORSE_4_CT31". Table 6.4 represent the analysis of the accuracy of the adaptive tolerance band method. This time, of the four stages, switchyard "*ATOMSBERG_4_FT61*" is not analysed because it does not have reactor shunt to control voltage.

Path 2					
Switchyard ID	**S_{sc} from Z_{BUS} [p.u.]**	**V_{before} [kV]**	**V_{after} [kV]**	**$V_{low}(ATB)$**	**Error [%]**
DALBO_4_FT41	1.86	440.84	414.74	412.04	0.65
RUTHUVUD_4_FT62	0.842	496.91	408.76	407.03	0.42
SYDKOPING_4_FT50	0.501	443.95	372.11	354.02	4.86

Table 6.4. Adaptive tolerance band results. Path 2.

The voltage drop predictions are accurate and the adaptive tolerance band is also precise with another path. In figure 6.12, the voltage evolution of switchyard "SYDKOPING_4_FT50" is represented, and the reactor hunting avoidance is clear. In this case the reactor hunting avoided is with shunt reactor 2.

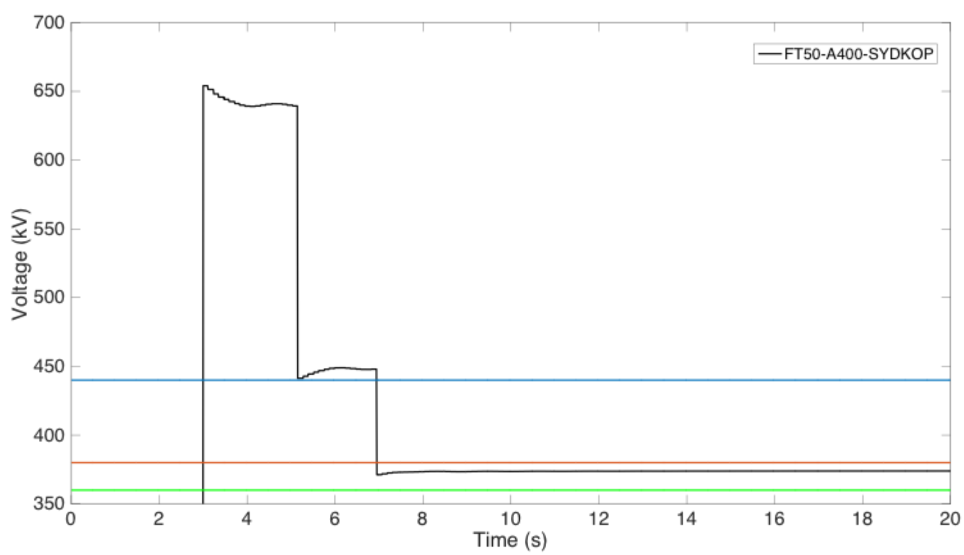


Figure 6.12. Adaptive tolerance band in Switchyard: "SYDKOPING_4_FT50". (Path 2)

Finally, the complete restoration path with adaptive tolerance band method is represented in figure 6.13.

