The Restoration Process following a major Breakdown in a Power System

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by

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Abstract

This thesis deals with the restoration process of the Swedish bulk-power transmission system following a partial or a total blackout. The two main issues during a restoration are voltage control and frequency control. Special attention is therefore given to the behaviour of network components, their control equipment and their system automatics as they affect the voltage and frequency regulation during the restoration process.

The energizing of the long transmission lines connecting the north of Sweden with the south and central part of the country will initially result in a large production of reactive power and high voltage levels. In order to compensate for this reactive power production there are a number of shunt reactors installed. These reactors are equipped with relays for automatic connection and disconnection. It is shown that during restoration these automatics may initiate a hunting phenomenon which includes an increasing number of reactors and is leading to severe voltage fluctuations in the system.

The dynamic and stationary frequency deviations in the system have been analysed. The different hydro turbine governor modes are investigated and it is shown that some modes improve both the dynamic and stationary frequency stability of the system. These modes can therefore be used with advantage during a restoration phase when the frequency deviations are larger as compared to a normal situation.

During the restoration it is difficult to predict the load size for different types of reconnected loads. An investigation of the cold load pick-up for large industries shows that processing industries such as the pulp and paper industry, the iron and steel industry and the chemical industry will consume considerably less power during the hours after an interruption as compared to the pre-outage situation. This is due to the fact that these industries have sensitive processes which take a long time to restart. When studying the residential sector the impact from the thermostatically controlled loads such as electrical heating, freezer, refrigerator etc. will lead to a significant increase in power consumption following an interruption.

Running parts of the system in island operation may be of interest during certain network conditions. Field measurements show that there are no major technical difficulties to operate parts of the Swedish system in an island grid. However, island operation results in quite other demands for both the personnel and the regulation equipment as compared to the normal operation of the main grid.

Keywords

Cold load pick-up, island operation, power system blackout, restoration.

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List of abbreviations and symbols

BFK	load shedding (In Swedish BelastningsFrånKoppling)
BTK	load reconnection (In Swedish: BelastningsTillKoppling)
DUBA	automatic restoration equipment (In Swedish: DriftUppByggnad-sAutomatik)
EBK	power shedding (In Swedish: EffektBortKoppling)
EHV	Extra High Voltage
HV	High Voltage
HVDC	High Voltage Direct Current
hrs.	hours
PID	Proportional Integrating Derivative
PSS/E	Power System Simulator for Engineering
ROBO	rotating disconnection of load (In Swedish: ROterande BOrt-koppling)
SVC	Static Var Compensator
α	firing angle [degrees]
α_s	steady state active load voltage dependence
α_t	transient active load voltage dependence
γ	extinction angle [degrees]
Δf	stationary frequency fault [Hz]
ΔP	active power peak [pu]
ΔP	mismatch between mechanical and electrical power [MW]
ΔP_0	connected single load at nominal frequency [MW]
ΔP_G	increase of generator production [MW]
ΔP_L	load decrease due to frequency decrease [MW]
τ_1, τ_2	time constants for cooling down of a house [hours]
ω	angular velocity [rad/s]
ω_0	pre-disturbance angular velocity [rad/s]

A, B	constants associated with the cooling down of a house
a_0, a_1, a_2	parameters for the load frequency dependence
Ep0-Ep3'	operating modes of the hydro turbine governor
f	system frequency [Hz]
f_0	reference value of system frequency [Hz]
H_n	unit inertia [s]
I_d	dc current [kA]
J_n	moment of inertia [kgm^2]
k	load frequency dependence [pu/Hz]
k_1	load frequency dependency in the system [MW/Hz]
L_c	commutation inductance [H]
L_d	inductance at the dc side of a HVDC station [H]
L_s	short circuit inductance [H]
L_t	transformer inductance [H]
n_p	exponential load frequency dependency
P	proportional regulation [pu]
P	active power consumption [MW, pu]
P_{tot}	total system load [MW]
P_0	total load before load connection [MW]
P_0	active power consumption at pre-fault voltage [pu]
P_r	active power recovery [pu]
Q	reactive power production [MVAr]
R	permanent droop [pu]
S	total static gain [MW/Hz]
S_G	static gain from the generators [MW/Hz]
S_L	”static gain” from the load [MW/Hz]
S_n	rated generator power [MVA]
S_s	short circuit power [MVA]

T_G	servo time constant [s]
T_i	inside house temperature [°C]
T_{i0}	pre-outage inside house temperature [°C]
T_o	outside temperature [°C]
T_{pr}	active load recovery time constant [s]
T_r	integrating time constant [s]
U_1, U_2	line voltage at the feeding and the receiving end [pu]
U_{di}	dc voltage over the line [kV]
U	phase to phase voltage [kV]
u	commutation angle [degrees]
V	supplying voltage [pu]
V_0	pre-fault value of the supplying voltage [pu]
W_k	kinetic energy [MWs]
Y_{ekv}, Z_{ekv}	parameters for the line equivalent circuit [Ω/phase]
X_L, X_π	parameters for the simplified line equivalent circuit [Ω/phase]
X_s	series capacitor [Ω/phase]

Contents

Chapter 1 Introduction

A major breakdown of a power system is a contingency which is rare but may sometimes occur. Following an outage it is important to restore the power system as fast and secure as possible in order to limit the social and economical consequences for the population. In order to be able to do this it is necessary to have a sufficient knowledge of how a power system operates during a restoration phase. Here the behaviour of components and system automatics is of particular significance. A proper restoration policy with guidelines and instructions for the personnel involved is also of a vital importance.

This thesis focuses on the Swedish power system and the problems encountered in case of a restoration following a blackout. However, most of the power systems have a similar design and therefore the results of this work may also be valid for other power systems.

In Chapter 2 a survey of the Swedish power system is given. The voltage control and frequency control are described and a description of the different automatics used is found here.

Chapter 3 gives an introduction to power system restoration. Different restoration strategies and problems associated with the restoration process are presented. A description of the two Swedish blackouts (1979 and 1983) and the ensuing restoration processes is given.

For the analysis the power system simulator ARISTO has been used. Chapter 4 gives a short presentation of the simulator and a description of the power system networks which have been used.

The phenomenon of cold load pick-up following an interruption in the power supply has been analysed in Chapter 5. Special attention has been given to the cold load pick-up for energy consuming industries and residential load. Also the frequency dependency of loads and their voltage behaviour is treated.

Voltage control and frequency control during a restoration process are analysed in Chapter 6. Problems associated with energizing long transmission lines and especially the impact of shunt reactor automatics are examined in depth. The different modes of the hydro turbine governor, the number of generators connected to the system and the load frequency behaviour are all examples of factors affecting the frequency regulation in the system and have been investigated in detail.

The possibility to run a system in island operation and to blackstart certain hydro power stations has been investigated with field studies. The results from these field studies are presented in Chapter 7.

Chapter 8 gives an overview of recommendations for power system restoration. Finally Chapter 9 summarizes the results and gives proposals for future work.

Chapter 2 The Swedish electrical power system

The power system of Sweden, Norway, Finland and the island Zealand in Denmark are under normal conditions linked together and constitute the synchronized Nordel network. Except these AC connections Sweden also has HVDC links to Jylland in Denmark, Finland and Germany. The total power consumption in the Nordel network varies depending on the season and whether it is day or night. The maximum power is about 60 GW of which the Swedish part is about 27 GW.

The electric energy production in Sweden is almost entirely generated by hydro and nuclear power. Approximately one half of the production is based on hydro power and the other half comes from nuclear power. Most of the hydro power is located on the big rivers (Lule älv, Ångermanälven, Indalsälven) in the northern part of the country, whereas the nuclear power is located in the south along the coast. In the case of high loads, lack of water or low accessibility of the nuclear power stations it is possible to start up conventional thermal power or gas turbine stations, which are situated in the south.

From a geographical point of view the Swedish transmission system is extensive, having a length of 1500 km from the north to south. The hydro power production in the north is transferred to the centre and south of the country where most of the consumption is concentrated. For this purpose a number of 400 kV lines are used. The active power transfer capability in the Swedish network is limited in three different sections (In Swedish: snitt, see figure 2.1). Originally the sections were called 1, 2 and 3 but since new lines have been built section 3 has been replaced by section 4 as a new limited section. The transfer limitations on the sections are based on the Nordel dimensioning criteria [29] that the system shall withstand any loss of a power line or a production plant.

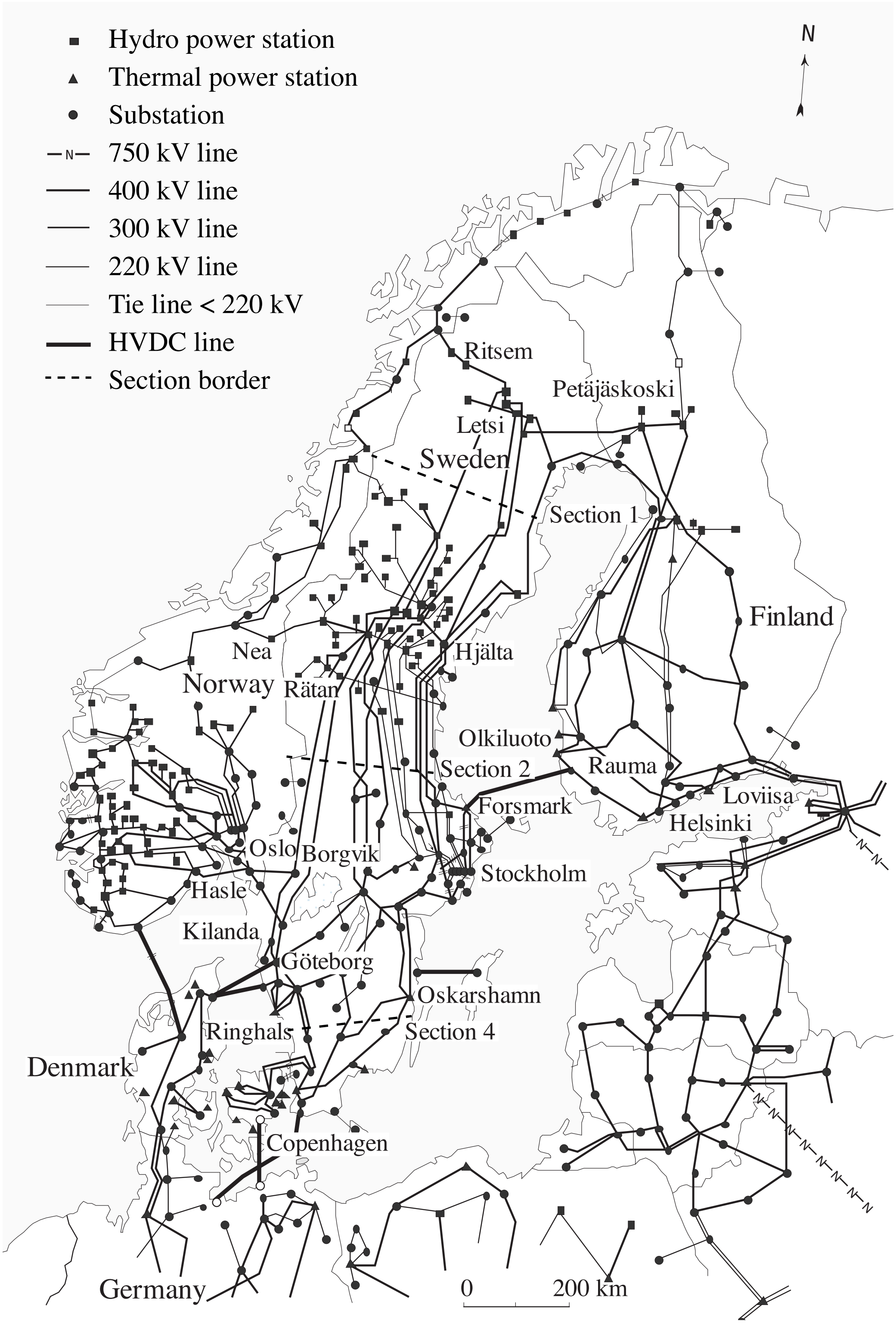

Figure 2.1 The power system in north-western Europe.

2.1 Voltage control - reactive resources

The long distances in the Swedish system and the large variation in active power consumption makes it necessary to have good reactive resources in the system. On the bulk-power transmission system the eight long 400 kV lines in section 2 (see figure 2.1) are equipped with series capacitors having a compensation degree of 35-85% of the line reactance. In a number of 400 kV stations there are reactors which are used during light load occasions in order to compensate for the large amount of reactive power produced. Three substations are equipped with static var compensators and some substations have access to synchronous compensators for a smooth regulation of the voltage. The substation voltage levels are normally in the range of 400-415 kV. The lowest acceptable voltage level is about 395 kV whereas the highest permissible value is approximately 420 kV. At the lower voltage levels (≤130 kV) the reactive compensation is mostly by shunt capacitors, but in a few long radially fed distribution lines there are series capacitors installed. Many industries have their own reactive power generation by using shunt capacitors; some even use static var compensators.

The large number of hydro units in the north makes it possible to have a well defined voltage regulation in most of the northern stations. A general requirement is that hydro power shall be able to produce reactive power equivalent to a third of the maximum active power production (seen from the 400 kV level). Reactive consumption should be up to a sixth of the maximum active power. As can be seen from figure 2.2 this is not the physical limit for a hydro generator and therefore it is possible to over/under excite the generators even more in case of an emergency.

The thermal plants do not have such strict regulations. Instead they should be able to produce reactive power corresponding to a third of the maximum active power production. During light load occasions the reactive power production should be limited to zero.

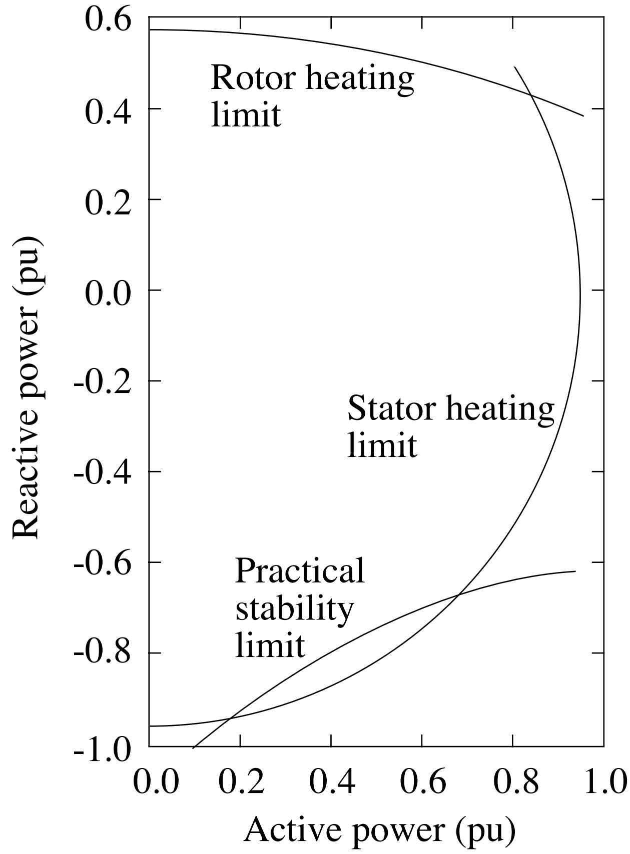

Figure 2.2 Capability diagram for a hydro generator.

2.2 Frequency control

In the Nordel system the frequency is allowed to fluctuate between 49.9 and 50.1 Hz. At the same time the integrated time fault should not exceed ±10 s. The disturbance power reserve in the system is about 1000 MW and the static gain is never less than 6000 MW/Hz. The disturbance power reserve is shared between the Nordel countries in proportion to the largest plant in each country. The national control centres in Sweden and Norway are responsible for the frequency regulation in the system. In Sweden the primary frequency regulation is taken care of by hydro units. The nuclear power plants do not take part in the frequency regulation and produce constant power. The conventional thermal units do have frequency regulating capacity but normally operate within a dead band.

The modern hydro turbine governors [7] in the system are usually equipped with five different working modes: Ep0, Ep1, Ep2, Ep3, Ep3'. These modes have different parameters for the static gain, the proportional regulation and the integrating time constant. Ep0-Ep2 are only manually connected, Ep3 may be both manually and automatically connected and Ep3' is only automatically connected. The governor will automatically change over to working mode Ep3 when the frequency deviates more than 0.15 Hz. Ep3, which has a high static gain, will then be disconnected 30 s after the frequency deviation is less than 0.15 Hz. Mode Ep3', which has a low integrating time constant (fast regulation), will be automatically used when both the frequency deviation is more than 0.15 Hz and the frequency derivative is higher than 0.07 Hz/s. This governor mode will be used during 30 s irrespectively of what happens with the frequency. During normal operation mode Ep0 is usually used.

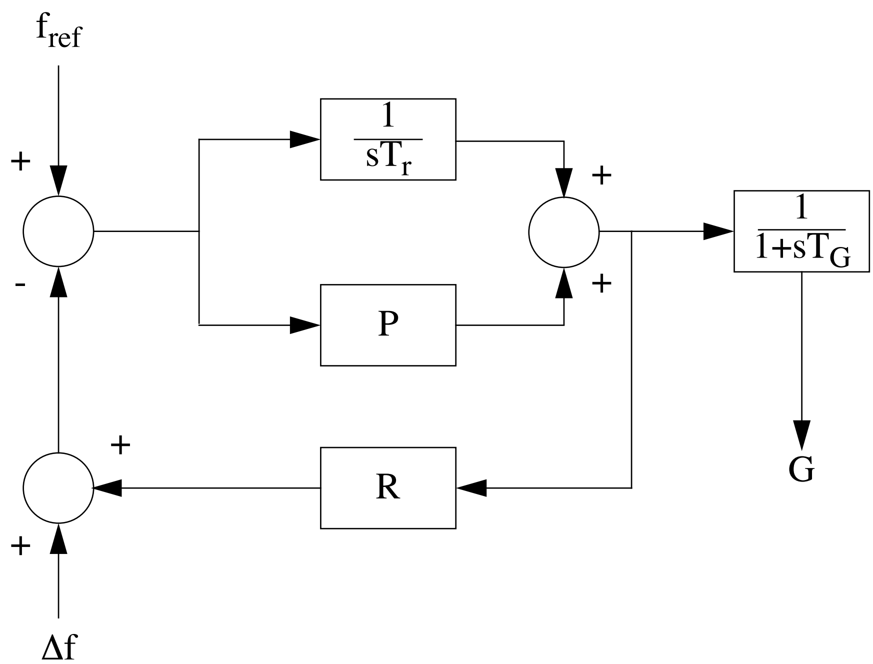

Figure 2.3 Hydro turbine governor model. R denotes permanent droop, P proportional regulation, T_r integrating time constant, T_G servo time constant, G gate opening and Δf frequency deviation.

2.3 Automatic equipment in the system

Overhead lines, transformers and generators are routinely equipped with relays in order to disconnect them in case of a fault. Apart from these conventional relays there are a number of automatics in the system which do not primarily protect a specific object. Instead they are used to save the system during severe situations. Criteria for these automatics may be frequency, voltage, current, active power etc.

As mentioned the frequency is allowed to vary between 49.9 and 50.1 Hz. If the frequency is less than 49.85 Hz, pumping in the pump storage power station Juktan is stopped [5, 12]. The emergency power from the HVDC lines is also activated at this frequency level. At 49.8 Hz electrical boilers are disconnected and at the same level the automatic restoration equipment is blocked. Hydro units which are run as synchronous compensators will change over to active power production and a number of gas turbines will start up when the frequency is below 49.7 Hz. Load shedding starts at 49.0 Hz and in total around 9000 MW load can be shed at five different frequency levels. If the frequency does not stop to decline the nuclear power stations will be disconnected from the grid at 47.5 Hz.

2.3.1 HVDC automatics

Sweden has HVDC links to Jylland in Denmark (Konti-Skan 1 and 2), Finland (Fenno-Skan) and Germany (Baltic Cable). In the case of over- or under-frequency the links may be used to increase or decrease the power export/import [12]. When the frequency declines below 49.85 Hz the first regulation step is made and when the frequency is less than 48.5 Hz all automatic regulation is activated. The power change may be as high as 100 MW/s for a link and each step is equipped with a time delay of some hundred ms. When the frequency exceeds 50.3 Hz the regulation starts in the other direction, which means that the import decreases or the export increases. There are a number of different regulation steps for over-frequency and the final step is activated when the frequency is higher than 51.3 Hz. Apart from the change of power due to over- or under-frequency the automatics may also change the power due to a low voltage level or when line circuit-breakers are disconnected.

The HVDC connections from Norway to Jylland and the back-to-back connection between Finland and Russia have similar possibilities as the Swedish links and therefore they are also a part of the disturbance power reserve in the Nordel system.

2.3.2 Load shedding

In extreme situations when the frequency has declined too much, load must be shed in order to save the system from a blackout [5, 12]. In Sweden 50% of the load south of section 2 (at 61° North) is equipped with load shedding (In Swedish: BelastningsFrånKoppling, BFK). The load shedding is performed in 5 consecutive steps where each step contains 10% of the total load. The load shedding area is divided in 10 different geographical blocks. In order to distribute the loads to be shed the automatics are situated on the lowest voltage level possible, which means 10, 20, 40, 70 kV and in some cases 130 kV. The load may be shed momentarily (0.15 s) or delayed (20 s), as can be seen in table 2.1.

Step	Momentary (0.15 s) Hz	Delayed (20 s) Hz
BFK 1	48.8	49.0
BFK 2	48.6	48.8
BFK 3	48.4	48.6
BFK 4	48.2	48.4
BFK 5	48.0	48.2

Table 2.1 The activation levels for the load shedding in Sweden.

On the Danish island Zealand 50% of the load is subjected to load shedding in 5 consecutive steps starting at 48.7 Hz and ending at 47.7 Hz. As in Sweden there is a momentary and a delayed step. Finland only has load shedding of about 20% of the total load. There are two steps which can be activated both momentary and delayed. The first delayed step starts at 48.7 Hz and the second momentary step starts at 48.3 Hz. In Norway about 30% of the load is subjected to load shedding. There are 9 different steps in the frequency range of 48.7-47.0 Hz.

Apart from load shedding due to under-frequency, under-voltage protection equipment has been installed in section 4. During a disturbance when all other actions have been performed to save the system the equipment will shed load by under-voltage protection in order to save the network from a voltage collapse.

2.3.3 Load reconnection

After load shedding the disconnected load may automatically be reconnected (In Swedish: BelastningsTillKoppling, BTK) when the system is stable and the frequency exceeds 49.8 Hz [5]. The reconnection procedure starts 3 minutes after these initial conditions are fulfilled. To avoid an initial heavy loading of the system the reconnections are made in small steps of approximately 50 MW. The reconnections are also geographically spread over the 10 different blocks. As long as the frequency exceeds 49.8 Hz a new load is reconnected every 12 seconds. If all load shedding steps have been activated it will take at least half an hour to reconnect the shedded load.

2.3.4 Power shedding

In order to allow higher transfer limits on some lines and sections, power shedding (In Swedish: EffektBortKoppling, EBK) is used [5, 28]. When the relays connected to these lines are activated they will not only send impulses to the line circuit-breakers but also to selected generator circuit-breakers. In the Swedish system this is used on the lines in section 1 combined with generators in the Lule river. During certain network conditions it may also be used on the lines around Forsmark north of Stockholm combined with the nuclear power stations in Forsmark. However, the generators in the nuclear power stations will not trip; instead the power production will decrease rapidly. In Sweden generators corresponding to a capacity of 4000 MW may be disconnected or regulated down due to this automatics. In Norway the power shedding is also widely used whereas it is never applied in Finland and only utilized to a limited degree in Zealand.

2.3.5 Reactor and shunt capacitor automatics

The shunt reactors which are used in order to regulate the voltage level on the bulk power system are equipped with automatics which connect and disconnect the reactors when the voltage exceeds certain limits [12].

Usually the reactors and their automatics are situated at the 400 and 220 kV level. On the 400 kV system the reactors are connected when the voltage exceeds 420-425 kV and disconnected when the voltage is lower than 390-395 kV. For the 220 kV system the connection is made at about 230 kV and the disconnection at 210 kV. The connection of a reactor is delayed by 0.4 s whereas disconnection is postponed by 2 s.

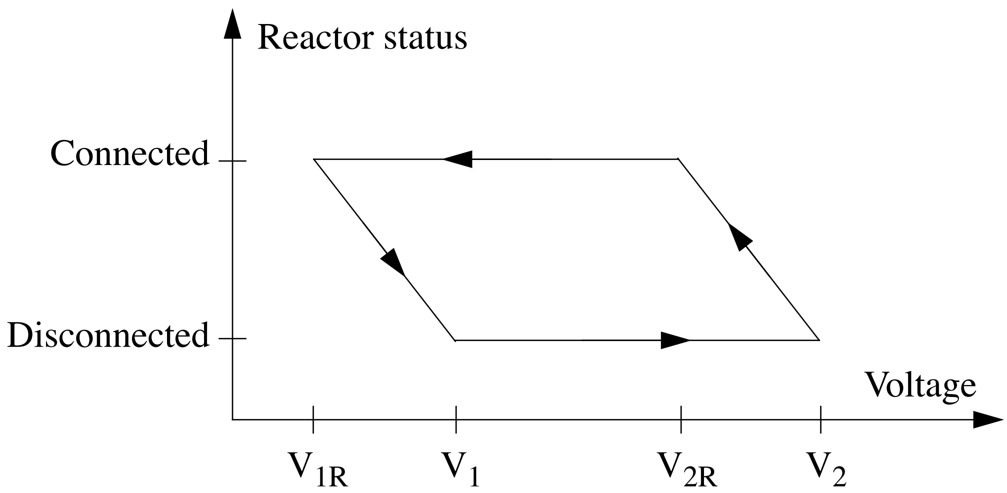

Figure 2.4 Hysteresis curve for the reactor automatics.

Some of the shunt capacitors which are installed in the regional and distribution networks have automatics which function like the reactor automatics except that they connect capacitors when the voltage is below a certain limit and disconnect them when it is above a certain limit. The time delay for connection is 2.5 s and for disconnection 0.5 s. After the capacitor has been disconnected the automatics are blocked for 4 minutes since the capacitor must be discharged.

To a varying degree the other Nordel countries also have automatics controlling the shunt reactors and shunt capacitors. However, this does not affect the Swedish system much since voltage problems are more related to local conditions and do not, as frequency variations, affect the entire system.

2.3.6 Reverse reactive power flow protection

If there are not sufficient reactive resources available around the northern end of the section 2 lines the voltage will increase much when a line is energized. In case of a high voltage the line will be tripped by a reverse reactive power flow protection if both the reactive power production from the line exceeds a certain value and the voltage in the northern end of the line is above a certain limit. The voltage level is about 440 kV for all line relays whereas the limit for the reactive power varies depending on the line length. A rule of thumbs is that the reactive power limit is equivalent to the reactive power production of the unloaded line fed with a voltage of 440 kV. The tripping of the relay is delayed by 3.2 s.

2.3.7 Automatics for network splitting

In the case of too large frequency variations or too high voltages the Nordel system will fall apart into subsystems [12]. The tie lines from Sweden to Zealand will be disconnected when the frequency is below 47.0 Hz for 0.5 s or below 47.5 Hz for 9 s. If the voltages around the tie lines exceed 470 kV for more than 1.0 s a disconnection will also be made. The tie lines in the north between Sweden and Finland will automatically trip if the frequency exceeds 51.5 Hz and the export from Sweden is higher than 900 MW. When there is only one 400 kV line in direction west or one 400 kV line in direction east from Hasle in the south-east of Norway in operation (see figure 2.1), a loss of another line will initiate a separation of the south Norwegian system from the rest of the Nordel system. Within the Swedish system no split up of the network is made due to automatics.

2.3.8 Automatic restoration equipment

Most of the faults that result in a disconnection of a system component are of a temporary nature. In order to restore the system back to a normal condition following such a disturbance it is important to have a adequate restoration policy for the objects in the station. Naturally it would be possible to restore all stations manually but since most of the stations are unmanned this would result in much work for the control centre personnel in case of disturbances in a number of stations. The use of automatics will therefore speed up the restoration process and eliminate the ”human factor”. In the Swedish system [5, 9] many unmanned power stations and substations are provided with automatic restoration equipment (In Swedish: DriftUppByggnadsAutomatik, DUBA). The main functions and logics are:

- The reconnection of circuit-breakers which have been tripped by certain relays.
- The reconnection of a circuit-breaker is not performed for those faults which do not allow a reconnection.
- The closure of a circuit-breaker is executed only once.

- No objects are connected which were disconnected prior to the disturbance.
- The start of generators which have been disconnected by certain relays. The generators are synchronized to the network but do not pick up load.

The restoration equipment is started either from a relay previously triggered or the zero voltage protection. When all conditions such as voltage levels, energizing direction, frequency etc. are fulfilled, synchronizing equipment is used to initiate the closing of the circuit-breaker. Reconnection of objects will be blocked if the circuit-breaker failure protection has been activated. However, the blocking is only valid for the triggered circuit-breaker and the other objects connected to the busbar may be reconnected. To avoid a hunting phenomenon due to a fault on the busbar, the busbar is energized only once following a disconnection caused by a busbar fault.

In the substation it is possible to ”re-program” the automatic restoration equipment. Objects can be switched off or on, the energizing direction may be changed and unblocking of signals may be performed. Signals indicating start, blocking and faults etc. are also available in the station.

In the control centre the chance to affect the restoration equipment is limited. The automatic restoration equipment may be switched between a working mode and a stand-by mode. In the stand-by mode no circuit-breaker will be operated but all the other functions such as receiving signals from relays and collecting voltage levels are in operation. Since the equipment has access to all the present values it is possible to change over from stand-by mode to working mode at any time.

2.3.9 Zero voltage protection scheme

The zero voltage protection (In Swedish: Nollspänningsautomatik) has been installed in the system in order to prepare it for restoration in case of a disturbance [9]. This is very important especially in those stations equipped with automatic restoration equipment. All objects in the station have their own zero voltage protection. On the bulk power system a voltage level less than 30% of the nominal voltage will initiate opening of the circuit-breakers. The operating time for the automatics is 7 s.

On the lower voltage levels the zero voltage protection disconnects objects that do not allow energizing. Examples of such objects are lines connected with generators or synchronous motors. The zero voltage protection will also split up the meshed networks in case of a blackout. The restoration may then proceed from the bulk power station and the risk for overloading of the lines is limited.

Chapter 3 The restoration process

The Swedish system is seldom exposed to major disturbances. In case of a blackout in the system it is essential to restore the power system as fast, smoothly and securely as possible in order to limit the social and economical consequences for the population. A suitable restoration philosophy is therefore recommended for this purpose. In order to avoid the restoration problems experienced during earlier disturbances, it is important to adapt the experience gained from those outages when formulating restoration instructions.

3.1 Philosophies in power system restoration

Two major strategies for restoring a power system following a blackout are known: the build-up strategy and the build-down strategy [1, 4, 13, 14, 15, 17]. Different approaches are used depending on the size of the interrupted area, the possibility to receive assistance from interconnecting systems, the amount of blackstart capability in the system and the type of production in the system.

3.1.1 The build-up strategy

The build-up strategy, which internationally is the most commonly used strategy, is often practised when the system has suffered a total blackout and when it is impossible to receive assistance from the neighbouring systems. After the disturbance the first step is to make an assessment of the power system status; which means circuit-breaker status, power plant conditions etc. The system is then divided into subsystems where each subsystem at a minimum must have one station with blackstart capability. The subsystems mostly will have rather good balance between production and consumption. They also must have the possibility to regulate both frequency and voltage in the subsystem. After blackstarting the station, emergency power is supplied to the stations without blackstart equipment in order to make it possible for the units in these stations to start (if possible a ”hot restart” of the thermal units) and to be synchronized to the system. Loads are connected and more units are taken into operation. The connections with the other subsystems are then synchronized. When there is enough reactive absorbing capacity in the systems the ties to the neighbouring systems are closed.

