Control of Reactive Shunts-Voltage Stability and Restoration

Mohammad Reza Safari Tirtashi

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Department of Biomedical Engineering

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Department of Biomedical Engineering
Faculty of Engineering
Lund University
Box 118
221 00 LUND
SWEDEN

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Abstract

Modern society significantly depends on the secure and reliable electricity supplies. In fact power networks are the backbones of modern industrial societies. The frequent danger which always threats the availability of secure power systems is the large scale blackouts. These large scale long-lasting disruptive power blackouts have significant impact on society and entire economy and pose serious challenges for people's daily life. The initial disturbances which lead to massive blackouts such as those that occurred in Sweden in 1983 and 2003 include: lightning, operator's errors, short circuit of transmission lines, protection device malfunction and so on. After these initial events, a sequence of disturbances occur lead to propagation of failures and in most cases they ultimately end up to large scale blackouts. Since cascading outages include many unlikely and unexpected events, then the prediction of them is really difficult. However voltage instability and in particular long-term voltage instability was the main reason behind many of recent large scale cascading outages and blackouts. Shunt reactors and capacitors are important reactive resources to prevent long-term voltage instability. The way to control them in both normal and emergency conditions is an important issue for power system operators. Reactive shunts are commonly controlled using a local scheme, which switches the shunt when the voltage at the local bus is outside the tolerance band. An alternative control strategy proposed in the thesis which can be used by Transmission System Operators (TSOs) around the world is called the neighboring scheme. In this strategy both the local voltage and the voltage at neighboring buses are considered. The neighboring scheme can raise the voltage stability-constrained transfer limit compared to the local one and it has better performance in the sense of suppressing the contingencies and improving the long-term voltage stability by connecting more shunt capacitors or connecting earlier. To study the voltage instability problem in detail, the full representation of the

power network is needed but it may for several reasons not be practical. For many applications, a reduced order network model is more convenient. For this purpose, the NORDIC32 CIGRE test system has previously been developed. This test system has the key long-term dynamics of the Swedish power system and is suitable to simulate long-term voltage collapses like what happened in 1983 and 2003 in Sweden. Although NORDIC32 is a reduced order model of the Swedish system, it is still a complex test system. The N3area test system which is proposed in the thesis is the simplest test system that can replicate the long-term voltage dynamics of NORDIC32 and the Swedish power system. The main advantage of the N3area test system is that it reduces NORDIC32 model complexity, so long-term voltage instability behavior and countermeasures can be analyzed much easier there than in NORDIC32, still retaining a dynamic behavior quite close to NORDIC32 and reality. While the dream for power system operators is to have a secure operation continually, blackouts indeed do occur. So power system restoration is an important task for TSOs and it should be done as fast and securely as possible to reduce social and economical consequences for the population. One problem which may increase the restoration time is the reactor hunting phenomenon. Large scale voltage fluctuations are the consequence of the reactor hunting. To speed up the restoration process also to avoid voltage fluctuations, reactor hunting must be handled as quickly as possible. The common practice for TSOs to avoid reactor hunting is turning off the shunt automatics during the restoration period. That leaves the shunts in manual operation which leads to longer restoration process. The adaptive tolerance band concept for shunt automatics is proposed in this thesis to handle the reactor hunting issue. This new control scheme uses short circuit capacity from Energy Management System (EMS) network model to change the Extreme Voltage Automatics (EVA) settings and make them adaptive based on the network strength. So automatic operation of the reactive shunts will continue during the restoration time, also the reactor hunting problem would be solved.

Acknowledgements

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Lund, April 2015
Mohammad Reza Safari Tirtashi

Contents

Chapter 1

Introduction

In this chapter the background and objectives of the work are provided, followed by the contributions and outline of the thesis.

1.1 Background

Recent large-scale blackouts highlight the need to have secure and reliable electricity infrastructure around the world. Many of those large blackouts were the consequence of cascading failures. In fact they are triggered by initial disturbances, and then a sequence of disturbances occur leading to propagation of failures. Mostly, these consecutive disturbances ended up to blackouts. Large scale blackouts have a huge and significant impact on daily life and the entire economy. However voltage collapse was the main reason behind many of recent blackouts. For the Swedish power system, since it has long transmission lines which connect northern and central areas, the risk of voltage collapse at the central or southern parts of the country is an inherent feature of the system. To have more secure power network, the voltage collapse issue must be handled. One option to handle this issue is using shunt reactors and capacitors to regulate the voltage through the entire network. These shunt elements are commonly controlled using a local scheme which switches the shunts when the voltage at the local bus is outside the tolerance band. The local scheme is utilized by the Transmission System Operators (TSOs) around the world for shunt automatics but it cannot save the system in all blackouts scenarios. Therefore other alternative schemes are of interest for power system operators to improve voltage stability. Moreover, since the blackout is a fact, power system restoration should be considered as an important issue for operators. The main goal for TSOs is to restore the power system as fast and securely as possible to reduce social and economical consequences for the population. In the restoration strategy used by the Swedish TSO, first the long transmission lines between northern and central areas are energized. This raises the voltage and reaches high voltage at the ending point of the transmission lines in the central areas. In order to lower the voltage, shunt reactors are connected to the system. The reactor automatics work based on the local scheme. During the restoration process, since the power system is weak, then connecting the shunt reactors might impact a lot and lead to extreme low voltage. If the voltage gets below the lower limit, then the automatics will turn off the reactor again. This phenomenon is called reactor hunting and causes voltage fluctuations in the system and happened in the 2003 Swedish/Danish blackout. The common practice to avoid reactor hunting is turning off the shunt automatics. That leaves the shunts in manual operation which increases the restoration process time. To speed up the power system restoration, reactor hunting issue must be handled as quickly as possible.

1.2 Objectives

The main purpose of this work is to understand and investigate the long-term voltage instabilities, also applying countermeasures to avoid large scale blackouts such as those that occurred in Sweden in 1983 and 2003. The shunt reactors and capacitors which are the traditional reactive resources for avoiding long-term voltage instabilities are investigated and used in this thesis for NORDIC32 and N3area test systems with the aim to prevent large scale blackouts. The second part of this work is directed towards methods to avoid reactor hunting during power system restoration. To reach this goal, the mechanism of reactor hunting is analyzed. After that adaptive tolerance band concept is proposed to be applied for the Extreme Voltage Automatic (EVA) of the shunts. Then our method is employed for the specified restoration scenarios on NORDIC32 test system to avoid reactor hunting.

1.3 Contributions

The main contributions of this thesis are listed below:

- The neighboring scheme is proposed as a new real-time countermeasure to control shunt reactors and capacitors to avoid long-term voltage instability and blackout. Neighboring scheme can raise the voltage stability-constrained transfer limit compared to the local one. It has also better performance in the sense of suppressing the contingencies and improving the long-term voltage stability by connecting more shunt capacitors or connecting earlier

- The new test system called N3area which is a textbook size version of NORDIC32 is proposed to be representative of the Swedish national transmission system in the long-term voltage stability studies. The local and neighboring schemes performances are applied on both N3area and NORDIC32 test systems.
- The new control concept called adaptive tolerance band is proposed for shunt reactors automatics to avoid reactor hunting during power system restoration. The simulation results show the capability of the proposed concept to avoid reactor hunting.

1.4 Outline

Chapter 2 first gives the general description of the power system blackouts. Then it covers different types of power system stability including; rotor angle stability, rotor speed stability, frequency stability and voltage stability. Voltage stability and in particular long-term voltage stability is explained further in this chapter. After that the Swedish transmission system is explained. Also the Swedish/Danish 2003 blackout is described in this chapter. Finally the overview of power system restoration is provided and the reactor hunting issue is introduced as a potential problem which leads to longer restoration process.

Chapter 3 describes different actuators which can be used to control the voltage and thereby improve voltage stability and prevent voltage collapse in power systems. Shunt reactors and capacitors are explained further as traditional actuators to enhance the long-term voltage stability.

Chapter 4 describes voltage control methods to improve the voltage stability in power systems. Primary and secondary voltage controls are described in this chapter. The neighboring scheme for shunt capacitor control as a new control scheme proposed in the thesis is comprehensively explained in this chapter.

Chapter 5 describes two considered test systems; NORDIC32 and N3area. After giving general information of these two test systems, their load and

Over Excitation Limiter (OXL) models which are two important dynamics in the long-term voltage instability phenomenon are thoroughly explained and discussed.

Chapter 6 covers the dynamic simulation results of N3area and NORDIC32 test systems. First the general picture of the long-term voltage collapse mechanism is explained using N3area test system, also the corrective actions are employed to counteract the long-term voltage instability. In the second part, the NORDIC32 test system and its simulation results are presented. Two long-term voltage instability scenarios including generator and transmission line outages are considered. Finally static analysis using PV curves is conducted to give deep understanding of the neighboring scheme concept.

Chapter 7 first gives the conceptual description of the reactor hunting phenomenon using a basic circuit. Then the adaptive tolerance band based on the short-circuit capacity is proposed for the shunt automatics as a new control scheme to avoid reactor hunting.

Chapter 8 introduces two applicable methods to eliminate the reactor hunting during power system restoration including; experimental method and using EMS network model. Both of these two proposed methods are applied to eliminate reactor hunting. The simulation results are presented and discussed.

Chapter 9 covers the conclusions and the future work.

1.5 Publications

1- M. Reza Safari Tirtashi, O. Samuelsson and J. Svensson "Control Strategies for Reactive Shunts to Improve Long-Term Voltage Stability"48th International Universities Power Engineering Conference (UPEC), Dublin, Ireland, 2-5 September, 2013.
2- M. Reza Safari Tirtashi, O. Samuelsson and J. Svensson "Long-Term Voltage Collapse Analysis on a Reduced Order Nordic System Model"49th International Universities Power Engineering Conference (UPEC), Romania, 2-5 September, 2014.

3- M. Reza Safari Tirtashi, O. Samuelsson and J. Svensson “New Approach to Control the Reactive Shunts to Avoid Long-Term Voltage Instability” to be submitted.
4- M. Reza Safari Tirtashi, O. Samuelsson and J. Svensson “ Adaptive Tolerance Band for Shunt Automatics to Avoid Reactor Hunting” to be submitted.

Chapter 2

Power System Blackouts

A power system blackout is the short-term or long-term loss of the electric power to an area. They have major direct or indirect consequences on the economy and national security [1]. Many large blackouts happened time by time around the world. For example the Swedish power system has experienced extensive blackouts in 1983 and 2003 [2,3].

Generally large blackouts rarely happen in power systems but still there is a potential risk to have them in power networks around the world. Many of large blackouts were the consequence of cascading failures. Since they are complex phenomena, many researchers around the world are trying to understand them. They are triggered by initial disturbances, and then a sequence of disturbances occur cause to propagation of failures. Mostly, these consecutive disturbances lead to blackouts. Initial disturbances include: lightning, operator's errors, short-circuit of transmission lines and protection device malfunction [4]. For avoiding cascading outages and blackouts, power system stability is considered as one of the most important issues in the realm of electric system operation. The importance of the power system stability is derived from the fact that power networks should maintain their frequencies and voltages at desirable levels both in normal and fault operations.

2.1 Power System Stability

Power system stability is recognized as a broad area to be managed for secure operation. In [5,6] power system stability is defined as ''the property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance''. Traditionally, power system stability concerns keeping all synchronous generators in synchronous operation. To reach this goal, generator rotor angle should be stable. The instability in power systems might come from other reasons like lack of voltage control in the system.

Power system stability can be divided into three different forms; rotor angle stability, frequency stability and voltage stability. The forth one, rotor speed stability, is proposed in [7], see Fig. 2-1. From time frame perspective, it could be either short-term or long-term stability.

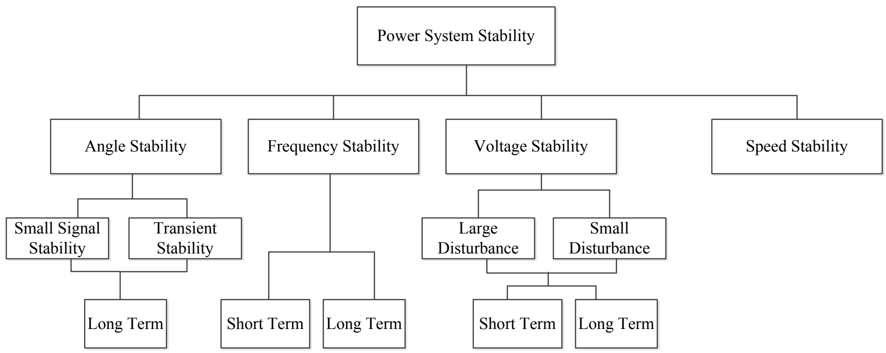

Fig. 2-1 Classification of power system stability [5,7].

Rotor angle stability

Rotor angle stability is the ability of the interconnected synchronous machines of a power system to keep synchronism under normal operating conditions and after being subjected to a disturbance [5,6]. Rotor angle stability depends on the ability of the power system to maintain equilibrium between electromagnetic torque and mechanical torque [6]. This type of instability appears either in the form of undamped electromechanical oscillations or in the form of monotonic rotor acceleration [8]. The first form is because of the lack of damping torque and the latter is because of the lack of synchronizing torque [8]. Lack of damping torque is usually because of small disturbances and is called small signal stability, while large disturbances leads to lack of synchronizing torque and it is called transient stability. The time frame of this type of stability typically lasts for a few seconds [9]. Rotor angle instability for small signal and large disturbances are shown in Fig. 2-2 and 2-3.

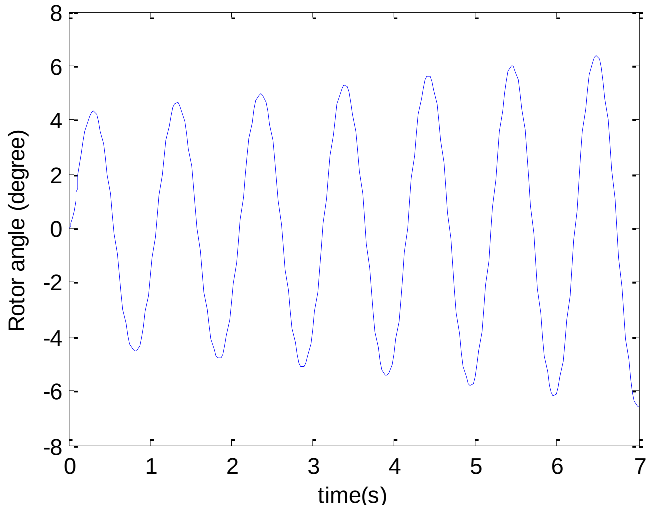

Fig. 2-2 Typical rotor angle instability for small disturbance.

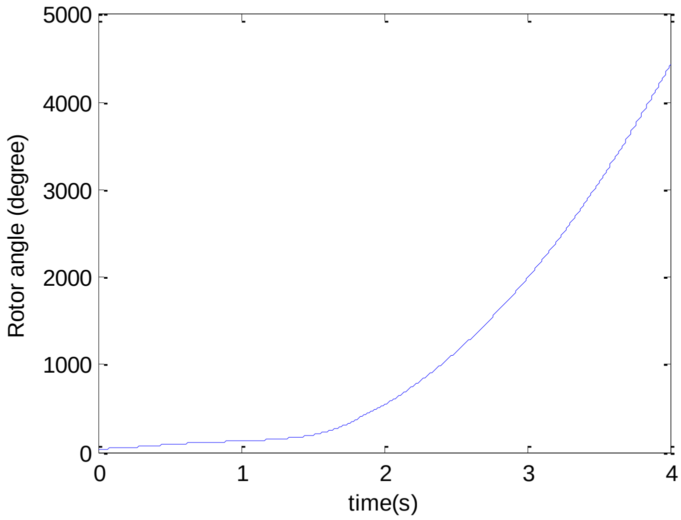

Fig. 2-3 Typical rotor angle instability for large disturbance.

Rotor speed stability

Using induction generators for wind power plants and distributed energy resources are frequently increasing. If a disturbance happens close to induction generators, it might lead to significant speed increase of the generator rotor which is far from the pre-fault value. To characterize this type of instability, the rotor speed stability concept is proposed in [7].

Rotor speed stability is ‘‘the ability of an induction machine to remain connected to the electric power system and running at a mechanical speed close to the speed corresponding to the actual system frequency after being subjected to a disturbance’’ [7]. To clarify more and give better understanding of the rotor speed stability issue, the test system in Fig. 2-4 is considered. The induction generator is connected at bus A. At t=1 s, a three-phase fault occurs at F on the transmission line. The fault is cleared after 0.9 s by opening the corresponding circuit breakers. The generator rotor speed is shown in Fig. 2-5 and it is clear that the rotor speed has increased too much and it reaches the level far above the normal operating point.

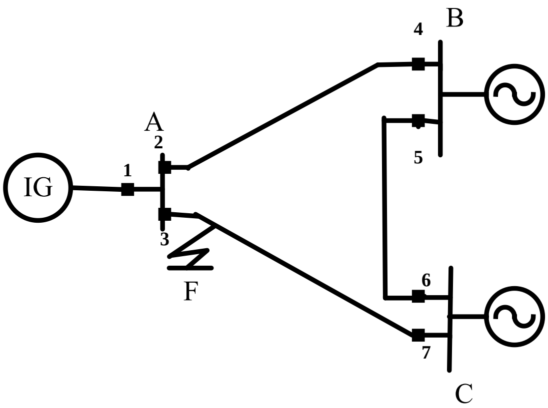

Fig. 2-4 Single-line diagram of the considered test system to investigate rotor speed instability [7].

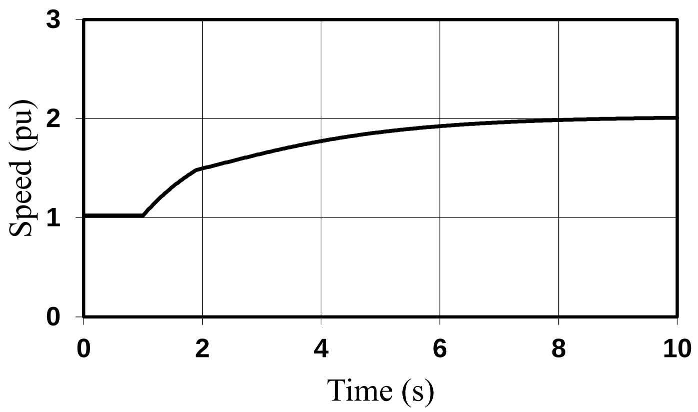

Fig. 2-5 Typical rotor speed instability of the induction generator [7].

Frequency stability

Frequency stability is the ability of the power system to maintain frequency within nominal range both in normal and fault operation [5,6]. This type of stability is mainly related to the balance between the generation and the consumtion and is irrespective of the network structure. From time frame perspective, it could be either short-term or long-term stability.

To show the frequency instability problem, the test system in Fig. 2-6 is considered. This test system consists of four synchronous generators where three of them participate in the primary frequency control [5].

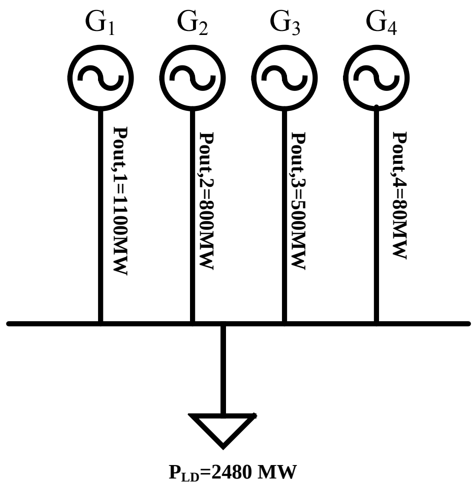

Fig. 2-6 Test system to investigate frequency instability problem.

By utilizing the lumped representation of the rotating masses and a very simplified model of the power controllers and the prime movers, the frequency of the system can be estimated from the block diagram shown in figure 2-7.

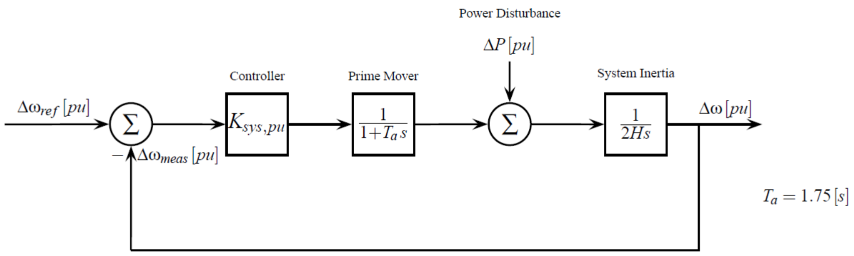

Fig. 2-7 Simplified block diagram of the considered test system to investigate the frequency instability [5].

