Voltage Collapse in Power Systems

Analysis of Component Related Phenomena
using a Power System Model

Magnus Gustafsson
and
Niclas Krantz

Technical Report No. 215L
Department of Electrical Power Engineering
1995
Voltage Collapse in Power Systems

Analysis of Component Related Phenomena
using a Power System Model

by

Magnus Gustafsson
and
Niclas Krantz

Submitted to the School of Electrical and Computer Engineering,
Chalmers University of Technology,
in partial fulfilment of the requirements for the degree of
Licentiate of Engineering

Department of Electric Power Engineering,
Division of Electrical Power Systems
Göteborg, December 1995
Upptäckter är resultatet av planmässigt famlande

K.F. Gauss
Acknowledgements

We would like to express our deepest gratitude to our supervisor, Professor Jaap Daalder, for his engagement, support and encouraging attitude during this project.

We are especially indebted to Professor Bertil Stenborg and Daniel Karlsson for initiating this project. Thanks are also due to the Sydkraft Research Foundation for their financial support. ABB Power Systems are acknowledged for the donation of laboratory equipment.

We have been very much helped by the M.Sc. thesis work that Gunnar Andersson and Michael Johansson made with the dynamic load model. Nina Lövgren and Henrik Svenningsson have made it possible to incorporate a static var compensator in future laboratory studies by their M.Sc. thesis work.

Special thanks are due to Sture Lindahl and Kenneth Walve for stimulating discussions. Thanks are also due to Mildred for taking care of tickets and bills and for being a good friend, to Jan-Olov for keeping our computers alive, and to all the colleagues for creating a cheerful atmosphere.

Thank you all, we’ve enjoyed it here!
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL</td>
<td>Armature Current Limiter</td>
</tr>
<tr>
<td>AVR</td>
<td>Automatic Voltage Regulator (generation control)</td>
</tr>
<tr>
<td>FCL</td>
<td>Field Current Limiter</td>
</tr>
<tr>
<td>MC</td>
<td>Microcontroller</td>
</tr>
<tr>
<td>OLTC</td>
<td>On-Load Tap Changer</td>
</tr>
<tr>
<td>pu</td>
<td>per unit</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
</tbody>
</table>

Remark regarding component values in the thesis:
All shunt components are denoted with their admittance values.
All series components are denoted with their impedance values.
Abstract

This thesis aims to give a physical approach to the problem of voltage instability and collapse. A laboratory power system model has been used to clarify basic voltage collapse phenomena. The laboratory setup is a model of a 400 kV transmission system and consists of a synchronous generator including a voltage regulator with current limiters, a transmission line model, transformers with on-load tap changers, a dynamic active load and an induction motor load. A significant advantage of the laboratory model is that it is easy to analyse what happens during the tests since the role of every component can be studied into detail.

It is shown in this thesis that a system can remain stable when operating on the lower side of the PV-curve, both with a constant impedance load and with a combination of constant impedance load and induction motor load. In the latter case, the fraction of induction motor load determines the location of the stability limit on the lower side. It is also shown, by experiment and analytical methods, that a pure induction motor load always stalls at the critical point of the PV-curve.

In order to bring the operating point from the lower side back to the upper side of the PV-curve, the ratios of feeding transformers should be decreased, shunt capacitors should be switched in and, if that is not enough, load should be shed as a stabilizing measure.

The reactive load in a system should be modelled as a function of the fraction of motor load, the active load behaviour and the characteristics of the network between the point from where the load is modelled and the load objects. Models of induction motor loads must include saturation effects to be accurate enough for voltage stability studies.

If an armature current limit is reached, the load behaviour is decisive whether a voltage collapse will occur or not. If the stationary load response is between constant current and constant power, the system will collapse.

As a result of insufficient coordination between load dynamics and OLTC dynamics, a temporary power/current overshoot might cause a voltage collapse, especially if an armature current limiter is activated due to the overshoot.
The field current limiter weakens the system in the sense that the voltage control is moved behind the synchronous reactance which becomes a part of the network. However, the FCL is not by far as detrimental for the system as the armature current limiter.

By identifying the load behaviour in the networks and making proper load models, voltage collapses can be avoided. The settings of active controllers, such as OLTCs and (if possible) generator AVRs should regard the load behaviour in order to minimize bad interaction with the load at situations close to voltage collapse.

**Keywords**

Voltage stability, voltage collapse, voltage instability, on-load tap changer, OLTC, armature current limiter, field current limiter, load modelling, dynamic load, induction motor load, active power, reactive power, power system model.
Chapter 2  The voltage collapse phenomenon

2.1 Methods for voltage stability analysis .................................2-1
  2.1.1 PV-curves and QV-curves .................................................2-1
  2.1.2 Analytical methods .........................................................2-1
  2.1.3 Index and sensitivity methods .........................................2-1
  2.1.4 Time domain simulations ...............................................2-2

2.2 Definitions ........................................................................2-2
  2.2.1 Voltage stability and collapse .........................................2-2
  2.2.2 Power system load .........................................................2-3

2.3 Examples of voltage collapse ...........................................2-3
  2.3.1 Belgium, August 4, 1982 .................................................2-4
  2.3.2 Sweden, December 27, 1983 ..........................................2-5
  2.3.3 France, January 12, 1987 ...............................................2-6
  2.3.4 Japan, July 23, 1987 .......................................................2-8

2.4 Preview ..............................................................................2-9

2.5 References .........................................................................2-10

Chapter 3  Laboratory equipment

3.1 The generator and its auxiliaries .......................................3-2
  3.1.1 Generator data ..............................................................3-2
  3.1.2 Voltage regulator and current limiters ............................3-3

3.2 The line model .................................................................3-5

3.3 Transformers with on-load tap changer .............................3-7
  3.3.1 Description of the design ................................................3-7
  3.3.2 The power circuit .........................................................3-9
  3.3.3 The tap changer ............................................................3-10
  3.3.4 The controller ...............................................................3-12
3.3.5 Tests and verification ............................................................. 3-15
3.4 Load models .............................................................................. 3-16
3.4.1 Dynamic active load model .................................................... 3-17
3.4.2 Motor load .............................................................................. 3-21
3.5 Data acquisition system ............................................................ 3-22
3.5.1 Data acquisition ................................................................. 3-22
3.5.2 Data processing ................................................................. 3-24
3.6 References ............................................................................. 3-25

Chapter 4 Voltage collapse with a laboratory power system model
4.1 Abstract ................................................................................. 4-1
4.2 Introduction ........................................................................... 4-1
4.3 Laboratory power system model ........................................... 4-2
4.3.1 Power plant ............................................................................. 4-2
4.3.2 Transmission lines ............................................................... 4-2
4.3.3 Transformers .......................................................................... 4-2
4.3.4 Dynamic active load ............................................................... 4-3
4.3.5 Induction motor load .............................................................. 4-4
4.3.6 Data acquisition ...................................................................... 4-4
4.4 Stable operation points on the PV-curve ......................... 4-5
4.4.1 Static operation on the lower side of the PV-curve .......... 4-5
4.4.2 Dynamic operation on the lower side of the PV-curve .......... 4-7
4.5 Current limiters ........................................................................... 4-11
4.5.1 Field current limiter (FCL) ..................................................... 4-11
4.5.2 Armature current limiter (ACL) ............................................. 4-12
4.5.3 Combination of current limiters ............................................. 4-13
4.6 Tap changer and load dynamics ............................................. 4-14
4.7 Conclusions ........................................................................... 4-16
4.8 Acknowledgements ................................................................. 4-16
4.9 References ............................................................................. 4-17

Chapter 5 Voltage stability: The significance of induction motor loads
5.1 Abstract ................................................................................. 5-1
Chapter 5  Power systems studies

5.2  Introduction .................................................................5-1
5.2.1  Power plant .................................................................5-2
5.2.2  Transmission lines .......................................................5-2
5.2.3  Transformers ...............................................................5-3
5.2.4  Dynamic active load .....................................................5-3
5.2.5  Induction motor load ...................................................5-3
5.2.6  Data acquisition ..........................................................5-3
5.3  Load modelling ...............................................................5-4
5.3.1  Static load models .......................................................5-4
5.3.2  Dynamic load models ...................................................5-5
5.4  Power voltage dependence .............................................5-7
5.4.1  The influence of different $\beta$ on simulation results .......5-7
5.5  Reactive power sensitivity measurements on an induction motor load .................................................................5-8
5.5.1  Load level of an induction motor ...................................5-10
5.5.2  Reactive compensation of induction motor load ..........5-11
5.5.3  Impact of feeder reactance and compensation ...............5-11
5.5.4  Induction motor saturation .........................................5-12
5.5.5  Derivation of induction motor model for voltage stability studies 5-12
5.5.6  The effect of neglecting saturation ...............................5-14
5.6  Induction motor load and collapse .................................5-16
5.6.1  Computer simulation of induction motor load ...............5-16
5.6.2  Combination of induction motor load and resistance load ....5-18
5.6.3  Induction motor collapse .............................................5-19
5.7  Conclusions .................................................................5-22
5.8  Acknowledgements ........................................................5-22
5.9  References .................................................................5-23

Chapter 6  Complementary results

6.1  More about load behaviour .............................................6-1
6.1.1  Impact of load characteristics at armature current limitation .6-1
6.1.2  The influence of mechanical torque-speed characteristics on induction motors .........................................................6-3
6.2  Load shedding ..............................................................6-5
6.3  Capability-curves at current-limitation .............................6-7
6.3.1  Armature current limiter ..............................................6-7
6.3.2 Field current limiter .......................................................... 6-8
6.4 Tap changers ...................................................................... 6-9
6.4.1 Cascaded tap changers ....................................................... 6-9
6.4.2 Tap changer blocking ....................................................... 6-12
6.5 References ........................................................................ 6-16

Chapter 7 Current limitation in larger systems

7.1 One generator and two load-nodes ...................................... 7-1
7.1.1 Armature current limitation ............................................. 7-1
7.1.2 Field current limitation ................................................... 7-4
7.2 Two generator nodes and one load-node ......................... 7-6
7.2.1 Armature current limitation ............................................. 7-6
7.2.2 Field current limitation ................................................... 7-9
7.3 Reduction of the generator active power at current limitation 7-11
7.3.1 Armature current limitation ............................................. 7-11
7.3.2 Field current limitation ................................................... 7-13

Chapter 8 Conclusions

Chapter 9 Future work

9.1 Future work in general ....................................................... 9-1
9.2 Future work with the laboratory power system model ... 9-1

Appendix

A Induction motor model ....................................................... A-1
Chapter 1  Introduction

During the last decades, power systems around the world have suffered a number of severe disturbances and breakdowns, voltage collapses, caused by voltage instability. These problems are mostly related to high stress levels in the networks. Because of environmental and political considerations, it is hard to obtain permission to build new transmission lines in many industrialised countries. Hence, the existing networks must transmit more power, making them more vulnerable at the same time. A disturbance, such as a line or power plant tripping, may initiate voltage instability and could lead to a voltage collapse.

The interruption in power delivery that follows a voltage collapse has economic consequences such as loss of income for the power utility and lost production for affected industries. Great efforts are being made to understand the phenomena involved in voltage collapse. With sufficient knowledge, a voltage collapse can be prevented and the correct emergency actions can be taken in case of an impending breakdown.

It is not possible to carry out tests on a real power system because of the safety risks. Many studies are therefore made by using an analytical approach. Continuous mathematical models of the system components are used to find bifurcation points (points that are common to more than one branch of solutions) in the system solution. Unfortunately, essential components in the power system cannot be properly described with continuous models. Therefore, the analytical approach has its limitations.

Detailed models of system components have been developed and are used in computer programs for dynamic simulations. One problem with these programs is that they are designed to work under certain conditions. If these conditions are not fulfilled, which can be the case in voltage stability studies, the programs might give a wrong solution or no solution at all.

This thesis presents another approach where a laboratory power system model is used to study voltage stability and collapse. The model contains essential system components and regulating equipment, and is driven under various conditions to determine how different components and their regulators affect voltage stability. Much effort is used to find out how the different components interact and what their impact is on the voltage stability of the system.
Chapter 1: Introduction

There are also limitations with this model. The limited number of system components excludes the formation of large systems e.g. a masked network with many production plants and loads. At this stage, the model lacks authentic relay protection equipment. Another limitation that is common for all types of simulations is the lack of accurate load models for large aggregate loads.

A survey of different analytical approaches and examples of voltage collapse are given in Chapter 2. Much of the laboratory equipment has been developed and built during this project. A description of the laboratory components is presented in Chapter 3. Chapter 4\(^1\) presents basic voltage stability phenomena. The functions of the different components as well as their interaction are examined. Chapter 5\(^2\) focuses on reactive load modelling and induction motor load. One reactive load model is studied and its deficiencies are emphasized. Important modelling aspects and the system stability limit for induction motor loads are also studied. Chapter 6 elaborates on the results given in Chapter 4 and 5. A first analysis of systems with more than one generator-node and one load-node is presented in Chapter 7. The results are concluded in Chapter 8 and ideas for future work are given in Chapter 9.

\(^1\) Chapter 4 was presented as a paper at Stockholm Power Tech, June 18-22 1995
\(^2\) Chapter 5 was presented as a paper at the North American Power Symposium, October 2-3 1995
Chapter 2 The voltage collapse phenomenon

2.1 Methods for voltage stability analysis

Voltage stability studies are performed with a number of different methods. Johansson and Sjögren [6] give a thorough description of the most common methods. A short summary of these methods is given below.

2.1.1 PV-curves and QV-curves

The most basic and commonly used method is to use the system’s theoretical PV-curve or QV-curve together with the load characteristic. These curves are also called “nose-curves” due to their characteristic shape. The nose-curve is a graph of the active or reactive power in a node as a function of the node voltage. The point on the nose-curve where the maximum power occurs is called the “critical point” and in literature is often considered to be the voltage stability limit.