3.1.2 The build-down strategy

The build-down strategy is mostly used in small systems without long high voltage lines or hydro power based systems with good reactive absorbing capacity, and for systems with a certain load concentration in an area. The strategy may also be used when it is possible to receive assistance from interconnecting areas or when the system has received a partial blackout. Initially following an outage an assessment of the system has to be made in order to determine the status of the circuit-breakers and the power plant conditions. The interrupted system has to include at least one station with blackstart capability. When this station has become operative, the lines are connected to other stations in order to supply them with emergency power which is necessary for their start. The generators are synchronized to the system and more HV and EHV lines are connected. During these initiating steps some load is connected but most of the load is connected when large parts of the bulk-power network are restored.

3.1.3 The Swedish strategy

As described in Chapter 2 the Swedish system contains a large portion of hydro generation which is mostly located in the north of the country. Most of the load is concentrated in the south and the middle parts of Sweden and therefore the power is transferred from the north to the south through long transmission lines. These facts make it natural that the Swedish restoration strategy is based on a build-down strategy. On the other hand Sweden is a part of the synchronized Nordel system and in case of a blackout in the entire Nordel system each country restores most of their own system before closing the ties to the interconnecting countries. In this perspective one can say that the Nordel system uses the build-up strategy.

The Swedish restoration strategy is designed to take care of a total blackout in the country [2]. There are local instructions for each control centre and they are formulated in such a way that if some parts of the system have succeeded in staying in operation the instructions start from that point. Initially when the hydro stations in the north, which are equipped with blackstart capability, receive an interruption the blackstart automatics start up the stations (more about blackstart and field tests is described in 7.1). Since the stations are mostly unmanned this is automatically done. When the station emergency duty personnel arrive at the stations the restoration process may continue. The black-started stations are then synchronized and other stations are energized in order to be able to start up. As more and more generation is taken into operation, overhead lines to the power stations along the other rivers are energized and more generation is started. When there is enough connected capacity in the north of the system it is possible to energize the long transmission lines to the south. The main strategy is to energize the lines to the nuclear power stations first and reconnect them to the system. If the stations have been successful in establishing household operation (the possibility is approximately 50%) they can start to produce power in a short time. On the other hand if the stations fail to reach household operation the stations must be cold started which may take more than one day. The other thermal plants (oil and coal fueled power stations) do not have as long starting times especially if they were in operation before the interruption and may be hot started. The thermal plants are therefore important since they limit the lack of power in the system until the nuclear power plants are in operation again. The interconnecting HVDC lines from Germany, Denmark and Finland may also give valuable power support during the restoration. In order to avoid overload, the regional control centres are not allowed to connect more than 50% of the pre-outage load levels unless the national control centre gives them permission.

As previously mentioned, the restoration process is carried out by the regional control centres and is based on written instructions. However, the instructions can also be executed by automatics (see 2.3.8) and this is the normal procedure for unmanned stations. The national control centre does not act during the initial phase of the restoration unless complications arise or the regional control centres ask for assistance. The frequency regulation is therefore accomplished by one of the regional control centres, preferably one of those containing a black-started station.

3.2 Blackouts in Sweden

The Swedish bulk-power transmission system is well designed and has a high technical standard. The system is therefore seldom exposed to major disturbances. In Sweden Svenska Kraftnät is responsible for the operation of the bulk-power transmission system and they estimate the risk for a partial or total blackout to be once per 20 years [28]. Sweden has experienced two major blackouts the last decades, one in 1979 and one in 1983.

3.2.1 The blackout in 1979

On Saturday January 13th 1979, the very northern part of the Swedish system collapsed, resulting in a loss of load corresponding to 23% of the Swedish consumption [21]. Before the interruption in the system the load was approximately 12000 MW. The production consisted of 63% hydro power, 19% nuclear power, 14% in back-pressure and condensing units and the resulting 4% was imported. The power transfer in section 1 (see figure 3.2) was fluctuating around the transfer limit some hours prior to the outage and the voltages at some stations around section 1 were as low as 380 kV. In the other Nordic countries synchronized with the Swedish system the situation was normal.

At 20.42 hrs. one of the overhead lines in section 1 was disconnected due to a fault in the voltage supply of the distance protection. As section 1 was above stability limit the disconnection of the line resulted in an immediate transient splitting and the two remaining lines in the section were disconnected. The Nordel system was thereby divided into two subsystems: a northern one including the Swedish system north of section 1, Finland and the northern parts of Norway, and a southern one including the Swedish system south of section 1, the main part of the Norwegian system, Zealand and the HVDC connections to Jylland.

In the southern system a production deficiency of 2500 MW arose, which prior to the outage was transferred on the lines in section 1. The frequency therefore decreased rapidly below 49 Hz and emergency power was transferred to the system through the HVDC links. Heavy oscillations occurred on a tie line to Norway (Borgvik-Hasle) which led to a disconnection of all the southern Norwegian ties due to oscillation and overcurrent. Load shedding started when the frequency declined to 48.3 Hz and two steps were activated before the frequency stabilized at 47.96 Hz. The frequency started to increase and the frequency was back to a stable level at 49.8 Hz after 1.5 minutes. After another three minutes the restoration process started and the shedded load was reconnected automatically (BTK, see 2.3.3). The power increase due to the reconnection of load was covered by thermal power and gas turbines. In 30 minutes all the load in the southern system was reconnected. During the load reconnection the frequency fluctuation was rather high. The tie lines to Norway were connected two hours after the disturbance when large parts of the northern system was energized. This long time was a result caused by overloading of the communication lines to the national control centre in Sweden.

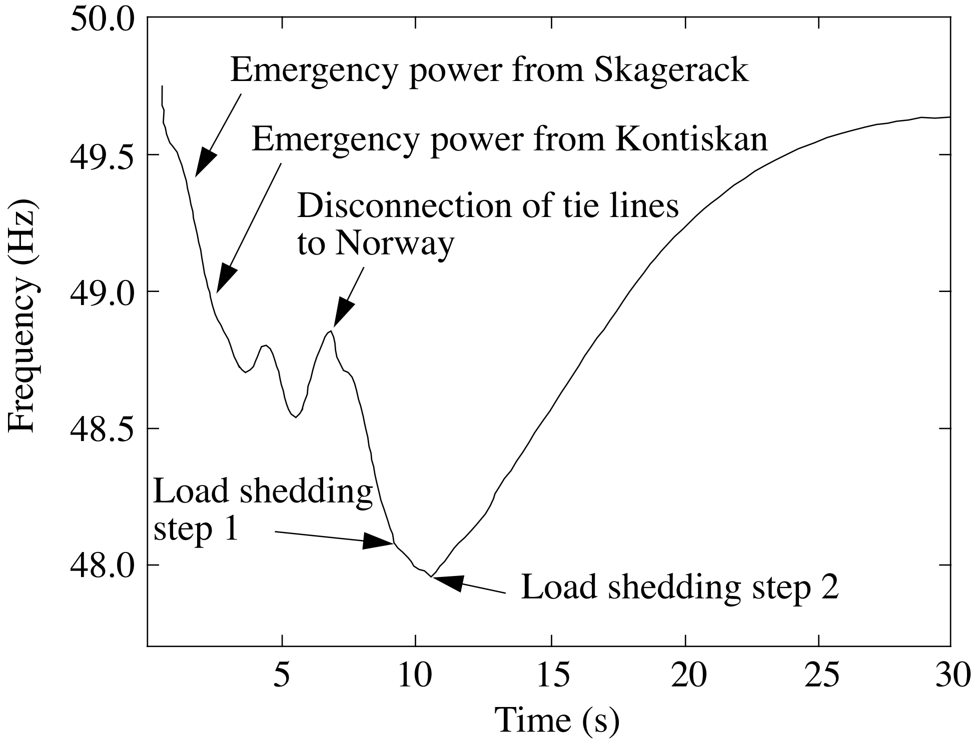

Figure 3.1 The frequency in the south of the Swedish system during the disturbance in January 1979.

In the northern system the production surplus resulted in an increased frequency. Due to automatics (EBK, see 2.3.4) 400 MW hydro power was disconnected immediately when the system disintegrated. When the frequency reached 51.5 Hz another 400 MW in hydro power was disconnected due to over-frequency and overcurrent. When the system stabilized at 51 Hz the export to Norway and Finland had increased significantly. Some power stations were shut down and some were regulated down in order to decrease the frequency. However, this process took too long time and 12 minutes after the initial disturbance Finland manually disconnected the tie lines. The northern part of the Swedish system therefore consisted of low loaded generators and little load. When the section 1 lines were now energized the voltage increased too much and the remaining generators tripped due to overcurrent and the northern part of the system received a total blackout 15 minutes after the initial disturbance. Again 10 minutes after the blackout the northern system was energized from the south and the restoration process started. Generators were started and lines to more stations were energized. Three hours after the initial disturbance almost the entire bulk-power system was restored and the tie lines to Finland were reconnected.

The analysis of the disturbance showed that section 1 was overloaded by 20% and therefore the system could not cope with a disconnection of one of the section lines. Since the communication lines from the national control centres in Sweden were overloaded there was a problem in contacting the national control centre in Finland and Norway and this strongly affected the blackout in the north but also delayed the resynchronization with Norway. In the south the emergency power supplied by the HVDC lines, the load shedding, the automatic start of gas turbines and the automatic reconnection of load worked well. In the north the EBK worked well and disconnected production immediately when the section 1 lines were tripped.

3.2.2 The blackout of 1983

At about 13.00 hrs. on Tuesday December 27th 1983, the southern part of Sweden was exposed to a major disturbance which resulted in a loss of load amounting to 67% of the national load [19, 24, 31]. The disturbance affected more people than ever in Sweden and nothing similar had happened since 1955.

Before the interruption the consumption was about 18000 MW which was generated by 60% hydro power, 32% nuclear power, 2% other thermal production and the remaining 6% was imported. Maintenance work was only performed in a few places and the network was almost fully in operation. The power transfer on the limiting sections in the system were below their margins.

The initial cause of the disturbance occurred in Enköping substation. Enköping substation contains three 400/220 kV transformers totalling 1300 MVA. From the station a 220 kV network supports Stockholm. There are two 400 kV lines from the north and two to the south connected to the station. The switchyard is of the ABC type (see figure 3.3) which means two main busbars and one auxiliary busbar. In Enköping substation the replacement breaker and sectionalizing breaker is combined into one circuit-breaker.

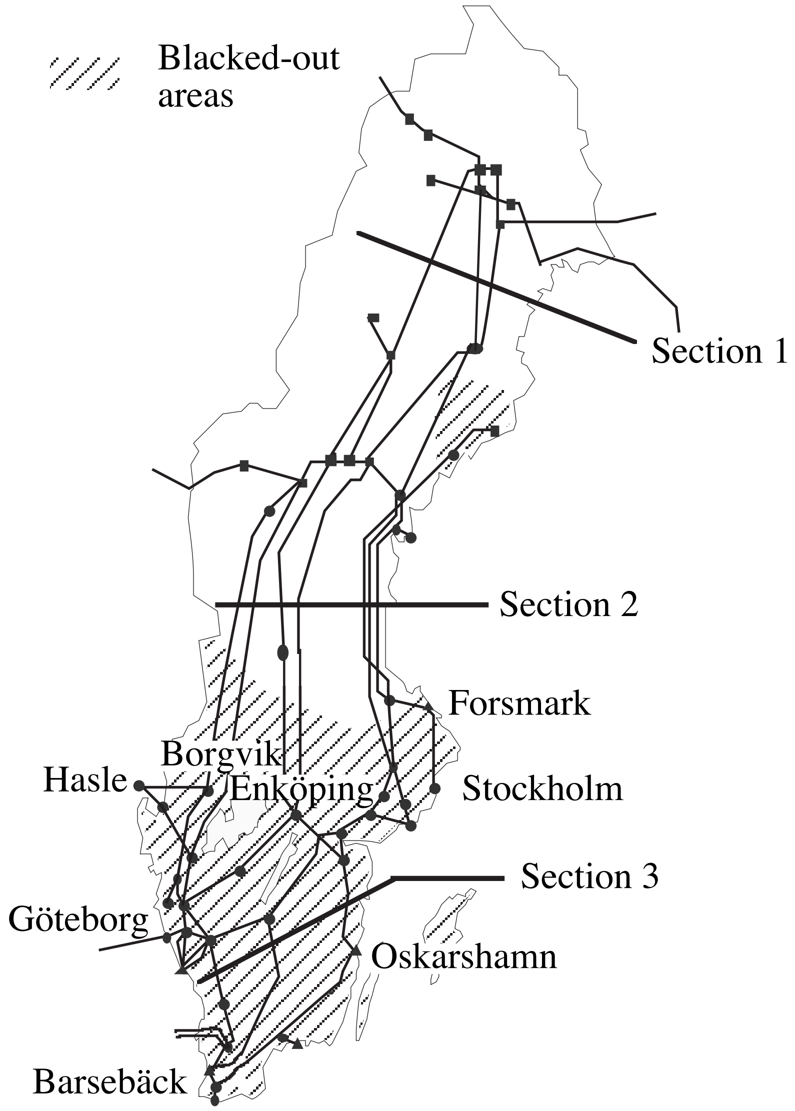

Figure 3.2 The Swedish 400 kV network 1983.

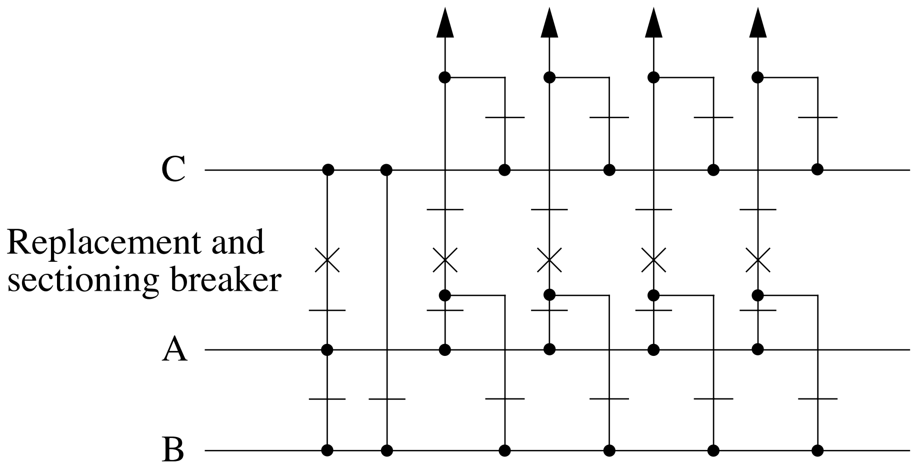

Figure 3.3 Example of an ABC switchyard with a combined replacement and sectioning breaker.

During an inspection of the switchyard, burn marks and an intermittent flame was observed on the line side of a disconnector. After permission from the national control centre work started in order to switch-over the line to the replacement circuit-breaker. The last step during the switch-over was to open the disconnector. When this was performed the contact arm on the line side came loose and fell down and caused a flash over to the earth. Since the sectioning between the two busbars was lost, the busbar protection tripped the entire station due to the earth fault. The system became highly stressed and the lines in section 2 became overloaded. The voltage decreased much in the central and western part of Sweden (down to 350-360 kV in some stations). This increased the stress on the 400 kV lines in section 2 even more. A 220 kV line which supplied Stockholm from the north was disconnected due to overcurrent 8 s after the primary fault. The tap-changers restored the voltage on the distribution level and the thermostatically controlled load started to recover. This led to a further decrease of the voltage and an increase of the current and 53 s after the initial fault a line was disconnected due to the distance protection. After one second the remaining lines between north and south were disconnected and the system was divided into two subsystems. After another second the tie lines to Zealand and the south of Norway were tripped due to heavy oscillations. As the southern system lost 7000 MW the frequency fell rapidly by 2-4 Hz/s (see figure 3.4).

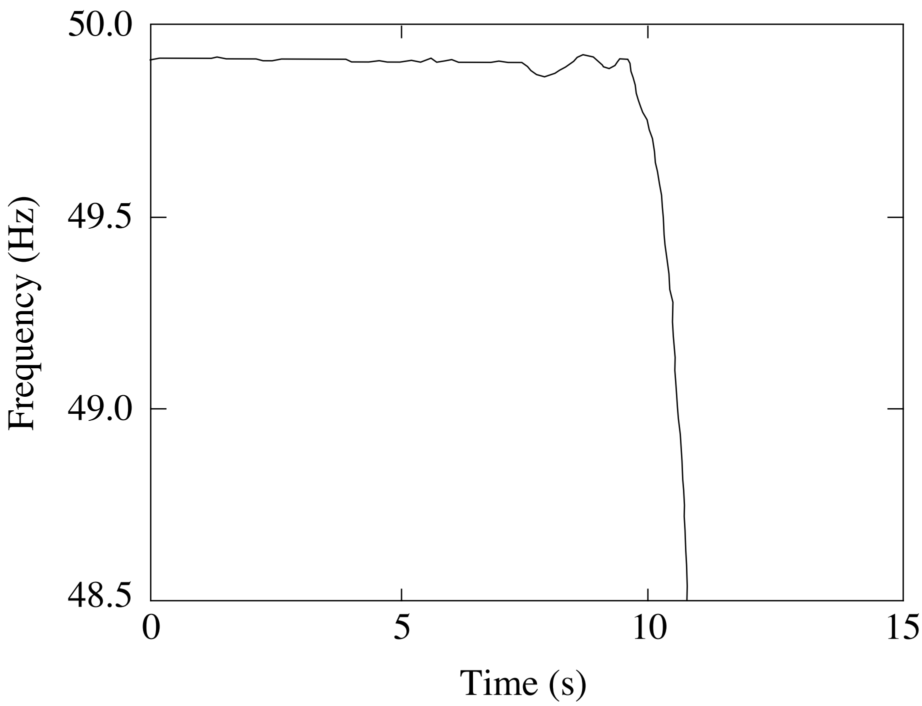

Figure 3.4 The frequency at Barsebäck nuclear power station during the breakdown.

Due to the high frequency derivative the system frequency decreased so fast that the load shedding was unable to save the system (only about 50% of the load shedding was activated). The nuclear power stations in the southern system: Oskarshamn, Ringhals and Barsebäck, were tripped both by overcurrent and underimpedance protection. None of them succeeded in staying in household operation. The remaining load which was not shed was disconnected by the undervoltage protection.

In the northern system the separation caused a production surplus of about 6000 MW. This surplus increased the frequency to 54.0 Hz after 5 s (see figure 3.5). The over-frequency protection tripped a number of hydro units and the production from the remaining stations were regulated down by the turbine governors. After 12 s the frequency was back to a normal level. In Forsmark nuclear power station one of the units succeeded in staying in operation whereas the other tripped. In Finland the import from Sweden increased and since only one line between the north and south of the country was in operation it tripped due to overload. The tie lines to Norway were also tripped and the northern part of the Swedish system became isolated.

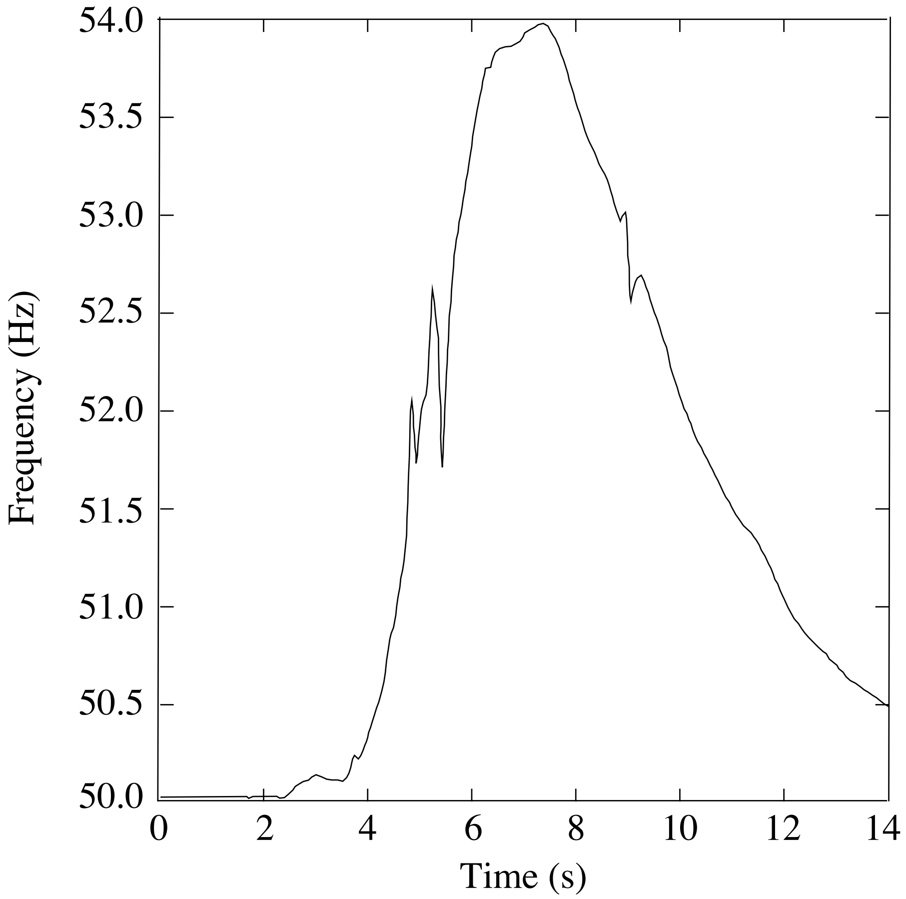

Figure 3.5 The frequency in the north system during the split up of the system.

In the national control centre in Stockholm the large amount of data which fed the computers blocked the normal system and instead an older system which fed the mimic board was used. Since it was impossible to study the frequency at the national control centre the responsibility for the frequency regulation was taken over by a regional control centre in the north. The first action was to regulate the frequency down to 50.0 Hz and after that the restoration process was started with help of written instructions. In the unmanned stations the DUBA (see 2.3.8) worked after the same principles. At 13.15 hrs. the network around Göteborg was energized and two minutes later Ringhals nuclear power station received voltage. Barsebäck nuclear power station was energized at 13.29 hrs. and some minutes later the station that supplied Malmö. The energizing of the lines to Oskarshamn nuclear power station was delayed due to problems with the DUBA and the power station was not energized before 13.41 hrs. Within one hour the entire 400 kV network was restored. The restoration of the 220 kV system around Stockholm was not completed until about 15.20 hrs., this was due to problems with the DUBA in some stations. The middle part of the Norwegian system stayed connected with the north of Sweden and at 13.35 hrs. when the western part of Sweden was energized it was possible to synchronize the southern part of the Norwegian system. The synchronization made it possible to import power from Norway to the western part of Sweden. When the system in the south was energized the lines to Zealand and Jylland were connected and power import was ordered. The tie lines to Finland and the north of Norway were reconnected only half an hour after the disturbance.

All nuclear power stations were subjected to quick shutdowns except Forsmark 1 which remained connected to the northern system. After the disturbance the stations were started as fast as possible and the first nuclear power station was synchronized to the system at 22.35 hrs.

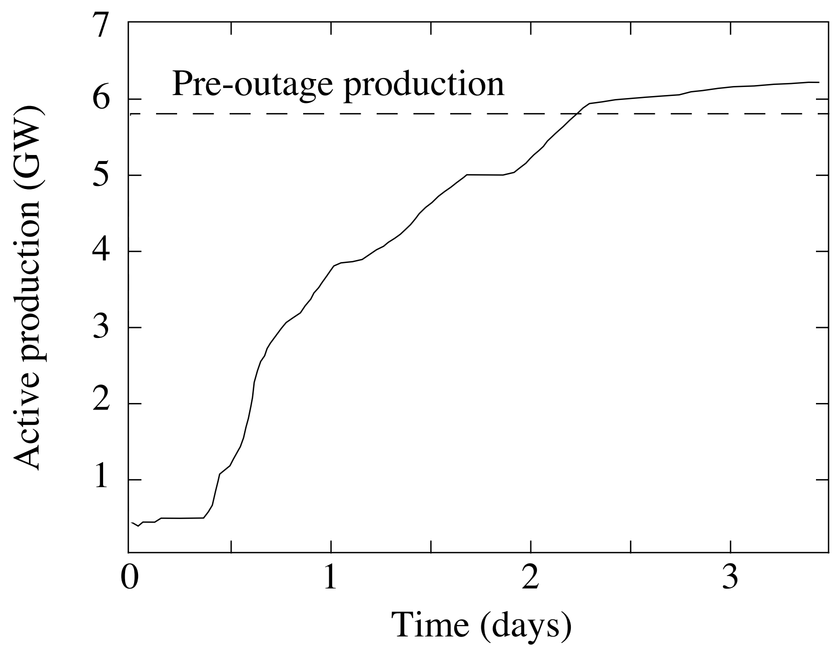

Figure 3.6 Power production from the nuclear power stations following the disturbance.

The oil and coal fired stations, of which only a few were in operation before the outage, were started and the first delivered power at 16.30. During the hours following the disturbance most of the gas turbines in the south were in operation and the hydro power in the north produced as much power as was possible given the section limits. The load reconnection in the south was made both manually and automatically with the BTK (more about BTK in 2.3.3). Since there was a lack of power the reconnection of load was limited until 18.20 hrs. when the national control centre gave permission for unrestricted reconnection.

The analysis following the blackout showed that the disturbance was caused by a voltage collapse. Initially when the two lines in section 2 were tripped the voltage in the south was reduced and therefore the power consumption momentarily decreased. When the thermostatically controlled loads recovered and the tap-changers increased the voltages at distribution level, the network was stressed even more which resulted in the collapse. The restoration process following the disturbance worked well despite problems with the monitoring system at the national control centre in Stockholm. At the control centres the work was much disturbed by phone calls from media and the public. In the system there were problems with the DUBA functions at some places. Due to the fact that the nuclear power stations failed to reach household operation there was a lack of power which delayed the reconnection of load.

3.3 Consequences following a blackout

The Swedish blackouts described in 3.2.1 and 3.2.2 have demonstrated how vulnerable modern society is in the case of a collapsing energy system [34]. They have also shown the importance of having sufficient backup power and the benefits of a fast restoration.

In case of a disturbance the consequences will be both socially and economically. The industries suffer from loss of production; especially the processing industry is vulnerable since even a short break in the power supply may lead to loss of production for days since the entire process has to be restarted.

Nowadays most of the work in the offices is carried out by help of computers. In case of an outage there will be loss of production but there is also a risk of loss of data. After the disturbance there will be extra work in order to start up the computer systems and other electrical equipment.

Shops and stores have to close down in the case of a disturbance, resulting in a loss of sales. The customers in the shops and stores have to be evacuated and since escalators, elevators and light do not function this may be rather complicated. The refrigerating plants will be warmed up and there is a risk that food is spoiled if the duration of the outage is too long.

In farms, animal breeding and milk production will be affected since the air conditioning will stop and the cows have to be milked by hand. However, most of the big farms have access to backup power and therefore the consequences may be limited.

The population will be affected in general since the communication systems breakdown. Trains can be halted anywhere along the railway and in the subway it may be difficult to evacuate people. If the disturbance lasts for a long time there might be a risk of breakdown of the telecommunication system since the battery backup resources in the stations are limited. When the pressure in the water pipes decreases there will be no water and there is a risk of penetration from slops into the water pipes which may endanger the water supply for many days. In the refrigerators and freezers the groceries will warm up especially since people may act irrationally and check whether the groceries are cold or not many times. During the winter the consequences for the heating supply may be substantial, especially if the outage lasts for a long time.

3.4 Problems during the restoration process

During the restoration process there are a number of abnormal situations which may cause problems. The blackstarting of the hydro stations may fail for a number of reasons: the diesel generator may fail to start due to discharged start batteries or lack of fuel, different kinds of control automatics may cause problems if they are improperly adjusted or improperly designed, etc. The station emergency personnel may not be sufficiently trained and are suffering from stress and therefore their work can be delayed or in extreme cases they may act wrongly. Communication problems between the regional control centres and the hydro stations can also delay the restoration. The public and the media will try to get information from the control centres almost directly after the disturbance and therefore there is a risk that the telephone lines will be overloaded. In the control centres the large amount of data which comes into the computer systems may make them unusable.

When energizing the long transmission lines from the north to the south the large amount of reactive power produced by these unloaded lines will increase the voltages in the system and therefore it is important to have sufficient reactive resources in the form of generators, SVCs or shunt reactors before these lines are energized.

The reconnection of load, which is made both manually and automatically, is accompanied by an increased power production. To avoid large frequency deviations the size of reconnected load must be limited. It is also essential to adjust the power production set-points on the generators as there otherwise will be a stationary frequency deviation in the system. During reconnection it is difficult to predict the expected amount of each load. Some loads will be substantially larger, particularly residential load, due to cold load pick-up, and some will be very small, especially industrial load, as compared to the pre-outage load level. Due to these circumstances the frequency regulation will be considerably more complicated since the operator also must regard the usual restrictions such as regulation of the water levels in the rivers and start up times of power plants.

In the system there are a lot of automatics in operation and especially in the case of a blackout and the following restoration these automatics will affect network objects. During the blackouts mentioned there have been problems with the DUBA automatics which in some cases have operated too fast. There is also a risk for reactor hunting (see 6.1.1 and 6.1.2) due to improperly adjusted dead bands and time delays of the automatics. If it takes too long time to energize stations there might be problem with the backup power from the batteries supplying the station equipment.

Chapter 4 The ARISTO power system simulator

In order to simulate phenomena associated with collapse and restoration of power systems it is important to have a suitable software. The software shall be able to handle both long and short term dynamics and the user interface shall be interactive making it possible to use it as a training simulator for operators. On the market a number of analysis tools are available and they are useful for studying certain phenomena in depth. There is also a variety of dispatch training simulators available with different levels of advanced operator interfaces. The training simulators are mostly used to educate in normal network operation and handling small disturbances. In cases of severe problems such as major breakdowns and restoration the scenarios are often based on off-line calculations. The power system dynamics are not as well modelled and the study of transient stability and relay operation is often limited to off-line calculations or done in a special calculation mode.

The real time power simulator ARISTO[1] [10], which has been used in this study, combines the advantages of an analysis tool and a dispatch training simulator. The simulator is therefore a suitable tool for advanced operator training and may also be used for analysis in depth.

Figure 4.1 ARISTO power system simulator

1. Developed by Svenska Kraftnät

4.1 Structure

ARISTO is based on a standard workstation combined with three 19” colour screens for presentation. The system uses UNIX and X-windows technology. Available software tools such as DataViews, Ingres relational database and Avanti real time database are applied.

The simulator may be divided into the three subsystems: the simulator kernel, a man-machine interface and the data preparation. The simulator kernel subsystem consists of the power system model and the real time database and it is in this part of the system that the simulation is carried out. The man-machine interface contains applications which are used to control the simulation. There is also a variety of possibilities to display the simulated data in different kinds of diagrams. In the data preparation part of the simulator the network data are stored. The work in this mode is made off-line and when all necessary data are available a load flow is carried out. All the data may then be loaded from the relational database to the real time database in the kernel. In order to extend the use of the simulator it is possible to import existing network data from the PSS/E[1] software.

4.2 Modelling

For a proper simulator it is essential to have sufficient modelling capability. The ARISTO models may be divided into the following main groups: network components, loads, production units and protection units.

4.2.1 Network component models

A detailed modelling of the substations can be carried out. The switchyards may be defined by several busbars, circuit-breakers and disconnectors in a variety of configurations. The transmission lines are modelled as conventional π-links and series capacitors can be installed in order to compensate for the line reactance. The transformers are equipped with tap-changers which can be operated both in the constant time and the invert time control mode. The substations may be equipped with shunt capacitors and shunt reactors combined with automatics which connect/disconnect them when voltage is below/above certain voltage levels.