Fig. 2-8 shows the frequency response of the system once a step increase in the load of 80 MW is applied. As shown in this figure, following the disturbance, the frequency starts to decrease and the minimum value for the frequency is 49.85 Hz. Then the primary frequency action leads to frequency restoration after around 20 s. To reach the nominal frequency (50 Hz), the secondary frequency control must be activated.

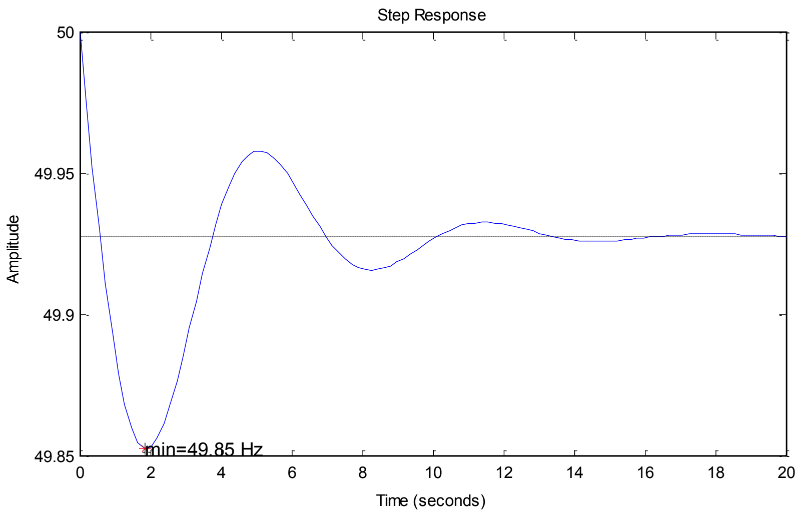

Fig. 2-8 Frequency response after step increase in the load.

Voltage stability

Voltage stability refers to the ability of a power system to keep all the bus voltages within the acceptable limits during both normal and emergency conditions [5,6]. Voltage stability depends on the network structure. Two time frames are normally considered relating to dynamics in the time-scale of seconds and several minutes [10].It means this type of stability could be either short-term or long-term. In short term voltage stability, behavior of induction motors, air conditioning loads and HVDC links are important factors while in long-term voltage stability, tap changer actions, distributed voltage regulators and thermostatic loads play important roles [11]. Voltage stability is sometime called load stability as some loads are the driving force for the voltage instability. Especially their recovery process after voltage changes must be considered in voltage stability studies and how the load is modeled is quite important. Also the capability of generators to inject reactive power and compensate locally for the lack of reactive power does affect the voltage stability significantly [8].

This type of instability usually occurs in heavily stressed systems. To get deeper understanding of the voltage stability, the following radial system is considered. This basic circuit represents a large system connected by lossless transmission line to a load bus.

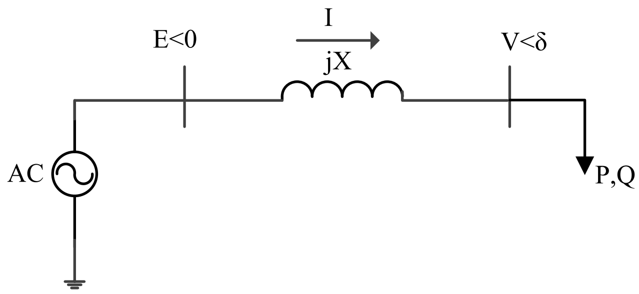

Fig. 2-9 Basic circuit represents a large system connected by lossless transmission line to a load bus.

The following equation relates the voltage at load bus (V) with respect to the line reactance (X), sending end voltage (E) and active and reactive powers delivered to the load bus (P, Q):

$$V = \sqrt{-XQ + \frac{E^2}{2} \pm \sqrt{\frac{E^4}{4} - X^2 P^2 - E^2 XQ}} \qquad (2.1)$$

Based on the Eq. 2.1, the following PV-curves for different load angles (ϕ) are plotted while E=100 kV and X=100 Ω.

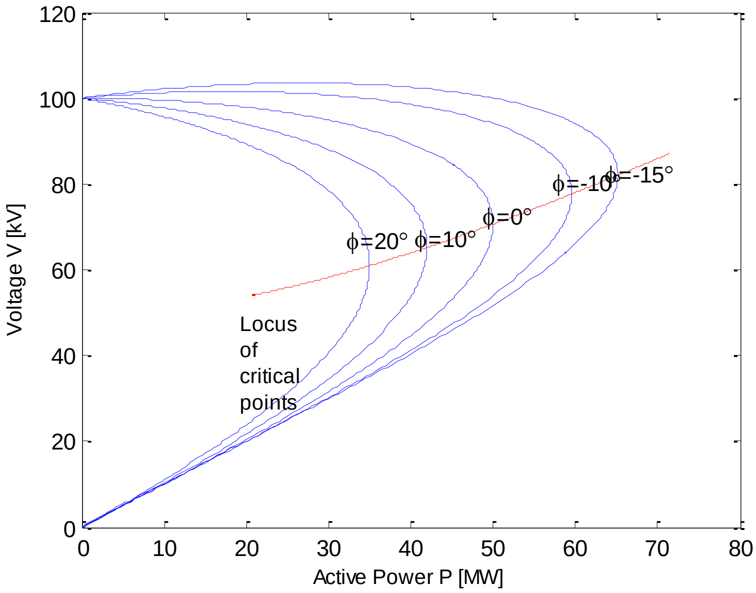

Fig. 2-10 PV curves for different load angles; P+jQ=S($\cos\phi + j\sin\phi$).

The operating points above the critical points (maximum power transfer) represent satisfactory operating conditions [5,11]. Based on the Fig. 2-10, it could be said that the reactive power strongly influences the voltage stability and also the maximum capability of the line. Also it is clear that two different voltage levels, high and low, are corresponding to a specified amount of active power. The power systems normally work on higher voltage level to lower the current also the transmission losses.

Long-Term Voltage Instability

If the power system survived from short-term dynamics perspective, then the long-term dynamics will take over the system and might still lead to voltage instability for the power system. This type of voltage instability is known as the long-term voltage instability.

There are some mechanisms for long-term voltage instability. The most common one is the process when the load is recovered either through Load Tap Changing (LTC) transformer action or through self-restoration [10].

Generally, in the long-term voltage instability process, there are some dynamics and elements which are central:

Loads: are called the driving force of voltage instability and the importance of load modeling for studying voltage stability issues has been acknowledged [12,13].

Transmission lines: have their own limits to transfer the power and this limit can be analyzed using the PV curve concept. This limitation is mainly known as maximum deliverable power [8].

Generation: generators are not ideal voltage sources and their modeling is quite important in voltage instability analysis [10]. In particular, their limitations on reactive power generation are of interest since these limitations cause strong reduction of the voltage stability margin in the nearby generator area [13].

Another term used in conjunction with voltage stability problem is voltage collapse [8]. Voltage collapse is usually characterized by a slow variation in the voltage magnitude till the point of the collapse when the voltage starts decreasing quickly in a very short time-scale of seconds [14]. To clarify more and distinguish between voltage instability and voltage collapse definitions [15], three different operating conditions for power systems can be considered based on the Fig. 2-11.

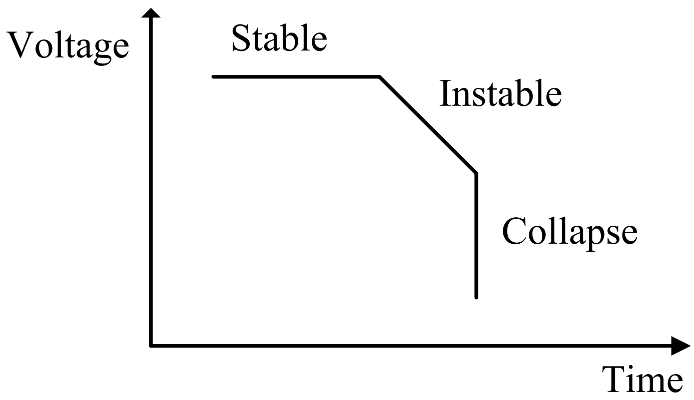

Fig. 2-11 Different operating conditions from voltage stability perspective.

First the power system is working in a stable situation and all voltages are within acceptable limits. Then after applying a disturbance, the long-term dynamics like tap changer actions, thermostatic load behaviors and OXL actions take over the system behavior and the voltage is unstable in this time period. This time frame which is corresponding to voltage instability typically lasts for a couple of minutes. Finally the short-term dynamics like distance relay protection actions, under voltage and out of step relay actions take over the power system behavior and voltage collapses in this time period. This time frame which is corresponding to voltage collapse typically lasts for a couple of seconds.

Voltage collapse has resulted in many recent large blackouts. Consequently voltage collapse is nowadays major concerns for power system planning and operation [16-22] .The major voltage instability events that occurred in 2003 are listed in Table 2-1 [23].

Table 2-1: Recent voltage collapse events [23]

Date	Location	Time Frame	Prior System Condition	Sequence of Events
14th August 2003	US/Canada	5 min	Operated in complience with north american electric reliability council policy	Apparent reactive power supply problems, state estimator and Real Time Contingency Analysis (RTCA) software problem
23th September 2003	Swedish / Danish System	7 min	Moderately loaded with two 400kV lines and three HVDC links were out on schedule maintenance	Loss of 1200MW nuclear unit in the southern Sweden, due to problems with steam valve. Occurrence of a double bus bar fault leading to the loss of 400kV lines and two 900MW nuclear units. A high power transfer on 400kV lines from north to south, then distance relays actions and finally blackout happened for southern part of Sweden and eastern part of Denmark
28th September 2003	Italy	4 min	Heavy power import into Italy	The automatic breaker controls did not reclose the previously tripped line. The phase angle difference across the line was too large due to the heavy power import. Frequency started to fall rapidly in the Italian system

Swedish Electricity Network and Voltage Instability

The Swedish electricity network consists of 538,000 km of conductors, of which 320,000 kilometres are underground cables. It has also 218,000 kilometres overhead lines [24]. Fig. 2-12 shows the Swedish transmission network. The electricity network can be divided into three levels: the transmission network, the sub transmission network and the distribution network [24]. The high voltage transmission network transports electricity over long distances, mainly from northern area which is hydro dominated part towards central and south areas. The sub transmission network transports electricity from the transmission network to the distribution networks. The distribution networks are connected to the sub transmission networks. Their task is to transport electricity to the households [24].The Swedish TSO, Svenska Kraftnät is responsible to transmit the electrical energy from the major power stations to regional electrical grids. It is also responsible for maintaining a balance between generation and consumption of the electricity in Sweden [25].

Even though the use of renewable energies like wind power has gained a lot of interest from Swedish electricity market, still most of the generations are hydro and nuclear powers [26].

The Swedish national transmission system is originally built to transfer hydro power from the northern part of Sweden which is mainly a generation area towards the southern part which is mainly a load area. The long transmission lines connect northern and central areas, the voltage collapse at the central or southern parts of Sweden is an inherent weakness of the system and indeed central to the blackouts that occurred in 1983 and 2003 [2,3]. These long transmission lines have some limited voltage support in the intermediate region.

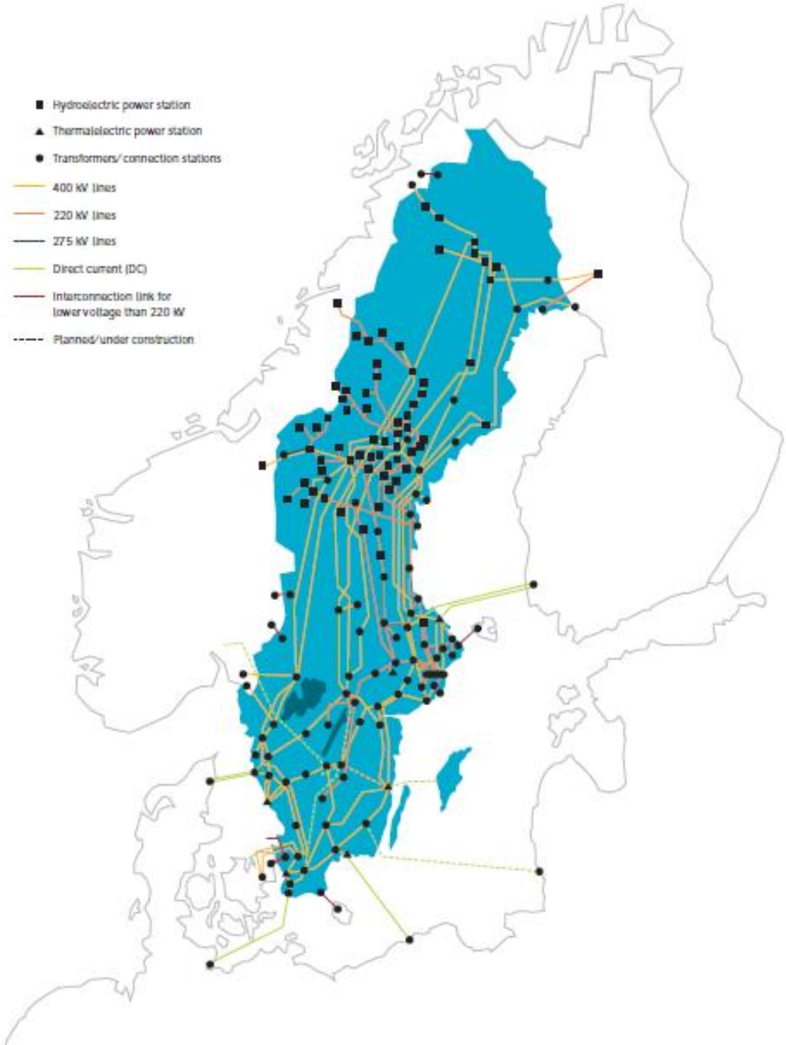

Fig. 2-12 Swedish transmission network [25].

A Brief Description of the 2003 Swedish/Danish Blackout

First, one unit (unit 3) of the nuclear power station in Oskarshamn at 12:30 was tripped because of the problem connected with its valve system. Consequently, the power system experienced a lack of 1250 MW. 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. The same rules allow 15 minutes to completely bring the reserve power (hydropower of Norway, north of Sweden and Finland) to tackle the next N-1 disturbance.
Subsequent to the lack of 1250 MW, the voltage level dropped 5 kV in the southern part of Sweden and the power system frequency reached 49.90 Hz. Secondly, at 12:35, on the western coast of Sweden, a fault occurrence in the double busbar at the Horred substation led to loss of 1750 MW generation (two units) at Ringhals nuclear power plant. Since this fault occurred 5 minutes after the first disturbance, the situation became at least N-5. Power oscillations and reduction of voltage and frequency (49 Hz) were the consequences. Southeast and south-central parts of Sweden experienced lack of reactive power to maintain the voltage at standard range. Subsequently, the voltage went down and then got critical and voltage collapse occurred. With operation of distance relays due to voltage collapse, the national grid split into two parts where the separated southern part of Sweden along with eastern part of Denmark were facing lack of generation. Within seconds after voltage collapse, the level of voltage and frequency in this area got the worst points causing the operation of under voltage relays for generators and other grid protections. As a result, the blackout happened in the separated part. During the blackout, 4500 MW load in Sweden and 1850 MW in Denmark went out [2]. Four million people were initially disconnected and the economic cost of the disruption has been estimated at around USD 310 million. In southern Sweden, services were cut to 1.6 million people. In eastern Denmark, services were cut to around 2.4 million people. The capital city of Copenhagen was the worst affected area, along with the international airport and rail services [27].

2.2 Power System Restoration

As mentioned in the previous sections, large blackouts are serious and they cannot be entirely avoided. So once the blackout is a fact, then it is really important to restore the power system as fast and securely as possible to reduce social and economical consequences for the population. At the same time all the constraints defined by the grid codes must be satisfied after the system restoration [28]. The power system works far away from normal condition during the restoration process. To restore the power system, understanding the system components functionalities and controlling methods for the power system during the restoration period are of interest.

The first step for power system restoration is to determine the status of the power system. So the operators usually need to get the real picture of the system status and know how to receive or give help.

Generally three different steps should be carried out for the power system restoration. Those steps are shown in Fig. 2-13 [28].

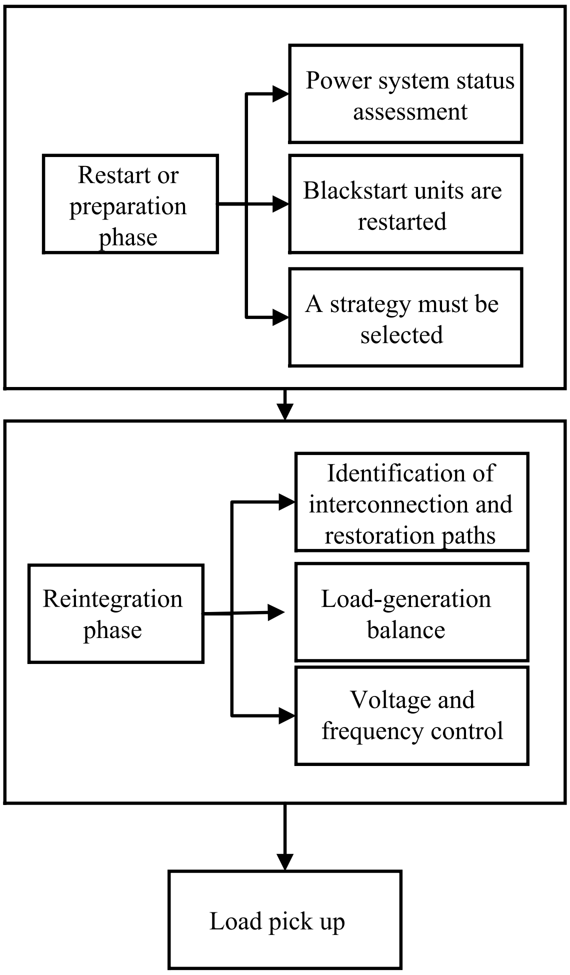

Fig. 2-13 Power system restoration overview [28].

The first task is to assess the status of the blacked out parts. This step is followed by the identification of the restoration paths, energizing the transmission lines, reconnection of the generation units and then finally load pick up where the loads are reconnected to the power system [28].

The average times for these steps are shown in Fig. 2-14. As it can be seen, the restoration process is long and can last for hours. The main restoration delay comes from the fact that the system status is unknown, also the blackout cause is not identified. Moreover, other electrical and mechanical constraints might contribute to longer restoration process [28].

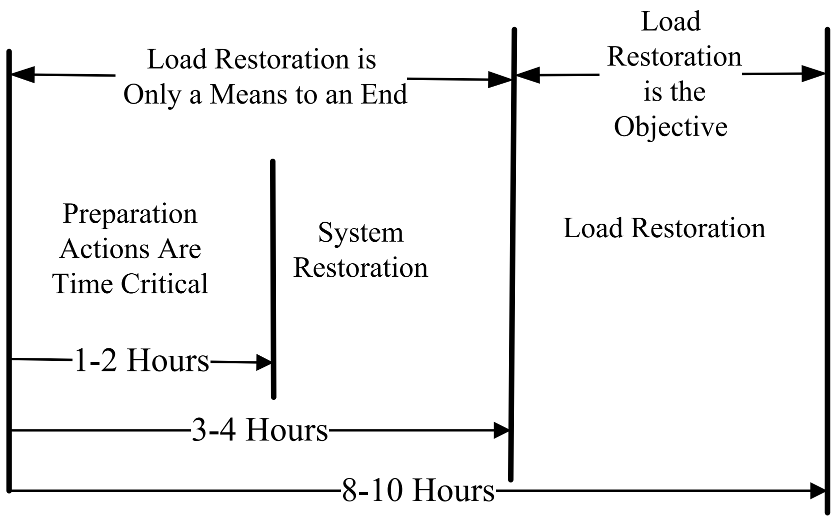

Fig. 2-14 Required time for power system restoration steps [28].

Once the blackout happened, the operators usually have some kind of prepared plans and strategies to accomplish the restoration and they will try to apply those plans for the current situation.

The build-up and build-down are two main strategies for restoring a power system following a blackout [28-31]. The decision to determine which strategy can be applied to restore the system securely and quickly depends on the network topology.

The build-up strategy

After checking the general status of the power system, the whole system would be divided into some sub-systems while each sub-system has one station as a black start capability. Fig. 2-15 shows the sectionalized network for the New England 39 bus system [32]. As it can be seen, the entire network is divided into some electrically isolated islands. The voltage and frequency are usually controlled and regulated in each island.

Loads are also connected gradually in each island. After making islands, then they should be synchronized and interconnected to restore the whole network.