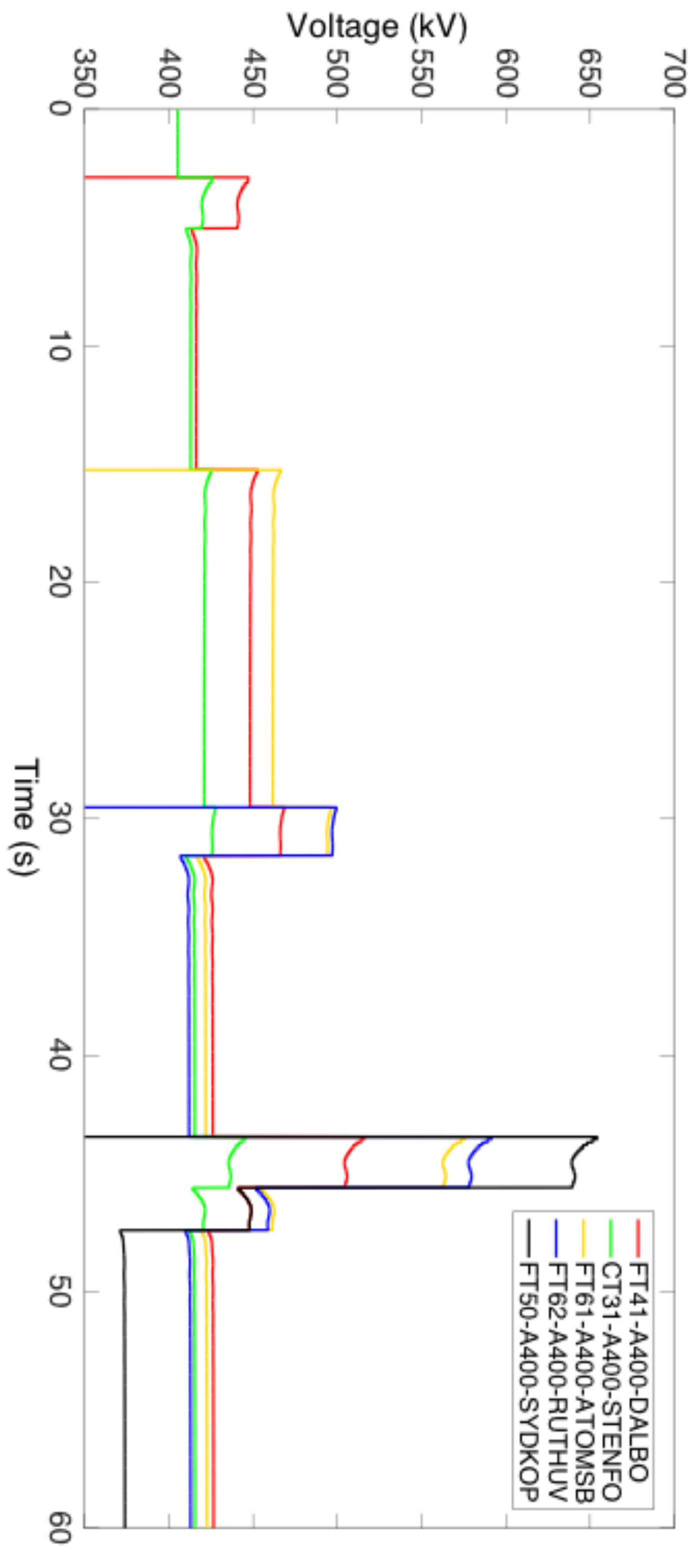


Figure 6.13. Restoration Process, Path 2, by applying the Adaptive tolerance band method.

6.4. Summary

With these two simulations completed and analysed, the contents of chapter 6 are finished. This chapter was intended to show all the software described in chapter 5 with real simulation of NORDIC32 system.

First of all, the data used to create the databases and the incidence matrix were correct. This allowed the software to calculate accurately the short circuit power S_{sc} of every switchyard of the initial NORDIC32 system used in this project, and also the S_{sc} of every new connected switchyard.

In addition, the program developed works perfectly, performing the correct connections and voltage measurements as the user command. Both restoration paths 1 and 2 were tested without reactor hunting avoidance to verify the performance of the program and the presence of the reactor hunting phenomenon at the last switchyard.

Finally, the two restoration paths were simulated, implementing the adaptive tolerance band method. The software detects reactor hunting, adjusts the tolerance band and avoid reactor hunting phenomenon. It can be concluded that the main objective of the project is reached: the adaptive tolerance band method is accurate for automatic reactor hunting avoidance.

CHAPTER 7. DISCUSSION AND CONCLUSIONS

Once the final results are presented, It is important to make a general evaluation of the whole project, where the main aspects of the work are outlined, and to discuss the conclusions of the project.