1. PSS/E: Power System Simulator for Engineering, developed by Power Technologies Inc.

4.2.2 Load models

The loads are modelled as constant admittances which eliminates the use of iterative solution methods. To obtain a realistic modelling of the loads the admittances are recalculated in time. For this procedure a number of models are available (some models are not implemented yet) as shown in figure 4.2

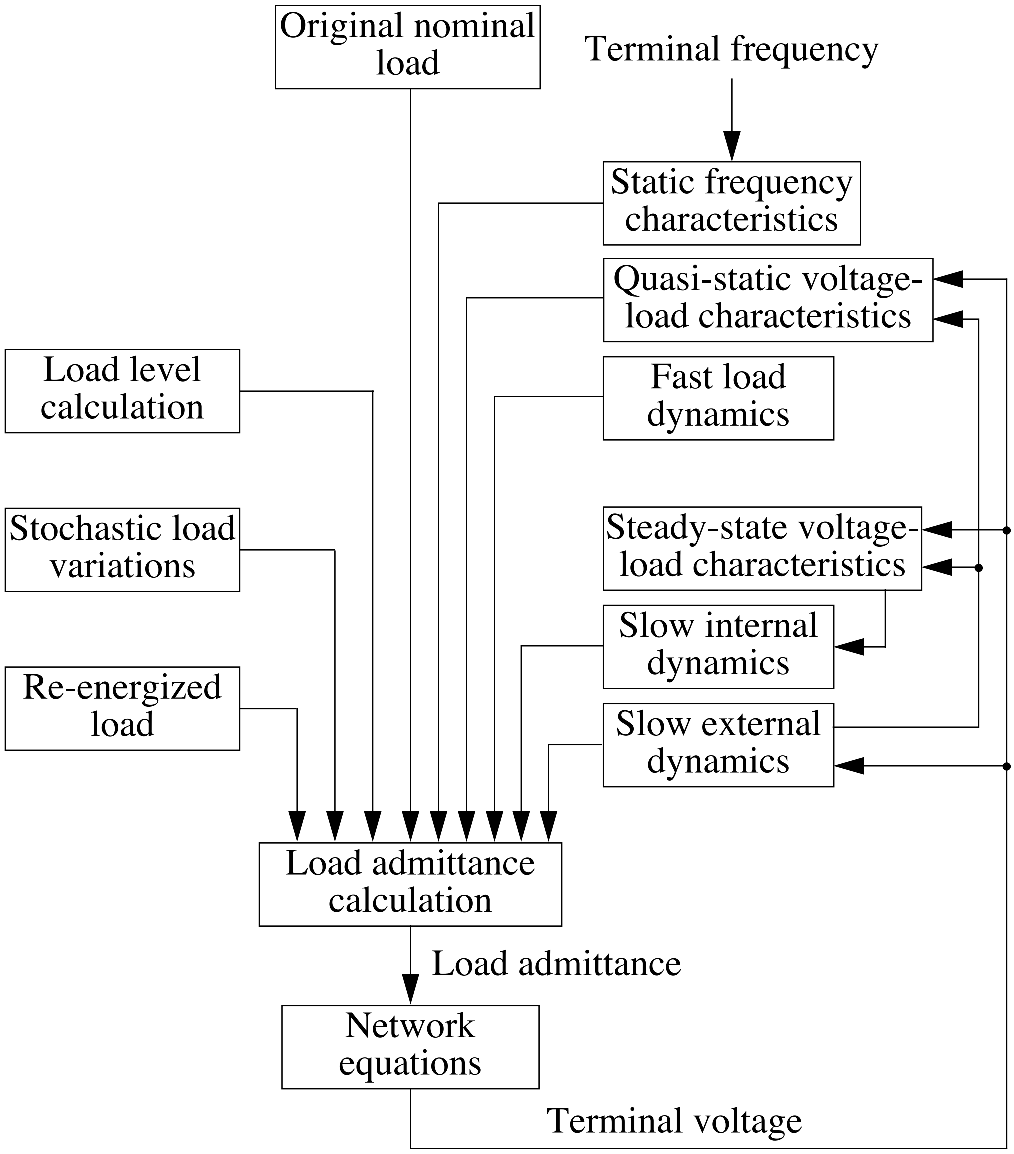

Figure 4.2 Overview of the available load models in ARISTO.

In the admittance calculation the static and dynamic dependency in frequency and voltage of the loads are taken into account. Stochastic load variations and cold load pick-up can also be modelled.

4.2.3 Production unit models

The synchronous machines are modelled using a fourth order model based on Parks equations. The models include saturation and the damper windings are taken into account in an approximate way. The excitation system can be simulated by the following models:

- Voltage regulator.
- MVAr regulator.
- Power system stabilizer.
- Stator and rotor current limiters.

The energy supply system can be described by the following models:

- Hydro and thermal turbine governors.
- Hydro turbine and water conduits.
- Thermal turbine and boilers.

4.2.4 Protection models

To simulate phenomena associated with a collapse or a restoration a variety of relay protection systems are implemented in the simulator. The relays are designed for generators, overhead lines, transformers, loads etc. and a summary of these protection systems is shown below:

- Over- and under-voltage relays for generators.
- Over- and under-frequency relays for generators.
- Distance relays for transmission lines.
- Overcurrent relays for transmission lines and transformers.
- Load shedding relays for under-frequency or under-voltage.
- Zero voltage relays.

4.3 User interface

The simulator is controlled by a user friendly interactive interface. From the Control Panel one can choose a power system model and initiate or conclude the simulation. Off-line preparation of the network and execution of load flow may be done in a forms system. The different models have their own forms where all parameters for the model are written.

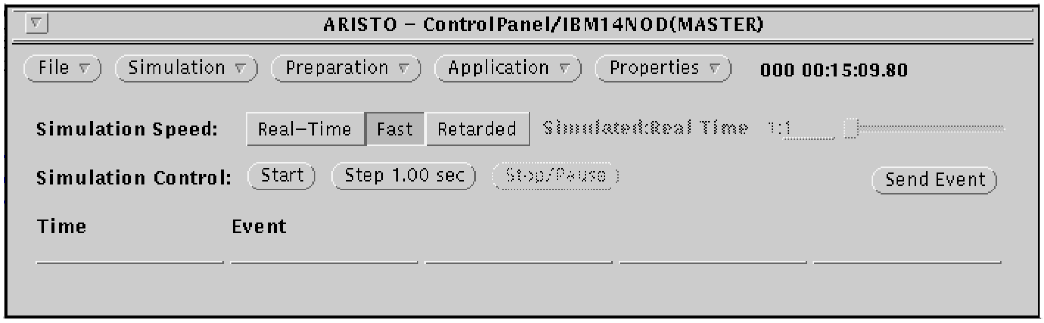

Figure 4.3 Control Panel.

In the network diagram it is possible to get an overview of the state of the network. To this purpose warnings and alarms may be connected to lines, transformers and switchyards; in case of overload or over-voltage the relevant objects will change colour in the network diagram. By using pop-up menus more information about specific objects may be found and these menus make it also possible to perform switching operations.

Figure 4.4 Network diagram.

In the curve diagram the network parameters which are of interest may be plotted. The presentation can be given in line graphs, bar charts meters or digital values. The trend curves may have different levels of resolution depending on the phenomena under study.

In the Event panel it is possible to pre-define a number of events that will be executed at a certain time. Network objects may be disconnected and connected, generation and consumption levels may be changed, relays blocked and faults initiated.

The Unit panel may be used both for the study of the generator parameters and for changing them. The set-point values for voltage, active and reactive power may be altered, but it is also possible to choose the working mode for the excitation and the turbine governor. Start, stop or tripping of the unit is also performed in the Unit panel.

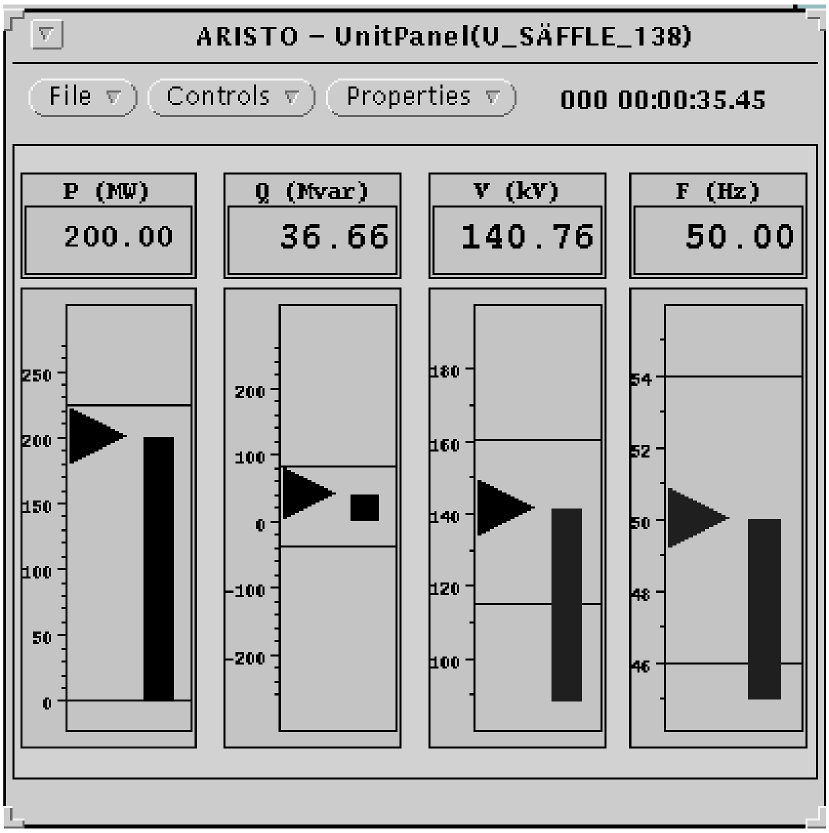

Figure 4.5 Unit panel.

In order to synchronize separated islands or execute a parallelling the synchroscope may be used. Switching is possible both manually and automatically. When using the automatic mode tolerances for the frequency, the voltage and the phase angle must be specified.

4.4 Implemented system

In this thesis the simulations have been performed using the Cigré Nordic 32 test system and a 600 node reduction of the power system in the nordic countries; the Nordel system.

4.4.1 The Cigré test system: Nordic 32

The Nordic 32 test system is a system which is constructed in order to study transient and voltage stability and long term dynamics [6]. The system consists of four major parts: ”North” with a large hydro production and some load, ”Central” with a heavy load and substantial thermal generation, ”South-west” with thermal generation and some load and ”External” with a high load and generation. The system has similarities with the Nordic power system and the ”North” may be seen as the northern part of Sweden, ”Central” the central and southern part of Sweden, South-west the Danish island Zealand and ”External” Finland. The system consists of 32 nodes and 29 generators on the voltage levels 400, 220 and 130 kV. The 400 kV transmission lines which connect the northern system with the central part have series compensation with a compensation degree of about 40-50%. Most of the network object models described in 4.2 are used and data for these models are similar to those in the Swedish system.

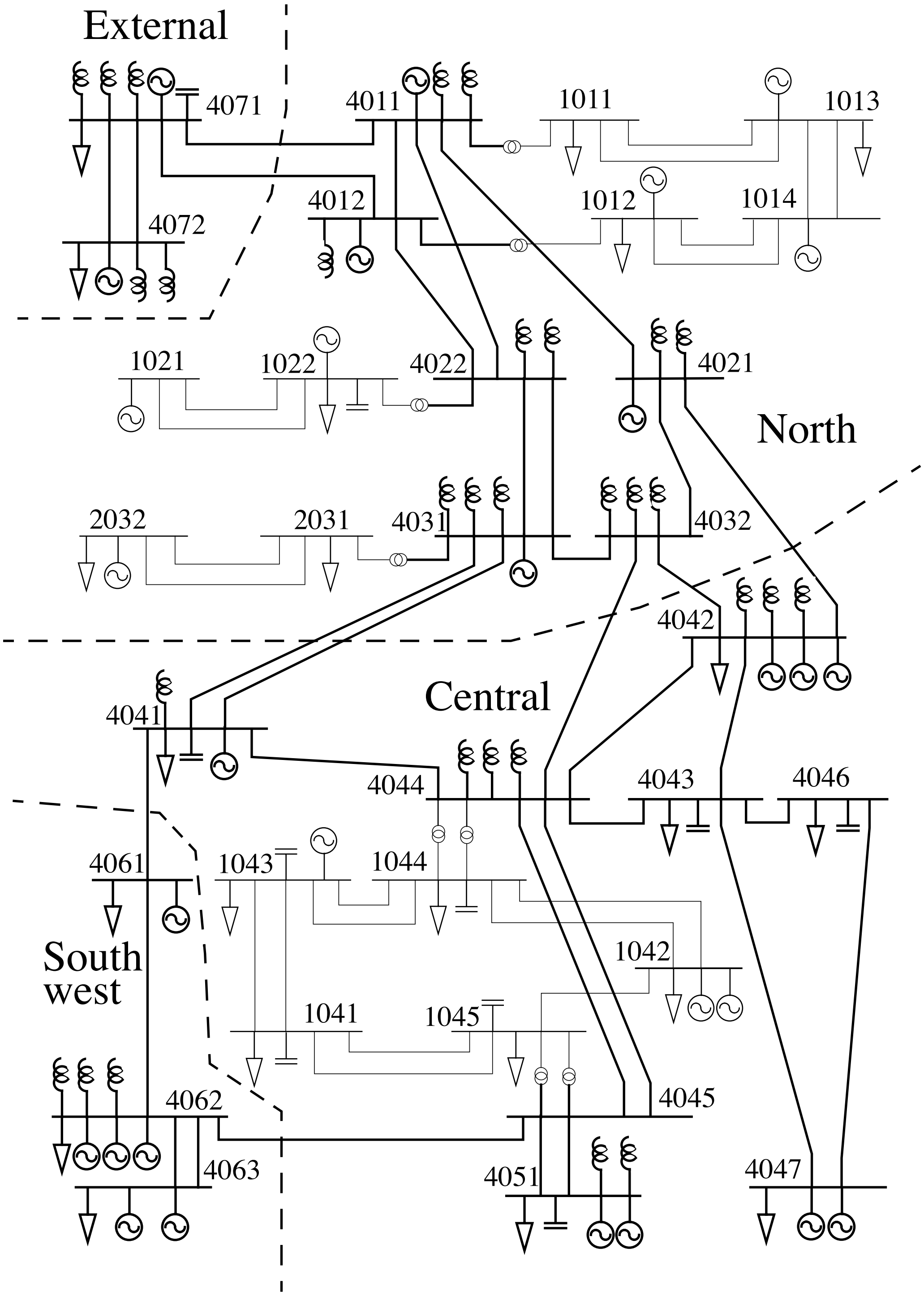

Figure 4.6 The Cigré Nordic32 test system. Bold lines represent 400 kV and thin lines represent 220 kV and 130 kV.

4.4.2 Nordel system

The simulator model of the Nordel power system [3, 30] consists of approximately 600 nodes. Finland, Norway and the island of Zealand in Denmark have been strongly reduced and are consisting of only a few equivalents. In Sweden all the 70 kV and large parts of the 130 kV system have been reduced. However, the entire 400 kV and 220 kV network are modelled in full scale. The power system model has been equipped with almost all the available network models. Data for the protection models and for the automatics in the system are the same as those which are used in the real Nordel power system (see 2.3).

4.5 The use of ARISTO

ARISTO has been created by Svenska Kraftnät and was initially constructed as a training tool for operators. So far it has been used in courses for the operators at the national control centres and also for other engineering courses at Svenska Kraftnät. During these courses network phenomena such as voltage collapse, islanding operation and restoration following a total or partial blackout have been studied. Predefined events have been implemented and the task for the operator has been to take care of the situations arising and to solve the problems related to these occasions. Since it is possible to connect a number of workstations to the simulator a role play may be performed where operators from power stations, control centres etc. may work in parallel and perform actions in the network simultaneously.

The simulator has been in operation at Chalmers University of Technology and is used both in education and research. The primary use of the simulator in education has been to give the students a better understanding of the dynamics in a power system and also show typical network phenomena such as transient stability, voltage collapse, restoration problems etc. In the research field the simulator has mostly been used to study restoration problems.

Chapter 5 Load behaviour

The restoration process following a major disturbance in a power system includes many reconnections of loads which will be done both manually and automatically. After an outage it is important to reconnect loads as fast and secure as is possible. An accurate knowledge of load behaviour for different load categories will be valuable in order to perform load reconnection in the proper sequence.

The dominating factor that affects the load size during the restoration is the cold load pick-up. As voltage and frequency will vary more than in case of steady state conditions, the effect of these parameters on load behaviour are also of importance.

5.1 Load categories in the Swedish system

The consumption of electricity per capita in Sweden is high when compared to other countries. During the seventies and eighties, when the nuclear power plants were taken into operation, the electric energy consumption increased significantly due to the change-over from oil based heating to electrical heating.

Consumer group	Consumption, TWh/year	in%
Industry	51.0	36.0
Communication	2.5	1.8
Housing, offices, shops, schools, hospitals, district heating power plants, etc.	74.4	52.5
Disconnectable power for electrical boilers in the industry, service and district heating power plants	4.7	3.3
Losses	9.0	6.4
Total consumption	141.6	100

Table 5.1 The electric energy consumption for different consumer groups in Sweden in 1995.

The energy consumption in Sweden may be divided into different groups as shown in table 5.1 [33]. Most of the consumption is due to residential load but the industrial consumption is also extensive.

Sweden is a country which has natural assets such as ore and forests and therefore the industry has different energy consuming sectors. The energy consumption in the main industrial branches is shown in table 5.2.

Branch of industry	Consumption, TWh/year	in%
Mining industry	2.5	1.8
Food industry	2.3	1.6
Textile and clothing industry	0.4	0.3
Timber and wood industry	2.0	1.4
Pulp and paper industry	19.0	13.4
Chemical industry	6.5	4.6
Farming and stone industry	1.1	0.8
Iron, steel and metal works	7.6	5.4
Engineering industry	6.6	4.6
Small industry, handicraft etc.	3.0	2.1
Total Consumption	51.0	36.0

Table 5.2 The electric energy consumption in the Swedish industry in 1995.

5.2 Cold load pick-up for different industries

The phenomenon of cold load pick-up has become of interest in the last years. The power suppliers try to utilize their networks as much as possible and in case of a restoration following a disturbance on a winter day the lines may be overloaded. This is due to the fact that a larger fraction of electrical heaters has been turned on. In extreme cold situations or when the power production at a number of plants is limited, Svenska Kraftnät may give order to the regional control centres to use a scheme with rotating disconnection of loads. This scheme is called ROBO (In Swedish: ROterande BOrtkoppling). If the loads included in ROBO contain a considerable part of electrical heating they will be larger when they are reconnected compared to the situation before the outage and for that reason more loads may have to be disconnected.

Lately the ROBO-scheme is also applied for another reason. The power supplier investigates whether it is possible to disconnect the electrical heating for households during a certain time in order to limit the power consumption in an area [16, 20, 25, 26]. This type of small ROBO may be used instead of reinforcing the network or using expensive power production and thereby both the power supplier and the customer will achieve economical advantages.

Here the cold load pick-up and its effect on the restoration following a blackout is studied. The reason is that usually there is a lack of power during restoration and therefore it is important to assess load behaviour in a restoring phase.

Load models for cold load pick-up are difficult to evaluate due to the fact that it is seldom allowed to provoke disturbances in the network. For industrial consumers even a short disturbance in the power delivery may lead to a loss of production for a number of hours and may cause damage to machines and equipment. Planned outages in industry or residential areas are not the same as a spontaneous disturbance. In the industry the production will be stopped in a controlled way and therefore it is much easier to restart after a planned outage compared to an unexpected one. In the households the load will probably increase as people will use the washing machine, dishwasher, oven etc. before the planned outage starts. Therefore these loads will not be in operation when the outage occurs and consequently do not play a role when the network is restored. The only way to get information about load behaviour following an outage is therefore to use data available from those disturbances that sometimes occur in the system.

An investigation of the majority of industries consuming more than 10 MW has been made. Many of these industries have their own measurement of energy consumption using different levels of time resolution. In those cases where these measurements are not available it is possible to receive values of the energy consumption per hour from the power supplier. A resolution of one hour may seem to be low but in those cases where the restarting time for an industry is up to one day, even measurements with a resolution of one hour can give valuable information.

5.2.1 Pulp and paper industry

The pulp and paper industry in Sweden has a high electricity consumption. This industrial sector is characterized by large plants consuming power up to 300 MW and can be divided into plants with either pulp production or paper production and plants which produce both.

The pulp production from wood (some plants also use recycled paper) can be done chemically or mechanically. In the first process the fibre and lignin are separated chemically whereas in the mechanical process the fibres are extracted by grinding. The mechanical process consumes up to four times as much energy as the chemical process, however, the chemical process consumes 100% more wood compared to the mechanical process.

Both the pulp and the paper production processes use a high number of pumps, fans, conveyers (i.e. most of the load consists of asynchronous machines). The main machines in the paper mill, however, usually are DC machines.

The production of pulp causes waste products such as bark from the trees and lyes including lignin. These products are burned in big furnaces and produce steam. Besides the waste products one usually has the possibility to burn oil in these furnaces. Much of the steam is used for drying of the pulp and paper but since the steam production is larger than the consumption these industries mostly produce electrical power in back-pressure turbo-generator units. For the chemical pulp industries the in-house electrical power production is almost equal to the consumption and therefore the import from the network is limited to those occasions when there is a lack of steam or there are problems with the turbine/generator.

Approximately half of the plants having an own generation capability has switchyards which are often based on a double busbar system as shown in figure 5.1. At busbar A the generator and loads with the highest priority are connected and at busbar B the feeding network and the rest of the loads are connected. During normal operation the circuit-breaker between the two busbars is closed but in case of network disturbances (under-voltage or under-frequency) the circuit-breaker will be opened and the generator and a part of the load will be running in island operation.

The success in changing over to island operation varies considerably. Some plants are highly successful whereas others only succeed in less than 50% of the cases. Since thunderstorms may cause problems a few industries will disconnect the circuit-breaker between the busbars and run in island operation as a protective measure against voltage impulses that may damage sensitive production processes.

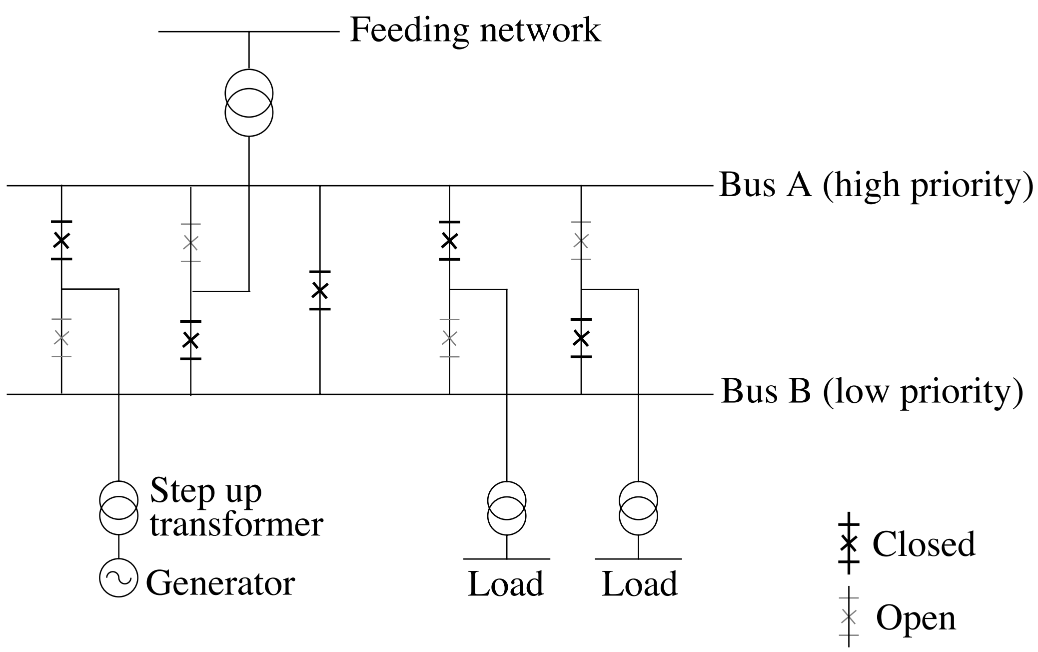

Figure 5.1 The substation layout for a pulp and paper industry.

Disturbances and outages in the network are troublesome for the pulp and paper industry. The consequences and the restarting time are dependent on whether the own power production can reach island operation, the duration of the outage, equipment damage and the available staff resources. Problems that arise following a disturbance are that pulp gets stuck in pumps and pipes and has to be removed, the steam production has to be restarted before other processes may start, the wire cloth has to be sluiced from pulp, paper or carton may stuck on the rollers. When the production has started it will also take time before a proper quality of the product is reached.

Figure 5.2 shows an example of the active power consumption and own power production following an outage for a 100 MW pulp and paper industry.

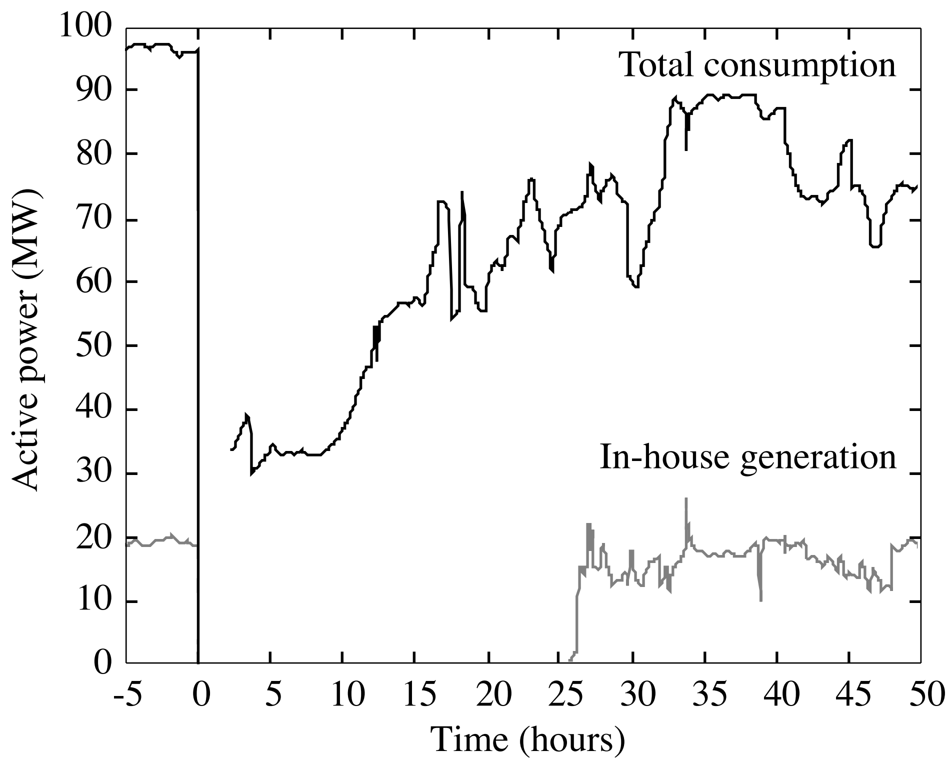

Figure 5.2 The active power production and consumption following a network disturbance at a pulp and paper industry.

In order to compare some different industries figure 5.3 shows the active power consumption following a restart after an outage for three different pulp and paper industries and figure 5.4 shows a comparison of the restart time for three pure pulp industries.

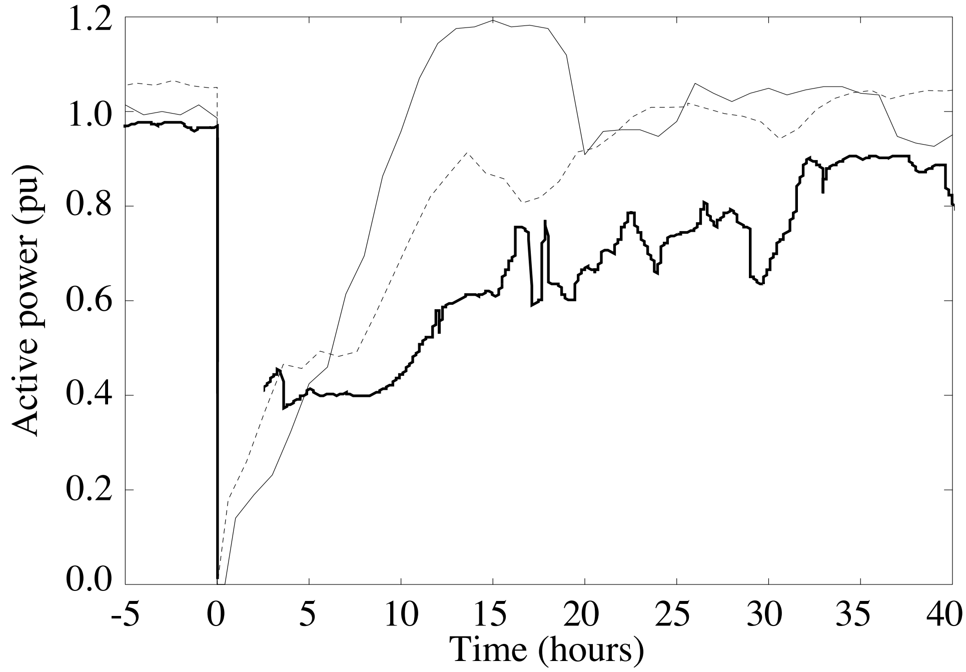

Figure 5.3 The active power consumption from three different combined pulp and paper industries following shutdown and restoration (base power is normal consumption). In one case (solid line) in-house production starts again after 18 hours leading to a temporary overshoot in power consumption from the grid.

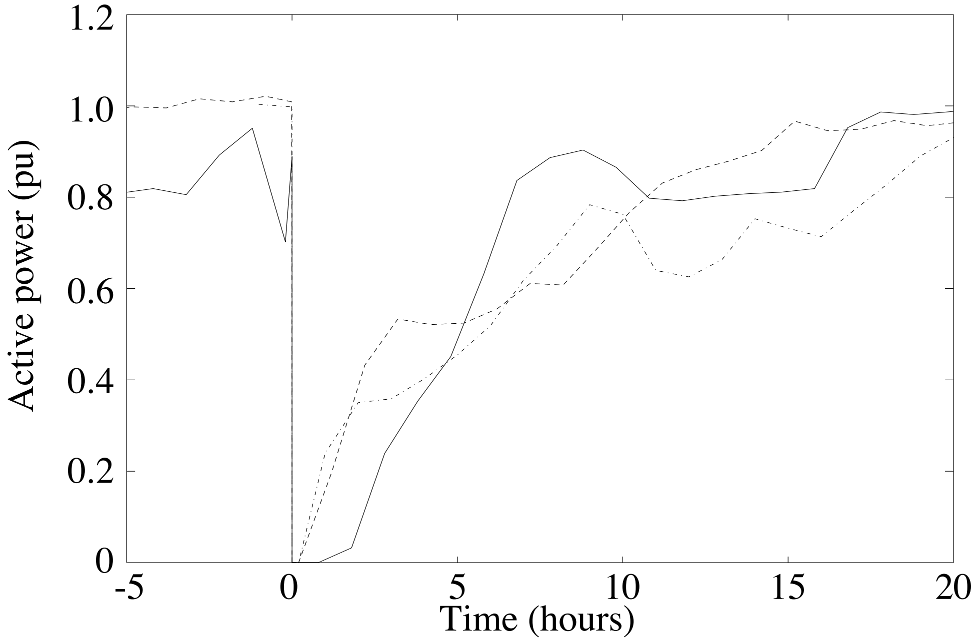

Figure 5.4 Active power consumption from three pulp industries following shutdown and restoration (base power is normal consumption).

In general one can say that the restarting of a paper industry only takes 1-3 hours whereas the restart of a pulp industry or a combined pulp and paper industry takes from 6 hours up to one day or more (compare figures 5.3 and 5.4).

5.2.2 Timber and wood industry

In the group of timber and wood industry sawmills, joineries and plants producing plywood and board are included [32].

Sawmills and joineries are often small plants with a power consumption of less than 1 MW. The electric energy consumption in these plants is largely related to the number of asynchronous machines. Following an interruption in the network the restoration is very fast since one only has to restart the machines. The electric energy consumption from these plants will be back to normal in less than an hour.