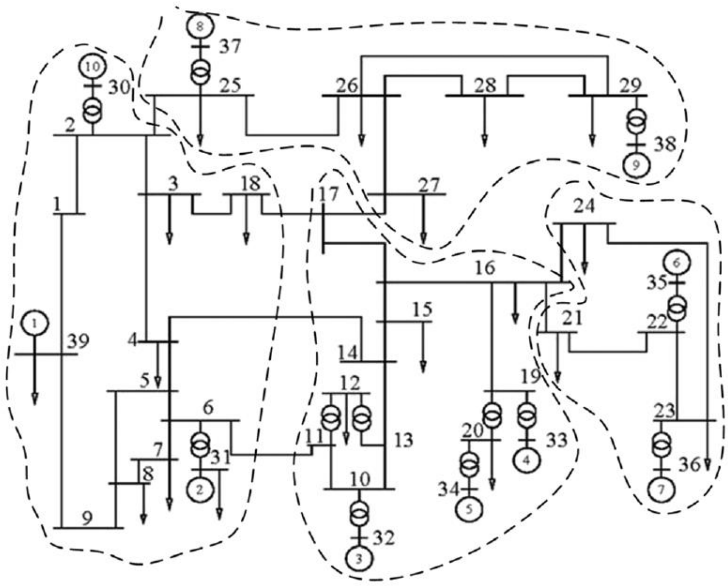

Fig. 2-15 The sectionalized new England 39 bus system [32].

The main advantages of the build-up strategy are first, the restoration time which is reduced significantly, secondly, if a large disturbance happens, then the blackout would only occur in the affected area. The drawback of this strategy is since the network is separated into islands, then the stability margins of the islands are an important, but difficult issue to consider during the restoration process [28,32].

The build-down strategy

This strategy is usually used for partial blackouts. First the status of the circuit breakers and also power plants are checked. Then from the running parts of the system, the transmission lines are connected to other stations in order to supply them with emergency power which is necessary to start them. In fact in this strategy the bulk network is reenergized before reconnecting the loads and also re-synchronizing the generators. After energizing the high voltage transmission lines, then the generators are synchronized to the system. The most loads are connected after the main part of the bulk-power system is restored. The main advantage of the build-down strategy is that the stability margins are significant. It means this strategy is quite reliable to restore the power system. The main drawback of this strategy is the time needed for whole network restoration [28].

In Sweden, since the large amount of hydro powers are located in the northern part and the main load areas are central and southern parts of the system, the blackouts have mainly happened in the central and south areas. Then it is natural to apply build-down strategy for the system restoration. So the restoration process usually starts with energizing the long transmission lines between north and central areas.

Reactor Hunting During Restoration

As mentioned, for the Swedish power system, the massive blackouts happened in the central and south areas and the long transmission lines between northern and central parts have been energized first. This energization initially resulted in excess of reactive power and high voltages. For example during the restoration for 2003 Swedish blackout, the voltage rose up to 476.5 kV in the southern part of the system [25]. The operating voltage level used by the Swedish TSO is 415 kV. In order to manage such voltages, shunt reactors are installed in the system. These reactors have their own automatics to switch them on/off. The reactor automatics work based on a local scheme. It means, they switch once the local bus voltage is out of a tolerance band. During the restoration process, since the power system is weak, then connecting the shunt reactors might impact a lot and immediately lead to extreme low voltage. If the voltage gets below the lower limit, then the automatics will turn off the reactor again. This repetitive connection and disconnection of the shunt reactors is called reactor hunting [30] and causes voltage fluctuations in the system as it happened in 2003 Swedish blackout and is illustrated in Fig. 2-16.

The traditional way to handle the reactor hunting is by turning off the automatics. That leaves the reactive shunts in manual operation which increases the restoration process time [33].

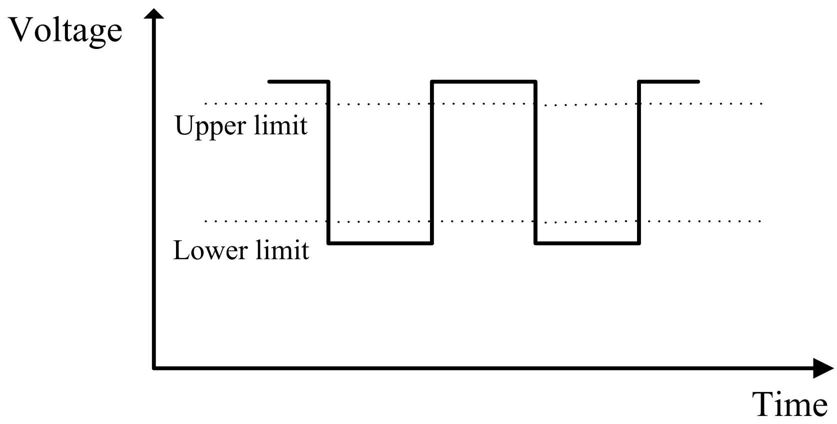

Fig. 2-16 Reactor hunting phenomenon during power system restoration.

2.3 Summary

Although the dream for power system operators is to have a secure operation continually, still there is a huge potential risk of large scale cascading outages and blackouts. To avoid them, power system stability is considered as an important issue in the realm of electric system operation. Also, once the blackout is a fact, then it is really important to restore the power systems as soon as possible. One problem that may increase the restoration time is the reactor hunting phenomenon. Large scale voltage fluctuations are the consequence of the reactor hunting. To speed up the restoration process also to avoid voltage fluctuations, reactor hunting must be handled as quickly as possible.

Chapter 3

Voltage Control Actuators

In the previous chapter, a general description of the power system blackouts was provided. Also voltage instability and in particular long-term voltage instability were explained further. This chapter aims to introduce the actuators which can be used to improve voltage stability and prevent voltage collapse in power systems. These actuators have their own constraints and from time viewpoint, they could be applied for short-term or long-term voltage instabilities. In particular, shunt reactors and capacitors are introduced and explained further as traditional actuators to enhance the long-term voltage stability.

3.1 Transformer Tap Changers

A tap changer is a device that changes the turns ratio of the transformer to keep the voltage level fixed for the distribution system. From the transmission system viewpoint, tap changers may be considered as part of the load. Following a disturbance, tap changers restore the voltage for the sub-transmission and distribution levels to their pre-disturbance values. This restoration usually takes several minutes and might lead to the voltage collapse in the system. Therefore, when approaching voltage collapse, the tap changers could be blocked to avoid further voltage reduction [34]. This helps to avoid long-term voltage collapse in power systems.

3.2 Synchronous Generators

Automatic Voltage Regulators (AVRs) of the synchronous generators are the main control measures to control the transmission voltage. They are installed on the synchronous generators excitations systems to regulate the terminal voltages based on local measurements. The action of AVRs affects strongly and contributes positively to the short-term voltage stability [5].

3.3 Load Shedding

As mentioned in chapter 2, many of the recent large scale blackouts happened because of the voltage instability problems in power systems. This leads to give more attention towards load shedding as an actuator to counteract the short-term voltage instability in power systems. The philosophy behind load shedding for voltage stability improvement is that a stressed system is a key factor, so when there is a disturbance in power systems and once the voltage drops to unacceptable values, some loads are shed in the system to recover the loading and the voltage to acceptable levels. To achieve better performance, coordination between protection engineers and system planners are needed to determine the amount of the load and also the right time for them to be shed [35]. Two basic types of the load shedding are usually applied in power systems: decentralized and centralized.

In a decentralized scheme, there are some relays installed at the transmission loads to be shed. When the voltage is too low at their buses, then the load assigned to that relay is shed.

In a centralized scheme, there are some relays installed at key system buses and trip information is usually available at various locations to shed the load [35].

3.4 VSC-HVDC Links

A VSC-HVDC system includes two Voltage Source Converters (VSCs) with the same configuration. Each of the converters has two degrees of freedom. One degree in each converter is used to control the reactive power, and other degree is used to control the active powers or DC voltages [36,37].

This new technology has many benefits over the conventional HVDC transmission system. One main feature of the VSC-HVDC transmission lines is that it has the ability to almost instantly change its working point within its capability and control active and reactive power independently. This can be used to support the grid with the best mixture of active and reactive power during stressed conditions and contribute positively to improve the long-term voltage stability [38].

3.5 Static Var Compensator (SVC)

SVC is a shunt connected widely used Flexible AC Transmission Systems (FACTS) device in power systems. It can provide rapidly reactive power control and therefore provide great control to the bus voltage. SVC usually applied by utilities in transmission applications for several purposes. The main purpose is usually to control the voltage at weak points in power systems. For this goal, SVC is placed at either the midpoint or end of the transmission lines to improve the short-term voltage stability [38].

3.6 Shunt Reactors

Shunt reactors are traditionally used to compensate for the effect of line capacitance and to limit voltage rise when the transmission line is lightly loaded. They are usually used for long Extra High Voltage (EHV) overhead lines [5,39]. In fact, when the long transmission line is not loaded, or only slightly loaded, it consumes little reactive power. This results in a voltage increase along the line that can reach damaging levels. This phenomenon is called Ferranti effect [40]. It usually happens when the long transmission line is energized during the power system restoration and to manage that, shunt reactors are used to consume the reactive power to lower the voltage.

A shunt reactor is similar in appearance to a transformer, as shown in Fig. 3-1, but with the difference that it has just a single voltage system [38,41].

Fig. 3-1 Typical shunt reactor [42].

3.7 Shunt Capacitors

Shunt capacitors are used to supply reactive power and boost the voltage in power systems [5]. Providing capacitive reactive compensation to improve the long-term voltage stability is the main contribution of the Shunt Capacitor Banks (SCB). A typical shunt capacitor bank is shown in Fig. 3-2.

Fig. 3-2 Typical shunt capacitor bank [43].

The use of SCBs has increased because they are relatively economical, easy and quick to install in the power systems [44]. They can be applied for distribution and transmission voltage levels.

In distribution systems, they are extensively used to correct the power factor and also to control the feeder voltage. The power factor correction objective is to provide reactive power which is needed locally instead of supplying it from remote sources. Moreover the capacitor banks are distributed along the length of the feeder to ensure that voltages are within the tolerance bands once the loads change [5].

For transmission system application, shunt capacitors are used to compensate the reactive losses of the transmission lines and keep the voltage within the tolerance band when the lines are heavily loaded. They are usually distributed throughout the transmission systems to minimize the voltage drops. Power flow studies are needed to determine the size and location for the capacitor banks to meet the system design criteria. They can be connected to the transmission systems either directly or to the tertiary winding of a primary substation transformer [5].

Generally, switching the capacitor banks is the conventional method to control the voltage also to increase the maximum transfer power by the transmission lines. Following descriptions based on the Fig. 3-3 aim to explain the effect of the shunt capacitor connections to increase the maximum transfer power also to improve the voltage stability [8].

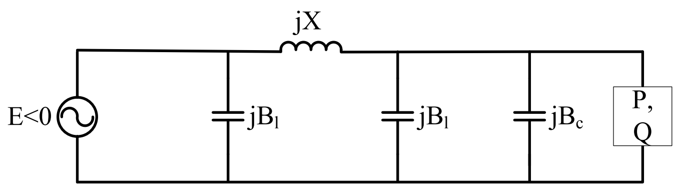

Fig. 3-3 Basic circuit to model a lossless transmission line with a large system at the sending end and shunt compensation and load at the receiving end [8].

As it can be seen, the shunt capacitor is connected at the end of the transmission line. The Thévenin equivalent seen by the load can be represented by the following equations:

$$E_{th} = \frac{1}{1-(B_c + B_l)X} E \quad (3.1)$$

$$X_{th} = \frac{1}{1-(B_c + B_l)X} X \quad (3.2)$$

Where E_{th} and X_{th} are the Thévenin voltage and reactance respectively, B_c and B_l are the shunt capacitor and transmission line susceptances, X is the transmission line reactance and E is the sending end voltage.

By doing some math and simplifications, the maximum transfer power and also the corresponding load voltage are represented in Eq. 3.3 and 3.4 (under power factor $\cos(\Phi)$):

$$P_{\max} = \frac{1}{1-(B_c + B_l)X} \frac{\cos(\Phi)}{1+\sin(\Phi)} \frac{E^2}{2X} \tag{3.3}$$

$$V_{\max P} = \frac{1}{1-(B_c + B_l)X} \frac{E}{\sqrt{2}\sqrt{1+\sin(\Phi)}} \tag{3.4}$$

Based on the above equations, it is obvious that both P_{max} and V_{maxP} are increased when capacitive compensation is added to the transmission lines. This means that the transmission line loadability will increase by adding the shunt capacitor banks in the system which significantly improves voltage stability.

3.8 Summary

To avoid voltage instabilities in power systems, there are some actuators and controllers which could be applied. Shunt reactors and capacitors are considered as traditional actuators to improve the long-term voltage stability in power systems. Switching of them to deal with voltage instabilities usually occurs quite frequently in power systems. Moreover shunt reactors are widely used to manage the voltage during the power system restoration to eliminate the Ferranti effect.

Chapter 4

Voltage Control Methods

To guarantee the satisfactory operation for all electric power equipment, different voltage control methods are employed in power systems to keep the voltage within the acceptable limits. In fact, the voltage must be continually controlled. This chapter focuses on the voltage control methods to control the voltage in power systems. In particular the neighboring scheme for shunt capacitor control as a new control scheme proposed in the thesis is comprehensively explained in this chapter.

4.1 Primary and Secondary Voltage Control

For efficient and reliable operation, voltage and reactive power controls are really important issues for power system operators. The main objectives to control the voltage in power systems are listed below [5]:

- To avoid malfunction and damage to the equipment

- To enhance system stability

- To minimize reactive power flows and reactive power losses

The direct link between voltage stability and reactive power balance in the system leads to more attention toward reactive power resources. Since reactive power cannot be transmitted over long distances efficiently, the voltage and reactive power controls are managed locally. It means using special devices which are distributed throughout the power systems, the voltage can be controlled.

Primary and secondary voltage controls are two well know strategies to regulate the voltage in power systems.

Primary Voltage Control

The goal of the primary voltage control is to keep the terminal voltage of the generators close to their set points and based on that the voltage can be controlled locally. The AVR is the key equipment which controls the synchronous machine field voltage with consideration to the capability curve limits to regulate the terminal voltage. The voltage drop of the generator transformer can be cancelled out totally or partially by the AVR action, and then it means the voltage at the high voltage side of the transformer could be kept constant. This leads to very fast and efficient control of the terminal voltage of the generators and for many cases it is the most powerful measure to control the voltage in power systems [34].

Secondary Voltage Control

With primary voltage control, the voltage is monitored and controlled locally. In case of having disturbance in power system, usually the voltage goes down for some parts of the system. So the broader perspective is needed to save the whole network from unacceptable voltage level. Secondary voltage control is centralized voltage control method to supervise all AVRs and other reactive power sources in a given part of the network to keep an appropriate voltage profile and enhance the voltage stability of the whole grid. To apply secondary voltage control scheme, normally the network is divided into some geographic regions. In each region, a special node called pilot node is selected and its voltage is controlled by the participating generators. In fact the pilot node is assumed to be representative of the voltage situation in its own region. The set-points for the AVRs and other reactive resources are the main actuators for the secondary voltage control scheme [34,45].

4.2 Automatic and Manual Control of Reactive Shunts

Switching of the capacitor banks and shunt reactors as one of the conventional methods dealing with long-term voltage stability usually occurs quite frequently in power systems, even on a daily basis [46]. They are switched on/off either manually or automatically [39]. In the manual case, system control engineers take a decision based on the system situation [47]. In the automatic case, shunt elements could be either mechanically switched or thyristor controlled by the EVAs. Usually they use a local scheme for controlling the shunt capacitors and reactors. It means, a shunt element will connect to or disconnect from the system once the voltage is out-of-range (typically, nominal range is between 0.95 and 1.05 pu) just in its own bus [8]. Moreover shunt reactors are widely used to manage the voltage during the power system restoration. In fact they are installed in the system to lower the voltage and eliminate the Ferranti effect when a long transmission line is energized.

4.3 Neighboring Scheme for Shunt Capacitor Control

In some cases a shunt capacitor remains unused in a region lacking reactive power just because the local voltage is within the tolerance band. An idea explored in this thesis is to let the capacitor respond also to the voltage at the neighboring buses. This is called the neighboring scheme. So by applying this scheme, a shunt element will respond to voltage deviations both at its own bus as well as at the neighboring buses. This scheme potentially leads to more or sooner action from shunt reactors and capacitors. This eliminates some action from tap changers in the system since the transmission level voltage recovers. This reduces the need for reactive power transfer through the nearby lines and associated additional loading. Consequently it should improve the long-term voltage stability and may save the system from voltage collapse.

The functional structure of the proposed neighboring scheme is shown in Fig. 4-1.

This control algorithm should be applied for all buses in the system with controllable reactive shunts. As shown in Fig. 4-1, first the voltage at the specified bus is measured. When approaching voltage instability, the voltage at some buses is out of the tolerance band, typically below the lower voltage level. The scheme for managing high voltages is analogous, but is omitted here for clarity. Also overvoltage is generally uncritical to voltage stability.

To tackle the lower voltage issue, first the algorithm tries to disconnect the available shunt reactors then connect the available capacitors at the local bus. In each step of disconnecting the shunt reactors or connecting the shunt capacitors, the algorithm waits for a specified time delay then the voltage is measured and checked. The reason for the waiting time is that the voltage should be stabilized and then be measured. Whenever the local bus voltage is above the lower limit, then the algorithm goes to the starting point. In this point, once the voltage is within the tolerance band for the local bus, the algorithm tries to satisfy the neighbor bus voltages signal which is indicated by the red arrow in Fig. 4-1. If the voltage is below the lower limit in the neighboring bus, then the same procedure is applied as for increasing the local bus voltage. So all the buses with controllable shunt reactors and capacitors are switched if either the local or neighbor bus voltage is below the lower limit. The neighbor bus in Fig. 4-1 means the bus(es) at the remote end of any line(s) connected to the local bus, see Fig. 4-2.

To understand better the proposed algorithm, the main control concept is illustrated in Fig. 4-3. Based on this figure, once either of the local or neighbor bus voltage in Fig. 4-2 is below the lower limit, then reactive power injection will increase at the local bus.

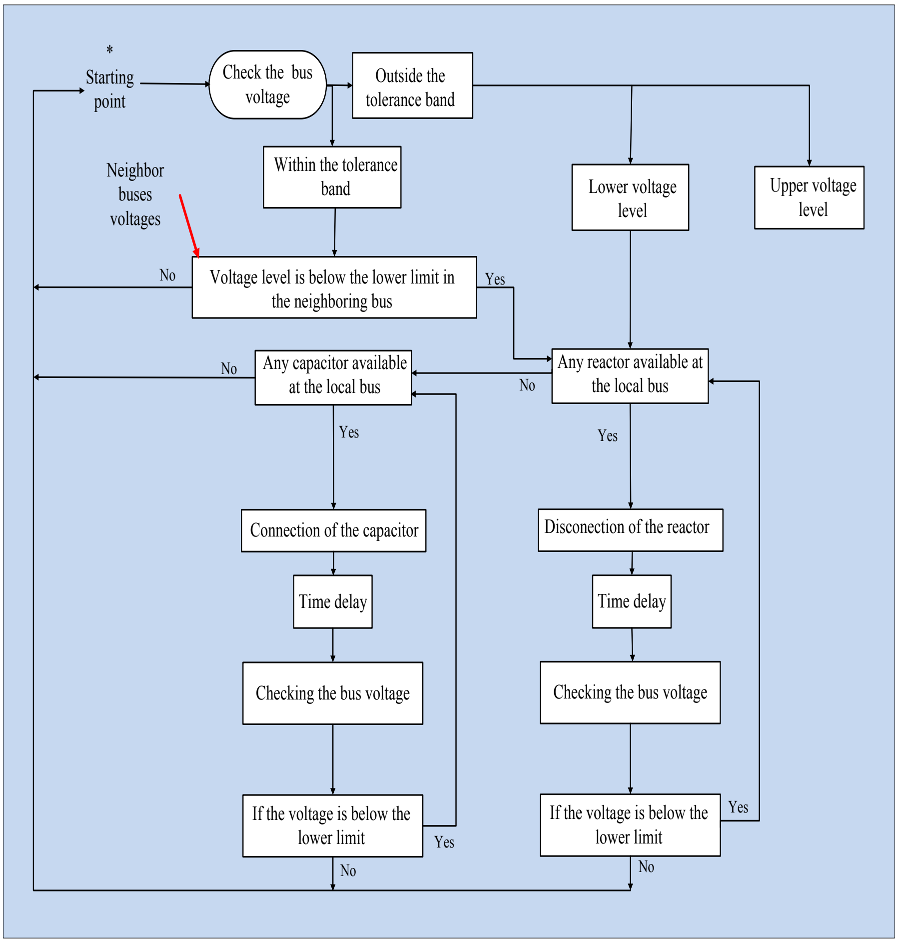

Fig. 4-1 Neighboring scheme flowchart to manage low voltage instability.