7.1. Discussion

Electric power systems are one of the basic parts on which actual society and actual economy is based. They are very complex systems with a wide range of variables. This project has been developed with the objective of studying one particular phenomenon during restoration after a power system blackout: Reactor hunting.

The first part of the project described the background behind the Reactor hunting phenomenon, introducing the critic aspects which are necessary to comprehend the singularity of the phenomenon.

To begin with, the theory relevant for the project is presented: the topology of an electric power system, the voltage profile along a transmission line, the Ferranti effect, the power blackouts and the restoration process. The particular case of Sweden and its electric power system is outlined.

It can be concluded that the Swedish power system has a particular topology (long transmission lines connecting the north to the south), which makes it susceptible of having power blackouts and to experience Reactor hunting phenomenon during the restoration process.

On the other hand, the reactor hunting phenomenon is discussed in depth: its causes, impacts and possible ways for avoidance. It is concluded that, during restoration, Reactor hunting is a critical problem that causes voltage fluctuation between overvoltages and extreme low voltages. Thus, this problem needs to be avoided.

In addition, Reactor hunting is actually avoided manually by turning off the EVAs. This increments the restoration time and makes it important to develop an automatic methodology for Reactor hunting avoidance in real time: “The Adaptive Tolerance Band method”.

To finish this part of the project, the software environment used is presented. The NORDIC32 system, which is a simplified model of the Nordic power system is simulated in ARISTO. The real-time program for Reactor hunting avoidance is developed in MATLAB and the communication between both environments is done by AMCX communication tool.

At this point, the next chapters of the project covered the core of the project: the automatic adaptive tolerance band method for reactor hunting avoidance during restoration process after a blackout in NORDIC32 system: the development of the method, the simulation and the result analysis.

With the final simulations, the program is finished and it can be concluded that the main objective of the project has been fulfilled: the adaptive tolerance band is accurate for automatic reactor hunting avoidance.

Consequently, implementing this method in real power systems will improve restoration process in two ways: preventing reactor hunting from happening and reducing the restoration process due to the elimination of the manual operation.

It is important to note that this proposal for reactor hunting avoidance is accurate, cost-efficient and fast because it just needs the software implementation to a pre-existing system where hardware investment is not relevant because the shunt reactors, EVAs and voltage measurements systems are already installed.

7.2. Conclusions

With the project finished, it is important to evaluate the general impact of the work, and to analyse the aims reached which were stated at the start of the project. The conclusions of the project are divided in main conclusion (regarding the program developed and the results) and secondary conclusions (regarding different goals reached while doing the project and studying relevant topics for the work).

7.2.1. Main Conclusions

As a result of the project, it is stated that the adaptive tolerance band method for reactor hunting avoidance is useful, and the program developed corroborates this idea after the simulations with the NORDIC32 test system.

The program implements “Automatic Adaptive Tolerance band method” for Reactor Hunting phenomenon in real time. The program allows the user to select any restoration path and the results are displayed on the screen.

The program is designed for ARISTO simulator and uses AMCX communication tool. It is adjustable for any initial situation or electric power system model of the program, so it is possible to simulate the reactor hunting avoidance in every possible scenario by configuring the database of the program.

In addition, although the program is designed specifically for the ARISTO simulator, the methodology is exportable and adjustable to any system and any simulator, being possible to export it to a real power system.

7.2.2. Secondary Conclusions

During the work, other conclusions have arisen apart from the main program and reactor hunting avoidance purposes. The most relevant are described as follows.

First of all, this project has allowed to get acquainted with the software involving electric power system simulators. This tools are very powerful and useful for research purposes and training operators for power system control.

Moreover, describing the reactor hunting phenomenon includes the study of voltage behaviour, its dependence with load and the Ferranti effect. These aspects, apart from explaining the causes that may produce reactor hunting, are useful to understand how an electric power system works. It is also important to know the different instruments used for voltage control.

Furthermore, during this project it has been studied how the network topology influences the behaviour of the overall power system. A power system is stronger when it is meshed and then, less susceptible to reactor hunting.