2.1.2 Analytical methods

The analytical methods use continuous models of the system components, and describe the system with a set of differential-algebraic equations. These equations are used to find bifurcation points in the system solution. Bifurcation points are common to more than one branch of solutions. Therefore it is possible for the system solution to change branch and thereby behaviour at such a point. Methods that use the eigenvalues of the Jacobian matrix can then be applied to determine how the system will behave at these points.

2.1.3 Index and sensitivity methods

Another method is to calculate a “distance” to the point where the system will collapse. The minimum singular value of the power-flow Jacobian matrix is one such value that is used as a stability index. The distances in MW or MVAr to the critical point of the nose-curves are other examples of indexes for this purpose.
Chapter 2: The voltage collapse phenomenon

2.1.4 Time domain simulations

Dynamic simulations can be very useful in voltage stability studies. Two steady state solutions might appear to be stable when using static methods, but it may be impossible for the system to move from one stable operating point to the other without collapsing on the way. These kinds of dynamic limitations can be found with time domain simulations.

The simulations are mostly performed with a computer program that uses detailed models of the system components. Both the simulation program and the models used must be adapted to the demands of long-term dynamic simulations to be useful in voltage stability studies. These demands are not always the same as for the more common transient stability simulations with a much shorter time perspective.

Time domain simulation can be used to investigate basic aspects in small power systems as well as more complex phenomena in larger systems.

The work presented in this thesis can be placed in the time domain simulation category, as though a laboratory power system model is used as a simulation tool instead of a computer.

2.2 Definitions

2.2.1 Voltage stability and collapse

The research area of voltage stability lacks unambiguous definitions. There are various definitions presented by different organisations, groups and individuals. Here we may mention the definitions by CIGRÉ [1], IEEE [5], Hill et al. [4] and Glavitch [2]. All these definitions are presented and discussed in [6].

The definitions according to IEEE are the most suitable for the analysis presented in this thesis and are as follows:

• Voltage stability is the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and so that both power and voltage are controllable.
• Voltage collapse is the process by which voltage instability leads to loss of voltage in a significant part of the system.
Voltage Collapse in Power Systems

• **Voltage security** is the ability of a system, not only to operate stably, but also to remain stable (as far as the maintenance of system voltage is concerned) following any reasonably credible contingency or adverse system change.

• The system enters a state of **voltage instability** when a disturbance, increase in load, or system change causes the voltage to drop quickly or drift downward, and operators and automatic system controls fail to halt the decay. The voltage decay may take just a few seconds or ten to twenty of minutes. If the decay continues unabated, steady-state angular instability or voltage collapse will occur.

The meaning of the first paragraph is that a power system can not operate on the lower side of the PV-curve and still be voltage stable. This thesis will show that a power system can operate on the lower side of the PV-curve and remain stable. Therefore, the following definition of voltage stability is used in this thesis:

• **Voltage stability** is the ability of a system to maintain voltage so that when load admittance is increased, voltage is controllable.

2.2.2 Power system load

• A power system **load** is an equivalent load object consuming the power delivered to a specific network node. The power is the aggregation of the power consumed by all load objects (heating, motors, lighting, etc.) including the network connected to the actual node.

• The power consumed by a **static load** is a function of voltage only.

• The power consumed by a **dynamic load** is a function of both voltage and time. At a voltage change, the load power has a transient voltage dependence, a power recovery and a steady state voltage dependence.

2.3 Examples of voltage collapse

Several voltage collapses have occurred around the world during the last decades. The contingencies have different reasons, but mostly the collapses are triggered by a fault situation or a component malfunction. Heavy load can also cause voltage instability and collapse. A few examples of voltage collapses are given below, [3] [6] [9] [10].
Chapter 2: The voltage collapse phenomenon

2.3.1 Belgium, August 4, 1982

The Belgian power pool consists of various types of power plants. These are firmly linked together through interconnecting systems at the 150 and 380 kV levels. There are 2 nuclear power plants and a storage pumping station, both connected to 380 kV, and a number of fossil fuel stations connected to 150 kV. One of the nuclear power plants, comprising three units, is situated in Doel in the north and the other (one unit) is situated in Tibange in the east of Belgium. The western part of the network is linked to the French power system and the eastern part is connected to the Dutch, French and German grids.

Wednesday, August 4 was characterized by a low load situation. Less than half of the installed capacity was operative. Prior to the incident, the major load was industrial, mainly consisting of motor load. The load consequently demanded a considerable amount of reactive power. A number of generation plants and transmission lines, including the western link to France, were disconnected due to maintenance work. In order to save fuel, a minimum of the oil fired plants were in operation. In the Doel nuclear power station, all three units were running. About half of the production was generated by the nuclear power stations and the pumping station. The rest was produced by fossil fuel plants.

A disturbance then occurred in the nuclear power plant in Doel. Unit 3 tripped as a result of the fortuitous operation of a turbine protection device. The voltage decreased in the region due to the loss of 449 MVAR reactive power production. The AVRs in Doel 1 and 2 intervened in order to raise the voltage. The field currents started to increase in both units, and reached their upper limits. The current limiters were then activated and prevented further voltage recovery. On-load tap changers in the network started tapping and caused a further field current limitation that lowered the voltages even more.

Decreasing voltages implied increasing currents, and due to protection relay operation, 5 units in the region successively tripped, including the nuclear power units in Doel. The loss of this production in the northern and central parts of the country lead to an increased power flow and one of the lines from the south tripped due to overload. Oscillations started between the north and the south of the country, and a considerable lack of both active and reactive power in the north and the central parts caused a disconnection of these parts from the 380 kV network. The collapse became a fact.
There were mainly two network components that caused the collapse. The field current limiters and the on-load tap changers interacted and caused low voltages and consequently high currents. In the Swedish nuclear power plants, the generator excitation controllers have armature current limiters in addition to the field current limiters. In the Belgian collapse, the nuclear power generators were tripped due to overcurrent, and if the AVRs had been equipped with armature current limiters, these would have been activated instead. In the Swedish power system, it is therefore also important to study the armature current limiter.

(Remark: Simulations with armature current limiters [6] have shown that a collapse is hard to avoid once an armature current limiter has become active.)

2.3.2 Sweden, December 27, 1983

The Swedish collapse occurred on a cold winter’s day, when the system was heavily loaded. The power transfer from the north to the south was 5600 MW, compared to the recommended maximum of 5800 MW.

An earthfault occurred in an important 400 kV switchyard in eastern Sweden about 150 km from Stockholm. Because of special circuit breaker arrangements, the whole station tripped. Consequently, the 220 kV connection to Stockholm and the transmission route from the north were interrupted. The supply to Stockholm and the eastern part of Sweden was then weakened. Power oscillations that followed from the fault died out quickly and the frequency remained unchanged since no generators were tripped. But the voltage in the south-eastern part of Sweden decreased due to the weakened transmission system.

The only remaining 220 kV line to Stockholm from the west became heavily overloaded and tripped 8 seconds after the initial fault. Due to the loss of transmission capacity from the north, the transfer on the central northern-southern lines increased and the voltage south of these lines decreased. One of these lines tripped 50 seconds after the initial fault due to overload and then a cascade tripping of the other lines took place. Southern Sweden was now isolated and a lack of power caused a frequency decay. The voltage and frequency drop caused tripping of all generators in the south, and the voltage collapse was a fact.

Initial calculations showed that the system should have been stable after the initial fault, and the cascaded tripping could not be explained. Further studies showed interesting phenomena that had occurred in the system.
Chapter 2: The voltage collapse phenomenon

• A small number of generators were running in the south-eastern region and the reactive output increased until the field current limiters were activated. This disabled a normal voltage restoration, since the generator voltages were reduced by the limiters.

• The voltage drop resulted, momentarily, in reduced power consumption. The on-load tap changer transformers started to restore the voltage in the distribution networks which resulted in power restoration and higher line loading.

(Remark: Studies on load behaviour [7] showed that the load has a restoration mechanism, due to thermostatically controlled heating.)

It can be concluded that the collapse was caused by the following contributing factors:

• load behaviour at low voltages,
• operation of on-load tap changers,
• current limiters of generators,
• relay protection.

2.3.3 France, January 12, 1987

The western part of the French system, in the Brittany region, suffered from a major disturbance on January 12, 1987. This region has a substantial generation capacity, mostly nuclear power, connected to the national 400 kV system. January 12 was a rather cold day. The power consumption on the national level was 52,000 MW and the power margin was 6,000 MW. The transmission voltage was normal in the Brittany area.

Between 10.55 a.m. and 11.41 a.m. three nuclear power units failed for unclear reasons and the region control centre ordered the start-up of gas turbines. Thirteen seconds after the last of the three units tripped, the fourth unit tripped due to maximum field current protection. The sudden loss of generation led to a sharp voltage drop. The voltage drop spread to adjacent areas and caused tripping of nine conventional and nuclear generation units within a few minutes. A loss of about 9,000 MW was recorded between 11.45 and 11.50 a.m. The voltage in the 400 kV system then stabilized at extremely low values: 300 kV was the average value in the Brittany area. The lowest value was 180 kV in the La Martyre sub-station, which is the most remote station in Brittany. The system “survived” in the sense that no lines were tripped. After
loadshedding, the voltages returned to normal again. The extremely low voltage levels indicate that the system was operating on the lower side of the PV-curve, and it seems that a stable equilibrium was reached before the load shedding took place. By our definition, there was no real collapse in Brittany, just a period of voltage instability that ended up in a stable operating point.

Harmand et. al., EdF [3] carried out a simulation analysis based on recordings from the incident, in order to understand the mechanisms that caused the incident. The load behaviour, the on-load tap changers, and field current limiters were given special attention.

- The voltage dependence of the load was determined from recordings during the incident and a linear dependency was found. However, no conclusions regarding the contributions to the voltage decay were made.
- The on-load tap changers were very much blamed for causing the instability. When the voltage dropped, the OLTCs tried to restore the voltage and thereby increased the load. Simulations were made with the tap changers on the highest voltage levels blocked. The system then remained stable.
- The role of the generator voltage control and its protection devices was also examined. Two phases can be distinguished in the incident. The EdF version is given first, and a comment is given by the authors (italics) as an alternative explanation.

A first phase (lasting 4 minutes) where continuous voltage degradation on the EHV system is accompanied by progressive increase of generated reactive power. *(The armature voltage decreases early during the first stage which indicates that the FCL is activated from the start. The reactive power is still allowed to increase which is possible when the FCL is activated).*

A second phase is where the generator reaches its limit in field current. This means that one part of the reactive resources necessary for the voltage control is going out and the collapse process accelerates. *(There is a sudden reactive power decrease which cannot be explained. The probable explanation is that another production plant is tripped at that second stage, causing the reactive power and the voltage to drop. The actual plant is apparently not tripped since it continues to deliver reactive power.)*
Chapter 2: The voltage collapse phenomenon

2.3.4 Japan, July 23, 1987

The Japanese electric power system has two frequencies, 50 and 60 Hz. Chubu Electrics has a 60 Hz system, and TEPCO has a 50 Hz system covering the Kanto Area, including Tokyo. The two systems are interconnected with two 300 MW back to back frequency converters. TEPCO owns 186 power plants, of which 155 are hydro, 28 conventional thermal and 3 nuclear power plants. The installed nominal power is 39,000 MW. The largest power stations (nuclear and thermal stations) are located in the eastern regions. Therefore, a large amount of power flows from the east to the west.

The system experienced a breakdown at about 1.20 p.m on July 23, 1987. The load level was very high that day and before lunch, the power demand was about 39,000 MW. A part of the load was imported from other utilities and the total prepared maximum power production was 41,500 MW. It was a very warm day and a large part of the load was air conditioners. During lunch, the power decreased to about 37,000 MW. The load pick-up after lunch, at 1.00 p.m, was very fast and large. The demand increased at a speed twice as fast as previously recorded: 1% per minute.

The voltage started to decrease and TEPCO supplied reactive power into the network by switching in shunt capacitors and by increasing the excitation level of the generators. By 1.07 p.m. all available shunt capacitors were connected. The power had now reached 39,300 MW, the highest load level of the day. The voltage started to decrease, and at 1.19 p.m, protective relays operated due to overcurrent in the transmission network. Two 500 kV substations were shut down, resulting in a 8,000 MW outage that affected 2.8 million people.

The reason for the collapse was the extremely high load level in combination with the extremely fast load pick-up after lunch. Another cause was the load characteristic. A considerable amount of the load was air conditioning, e.g small induction motors. With motor load, the current increases as the voltage drops, which also accelerates the collapse. The Japanese report indicates that for a constant power load, which is the case for motors, operating points on the lower side of the PV-curve are unstable.

Immediate countermeasures for stabilizing the system were carried out shortly after the incident. The voltage was slightly increased in order to increase the power transfer capacity, strategies for fast power interchange with the 60 Hz system via the frequency converters were made,
and loadshedding strategies were formulated. Several static var compensators, SVCs, have been installed in the system in order to improve the reactive power support in critical situations.

2.4 Preview

The whole idea of the project presented in this thesis was to study voltage stability and collapse on a laboratory scale, in order to establish a physical approach to the problem. To our knowledge, this has not been done previously.

Results from measurements contribute to the understanding of the different phenomena involved. This will enable more accurate modelling for computer simulations. It would be even better to make tests on real power systems, but that is not possible, due to the safety risks involved.

The experience gained from the real incidents with voltage collapse highlights three system components as very important for voltage stability and collapse; on-load tap changers, automatic voltage regulators (AVRs) for generators with current limiters, and loads. The main load types mentioned in the field are thermostatically controlled heating and motor loads.