The board industry has similarities with the pulp and paper industry. The main difference is the drying process which in the board production due to the thickness of the plates, can not be made using heated cylinders. The restarting time following an outage for these types of plants will therefore be in the same range as for pulp and paper industries which means a number of hours.

5.2.3 Mining industry

The mining industry in Sweden may be divided into two major branches: iron ore and sulphide ore mining [32]. The iron ore production which consumes more than half of the electrical energy in this sector is concentrated to two mines in the north of Sweden, whereas the sulphide ore production is situated both in the north and the central area of Sweden. The mining is mostly done underground but there are also some open-casts.

The different production stages such as haul of ore and pumping of water from the mine, crushing, grinding and sifting, dressing and sintering to pellets consume much electricity, mostly by motors. Also the ventilation necessary in mining is a large energy consumer.

The restart of the production following an outage varies for different processes and types of mines. The duration of the interruption is very important since pumps and pipes may get stuck and have to be dismantled and flushed clean with water. Some mines experience an increased water flow during spring time. An outage that lasts more than an hour will flood the mine and the pumps resulting in severe consequences.

Generally one can say that the restarting time for the production varies between 30 minutes and 12 hours. A mean value of the restoration time may be 2-4 hours.

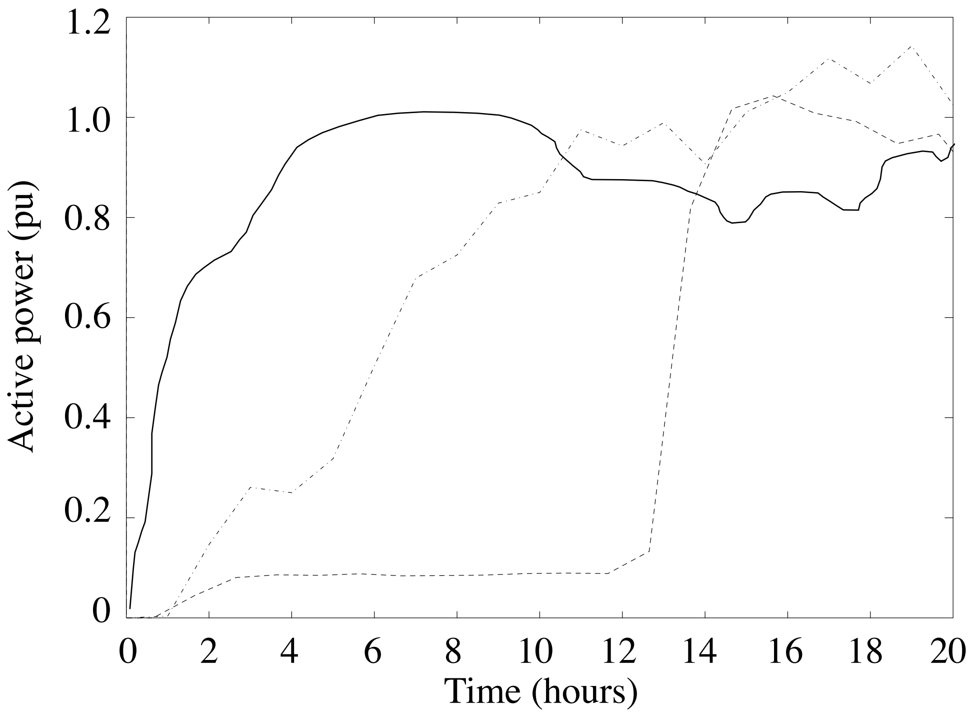

Figure 5.5 Active power consumption for three different mines during restoration (base power is normal consumption). Solid line shows the restart of an iron ore mine following a number of disturbances. Dashdotted line shows the restart of a sulphide ore mine following a planned outage. Dashed line shows an iron ore mine during and after a 12 hours long disturbance. Some power is produced by diesel generators during this outage.

5.2.4 Iron and steel industry

The iron and steel industry is mostly located in Bergslagen in the middle part of Sweden. There are also some plants in the south and a large steelworks in Luleå [32].

The processes are energy consuming; most of the consumption (about 40%) is related to the melting process which takes place in arc and induction furnaces. At those plants without a steelworks the steel is usually warmed up in induction ovens in order to achieve a temperature of over 1000 ˚C. It is then possible to start with the warm rolling process followed by cold rolling and other different process stages such as galvanization and hardening.

The power consumption from iron and steelworks varies considerably during the day since the load of the rolling-mill is intermittent whereas the melting process takes some hours. During this cycle the power consumption varies from maximum to almost zero when the furnace gets drained.

An interruption in the power supply may cause severe problems for some of these plants. In foundry plants an interruption that lasts more than 1-2 hours has catastrophic consequences since the material in the furnaces will solidify and therefore the whole furnace must be rebuild which can take up to a month. The hot material in the warm rolling-mill may cause damage to the rolls and changing these will take much time. In the cold rolling-mill there is a risk for a rupture of the steel strip and the cleaning up time following such an event will take up to four hours.

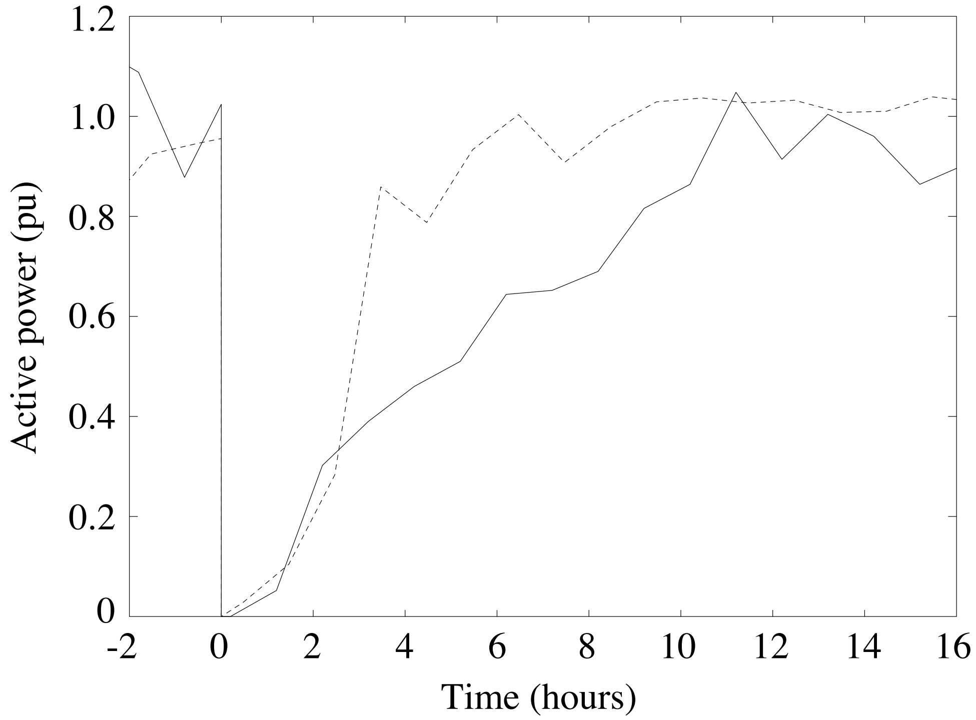

Figure 5.6 The power consumption of two iron and steel industries following an outage (base power is normal consumption).

Generally one can say that the restarting time for an iron and steel industry following a blackout takes from 30 minutes up to 12 hours. This is valid as long as nothing is damaged in the plant during the outage. Production may be stopped for a month in the most severe case.

5.2.5 Chemical industry

The chemical industry sector contains a number of sub-branches as chemical base industry, petroleum refinery, rubber and plastics industry and other chemical industries [32].

The chemical base industry includes production of chemicals for pulp and paper industry and the metal industry. The production of industrial gas and base plastics is also included in this sub-branch. Most of the energy consumption is due to electrolysis which consumes about 50% of the electric energy. The remaining part of the consumption is related to the use of compressors, pumps, fans and melting processes.

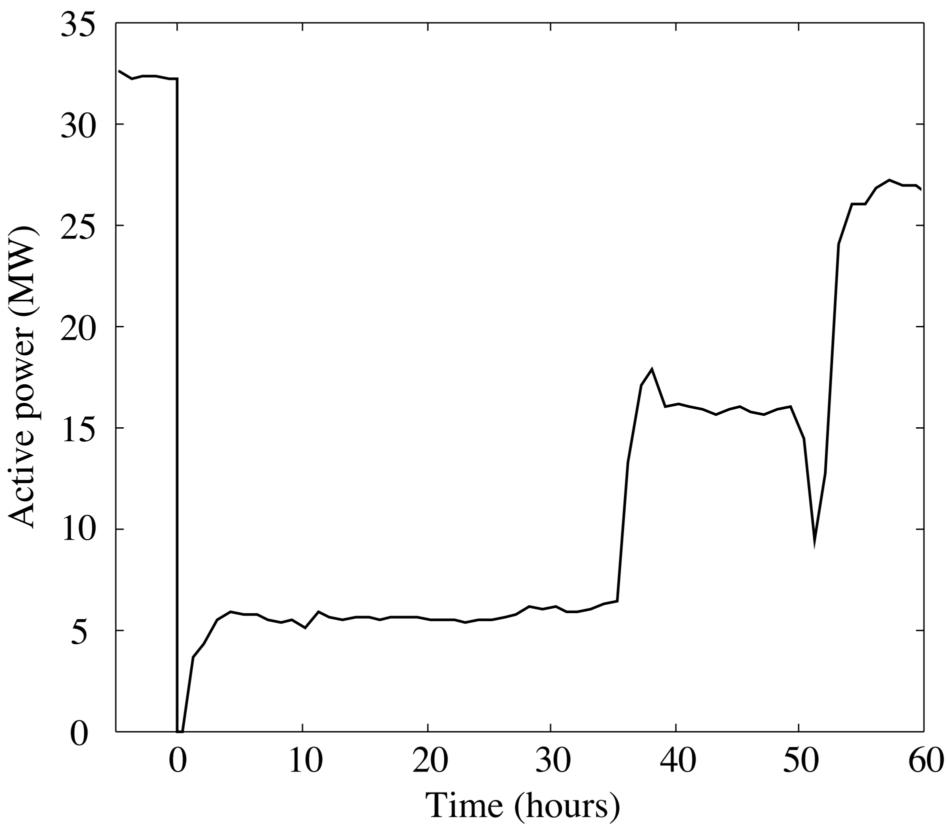

Figure 5.7 The power consumption of a cracker and polyester industry after an outage.

The restart of the production following an outage varies for different types of industries. The duration of the outage affects the restarting time as problems may arise such as gas condensation. Pipes have to be drained in such a case before restarting of the production.

The are only a few refineries in Sweden mostly situated on the west coast. They consume quite a lot of energy but since the processes generate waste products such as inflammable gases they also produce much energy by their own generators. The energy consumption in these plants is often related to pumps, fans, compressors and in some cases heating processes. The restart time of the production for these plants varies depending on the duration of the outage. The process may handle short interruptions less than 0.5 s but for longer interruptions the processes will be stopped and the restart of the production may take some days. However, the power consumption following such a severe interruption will be back in a day.

At one refinery plant the in-house power generation exceeds the own consumption and therefore the refinery sells electric energy to the power supplier. In case of a disturbance this plant will be disconnected from the network and work in island operation. In those cases when the generator fails to reach island operation there is a diesel generator which will start and thereby may give support for the restart of the gas turbine.

The rubber industry is mostly related to the production of car tires and other components for the car industry whereas the plastic industry for example produces plastic film, car components and boat hulls. Following an interruption these industries will be affected since the processes will be stopped and material will solidify. After the interruption machines have to be cleaned from solidified material and the processes have to be restarted which can take a number of hours.

5.2.6 Residential load

The residential sector consumes about a third of the Swedish electricity. The dominating part consists of electrical heating which alone stands for more than half of the consumption in this sector. The electrical heating is dominantly used during the winter period. Apart from heating refrigerators, freezers, washing and drying machines, dishing machines and illumination stands for a substantial part of the consumption.

Following an interruption in the system there may be a problem with overloading when reconnecting. The overloading is related to the thermostatically controlled loads such as electrical heating, refrigerators, freezers and water heaters. A part may also be associated with the psychological behaviour of people. During the outage people will switch on more lamps and in some cases they will open and check the food in the refrigerator and the freezer and thus contributing to a higher load during reconnection.

The cold load pick-up may be divided into several phases: one with a time constant of seconds and a number of phases with time constants of minutes-hours (and strongly dependent on the duration of the outage). The loads containing asynchronous motors such as refrigerators, freezers circulating pumps etc. will, when they start up, cause a peak in the power consumption. This peak will have a duration of less than one second. This phenomenon was observed when reconnecting loads during the restoration of the island grid as described in 7.2 and is shown in figure 5.8. The peak for these particular loads were between 0.6 and 1.7 pu and had a duration of less than 1 s. The reason for this large variation may be that the loads have different proportion of connected asynchronous machines.

Longer time constants arise from the cooling down of houses and water heaters and warming up of refrigerators and freezers. In houses with electrical heating initially most or all radiators will be on when the network is restored. The time it takes for the load to reach normal level is strongly associated with the duration of the interruption and the outside temperature.

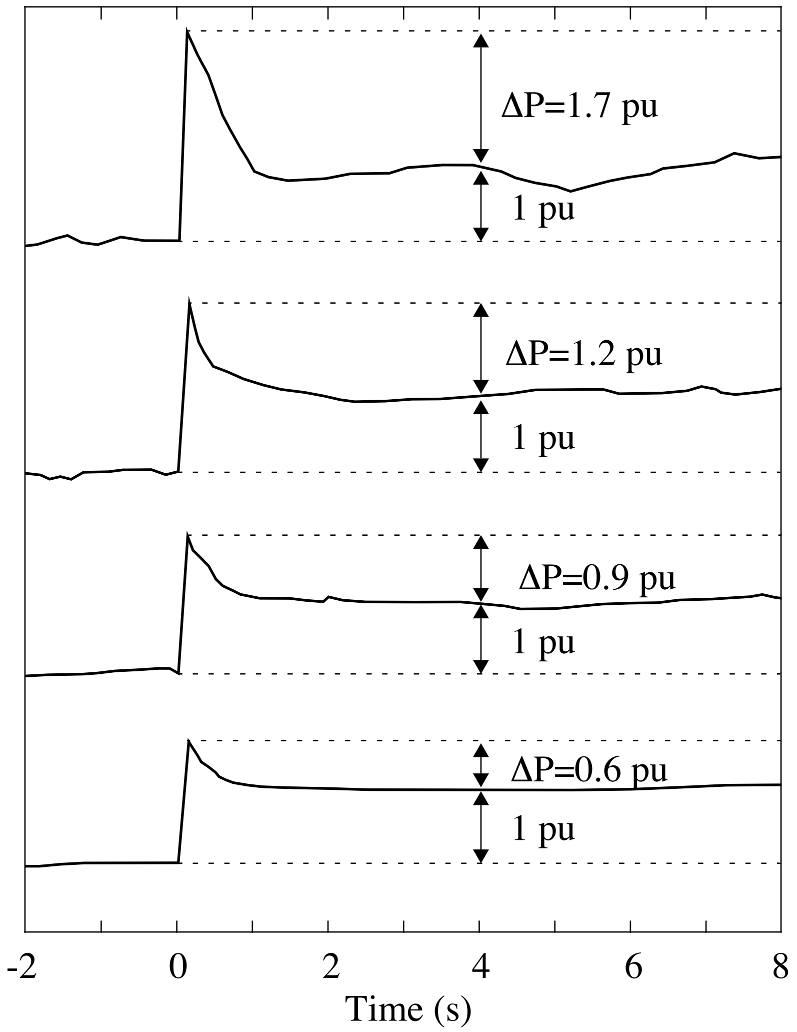

Figure 5.8 The active power consumption for four different loads. Each load has the nominal value of 1 pu (after 4 s) and the overshoot varies between 0.6 and 1.7 pu.

As described earlier it is difficult to make field measurements of the cold load pick-up. Since the time constant for the load recovery is in the range of minutes-hours the values of the energy consumption with a resolution of one hour (and is possible to receive from the power supplier) is not sufficient. Figure 5.9 shows an example from a field measurement performed in the south of Sweden a number of years ago.

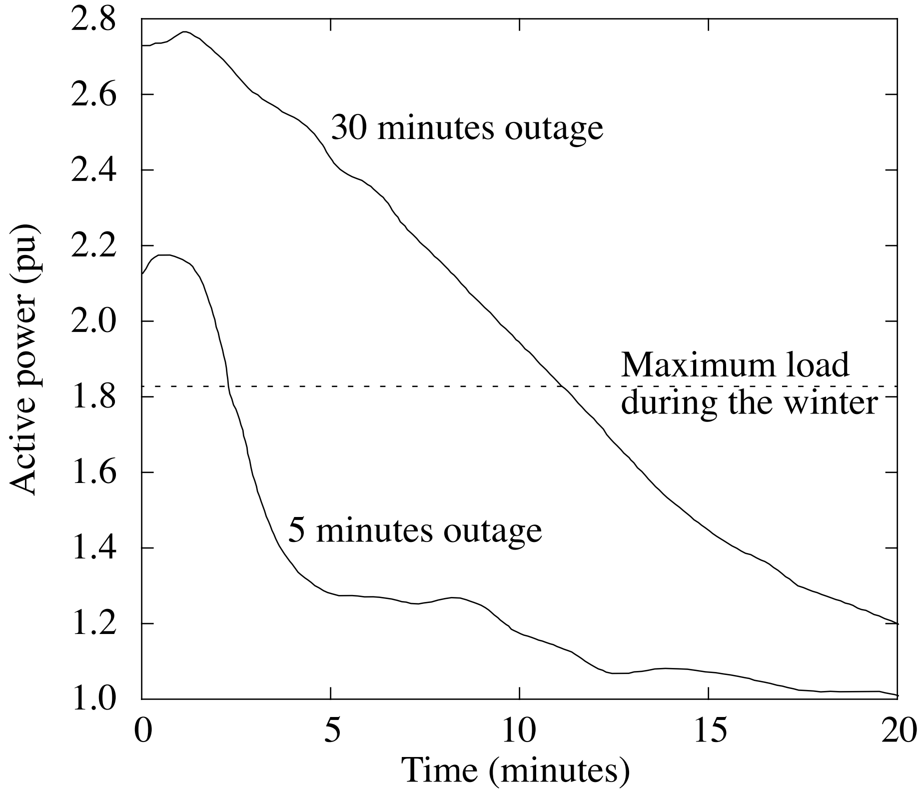

Figure 5.9 Field measurement of the cold load pick-up for 625 houses of which 525 have electrical heating. The field study was performed during the night and the outside temperature was -5 °C (base power is the consumption before the interruption).

During the field study the weather was calm and the outside temperature was -5 °C. In order to study the behaviour of the thermostatically controlled loads the measurements were performed during the night when the load basically consisted of electrical heating, freezers, refrigerators and electrical boilers. Two field measurements were carried out: one with an outage lasting 5 minutes and one lasting 30 minutes. As can bee seen from the figure, the load level immediately after the reconnection of the load following a 30 minutes interruption, is almost three times as high compared to the pre-outage load level. The load level is also substantially larger compared with maximum load which was measured during the coldest days in January. Also for the five minutes long interruption the load level is more than twice as high compared with the load before the outage.

A comparison between the lost energy during the interruption and the increased energy consumption following the outage shows that for the five minutes interruption the recovered energy after 20 minutes is about 115% of the lost energy. For the 30 minutes interruption the recovered energy after 20 minutes is about 65% of the lost energy. However, the power consumption for the 30 minutes outage, is higher than the pre-outage level even after 20 minutes and therefore the energy recover will continue.

In order to investigate the possibility to control the power consumption of loads, work has been done in Sweden [16, 20, 22, 25, 26] which has similarities with the cold load pick-up phenomena. The results from these studies can give valuable information on the cooling down time of houses but since the loads are controlled the results will not tell so much about the peak following an interruption.

When studying the cooling down of a house there are a number of factors that affect the temperature, such as the outside temperature, wind and solar radiation. Also the duration of the outage, the insulation, the quantity of furniture and other objects in the house are factors that are important. The number of people in the house should also be taken into account since a person produces 60-100 W.

In [22] an investigation was made of the time constants for a house. The result showed that the cooling down time is associated with two time constants according to equation 5.1.

$$T_i = (T_{i0} - T_o) \cdot \left(A e^{-\frac{t}{\tau_1}} + B e^{-\frac{t}{\tau_2}} \right) + T_o \tag{5.1}$$

where

T_i = inside temperature [°C],
T_{i0} = inside temperature before the outage [°C],
T_o = outside temperature [°C],
τ_1 = short time constant [hours],
τ_2 = long time constant [hours],
A, B = constants with the value $A \approx 0.1$ and $B \approx 0.9$.

The short time constant, τ_1, represents the cooling down of the air inside and is approximately one hour. The long time constant, τ_2, is related to the cooling down of the building itself and is about 28 hours. Since the study was performed in an empty house without furniture etc. the long time constant will probably be even longer. Using equation

5.1 and the given constants will result in a temperature decrease according to figure 5.10.

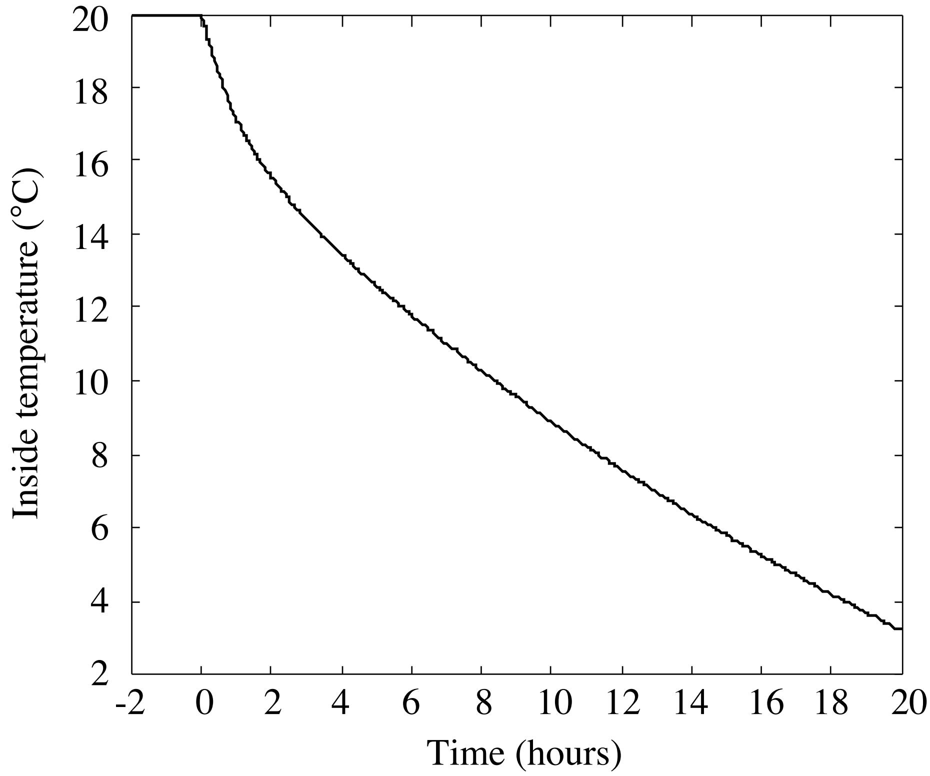

Figure 5.10 Inside temperature in a house as a function of outage time. Inside temperature prior to the outage was 20 °C and the outside temperature was -10 °C.

5.3 The voltage dependency of loads

The voltage in the system will fluctuate much more during the restoration process compared to normal conditions. The variations in the bulk-power system will also affect the voltages on the lower voltage levels. However, these variations will be reduced after some time due to the tap-changers on the transformers. At the distribution level (less than 10 or 6.6 kV) the voltages are not regulated with on-load tap-changers and variations in the load level will therefore lead to a variation in the voltage drop on the lines. The fluctuations in voltage will affect the power consumption in the network.

A load model proposed in [18] which is based on field measurements on two substations in the south of Sweden takes both the static and the dynamic load behaviour into account. The model may be written as

$$T_{pr}\frac{dP_r}{dt} + P_r = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{5.2}$$

$$P = P_r + P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \tag{5.3}$$

and for a voltage step the active power recovery may be written as

$$P_r = \left[P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t}\right]\left[1 - e^{-\frac{(t-t_0)}{T_{pr}}}\right] \tag{5.4}$$

where

V = supplying voltage [pu],
V_0 = pre-fault value of supplying voltage [pu],
P_0 = active power consumption at pre-fault voltage [pu],
P = active power consumption [pu],
P_r = active power recovery [pu],
α_s= steady state active load voltage dependence,
α_t= transient active load voltage dependence,
T_{pr} = active load recovery time constant [s].

The parameters α_s, α_t and T_{pr} will vary with the season of the year, time of the day and naturally with the type of load. α_s may vary from about 0.05 to about 1.4. For α_t the variation is from about 1.5 to 2.5 and the time constant T_{pr} varies from 80 to 360 seconds.

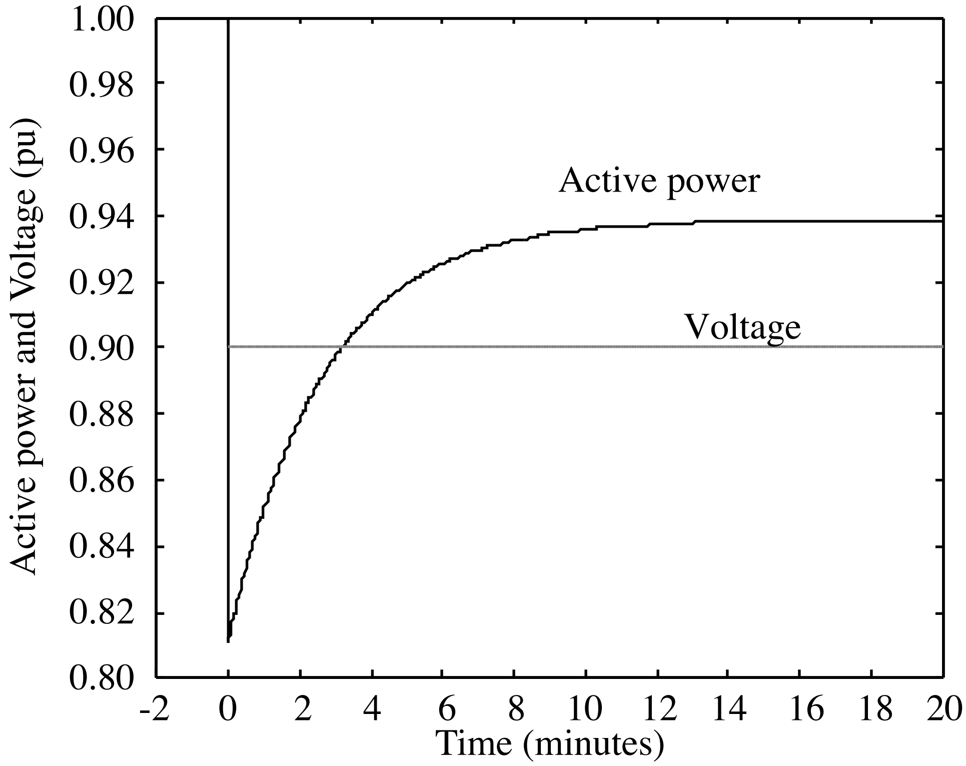

Figure 5.11 Active load recovery following a step decrease of the voltage from 1.0 to 0.9 pu. T_{pr}=160 s, α_s=0.6, α_t=2.

The dynamic load behaviour is related to the thermostatically controlled radiators. After a voltage step the radiators behave initially as a resistance load and the active power will therefore change with the square of the voltage.

The recovery phase is controlled by two processes. The first process is caused by the change in power supplied to the radiators due to the voltage change. The heat requirement will not alter for short periods of time and the result is that the ratio of the on-off times of the thermostats will be adjusted so that the same amount of electrical energy over time is delivered as prior to the voltage change. The second process controlling the recovery is caused by the voltage dependency of bimetallic thermostats. Due to their design a voltage decrease will lead to an increase in the temperature set-point and vice versa. Measurements [23] show that a 10% increase of the voltage using a bimetallic thermostat leads to a reduction of the mean power with 20-30% after 10-15 minutes and 10-20% after 30-40 minutes. A reduction of the voltage with 10% leads to an increase of the mean power with 30-40% after 10-15 minutes and 5-10% after 30-40 minutes. In the same thesis [23] an electronic thermostat is investigated and the results show that the mean power from the radiator varies around the pre-fault value during 30 minutes after the voltage change and for longer time the mean power is approximately equal to the power before the voltage change.

During an outage the temperature in the house will decrease. The primary effect during the restoration is therefore that a higher number of thermostats of the electrical heating will be in the on position. Since the power consumption will be much higher after the outage, the voltage drop on the lines/cables will be higher compared to the pre-fault value. This voltage drop will affect the power consumption in two ways. Firstly, the voltage drop will reduce the power consumption since the power consumption from a radiator is proportional to the square of the voltage. Secondly, the lower voltages on the radiators results in an increased power consumption due to the voltage dependency of bimetallic thermostats as previously described.

5.4 The frequency dependency of loads

During the restoration of the power system the frequency variations will be higher as compared with normal conditions (see 3.4 and Chapter 7). Due to these variations it is important to study the frequency dependency of the load in the power system. An investigation of the loads in the Nordic power system has been performed [8]. Laboratory measurements were made on the most common types of individual loads present in the system. In order to verify the laboratory results a field study was made on an island grid.

The laboratory measurements resulted in the following static polynomial and exponential load models:

$$P(f) = a_2\left(\frac{f}{f_0}\right)^2 + a_1\left(\frac{f}{f_0}\right) + a_0 \tag{5.5}$$

$$P(f) = \left(\frac{f}{f_0}\right)^{n_p} \tag{5.6}$$

where

f = system frequency [Hz],
f_0 = reference value of system frequency [Hz],
a_0, a_1, a_2 and n_p are load parameters.

For the investigated load types the following table shows the calculated parameters.

Load	a_0	a_1	a_2	n_p
Asynchronous machine (constant load torque)	2.50	-2.50	1.62	0.91
Asynchronous machine (linear load torque)	1.22	-2.14	1.91	1.86
Asynchronous machine (square load torque)	2.27	-5.10	3.84	2.91
Motor run by frequency converter	1.0	0	0	0
Electrical heating	1.0	0	0	0
Refrigerator/freezer	2.54	-3.63	2.09	0.34
Fluorescent lamp	4.05	-4.96	1.91	-1.36
Mercury lamp	3.52	-3.81	1.29	-1.39
High pressure sodium lamp	7.10	-10.05	3.95	-2.05
Low pressure sodium lamp	2.19	-4.38	3.19	1.93

Table 5.1 Load model parameters for different types of loads.

Except for these investigated loads a power system also includes loads like electrolysis in the chemical industry and frequency independent loads such as disconnectable electric boilers, arc furnaces in the iron and steel industry etc.

Table 5.2 gives a description of the power composition in the Swedish system during a normal and a light load occasion. The table is divided in four different types of load with different levels of frequency dependence according to the derived models. Using these load compositions and the proposed load models give the total frequency dependency of the Swedish system as shown in figure 5.12

Type of load	Normal load	Light load
Lighting (GW)	1.8	1.6
Refrigerator/freezer (GW)	0.7	0.6
Motors and electrolysis (GW)	5.8	5.8
Frequency independent loads (GW)	7.3	2.3
Total load (GW)	15.6	10.3

Table 5.2 The power composition in Sweden during a normal and a light load occasion.