It is also important to note that, a connection of several new buses creating a radial path from the initial system does not change the strength of the original buses. However, the further the new bus connection, the weaker is that bus, becoming more vulnerable for reactor hunting.

To conclude, regarding computer methods in electric power system, it has been concluded that the management of network matrices with computers is a very fast and powerful tool that allow automatic implementation of a wide range of application, such as the one implemented in this project.

CHAPTER 8. FUTURE WORK

With the project finished and the conclusions discussed, it is interesting to analyse the possible future works that may be carried out, taking as starting point some of the results, ideas or conclusion presented in this project. There are a lot of possibilities due to the wide range of topics discussed in this work. Some of the most relevant ideas that could state a base for future work are presented as follows:

- First of all, it is easy to see that one of the logical lines of investigation is evaluating the proposed control scheme performance on other test systems, simulators, or also for other operating conditions. Using the program for different situations and also exporting it to other simulation environments will help to take conclusions on the utility of this program or control scheme.

- As it was explained before, the adaptive tolerance band method presented, resets the tolerance band to the default values (380 – 440 kV), once the restoration process is finished. During the whole restoration process the lower limit is the value predicted and stays constant. However, when some lines are connected between two already connected buses, the strength of the buses changes, becoming stronger.

  Implementing the possibility of adding lines to already connected switchyards and readjusting the tolerance band, when the strength of the bus changes, may be a great solution to add to the current work because the tolerance band will be more precise and will control the voltage in case of external faults in a more secure way and a complete restoration path would be possible.

- Improve the program overall performance, or implementing new applications for the restoration process. Some interesting features can be added to the program. For example, the program can evaluate all the possible restoration paths predicting the strength of each bus, the voltage drop and the reactor hunting vulnerability. Then, it can calculate the best restoration path for a given initial system.

- In a more general way, this project may be useful for finally adapt the actual electric power system and implement the adaptive tolerance band in real operation. Then, automatic restoration may be carried out, and the results will be conclusive in order to select this method for restoration processes and reactor hunting avoidance.

- As far as computer methods and network matrices are concerned, this project can be useful to see an example of how to construct network matrices for a given system. Then, this methodology can be used for other purposes because the bus impedance matrix is useful in a wide range of application, such as: short-circuit faults, Energy Management Systems (EMS), etc.

These are some of the possible investigations that can be carried out, using this project as reference. However, this project may be used in other applications, because it was done with a very general purpose and it would be very interesting if this work sets the start for other interesting projects.

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APPENDIX A

This appendix presents the data necessary for the simulations of the NORDIC32 system. This information is taken from the ARISTO database.

Table A.1 represents the line parameters of the initial NORDIC32 system. These are the values of the transmission line model represented in figure 5.1.

LINE ID	R [p,u,]	X [p,u,]	G1 [p,u,]	B1 [p,u,]
AL1	0,1	0,7	0	0,00069
AL2	0,1	0,7	0	0,00069
AL3	0,07	0,5	0	0,0005
AL4	0,07	0,5	0	0,0005
AL5	0,14	0,9	0	0,0009
AL6	0,14	0,9	0	0,0009
AL7	0,3	2	0	0,0015
AL8	0,3	2	0	0,0015
AL9	0,12	0,9	0	0,0076
AL10	0,12	0,9	0	0,0076
CL1	0,05	0,45	0	0,07012
CL2	0,06	0,6	0	0,089
CL3	0,04	0,4	0	0,06007
CL4	0,01	0,08	0	0,0105
CL5	0,05	0,5	0	0,0749
CL6	0,03	0,3	0	0,15
CL7	0,03	0,3	0	0,15
CL8	0,04	0,35	0	0,05253
CL9	0,04	0,4	0	0,06007
CL10	0,04	0,4	0	0,06007
CL11	0,04	0,4	0	0,06007
CL13	0,01	0,1	0	0,01508

Table A.1. Line parameters of the initial system.