When we started working on this project, the power system model in the laboratory consisted of a generator and a transmission line model. A considerable effort was made to modernize and extend the power system model before measurements took place:

• Two identical transformer models with on-load tap changers were designed and manufactured.
• The generator was equipped with a modern automatic voltage regulator with current limiters.
• An induction motor load with a PWM-converter driven DC-machine was installed.
• An active power load with dynamic behaviour was designed and manufactured as a M.Sc. thesis work.
• A new PC-based data acquisition system was built up and a computer program was developed for data acquisition and processing.
Chapter 2: The voltage collapse phenomenon

2.5 References


Chapter 3  Laboratory equipment

The power system model used in this work is a three-phase model of a 400 kV transmission system. It consists of a power plant model, a transmission line model, two transformer models with on-load tap changers (OLTCs), and two different dynamic loads. The entire model operates at 400 V and the rated generator power is 75 kVA. Consequently the voltage scale of the model is 1:1000. The power scale is 1:18,800 due to the impedance scale of the line model. The model can be run on its own or may be connected to the utility grid.

The line model and the power plant model were acquired during the period when the first 400 kV connection was about to be built in Sweden. Transient stability and voltage problems at unloaded transmission lines were the areas of most interest. The loads, the transformer models and new excitation equipment for the generator have been added to the system during this thesis work. Our aim has been to use controllers and regulators identical to those installed in real power systems.

As a result, the model is now suitable for studying voltage stability. The model contains most of the key components which are important for voltage stability. These are mentioned in chapter 2 and comprise dynamic loads, OLTCs and generator current limiters. The behaviour of these components and the interaction between them can be studied. Results from tests on the model are mostly more accurate than computer simulations since many model parts correspond exactly to a real system. Of course there are also limitations: It is, for instance, not possible to obtain a masked network including many production plants.

Besides its use in research, the model is widely used in education. It is very useful to show different phenomena, illustrating both component and system behaviour. At present, short-circuits, transient stability, and voltage stability are topics that are demonstrated in different courses.
Chapter 3: Laboratory equipment

3.1 The generator and its auxiliaries

The power plant is an accurate model based on the large Harsprånget hydro power plant, situated by the Lule river in northern Sweden.

The model generator is driven by an 85 kW DC motor. The DC motor is fed from a one-quadrant converter and can be controlled by either speed or armature current, corresponding to frequency- or active power control of the generator. Due to limitations in the feeding converter it has not been possible to load the DC motor with more than approximately 40 kW. On the shaft between the DC motor and the generator there is a large flywheel that gives the model the same mechanical behaviour as the real power plant.

3.1.1 Generator data

The model generator is of a very robust construction, being designed to withstand the stress caused by short-circuits and following loss of synchronism as can be the case in transient stability studies. The armature windings are Y-connected and the terminals are connected to the line model by a circuit breaker. The field winding is fed from a static exciter.

Figure 3.1 The power plant model. The synchronous generator (to the left), the flywheel, and the DC-motor (to the right).
General data:

3-phase, 50 Hz, 6 poles, 1000 rpm,

Data for the armature winding:

\[ S_n = 75 \text{ kVA}, \]
\[ V_n = 400 \text{ V}, \]
\[ I_n = 108,3 \text{ A}, \]
\[ X_d = 2.93 \Omega/\text{phase}, \]
\[ X_d' = 0.437 \Omega/\text{phase} \quad \text{(Unsaturated machine)}, \]
\[ X_d'' = 0.332 \Omega/\text{phase} \quad \text{(Unsaturated machine)}, \]
\[ R_s = 0.081 \Omega/\text{phase}. \]

Data for the field winding:

\[ V_{fn} = 110 \text{ V}, \]
\[ I_{fn} = 4.7 \text{ A}. \]

3.1.2 Voltage regulator and current limiters

The generator is equipped with a modern microprocessor-based voltage regulator. The regulator can control terminal voltage, field current, reactive power or power factor. To enhance angular stability, a power system stabilizer (PSS) is included.

The voltage regulator is equipped with both a delayed field current limiter and a delayed armature current limiter.

- The delayed field current limiter protects the field winding and the exciter from thermal overload under stressed operation conditions. The delay permits a temporary overload of the generator to support the network with extra reactive power (at constant active power) before the limiter is activated, which brings the field current down to its limit.

- The delayed armature current limiter protects the armature winding from thermal overload under stressed operation conditions. Similar to the delayed field current limiter, the delay permits a temporary overload of the generator. In Swedish nuclear power plants, the generators are equipped with delayed armature current limiters. In other countries, this feature is not so common.

1. ABB HPC 840, Masterpiece 90.
Chapter 3: Laboratory equipment

The behaviour of these delayed limiters is illustrated in Figure 3.2 for a constant overload situation.

![Diagram](image)

**Figure 3.2 Principal operation for delayed current limiter at constant overload.**

where:

- \( t_1 \) = delay time,
- \( t_2 \) = limitation time,
- \( t_3 \) = recovery time.

The delay time \( t_1 \) has a minimum value of a couple of seconds. An integrator, that uses the difference between the measured current and the current limit as an input, adjusts the time \( t_1 \) to optimize the use of the generator’s thermal capability. The recovery time \( t_3 \) is the time the generator needs to cool before it can allow a new temporary overload. If the current for any reason should exceed the limit again before the recovery time has past, the limiter acts momentarily.

Since the field winding is fed from a static exciter the voltage regulator is also equipped with an instantaneous field current limiter.

- The instantaneous field current limiter protects the semiconductors in the static exciter, which have very short thermal time constants, from faults of short-circuit character in the field circuit. The instantaneous current limit is usually about twice the delayed field current limit. This function is of little importance for voltage stability studies.

All three limiters limit the current by decreasing the field voltage. As soon as one of the limiters is activated, the terminal voltage of the generator will start to decrease.
3.2 The line model

The line model consists of six identical \( \pi \)-sections, each corresponding to 150 km of a 400 kV line. The sections can be connected arbitrarily in series or parallel. Each section contains reactors and capacitors. The capacitors can be disconnected if desired.

![Scheme of one line model section.](image1)

![Three line model sections. The capacitors are below the panel, and on the floor behind the model are the reactors.](image2)
The reactors represent the line impedance. They are wound on a five leg iron core in order to ensure proper zero-sequence reactance. The windings are transposed in order to secure symmetrical conditions. By using different closing links (Figure 3.5) the data can be varied. Connection 3-4 is used here, as the reactance together with the shunt capacitance then corresponds exactly to a 150 km 400 kV line.

Figure 3.5 Reactor scheme.

The data for a reactor are:

3-phase, 50 Hz, 7.9/5.3 kVA (continuously), $I_n = 56$ A, $X_1 = 0.95 \, \Omega$, $X_0 = 2.50 \, \Omega$, $R_1 = 0.05 \, \Omega$.

The positive-sequence and zero-sequence capacitance is obtained from the values of $C_j$ and $C_f$.

\[
\begin{align*}
\gamma_j &= 40 \mu F \\
\gamma_f &= 6 \mu F \\
\Rightarrow C_1 &= 46 \mu F \\
C_0 &= 40 \mu F
\end{align*}
\] (3.1)

The data for a real 150 km section are:

$X_1 = 50.4 \, \Omega$/phase,
$R_1 = 4.17 \, \Omega$/phase,
$C_1 = 0.065767 \, \mu F$/phase.

Comparing model data with real data gives an impedance scale of 1:53.2. The voltage scale, together with the impedance scale, gives the power scale of 1:18,800. Consequently, the power plant model corresponds to a 1,410 MVA plant.
3.3 Transformers with on-load tap changer

In Chapter 2 it was shown that it is important to consider transformer OLTCs when studying voltage stability. Two identical transformer models with OLTCs have therefore been developed and built. The scaled-down laboratory model made it necessary to use a special design adapted to the conditions in the laboratory. The aim was to develop a tap changer with the same tap sizes and time constants as those used in real power transformers, and to apply controllers identical to those installed in the Swedish power system.

3.3.1 Description of the design

The voltage level is the same for the whole laboratory model, which means that the nominal transformer ratio must be 1:1. The same regulation span as that in a real power transformer was desired. A common regulation span in the Swedish power system is ± 13.5% in ± 9 steps of 1.5% each. The power and voltage ratings were given the same values as for the generator: 75 kVA and 400 V respectively.

After several discussions with different transformer manufacturers, a design called a buck/boost-converter was chosen. A buck/boost converter consists of a full winding transformer and an autotransformer connected to each other (see Figure 3.6 and 3.8). The benefits of the design are that the rated power of the transformers is much lower than of the whole converter, and that the current to be switched is much smaller than the load current. This implies a smaller and cheaper tap changer compared to a conventional one.

An ordinary tap changer is a complicated mechanical device operated by a motor driven spring mechanism. The equipment is mostly placed in an oil tank separated from the transformer itself. To build a copy of a real tap changer would be too complex. In this application contactors were used instead (see Figure 3.7).

The contactors must be controlled by some form of electronics in order to achieve correct switching sequences and to incorporate alarms and safety functions. A basic-programmable microcontroller (MC) was used for this purpose. Peripheral circuits for measurement and for the switching control were also designed and manufactured. The contactors are switched using semiconductor relays; triacs.

The voltage regulating relay used is an ABB relay called RAYA. It consists of the controller RXCE41, and a blocking unit RXTNB22.
Figure 3.6  The two interconnected transformers, with the autotransformer at the rear and the full winding transformer at the front.

Figure 3.7  The tap changer with all contactors to the left and the controllers to the right. In the right upper corner is the MC and below is the regulating relay RAYA.
3.3.2 The power circuit

The regulation span and the rated power of the whole converter determine the transformer ratios and the power ratings.

![One phase circuit for the buck/boost converter.](image)

From the scheme in Figure 3.8, an expression for the voltage ratio is given by:

\[
\frac{V_2}{V_1} = \frac{n}{n + m - k}
\]

(3.2)

where

- \(n\) = full winding transformer ratio,
- \(m\) = “middle tap” position (m=0 at the bottom and 1 at the top),
- \(k\) = position of the connected tap (0 at the bottom and 1 at the top).

By solving Equation 3.2 for maximum and minimum ratio, \(m\) and \(n\) can be solved. \(m\) is the point where the fixed connection with the full-winding transformer is made.

\[
1.135 = \frac{n}{n + m - 1} \quad \text{and} \quad 0.865 = \frac{n}{n + m - 0}
\]

(3.3)

which gives \(n = 3.6360, m = 0.5680\)
Elsund AB in Laxå manufactured the following transformers, with data based on the above:

**Full winding transformer:**
- 3-phase, air-cooled, 10 kVA, 31/113 V, open windings.

**Auto-transformer:**
- 3-phase, air-cooled, 25 kVA, 30 A, 171 turns, with 19 taps distributed as close to the positions k, shown in Table 3.1, as possible. Because the number of turns of the auto-transformer is not infinite, the taps could not be distributed exactly as in Table 3.1.

<table>
<thead>
<tr>
<th>$V_2/V_1$</th>
<th>k</th>
<th>$V_2/V_1$</th>
<th>k</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.865</td>
<td>0</td>
<td>1.0150</td>
<td>0.6217</td>
</tr>
<tr>
<td>0.8800</td>
<td>0.0722</td>
<td>1.030</td>
<td>0.6739</td>
</tr>
<tr>
<td>0.8950</td>
<td>0.1414</td>
<td>1.045</td>
<td>0.7246</td>
</tr>
<tr>
<td>0.9100</td>
<td>0.2084</td>
<td>1.060</td>
<td>0.7738</td>
</tr>
<tr>
<td>0.9250</td>
<td>0.2732</td>
<td>1.075</td>
<td>0.8217</td>
</tr>
<tr>
<td>0.9400</td>
<td>0.3359</td>
<td>1.090</td>
<td>0.8682</td>
</tr>
<tr>
<td>0.9550</td>
<td>0.3967</td>
<td>1.105</td>
<td>0.9135</td>
</tr>
<tr>
<td>0.9700</td>
<td>0.4555</td>
<td>1.120</td>
<td>0.9576</td>
</tr>
<tr>
<td>0.9850</td>
<td>0.5126</td>
<td>1.135</td>
<td>1.0000</td>
</tr>
<tr>
<td>1.0000</td>
<td>0.5680</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1  Voltage ratio versus the desired tap distribution of the auto transformer.

### 3.3.3 The tap changer

The tap changer has the task of switching the current from one tap to the next without interrupting the current and without shortcircuiting the taps. To accomplish that function, the same principle as ABB applies in many of their tap-changer designs is used. The tap changer consists of two selector branches and a selector switch (Figure 3.9). Every other tap is connected to the left and the right selector branch respectively.
When a raise/lower signal orders a tap change, the new tap on the currentless side is connected. It is always the tap closest to the present tap that is connected. The selector switch then switches the current from the present side to the new side. This is made through resistors in order to ensure a smooth transition of the current without interrupting the load current.

The selector switch, consisting of four contactors, must perform a switching very quickly in order to avoid damage to the equipment or disturbances in the network. In this application, the whole sequence is performed by taking advantage of the time delay of the contactor coils (solenoids). By connecting the contactor coils via auxiliary contacts on the other contactors according to Figure 3.10, a switching sequence is initiated by just a short pulse on SS2 or SS3 respectively. An entire switch operation only takes 40 - 50 milliseconds. Example: A switch sequence from SS4 to SS1 (right to left) is made in the following order:

- SS4 is presently connected via contacts 1_o, 2_o, and 4_c.
- SS2 is switched in (from MC), (10-20 milliseconds).
- SS4 is switched out by contact 2_o, (10-20 milliseconds).
- SS1 is switched in by contact 4_o, (10-20 milliseconds).
- SS2 in disconnected (from MC).