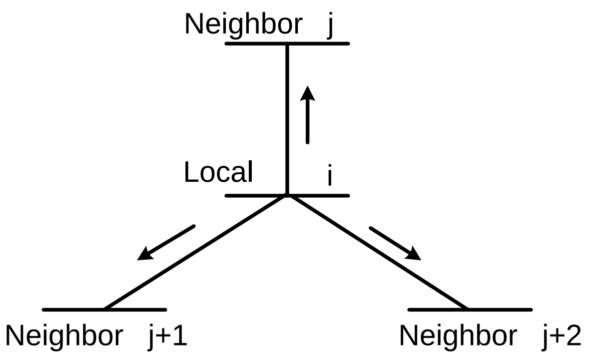

Fig. 4-2 Illustration of the concept of neighbor buses of local bus i for a case with three neighbors j, j+1 and j+2.

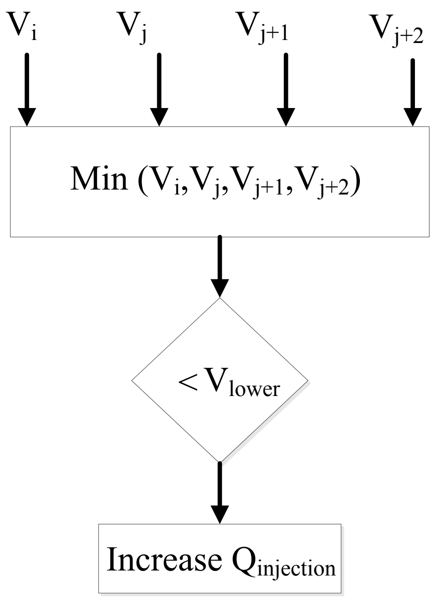

Fig. 4-3 Basic flow chart of the neighboring method for control of reactive shunts. Here shunts at bus i are controlled using voltages at bus i and the neighboring buses j, j+1 and j+2. Increase $Q_{injection}$ box corresponds to first reactors disconnection and then capacitors connection.

4.4 Summary

To get satisfactory operation of the electric power equipment, there are some methods to control the voltage and reactive power. Primary and secondary voltage controls are two well-known strategies to regulate the voltage in power systems. In the primary scheme, the terminal voltages of the generators are aimed to be controlled. On the other hand, in the secondary voltage control, all AVRs and other reactive power resources in a given part of the network are monitored and controlled. Moreover shunt reactors and capacitors are traditional actuators to improve the long-term voltage stability. They usually switched on/off based on the local scheme which switches the shunt when the voltage at local bus is outside the tolerance band. Neighboring scheme is an alternative control strategy proposed in this thesis. In this strategy both the local voltage and the voltage at neighboring buses are considered.

Chapter 5

Test Systems and Modelling

To investigate, understand and explain the performance of the neighboring and local schemes for avoiding long-term voltage collapse, two test systems are considered; NORDIC32 and N3area. NORDIC32 is a CIGRE test system and has the key long-term characteristics of the Swedish national power system. N3area is a new test system proposed in this thesis and is a simplified version of NORDIC32 with the same long-term voltage collapse characteristics. It reduces the NORDIC32 model complexity, so long-term voltage collapse behavior and countermeasures can be analyzed much easier there than in NORDIC32. These two test systems are explained in this chapter.

5.1 NORDIC32 Test System

To study the voltage collapse problem in detail, the full representation of the power network is needed [8] but it is normally difficult or even impossible to access it. For many applications, a reduced order network model is more convenient. For this purpose, the NORDIC32 CIGRE test system [48] has been developed. This test system is shown in Fig. 5-1. NORDIC32 is suitable to simulate the long-term voltage collapses like what happened in 1983 and 2003 in Sweden. The model includes three voltage levels; 400, 220 and 130 kV and is divided into four main areas, see Fig. 5-1 [48]:

-North: mostly hydro generation and some load

-Central: with much load and large thermal power plants

-Southwest: few thermal units and some load

-External: connected to the north. It has a mixture of generation and load.

One of the main characteristics of this test system is that voltage collapses at the midpoint of the system first. The Advanced Real-time Interactive Simulator for Training and Operation (ARISTO) [49] is used for dynamic simulations of NORDIC32. ARISTO is a real-time simulator developed and used by the Swedish TSO. The NORDIC32 model is available in ARISTO.

Another characteristic of the NORDIC32 test system is the long distances between the production center (North) and consumption center (Central). The large electrical distance between these areas has been reduced by the usage of series capacitance compensation in the 400kV transmission network [48].

A general graphical outline of the 400 kV transmission network for NORDIC32 test system is shown in Fig. 5-2. The percentages of compensation for the long transmission lines between northern and central areas are shown in this figure.

Basically two types of voltage collapses may occur for NORDIC32 test system [48]:

- Voltage collapse in the central or south regions because of the contingency that weakens the transfer system from north to the central area

- Voltage collapse in the central area because of the contingency that decreases the voltage support in that area

These types of voltage collapses could happen by tripping the generation units or transmission lines. In case of generation unit in south part, the voltage collapse in the central region is possible. On the other hand, for line tripping in the transfer section, voltage collapse somewhere between the north and the central part is possible [48].

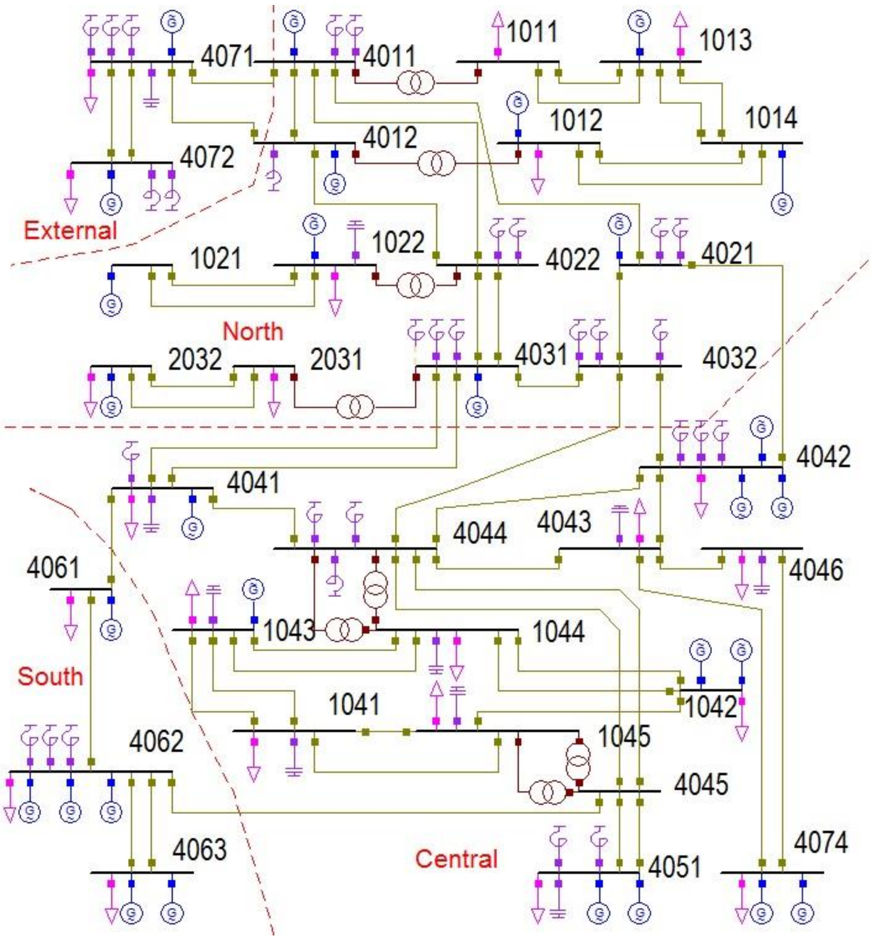

Fig. 5-1 NORDIC32 test system.

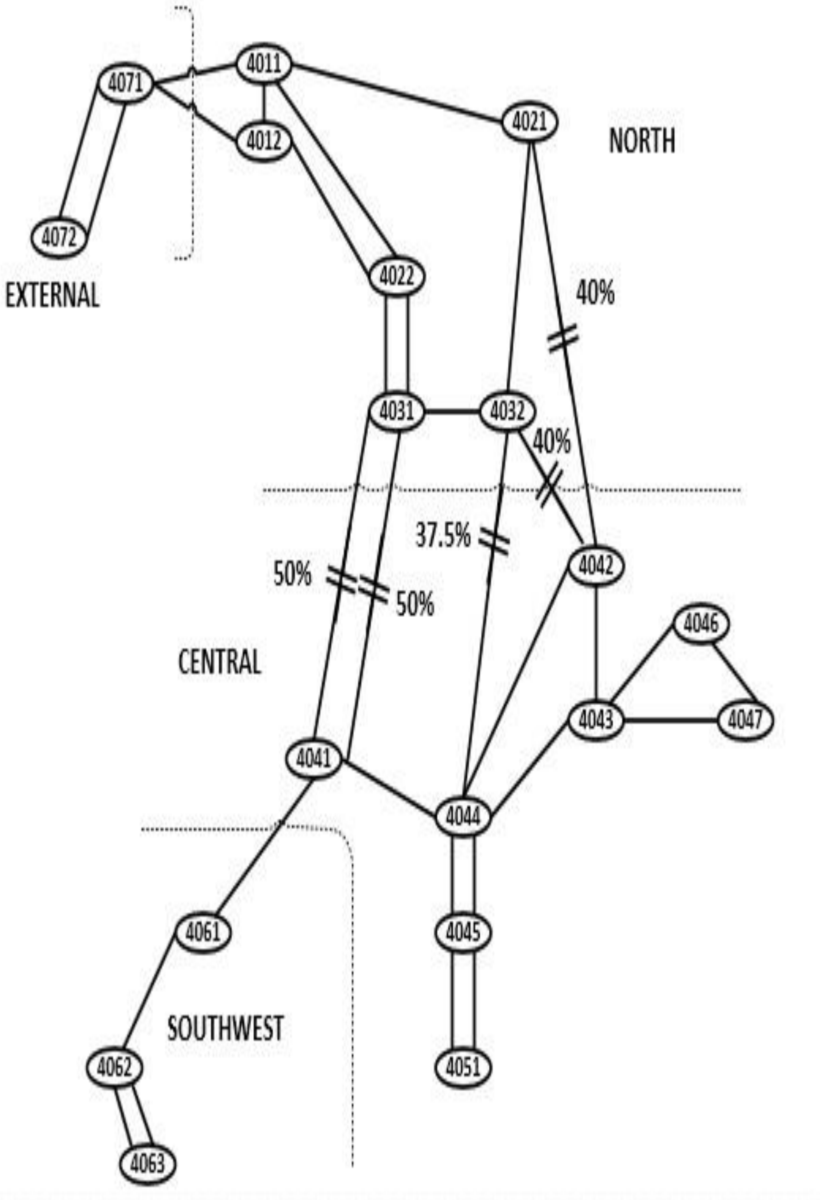

Fig. 5-2 Outline of the 400 kV transmission network of the NORDIC32 test system.

5.2 N3area Test System

NORDIC32 is the reduced order model of the Swedish power system, but still a complex test system.N3area is a simplified version of NORDIC32 and has the main long-term voltage collapse characteristics of it. This test system is shown in Fig. 5-3 and Table 5-1.

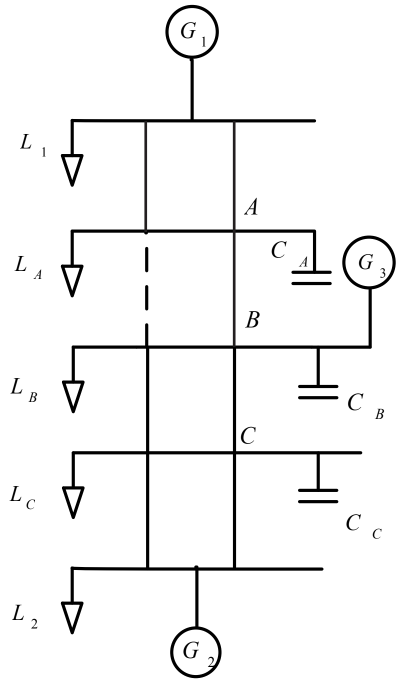

Fig. 5-3 N3area test system.

Table 5-1: Load flow parameters of N3area test system

Component	MW	Mvar	Component	MW	Mvar
G_1	2000	Slack bus	L_A, L_C	100	50
G_2	50	PV bus	L_B	1500	550
G_3	100	PV bus	C_A	-	100
L_1	200	100	C_B	-	200
L_2	125	75	C_C	-	150

Like NORDIC32, the main generation area is located in the northern part, while the main load area is placed in the central part. G_1 and L_1 represent the northern part which is an export area, G_2 and L_2 represent the southern part of NORDIC32 which is an import area while G_3 and L_B represent the central part of NORDIC32 which is a mixture of load and generation areas. G_3 helps to control the voltage at the midpoint. In Fig. 5-3, all transmission lines are of equal length. To show the generality of the proposed neighboring scheme, the N3area is built up in PowerFactory [50] which is more widespread than the ARISTO and the neighboring scheme is applied there also.

5.3 Load Model of NORDIC32 Test System

The load recovery process due to tap changer operation and thermostatic characteristics of the loads is a really important factor for long-term voltage stability studies. This makes the dynamic load modeling an important area in voltage stability field. In ARISTO the dynamic load model is based on the following descriptions:

Once the voltage changes, the load will change accordingly. After that, some loads like thermostatic loads will recover and try to get back their original values. The load recovery dynamics could last from a couple of seconds to some minutes. The origin of the long-term load recovery dynamic comes either from tap changers in the transformers or natural load variations due to thermostats and other process controls. To consider the long-term load recovery dynamics, the ARISTO has a Slow Load Dynamics (SLD) model. In fact, the SLD model defines the load recovery due to tap changer operation. The functional description of the SLD model is shown in Fig. 5-4 [51].

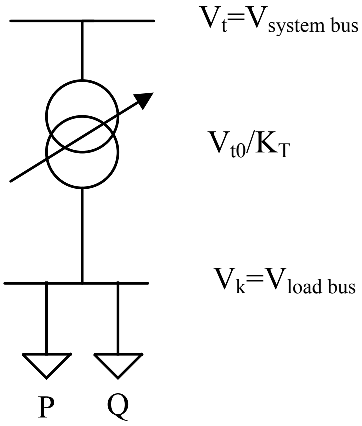

Fig. 5-4 Conceptual description of the Slow Load Dynamics (SLD) load model in ARISTO [51].

What SLD modeling actually does is to calculate the K_T factor that defines V_k=V_{load}. The SLD model does not recalculate the load itself but it calculates the bus voltage of the load. At the initial point of the simulation, the K_T is 1 and the tap ratio is $V_{t0}/1$. If the voltage goes below a certain value, then further change of K_T is blocked. By applying this mechanism, the long-term load recovery process is included in dynamic simulations in ARISTO [51].

5.4 Load Model of N3area Test System

The load model used for the N3area test system in PowerFactory is the multiplicative generic load model which can be expressed by the following equations [8]:

$$P = P_0 Z_p (\frac{V}{V_0})^{\alpha_t} \tag{5.1}$$

$$Q = Q_0 Z_q (\frac{V}{V_0})^{\beta_t} \tag{5.2}$$

$$T_p \frac{dZ_p}{dt} = (\frac{V}{V_0})^{\alpha_s} - Z_p (\frac{V}{V_0})^{\alpha_t} \tag{5.3}$$

$$T_q \frac{dZ_q}{dt} = (\frac{V}{V_0})^{\beta_s} - Z_q (\frac{V}{V_0})^{\beta_t} \tag{5.4}$$

Where P and Q are the active and reactive power consumed by the load respectively, while P_0 and Q_0 are their initial values. V is the load voltage with initial value V_0. Z_p and Z_q are dimensionless state variables, α_t and β_t are transient load exponents, α_s and β_s are steady state load exponents and T_p and T_q are recovery time constants for active and reactive power respectively [52]. Digsilent Simulation Language (DSL) is used to implement the load dynamic model.

Parameters for the load model implemented in N3area are given in Table 5-2 [53]. These transient and steady state load exponents, also the time constants could be derived from the field tests at the main HV/MV substations [8]. In this thesis, these parameters are selected to replicate the thermostatic load behavior which is dominant in Sweden due to a large amount of electrical heating [53].

Table 5-2: Load dynamic model parameters [53]

T_p	T_q	α_t	α_s	β_t	β_s
127.6 s	75.3 s	2.26	0.38	5.22	2.68

5.5 OXL Model of NORDIC32 Test System in ARISTO

The OXL or field current limiter action is responsible for protecting the rotor of the generator from over excitation current and overheating. To avoid first swing instability, the field current is allowed to reach the maximum value which is usually twice the permanent admissible current [8] for a short time but it should return to the normal value after a few seconds. OXL action limits reactive power generation and it means generators cannot produce unlimited reactive power. So it is really important to consider OXL action in the long-term voltage stability studies.

OXL is implemented in ARISTO for all NORDIC32 generators based on the block diagram shown in Fig. 5-5. Parameters for the OXL model in ARISTO are given in Table 5-3 [51].

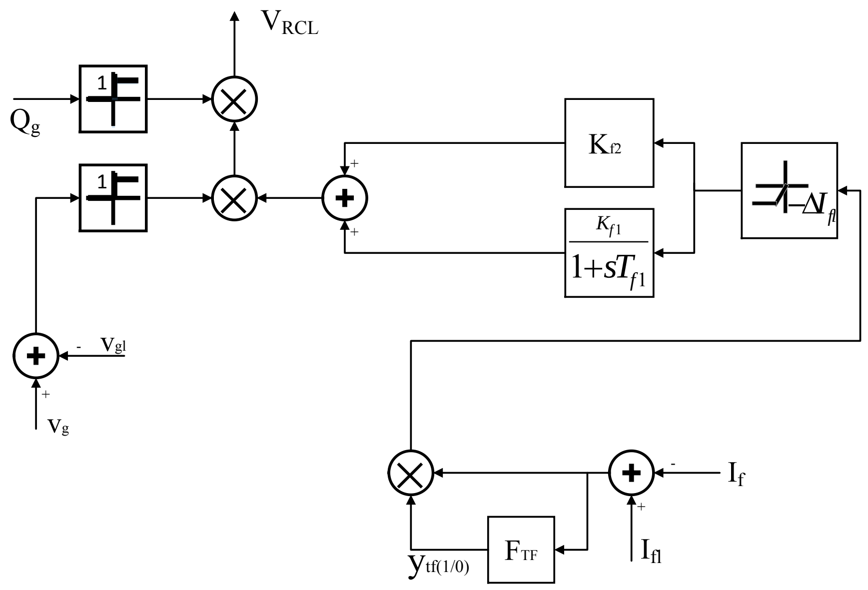

Fig. 5-5 OXL model implemented in ARISTO [51].

Table 5-3: OXL model parameters used for NORDIC32 test system [51]

Notation	Description	Typical Range	Default
I_{fl}	Rotor current limit (pu)	1.0-1.1	1.0
ΔI_{fl}	Limit on current difference (pu)		1.0
K_{f1}	Gain with phase shift		0
K_{f2}	Proportional gain	2-20	4
T_{f1}	Time constant (s)		0
V_{gl}	Low voltage level for action (pu)		0.6
T_{1f}	Time delay (s)	2-20	10
T_{2f}	Activation time (s)	120	120

The functional behavior of the limiter can be described as follows:

First, the field current is compared with the maximum limit. If the limit is exceeded, then the current deviation signal will pass on to F_{TF} which is a time function. It may also pass a gain constant and a time constant, see Fig. 5-5. The ultimate signal will be blocked if the generator voltage V_g is below a certain limit or if the generated reactive power becomes lagging [51]. Moreover, the time function F_{TF} works based on the Fig. 5-6:

During the normal operation, the F_{TF} output signal is equal to zero. Once the field current is higher than the limit, the clock starts. The clock continues to run even as the field current gets below the limit temporarily. Once the time passes T_{1f}, then Y_{tf} turns to 1 and the negative signal from the current comparison can pass and it means the limiter is in action. This mode of operation will continue till the time passes T_{2f}. After that, the limiter will become inactive as soon as the current becomes lower than the limit [51].