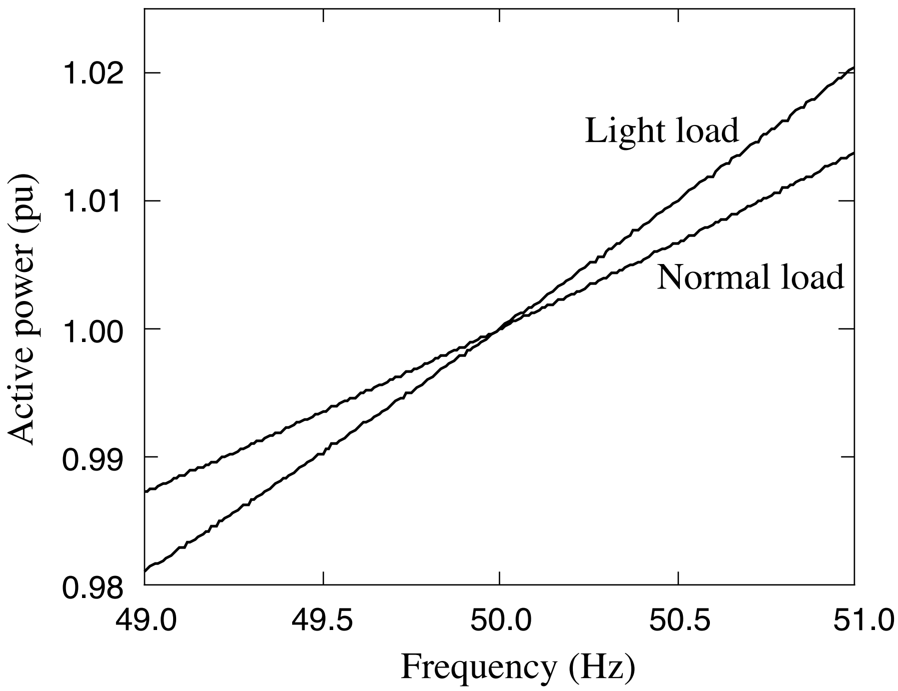

Figure 5.12 Frequency dependency of the load in the Swedish system during a normal and a light load occasion.

As can be seen the total load varies almost linearly with frequency. During normal load the variation is approximately 0.013 pu/Hz and during light load 0.020 pu/Hz.

In order to verify the results from the laboratory measurements a field study was made on an island grid as described in 7.3. During the field study it was difficult to keep a stable frequency and since a change in the frequency also resulted in a change in the voltage the variation in power consumption in the system was affected by both the frequency and the voltage. A load composition of the island grid was performed where the derived load models were used. These data and data from the grid were implemented in the simulation program PSS/E. The load voltage dependency was also taken into account during the simulations by using the load model proposed by [18]. The simulated results for the active power showed a good agreement with measured values. For the reactive power, however, the results from the simulations and the measured values disagreed. No satisfactory explanation for this disagreement was found.

5.5 Conclusions

The investigation of the load behaviour following a disturbance has shown that the cold load pick-up phenomenon is important and has to be taken into account. In the residential sector the load will be higher after an outage which is a result of thermostatically controlled loads. The industrial load will be substantially lower compared with the load before the outage and for some industries it may take more than a day to restart the production following a disturbance.

The voltage and frequency dependencies of the load will also affect the system. However, these variations are not as extensive as those caused by cold load pick-up.

Chapter 6 Analysis of voltage and frequency control

During restoration the control of voltage and frequency is most important. It is therefore necessary to have a sufficient knowledge of how different system components and their automatics affect the regulation of voltage and frequency.

6.1 Voltage control

As described in chapter 2 there are a number of long 400 kV transmission lines connecting the northern part of Sweden with the centre and the south of the country. During a restoration process these lines will be energized and it is necessary to have reactive resources available, such as shunt reactors, SVCs and generators. They are used to compensate for the reactive power production of these lines in the initial phase of no load or low load.

A long transmission line with a series capacitor installed in the middle of the overhead line may be modelled using π-link sections as shown in figure 6.1.

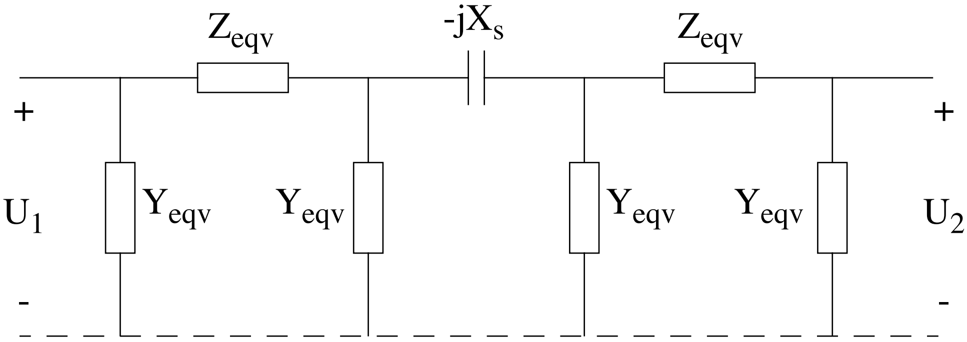

Figure 6.1 Equivalent circuit for a transmission line with a series capacitor installed in the middle of the line.

If the line is assumed to be lossless and the shunt branches around the series capacitor are placed at the feeding and the receiving end of the line the equivalent circuit may be simplified according to figure 6.2.

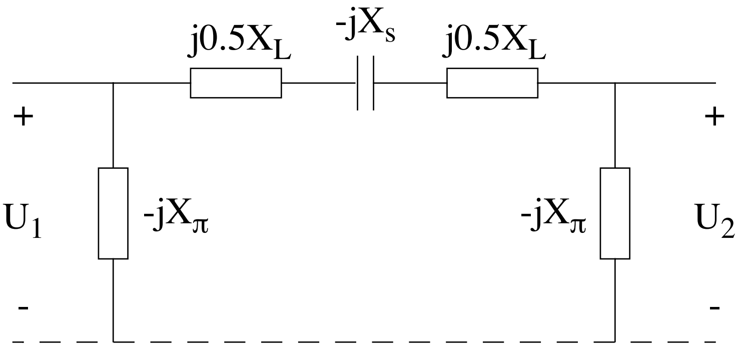

Figure 6.2 Simplified equivalent circuit for a transmission line with a series capacitor installed in the middle of the line.

The reactances in the π-section are

$$X_L = Z_v \sin\gamma l \tag{6.1}$$

$$X_\pi = Z_v \cot\frac{\gamma l}{2} \tag{6.2}$$

where

$$Z_v = \sqrt{\frac{x}{b}} \tag{6.3}$$

$$\gamma = j\sqrt{xb} \tag{6.4}$$

and

x = line reactance [Ω/km, phase],
b = line susceptance [S/km, phase],
l = line length [km],
X_s = series capacitor [Ω/phase].

The voltage at the receiving end of the line in no-load is then given by equation 6.5 and the reactive power production from the same line is shown by equation 6.6.

$$U_2 = U_1 \frac{X_\pi}{X_\pi + X_s - X_L} \tag{6.5}$$

$$Q = U_1^2 \left(\frac{1}{X_\pi} + \frac{1}{X_\pi + X_s - X_L} \right) \tag{6.6}$$

The voltage at the feeding end can be assumed to be constant; this is a good assumption in the Swedish system since there are a number of hydro units at the feeding end in the north which regulate the voltage. The voltage at the receiving end as a function of line length may then be plotted as shown in figure 6.3 (case of no load).

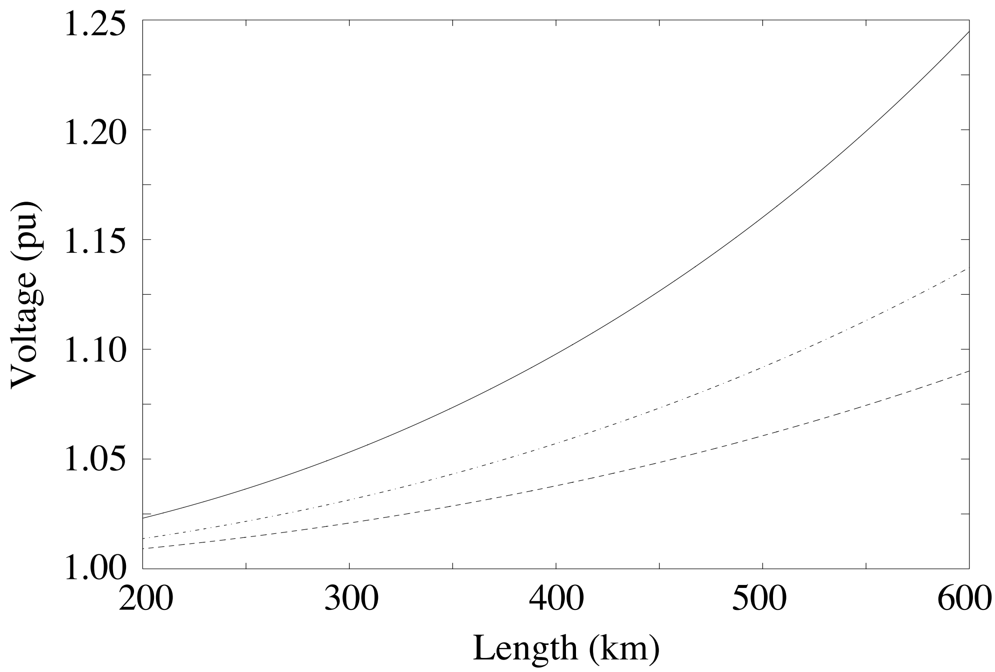

Figure 6.3 The voltage at the receiving end of an unloaded 400 kV line as a function of the line length. The voltage at the feeding end is 1.0 pu. The equivalent circuit according to figure 6.1 is used (no simplification). Solid line: without series compensation. Dashdotted line: series compensation corresponding to 40% of the line reactance. Dashed line: series compensation corresponding to 60% of the line reactance.

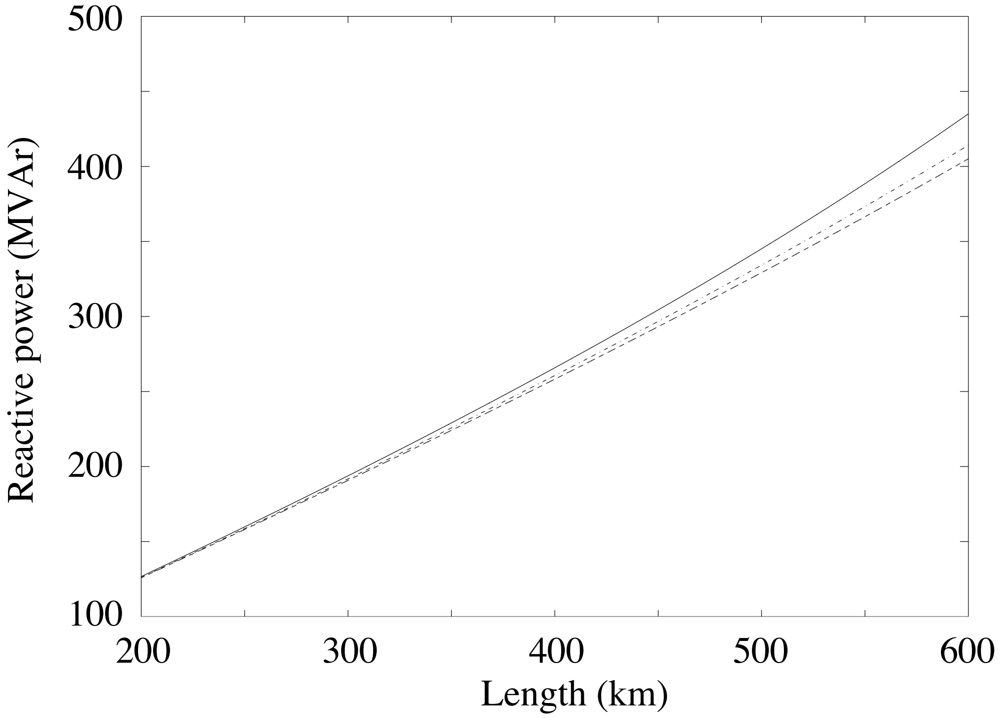

Figure 6.4 The reactive power production of an unloaded line as a function of line length. The voltage at the feeding end is 400 kV. Solid line: without series compensation. Dashdotted line: series compensation corresponding to 40% of the line reactance. Dashed line: series compensation corresponding to 60% of the line reactance.

As can be seen in figure 6.3 the voltage at the receiving end of a long transmission line in no-load decreases with an increased series compensation. The same applies for the reactive power produced which is shown in figure 6.4. The series compensation is therefore valuable when energizing an unloaded transmission line since it both decreases the voltage and to a lesser extent, the reactive power production.

6.1.1 Shunt reactors

The shunt reactors which are installed in order to compensate for the reactive power produced by transmission lines are equipped with automatics as described in 2.3.5. The voltage levels for connection and reconnection of the reactors are dimensioned for normal operation, which implies that *all the lines to the station are connected*. Figure 6.5 shows the hysteresis curve of a shunt reactor relay both for normal and abnormal operation.

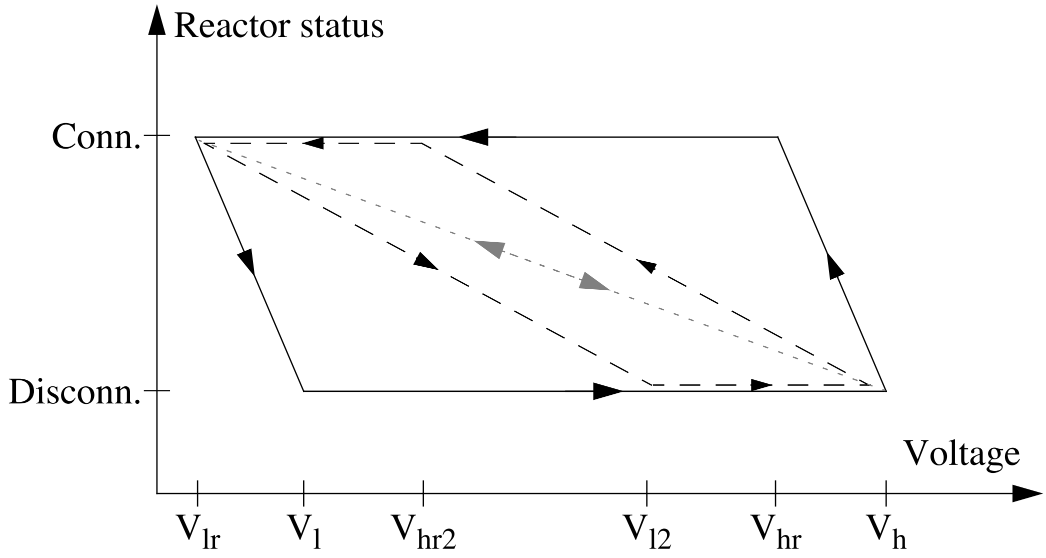

Figure 6.5 Hysteresis curve for the shunt reactor automatics. Solid line is valid when all station lines are connected. Dashed and dotted lines are valid when only one or a few station lines are connected.

In the case that not all the lines to the station are connected the dead band decreases due to overcompensation by the reactor (dashed line) and in an extreme situation it is possible that the dead band totally disappears (dotted line). This may lead to a repetitive process of connection and reconnection of the reactor: a phenomenon known as hunting. Reactor hunting may cause severe problems as the voltage will strongly fluctuate. The repetitive process has a time cycle governed by the delay times of the reactor relay in combination with the response time of the circuit-breaker. Normally the circuit-breaker is dimensioned for a open-close-open cycle after which it is blocked for around 20 s until the mechanism has recharged. In case the reactor is disconnected only a close-open cycle can be performed. The usual set-points for the relays are a 0.4 s delay for connection and 2.0 s for disconnection. A hunting cycle will then have the following time cycle:

disconnection - 0.4 s - connection - 2.0 s - disconnection - 20 s - connection - 2.0 s - disconnection etc.

6.1.2 Simulation of reactor behaviour

In order to analyse the hunting phenomenon for shunt reactors simulations have been performed on both the Nordic 32 test system and the 600 node Nordel network (see 4.4 for description of these systems).

In the Nordic 32 test system, there are rather few stations and therefore the stations are equipped with up to three reactors each whereas normally each station only has one or two reactors. The reactors in the test system are either 100 MVAr or 150 MVAr which could be compared with the real system where the reactors can be as large as 200 MVAr. All simulations are made in agreement with the instruction philosophy used during a restoration.

The first test case in the Nordic 32 test system is to energize a long transmission line (4032-4044) having a length of about 400 km and connecting the system ”North” with ”Central” (see figure 4.6). During the line energizing all the generators in the region ”North” are in operation which gives the ”North” system good reactive absorbing capacity. The ”South-west”, ”Central” and ”External” parts of the system are out of operation before the line energizing. The total load in the ”North” system is 1180 MW and the production capacity is 6250 MVA.

0.4 s after the line is connected four shunt reactors in the ”North” (4031 and 4032) and three shunt reactors in the ”Central” part are connected due to the automatics (see figure 6.6, 6.7 and 6.8). As a result the voltages decrease to such an extent that not only the seven reactors are disconnected again but also another two. The disconnection of the reactors causes very high voltages which results in the connection of four other shunt reactors in the ”North”. The voltage is now on an acceptable level in the ”North” whereas it is too high in the ”Central”. After an additional 20 s the circuit-breaker springs are recharged (the charging times are assumed to be equal for all circuit-breakers) and the three shunt reactors in ”Central” are reconnected. The connection result in a too low voltage level in substation 4044 and two s later the three shunt reactors in substation 4044 are disconnected. The disconnection of the reactors gives high voltages in both substation 4044 and 4032 and two reactors in substation 4032 are connected. After another 20 s when the circuit-breaker springs on the reactors in substation 4044 are recharged the hunting phenomenon will be repeated.

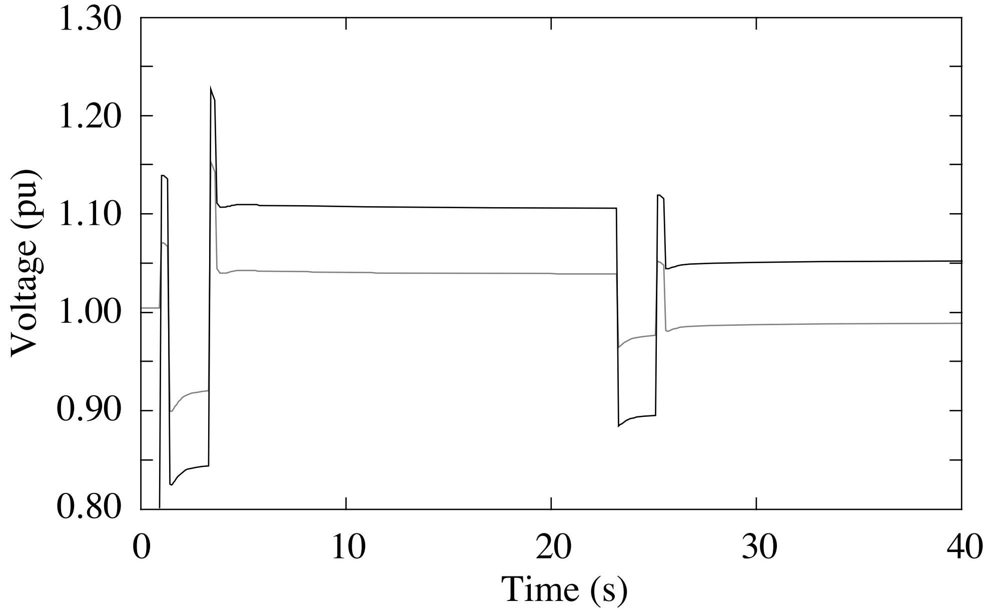

Figure 6.6 Voltage variations following an energizing of the line 4032-4044 (unloaded). Solid line: substation 4044 (receiving). Dotted line: substation 4032 (feeding).

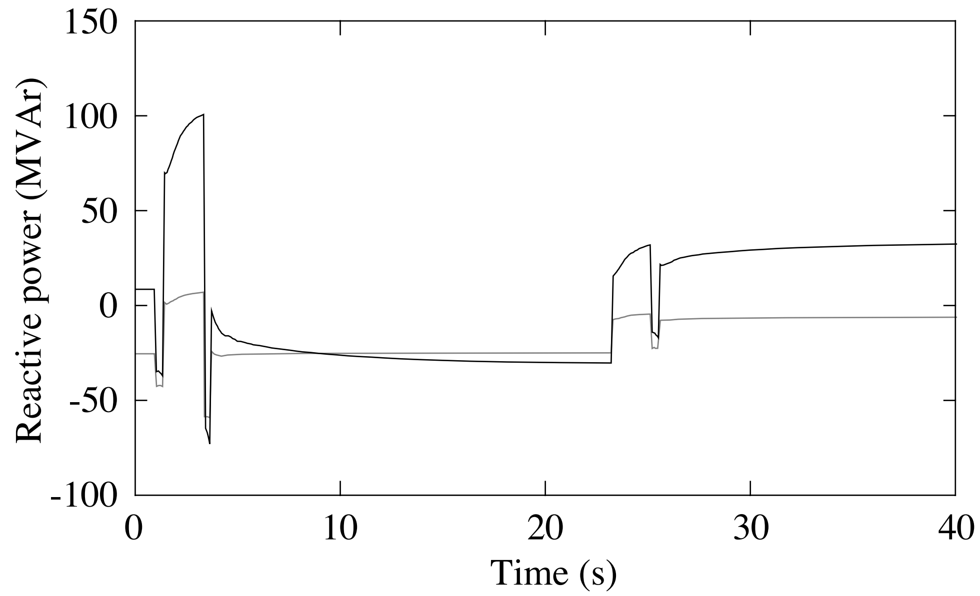

Figure 6.7 The reactive power production from generators close to the connected transmission line. Solid line: unit 4031. Dotted line: unit 1022. A negative sign indicates that the generator absorbs reactive power.

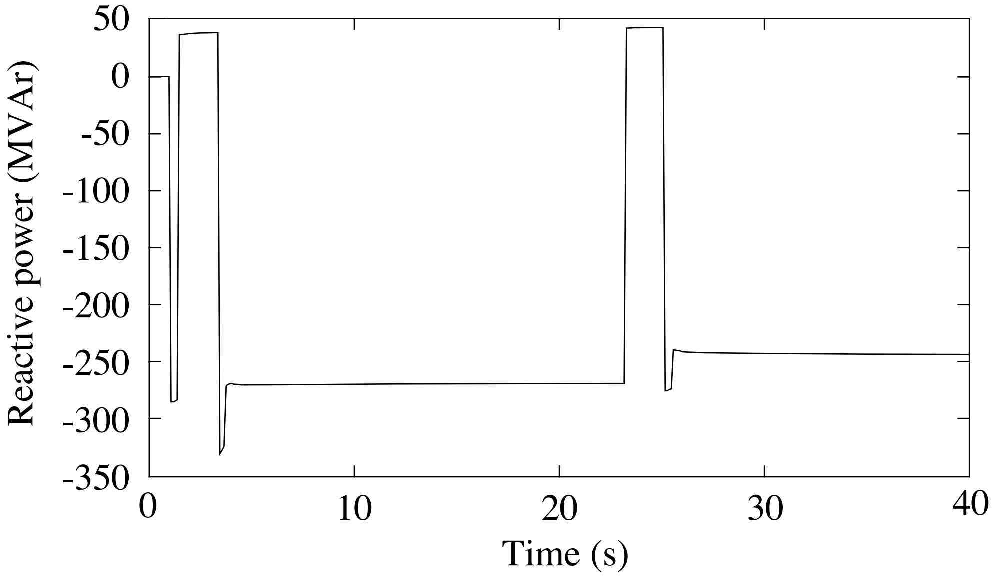

Figure 6.8 Reactive power transfer as seen from the feeding end of the connected transmission line 4032-4044. A negative sign indicates reactive power production by the line.

A number of simulations have been carried out in order to investigate the importance of the time delay settings, the voltage levels or a combination of both of these parameters. Figure 6.9 shows the energizing of the same line as in figure 6.6, 6.7 and 6.8 when the time delays according to table 6.1 have been used.

Shunt reactor	Connection		Disconnection	
	Voltage (kV)	Time delay (s)	Voltage (kV)	Time delay (s)
Reactor 1	420	0.4	380	2.0
Reactor 2	420	0.5	380	2.1
Reactor 3	420	0.6	380	2.2

Table 6.1 Altered time delays for the connection/disconnection of shunt reactors in the system. Settings are the same for each substation (voltage set-points unchanged).

The line energizing results in high voltages in both ”North” and ”Central” and after 0.4 s one shunt reactor in substation 4044 is connected (In substation 4032 and 4031 the reactors with a 0.4 s delay are already connected before the line energizing). The connection of one shunt reactor decreases the voltages below 420 kV both in ”North” and ”Central” and no further shunt reactor connections are made. However, the voltages are still high and it would be advisable to manually connect an additional shunt reactor.

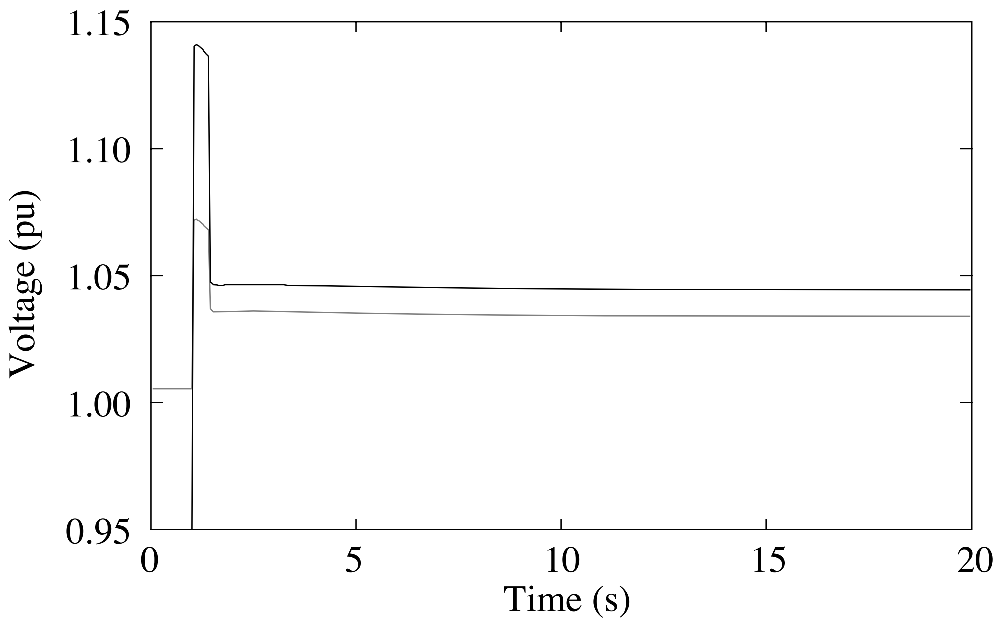

Figure 6.9 The voltages at the feeding and the receiving end of an unloaded transmission line. The shunt reactors in the same substation have different time delays for the automatics. Solid line: substation 4044 (receiving). Dotted line: substation 4032 (feeding).

Figure 6.10 shows the energizing of the line 4032-4044 when the voltage ranges for the shunt reactors situated in the same station have been varied according to table 6.2.

Shunt reactor	Connection		Disconnection	
	Voltage (kV)	Time delay (s)	Voltage (kV)	Time delay (s)
Reactor 1	417.5	0.4	382.5	2.0
Reactor 2	420.0	0.4	380.0	2.0
Reactor 3	422.5	0.4	377.5	2.0

Table 6.2 Altered voltage levels for the connection/disconnection of shunt reactors in the system. Settings are the same for each substation (time delays unchanged).

The energizing of the line gives high voltages and after 0.4 s three shunt reactors in ”North” and three in ”Central” are connected. The connection of six reactors decreases the voltages too much and after additional two s three shunt reactors in substation 4032 and three in substation 4044 are disconnected. As the voltages in both ”North” and ”Central” become too high two reactors in ”North” are connected. In substation 4044, however, the springs of the circuit-breakers must be recharged before the reactors can be connected. After 20 s when the springs are recharged, the three shunt reactors in substation 4044 are connected. Since the voltage in ”Central” becomes too low the reactors are disconnected two s later. The hunting phenomenon with the reactors in substation 4044 will then be repeated every 20 s after recharging of the circuit-breaker springs.

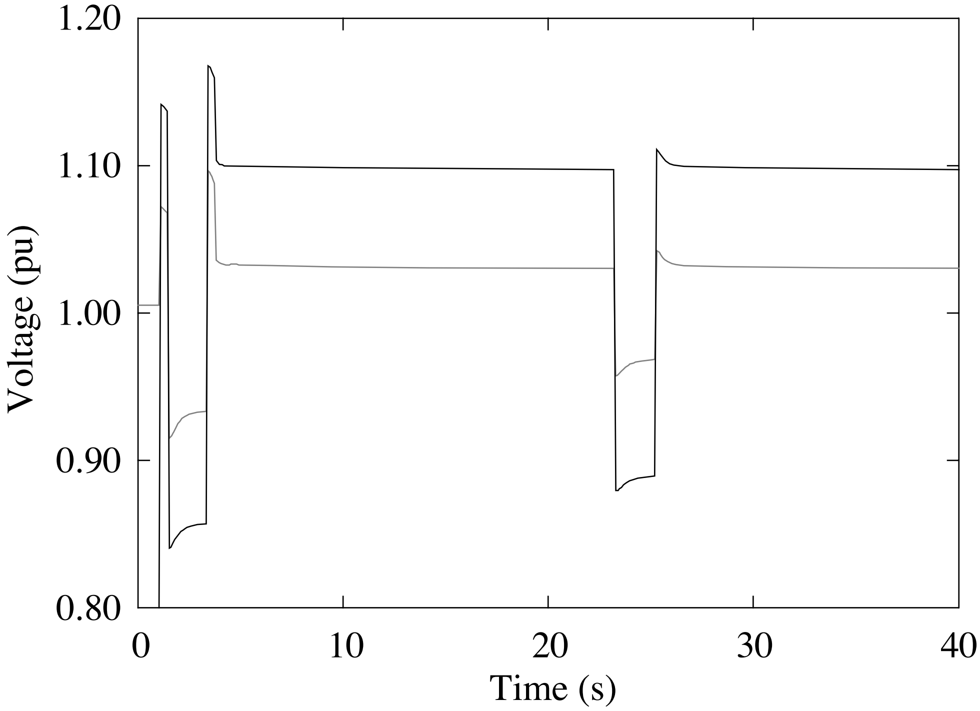

Figure 6.10 The voltages at the feeding and the receiving end of an unloaded transmission line. The shunt reactors in the same substation have different voltage levels for the automatics. Solid line: substation 4044 (receiving). Dotted line: substation 4032 (feeding).

Figure 6.11 shows a simulation where both time delays and voltage levels have been altered for shunt reactors situated in the same station (see table 6.3).

Shunt reactor	Connection		Disconnection	
	Voltage (kV)	Time delay (s)	Voltage (kV)	Time delay (s)
Reactor 1	417.5	0.6	382.5	2.2
Reactor 2	420.0	0.5	380.0	2.1
Reactor 3	422.5	0.4	377.5	2.0

Table 6.3 Altered time delays and voltage set-points for the connection/disconnection of shunt reactors in the system. Settings are the same for each substation.

0.4 s after the line is energized one shunt reactor in substation 4032 and one in substation 4044 are connected due to high voltages. As a result of these connections the voltages decrease to acceptable levels and no further shunt reactor connections are made.

The simulation shows that in this case hunting can be avoided by a simple change of voltage/time delay settings.