Figure 3.9 The tap changer mechanism.
Chapter 3: Laboratory equipment

3.3.4 The controller

The voltage regulating relay RAYA gives “raise” or “lower” signals when the secondary voltage of the transformer deviates from the set value. The contactor circuits do not work as a tap changer on their own though, so a controller is needed to switch the contactors properly. A microcontroller (MC) and external electronics are used for measurements, contactor switchings and for safety functions. The processor is the INTEL 8052AH-BASIC, which has a built-in basic interpreter.
The MC circuit board has an 8-bit output bus. It is divided into two parts, the four least significant bits, LSB, and the four most significant bits, MSB. LSB is used for the left selector branch and MSB is used for the right selector branch. Two four-bit decoders with latches are used to control the triacs that switch the contactors. The triacs have zero-crossing detection in order to decrease switching transients. Two T-latches, one for the left branch and one for the right branch, control two triacs which feed all the contactors via the auxiliary contacts. The T-latches supply the active selector branch with a clamping voltage that allows just a short pulse when connecting a contactor. The decoders can then perform other tasks instead of keeping a contactor switched in (see Figure 3.12).

To ensure that the contactors operate the way they should, the coil voltages are measured. These voltages are transformed to binary 5 V DC-signals by voltage dividers, optocouplers and schmittriggers. Logic circuits then make two status signals and one alarm signal that captures switching malfunction even if the MC stops working. The reason for this extra precaution is that if two contactors in the same branch should connect simultaneously, a part of the autotransformer winding will be shortcircuited, resulting in transformer damage.
A basic-program is loaded into an EPROM on the MC. When the controller starts, there is first a sequence that switches in tap no. 10. The program then starts reading the input gate and waits for a raise/lower signal. This signal comes from the voltage regulating relay RAY A, or if manual mode is chosen, from push-buttons. The program is designed to give the tap changer the same time constants as in a real tap changer. The shortest time between two consecutive steps is 5 seconds.

Figure 3.13 Block scheme of the microprocessor program.
3.3.5 Tests and verification

Once the transformer models were completed, they were tested. In Figure 3.14, the desired ratios (+) are compared to the measured ratios (o) for a no-load measurement. The agreement is good, but it can be concluded that the tap sizes vary slightly, which is a consequence of that the number of winding turns is limited (171 turns). The step size varies from 1.3% to 1.7%.

The automatic voltage control was tested with a setup according to Figure 3.15. The transformer was supplied from the generator over a transmission line. In Figure 3.16, the PV-curve is plotted for the transformer load side with automatic voltage regulation.
The load was increased until point a) was reached with the regulating relay blocked. The relay was then activated and when the voltage was within the deadband, the load was further increased slowly. The tap changer kept the voltage within the deadband until no more taps were available. The dotted curve shows a simulated curve for the voltage ratio 1:1.

![Figure 3.16 PV-curve at tap changer regulation for slow load increase.](image)

The equivalent reactance and resistance were determined by load tests with both active and reactive load. Even if the data for the two included transformers alone are known, it is not obvious what data the whole construction has. The tests showed that the transformer models can be regarded as almost ideal. The resistance is $r_{ekv} = 0.009$ pu, and the reactance is $x_{ekv} = 0.003$ pu. A full description of the OLTCs is given in [5].

### 3.4 Load models

In Chapter 2, the power system load was defined as being an aggregation of a large number of individual loads. Therefore it is hard to find devices that have the same behaviour as a power system load. One way to achieve this is to implement load models which are based on field measurements.
To represent an active dynamic load, i.e. heating with recovery, immersion heaters controlled by a computer have been used. The industrial load mainly consists of motors. Therefore, an induction motor is used to model industrial load.

### 3.4.1 Dynamic active load model

The dynamic load model was built in order to enable modelling of any active load behaviour in a power system. Immersion heaters were chosen to constitute the load, and a 350 litre water tank to install them in was manufactured. The size of the immersion heaters was chosen in order to compose a binary ladder. The smallest element is 375 W, the next is 750 W, 1500 W etc, where the largest element is 12 kW. The total power is 47.625 kW at 400 V. Thus, the nominal power can be varied in steps of 375 W from zero to 47.625 kW. The dissipated heat is conducted away by cooling water flowing through the tank.

![Dynamic load model diagram](image.png)

**Figure 3.17 Front view of the dynamic load.**

- **A**: Water tank
- **B1**: Air-cooled resistors
- **B2-B8**: Immersion heaters
- **C**: Control box with contactors and relays
- **D**: Thermostat for water valve
The load model implementation and control of the heaters were carried out as a M.Sc. thesis work [1]. Figure 3.18 shows how different parts were arranged. The computer output port was connected to relays. Contactors perform the heater switching and a thermostat control regulates the cooling water flow.

A literature search was made for existing load models. Three models were implemented in the computer. They are all first order models with similar behaviour. The model described in Chapter 5 is one of the models implemented and the one used in all measurements in this thesis. The other models are described in [2] and [3]. Before the models were implemented they were tested using MATLAB/SIMULINK®.

The control program was written in HP-basic, and its algorithm follows the flow chart in Figure 3.19. The user chooses the initial load level and the power is stepped up. Then the parameters that determine the transient and stationary behaviour and the time constant are chosen. The program loop starts and collects the voltage, calculates the load demand and adjusts the power by switching in and out the appropriate heating elements. This sequence is run through two times per second.
When the dynamic load was completed, measurements were made in order to verify its function. The measurements were then compared to the SIMULINK® simulations. In Figure 3.20 the model in [4] was used, with a constant impedance transient response, a constant power stationary response and a time constant of 100 seconds. The voltage is ramped down about 10%, whereas the power decreases. The recovery then takes the power to the stationary level. The solid curve is the measured response and the dotted curve is the response from a SIMULINK® simulation with the measured phase voltage as the input.
Figure 3.20  Dynamic load model verification.
3.4.2 Motor load

The industrial part of the system load is modelled as a 30 kW induction motor (33 kW electrical power, corresponding to 0.44 pu on system base). A DC machine, connected to the grid by a four-quadrant converter, loads the induction motor mechanically. A DC tachometer is mounted on the DC machine to control speed.

General data:

Induction motor: ASEA MBG 180L-4

380 V Δ, 62 A, 1450 r/min, cos φ = 0.81.

DC motor: ASEA LAC225

400 V, 96 A, field: 220 V, 1850 r/min.

Converter: Siemens 6RA24-30-6DV62

4-quadrant, 400 V, 100 A.
Chapter 3: Laboratory equipment

The converter is microprocessor based and can be programmed to obtain a desired behaviour. In this application, the converter may be run in three different modes: speed control, current limitation and torque limitation control. In order to make the mechanical load correspond to different loads, the torque limiter is designed to be speed dependent. Three options can be used. The torque can be constant, proportional to the speed or proportional to the speed square. Almost any mechanical load can be modelled with these options.

![Motor load setup](image)

In order to study the voltage dependence of the motor, a motor model has been implemented in a MATLAB® program. The chosen model is the classical equivalent circuit. An important difference compared to the usual model is that magnetic saturation has been accounted for. The reason is that the motor is studied in a wide voltage range. Chapter 5 and Appendix contains a detailed description of the model.

3.5 Data acquisition system

A PC-based data acquisition board\(^1\) is used to collect data from the power system model. Instantaneous values of phase voltages and currents are measured. When the acquisition is completed, the RMS-values of voltages, currents, active, reactive and apparent powers are calculated and presented graphically. An application is developed in DT VEE\(^2\) to handle both the measuring process and the following calculations.

3.5.1 Data acquisition

The power system model quantities are adapted to signal level before they are connected to the acquisition board. The voltages are reduced

---

\(^1\) DT2831-G from DATA TRANSLATION\(^\text{®}\)

\(^2\) DT VEE\(^\text{™}\) visual programming software from DATA TRANSLATION\(^\text{®}\)
with resistive voltage dividers and the currents are measured with LEM modules\textsuperscript{1} whose secondary currents are sent through precision resistors. The voltages over the precision resistors, which are proportional to the primary currents, are measured with the acquisition board.

To save computational time when the system dynamics are rather slow, as is often the case with voltage stability phenomena, only one 50 Hz period at the time is sampled at a rate of 12.5 kHz (250 samples per 50 Hz period). A counter is used to control the number of samples in each burst. The time between two measured periods can be varied between 0.5 to 2 seconds from the screen with a slider. This can be done both before the data acquisition starts and while it is in progress, to adapt the measuring rate to the measured process.

Figure 3.23 illustrates the structure of the data acquisition program.

---

\textsuperscript{1} LA 100-S/SP1 from LEM (Liaisons Électroniques Mécaniques)
3.5.2 Data processing

The RMS-values of voltages, currents, active, reactive and apparent power for each measured 50 Hz period are calculated using the following relations:

\[
V = \sqrt{\frac{1}{n} \sum_{k=1}^{n} v_k^2} \tag{3.4}
\]

\[
I = \sqrt{\frac{1}{n} \sum_{k=1}^{n} i_k^2} \tag{3.5}
\]

\[
S = VI \tag{3.6}
\]

\[
P = \frac{1}{n} \sum_{k=1}^{n} v_k i_k \tag{3.7}
\]

\[
Q = \sqrt{S^2 - P^2} \tag{3.8}
\]

where:

\( v \) = voltage, instantaneous value [V],

\( V \) = voltage, RMS value [V],

\( i \) = current, instantaneous value [A],

\( I \) = current, RMS value [A],

\( n \) = number of samples,

\( P \) = active power [W],

\( Q \) = reactive power [VAr],

\( S \) = apparent power [VA].
3.6 References


Chapter 3: Laboratory equipment
Chapter 4 Voltage collapse with a laboratory power system model


4.1 Abstract
This paper deals with voltage stability phenomena investigated with a three phase power system model. The classical PV-curve is used to illustrate basic stability issues. Dynamic loads such as thermostatically controlled heating and induction motors have been treated. Measurements show that it is possible to run the system on the lower side of the PV-curve, and different actions to end up in a stable situation are proposed. The interactions between dynamic loads, transformer tap changers and generator current limiters are also investigated.

Keywords
Voltage stability, voltage collapse, on load tap changer, armature current limiter, field current limiter, dynamic load, physical power system model.

4.2 Introduction
Voltage stability has become an important issue in operating power systems. The reason is a higher stress level due to increasing loads in the systems. Many studies have been made on the issue lately, mainly by the use of mathematical models in computer simulations. This method requires good modeling of the system to come up with valid results. A power system model that is valid for all relevant states is difficult to achieve due to the fact that the level of detail in the model you need is hard to define. A model might be adequate in one case but not in the other and there is a risk that the results do not correspond to real system behaviour. This paper deals with the voltage collapse from a practical point of view. A laboratory power system model is used to investigate how the different system components interact and affect voltage stability. The system is driven into collapse under different conditions and the reason for collapse is investigated. Special attention is given to generator current limiters, transformers with tap changers and load dynamics.
4.3 Laboratory power system model

The power system model (Figure 4.1) consists of a power plant feeding different kinds of loads over a transmission line configuration which can include one or two transformers with on load tap changers (OLTCs). Control systems used in the model are identical to those used in real power systems. The rated voltage for the model is 400 V.

![Diagram of the laboratory power system model](image)

This type of power system is very useful and often used in voltage stability studies since it contains all the components that are essential to the voltage stability phenomena.

4.3.1 Power plant

The power plant is an accurate model of a large hydro power plant. A DC motor drives a 6 pole salient pole generator with a rated power of 75 kVA at 400 V. The static feeder is controlled by an ABB HPC840 voltage regulator equipped with both a field current limiter and an armature current limiter. Current limiters are described in 4.5.

4.3.2 Transmission lines

The transmission line model consists of six identical \( \pi \)-sections. Each section represents 150 km of 400 kV transmission line. These sections can be connected in series or in parallel to form a grid.

4.3.3 Transformers

Two transformers with OLTCs are available [8]. The transformers are of buck-boost type with the nominal ratio 1:1. The regulating span is \( \pm 13.5\% \) in steps of 1.5\%. The voltage regulating relay is the type RAYA from ABB which can operate with inverse or constant time lag characteristics (\( T_{OLTC} = 15-120 \) s) as well as with constant or pulsed control signal. The shortest time between two consecutive steps is 5 s.
due to the mechanical limitations of a mechanical tap changer. The relay is described in [1].

4.3.4 Dynamic active load

To represent the active part of a large aggregate load, some established dynamic load models (i.e. with recovery) [4] [5] [7] have been implemented in a computer program controlling the switching of immersion heaters of different sizes [2].

The maximum nominal load is 47.6 kW at 400 V and the dynamics is performed in steps of 0.375 kW.

The model of [7] is developed from field measurements and is the load model used in this paper. The active power is given by:

\[
T_{pr} \cdot \frac{dP_r}{dT} + P_r = P_0 \cdot \left( \frac{V}{V_0} \right)^{\alpha_s} - P_0 \cdot \left( \frac{V}{V_0} \right)^{\alpha_t}
\]

\[
P_m = P_r + P_0 \cdot \left( \frac{V}{V_0} \right)^{\alpha_t}
\]

where

\( V \) = supplying voltage [V],
\( V_0 \) = pre-fault value of supplying voltage [V],
\( P_0 \) = active power consumption at pre fault voltage [W],
\( P_m \) = active power consumption [W],
\( P_r \) = active power recovery [W],
\( \alpha_s \) = steady state active load voltage dependence,
\( \alpha_t \) = transient active load voltage dependence,
\( T_{pr} \) = active load recovery time constant [s].