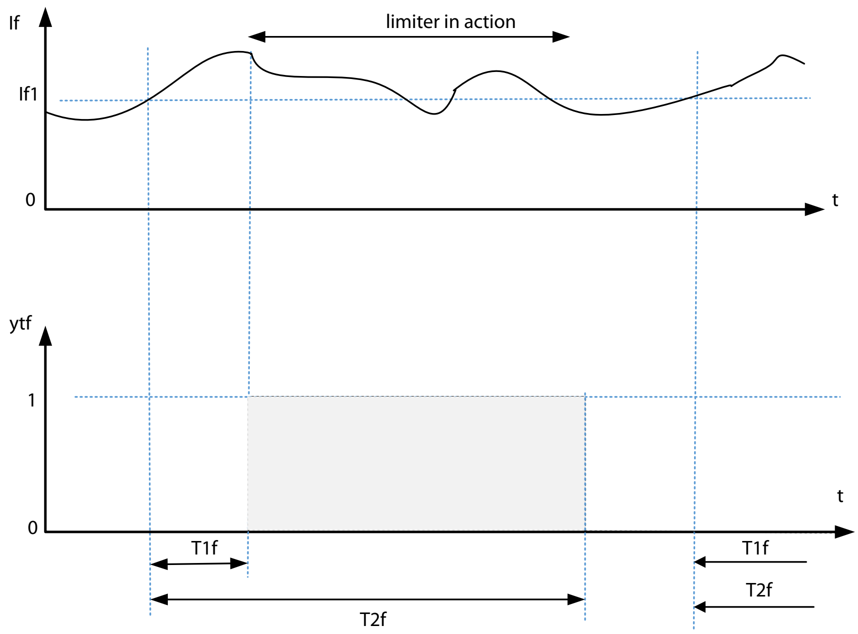

Fig. 5-6 The function of the time delay for OXL in ARISTO [51].

5.6 OXL Model of N3area Test System

In N3area test system, all the generators are equipped with OXL protection. The block diagram model of the OXL implemented in PowerFactory is shown in Fig. 5-7 [8]. DSL is used to implement this model.

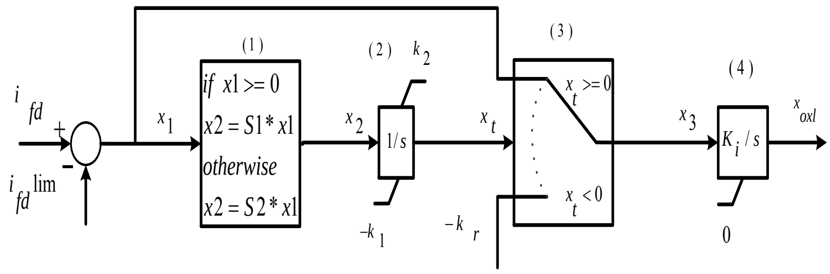

Fig. 5-7 OXL model implemented in PowerFactory [8].

Based on the Fig. 5-7, if the excitation current is bigger than the predefined limit, the timer (block 2) will be activated. After K_1 seconds, the x_t signal goes positive and then the x_{oxl} signal is injected to AVR to enforce the field limit. Block 1 implements the inverse time characteristic of the controller so that higher excitation current deviation leads to sooner action from limiter. S_1, S_2, K_1, K_2, K_r and K_i are constant positive values which are given in Table 5-4.

Table 5-4: OXL model parameters used for N3area test system

S_1	S_2	K_1	K_2	K_r	K_i
3	2	20	5	5	0.01

Based on the Fig. 5-7, once the field current is above the rated value, after a waiting time, x_t goes positive. This waiting time or switching time could be derived by the following equation [8]:

$$T_{sw} = \frac{K_1}{S_1 \times \Delta I} \tag{5.5}$$

Also K_r and S_2 force x_{oxl} to be reset when $i_{fd} \langle i^{\lim}{}_{fd}$.

5.7 Summary

NORDIC32 test system is built to capture the key long-term dynamics of the Swedish transmission network. This test system is the reduced order model of the Swedish power network but still is a complex test system. The N3area test system which is proposed in the thesis is the simplest test system that can replicate the long-term voltage dynamic behavior of the NORDIC32 and the Swedish power system. Moreover, load recovery and OXL action are two dominant dynamics that must be considered in the long-term voltage stability studies. The load recovery process leads to more voltage reduction in transmission side of the transformers while the OXL action limits the generators capability in reactive power generation. Both of these dynamics contribute to the long-term voltage instabilities and are included in the N3area and NORDIC32 test systems.

Chapter 6

Voltage Instability Simulations

This chapter focuses on the dynamic simulation results of N3area and NORDIC32 test systems. First, the general picture of the long-term voltage collapse mechanism is explained using the N3area test system, also the corrective actions are employed to counteract the long-term voltage instability. In the second part, the simulation results of the NORDIC32 test system are presented. Two long-term voltage instability scenarios including generator and transmission line outages are considered. Finally static analysis is conducted to get deep understanding of the neighboring scheme concept.

6.1 Long-Term Voltage Collapse of N3area Test System

In this part, first, the basic mechanism behind long-term voltage collapse is explained based on the simulation of the N3area test system. Then the two control strategies, local and neighboring schemes, are demonstrated as countermeasures to save the system from voltage collapse. Their performances are evaluated and compared.

Long-Term Voltage Collapse Mechanism

To analyze the basic trend behind the long-term voltage collapse phenomenon, a specified long-term voltage collapse scenario is applied to the N3area and the results are presented. PowerFactory is utilized to obtain the simulation results. The OXL protection and dynamic load model in N3area are implemented with Digsilent Simulation Language (DSL) as illustrated in chapter 5. In the simulated scenario, one of the transmission lines (dashed line in Fig. 5-3) between buses A and B is tripped at 400 s, which finally leads to voltage collapse. Fig. 6-1 shows the voltage evolution for different buses.

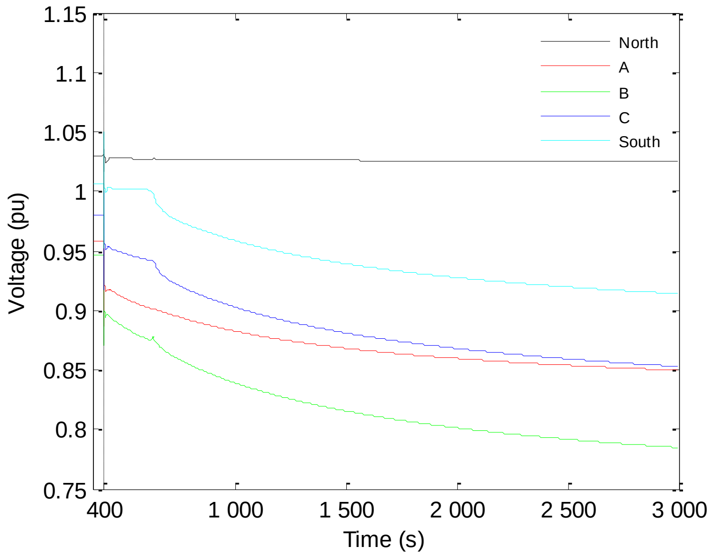

Fig. 6-1 Voltage at different buses of the N3area test system for tripping transmission line and without applying any control algorithm.

As it can be seen in Fig. 6-1, before the disturbance (400 s), the voltage is low for the intermediate buses. This means pre-disturbance stressed condition for the system but still the voltages settle down to acceptable levels. The applied disturbance leads to an initial transient which dies out quickly. In fact, the system is stable from short-term dynamics perspective. After that, the long-term dynamics are driving the system. The effective long-term dynamics here are load recovery and OXL protection action.

Based on the Fig. 6-1, the voltage in the northern part which is a generation area is intact. The voltage goes down for the rest of the system and collapses for the intermediate buses. In fact, after the initial transient, the load recovery process and OXL action led to further reduction of the bus voltages and ultimately ends up with the collapse and one voltage being only 0.78 p.u. It is good to mention that there are several definitions for the term voltage collapse and what collapse actually means. Based on the CIGRE definition [54]: ‘‘Following voltage instability, a power system undergoes voltage collapse if the post-disturbance equilibrium voltages are below acceptable limits’’ and if we consider [0.9-1.1] pu for acceptable voltage limit, then Fig. 6-1 is showing voltage collapse for the intermediate buses. In Fig. 6-1, the voltage at bus B (midpoint) is lowest and collapses first. This is one main property of the Swedish national power system which is reproduced by NORDIC32.

Fig. 6-2 shows the generator excitation currents for different buses. After tripping the line, the excitation current in generator at bus B (middle) goes up very quickly to avoid the potential risk of first swing instability, but the protection system restores it to normal level after around 20 s. Also, the excitation current increases slowly in G_2 (south) to generate more reactive power. This happens also for G_1 (north). The OXL is activated for G_2 as well to avoid overheating. During the time when excitation current is decreasing in G_2, the excitation increases in G_3 (middle) to partially compensate the lack of reactive power.

Fig. 6-3 shows the active and reactive power consumed by the load at bus B. It is clear that active power is restoring which contributes to the voltage collapse. The reactive power is not recovered and it is because of the selected parameters for load dynamic model and it is representing the loads like the combination of thermostatic and lightly loaded induction motors.

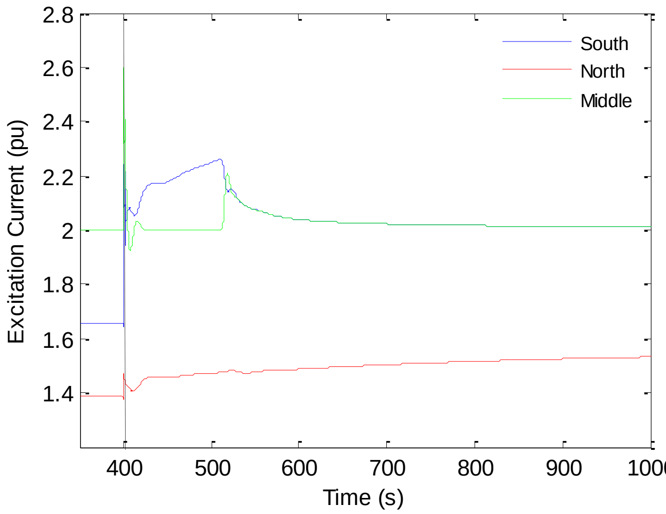

Fig. 6-2 Excitation currents for the generators of the N3area test system for tripping transmission line and without applying any control algorithm.

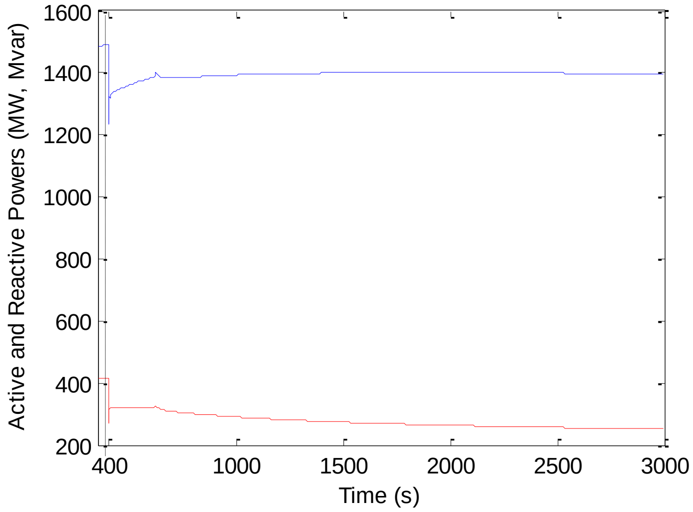

Fig. 6-3 Active (blue curve) and reactive (red curve) powers for the load at bus B of N3area for tripping transmission line and without applying any control algorithm.

To get deeper insight into the long-term voltage collapse phenomenon, the dynamic PV curve for bus B during the same time period as in Fig. 6-1 is shown in Fig. 6-4.

This dynamic PV curve is showing the main principle of the long-term voltage collapse phenomenon. The prefault situation and the quick voltage drop after the line trip is found in section ‘a’. The short-term dynamics are driving the power system in section ‘b’. The power system is stable after the transient period of the line tripping (after section ‘b’). In section ‘c’ the long-term dynamics including OXL action and load recovery process are driving the system along a new shape of the PV-curve, where ultimately the voltage collapses.

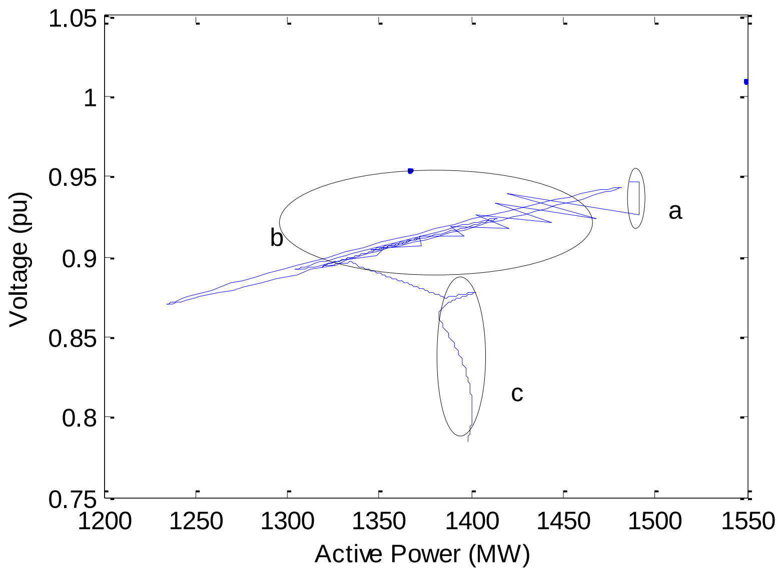

Fig. 6-4 Dynamic PV curve for the load at bus B of the N3area test system for tripping transmission line and without applying any control algorithm.

To analyze the effect of current limiter actions on the voltage collapse phenomenon, a static analysis based on the PV curves is done in this part. Fig. 6-5 shows PV curves for buses A and C of N3area test system for two cases; with and without the action of OXL. Bus B is excluded since when OXL is not activated, this bus is PV bus and the voltage is constant all the time. As it can be seen, with the action of OXL, the maximum deliverable powers for both buses decreased dramatically and this negatively contributes to voltage stability in the system.

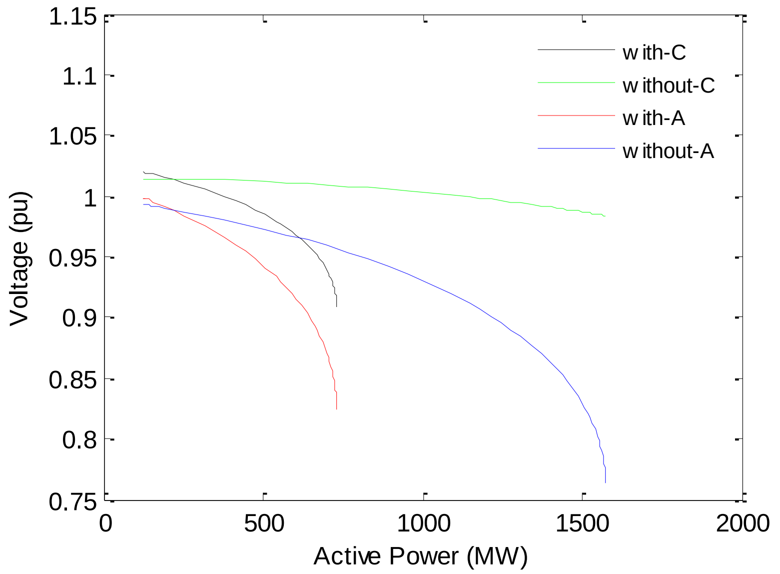

Fig. 6-5 PV curve for buses A and C of the N3area; with and without OXL action.

Corrective Actions against Long-Term Voltage Collapse

In this part, the real-time countermeasures to avoid voltage collapse are presented and applied to the N3area test system. Meanwhile, the capability of N3area test system for easy implementation of the countermeasures is proved. The control action as real-time countermeasures aiming to restore the long-term equilibrium is switching the shunt capacitors. The two different strategies called local and neighboring schemes are applied. These two control strategies are implemented using DSL in PowerFactory based on the control algorithm presented in section 4.3. Fig. 6-6 and 6-7 show the system voltage curves for different buses for the local and neighboring schemes respectively while again one of the transmission lines between buses A and B of the N3area test system is tripped at 400 s.

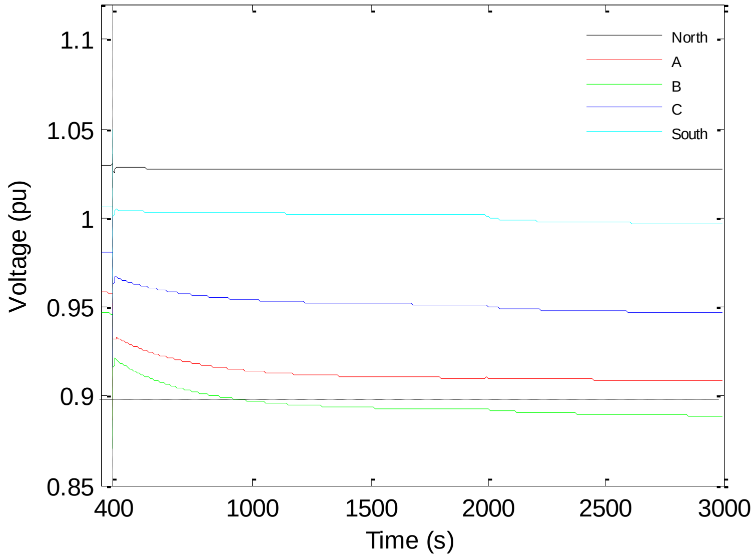

Fig. 6-6 Voltage for different buses of the N3area test system using the local scheme for the transmission line tripping scenario.

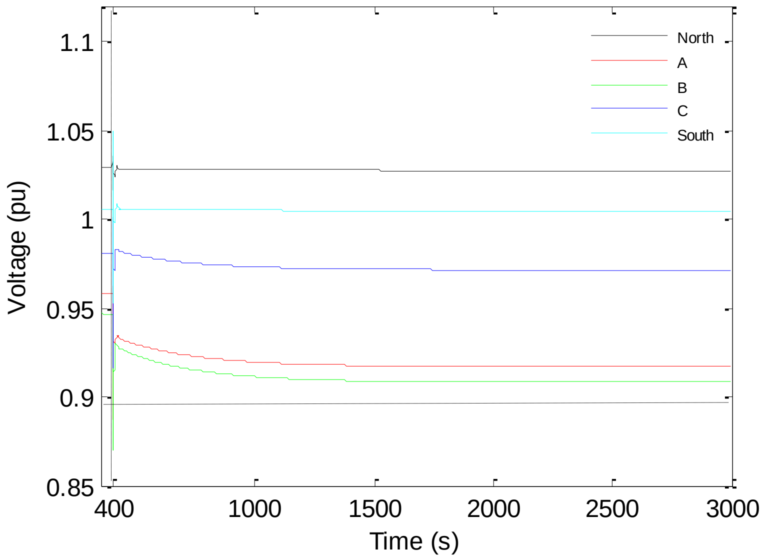

Fig. 6-7 Voltage for different buses of the N3area test system using the neighboring scheme for the transmission line tripping scenario.

By applying the local strategy, the voltage is above 0.9 pu for all buses except the midpoint bus (bus B). In case of neighboring scheme application, voltage is above 0.9 pu for all buses. So neighboring scheme apparently gives better performance, but in both cases, the system is stable. The neighboring scheme ends up connecting all available capacitors in the N3area test system while with the local scheme the capacitor at bus C is never connected to the system. This explains why the neighboring scheme results are better than those of the local one.

Generally, in case of shunt capacitor and reactor switching as real-time voltage collapse countermeasure, two main aspects are of central importance; how much reactive power is injected/drawn by switching them, and how soon they are switched on/off. Here, the neighboring scheme leads to higher amount of reactive power injection with one more capacitor connection at bus C but timing aspect is the same for both cases. It means the capacitors at bus A and B are connected at the same time by the local and neighboring schemes.

Fig. 6-8 and 6-9 show the excitation current curves for generators in the system by applying the local and neighboring schemes respectively.

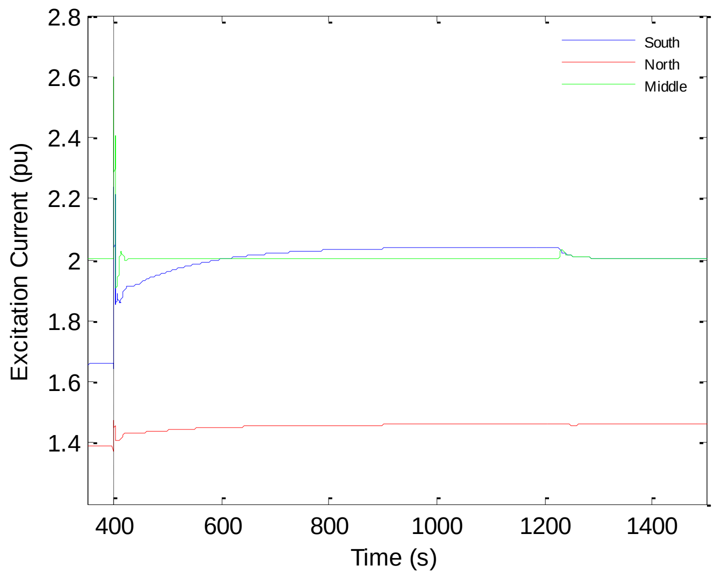

Fig. 6-8 Excitation currents for different generators of the N3area test system using the local scheme for the transmission line tripping scenario.