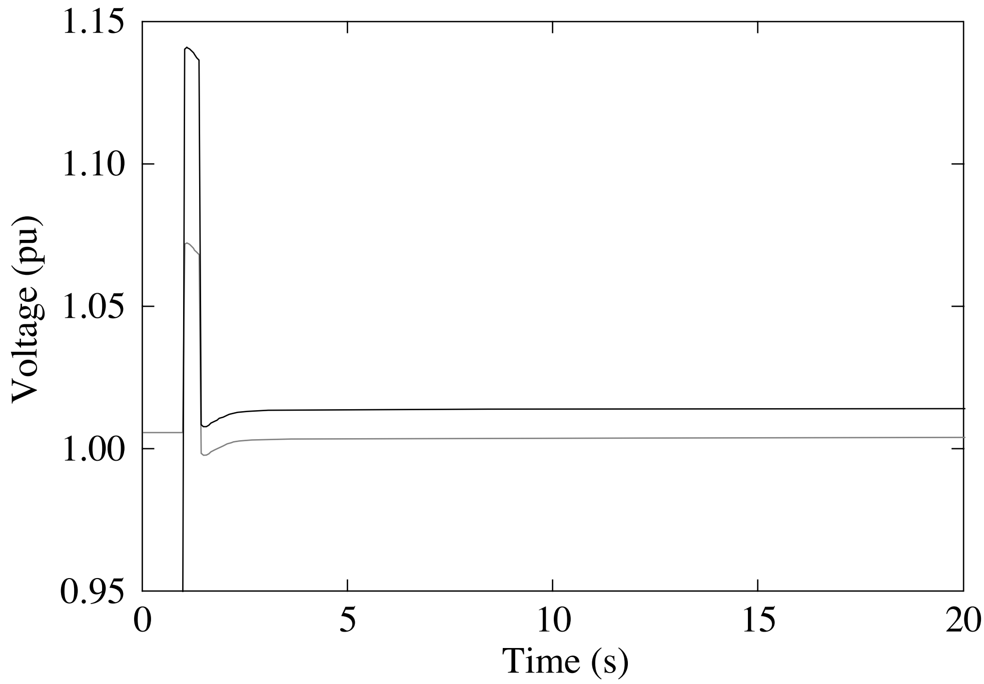

Figure 6.11 The voltages at the feeding and the receiving end of an unloaded transmission line. The shunt reactors in the same substation have different voltage levels and time delays for the automatics. Solid line: substation 4044 (receiving). Dotted line: substation 4032 (feeding).

In test case two of the Nordic 32 test system the ”Central” part of the system is already energized and an additional line, 4032-4044, is connected. When the line is energized the voltages in the regions ”North” and ”Central” increase too much which initiate a connection of two shunt reactors in the ”North” and two in the ”Central” part of the system (see figure 6.12) after 0.4 s. The connection of shunt reactors results in very low voltage levels both in region ”North” and ”Central” and two s later six reactors in ”Central” are disconnected. Since the voltages become too high four shunt reactors in ”Central” and two in ”North” are connected after additional 0.4 s. These connections give acceptable voltage levels in the system. In total 16 connections/disconnections are performed before the voltages are within tolerable levels.

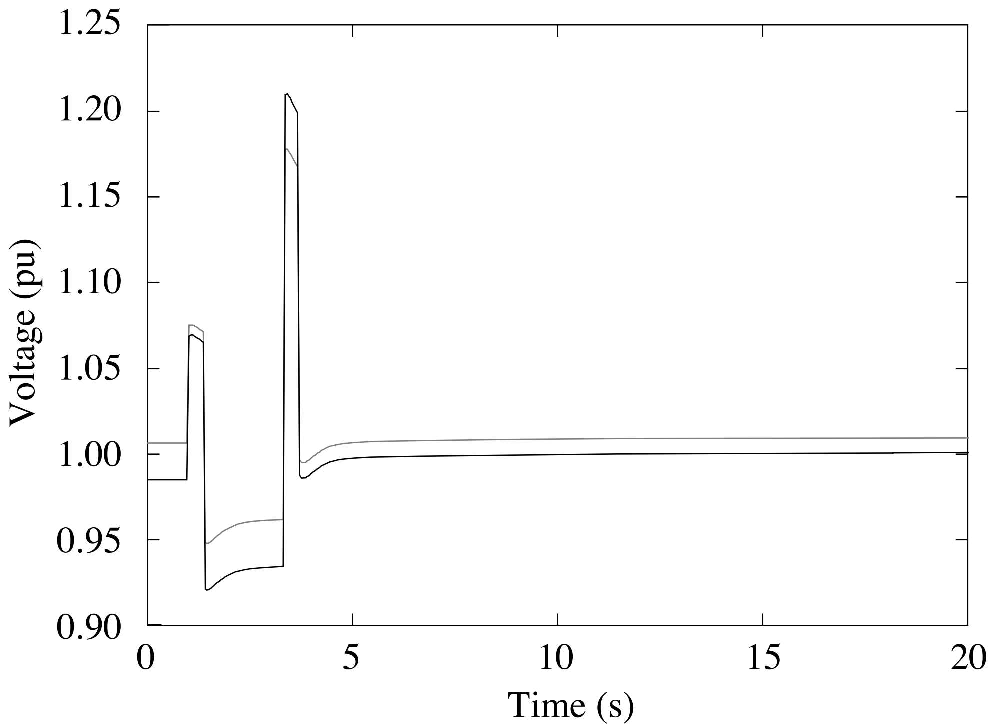

Figure 6.12 The voltages in the ”Central” part of the system following the connection of a line. 2.8 s after the line energizing the voltages are within tolerable levels and no further connections/disconnections are made. Solid line: substation 4044. Dotted line: substation 4041.

If time delays according to table 6.1 are used, the line energizing will only result in six connections/disconnections before the voltage profile is satisfactory.

The use of different voltage levels (see table 6.2) results in 14 connections/disconnections before the voltages are within acceptable levels.

Figure 6.13 shows the energizing of the line 4032-4044 when both different voltage set-points and time delays are used (see table 6.3). In total four connections/disconnections are made in the system before the voltage levels are acceptable.

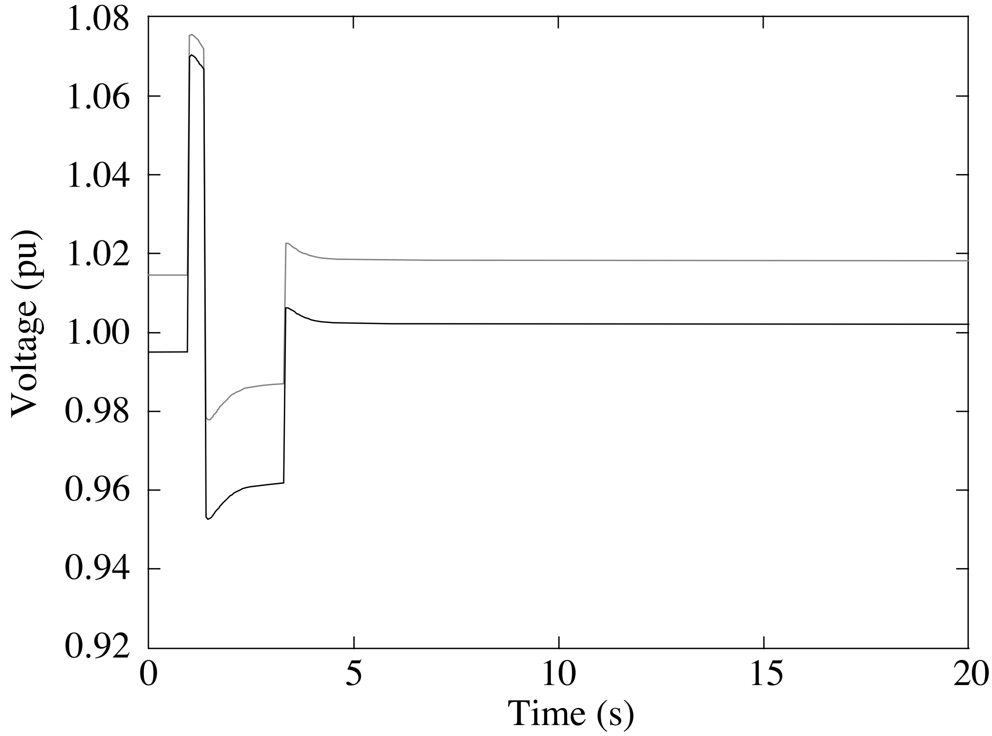

Figure 6.13 The voltages in the central part of the system following the connection of a line. 2.8 s after the line energizing the voltage levels are acceptable and no further connections/disconnections are made. Solid line: substation 4044. Dotted line: substation 4041. The time delays and voltage set-points are different for shunt reactors situated in the same station.

As the Nordic 32 test system only consists of a few stations it is of interest to verify the obtained results by using the 600 node reduction of the Nordel system (see 4.4.2). Therefore a number of simulations have been performed where a line in section 2 has been energized. The simulations have been carried out when the northern part of the system is in full operation and there are large generating margins in the hydro power stations (load 5100 MW and total generating capacity 11500

MVA). The line energizings are again made according to the instructions which are used during a restoration phase.

Figure 6.14, 6.15 and 6.16 show a simulation where the line from Borgvik to Kilanda is energized (see figure 2.1). Before this line is taken into operation the energizing of the section 2 line from Rätan to Borgvik has been performed. In Borgvik one of the shunt reactors (80 MVAr) is manually connected prior to this and thereby the voltage reaches an acceptable value. In Rätan substation the 200 MVAr shunt reactor is also connected before the energizing of the line.

When the line Borgvik-Kilanda is energized the voltage in Kilanda becomes too high and therefore the 200 MVAr shunt reactor in the station is connected. At the same time the second shunt reactor in Borgvik (80 MVAr) is connected due to high voltage. Since the reactive compensation becomes too large the voltages in Kilanda, Borgvik but also Rätan become too low and the reactors in Kilanda, Borgvik and Rätan are disconnected. These disconnections give a very high voltage level in Rätan, Borgvik, Kilanda and Storfinnforsen substations and consequently the reactors in Rätan (200 MVAr), Storfinnforsen (200 MVAr) and one of the reactors in Borgvik (80 MVAr) are connected. The second reactor in Borgvik and the reactor in Kilanda are not re-connected since their circuit-breaker springs must be recharged.

After 15 s the circuit-breaker spring in Kilanda is recharged and the shunt reactor in Kilanda is connected (We assume here that the circuit-breaker spring in Kilanda is recharged after only 15 s in order to observe the significance of varying charging times; all other circuit-breakers are here assumed to take around 20 s). As a result the voltages in Kilanda, Borgvik and Rätan become too low and the reactors in Kilanda, Rätan and the connected one in Borgvik are disconnected. The voltages become very high since no reactor is connected either in Kilanda, Borgvik or Rätan. The possibility to connect any of the reactors are blocked since all the circuit-breaker springs are deenergized. After 3.2 s the high voltages and the large reactive power production from the unloaded lines initiate a tripping of the line Rätan-Borgvik due to the reverse reactive power flow protection (see 2.3.6).

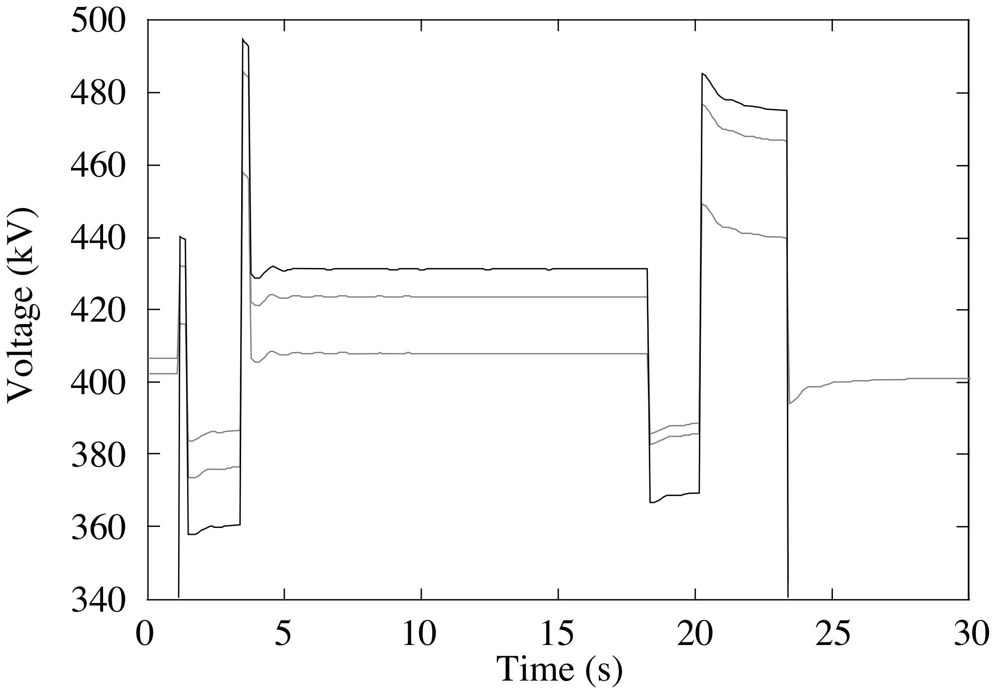

Figure 6.14 The voltages in Rätan (dotted line), Borgvik (dashed line) and Kilanda (solid line) substations following an energizing of the line from Borgvik to Kilanda.

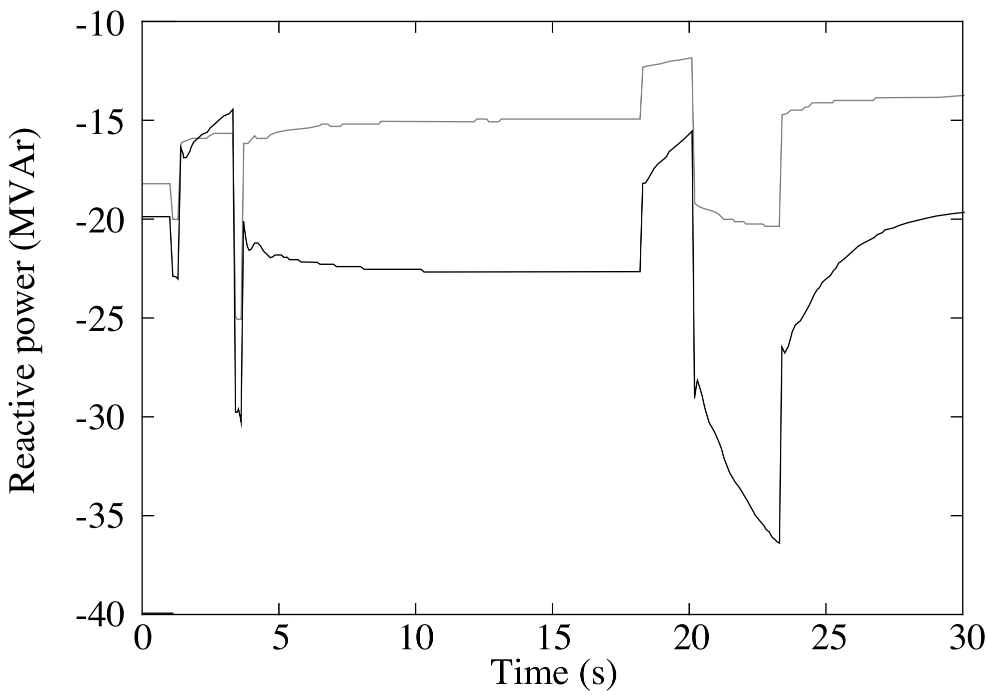

Figure 6.15 The reactive power production from generators in Rätan (solid line) and Storfinnforsen (dotted line) substations following the connection of line Borgvik-Kilanda. A negative sign indicates the generator absorbs reactive power.

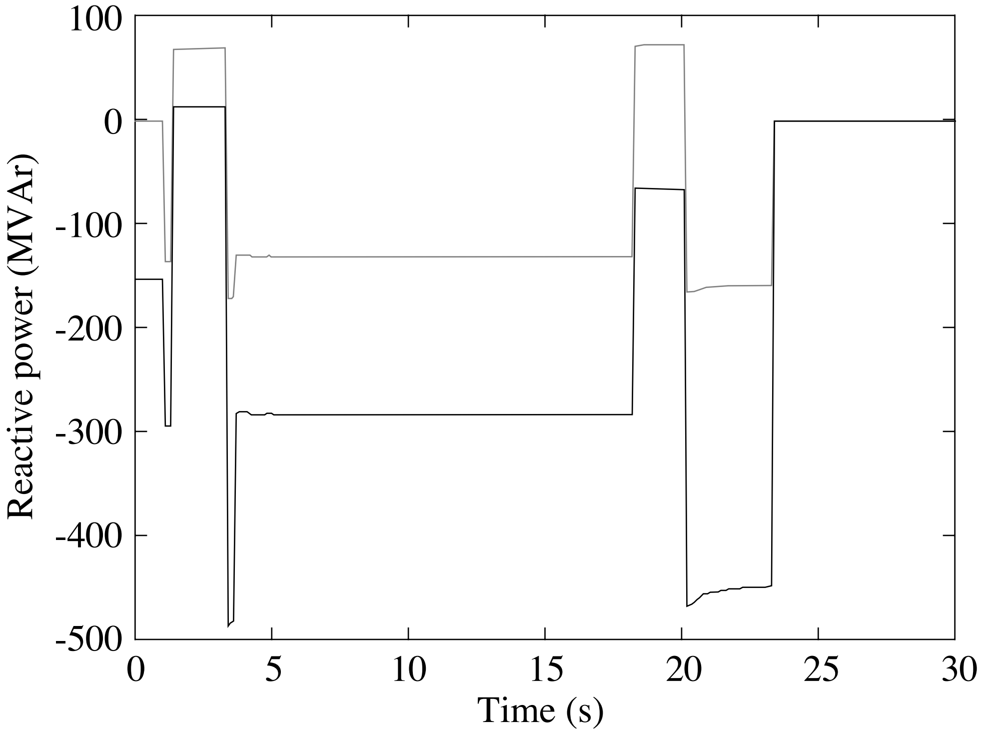

Figure 6.16 The reactive power transfer on the line Rätan-Borgvik (solid line) and the line Borgvik-Kilanda (dotted line) following the energizing of line Borgvik-Kilanda. A negative sign indicates reactive power production by the line.

Figure 6.17 shows the energizing of the same line (Borgvik-Kilanda) when the time delays of the shunt reactor automatics are shorter for the reactors in Borgvik compared with the time delay of the reactor in Kilanda. 0.4 s after the line energizing the second reactor in Borgvik is connected. As can be seen from the figure the voltages in Kilanda and Borgvik decrease below 425 kV and no more reactors are connected.

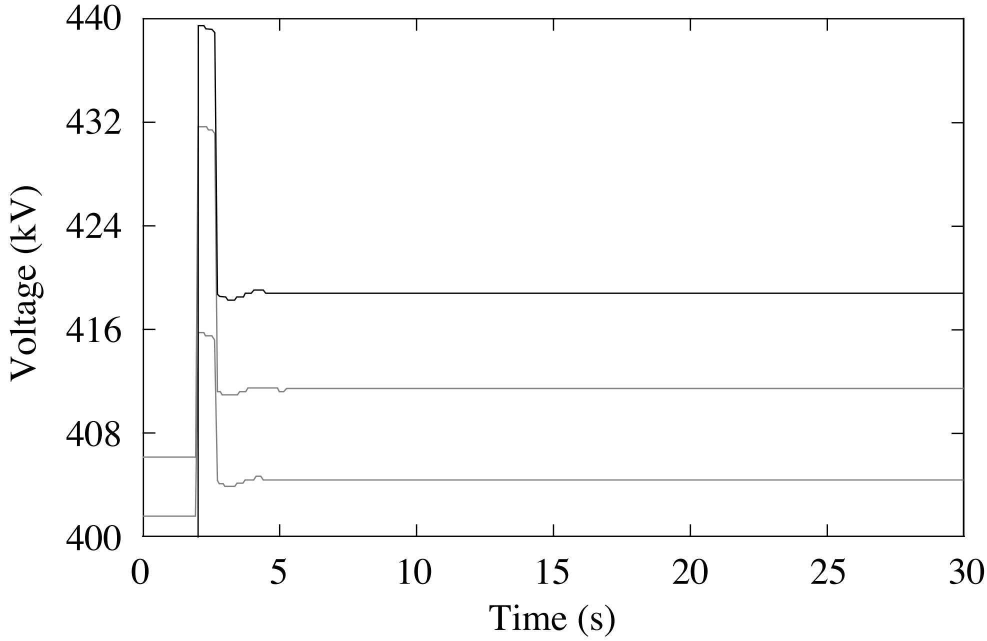

Figure 6.17 The voltages in Rätan (dotted line), Borgvik (dashed line) and Kilanda (solid line) substations following an energizing of the line from Borgvik to Kilanda. The time delays of the shunt reactors in Borgvik substation are shorter compared with the time delay of the shunt reactor in Kilanda substation.

The simulations on both the Nordic 32 test system and the 600 node reduction of the Nordel network have shown that there is a considerable risk of reactor hunting and even line tripping during restoration. If all the automatics have the same time delay a connection of a long transmission line may initiate hunting of many shunt reactors in the system resulting in large voltage fluctuations. In order to avoid this it is important to have a proper selectivity scheme for the shunt reactor automatics in the system. As shown this can be accomplished by varying the time delay and this is especially important in substations adjacent to long lines. In those stations containing more than one shunt reactor the voltage ranges of the automatics should be varied for all the reactors. Another alternative would be to use an inverse time mode for the reactor automatics with different time and voltage settings in order to achieve selectivity.

In some cases these proposals will not be sufficient to stop the hunting of a single reactor. It is then advisable to disconnect the automatics during the restoration process. Another possibility is to use a special working mode for the reactor automatics until the system is back to normal operation again. At any case a careful analysis will be necessary for different network topologies to avoid hunting during restoration.

6.2 Frequency control

The frequency control in the system has two major phases in time: one which is associated with the dynamic frequency behaviour and one which affects the stationary frequency control.

When connecting a load the mechanical power of the turbines will become less than the electrical power required by the network and this leads to a decreased frequency.

The total kinetic energy, W_k, in a system may be written as

$$W_k = \frac{1}{2}\omega^2 \sum J_n \tag{6.7}$$

where

ω = angular velocity [rad/s],
J_n = moment of inertia for each unit [kgm^2],
n = number of units.

About 95% of the rotating kinetic energy in the Swedish system is due to the generators and turbines whereas only 5% is related to motor loads [28].

The time derivative of the kinetic energy gives the difference between produced and consumed active power, ΔP, in the system. When connecting a load or disconnecting a generator in the system ΔP may also be seen as the active power of this load or the production loss due to the disconnected generator.

$$\omega \frac{d\omega}{dt} \sum J_n = -\Delta P \tag{6.8}$$

By using equation 6.7 and 6.8, the angular velocity derivative at the moment of the load (or production) change may be written as

$$\frac{d\omega}{dt} = \frac{-\Delta P \omega_0}{2W_k} \tag{6.9}$$

For each station there is usually a value given for the inertia, H_n, of the generator and the turbine. The total inertia of the stations in the system may therefore be written as

$$\sum H_n = \frac{W_k}{\sum S_n} \tag{6.10}$$

where S_n is the rated power of each generator in the system.

By using equation 6.10 in 6.9 together with the fact that the angular frequency, ω, is proportional to the network frequency, f, one obtains

$$\frac{df}{dt} = \frac{-\Delta P f_0}{2\sum S_n H_n} \tag{6.11}$$

The frequency decrease, following a load connection or a disconnection of a production plant in the Nordel network, lasts about 5 s until the balance between mechanical and electrical power is restored (see figure 6.18). The balance is mainly accomplished by the hydro turbine governors which increase the water flow. If the frequency decreases below certain levels other actions such as disconnection of electrical boilers and import from HVDC links will be automatically performed (see 2.3). If the power production set-points on the generators are not adjusted there will be a stationary frequency fault, Δf (see figure 6.18). The frequency fault is dependent on the static gain of the generators in the system, the active power mismatch between set-point value and actual value and the frequency dependency of the load.

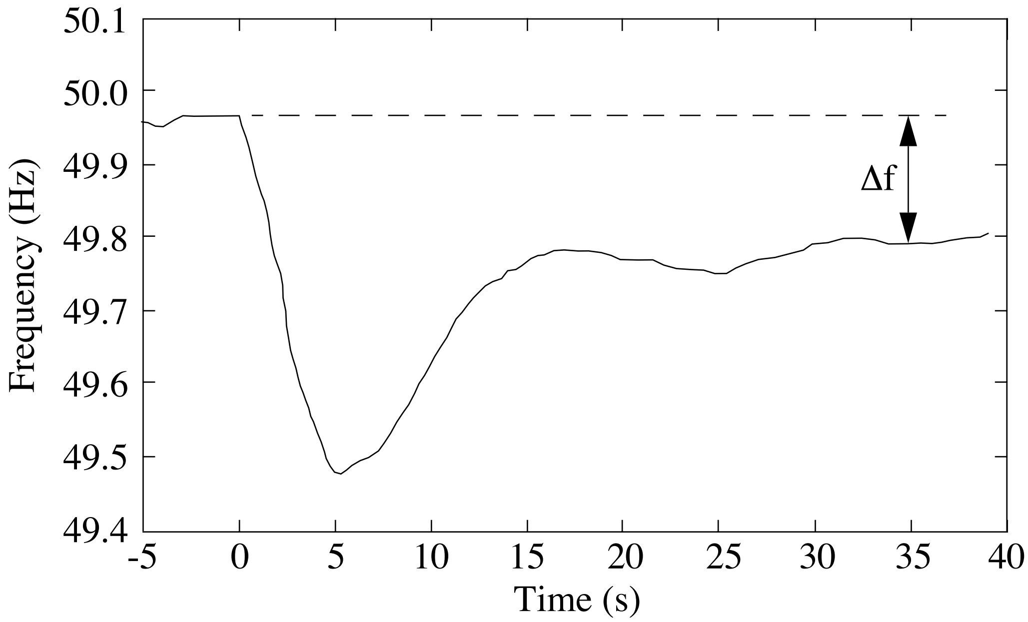

Figure 6.18 The frequency in the synchronized Nordel network following the disconnection of a large unit.

In order to be able to determine the stationary frequency fault following a load connection it is therefore essential to take the static gain from the generators in the system *and* the total load frequency dependency into account.

According to 5.4 the total load in the Swedish system is almost linearly dependent with the frequency. Consequently the total load in the system may be written as

$$P = P_0 + k_1 (f - f_0) \tag{6.12}$$

where

P_0 = total load in the system at nominal frequency [MW],
P = total load in the system [MW],
f = system frequency [Hz],
f_0 = nominal frequency [Hz],
k_1 = load frequency dependency in the system [MW/Hz].

If all loads are assumed to have the same linear frequency dependency (pu/Hz) the load frequency dependency in the system will be affected by the size of the load in the system according to the following equation

$$k_1 = P_0 k \tag{6.13}$$

where k is the frequency dependency for all loads [pu/Hz].

A combination of equation 6.12 and 6.13 results in equation 6.14.

$$P = P_0 + P_0 k (f - f_0) \tag{6.14}$$

The static gain from the load in the system, S_L, can be defined as

$$S_L = \frac{dP}{df} = P_0 k \tag{6.15}$$

and as can be seen is dependent on the load size in the system.

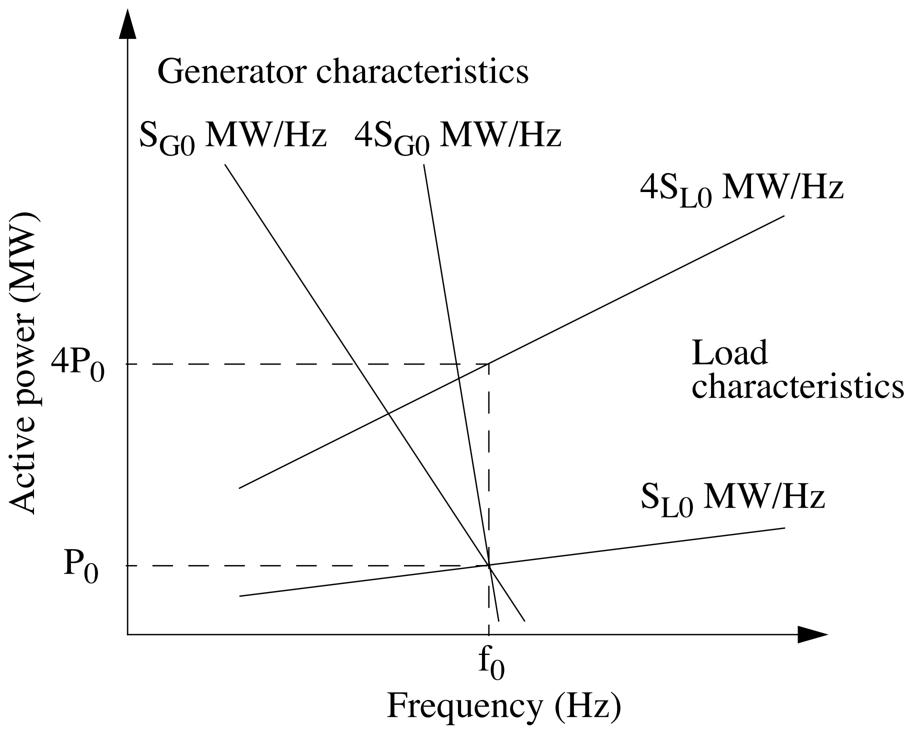

Figure 6.19 The total load frequency dependency (MW/Hz) in a system for different load levels and the generator characteristics for different values of the static gain. All loads in the system have the same frequency dependency (pu/Hz). The variation in static gain is due to the number of connected generators in the system or the variation in hydro turbine governor modes.

The static gain of the generators in the system, S_G, is defined as

$$S_G = \frac{-\Delta P_G}{f - f_0} \tag{6.16}$$

where ΔP_G is the active power mismatch between the actual value and set-point value of the generators in the system.

The static gain in the system may also be written as the sum of the static gain from all the generators in the system according to equation 6.17.

$$S_G = \sum_{n=1}^{m} S_{G_n} \tag{6.17}$$

where m is the number of generators in the system.

If a single load, ΔP_0, is connected, the total load, P, in the system may be written as

$$P = (P_0 + \Delta P_0) + (P_0 + \Delta P_0)k(f - f_0) \tag{6.18}$$

The production from all the generators in the system can be written as

$$P_G = P_0 - S_G(f - f_0) \tag{6.19}$$

Since the total load is equal to the production from all the generators in the system ($P = P_G$) a combination of equation 6.18 and 6.19 results in

$$(P_0 + \Delta P_0) + (P_0 + \Delta P_0)k(f - f_0) = P_0 - S_G(f - f_0) \tag{6.20}$$

The use of equation 6.15 in equation 6.20 gives after rewriting

$$\frac{-\Delta P_0}{f - f_0} = \left(1 + \frac{\Delta P_0}{P_0}\right)P_0 k + S_G = \left(1 + \frac{\Delta P_0}{P_0}\right)S_L + S_G \tag{6.21}$$

If equation 6.17 is used for the static gain of the generator and P_0 is assumed to be considerably larger than ΔP_0 equation 6.21 may be rewritten as

$$\frac{-\Delta P_0}{f - f_0} = S_L + S_G = \sum_{n=1}^{m} S_{G_n} + P_0 k = S \tag{6.22}$$

where S denotes the total static gain in the system and includes the static gain from the generators in the system *and* the load frequency dependency.

The equation of the total static gain in a system is demonstrated in figure 6.20 where a single load, ΔP_0, is connected. If the total load would have been frequency independent the total load following the load connection would have been P' and the frequency f'. If the load frequency dependency is taken into account the total load in the system following a load connection will be P (P<P') and the frequency f (f>f'). The difference between the load levels P' and P is the decrease of the total load due to its frequency dependency and is denoted ΔP_L in the figure. By combining the effect from the generator static gain and the load frequency dependency a total static gain curve, S, may be plotted as is shown. When using this new curve, however, the y axis denotes the value of the connected single load, ΔP_0, and not the total load in the system.