In Figure 4.2 the response of the dynamic load model is shown for a step change in load voltage from 1.0 pu to 0.9 pu. Load parameters are chosen to correspond to a dynamic constant power load. The recovery originates from electrical heating that strive to deliver a constant amount of energy over a specific time. Measurements in [7] showed that the recovery time constant is of the order of one minute.
4.3.5 Induction motor load

The induction motor part of an industrial load is represented by a 30 kW induction motor loaded by a DC-machine with a PWM inverter. The inverter is programmed to produce a DC-machine torque that is either constant, proportional to the speed or proportional to the square of the speed in order to simulate different kinds of loads (fans, pumps, etc.).

4.3.6 Data acquisition

To collect data from the power system model, a PC with a data acquisition board is used. The corresponding values of voltage and current are sampled in one phase at a rate of 12.5 kHz each for one period every half second. When the acquisition is completed, RMS-values of voltage and current, apparent-, active- and reactive power are calculated and converted to per unit.

Base values are: \( V_{\text{base}} = 400 \text{ V} \), \( I_{\text{base}} = 108 \text{ A} \) and \( S_{\text{base}} = 75 \text{ kVA} \). 1.0 pu field current is defined as the field current required at \( v_{\text{gen}} = 1.0 \text{ pu} \) and \( p_{\text{gen}} = q_{\text{gen}} = 0 \text{ pu} \).
4.4 Stable operation points on the PV-curve

The most common way of analysing voltage stability is to study the system PV-curve and load characteristics. It is often claimed that the upper side of the PV-curve is the region where the system can operate and maintain its stability. The critical point is considered to be the stability limit and the operation region on the lower side of the curve is considered to be unstable. In this section, both static and dynamic operation on the lower side of the PV-curve are investigated.

![Figure 4.3 Basic system setup.](image)

4.4.1 Static operation on the lower side of the PV-curve

**Resistive load**

The setup in Figure 4.3 is used. \( z = 0.068 + j1.282 \text{pu}, \ y_c = j0.095 \text{pu}. \) The load admittance (\( \cos \phi = 1 \)) is varied from zero to its maximum, \( g_{L_{\text{max}}} \).

![Figure 4.4 Static operation on the PV-curve with resistance load.](image)
The measured static PV-curve, together with a simulated one for the system (dotted line) is presented in Figure 4.4. With a voltage applied over a constant impedance, Ohms law will always give a specific current. Therefore with a constant impedance load, every operation point on the PV-curve is stable.

**Mixed load**

In this section the same line configuration as in Figure 4.3 is used, but the load is composed of an induction motor and a constant resistance. In all three cases in Figure 4.5 the loading of the motor is slowly increased until it stalls and the system collapses. Curve (a) shows the case where the load consists of only the induction motor. The motor stalls and the system collapses at the point of maximum power transfer (critical point).

If the motor is combined with a constant resistance, the system does not collapse at the point of maximum power transfer (curve (b) and (c)). The reason for this is that the constant resistance load decreases due to the lower voltage when the motor load is increased. However, the lower voltage also makes the torque-speed characteristic of the induction motor to...
shrink. How far down on the PV-curve the operating point can come before the motor stalls depends on how much the constant resistance load unloads the system and how much the torque-speed characteristic shrinks due to the lower voltage. In curve (c) the constant resistance part of the load is 1.67 times larger than in curve (b). The experiment therefore shows the importance of load composition.

4.4.2 Dynamic operation on the lower side of the PV-curve

Change in load voltage

To investigate the system behaviour when the load voltage is changed, the setup in Figure 4.3 is used but with the load fed through a transformer with OLTC. \( z = 0.084 + j 1.654 \text{pu} \), \( y_c = j 0.129 \text{pu} \). The system is first brought to an operating point on the lower side of the PV-curve. Load parameters are \( \alpha_t = 2 \), \( \alpha_s = 0 \) and \( T_{pr} = 60 \text{ s} \). To introduce a disturbance, the OLTC is used to decrease the transformer ratio. A decrease of the ratio causes a shift downwards of the entire PV-curve as seen from the load side of the transformer. In Figure 4.6 the system trajectory is shown together with theoretical PV-curves for the system with the two different transformer ratios and the load characteristic for a constant impedance load.

Figure 4.6 System behaviour when OLTC decreases the transformer ratio.
The pre-disturbance operating point (a) is the intersection between the actual load characteristic and the pre-disturbance PV-curve. When the transformer ratio is changed the operating point follows the transient load characteristic ($\alpha_t = 2$) to the post disturbance PV-curve. At this point (b) the active power load is higher than it was in the pre-disturbance case. Since the steady state active load voltage dependence is constant power ($\alpha_s = 0$) the load tries to decrease the active power by decreasing the load conductance. As the load conductance decreases the operating point follows the post-disturbance PV-curve up on the upper side towards the pre disturbance power (c).

The case where the pre-disturbance operating point is on the upper side of the PV-curve (d) is also shown in Figure 4.6 as a comparison. When the transformer ratio is changed the operating point jumps to (e) and ends up at (f) where the load has recovered.

In the case presented in Figure 4.7 the OLTC is used to increase the transformer ratio. As in Figure 4.6 the operating point follows the load characteristic from the pre-disturbance PV-curve (a) to the post-disturbance PV-curve (b) when the ratio is changed.

Figure 4.7  System behaviour when OLTC increases the transformer ratio.
But in this case the post-disturbance active power is lower than before the increase of the transformer ratio. Therefore the load will react to restore the active power to its pre-disturbance value by increasing the load conductance. On the lower side of the PV-curve this will lead to a further decrease in active power and the operating point will continue down the PV-curve and collapse, or in this case continue until no more load objects can be added (c).

The conclusion is that with a dynamic load, stable operation on the lower side of the PV-curve can not be achieved since a disturbance that causes a decrease in active power will lead to voltage instability. From another point of view, if the system for any reason is brought to the lower side of the PV-curve the situation can be improved by decreasing the transformer ratio.

**Reactive support**

Also in this section the setup in Figure 4.3 is used but in this case the load is supported by shunt capacitors, see also [10]. A disturbance is introduced into the system by adding a small constant impedance load to the existing dynamic load having the same parameters as before. Shunt capacitors are switched in 60 s after the disturbance.

For the case illustrated in Figure 4.8, two capacitors ($y_{sh} = j0.031$ pu each) were switched in. The pre-switch PV-curve, the post-switch PV-curve and the constant impedance characteristic for the load in (c) and (d) are drawn with dotted lines.

![Figure 4.8 Reactive support from two capacitors.](image-url)
The operating point jumps from its pre-disturbance position on the pre-switch PV-curve (a) to a point further down on the same curve (b) when the constant impedance load is added. Since the dynamic load has a constant impedance transient behaviour and a constant power steady state behaviour it tries to restore the load in the same way as in the case illustrated in Figure 4.7. When the capacitors are switched in (c) the operating point follows the load characteristic to the post-switch PV-curve (d). At this moment the dynamic load power is higher than the pre-disturbance power ($P_0$). Like in Figure 4.6 the operating point follows the post-switch PV-curve up on the upper side.

If only one capacitor is switched in after 60 s (Figure 4.9) the voltage increase caused by the capacitor is not large enough to make the dynamic load power higher than the pre-disturbance power.

![Figure 4.9 Reactive support from one capacitor.](image)

This is similar to the case where the transformer ratio was increased (see Figure 4.7). The steady state constant power demand of the dynamic load will bring the operating point further down the PV-curve until the system collapses, or in this case until no more load objects can be added.
4.5 Current limiters

Automatic voltage regulators (AVR) for large synchronous generators mostly have field current limiters to protect the generator field winding from overheating. The AVRs for the generators in the Swedish nuclear power stations also have armature current limiters thereby avoiding that other protection relays trip the generator for overcurrent.

Current limitation mostly implies decreasing voltage, which in most cases is devastating for a stressed system. Voltage instability and a collapse may follow. In order to understand the function of the current limiters, the system described in Figure 4.3 has been used. $Z = 0.068+j1.282\text{pu}$, $\gamma_c=j0.095\text{pu}$. The load $g_L$ is ramped slowly from zero to $g_{L\text{max}}$.

4.5.1 Field current limiter (FCL)

In Figure 4.10, curve 1 shows the result in case the load is increased until and after the field current limit is reached. The limit is set to 1.05 pu and when it is exceeded (a) there is a 5 s. delay before the limiter is activated (b). When the FCL becomes active the control is changed so that the field current, and thereby the excitation voltage is regulated instead of the terminal voltage. This means that the point of voltage control is moved behind the machine synchronous reactance, $X_s$, which now becomes a part of the network. The operating point is transferred to a new PV-curve (c). Although the point of regulation has changed, the generator can still be considered as a constant voltage source located behind $X_s$.

![Figure 4.10 Field current limiter in action.](image)
In order to analyse the new PV-curve (curve 2), constant field current control was used, set to the same value as the current limit in curve 1. The load was ramped down from its maximum. Because of the high no load voltage, the load was not brought to zero. Extrapolating the curve it can be seen that the no load voltage is approx. 1.3-1.4 pu. It is difficult to calculate the PV-curve for constant field current analytically since the machine synchronous reactance ($X_s$) changes with saturation in the generator. An example of calculating the saturated value of $X_s$ for a no load synchronous machine with Potiers method is shown in [3].

Neglecting saturation introduces substantial errors. As an example, the no load voltage ($V_0$) was calculated for the case with constant field current shown above. Using the unsaturated synchronous reactance, $V_0$ becomes about 2 pu which is far from the actual value.

4.5.2 Armature current limiter (ACL)

Figure 4.11 shows the result in case the armature current limit is reached. The limit is set to 0.4 pu and when it is exceeded (a) there is a 5 s. delay before the limiter is activated (b). The operating point is transferred from the PV-curve to the characteristic $P/V \approx I_s = \text{constant}$ (c). With the armature current limiter active, the generator can be considered as a constant current source [9].
4.5.3 Combination of current limiters

Figure 4.12 shows a case where both current limiters become active. The field current limit is 1.05 pu and the armature current limit is 0.36 pu. As before, the active load is slowly ramped from zero to $g_{L\text{max}}$. First the field current limit is exceeded (a) and after a while the armature current limit is also exceeded (b).

![Figure 4.12 Both current limiters in action.](image)

Looking at the capability diagram of the generator [9], one can see that the normal area of operation is decreasing when a generator has gone into current limiter control (see also 6.3). Once the armature current limiter has become active it is not easy to save the system.

In a single machine system such as used here, current limitation always implies decreasing terminal voltage and thereby a lower system voltage. The decreasing voltage triggers dynamics such as tap changer relays and dynamic loads, that makes it almost impossible to reverse the process. In section 4.6 it is shown that even if there is only a short transient increase of the current, limitation might threaten system stability.
4.6 Tap changer and load dynamics

In order to study the interaction between load dynamics and tap changer regulation the system setup shown in Figure 4.13 is used.

Figure 4.13 Setup for OLTC measurements.

Figure 4.14 shows the secondary voltage and the primary current using two of the four possible OLTC control modes \( T_{oltc} = 30 \text{ s} \). Load parameters are \( \alpha_s = 0, \alpha_t = 2 \) and \( T_{pr} = 60 \text{ s} \). A disturbance is initiated by disconnecting one of the lines causing a voltage drop at the load end. The active load restoration starts immediately (a) and after a delay determined by the OLTC relay the voltage restoration starts (b). The time for voltage restoration varies depending on the control mode chosen.
The combination of load dynamics and OLTC regulation might cause a power/current overshoot. The worst case in this setup is due to control mode I, constant time delay and continuous control signal. The time delay, $T_{\text{oltc}}$, allows the load dynamics to restore a considerable part of the power and a following fast voltage restoration causes a power/current overshoot because of the transient load behaviour (dash dotted line). The other control mode shown (solid line), inverse time delay and pulsed control signal, causes almost no overshoot.

If the overshoot activates a generator armature current limiter it implies a decreasing voltage that could threaten the voltage stability [6]. Figure 4.15 shows the generator current, the load voltage and the active power for two cases. In case 1 (solid line) the ACL is activated because of the current overshoot and in case 2 (dash dotted line) there is no current limit. The overshoot and the stationary current do not cause any stability problems as such, however current limitation in combination with the overshoot results in a collapse.
By exploiting the thermal status of the generator better, a temporary generator overload could be allowed. Hereby the current limitation during an overshoot could be avoided and the system can remain stable.

4.7 Conclusions

The measurements made with the power system model described show that many nonlinear dynamic phenomena in a power system can be investigated and illustrated in a way that is difficult to achieve by other means. The smallness of the system makes it relatively easy to understand system response in different situations.

Generally the point of collapse does not coincide with the critical point of the PV-curve. It is possible to run the system on the lower solution of the PV-curve with a constant impedance load as well as with a mixed load.

A system that is heading towards a collapse on the lower part of the PV-curve can be rescued by decreasing the transformer ratio or and switching in additional capacitor banks.
Load dynamics and OLTC regulation might cause a power/current overshoot that could endanger the system stability. If the OLTC relays time constants and modes can be set to minimize overshoot and if the current limiter actions can be further delayed by allowing temporary overloading, voltage collapse might be avoided.

It is extremely important to understand dynamic load behaviour in order to predict voltage unstable situations. Field measurements in important buses in the system and further load model identification as made in [7] could be strongly beneficial.

It was shown that the system characteristics change dramatically in case the generator is armature current limited and/or field current limited. In our opinion current limitation is a main issue when studying voltage stability.

4.8 Acknowledgements

The authors would like to thank the Sydkraft company and the Sydkraft Research Foundation for their financial support. The authors are indebted to Mr. Sture Lindahl and Mr. Daniel Karlsson for their valuable contributions and stimulating discussions.

We would also like to thank ABB Power Systems for their donation of laboratory equipment.

4.9 References


Chapter 4: Voltage collapse with a laboratory power system model

Published at Cigre, Paris, France, 1984.