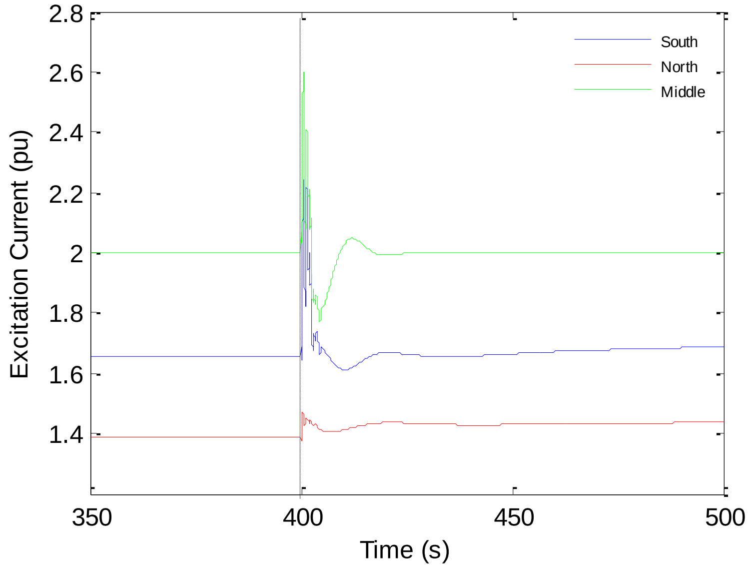

Fig. 6-9 Excitation currents for different generators of the N3area test system using the neighboring scheme for the transmission line tripping scenario.

It is clear that, the neighboring scheme leads to less excitation current for the southern generator because of injecting reactive power by the capacitor at bus C of the N3area test system, while this capacitor is never connected to the system by the local scheme application.

6.2 Long-Term Voltage Collapse of NORDIC32 Test System

In this part, to evaluate the local and neighboring schemes performances in large scale power system, NORDIC32 is used and two different long-term voltage instability scenarios are considered.

Generator Outage

The long-term voltage collapse scenario starts with tripping of one generator at bus 4047 in Fig. 5-1 at 60 s. The local and neighboring schemes are implemented in the NORDIC32 test system in ARISTO. The minimum voltage level for shunt actions is set to 395 kV, which is 5% below the operating voltage level of 415 kV used by the Swedish TSO.

Fig. 6-10 shows the voltage curves for neighboring and local schemes at bus 4044 in NORDIC32 which is located in the central area. The stochastic load model used in ARISTO causes voltage variations as it can be seen in this figure.

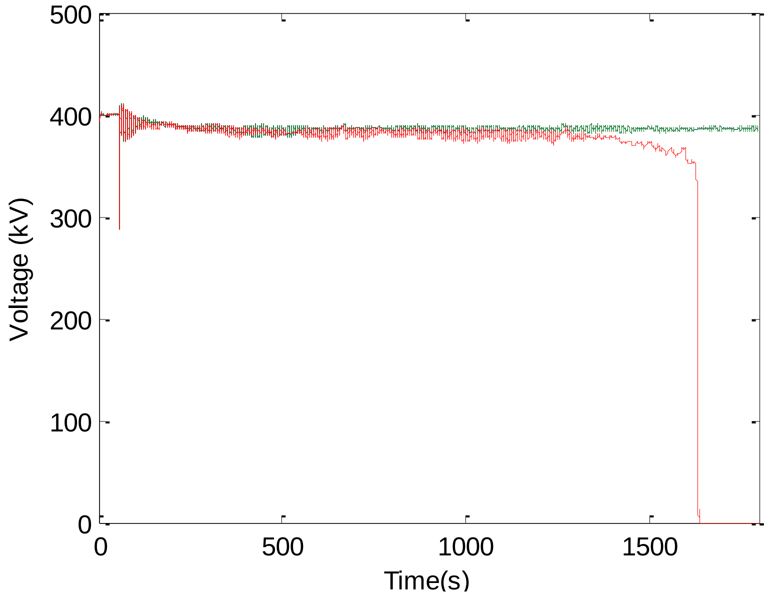

Fig. 6-10 Voltage at bus 4044 in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the generator outage scenario.

As it can be seen, at the early stage following the disturbance, there are some transients coming from short-term dynamics in the system. These transient oscillations are damped out after few seconds and the short-term equilibrium is established. Then the power system is driven by the long-term dynamics which are tap changer and OXL actions. Tap changer actions lead to load recovery on the distribution side of the transformers and it causes further sag in transmission side voltages. Also, some of the generators in the central area reach their over excitation limits and their OXL act to return the field currents to the rated values. Lack of reactive power is the consequence of OXL action. Then the more remote generators try to provide the demanded reactive power. This is not the efficient way to compensate the lack of the reactive power. Meanwhile, to counteract the disturbance effect and compensate the lack of the reactive power, there are some connections and disconnections of the shunt elements in the system by applying the local and the neighboring schemes as real-time countermeasures. Since the system is lacking the reactive power, then the connection of the capacitors is of interest. The reaction time spent to connect the first and second capacitors for the local and neighboring schemes are given in Table 6-1.

Table 6-1: Reaction time for capacitors connection for generator outage scenario

Conditions	Bus	Time (Sec)	
		Neighboring	Local
First capacitor	4041	64s	109s
Second capacitor	4051	321s	1584s

The neighboring scheme application apparently gives sooner action of the shunts and leads to avoiding voltage collapse in the system. In the local scheme case, because of the tap changer action and thermostatic load behavior, the voltage gradually continues to decline further and further at transmission level ultimately leading to action of distance protection and cascading line tripping. Finally under voltage protection for generators act, leading to collapse in some parts of the central area in the system. For some generators, the out of step relay is also activated before the collapse and cause the loss of synchronism for them. So it could be said that the evolution of the long-term variables lead to loss of short-term equilibrium in the system or since the voltage collapses in the central (load) area, then the long-term voltage instability ultimately causes the rotor angle instability as it happened in 1983 and 2003 Swedish blackouts.

In section 6.1, the neighboring scheme application connected more shunts, while here it leads to sooner action of the shunts. In this case, the amount of the capacitors connected to the system is the same for local and neighboring schemes but they are connected at different time instants. It can also be noted that the voltage again collapses in the central part of the system as it was expected.

Fig. 6-11 to 6-13 show the voltage curves for other parts of the system. As it can be seen, the voltage goes up in the north part after the collapse (Fig. 6-11). This is because of when the collapse happened, three out of five lines from north to center in NORDIC32 disconnected from the system. The decrement in the transfer power from north to center leads to increment of the voltage level in the northern part after the collapse.

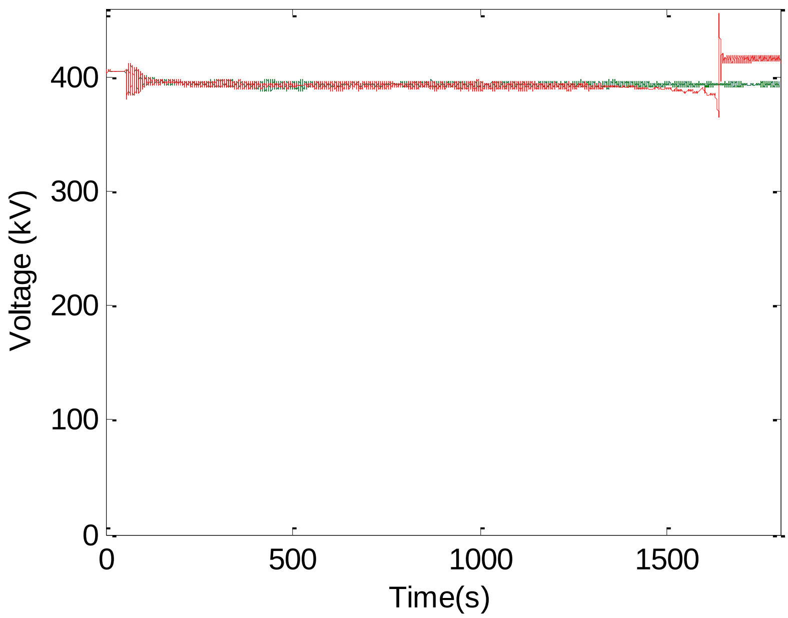

Fig. 6-11 Voltage at bus 4011 (north) in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the generator outage scenario.

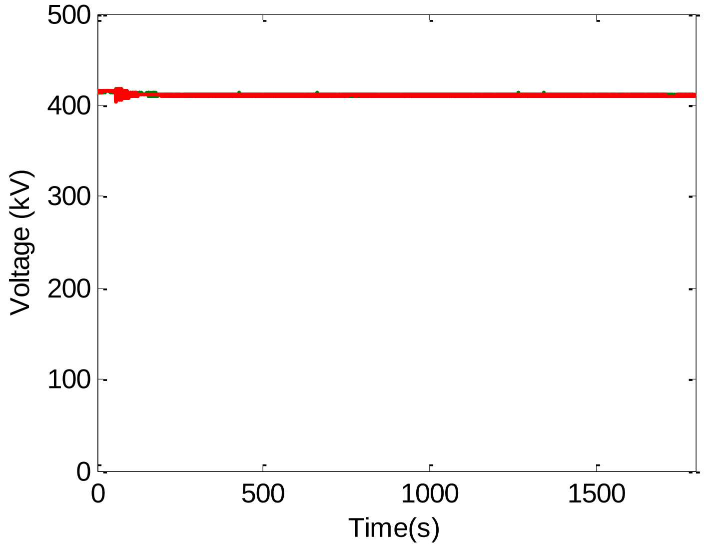

Fig. 6-12 Voltage at bus 4071 (external) in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the generator outage scenario.

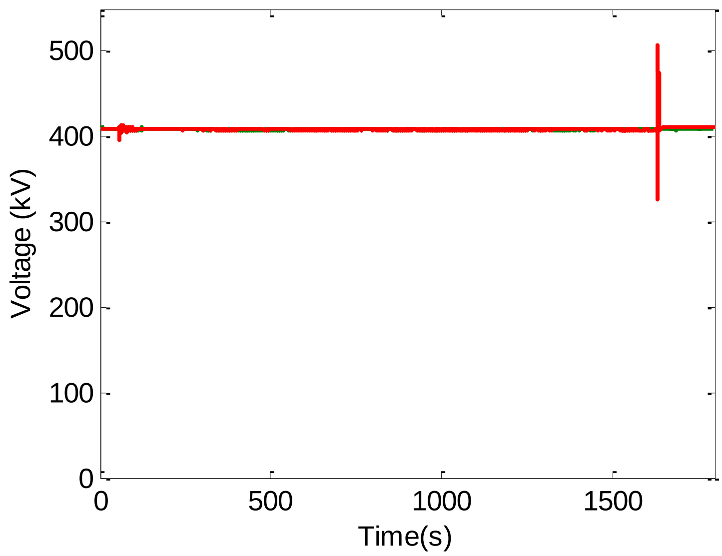

Fig. 6-13 Voltage at bus 4063 (south-west) in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the generator outage scenario.

For the rest of the system, the generation and consumption are balanced and it seems they are isolated from the disturbance. That is why the external and south west areas have unaffected voltages at buses 4071 (Fig. 6-12) and 4063 (Fig. 6-13).

As mentioned, by applying the neighboring scheme, the power system could avoid the blackout as shown in Fig. 6-10. In the local scheme case, blackout ultimately happened for some parts of the system. In fact by applying the local scheme, the five interconnecting transmission lines between northern and central parts in NORDIC32 got heavily overloaded and could carry less power than when applying the neighboring scheme. So if the transfer in those five lines decreases, then the system could survive by applying the local scheme as well. By changing the transfer on the five long interconnecting lines, it can be found that the transfer limit with respect to voltage collapse is 3035 MW for the local scheme and 3291 MW for the neighboring scheme. The neighboring scheme thus raises the transferred power by 256 MW.

Line Tripping

The second long-term voltage instability scenario applied on NORDIC32 is tripping the two transmission lines between buses 4044 and 4045 in NORDIC32 (Fig. 5-1) at 60 s. This instability scenario is similar to the disturbance applied in the N3area test system in section 6.1. Fig. 6-14 shows the voltage curve for the local and neighboring schemes in bus 4044 in NORDIC32 which is located in the central area.

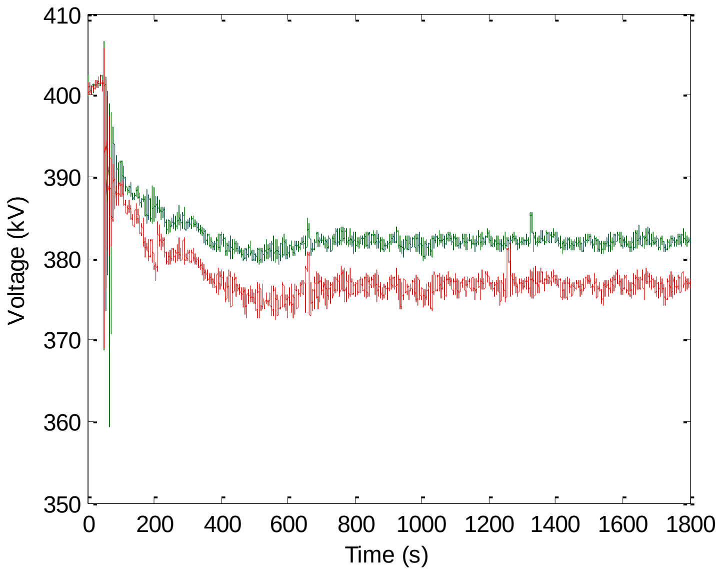

Fig. 6-14 Voltage at bus 4044 in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the transmission line tripping scenario.

After the initial transient period which is excited by the short-term dynamics, the long-term dynamics took over the system behavior lead to voltage reduction in this station. As it can be seen, the neighboring scheme application led to higher steady-state voltage. The voltage level is less than the acceptable limit in both cases but the system is stable.

Fig. 6-15 to 6-17 show the voltage curves for other parts of the system. Apart from the initial transients, the voltage does not collapse for those stations and in all cases, the neighboring scheme application gives higher voltages.

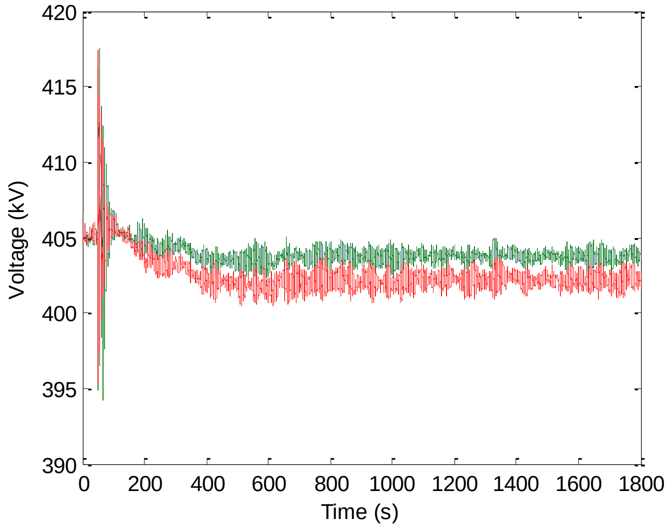

Fig. 6-15 Voltage at bus 4011 (north) in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the transmission line tripping scenario.

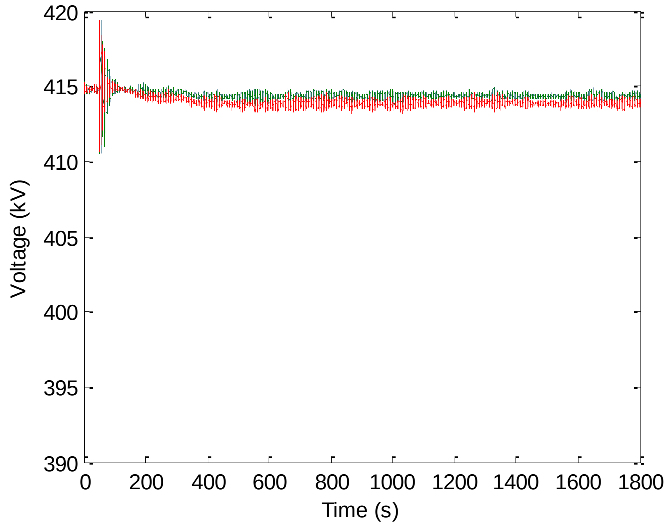

Fig. 6-16 Voltage at bus 4071 (external) in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the transmission line tripping scenario.

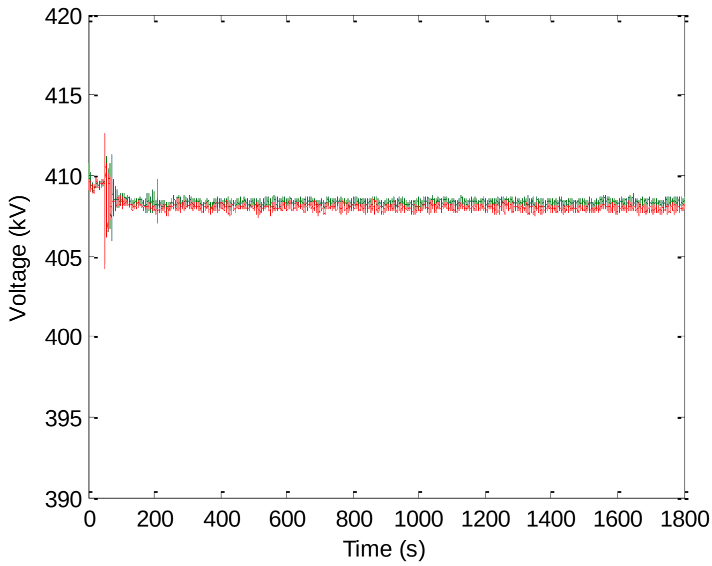

Fig. 6-17 Voltage at bus 4063 (south-west) in NORDIC32, for the local scheme (red) and for the neighboring scheme (green) for the transmission line tripping scenario.

Following the disturbance, the first capacitor is connected to the system at bus 4051 for the neighboring scheme and bus 4041 for the local scheme after 15 s and 159 s respectively. Also the neighboring scheme leads to connection of the second capacitor at bus 4041 (18 s after the disturbance) while this capacitor is never connected by the local scheme application. So more reactive power is injected by the neighboring scheme application, also the capacitor connections are faster in the neighboring scheme compared to the local one.

Based on the simulation results from sections 6.1 and 6.2, it is true that N3area provides simulation results qualitatively similar to the NORDIC32. In both test systems, the voltage collapses in the central part of the system and voltage is lowest there. Also, by applying the neighboring scheme, more capacitor connections are made compared to the local one in both test systems. These results verify the capability of the proposed N3area as a simplified test system to emulate the long-term voltage collapse behavior of NORDIC32 and the Swedish transmission system.

6.3 Static analysis of the neighboring scheme

This part aims to explain, using PV curves, why the neighboring scheme performance was better than the local scheme in the dynamic simulation for the NORDIC32 test system and how it led to avoiding the collapse in the generator outage scenario.

To generate PV curves, the N3area test system is considered and the load in the southern area (L_2 in Fig. 5-3) is increased. The PV curves for the three buses A, B, C in Fig. 5-3 are plotted in Fig. 6-18 while there is no capacitor in operation.

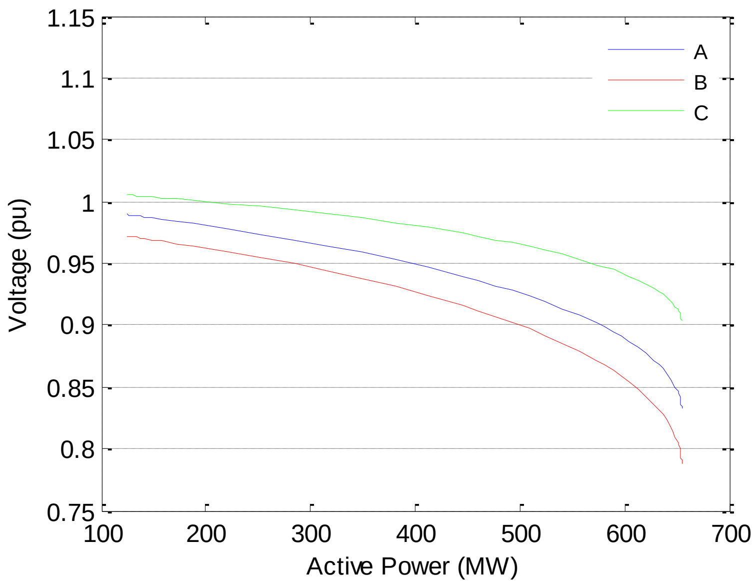

Fig. 6-18 PV curves without any capacitor connected; red line (bus B), blue line (bus A), and green line (bus C). P here represents the active power consumed by the load at southern area, L_2.