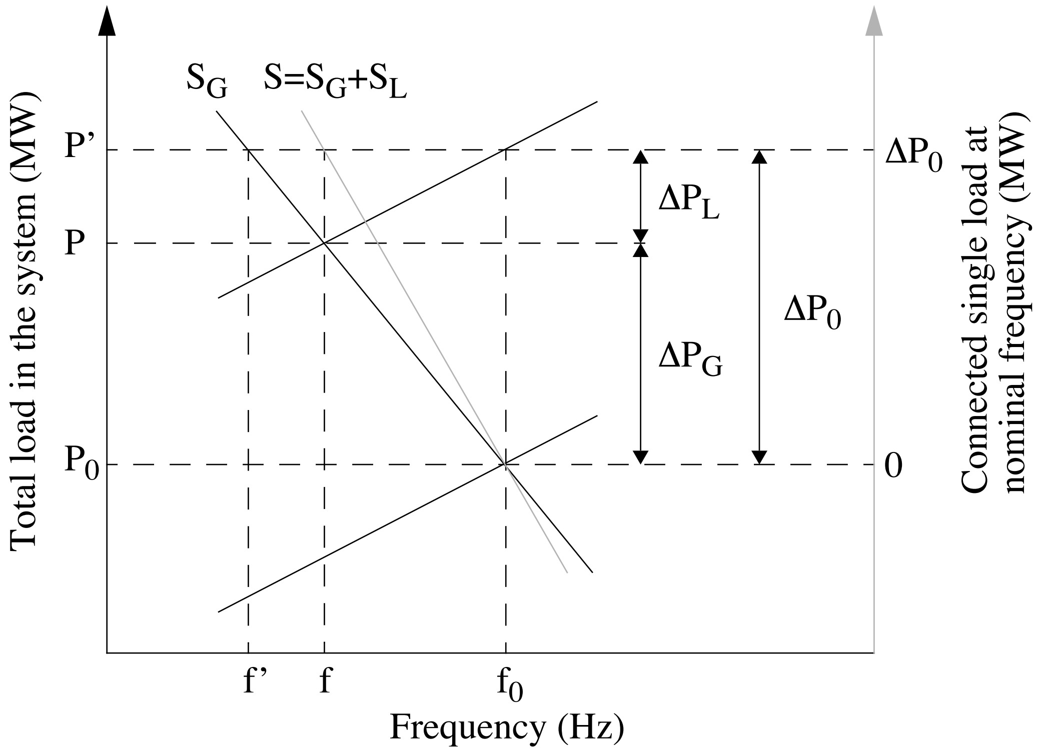

Figure 6.20 The frequency and power production response in the system following a connection of a load. All loads in the system have the same load frequency dependency (pu/Hz).

6.2.1 Simulations

In order to study the frequency response when the load varies a number of simulations have been performed using the Nordic 32 test system. During the simulations the total inertia in the system and the hydro turbine governor modes have been varied. In the Swedish system the hydro turbine governor will change operating mode when certain conditions for the frequency and the frequency derivative are fulfilled (see 2.2). However, it is not possible to change the operating mode during the simulation and therefore the hydro turbine governors have the same operating mode throughout the whole simulation. Parameters according to table 6.1 have been used for the different modes of the hydro turbine governor.

Figure 6.21 shows two simulations where the total inertia in the system has been varied. As can be seen from the figure, and in agreement with equation 6.11, an increased inertia in the system will result in a lower frequency derivative and consequently the maximum frequency deviation will be less. This is due to the fact that the hydro turbine governors will have ”more time” to regulate the water flow.

Mode	P (pu)	R (pu)	T_r (s)	T_G (s)
Ep0	1.5	0.1	45	0.5
Ep1	3	0.04	45	0.5
Ep2	3	0.02	60	0.5
Ep3	1	0.004	78	0.5
Ep3’	0.1	0.02	5	0.5

Table 6.1 Parameters for the different modes of the hydro turbine governor which have been used during the simulations. P denotes proportional regulation, R permanent droop, T_r integrating time constant and T_G servo time constant.

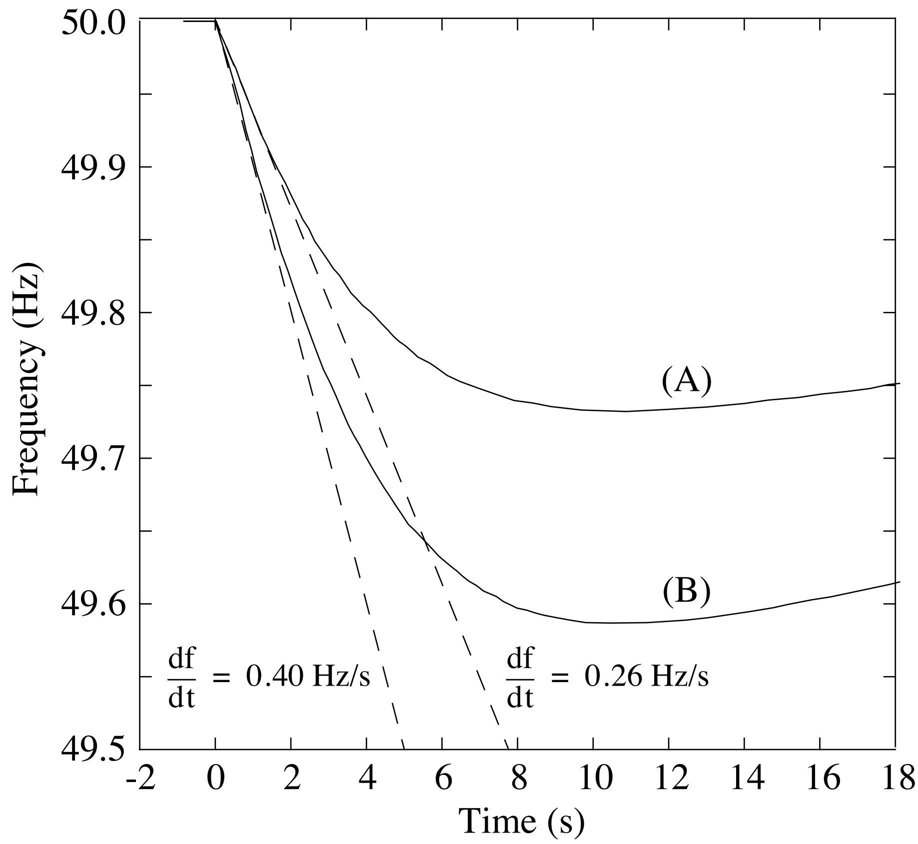

Figure 6.21 The frequency response following a 50 MW load connection. The total kinetic energy in the system is 19350 MWs (A) and 12450 MWs (B) respectively. The hydro turbine governor modes are working in mode Ep0 in both simulations.

Figure 6.22 shows simulations where different hydro turbine governor modes have been used. In the curves Ep0-Ep3 all the generators have been equipped with the same operating mode whereas in Ep3' 15% of the hydro turbine governors have been equipped with the Ep3' mode and the remaining with mode Ep3. The reason for using 15% Ep3' is that in the Swedish system the approximate fraction of hydro turbine governors equipped with this operating mode is 15% [7].

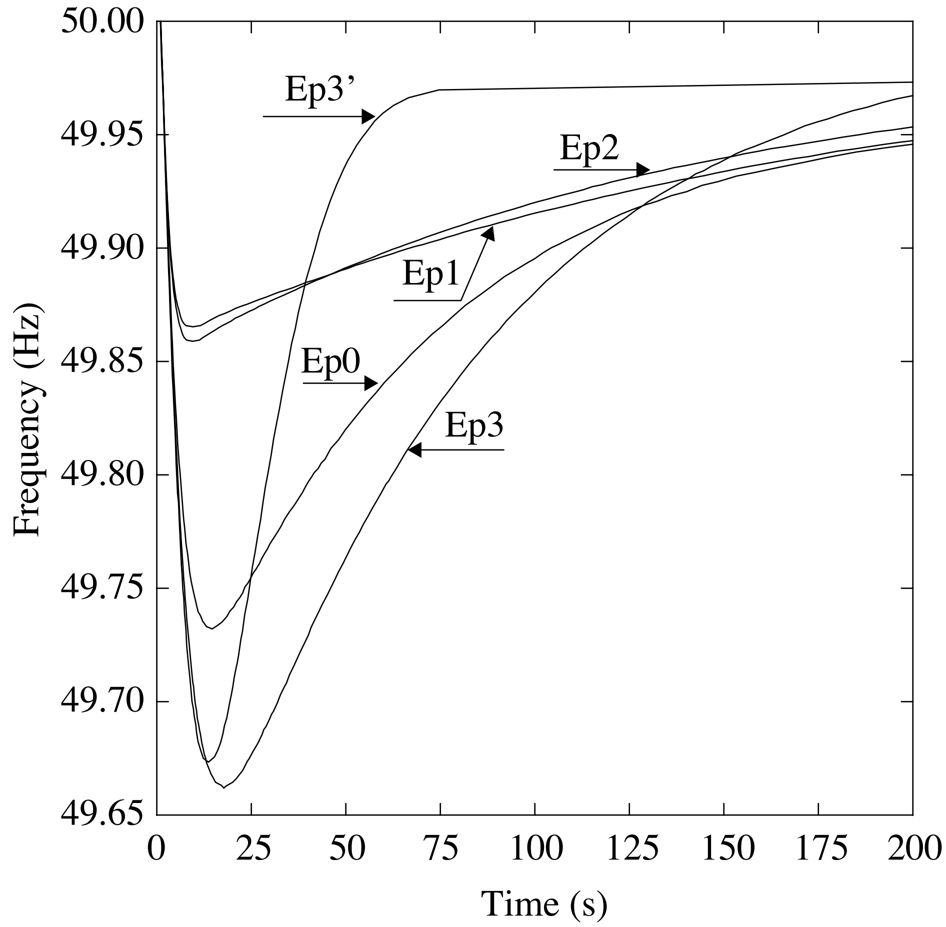

Figure 6.22 The frequency behaviour following a 50 MW load connection for five different working modes of the hydro turbine governor. The connected capacity is 6250 MVA and the load before the load connection was 1180 MW.

As can be seen from figure 6.22 the frequency decrease in operating mode Ep0 is larger compared to Ep1 and Ep2. Since the droop in mode Ep0 is larger than in mode Ep1 and Ep2 the stationary frequency fault will also be larger. Mode Ep3 which have a high static gain will give a very small stationary frequency fault in the system. However, the frequency will decrease much after the load connection since the proportional regulation is low and the integrating time constant is very long. Mode Ep3' which only can be automatically connected will rapidly restore the frequency back to a normal value. Since the proportional regulation is very low for mode Ep3' the initial frequency decrease will be substantial also in this mode. Based on the behaviour of the different modes it might be better to use Ep1 and Ep2 instead of Ep0 during a restoration process in order to keep the frequency deviations as low as possible.

6.3 The use of HVDC during a restoration

As described in 2.3.1 Sweden has some HVDC links which connect the south of Sweden with Finland, Jylland in Denmark and Germany. In case of a blackout in the system these links can give power support to certain areas.

6.3.1 Description of the main circuit of a HVDC station

A normal layout of the main circuit of a converter station is shown in figure 6.23 [11].

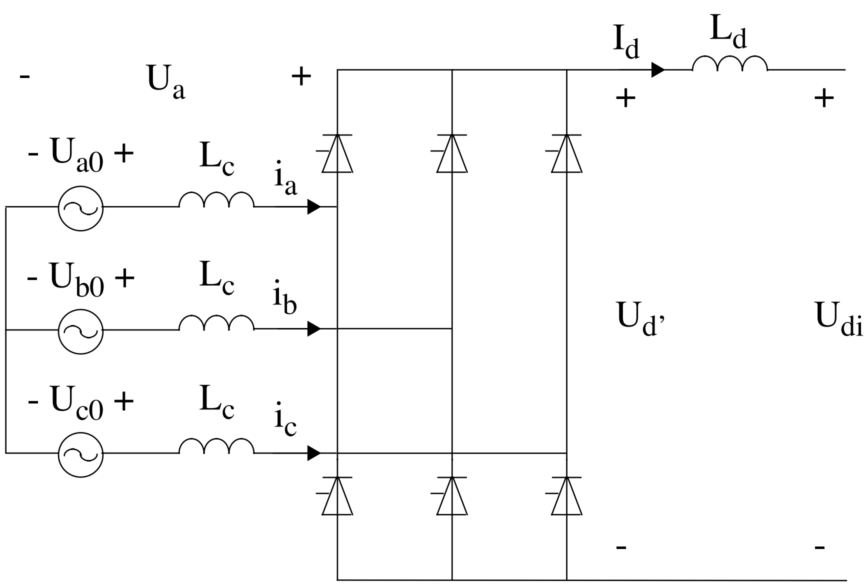

Figure 6.23 Two-way 6-pulse converter station. U_a denotes phase voltage, U_{a0}, U_{b0} and U_{c0} phase voltage, $U_{d'}$ voltage over the converter bridge, U_{di} dc voltage, i_a, i_b and i_c phase current, I_d dc current, L_c commutation inductance and L_d inductance on the dc side.

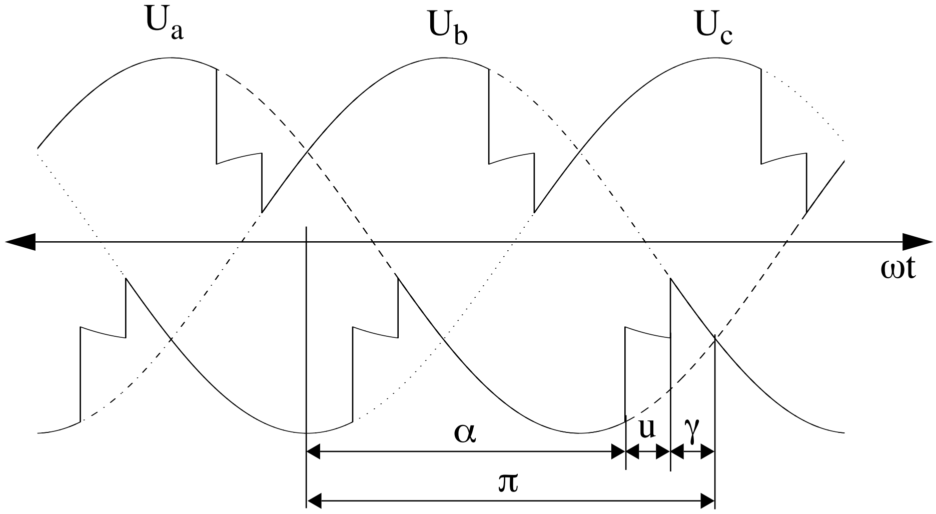

Figure 6.24 Phase voltages U_a, U_b and U_c at inverter operation. α denotes firing angle, u commutation angle and γ extinction angle.

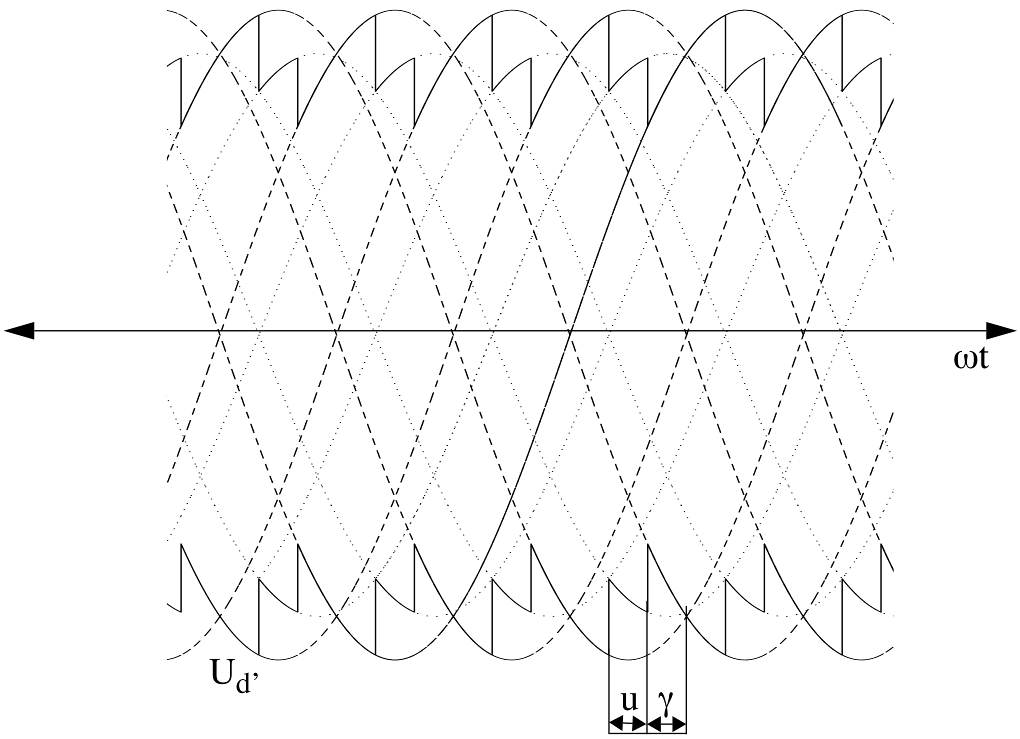

Figure 6.25 Voltage over the converter bridge, $U_{d'}$ in inverter operation. α denotes firing angle, u commutation angle and γ extinction angle.

During normal operation two or three valves will be conducting simultaneously. Commutation from one valve to another will depend on a number of factors. If the dc current is assumed to be constant the following equation may be written for inverter operation [11]

$$\cos\gamma - \cos(\gamma + u) = \frac{\sqrt{2}\omega L_c I_d}{U} \tag{6.23}$$

where

U = phase to phase voltage [kV],
ω = angular frequency [rad/s].

The commutation inductance is related to both the transformer inductance and the short circuit inductance from the feeding network as

$$L_c = L_t + L_s \tag{6.24}$$

where

L_t = transformer inductance [H],
L_s = short circuit inductance [H].

The relation between the short circuit power, S_s, and the short circuit inductance is

$$S_s = \frac{U^2}{\omega L_s} \tag{6.25}$$

In weak networks (low short circuit power) is $L_s >> L_t$. By using this in combination with equation 6.23 and 6.24 gives the following equation for the dc current

$$I_d = \frac{S_s(\cos\gamma - \cos(\gamma + u))}{\sqrt{2}U} \tag{6.26}$$

The dc voltage over the line, U_{di}, in inverter operation may be written as [11]

$$U_{di} = -\frac{3\sqrt{2}U}{\pi}\left(\frac{\cos\gamma + \cos(\gamma + u)}{2}\right) \tag{6.27}$$

By multiplying the dc voltage and the dc current the transferred power on the line may be written as

$$P = U_{di} I_d = -\frac{3S_s}{2\pi}(\cos^2\gamma - \cos^2(\gamma + u)) \qquad (6.28)$$

As can be seen from equation 6.28 the transferred power is strongly associated with the short circuit power and the extinction and commutation angles. In normal operation the extinction angle should be more than 17-18 degrees and the commutation angle for a six-pulse inverter can be from 0 to 60 degrees. This means that the factor between brackets is always < 1.

6.3.2 Possibilities to use HVDC during the restoration

In case of a weak network around the inverter station or an area with a total blackout the short circuit power will be low or zero. According to equation 6.28 this will give a low or zero active power transfer on the line.

Based on this explanation the HVDC links can not be used unless their inverter stations are energized from other lines than the HVDC links. However, they will give a valuable power support during the further restoration process when there usually is a lack of power in the system.

Chapter 7 Island operation

The possibility of island operation is seldom used in Sweden. As there is much hydro power available which is easily regulated there is no technical difficulty to run parts of the system in island operation. Large sections of the northern part of Sweden could be operated with only hydro power. In the south were the production is dominantly nuclear power it should be possible to operate each nuclear power station in combination with gas turbines, oil and coal fired power stations and some hydro stations in island operation. Areas around the rivers in the southern sections may also be run as an island grid. However, running a system in island operation is not as safe and economical as being synchronized to the main grid. In the island the spontaneous load variations will be relatively larger compared with the synchronized nordic power system and this will result in larger frequency fluctuations (±0.1 Hz is tolerable in the Nordel system during normal operation). Naturally the island contains a primary frequency regulation which will take care of the frequency fluctuations. However, the Swedish system does not contain any secondary frequency regulation and therefore an operator has to change the power set-point values in order to avoid a stationary frequency fault.

In case of extreme circumstances (e.g. a war situation) severe interruptions and/or a collapse of the main grid is possible. In these circumstances it may be advantageous to use island operation as an operating mode. In order to verify this possibility it is important to make field measurements. During the project some field measurements have been made on systems which have been run in an island grid. The purpose with these field studies has been to verify station equipment such as blackstart capability and the functioning of the hydro turbine governor. Another important part of these tests has been the training of the station personnel so that they know how to act during these extraordinary occasions.

7.1 Test of the blackstart capability in the north of Sweden

In may 1994 Svenska Kraftnät and Vattenfall performed a blackstart in two hydro power stations in the north of Sweden [2]. These two stations are important since in case of a total blackout the restoration of the Swedish system starts from these stations. The power stations are equipped with a number of generators and two in each station have blackstart capability.

In order to verify the blackstart equipment, four tests were performed on the generators. First the station was disconnected from the network. As a result the battery backup took over the power supply to control equipment and emergency lighting. The diesel generator started in order to supply the station with power. When power was available it was possible to start a hydro unit and it only took some minutes before the hydro unit had taken over the power supply of the station from the diesel generator. The diesel generator then operated in parallel during some minutes to secure power in case of a fault in the hydro unit. All these steps will be made automatically following a blackout in the system and nothing more will happen until the station personnel continues the restoration process.

The second part of the test was carried out manually with the help of written instructions.The busbars were energized and after that it was possible to connect the line between the two stations and synchronize them. The remaining generators in the stations were started and synchronized. During the synchronizing some of the generators had a tendency to take up load and since the load was almost zero some of the other machines therefore operated as motors and were tripped due to the reverse power protection. In order to receive some load in the system some of the generators were run in synchronous operation (i.e. connected to the system but without any water flow).

The last step during the test was to energize a long transmission line in order to study the network response. Initially after the energizing of the line the voltage increased but after only a second the voltage regulation in the synchronous machines had regulated the voltage back to a normal level. The frequency change during the energizing was hardly noticeable due to the fact that very little active load was connected (only line losses) and the system inertia was quite high.

7.2 Test of Röttle power station

Röttle hydro power station which is situated close to Gränna is equipped with a generator of 7.2 MVA. The power station is mostly used during high load occasions but since Gränna is only connected with one 40 kV overhead line the possibility to run the station in island operation during fault or maintenance work is of a vital interest. Following a revision of the station which was made in 1994 a new voltage regulator and a hydro turbine governor was installed. The governor has four different modes with various parameters for the PID regulator and the static gain. In May 1995 a test was performed in order to check the new equipment and the possibility to blackstart and run the station in island operation.

The test was divided into two parts, where the first part was to verify the possibility to run the station in island operation and the second part was to study the blackstart capability of the station. In order to have a proper load in the area some of the loads were fed from another direction. The under- and over-frequency protection relay (47 and 52 Hz with a time delay of 10 seconds) for the generator was also blocked since the frequency variations could be expected to be rather high.

7.2.1 Test of island operation

The disconnection from the main grid caused a small increase in the power production since it is difficult to adjust the power production exactly to the consumption (see figure 7.1). The frequency in the island fluctuated much more compared to the stable frequency which is achieved in a large power system. However, the station had no problems to regulate the frequency of the system.

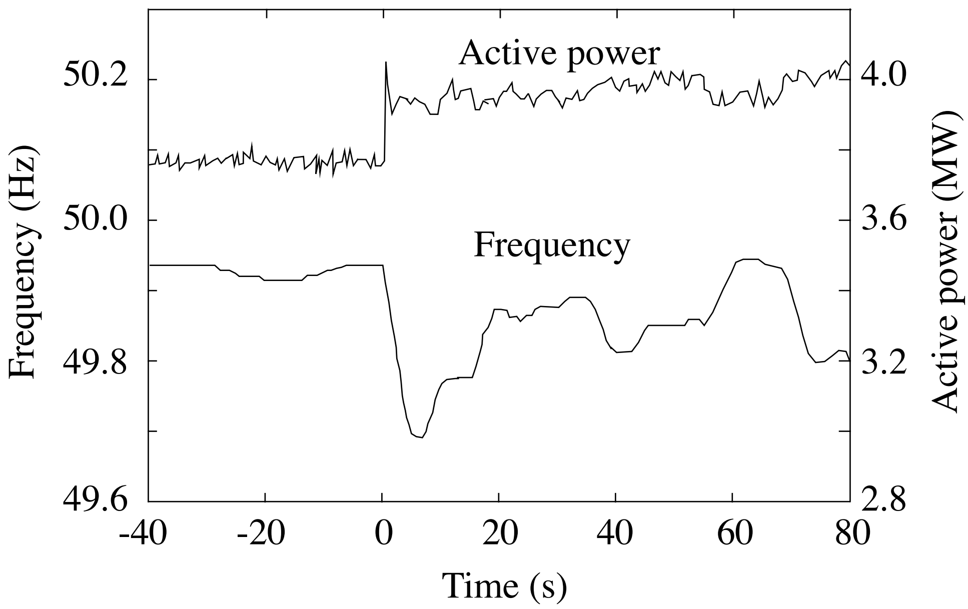

Figure 7.1 The frequency and active power production response in the island following a disconnection from the main grid.

The next step was to disconnect a load from the system and then reconnect it in order to study the behaviour of the generator. The size of the load was approximately 0.5 MW which corresponded to more than 10% of the station generation. The disconnection resulted in a frequency increase of 1.8 Hz but as can be seen from figure 7.2 the frequency went back to a stationary level within 30-40 seconds.

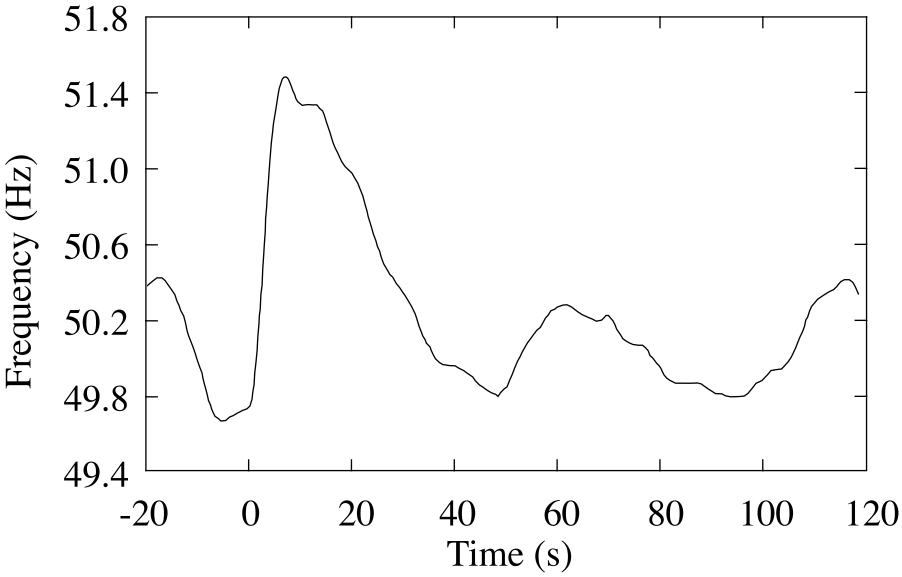

Figure 7.2 The frequency response in the island following a disconnection of a load.

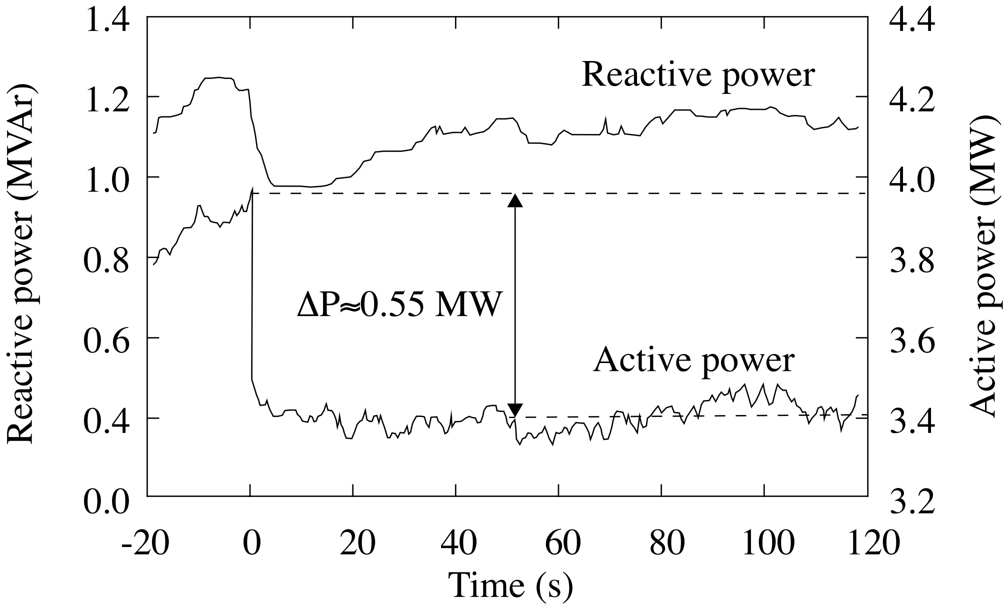

Figure 7.3 The active and reactive power production response in the island following a disconnection of a load.

After about 6 minutes the load was reconnected (see figure 7.4 and 7.5). As can be seen from figure 7.5 there will be a peak in the active and reactive power consumption which lasts less than two seconds. This peak originates from the heating and the start up of asynchronous machines in refrigerators freezers etc. (see 5.2.6). The frequency decreases 1.8 Hz due to the reconnection. A comparison between the values of the disconnected and reconnected load (50 s after the disconnection/reconnection when the frequency is back to a normal value) shows that they are almost the same. The cold load pick-up phenomenon will not be as obvious as for the electrical heating load shown in figure 5.9. This is due to the fact that the duration of the outage only was 6 minutes and the outside temperature was quite high.

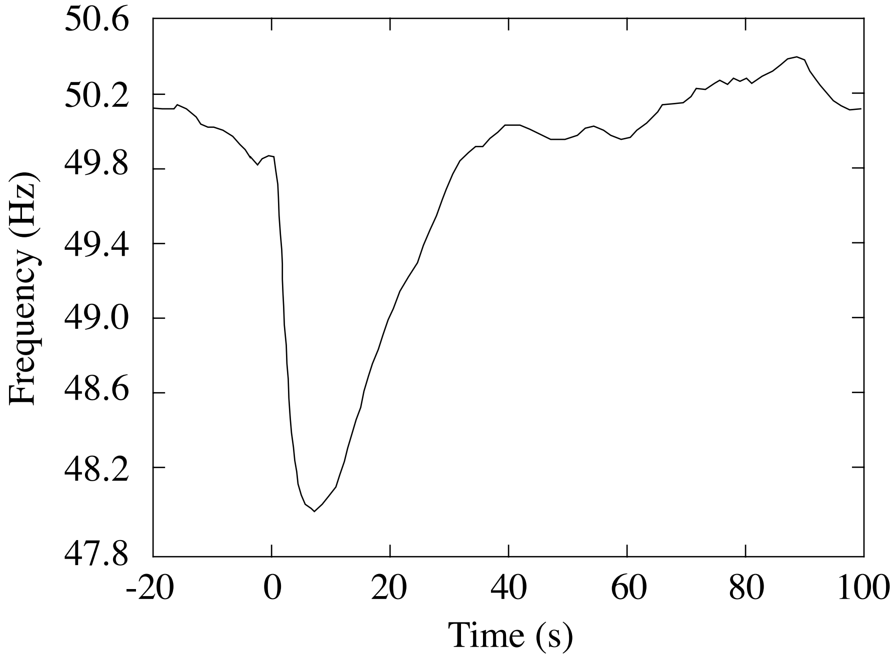

Figure 7.4 The frequency response in the island following a reconnection of a load.