Chapter 5  Voltage stability: The significance of induction motor loads


5.1 Abstract
This paper is focusing on reactive power load models and the induction motor in a voltage stability context. Measurements on a three phase power system model offer an explanation for the large differences in reactive load voltage dependence as found in literature. Errors introduced when neglecting saturation effects in induction motors are demonstrated. Stable operating points on the PV-curve with induction motor load and with a combination of induction motor- and resistance load are discussed using torque(speed)- and PV-curves. Finally, it is shown by measurement that a system with a pure induction motor load and operating on the lower side of the PV-curve, can be saved by switching in shunt capacitors.

Keywords
Voltage stability, voltage collapse, load modelling, reactive power, induction motor load, dynamic load, physical power system model.

5.2 Introduction
The power system load as seen from a specific point in the system, is one of the most difficult parts to identify and to model. This is due to its complexity and varying composition. Also poor knowledge of certain types of load contributes to inaccurate assumptions on load behaviour. The induction motor load represents at least half of the active power load in many power systems, and almost purely resistive loads stand for most of the rest. The induction motor load therefore is the dominant reactive power load. This paper deals with reactive power load models and the induction motor part of the load. A laboratory power system model is used to investigate an induction motors’ impact on the voltage stability. Special attention is given to the reactive power consumed by the motor.
Chapter 5: Voltage stability: The significance of induction motor loads under various conditions and to stable versus unstable operating range on the PV-curve.

The power system model (Figure 5.1) consists of a power plant feeding different loads over a transmission line configuration which can include one or two transformers with on-load tap changers (OLTC:s). Control systems used in the model are identical to those used in real power systems. The rated voltage for the model is 400 V.

![Laboratory power system model.](image)

This type of power system is very versatile, and can be used in voltage stability studies, since it contains all the components that are essential to voltage stability phenomena.

### 5.2.1 Power plant

The power plant is an accurate model of a large hydro power plant. A DC motor drives a 6 pole salient pole generator with a rated power of 75 kVA at 400 V. The static feeder is controlled by an ABB HPC840 voltage regulator equipped with both a field current limiter and an armature current limiter.

### 5.2.2 Transmission lines

The transmission line model consists of six identical π-sections. Each section represents 150 km of a 400 kV transmission line. The sections can be connected in series or in parallel to form a grid.
5.2.3 Transformers

Two transformers with OLTC:s are available. The transformers are of the buck-boost type with the nominal ratio 1:1. The regulating span is ±13.5% in steps of 1.5%. The voltage regulating relay is of the type RAYA from ABB, which can operate with inverse or constant time lag characteristics ($T_{OLTC} = 15-120$ s) as well as with constant or pulsed control signal. The shortest time between two consecutive steps is 5 s due to the mechanical limitations of a tap changer.

5.2.4 Dynamic active load

A load with the characteristics of a large aggregate load can not be achieved in a laboratory environment, therefore it has to be simulated. In order to represent the active part of a large aggregate load, some established dynamic load models (i.e. with recovery) [6], [9] and [10] have been implemented in a computer program controlling the switching of immersion heaters of different sizes.

The maximum nominal load is 47.6 kW (at 400 V) and the dynamics is performed in steps of 0.375 kW (at 400 V).

5.2.5 Induction motor load

The induction motor part of an industrial load is represented by a 30 kW induction motor loaded by a DC-machine with a PWM inverter. The inverter is programmed to produce a DC-machine torque that is either constant, proportional to the speed or proportional to the square of the speed in order to simulate different kinds of loads (fans, pumps, etc.).

5.2.6 Data acquisition

To collect data from the power system model, a PC with a data acquisition board is used. The corresponding values of voltage and current are sampled in one phase at a rate of 12.5 kHz each for one period every half second. When the acquisition is completed, RMS-values of voltage and current, apparent-, active- and reactive power are calculated and converted to per unit.

Base values: $V_{\text{base}} = 400$ V, $I_{\text{base}} = 108$ A and $S_{\text{base}} = 75$ kVA. 1.0 pu field current is defined as the field current required at $v_{\text{gen}} = 1.0$ pu and $p_{\text{gen}} = q_{\text{gen}} = 0$ pu.
5.3 Load modelling

In literature, a large number of different load models for power system stability studies can be found. [1] gives a summary of load models used in dynamic studies of power systems. Some load models often used are discussed here.

5.3.1 Static load models

Power companies mostly use static load models to represent the system load. Active and reactive power are represented as functions of voltage magnitude (and of frequency if taken into account) at the bus from which the load is modelled. The basic static load models are the constant power, constant current and constant impedance models. The polynomial load model is a combination of the these three basic models:

\[
P_m = P_0 \left( a_p + b_p \left( \frac{V}{V_0} \right) + c_p \left( \frac{V}{V_0} \right)^2 \right) \tag{5.1}
\]

\[
Q_m = Q_0 \left( a_q + b_q \left( \frac{V}{V_0} \right) + c_q \left( \frac{V}{V_0} \right)^2 \right) \tag{5.2}
\]

where

\[V = \text{supply voltage [V]},\]
\[V_0 = \text{reference value of supply voltage [V]},\]
\[P_0 = \text{active power consumption at reference voltage [W]},\]
\[P_m = \text{active power consumption [W]},\]
\[Q_0 = \text{reactive power consumption at reference voltage [VAr]},\]
\[Q_m = \text{reactive power consumption [VAr]}.\]

Another common static load model is the exponential load model:

\[
P_m = P_0 \left( \frac{V}{V_0} \right)^\alpha \tag{5.3}
\]

\[
Q_m = Q_0 \left( \frac{V}{V_0} \right)^\beta \tag{5.4}
\]

where

\[\alpha = \text{active load voltage dependence},\]
\[\beta = \text{reactive load voltage dependence}.\]
5.3.2 Dynamic load models

When voltage stability problems are studied with static methods, there is a possibility that a post contingency steady state solution is found even though the system would have collapsed during its way towards this new steady state. This collapse can be caused by generator current limiters, triggered by an overshoot in current due to transformers with on load tap changers in combination with load dynamics [11]. Therefore, long term dynamic methods should be used when studying voltage stability.

In a dynamic load model active and reactive power are modelled as a function, not only of voltage, but also as a function of time. The model chosen here [10] is an example of a dynamic load model. The model is based on field measurements executed in 10 and 20 kV networks in the southern part of Sweden. The active power is given by:

\[
T_{pr} \frac{dP_r}{dT} + P_r = P_0 \left( \frac{V}{V_0} \right)^{\alpha_s} - P_0 \left( \frac{V}{V_0} \right)^{\alpha_t}
\]  
\( (5.5) \)

\[
P_m = P_r + P_0 \left( \frac{V}{V_0} \right)^{\alpha_t}
\]  
\( (5.6) \)

where

\( P_r = \) active power recovery [W],
\( \alpha_s = \) steady state active load-voltage dependence,
\( \alpha_t = \) transient active load-voltage dependence,
\( T_{pr} = \) active load recovery time constant [s].

The reactive power is given by:

\[
T_{qr} \frac{dQ_r}{dT} + Q_r = Q_0 \left( \frac{V}{V_0} \right)^{\beta_s} - Q_0 \left( \frac{V}{V_0} \right)^{\beta_t}
\]  
\( (5.7) \)

\[
Q_m = Q_r + Q_0 \left( \frac{V}{V_0} \right)^{\beta_t}
\]  
\( (5.8) \)

where

\( Q_r = \) reactive power recovery [VAR],
\( \beta_s = \) steady state reactive load-voltage dependence,
Chapter 5: Voltage stability: The significance of induction motor loads

\[ \beta_t = \text{transient reactive load-voltage dependence}, \]
\[ T_{qr} = \text{reactive load recovery time constant [s]}. \]

In Figure 5.2 the response of the dynamic load model is shown for a voltage step from 1.0 pu to 0.9 pu. The recovery of the active power originates from voltage dependent setting points in many thermostat controlled home heating devices [10]. When it comes to the reactive power, there is no load object that can explain the recovery as seen in Figure 5.2. Electrical heating does not consume reactive power. Induction motors that represent more than 50% of the total load in many systems consume reactive power, but they recover within a few seconds and do not have a recovery time constant in the scale of minutes. In our opinion the reactive power recovery results from the active power recovery. The increase of current during recovery following a voltage decrease leads to an increase in reactive losses in the network.

![Figure 5.2](image.png)

*Figure 5.2 Example of step response of a dynamic load model. Load parameters: \( \alpha_t = 2.0, \alpha_s = 0.4, \beta_t = 4.0, \beta_s = 2.5 \) and \( T_{pr} = T_{qr} = 60 \text{ s} \).
5.4 Power voltage dependence

When the voltage dependence of loads is discussed, it is often done in terms of the exponents $\alpha$ and $\beta$ in Equation 5.3 and Equation 5.4 and $\alpha_s$ and $\beta_s$ in Equation 5.5 to Equation 5.8. A range of values of $\alpha$ and $\beta$ are known for different loads around the world [1], [2], [10], [15] and [16]. It must be kept in mind that loads are modelled as viewed from a bus somewhere between the transmission level and distribution level. This means that the load models represent an aggregate of load objects fed through a network. The values of $\alpha$ roughly varies between 0.1 (close to constant power load) and 1.7 (close to constant resistance load). The values of $\beta$ varies between 0.5 and 6 with a majority of values around 3. In measurements on a 30 kW induction motor, (section 5.5), $\beta$ values varying between -2.5 and 21 were obtained.

5.4.1 The influence of different $\beta$ on simulation results

A voltage collapse scenario was simulated in the NORDIC 32-A test system with the PSS/E program. The program uses the dynamic load model [10] presented in section 5.3.2 in.

Three simulations with different values of $\beta_s$ were carried out. The simulation results are presented in Table 5.1.

<table>
<thead>
<tr>
<th>$\beta_s$</th>
<th>result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>collapse after 38 s</td>
</tr>
<tr>
<td>2</td>
<td>collapse after 52 s</td>
</tr>
<tr>
<td>3</td>
<td>collapse after 77 s</td>
</tr>
</tbody>
</table>

Table 5.1 Simulation results.

These simulations show that the voltage dependence of the reactive load is not unimportant for the obtained results.
5.5 Reactive power sensitivity measurements on an induction motor load

This section describes how a number of variables affect induction motor load behaviour and thereby the quantity $\beta$ in Equation 5.4. The laboratory model described in section 5.2 is used to achieve different circuits.

In Figure 5.3 the 30 kW induction motor described in section 5.2.5 was loaded with 21 kW for two different mechanical load characteristics and exposed to a negative voltage step (17%).

![Graph showing motor power over time with solid and dotted lines representing different load characteristics.](image)

Figure 5.3 Motor power when exposed to a negative voltage step. Solid lines: constant torque. Dotted lines: torque proportional to the square of the speed.

The transient response disappears within a second and can be disregarded in long term voltage stability studies. Only the quasi stationary quantities are monitored in the following. The active power is almost unchanged, and only small differences between the two mechanical load characteristics can be observed. As a consequence, the active power is considered to be constant and not dependent of voltage variations and mechanical torque characteristics. In Figure 5.4 the static voltage dependence for a specific load level ($P = 0.83P_n$) is shown. The rated voltage for the induction motor is 0.95 pu.
From the reactive power curve in Figure 5.4, $\beta$ values can be calculated for voltages differing from the rated voltage using the relation:

$$\beta = \frac{\ln\left(\frac{Q_m}{Q_0}\right)}{\ln\left(\frac{V}{V_0}\right)}$$

(5.9)

Three different setups have been studied: a) the motor directly fed from the transformer, b) the motor was 50% shunt compensated at rated voltage and c) the motor was 50% shunt compensated and was fed through an impedance corresponding to a length of 150 km of transmission line.
Chapter 5: Voltage stability: The significance of induction motor loads

5.5.1 Load level of an induction motor

In this section the aim is to illustrate how the load level of the induction motor affects the reactive load model. The motor is fed directly from the transformer and five different load levels have been studied: no load, 27%, 44%, 62% and 83% of the rated active power. In Figure 5.6, $\beta$ is plotted as a function of the load level and the voltage deviation from rated voltage $V_0$. As seen from the figure, both the load level and the voltage strongly affect the value of $\beta$. $\beta$ varies from 0.6 to 4.7 depending on the load level and voltage deviation. Some of the lowest load levels might seem to be unrealistic, but even with moderate variations $\beta$ varies considerably.

The reason for the $\beta$ variation can be found by studying the induction motor’s equivalent circuit. The iron core is designed to be saturated to a certain degree at the rated voltage in order to save weight and size. This leads to a voltage dependent magnetizing reactance. The reactive consumption of the leakage reactance varies both with load level and voltage. Voltage changes imply current changes that affect the reactive consumption. At low load levels the magnetizing reactance dominates the reactive consumption (high $\beta$ values) and at high load levels the leakage reactance dominates (lower $\beta$).

![Figure 5.6 $\beta$ variation at different load levels and voltage steps.](image)
5.5.2 Reactive compensation of induction motor load

When compensating an induction motor with shunt capacitors, the combination of the squared voltage relation of the capacitors and the non-linear behaviour of the induction motor causes a high voltage sensitivity [7]. In Figure 5.7 measured values are shown for a compensation of about 50% at rated voltage. Two different load levels are represented and the voltage is varied from 0.77 to 1.04 pu. \( \beta \) values up to 7 were observed in case of 50% compensation. In case of close to a 100% compensation, \( \beta \) values up to 21 were observed.

![Figure 5.7 \( \beta \) variation with varying compensation and load level. Solid lines: compensated motor (50%). Dotted lines: uncompensated motor.]