The lower acceptable voltage level is 0.95 pu. It means, below this level the capacitors will connect to the system. Based on Fig. 6-18, bus B has the lowest voltage and is the first bus which violates the nominal voltage range as it was expected. So the first local action of the capacitors would be at bus B. By bringing the capacitor at bus B in operation, new PV curves are generated for these three buses as depicted in Fig. 6-19.

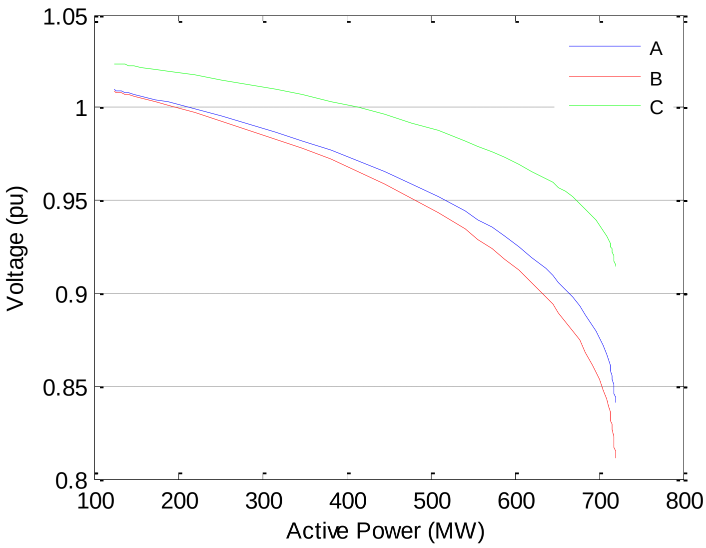

Fig. 6-19 PV curves with one capacitor connected at bus B; red line (bus B), blue line (bus A), and green line (bus C). P here represents the active power consumed by the load at southern area, L_2.

If the local scheme is taken into consideration, based on the Fig. 6-19, the next action of the capacitors would be at bus A (blue line). Because, in Fig. 6-19, the first line which violated the voltage nominal range is the red line (corresponding to bus B) and the second line is blue line (corresponding to bus A). But the capacitor at bus B is already connected to the system. It means that the next step is connection of capacitor at bus A. Using the local scheme, the capacitor at bus A will be connected to the system once the voltage is below the lower limit at its own bus. By instead using the neighboring scheme, the capacitor at bus A will be switched on once the voltage either at its own bus or at the neighboring bus (bus B) violates the nominal voltage range (below 0.95 pu). It means once either red line or blue line in Fig. 6-19 goes below 0.95 pu, the capacitor at bus A will be connected to the system. Based on Fig. 6-19, the red line (corresponding to bus B) is going below 0.95 pu earlier than the blue line. So the neighboring scheme leads to sooner action of the capacitor at bus A.

Acting earlier is known to be beneficial near voltage instability [8] and the neighboring scheme is a simple yet efficient way to achieve this, which suits the characteristics of the N3area system and should apply to similar systems.

6.4 Summary

Reactive shunts are the traditional actuators to control the voltage in power systems. They are commonly controlled using a local scheme. An alternative control strategy proposed in this thesis is called the neighboring scheme. To evaluate the performances of these two control strategies, different instability scenarios are applied on N3area and NORDIC32 test systems. The dynamic simulation results have been explained and discussed for generator and line outages scenarios. Based on the simulation results, the neighboring scheme performance is superior to the local scheme and it improves long-term voltage stability by connecting more shunt capacitors or connecting earlier. Also the concept of neighboring scheme is explained further in this chapter using static analysis and PV curves.

Chapter 7

Reactor Hunting

This chapter first introduces and explains the reactor hunting phenomenon using a simple circuit. Then adaptive tolerance band concept is proposed as a new control scheme for shunt automatics to eliminate reactor hunting.

7.1 Demonstrating the Problem

To get better understanding of the reactor hunting phenomenon, a simple model circuit is considered in Fig. 7-1. The energized portion of the system is modeled by the Thévenin equivalent circuit. Then a lossless transmission line which has the PI model is energized from the intact point of the functioning network. A shunt reactor can be connected to the remote end of the line to lower the voltage. To show the reactor hunting phenomenon, three cases are considered:

- Case 1: one transmission line is energized from a weak network
- Case 2: one transmission line is energized from a strong network
- Case 3: two parallel transmission lines are energized from a strong network

This basic network topology can represent the situation like that the power system in the north of Sweden is intact while the blackout happened in the central and south areas.

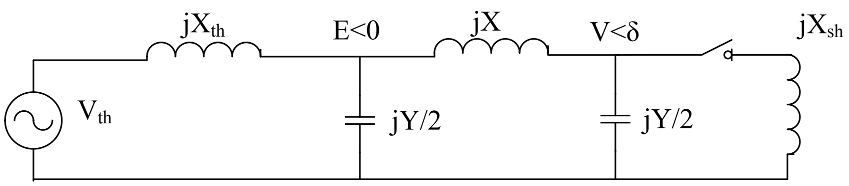

Fig. 7-1 Simple model circuit to demonstrate the reactor hunting phenomenon.

The end point voltage V of the transmission line is calculated for two different conditions; without shunt reactor connection and with shunt reactor connection.

If the shunt reactor is not connected to the transmission line then:

$$V = \left[\frac{-j2/Y}{-j2/Y + jX}\right]\left[\frac{\dfrac{-j2/Y(X-2/Y)}{-2/Y+(X-2/Y)}}{\dfrac{-j2/Y(X-2/Y)}{-2/Y+(X-2/Y)} + jX_{th}}\right]V_{th} \tag{7.1}$$

While V_{th} and X_{th} are the Thévenin voltage and reactance, Y and X are the transmission line admittance and reactance and X_{sh} is the shunt reactor value.

On the other hand with shunt reactor connection, if we consider

$$A = \left[\frac{X_{sh}}{-2/Y + X_{sh}}\right] \tag{7.2}$$

Then:

$$V = \left[\frac{-j2/Y}{-j2/Y + jX}\right]\left[\frac{\dfrac{-j2/Y(X-2A/Y)}{-2/Y+(X-2A/Y)}}{\dfrac{-j2/Y(X-2A/Y)}{-2/Y+(X-2A/Y)} + jX_{th}}\right]V_{th} \tag{7.3}$$

The parameters of the network, transmission line and the shunt reactor are provided in Table 7-1.

Table 7-1: Network, transmission line and shunt reactor parameters

Network	Transmission Line	Shunt Reactor
V_{th}=400 kV	X=120 Ω	Q=200 Mvar
X_{th}=8 Ω Strong	Y=0.000819 S	
X_{th}=80 Ω Weak	Length=400 km	X_{sh}=800 Ω

For each case, the voltage at the end of the transmission line is calculated before and after the reactor connection and is shown in Fig. 7-2. The horizontal black dashed lines show the default tolerance band for the shunt automatics, [380-420] kV.

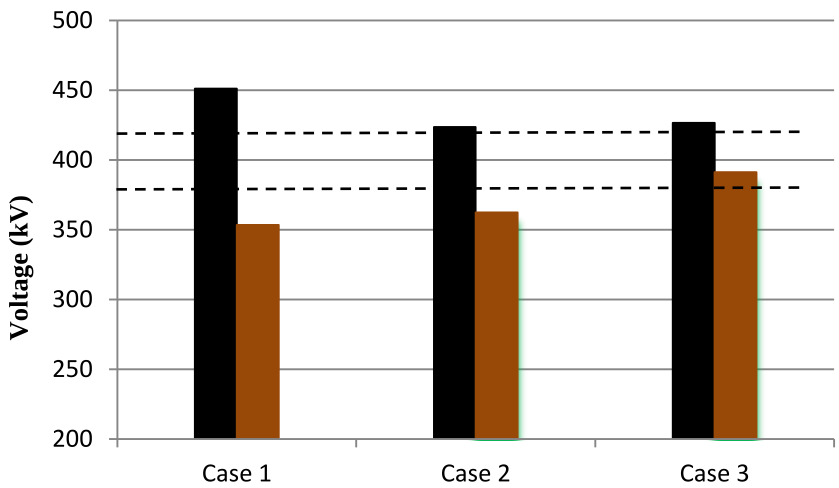

Fig. 7-2 Voltage at the ending point of the transmission line before (black bar) and after (orange bar) the shunt reactor connection.

To calculate the short circuit power of the shunt reactor bus;

If we consider $D = \left[\dfrac{-j(2/Y)X}{X - (2/Y)} \right]$ (7.4)

Then the short circuit current is:

$$I_{sc} = \left[\frac{V_{th}}{jX_{th} + D} \right] \left[\frac{2/Y}{(2/Y) - X} \right] \quad (7.5)$$

The short circuit power is calculated based on the following equation:

$S_{sc}=V_{sc}I_{sc}$ (7.6)

While V_{sc} is the ending point voltage of the transmission line before the shunt reactor connection (no load voltage).

The short circuit power of the shunt reactor bus for three cases of Fig. 7-2 is provided in Table 7-2.

Table 7-2: Short circuit power of the shunt reactor bus

Case 1	Case 2	Case 3
S_{sc}=920 MVA	S_{sc}=1327 MVA	S_{sc}=2522 MVA

Based on the Fig. 7-2 and Table 7-2, the lower short circuit power is corresponding to the higher voltage change. If we consider [380-420] kV as acceptable voltage limit for shunt automatics actions, then a reactor is connected when the voltage exceeds 420 kV and is disconnected as voltage goes below 380 kV. From Fig. 7-2, in case 1 and case 2 reactor connection causes the voltage to go below the lower limit, and while reactor disconnection leads to a voltage level above the higher limit. With these EVA settings, neither position is acceptable and the reactor will repeatedly be connected and reconnected. This repetitive process of connection and disconnection of the shunt reactors is called reactor hunting and naturally causes large voltage fluctuations with a time cycle governed by the delay times of the reactor relay in combination with the response time of the circuit breaker.

To cope with this phenomenon and also to speed up the restoration process, the common practice for the TSOs around the world is turning off the Extreme Voltage Automatics (EVA) during the restoration time. That leaves the reactor shunts in manual operation which leads to slow down the restoration process [33].

7.2 Adaptive Tolerance Band for the Shunt Automatics to Avoid Reactor Hunting

To avoid reactor hunting, the control method proposed is instead of having fixed tolerance bands for the shunt automatics, they can be flexible and adaptive based on the network strength. In fact the EVA settings will change based on the operating condition and automatic operation of the shunts can continue during the restoration time. This speeds up the restoration process.

As demonstrated above, one indicator for the network strength is the short circuit capacity. If the short circuit capacity is high at the specified node, then that node is strong. On the other hand, if the short circuit capacity is low for a specified node, then that node is considered weak. To derive the approximate formula to relate the short circuit capacity to the voltage and reactive power changes, Fig. 7-1 is considered while the shunt reactor is not connected at the remote end of the transmission line. Moreover, Thévenin reactance is disregarded since it is assumed that the voltage at the sending point of the transmission line ($E<0$) is fixed. Also transmission line admittances are disregarded since they do not affect too much the short circuit power at the remote end of the line.

By applying all above simplifications, the reactive power received at the remote end of the transmission line can be written as Eq. 7.7. Then the approximate amount of the shunt compensation needed to adjust the voltage at the remote end of the line can be derived from Eq.7.8. This equation represents the voltage sensitivity with respect to the reactive power.

$$Q = \left(\frac{EV}{X} \cos\delta - \frac{V^2}{X} \right) \tag{7.7}$$

$$\frac{\partial V}{\partial Q} = \left(\frac{\partial Q}{\partial V} \right)^{-1} = \left(\frac{E}{X} \cos\delta - \frac{2V}{X} \right)^{-1} \tag{7.8}$$

If the equivalent system is unloaded, then $\delta = 0$ and E=V=1, also since the pu short circuit capacity is S_{sc}=1/X, the above equation can be simplified as follows:

$$\frac{\partial V}{\partial Q} = \left(\frac{\partial Q}{\partial V} \right)^{-1} = \left(\frac{E}{X} - \frac{2V}{X} \right)^{-1} = -\frac{X}{E} \approx -X(pu) \approx \frac{-1}{S_{sc}(pu)} \tag{7.9}$$

Then finally:

$$\frac{\partial V}{\partial Q} \approx \frac{-1}{S_{sc}(pu)} \tag{7.10}$$

Based on the Eq.7.10, when the specified node is strong enough (high short circuit power), drawing or injecting the reactive power does not affect too much the voltage at that node. But if the short circuit power is low at the specified node, then voltage is sensitive to the reactive power change. This equation shows how short circuit capacity can be used as an indicator for voltage sensitivity to the reactive power change.

Also based on this equation the voltage variation can be derived as follows:

$$\partial V \approx \frac{-\partial Q}{S_{sc}(pu)} \tag{7.11}$$

Eq. 7.11 shows that the voltage change at the specified node can be predicted if the short circuit power of the node also the amount of nominal reactive power change is known. During the restoration process, when a specified transmission line is energized, Eq. 7.11 can be employed to predict the bus voltage after shunt reactor connection. Then before the reactor connection, the EVA setting of the shunt reactors can change accordingly to avoid reactor hunting.

To show how Eq. 7.11 could be used to avoid reactor hunting, this equation is applied for cases 1 and 2 of Fig. 7-2. If the nominal value of the shunt reactor which is 200 Mvar considers, then the voltage change for case 1 is around 22% and for case 2 is around 15%. For case 1, the predicted voltage is around 352 kV and for case 2 it is around 360 kV after shunt reactor connection. Therefore if the EVA lower limit set below 352 kV for case 1 and below 360 kV for case 2, then the reactor hunting would be removed completely. Fig. 7-3 illustrates how the lower threshold should be adjusted to avoid reactor hunting. The reason to choose the lower limit is that the voltage will rise due to the Ferranti effect when a new transmission bus is energized. So if the upper limit is selected to be adjusted, then energizing the new transmission bus makes the situation worse and leads to even higher voltage.

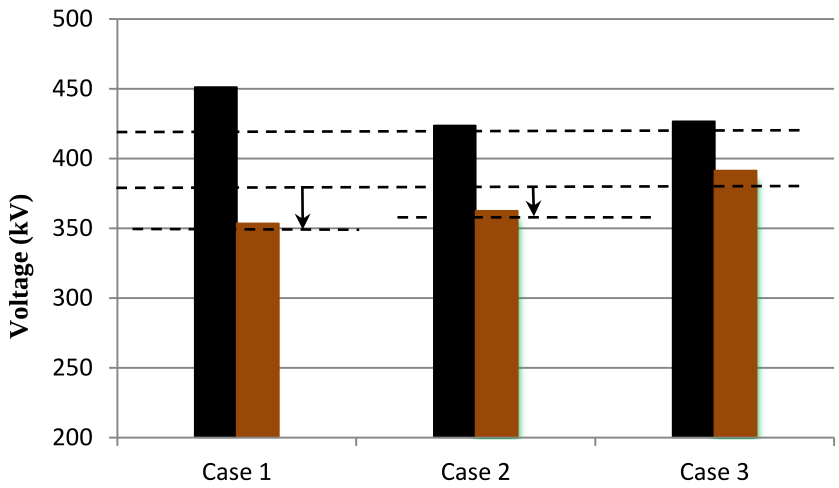

Fig. 7-3 Lower threshold adjustment to avoid reactor hunting.

Obviously short circuit power can be utilized as a parameter to describe how strong a specified node in the system is, and then shunt reactor tolerance bands can be adjusted based on that to avoid reactor hunting.

7.3 Summary

Reactor hunting may be a problem for TSOs during the restoration after blackouts. The consequence of reactor hunting is large voltage fluctuations. The common practice for TSOs to avoid reactor hunting is turning off the shunt automatics during the restoration period. That leaves the shunts in manual operation which leads to longer restoration process. The adaptive tolerance band concept is proposed in this thesis to handle the reactor hunting issue. By applying this control scheme, the automatic operation of the reactive shunts will continue during the restoration time and the reactor hunting problem would be solved.

Chapter 8

Reactor Hunting Simulations

This chapter proposes two methods to eliminate the reactor hunting during power system restoration. In the first one called experimental method, once the shunt reactor is connected to the system, the voltage change is measured then the shunt reactor tolerance band is adjusted based on this. The performance of the experimental method is evaluated on NORDIC32 test system in ARISTO for two random restoration strategies. ARISTO is used since it has been mainly developed for operators training to handle the restoration process. Simulation results prove the capability of the proposed experimental method to prevent reactor hunting. In the second part, it is assumed that the short circuit power is available from EMS network model and the change of tolerance band for the shunt automatics is calculated based on that. This scheme is applied for a specified restoration scenario in PowerFactory for NORDIC32 test system and the simulation results show the capability of the proposed method to avoid reactor hunting. PowerFactory is used since the short circuit power of the transmission buses is available there.

8.1 Experimental Method Application to Avoid Reactor Hunting

This method is based on the voltage change measurement at buses in the system. First the shunt reactor at the target bus is connected, then voltage change measurement (deltaV) is noted and the shunt automatic threshold band is adjusted based on this. As mentioned in chapter 7, to avoid reactor hunting, the tolerance band lower limit for the shunt automatics will change based on the measured deltaV.

To evaluate the performance of the proposed method, two random restoration strategies are considered in ARISTO for the NORDIC32 test system (Fig. 8-1). The simulation results are obtained once the blackout happened in the south and central areas. As it can be seen in Fig. 8-1, some buses are pointed out by the red letters. These are the buses involved in the random restoration strategies. Moreover, red, green and blue tracks are different paths to reach the bus 4041. They will be used in the sequel to give deeper understanding of the adaptive tolerance band concept. The default tolerance band for shunt automatics is [380-420] kV in ARISTO. The new upper limit during the restoration is set to 440 kV to create a safer margin for avoiding hunting and the lower limit is adjusted based on the voltage change measurement.

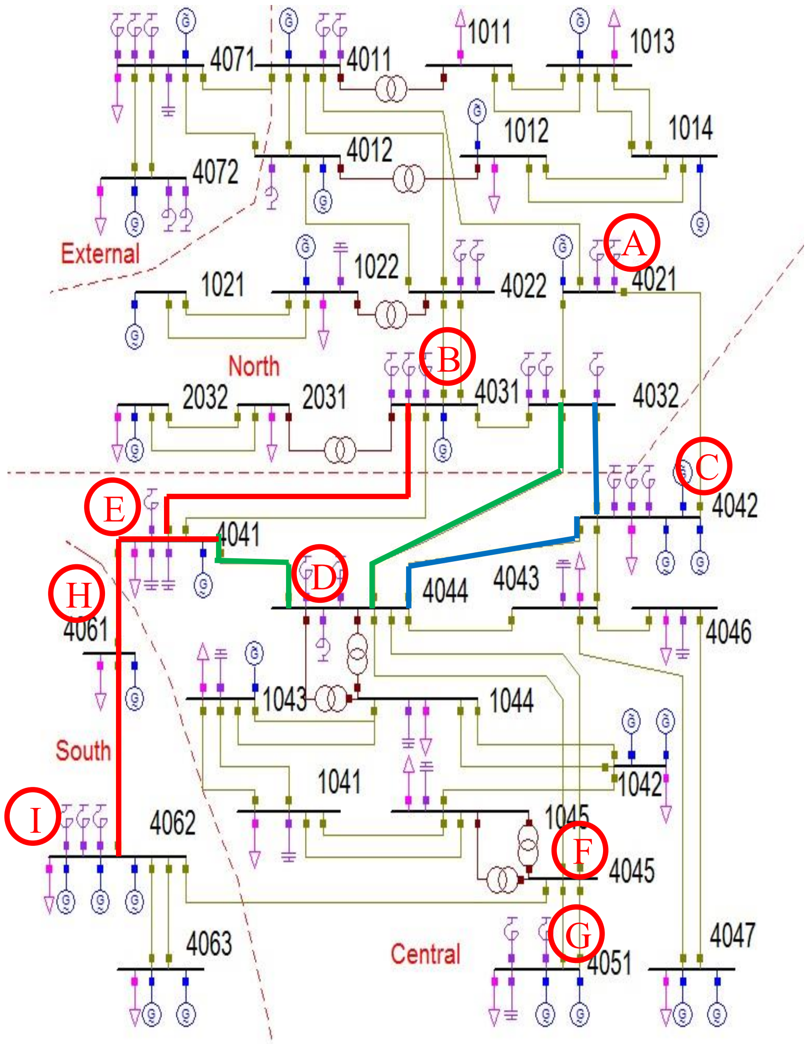

Fig. 8-1 NORDIC32 test system, some buses are pointed out by the red letters which are involved in restoration strategies. Also different tracks including red, green and blue are shown to reach the bus 4041. These tracks will be used in section 8.2 to give deeper understanding of the adaptive tolerance band concept.

Random Restoration Strategy 1

The sequence of energizing the transmission buses for this restoration scenario is as following (see Fig. 8-1):

ED then AC then EI then IF then FG.