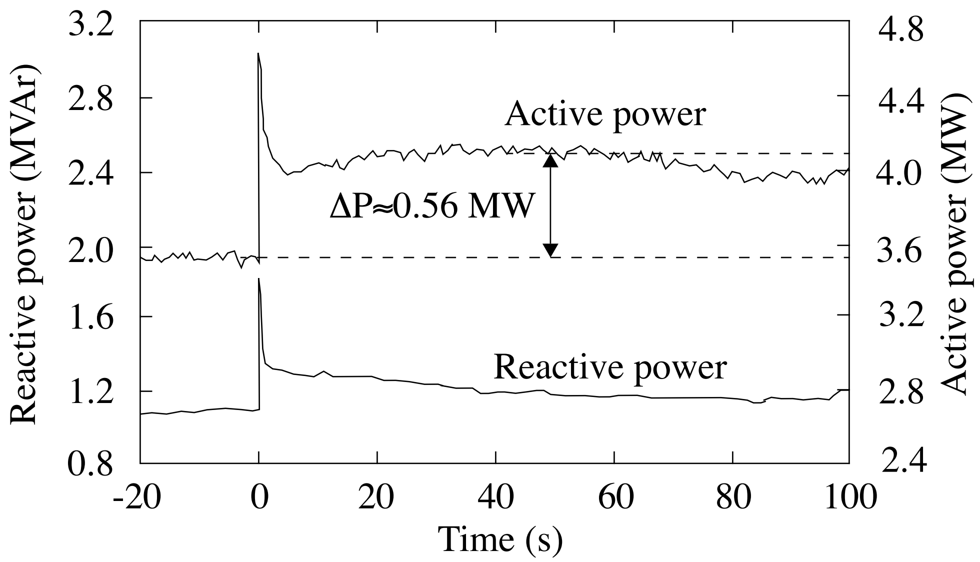

Figure 7.5 The active and reactive response in the island following a reconnection of a load.

After the load was reconnected the test was finished by synchronizing the island with the main grid.

7.2.2 Test of the blackstart capability

After the islanding test a blackstart of the station was performed. The generator was shut down and the 40 kV feeder was disconnected. The batteries took over the power supply of the control equipment and emergency lighting. By opening the water supply to the turbine it was possible to start up the turbine and the generator. Since there is remanence in the rotor of the generator it is possible start it without an external voltage source for magnetization.

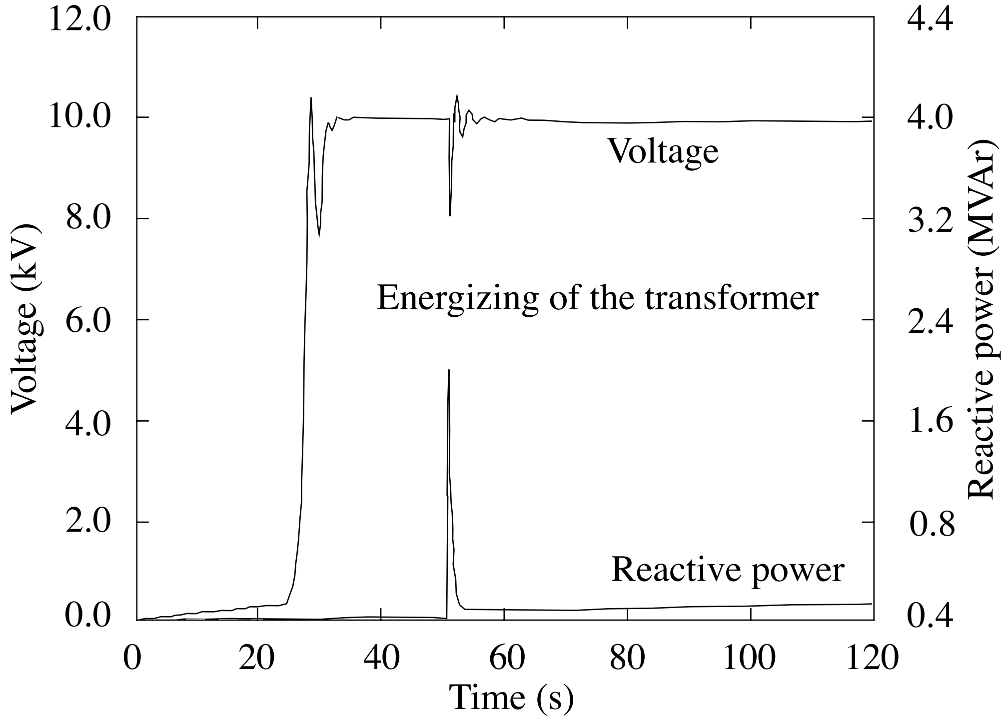

Figure 7.6 Blackstart of Röttle power station followed by an energizing of the transformer.

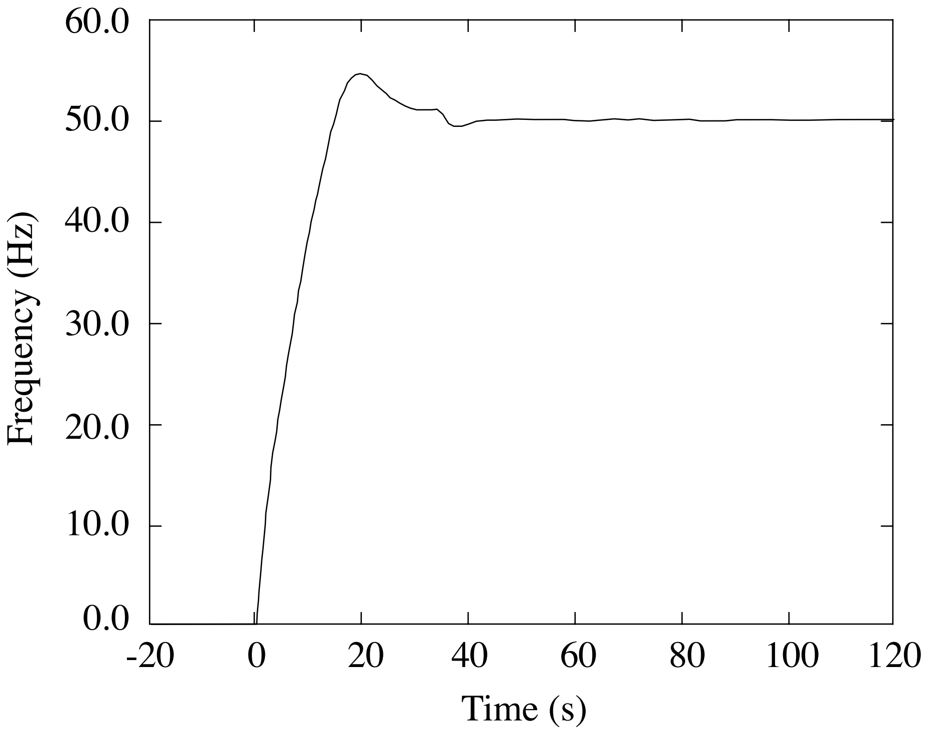

Figure 7.7 Blackstart of Röttle power station followed by an energizing of the transformer.

Following the blackstart of the station and the energizing of the transformer the load was reconnected step by step. Figure 7.8 and 7.9 show the reconnection of the same load as in figure 7.4 and 7.5. As can be seen the reconnected load is higher when compared with the first test and the reason for this may be the increase in consumption due to the normal consumption behaviour in combination with the cold load pick-up phenomenon. The duration of the outage was about 20 minutes compared to the first outage which only lasted 6 minutes.

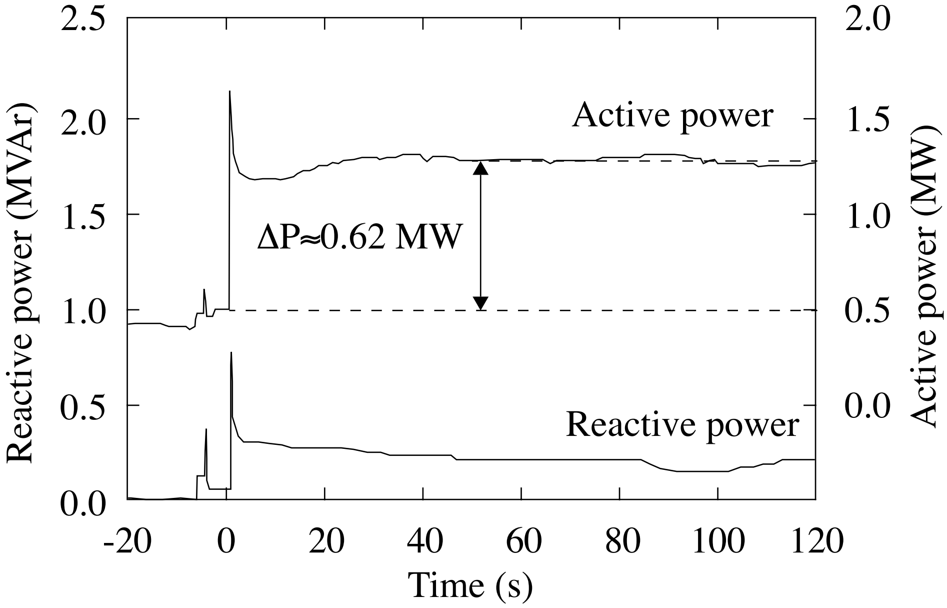

Figure 7.8 Active and reactive power production response in the island following a partial reconnection of the load.

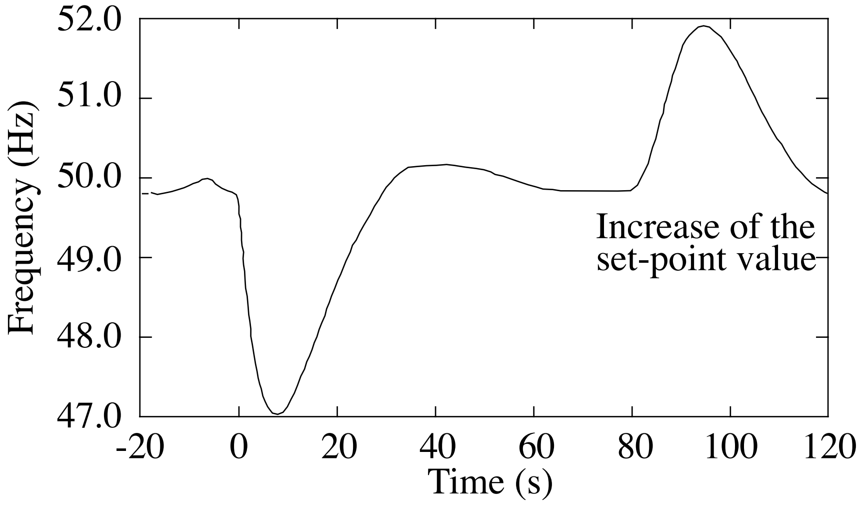

Figure 7.9 Frequency response in the island following a partial reconnection of the load.

After 70 minutes and a number of load reconnections the entire system was restored and 20 minutes later the island was synchronized with the main grid.

7.3 Test of Yngredsfors power station

In August 1995 a field test was performed on an island grid in Ätrandalen [8]. The area of Ätrandalen consists of a number of small hydro power stations and is rather weakly connected to the main grid. The load consists of countryside with farms and houses, a few industries, some villages and a shopping centre. The production capacity in the area is more than the consumption and normally the area exports power to the main grid. Ätrandalen was one of the few places which succeeded to stay in operation as an island during the blackout in 1983 (more about this blackout in 3.2.2). Based on this fact the area is deemed suitable for island operation.

The field study was made during a summer night which corresponds to a light load occasion. Reasons for making the test during the night were that the spontaneous load variations are less, the load is at a minimum and the consequences following an interruption will be minimized. Since the load in such a situation is very small only one station had to be used during the test. The most suitable station was Yngredsfors power station which has two generators. Due to the low load it was sufficient to use only one of the generators in the station.

In order to establish island operation all hydro stations were shut down with the exception of one generator in Yngredsfors power station. When disconnecting the system from the main grid it is important that the power production in the area is approximately the same as the consumption. Therefore the production from the generator was adjusted until the power flow on the line to the main grid was about zero. Figure 7.10 shows the active power production and the frequency variation in the network. After the initial frequency peak, which was caused by the mismatch between production and consumption in the area, the frequency is regulated back to a normal level. As can be seen the frequency fluctuation will increase much when running the system in island operation as compared to the normal synchronized case. The frequency deviation is in the range of ±0.2 Hz and is explained by the increased fraction of the spontaneous load variations and the decreased stability which results from the fact that only one generator is in operation.

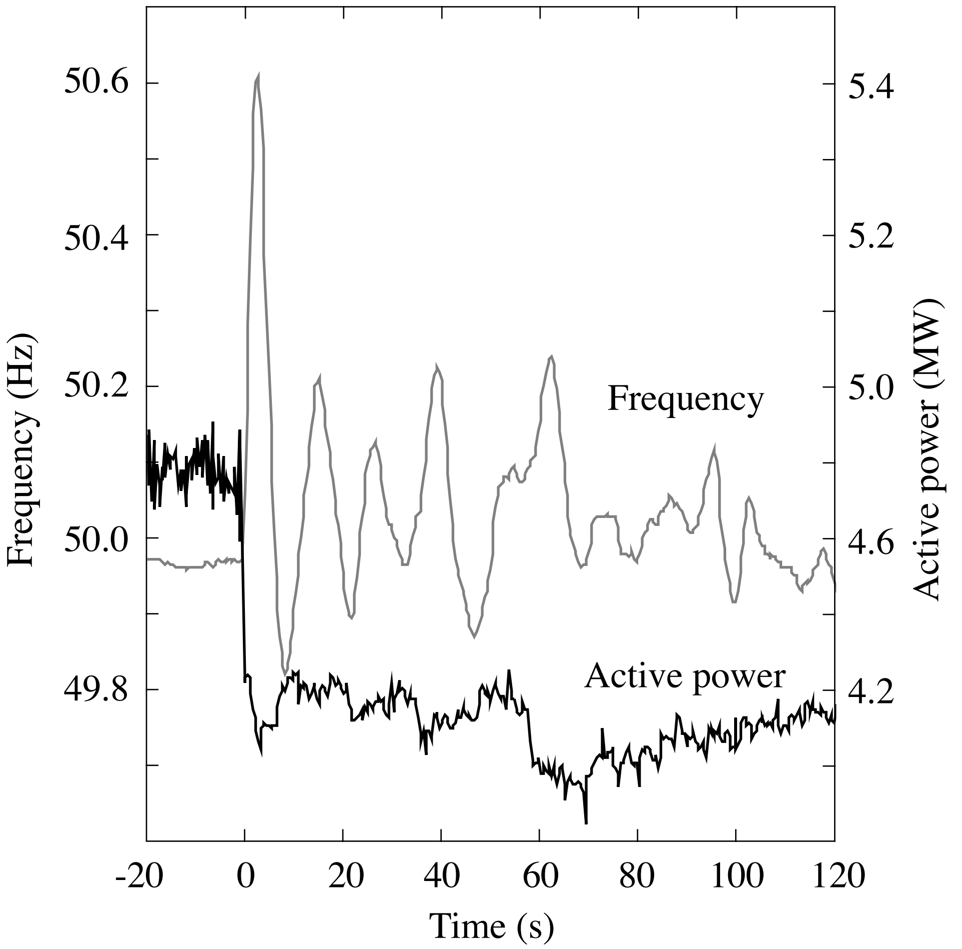

Figure 7.10 Active power production and frequency response in Yngredsfors hydro power station following the establishment of an island grid in Ätrandalen.

The next part of the field study was to initiate a frequency increase/decrease in order to study the system response. The frequency change was achieved by changing the power set-point of the generator. When trying to make a rapid change in the frequency oscillations occurred and the station was tripped manually. After restarting the station the test continued but instead of changing the power set-point the frequency set-point was regulated. This worked better and some measurements were made until the same problem with an oscillating frequency occurred and the generator had to be manually tripped.

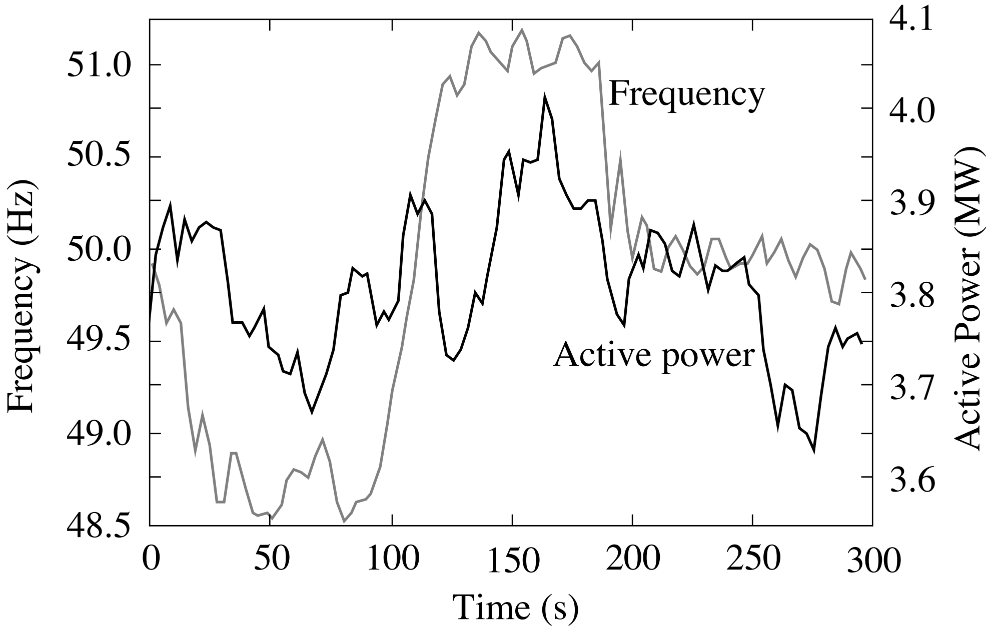

Figure 7.11 Active power and frequency following a step change in the frequency.

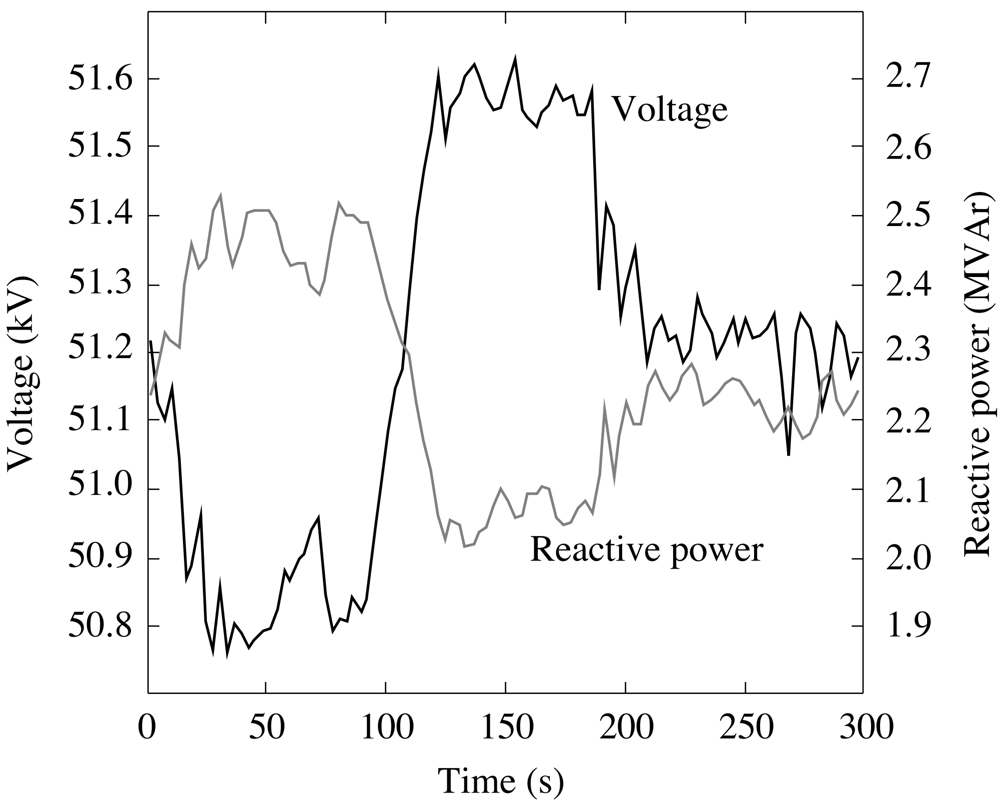

Figure 7.12 Reactive power and voltage following a step change of the frequency.

The measurements show that a change in the frequency affects the active and reactive power consumption. However, as also the voltage is affected the change in power consumption is a result of both the change in frequency and voltage. More about the frequency dependency of the load is found in 5.4.

7.4 Example of other tests made in the Swedish system

In Sydkrafts distribution area in the south of Sweden some field studies have been performed on the blackstart capability of stations.

In August 1984 a test was made in order to study the possibility to supply Barsebäck nuclear power station with emergency power. The test system included some gas turbines and hydro power stations and the total production capacity in the system was about 190 MW. A 25 MVAr synchronous compensator was also included in order to obtain a more stable voltage. The grid contained 370 km 130 kV lines and 20 km 50 kV lines.

The test started with a blackstart of a gas turbine followed by energizing of lines to the other stations. More production capacity and the synchronous compensator were connected to the system. In a real situation large pumps for the cooling system in the nuclear power stations and other thermal power stations will start and in order to study the system response asynchronous machines of 0.8 to 5 MW were started. The tests were made with different levels of already connected capacity in the system. As can be expected the frequency fluctuated much during the motor start (48.85 Hz at the lowest) but the voltage deviation was not more than during normal operation which was probably due to the large synchronous compensator. The static gain in the stations was very low which means that most of the frequency regulation was made manually. During a real island operation of this network the load variations will create large demands on the frequency regulation made by the station personnel. However, the test showed that it is possible to run the system in island operation.

In October 1986 a similar test was performed in order to investigate the possibility to supply parts of Malmö with power. The generation in the test system included a gas turbine with blackstart capability and an oil fired back-pressure station. The total capacity in the system was 110 MVA. For the voltage regulation a 25 MVAr synchronous compensator was used. The grid contained 3.5 km overhead line and about 10 km cable, all at 130 kV level. The load in the system consisted of an electric boiler which was regulated between 10 and 33 MW. After black-starting the gas turbine, energizing the system and connecting the synchronous compensator the load was connected. 10 MW was connected momentarily and the frequency decreased to 49.55 Hz. Since only an active load was connected and the reactive losses in the system became low there was no problem with the voltage regulation. The large synchronous compensator also had a positive impact on the voltage regulation. The power demand from the electric boiler was regulated up and down and the system response was studied. The back-pressure station was synchronized to the system and more tests were made with a varying load level of the electrical heater. During all the tests there were no problems with the voltage regulation but the frequency fluctuated quite much as a result of the load variations (± 0.4 Hz).

7.5 Experiences from island operation

The results from the field studies which have been made show that it is possible to run parts of the system in island operation. However, running in island operation is very labour intensive since the stations have to be manned. The secondary frequency regulation has to be made manually in each island and in those systems/islands were the static gain is too low the momentary frequency regulation is also made manually. In a small system the spontaneous load variations will be relatively large compared to an extensive system and in case of a blackout the cold load pick-up phenomenon will make it even more difficult to predict the load. The frequency fluctuation will therefore be much higher compared to a normal situation. The fluctuations in the frequency may cause disconnection of loads due to load shedding. In an island grid there will be different conditions for the relays compared to normal operation. In case of a fault the earth current will probably be less and therefore there is a risk that the earth protection relay may be disconnected by the delayed steps instead of the momentary one. At the lower voltage levels where overcurrent protection with invert time characteristic is usual the time delay will increase due to the lower short-circuit power.

All the tests described have been planned but in a real situation the personnel in the stations and in control centres are not prepared and it will probably take much more time and cause more problems than as shown by these tests. Therefore it is very important that the personnel is regularly trained thereby increasing their competence in handling these extreme situations.

Chapter 8 Recommendations

This thesis has focused on issues which, during a restoration process, may cause complications. In order to limit these problems some recommendations are suggested. These recommendations may be divided into three categories: general recommendations, recommendations for voltage control and recommendations for frequency control.

8.1 General recommendations

• *Do not change the restoration philosophy.* A change over to the ”build-up philosophy” is not recommended. Most of the hydro power is concentrated in the north and is used for the frequency control. In the south where most of the consumption is located, production is based on nuclear and thermal power and normally these stations are not used for frequency control. The personnel in control centres and production plants are not trained for running a system as an island grid.

• *Improve the education and training for the personnel who are responsible for the blackstart of the hydro stations.* The training shall be focused on blackstart procedures so that the people involved exactly know how to act during such a contingency. It is very important that the training is made regularly and that all personnel which has emergency duty is included. In order to achieve a training which is as realistic as possible, some of the tests should be made unexpectedly.

• *Improve the education of the personnel in the regional and national control centres.* The training shall be focused on the operation of the system during the restoration process and the specific problems that might arise. It is important that the regional control centre personnel can work according to the restoration instructions, but is also necessary that they have an understanding of voltage problems, frequency regulation, the behaviour of network components that are disconnected and reconnected due to automatics, cold load pick-up etc. For this type of training, role play using power system simulators can be a valuable training tool.

• *Improve communication.* In case of a blackout it is important that the control centre personnel can work without being disturbed by the public, the media or other persons who are not responsible for the operation of the grid. Therefore telephone numbers with limited access should be used during the restoration process. In order to be kept secret the phone numbers should be placed in sealed envelopes which only may be opened by order of Svenska Kraftnät.

• *Try to energize the lines to the nuclear power stations as fast as possible*. A nuclear power station can only stay in household operation for some hours. In those cases where a station has failed to establish household operation it is important to restart the production as fast as possible since there is otherwise a risk for lack of power in the system.

• *Disconnect the automatic reconnection of load (BTK) in case of a total blackout in the system*. BTK is useful when the system, following a disturbance, is still in operation and shedded load shall be reconnected. However, in case of a total blackout in the system the control centres are not allowed to reconnect more than 50% of the load during the initial part of the restoration. Since the loads subjected to load shedding often have a lower priority compared to the rest of the loads the disconnection of BTK automatics may be advisable.

• *Use the possibility of in-house power production in the pulp and paper industries in case of lack of power*. However, this should be based on an agreement between the power supplier and the factory. For instance the agreement can be to reconnect the industry prior to other loads if the industry produces a certain amount of power.

8.2 Recommendations for voltage control

• *Connect many generators as the reactive power production/consumption capacity in the system will increase*. If the generators are not necessary for the active power production the generators can be used in synchronous operation.

• *Connect shunt reactors in the feeding and the receiving end of the transmission lines in section 2 before energizing these lines*. This will give good reactive resources in the synchronous generators in the north as they will be overexcited in some cases. The voltage fluctuations will also be limited if the shunt reactor is connected at the receiving end of the line before the line is energized. In some stations, however, remote connection of a shunt reactor is not possible before the station is energized.

• *Do not disconnect the series capacitor*s. The series capacitors always improve the voltage and decrease the reactive power production from an unloaded transmission line.

• *Make a proper choice of the set-points of the shunt reactor automatics*. The time delays should not be the same for reactors which are situated close to each other. The purpose of this is to eliminate the risk for hunting of a group of reactors. In substations containing more than one shunt reactor it is advisable to have different settings of the voltages. In those cases where there is a risk for hunting of a single reactor the automatics should be blocked during the restoration process. It is also possible to use another operating mode for the reactor automatics during the restoration phase compared to normal operation. This mode can contain different time delays for reactors that might start to hunt together and voltage increased settings. In order to achieve proper set-points of the automatics it is advisable to analyse different network conditions by simulation.

• *Block the automatic restoration equipment in those substations where they may act too fast*. This may be valid for the stations in the northern and central part of the country which are connected to the lines from section 2.

8.3 Recommendations for frequency control

• *Connect many generators*. This will increase the total inertia in the system and thereby improve the dynamic frequency stability. The increased number of generators will also enhance the static gain in the system resulting in a lower stationary frequency deviation.

• *Use the hydro turbine governor modes Ep1 and Ep2 instead of Ep0*. Ep1 and Ep2 have a higher proportional regulation and static gain compared with Ep0 and therefore both the dynamic and stationary frequency deviations in the system will decrease by using these modes.

• *Connect moderate loads in each step*. As the frequency derivative is proportional to the load step a connection of a moderate load will result in an acceptable frequency deviation.

• *Energize the lines to the HVDC stations in an early stage of the restoration*. The HVDC links can give valuable power support. They are also capable of regulating the power transfer very fast and therefore they will increase the frequency stability in the system.

Chapter 9 Conclusions and future work

9.1 Conclusions

The restoration of a power system following a major disturbance is a process which includes many specific problems which are not relevant during normal operation. In this thesis some of these problems have been discussed and analysed.

The two main problems that arise during a restoration phase are voltage control and frequency control. The difficulties with the voltage regulation are strongly associated with the long transmission lines connecting the northern and central part of Sweden. When these lines are energized they will produce a large amount of reactive power and as a consequence, the voltage at the unloaded end of the line will be high. During restoration the connection of shunt reactors may lead to overcompensation and low voltage levels. Since the reactors are equipped with automatics, which disconnect/connect the reactor when the voltage is below/above certain levels, the voltage control will be more complicated since the reactors may start to hunt. As the shunt reactors at present have the same time delays for connection and disconnection in the entire system the hunting phenomenon may be distributed geographically in the network and include an increasing number of reactors.

The frequency stability in the system is dependent on a number of factors. It is shown that during restoration the frequency stability in the system will be improved by an increased inertia in the system, the connection of moderate loads and the use of hydro turbine governor modes with high static gain and proportional regulation.

When connecting a load it is important to know the expected load level to avoid overloading. The investigation of the cold load pick-up for industries shows that the power consumption following an outage will be less compared to the pre-outage load level. The time it takes for the industries to restart the production is varying depending on the different types of industries. In some extreme situations the restarting time may take some days. However, for the residential load the consumption will be higher or much higher after a disturbance. This load increase is mostly related to the thermostatically controlled load such as electrical heating, freezers, refrigerators and electrical boilers.

The possibility to blackstart and operate a small system in island operation has been investigated. The results from the field studies show that there are no major difficulties to operate an island grid. However, the frequency fluctuations will be higher since the load variations in a small system will be relatively larger as compared to an extended system. The island operation will also be labour intensive since an operator has to take care of the secondary frequency regulation; in some cases also the primary frequency regulation.

9.2 Future work

This thesis has analysed some basic problems related to the restoration process following a blackout in a large power system. However there are still a number of areas which should be given more attention.

9.2.1 Cold load pick-up

Little is known about the cold load pick-up phenomenon. In case of a restoration it is important to know the expected value of the reconnected loads to avoid a system overload. An even more interesting situation where cold load pick-up may have a strong influence on the power system, is in a case of lack of power in the system and a rotating disconnection of load (ROBO) is used. If the loads included in the ROBO scheme consist largely of residential load the value of the reconnected load may be much higher (2-3 times) than before the disconnection. In such a situation the ROBO system may initiate an overloading of the system which may result in severe consequences.

In order to get a better understanding of the cold load pick-up phenomenon it is essential to perform more studies in this area. For residential load the studies can be performed on individual objects such as electrical boilers, refrigerators and freezers. The effect from electrical heating in houses and block of flats and the load consumption from offices, shops etc. can be measured and investigated on individual houses and buildings. Load compositions can then be made for different areas and in order to verify the results it is important to make field measurements on typical residential load areas. For the industry sector an extended investigation is also of interest. The possibility to obtain measurements with a higher resolution has increased since many industries are implementing new measurement equipment.

9.2.2 Island operation

In case of war situations or terrorist attacks which may cause severe damage to the power system it might be necessary to run parts of the system in island operation. Therefore it is necessary to investigate which stations that have access to blackstart capability and also the frequency regulation capacity of the stations. Much of this work can be made without field studies but it is important to verify the results by real test in the stations.

9.2.3 Operator training

Since blackouts seldom occur station and control centre personnel have little experience in restoration work. In order to train the personnel role play can be performed with power system simulators such as ARISTO. Different network scenarios can be prepared and thereby the personnel can gain experience in handling unusual network situations.

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