Tables A.2 and A.3 represent the parameters of the transformers and generation units of the initial NORDIC32 system, respectively.

Transformer ID	R [p,u,]	X [p,u,]
CT11_T401	0	0,008
CT12_T401	0	0,008
CT22_T401	0	0,012
CT31_T401	0	0,012

Table A.2. Transformer parameters for the initial system.

Generator ID	R [p,u,]	X [p,u,]
AGGAN_G1	0	0,06
AGGAN_G2	0	0,09
NORRSELE_G1	0	0,15
NORRSELE_G2	0	0,15
STENFORSEN_G1	0	0,429
STORFORS_G1	0	0,15
STORTRÄSK_G1	0	0,15
STUPET_G3	0	0,15
STUPET_G4	0	0,15
HÄLLAN_G1	0	0,15
HÄLLAN_G2	0	0,15
HÄLLAN_G3	0	0,15
HÄLLAN_G4	0	0,15
JAURAS_G1	0	0,15

Table A.3. Generator parameters for the initial system.

In table A.4, it is represented the equivalence between the switchyard ID and the number given in the bus impedance matrix. The strength of any particular switchyard will be found in the element with his number in the bus impedance matrix.

Switchyards ID	Number
VATTEN_1_AT111	1
AGGAN_1_CT11	2
OLMAFALL_1_AT121	3
STUPET_1_CT12	4
STORFORS_1_AT131	5
STORTRASK_1_CT22	6
NORRSELE_2_AT241	7
STENFORSE_2_CT31	8
AGGAN_4_CT11	9
JAURAS_4_CT711	10
STUPET_4_CT12	11
HALLAN_4_CT72	12
STORTRASK_4_CT22	13
STENFORSE_4_CT31	14
NJAGGO_4_CT21	15
TORNA_4_CT32	16
KARNAN_4_FT44	17
UPPMARK_4_FT43	18
MITTLANDA_4_FT45	19
ERIKSHAMN_4_FT47	20
NORRAS_4_FT42	21
NORRAS_1_FT42	22
YTTERFORSEN_1_RT131	23
HASTSJO_1_RT132	24
NYSTAD_1_RT133	25
SYDKOPING_1_FT50	26
SYDKOPING_4_FT50	27
BLOCKET_4_FT51	28
DALBO_4_FT41	29
ATOMSBERG_4_FT61	30
RUTHUVUD_4_FT62	31
SYDBACK_4_FT63	32

Table A.4. Switchyard ID - Number equivalence

Table A.5 is the incidence matrix of the initial NORDIC 32 system, where the rows are the different lines, transformers and generators and the columns the first 16 switchyards.

Incidence Matrix	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
AL1	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AL2	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AL3	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
AL4	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
AL5	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
AL6	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
AL7	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0
AL8	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0
AL9	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0
AL10	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0
CL1	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0
CL2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	-1	0
CL3	0	0	0	0	0	0	0	0	1	0	0	0	-1	0	0	0
CL4	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0
CL5	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0
CL6	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0
CL7	0	0	0	0	0	0	0	0	0	-1	0	1	0	0	0	0
CL8	0	0	0	0	0	0	0	0	0	0	1	0	-1	0	0	0
CL9	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0
CL10	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0
CL11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1
CL13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	-1

CT11_T401	0	1	0	0	0	0	0	0	-1	0	0	0	0	0	0	0
CT12_T401	0	0	0	1	0	0	0	0	0	0	-1	0	0	0	0	0
CT22_T401	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	0
CT31_T401	0	0	0	0	0	0	0	1	0	0	0	0	0	-1	0	0
AGGAN_G1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
AGGAN_G2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
NORRSELE_G1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
NORRSELE_G2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
STENFORSEN_G1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
STORFORS_G1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
STORTRÄSK_G1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
STUPET_G3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
STUPET_G4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
HÄLLAN_G1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
HÄLLAN_G2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
HÄLLAN_G3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
HÄLLAN_G4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
JAURAS_G1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0

Table A.5. Incidence Matrix of the initial NORDIC32 system.