5.5.3 Impact of feeder reactance and compensation

When studying voltage stability the load is often seen from a higher voltage level and therefore a distribution network is included in the load model. The same combination as in section 5.5.2 is used with a motor compensated to 50% but in this case there is a line impedance added in order to represent some kind of network. In Figure 5.8, \( \beta \) is plotted as a function of voltage for two different load levels. Compared to the curves in Figure 5.7, the non-linear behaviour of the load is reduced by the line impedance.
5.5.4 Induction motor saturation

In induction motor models used for voltage stability studies magnetic saturation is usually neglected. The models are either based on the equivalent circuit, [1], [12], [13] or, if dynamics are required, some form of state-space model, [4], [5], [8], [12]. Using these models, the reactive power non-linearities do not appear and $\beta$ never exceeds 2 whereas observed values usually are $\beta \geq 3$. In this section the significance of saturation in motors when modelling reactive power is examined.

5.5.5 Derivation of induction motor model for voltage stability studies

An induction motor model including saturation has been derived based on the classic equivalent circuit.

![Diagram of induction motor model](image-url)

Figure 5.9 a) Equivalent circuit for an induction motor. b) Thevenin equivalent.
Frequency dependence and transient behaviour are not captured as for long term voltage stability studies these variables are not deemed to be of importance. The parameters have been determined by using data from the no load test and the blocked rotor test. The saturation has been accounted for by letting the magnetizing reactance \( X_m \) vary with the terminal voltage. \( R_1 \) is measured with a multimeter and corrected for temperature. The leakage reactances \( X_1 \) and \( X_2 \) and the rotor resistance \( R_2 \) are derived from the blocked rotor test. The magnetizing reactance \( X_m \) is approximated by a 2:nd order polynome that is extracted from the no load test. \( X_m \) varies with the terminal voltage according to Figure 5.10. The iron core losses are neglected.

![Figure 5.10 Voltage dependence of the magnetizing reactance \( X_m \).](image)

The equivalent circuit is simplified by using the Thevenin theorem. From Figure 5.9 b the torque can be calculated. \( q_1 \) is the number of phases, \( \omega_s \) is the mechanical synchronous angular velocity.

\[
T = \frac{q_1 \times V_{1a}^2 \times R_2/s}{\omega_s \times ((R_{e1} + R_2/s)^2 + (X_{e1} + X_{e2})^2)}
\]

The model has been implemented in a computer using MATLAB®. From a given torque and voltage, active power, reactive power, current
and slip are calculated. The torque can be either constant, proportional to the speed or proportional to the square of the speed. In Figure 5.11 a simulation with constant load torque and saturation included is compared with measurements.

As seen from the curves, agreement is very good. The reactive power decreases with decreasing voltage, mostly due to the increasing magnetizing reactance. Below 0.82 per unit the reactive power increases again due to a dramatic increase in the reactive losses in the leakage reactances. For a lower load level the minimum reactive power occurs at an even lower voltage. The load level in the figure is about 84% of the rated load.

5.5.6 The effect of neglecting saturation

To examine the errors introduced by neglecting saturation, simulations were made with both constant and voltage dependent magnetizing reactance $X_m$. The load level is $0.68*P_n$. The result in Figure 5.12 shows that $\beta$ is strongly affected by the assumption of an unsaturated motor. When neglecting saturation, $\beta$ values are not realistic. If saturation is included, the $\beta$-values are much higher. In combination with
reactive compensation $\beta$ is further increased and values $\geq 3$ can be explained. Consequently, neglecting saturation introduces substantial errors when modelling reactive power in a power system.

![Figure 5.12](image)

From the measurements in sections 5.5.1, 5.5.2 and 5.5.3 it can be concluded that the reactive power consumed by an induction motor load varies with the load level, the degree of compensation and the network feeding the load. $\beta$ is strongly affected by these parameters and also by the voltage deviation from the reference value $V_0$ ($-2.5 \leq \beta \leq 7$ in these measurements). The simulations in this section show that saturation must be accounted for when $\beta$ values are calculated for an induction motor load.

It is the opinion of the authors that the wide range in $\beta$ values observed in literature is due to variations in distribution networks, the degree of compensation of induction motor loads and the different levels of motor load. The shown variation of $\beta$ with voltage makes this parameter less suitable for investigating the role of reactive power demand in case of voltage instability. The reactive demand of aggregate loads should instead be based on the active power demand, the fraction of induction motor load and the structure of the network feeding the load.
Chapter 5: Voltage stability: The significance of induction motor loads

5.6 Induction motor load and collapse

In [11] it was shown that with an induction motor load (one large machine) it is impossible to operate on the lower part of the PV-curve. It was also shown that with a combination of induction motor load and resistive load it is possible to operate on the lower part of the PV-curve.

Here it will be shown when and why a single machine induction motor load stalls and causes a collapse. The model described in section 5.5.5 is used to simulate an induction motor fed over a weak connection from an infinite bus. Measurements are also made in order to verify theoretical results. In some figures the active power is given as per unit of the rated motor data ($P_{\text{base}} = 33$ kW).

5.6.1 Computer simulation of induction motor load

![Figure 5.13 Model for motor load simulation.](image)

Figure 5.14 and Figure 5.15 show results based on the system as above. The slip is varied from 0.0 to 0.2 and the corresponding values for terminal voltage $V_t$, active power and torque are calculated. The torque curve can be seen as a combination of the static torque curves corresponding to different terminal voltages due to changing slip. The breakdown slip is constant for all motor terminal voltages and the breakdown torque is proportional to the voltage square. But when the terminal voltage varies with the slip, the breakdown speed becomes higher. The weaker the connection is, the higher is the breakdown speed.

As known, operating points to the left of the breakdown speed are unstable and points to the right are stable. Figure 5.14 shows that the breakdown torque occurs at a slightly higher speed than the critical power, but the difference due to losses is so small that it can be neglected for all practical purposes. It can be concluded that the stalling occurs at the critical point of the PV-curve and that the stability limit occurs at the critical point. That is, no stable operating point exists on the lower part of the PV-curve with an induction motor load.
Figure 5.14  Induction motor load. Dotted lines: static torque.

Figure 5.15  PV-curve for induction motor load.
5.6.2 Combination of induction motor load and resistance load

In this case the induction motor load is combined with a constant resistance load. (see Figure 5.16 and 5.17).

![Figure 5.16 Combination of induction motor load and resistance load.](image)

![Figure 5.17 PV-curve for a combination of induction motor load and resistance load.](image)
When plotting the total active power together with motor torque and terminal voltage versus motor speed it is concluded that the breakdown speed does not coincide with the speed at the critical power. This means that it is possible to operate on the lower part of the PV-curve down to the point of the breakdown speed.

### 5.6.3 Induction motor collapse

In this section, statements made in [13] and [15] concerning induction motor loads are elucidated and verified by measurements. It is claimed that switching in shunt capacitors when the operating point is on the lower part of the PV-curve can lead to a voltage recovery and thereby the avoidance of a voltage collapse. That is shown to be true. Similar theories are presented in [17]. In [11] it was shown to be true for heating. A detail that is not explained is how the operating point for an induction motor load is transiently transferred to the lower part of the PV-curve.

It is the opinion of the authors that it is not possible to transiently transfer the operating point from the upper side to the lower side of the PV-curve unless the load demand exceeds the critical power of the PV-curve. If the load demand is increased until the critical power is reached the motor load stalls and the system collapses (as shown in [11] and section 5.6.1). When the operating point has reached the lower part of the PV-curve urgent emergency control actions are necessary because no stable equilibrium point exists on the lower part. The emergency action must imply that motor power is transiently higher than the load demand so that the motor is accelerated.

In order to verify the theories presented above concerning the breakdown point, and the emergency controls proposed in [13], measurements have been made, using the setup shown in Figure 5.18. The generator is feeding the motor over an impedance corresponding to a 450 km transmission line. The shunt branches are omitted.

![Figure 5.18 Setup for measurement.](image-url)
In Figure 5.19, Figure 5.20 and Figure 5.21 two measurements are presented. In a stressed load case the motor torque is momentarily increased. The critical power is reached and a collapse is initiated. The shunt capacitor is switched in at two different instants. In the first case this is done so quickly that the motor power transiently becomes higher than the power demand. This involves a motor acceleration and the operating point is transferred to the upper side of a new PV-curve.

In the second case the capacitors are switched in too late and therefore the motor power never exceeds the power demand and a collapse follows. Even if the power demand is raised slightly over the critical power it only takes about 1-1.5 seconds before an inevitable collapse occurs.

Figure 5.19 Measurement to verify theory about emergency control. Solid lines: successful switching of shunt capacitors (1). Dash dotted lines: switching too late to save system (2). Dashed lines: extrapolated system trajectories.
Figure 5.20  PV-curve. Solid lines: successful switching of shunt capacitors (1). Dash dotted lines: switching too late to save system (2). Dashed lines: extrapolated system trajectories.

Figure 5.21  Power and voltage versus time. Solid lines: successful switching of shunt capacitors (1). Dash dotted lines: switching to late to save system (2).
5.7 Conclusions

The dominant components in the reactive power consumption are induction motor loads and reactive losses in the network. Generally this reactive consumption is described by an exponential model, and its voltage dependence is characterized by an exponent $\beta$. This parameter varies considerably. It was shown that this variation can be explained by the non-linear behaviour of induction motor loads, their load factor, the degree of shunt compensation (if present), the voltage deviation from the reference value and the reactances of the connecting network. The parameter $\beta$ must therefore be considered as unsuitable for voltage stability studies.

A proper modelling of induction motor loads should at least include the non-linear behaviour of their magnetic circuits. Additionally the reactive load should be modelled as a function of the fraction of motor loads, the active load power behaviour and the characteristics of the network between the point where the load is modelled and the load objects.

An induction motor load cannot operate on the lower part on the PV-curve since the breakdown torque coincides with the critical point of the PV-curve. On the other hand, with a combination of motor load and resistance loads the breakdown point of the motor load is shown to exist on the lower part of the PV-curve.

Once a collapse has been initiated with a pure induction motor load, energizing shunt capacitors can save the system and bring the operating point to a stable equilibrium. The speed of such a collapse demands very fast automatic action.

Motor loads have a major influence on the voltage stability of the network. It is therefore essential to know accurately the composition of the load and the fraction of motor load present.

5.8 Acknowledgements

The authors would like to thank the Sydkraft company and the Sydkraft Research Foundation for their financial support. The authors are indebted to Mr. Sture Lindahl and Mr. Daniel Karlsson for their valuable contributions and stimulating discussions. The authors would also like to thank ABB Power Systems for their donation of laboratory equipment.
5.9 References


Chapter 5: Voltage stability: The significance of induction motor loads


Chapter 6  Complementary results

This chapter deals with complementary results to the two papers presented in Chapter 4 and 5.

6.1  More about load behaviour

In this section, different load characteristics and their influence on voltage stability is further discussed. Both the inherent qualities of individual loads and their behaviour together with other system components are analysed.

6.1.1  Impact of load characteristics at armature current limitation

If a disturbance causes the load voltage to drop and the armature current limit is exceeded, the load characteristics are extremely important for the voltage stability. Figure 6.1 shows two measurements obtained with the same system as in Figure 4.13, but without OLTC control. A comparison is made between two active loads ($Q_{\text{load}} = 0$) having a different steady state characteristic.

![Figure 6.1 Armature current limitation with two different steady state load characteristics. Solid line: $\alpha_s = 1.2$. Dash dotted line: $\alpha_s = 0.8$.]
Chapter 6: Complementary results

The final steady state solutions do not depend on the transient behaviour of the system. However, the time plots illustrate the large difference in system behaviour for the two different loads.

In the first case, the steady state load characteristic is between constant impedance and constant current, $\alpha_s = 1.2$, and in the second case between constant current and constant power, $\alpha_s = 0.8$. In the initial working point (a), the generator armature current is close to its limit. A small additional load is connected (b), the ACL triggers immediately and is activated 5 seconds later (c). Since the load voltage has changed, the dynamic load moves the system towards a new steady state. In the first case, the system converges to a stable operating point at the intersection between the steady state load characteristic and the new PV-curve. However, in the second case there is no intersection between those two curves and hence no stable operating point.

[1] shows that the critical value for $\alpha_s$ at armature current limitation is $\alpha_s = 1.0$. In Figure 6.2, the measured PV-curve for the armature current limited machine is shown together with the load characteristics for a load with $\alpha_s > 1$ and for another one with $\alpha_s < 1$.

*From Figure 6.2 it can be concluded that if the load is purely active with $\alpha_s < 1$, and the ACL is activated, the system will always collapse.*

![Figure 6.2 Armature current limitation and different load characteristics.](image-url)
Suppose that we have a large system and that the load seen from the node where the studied generator is connected has $\alpha_s < 1$. If the system conditions are so stressed that the ACL is activated, the generator will not find a new operating point (Figure 6.2) and will therefore be tripped automatically as a protective action when the node voltage has reached a lower limit (0.7 - 0.8 pu). With the generator disconnected, with low voltages in the area and with an $\alpha_s < 1$, we may have a cascaded effect where other local generators will reach their current limits or trip due to low voltages and where lines from other areas will trip due to over-current.

The conclusion is that even a large system will probably collapse if the ACL on a large generator is activated and the load as seen from the generator node has $\alpha_s < 1$.

6.1.2 The influence of mechanical torque-speed characteristics on induction motors

In Chapter 5, an induction motor was exposed to a negative voltage step of 17%. It was shown that the torque-speed characteristic of the induction motor’s mechanical load hardly affects the change in active and reactive power consumption, as caused by the voltage step.

Here we analyse the mechanical load characteristic when the voltage is varied in a larger interval. The static voltage dependence of the induction motor was examined for three different mechanical load characteristics, $T=\text{constant}$, $T\sim n$ and $T\sim n^2$. Figure 6.3 shows the motor current and the active and reactive power consumption when the voltage is varied between 0.77 pu and 1.04 pu. The rated motor voltage is 0.95 pu.
Chapter 6: Complementary results

Figure 6.3  Static voltage dependence for an induction motor load with different mechanical torque-speed characteristics. Solid lines: T=constant. Dotted lines: T~n. Dash-dotted lines: T~n^2.