To explain the above energizing sequence; note that for example ED means the bus D is energized from bus E in Fig. 8-1, then AC means bus C is energized from bus A and so on. In case of existing two parallel transmission lines between two buses, only one of them will be energized.

Fig. 8-2 shows the reactor hunting at bus 4042 while the default tolerance band for the restoration [380-440] kV is used. Note that the voltage base is 400 kV, so the default tolerance band is equal to [0.95-1.1] pu.

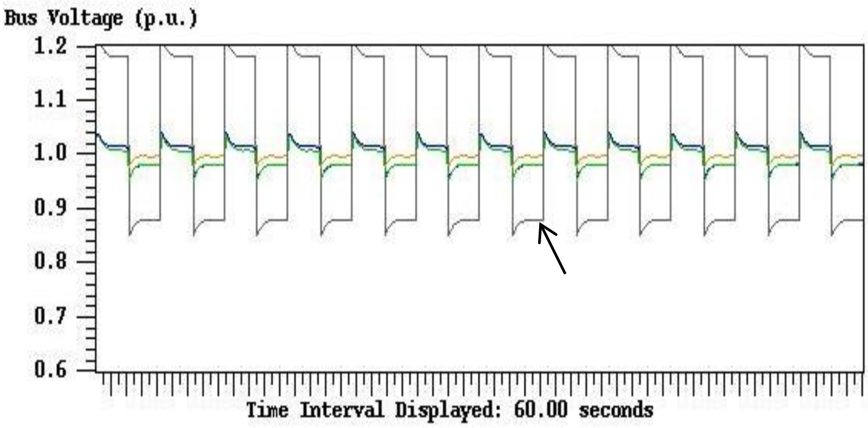

Fig. 8-2 Reactor hunting at bus 4042 while the default tolerance band is used. The voltage at bus 4042 is pointed out by the black arrow. Orange, blue and green curves show the voltage at buses 4022, 4031 and 4044 respectively.

By applying the proposed experimental method, the reactor hunting is removed at bus 4042 as it is shown in Fig. 8-3.

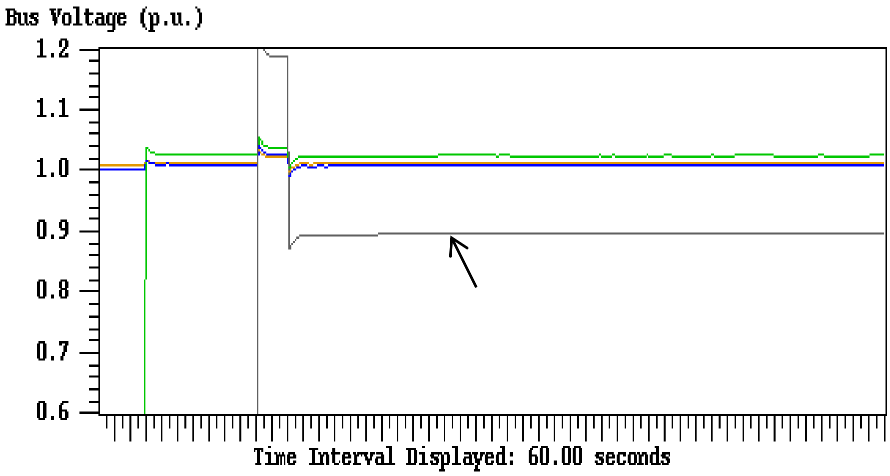

Fig. 8-3 No reactor hunting at bus 4042 after applying adjusted threshold bands. The voltage at bus 4042 is pointed out by the black arrow. Orange, blue and green curves show the voltage at buses 4022, 4031 and 4044 respectively.

Random Restoration Strategy 2

The sequence of energizing the transmission buses for this restoration scenario is as following (see Fig. 8-1):

EI then IF then FG then FD then DC.

Fig. 8-4 shows the reactor hunting at bus 4062 while the default tolerance band for the restoration [380-440] kV is used.

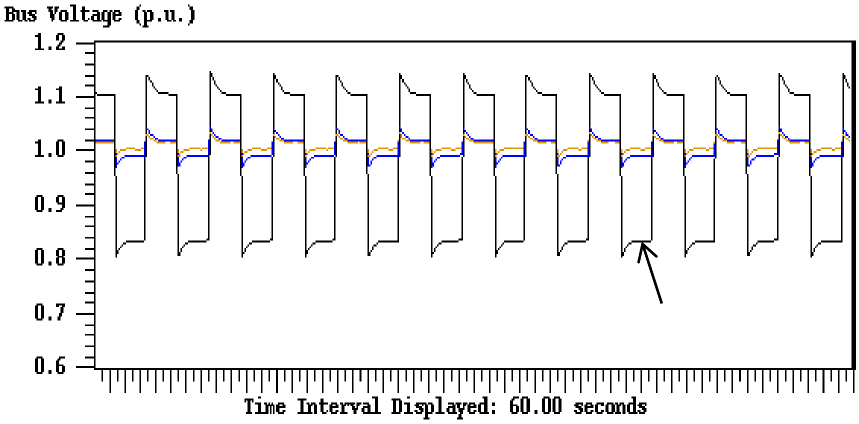

Fig. 8-4 Reactor hunting at bus 4062 while the default tolerance band is used. The voltage at bus 4062 is pointed out by the black arrow. Orange and blue curves show the voltage at buses 4022 and 4031 respectively.

By applying the proposed experimental method, the reactor hunting is removed at bus 4062 as it is shown in Fig. 8-5.

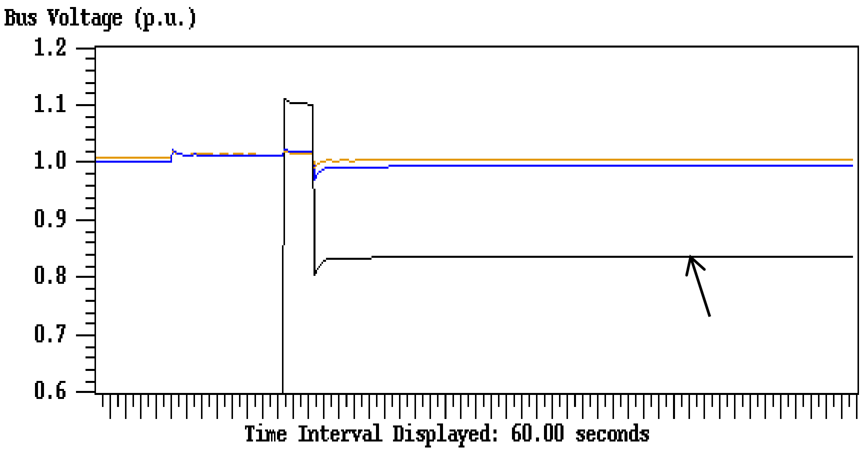

Fig. 8-5 No reactor hunting at bus 4062 after applying adjusted threshold bands. The voltage at bus 4062 is pointed out by the black arrow. Orange and blue curves show the voltage at buses 4022 and 4031 respectively.

8.2 EMS Network Model Application to Avoid Reactor Hunting

Energy Management System (EMS) supervises, controls and manages the generation and transmission systems. It collects and analyzes data from hundreds of thousands of data points in national networks. This supervisory system is a vital part of the modern power networks. The primary functions of the EMS are listed below [38]:

- Network topology processer
- State estimation
- Contingency analysis
- Optimal power flow

Network topology processor functionality of the EMS can be used to calculate the short circuit power of the transmission buses. If the network topology is available during power system operation, then based on the network admittance matrix, the short circuit power can be calculated continually during system operation.

Simulation Results

In this part, it is assumed that the short circuit power is calculated using EMS network model. Then based on the equation Eq. 7.11, the voltage change at a specified node can be predicted before shunt reactor connection. So the EVA setting of the shunt reactors can change accordingly to avoid reactor hunting. This remedial mechanism is applied to NORDIC32 test system (Fig. 8-1) in PowerFactory once the blackout happened in the south and central areas. The considered restoration path is as following and pointed out by the red track in Fig. 8-1:

BE then EH then HI.

The transmission line between buses 4061 and 4062 is energized at t=10 s. Fig. 8-6 shows the reactor hunting at bus 4062 once the default tolerance band [380-440] kV is applied for the shunt automatic. As mentioned, the voltage base is 400 kV, then the default tolerance band is [0.95-1.1] pu which is shown by the horizontal black dashed lines.

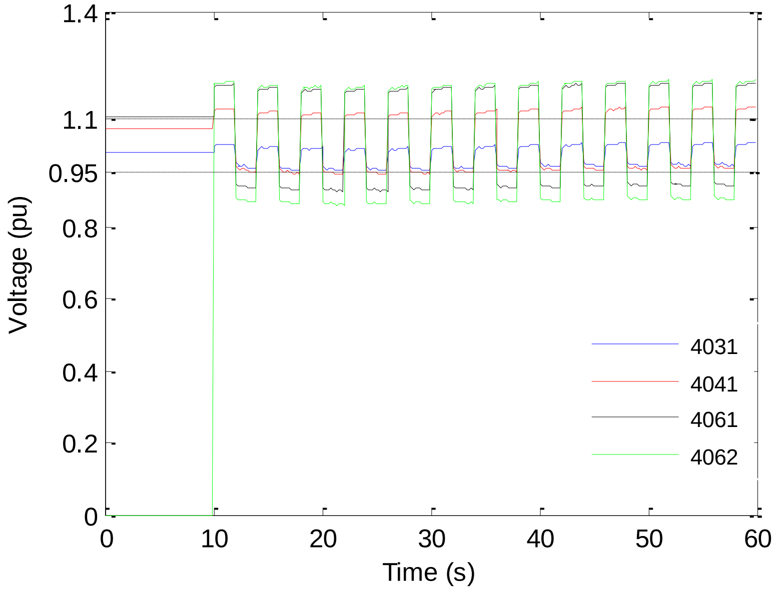

Fig. 8-6 Reactor hunting at bus 4062 while the default tolerance band is used.

To remove reactor hunting at bus 4062, the corresponding short circuit power from PowerFactory is utilized in Eq. 7.11. After that the tolerance band lower limit is adjusted and set to 0.83 pu based on the Eq. 7.11 to avoid reactor hunting. Simulation results are shown in Fig. 8-7. As it can be seen in this figure, the reactor hunting is eliminated using proposed adaptive tolerance band concept. Note that with the EMS-based method, shunt reactors thresholds are returned to normal levels as the network situation is normalized.

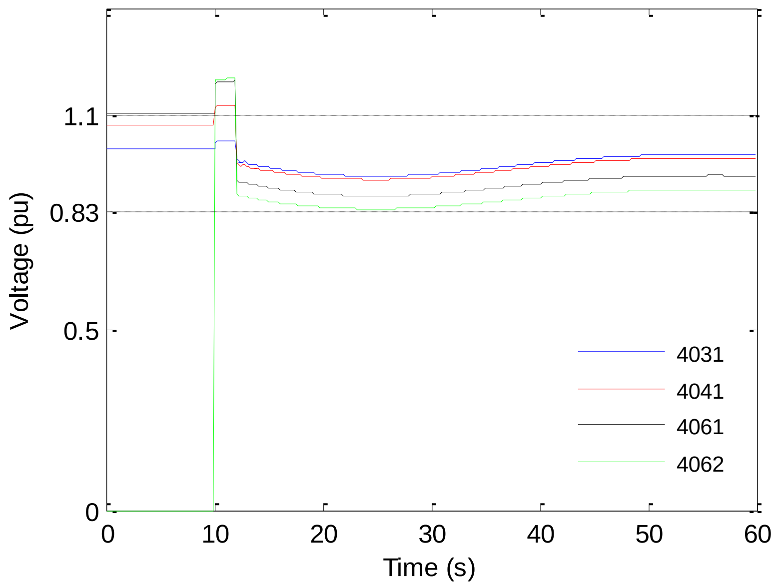

Fig. 8-7 No reactor hunting at bus 4062 after applying adjusted threshold bands.

To show the concept of adaptive tolerance band in a better way, the voltage profile for the buses of the restoration path in Fig. 8-1 (red path) is shown in Fig. 8-8. This profile is dedicated to three different restoration situations. In fact three different tracks are utilized to reach the bus 4041, see Fig. 8-1:

- Red track: BE (bus E, 4041 is energized just from bus B, 4031)
- Green track: bus 4041 is energized from both red and green tracks in Fig. 8-1
- Blue track: bus 4041 is energized from both red, green and blue tracks in Fig. 8-1

In Fig. 8-8, the corresponding voltage profile for these three tracks has the same color as it is in Fig. 8-1. For bus I, there are two values for each track, one without shunt reactor connection and another one with shunt reactor connection. The default tolerance band, [380-440] kV, is also depicted in Fig. 8-8 by the horizontal black dashed lines. Moreover, to explain how voltage profile of the buses is affected by the network strength, the corresponding short circuit powers for three tracks of Fig. 8-1 are depicted in Fig. 8-9. For the red track which is corresponding to the lowest short circuit powers, once the shunt reactor is connected at bus 4062, the lowest voltage reaches 351.6 kV while for stronger cases it is 367.63 kV and 389.75 kV, see Fig. 8-8. This means if the shunt automatic tolerance band is fixed to [380-440] kV, then reactor hunting will occur at bus 4062 for the red and green scenarios. So if we aim to avoid reactor hunting, then the tolerance bands for the shunt automatics cannot be fixed and it must be adaptive based on the network strength. It is also noticeable that in the blue track, strongest case, there is no hunting since the lowest voltage after shunt reactor connection (389.75 kV) is within the default tolerance band.

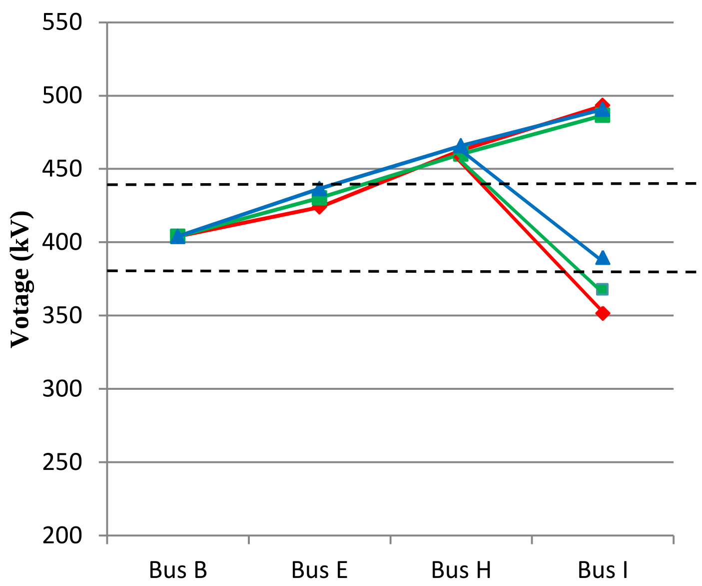

Fig. 8-8 Voltage profile for different buses of the considered restoration path.

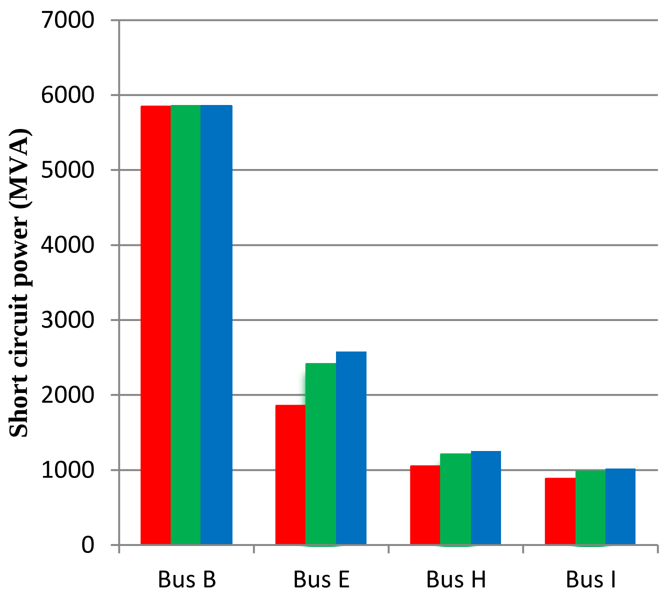

Fig. 8-9 Short circuit powers for different buses of the considered restoration path.

8.3 Summary

Two methods to eliminate the reactor hunting issue during power system restoration have been presented in this chapter including; experimental method and using EMS network model. Then to evaluate the experimental method performance, two random restoration scenarios are considered on the NORDIC32 test system in ARISTO. After that, the EMS network model application to reach the short circuit capacity is utilized. This scheme performance is also evaluated on the NORDIC32 test system in PowerFactory for a specified restoration scenario. Simulation results both in ARISTO and PowerFactory show the capability of the proposed methods to eliminate reactor hunting.

Chapter 9

Conclusions and Future Work

In this dissertation, the long-term voltage instability problem and also the countermeasures to avoid it have been investigated. The shunt reactors and capacitors are the traditional actuators which are used in power networks to regulate the voltage. Consequently they have large impact on voltage stability. The most common control scheme to switch the shunt reactors and capacitors is called the local scheme. This scheme switches the shunts when the voltage at the local bus is outside the nominal range. As an alternative, the neighboring scheme is proposed in this thesis to control the shunt reactors and capacitors. In this scheme, both the local voltage and the voltage at neighboring buses are considered. To investigate the local and neighboring scheme performances, two test systems are utilized; NORDIC32 and N3area. NORDIC32 is a CIGRE test system and has the long-term characteristics of the Swedish national power system. Although NORDIC32 is a reduced order model of the Swedish system, it is still a complex test system. The N3area test system which is proposed in the thesis is the simplest test system that can replicate the long-term voltage dynamics of NORDIC32 and the Swedish power system. The main advantage of the N3area test system is that it reduces NORDIC32 model complexity, so long-term voltage instability behavior and countermeasures can be analyzed much easier there than in NORDIC32, still retaining a dynamic behavior quite close to NORDIC32 and reality. Load recovery and Over Excitation Limiter (OXL) action are included in both test systems to obtain a more realistic picture of the long-term voltage instability phenomenon. Dynamic simulations using both N3area and NORDIC32 test systems are conducted for different instability scenarios. The simulations show that the neighboring scheme improves voltage or long-term voltage stability by connecting more shunt capacitors or connecting earlier. Also the closeness of N3area and NORDIC32 simulation results proved the capability of N3area to emulate the long-term voltage collapse behavior of NORDIC32.

The second part of the thesis is devoted to power system restoration. The aim for Transmission System Operators (TSOs) during the restoration period is to restore the power system as fast and securely as possible to reduce social and economical consequences for the population. One barrier which increases the restoration process time is reactor hunting. This problem occurred in southern part of Sweden during the 2003 Swedish/Danish blackout. To handle the reactor hunting, the common practice for TSOs is to shut down the shunt automatics during the restoration. This leaves the shunts in manual operation which increases the restoration time. To remove the reactor hunting issue and to keep the automatic operation of the shunts during the restoration period, the adaptive tolerance band concept is proposed in the thesis for shunt automatics. The main idea is instead of having fixed tolerance band for the shunt automatics, it can change and be adaptive. This concept is applied to eliminate reactor hunting for restoration of the NORDIC32 test system. Two applicable methods have been proposed to apply the adaptive tolerance band concept; experimental method and using Energy Management System (EMS) network model. In the experimental method application, once the shunt reactor is connected to the system to lower the voltage, the voltage change is measured then the shunt reactor tolerance band is adjusted based on this. The performance of the experimental method is evaluated on NORDIC32 test system in ARISTO for two random restoration strategies. In the EMS network model case, it is assumed that the short circuit power is calculated from the network admittance matrix then based on that the tolerance band of the shunt automatics is adjusted to avoid hunting. The EMS network model application performance is also investigated for a specified restoration strategy on NORDIC32 test system in PowerFactory. The simulation results both in ARISTO and PowerFactory show the capability of the adaptive tolerance band concept to avoid reactor hunting.

This thesis can be extended in some possible future research directions. From countermeasures perspective, the real time optimizer like Model Predictive Control (MPC) could be used to switch the shunt reactors and capacitors to improve the long-term voltage stability. From actuators point of view, the VSC-HVDC transmission lines capability could be used to control the active and reactive powers independently to improve the long-term voltage stability. Other actuators like synchronous generators and tap changers can also be considered.

For the second part of the thesis, it might be possible to use MPC to predict the shunt reactor bus voltage then take the proper action in advance for the shunt automatics to avoid reactor hunting.

Also what we proposed in the thesis are two main ideas including: neighboring scheme to improve the long-term voltage stability also adaptive tolerance band to eliminate reactor hunting. A scientific evaluation obviously remains to be carried out. Moreover to prove the obtained results, two test systems including NORDIC32 and N3area are utilized. Evaluating the proposed control schemes performances on other test systems, also for other operating conditions is another interesting point for further investigation.

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