APPENDIX B

This appendix presents the simulation dialog, registered in MATLAB, that the program uses during simulations of restoration paths 1, and 2. As it was presented in the flow diagram of the program in chapter 5, It is represented the two blocks: Creation of Zbus and Restoration Process. The second block is divided in stages for each new connection. In each stage, the switchyards selected, the connections, and results are represented.

Path 1

```
Automatic Reactor Hunting Avoidance during Power System Restoration
                   Master Thesis
               Guillermo Amor Alonso
-----------------------------------------------------------------------
                   1.- CREATION of Zbus
Zbus for the system after southern blackout completed.
The restoration process may proceed.
-----------------------------------------------------------------------
                  2.- RESTORATION PROCESS
Stage 1:
Which Switchyard is connected first? KARNAN_4_FT44
From Which Switchyard do you want to connect KARNAN_4_FT44? NJAGGO_4_CT21
There is ONE line connecting KARNAN_4_FT44 and NJAGGO_4_CT21: CL12.

The impedance matrix has been updated successfully with KARNAN_4_FT44.
The Short Circuit Capacity of KARNAN_4_FT44 is: Ssc= 1057.72 MVA.
line connected
EVAs X1
The Voltage BEFORE Shunt Reactor 1 Connection is: 507.76 kV. The decrease expected is: 427.2 kV
Lower limit of the tolerance band is set to: 427.2 kV
The Voltage AFTER Shunt Reactor 1 Connection is: 432.29 kV.

The switchyards KARNAN_4_FT44 and NJAGGO_4_CT21 are connected through the line CL12
-----------------------------------------------------------------------
```

Stage 2:

Which Switchyard is connected next? NORRAS_4_FT42

From Which Switchyard do you want to connect NORRAS_4_FT42? KARNAN_4_FT44

There is ONE line connecting NORRAS_4_FT42 and KARNAN_4_FT44: FL16.

The impedance matrix has been updated successfully with NORRAS_4_FT42.

The Short Circuit Capacity of NORRAS_4_FT42 is: Ssc= 872.38 MVA.

line connected

EVAs X1

The Voltage BEFORE Shunt Reactor 1 Connection is: 463.81 kV. The decrease expected is: 409.83 kV

Lower limit of the tolerance band is set to: 409.83 kV

The Voltage AFTER Shunt Reactor 1 Connection is: 411.65 kV.

The switchyards NORRAS_4_FT42 and KARNAN_4_FT44 are connected through the line FL16

Stage 3:

Which Switchyard is connected next? SYDKOPING_4_FT50

From Which Switchyard do you want to connect SYDKOPING_4_FT50? NORRAS_4_FT42

There are TWO lines connecting SYDKOPING_4_FT50 and NORRAS_4_FT42.

Which Line is going to be connected: FL7 or FL8? FL8

The impedance matrix has been updated successfully with SYDKOPING_4_FT50.

The Short Circuit Capacity of SYDKOPING_4_FT50 is: Ssc= 742.29 MVA.

line connected

EVAs X1

The Voltage BEFORE Shunt Reactor 1 Connection is: 444.88 kV. The decrease expected is: 353.6 kV

Lower limit of the tolerance band is set to: 353.6 kV

The Voltage AFTER Shunt Reactor 1 Connection is: 366.59 kV.

The switchyards SYDKOPING_4_FT50 and NORRAS_4_FT42 are connected through the line FL8

```
------------------------------------------------------------------------
Stage 4:
Which Switchyard is connected next? EXIT
```

Path 2

```
Automatic Reactor Hunting Avoidance during Power System Restoration
                   Master Thesis
               Guillermo Amor Alonso
------------------------------------------------------------------------
                   1.- CREATION of Zbus
Zbus for the system after southern blackout completed.
The restoration process may proceed.
------------------------------------------------------------------------
                  2.- RESTORATION PROCESS
Stage 1:
Which Switchyard is connected first? DALBO_4_FT41
From Which Switchyard do you want to connect DALBO_4_FT41? STENFORSE_4_CT31
There are TWO lines connecting DALBO_4_FT41 and STENFORSE_4_CT31.
Which Line is going to be connected: CL14 or CL15? CL14
The impedance matrix has been updated successfully with DALBO_4_FT41.
The Short Circuit Capacity of DALBO_4_FT41 is: Ssc= 1876.79 MVA.
line connected
EVAs X1
The Voltage BEFORE Shunt Reactor 1 Connection is: 440.84 kV. The decrease expected is: 412.04 kV
Lower limit of the tolerance band is set to: 412.04 kV
The Voltage AFTER Shunt Reactor 1 Connection is: 414.74 kV.

The switchyards DALBO_4_FT41 and STENFORSE_4_CT31 are connected through the line CL14
------------------------------------------------------------------------
```

```
Stage 2:

Which Switchyard is connected next? ATOMSBERG_4_FT61

From Which Switchyard do you want to connect ATOMSBERG_4_FT61? DALBO_4_FT41

There is ONE line connecting ATOMSBERG_4_FT61 and DALBO_4_FT41: FL6.


The impedance matrix has been updated successfully with ATOMSBERG_4_FT61.

The Short Circuit Capacity of ATOMSBERG_4_FT61 is: Ssc= 1013.37 MVA.

line connected

There are no shunt reactors in ATOMSBERG_4_FT61


The switchyards ATOMSBERG_4_FT61 and DALBO_4_FT41 are connected through the line FL6

-----------------------------------------------------------------------

Stage 3:

Which Switchyard is connected next? RUTHUVUD_4_FT62

From Which Switchyard do you want to connect RUTHUVUD_4_FT62? ATOMSBERG_4_FT61

There is ONE line connecting RUTHUVUD_4_FT62 and ATOMSBERG_4_FT61: FL10.


The impedance matrix has been updated successfully with RUTHUVUD_4_FT62.

The Short Circuit Capacity of RUTHUVUD_4_FT62 is: Ssc= 841.95 MVA.

line connected

EVAs X1

The Voltage BEFORE Shunt Reactor 1 Connection is: 496.91 kV. The decrease expected is: 407.03 kV

Lower limit of the tolerance band is set to: 407.03 kV

The Voltage AFTER Shunt Reactor 1 Connection is: 408.76 kV.


The switchyards RUTHUVUD_4_FT62 and ATOMSBERG_4_FT61 are connected through the line FL10

-----------------------------------------------------------------------
```

Stage 4:

Which Switchyard is connected next? SYDKOPING_4_FT50

From Which Switchyard do you want to connect SYDKOPING_4_FT50? RUTHUVUD_4_FT62

There is ONE line connecting SYDKOPING_4_FT50 and RUTHUVUD_4_FT62: FL11.

The impedance matrix has been updated successfully with SYDKOPING_4_FT50.

The Short Circuit Capacity of SYDKOPING_4_FT50 is: Ssc= 501.20 MVA.

line connected

EVAs X1

The Voltage BEFORE Shunt Reactor 1 Connection is: 639.49 kV. The decrease expected is: 440.15 kV

Lower limit of the tolerance band is set to: 440.15 kV

The Voltage AFTER Shunt Reactor 1 Connection is: 443.97 kV.

EVAs X2

The Voltage BEFORE Shunt Reactor 2 Connection is: 443.95 kV. The decrease expected is: 354.02 kV

Lower limit of the tolerance band is set to: 354.02 kV

The Voltage AFTER Shunt Reactor 2 Connection is: 372.11 kV.

The switchyards SYDKOPING_4_FT50 and RUTHUVUD_4_FT62 are connected through the line FL11

Stage 5:

Which Switchyard is connected next? EXIT