For voltages around the rated voltage, there is essentially no difference between the three types of mechanical load. The largest difference occurs for the lowest voltage (0.77 pu) and is 3.8% for the two currents corresponding to the T~n^2 load and to the T=constant load.

For a larger motor, the difference in active power for different voltages becomes even smaller since a larger motor has a steeper torque-speed characteristic than a smaller one. The difference in active power between the three types of mechanical loads will also be smaller with a larger motor. This is because the intersection between the torque-speed characteristics of the mechanical load and the induction motor will occur at both a higher torque and a higher speed for the two speed dependant loads. With a smaller difference in active power between the three mechanical loads, the differences between the currents and the reactive powers drawn by the motor will also be smaller.

The conclusion is that, in most cases, one can treat the induction motor as a constant active power load and disregard its mechanical load characteristic.

6-4
6.2 Load shedding

In 4.4.2, switching in shunt capacitors and decreasing transformer ratios were discussed as methods to bring a system whose operating point has reached the lower side of the PV-curve back to the upper side.

Another method that can be used is load shedding. In [2] load shedding is discussed as an emergency control action. Two methods are proposed. One method is to shed as little load as possible in order to limit the inconvenience to the customers. Another method is to shed a larger amount of load in order to bring the system back to a stable operation point as quickly and safely as possible. In [2], the latter method is advocated since it is the most secure one to use.

In the following experiment, the setup in Figure 6.4 is used to show what happens when load is shed to save the system.

![Figure 6.4 System setup for load shedding tests.](image)

The load consists of a dynamic load (I), see 5.3.2, with the time constant \( T_{pr} = 30 \) seconds and two constant resistance loads (II and III).

A disturbance is introduced into the system by adding a small constant resistance load (IV) to the existing load. In Figures 6.5 and 6.6 it can be seen that the operating point then jumps from (a) to (b). However, at this point, the dynamic load power is lower than it was before the disturbance (\( P_I < P_{I0} \) in Figure 6.6). Therefore, the dynamic load will react to restore the active power, similar to the two cases in 4.4.2, and the operating point will continue to move down the PV-curve. At (c), one of the constant resistance loads (III) of the initial load is disconnected.
Chapter 6: Complementary results

Figure 6.5  System trajectory when load is shed to save the system.

Figure 6.6  Active power. $P_I$ is the active power of the dynamic load and $P_{II+III+IV}$ is the active power of the constant resistance loads.
The operating point jumps from (c) to (d) where the dynamic load power is higher than its pre-disturbance power ($P_l > P_{I0}$ in Figure 6.6). Once again, similar to the cases in 4.4.2, the operating point follows the PV-curve up on the upper side. The larger the difference is between $P_{I0}$ and $P_l$ just after the load is shed, the faster the system moves to the upper side of the PV-curve.

To bring a simple two node system that is loaded with a dynamic load back to the upper side of the PV-curve, an action must be taken that makes the dynamic load’s active power higher. This action could be to decrease the ratio of the transformer that feeds the load, to switch in shunt capacitors, or to shed load. A combination of two or all three actions gives the fastest result.

### 6.3 Capability-curves at current-limitation

In Chapter 4, the PV-curves are shown for a system where the armature and the field current limits are reached. The limitation process can be viewed in the capability diagram of the generator as well, in order to study the effects on the power ratings. The capability diagram is also discussed in [1].

#### 6.3.1 Armature current limiter

The capability diagram is shown in Figure 6.7 for the same event as in figure 4.11. The generator active power is increased until the armature current limit is reached. The outer circle is the output limit at $V_t = 1.0$ pu. The generator is underexcited in the beginning because of the line charging. When the current limit is reached in point a, and the ACL is activated in point b, the capability circle shrinks because the voltage decreases. When the operating point has reached point c, the capability corresponds to the inner circle. Consequently, the generator power rating decreases when the armature current limit is reached.
6.3.2 Field current limiter

The capability diagram in Figure 6.8 shows the same event as in figure 4.10. The field current limit is characterized by a circle defined by:

$$\left( Q + \frac{V_t^2}{X_s} \right)^2 + P^2 = \left( \frac{EV_t}{X_s} \right)^2$$

(6.1)

The limit (left circle segment) is reached in point a, and, at a further load increase, the circle segment moves to the right. The MVA rating circle shrinks at the same time as the voltage decreases, and the operating point finally reaches the armature current limit at point b.
6.4 Tap changers

Much attention is paid to the role of transformers with on-load tap changers (OLTCs) in voltage stability studies around the world. The interaction with dynamic load, effects of cascaded transformers and stabilizing actions such as OLTC blocking are some of the topics discussed. The interaction with loads was treated in Chapter 4 and the effect of cascaded OLTCs and OLTC blocking is discussed in this section. A few examples are shown to illustrate problems and possibilities. More thorough studies should be made in order to enable an exact formulation of guidelines for OLTC control.

6.4.1 Cascaded tap changers

In Chapter 4, it was shown that a combination of load recovery and tap changer control might cause a power and current overshoot. The overshoot magnitude depends on how well tuned the tap changer regulating relay is in relation to the load behaviour. Four control modes are possible\(^1\) in the case of the relay used here; additionally, the time delays can be varied.

---

\(^1\) A combination of constant or inverse time delay and continuous or pulsed control signal.
Chapter 6: Complementary results

For the cases investigated in Chapter 4, the inverse time delay and pulsed control signal seemed to give the smallest overshoot. However, there are often several OLTC-transformers present at different voltage levels between the 400 kV system and the distribution network. The relation between the settings of the different regulating transformers also affects the current overshoot. Simulations with cascaded OLTCs are presented in [3], where current overshoot and oscillatory behaviour was found. In [4], tuning rules are developed for settings of tap changer relays in order to accomplish selectivity of cascaded OLTCs. Tests were also made in the laboratory on a setup according to Figure 6.9.

Two cases with a different time delay on transformer T2 are shown in Figures 6.10 and . A disturbance is caused by disconnecting one of the parallel sections. The load is restored and the OLTC controls restore the voltages. When $T_{01} = T_{02}$ there is a large current overshoot (Figure 6.10) followed by an oscillation. A “hunting” phenomenon appears which causes both many unnecessary OLTC switchings and an unstable situation. In the second case, $T_{02}$ is twice as long as $T_{01}$. This setting causes a much smaller overshoot and no oscillation.

The control mode, which caused almost no overshoot with only one OLTC, may give large overshoots with cascaded OLTCs if there is a bad coordination of the regulating relays. The experiment indicates that the OLTC at the highest voltage level should have the fastest regulation to avoid current overshoot and to minimise switching and thereby wear of the OLTCs.
Figure 6.10  Primary current on $T_1$ for cascaded OLTC tests.

Figure 6.11  Load voltage for cascaded OLTC tests.
6.4.2 Tap changer blocking

Blocking of OLTCs following large voltage drops is sometimes suggested as a stabilizing measure. A brief discussion is made in [3] and [5] concerning OLTC blocking, and it is pointed out that blocking is beneficial only under certain conditions determined by the load behaviour. A thorough analysis is presented in [6], where it is concluded that blocking is beneficial only if the trajectory is within certain boundaries. It seems that the load composition and the configuration of the network connected to the transformer determines if it is preferable to block the OLTC or not. Experiments have been made to show that a careful analysis has to be made before a decision about blocking OLTCs can be justified. Figure 6.12 shows the setup used in this study. Three different loads are used: the dynamic active load, a motor load, and a shunt compensated motor load. A reactance is placed between the transformer and the load in order to represent a radial line.

A criterion for the blocking decision has to be formulated. The blocking could, for instance, be based on the generator current magnitude, the reactive or the active power flows or a specific bus voltage. In the following illustration, the voltage on the upper side of transformer V₂ is used for the blocking decision. If V₂ for the blocked case, V₂block, is higher than V₂ in the regulating case, V₂reg, the OLTC should be blocked. One of the parallel lines is disconnected in order to introduce a disturbance. The OLTC relay has a constant time delay and a continuous control signal. The time delay, T_{OLTC}, is 30 seconds.

![Diagram of tap changer blocking tests](image)

Figure 6.12 Setup for tap changer blocking tests.

1) The dynamic load is used, with the time constant T_L = 60 s. Figure
6.13 shows the voltage $V_2$ for the blocking case and the regulating case. In the blocking case there is just a plain recovery that decreases the voltage towards a steady state level. In the regulating case, the OLTC causes the known current overshoot which implies a voltage dip. The steady state voltage is higher than in the blocking case. The steady state power is the same in the two cases due to the constant power load. The load current therefore becomes higher in the blocking case and the line losses as well, causing a lower $V_2$. Consequently, from the point of view of $V_2$, it is not desirable to block the OLTC.

![Figure 6.13 Voltage $V_2$ with the dynamic active load.](image)

2) An induction motor load with constant torque is used. Figure 6.14 shows the load voltage $V_3$ and the voltage $V_2$ for the two OLTC cases. The induction motor time constant is very short and the steady state power, which is independent of voltage, is almost constant. In the regulating case, the OLTC tries to restore the voltage $V_3$ but the tap limit is reached before the voltage is within the deadband. It is concluded that the voltage $V_2$ in the blocking case is higher than in the regulating case. The reason is that the reactive power consumption of the motor is lower at lower voltage because of saturation effects. OLTC blocking is therefore desirable. According to the chosen blocking criterion, the OLTC should be blocked. But this could be detrimental. The voltage
Chapter 6: Complementary results

$V_{3\text{block}}$ is below 0.8 pu and since the load is an induction motor load, the risk for motor stalling is high. In this case, it would be better advice to keep $V_3$ as high as possible in order to avoid motor stalling.

![Figure 6.14 Voltages $V_2$ and $V_3$ with induction motor load.](image)

3) The induction motor load with constant torque and $\approx 50\%$ shunt compensation is used. Figure 6.15 shows the load voltage $V_3$ and the voltage $V_2$ for the two OLTC cases. With this load case, the voltage is not affected by the OLTC blocking. In the regulating case, the total amount of both active and reactive power is almost constant. The reactive support from the capacitors decreases about as much as the consumption of the reactive motor power. The conclusion is that there is no motivation for blocking. If $V_2$ is not increased by the blocking, it is better to keep the load voltage $V_3$ as high as possible.
These examples show that before a decision on blocking of OLTCs is made, a careful analysis of the load situation has to be made for every specific case. No general criteria can be formulated from these few examples but they indicate the complexity of the problem. The network structure, shunt compensation and the loads are all factors that have an impact on the suitability for blocking OLTCs. Daily and yearly load variations might change the blocking conditions as well.
Chapter 6: Complementary results

6.5 References


Chapter 7  Current limitation in larger systems

Two-node systems like those we have discussed so far are comparatively easy to analyse and to understand. For such a system, it is clear how to define the PV-curve and how to use it to analyse voltage stability. In reality, power systems have more than one generation node and one load node. The results from a two-node system must therefore be generalised and made applicable to larger systems in order to have more than academic value.

7.1  One generator and two load-nodes

The first expansion of the two-node system is to add another load node. The system in Figure 7.1 is used in the following section to generalise previous results on current limiters and different kinds of loads. In order to simplify the analysis, no line capacitors are used here.

![Figure 7.1 System setup with two load-nodes.](image)

7.1.1  Armature current limitation

In the system shown in Figure 7.1, node 2 can be seen as a load-node similar to the load-node in two-node systems. The load consists of two parts: the motor with its feeding line, and the resistive load with its connection.

In Figure 7.2, the measured PV-curves for node 2, 3 and 4 are drawn for a case where the induction motor is rather lightly loaded with a constant torque (constant active power, see Chapter 6.1.2). The resistive load is slowly ramped up from zero towards maximum conductance. When the load-increase in node 3 activates the generator ACL, the voltages in all
the nodes begin to decrease. The induction motor current increases with decreasing voltage, because of constant active power, which gives lower voltages in the system. At the same time, the resistive load conductance is still increasing and contributes to the voltage decrease. For node 2, three load characteristics for three different moments in time are drawn with dotted lines. The first one is for the load at the moment the current limit is exceeded. The second one has an intersection with the current limited system characteristic and is stable. But at the moment the third load characteristic is valid, there is no longer an intersection between the characteristics and the system collapses.

![Figure 7.2 PV-curves for node 2, 3 and 4 in Figure 7.1 with ramped resistive load and constant active power drawn by the induction motor. Dotted lines: load characteristics for the active load in node 2 at three different moments.](image)

The PV-curve for node 4 is a vertical line since the induction motor is a constant active power load. As soon as the ACL is activated, the operating point for node 2 follows a straight line that corresponds to a constant current. This is similar to the two-node system, see Chapter 4.5.2. However, in this case the line will not end up at the origin since the load is not purely resistive. The current limit characteristic is determined by the apparent power and not by the active power, meaning that the relation P/V is not necessarily linear. The system
trajectory seen from node 3 is the difference between the trajectories for nodes 2 and 4.

If the resistive load is a constant resistance and the induction motor load is slowly increased (manually) until the armature current limit is reached, we have the case presented in Figure 7.3. When the armature current limit is reached, the induction motor power is no longer increased, and statically, the induction motor becomes a constant active power load. The dotted line for node 2 represents the active load seen from this point at the moment the induction motor becomes a constant active power load.

![Figure 7.3 PV-curves for node 2, 3 and 4 in Figure 7.1 with constant resistance load and ramped induction motor load. Dotted lines: load characteristics for the active power load in node 2 and 3.](image)

There is no intersection between the static load characteristic and the characteristic for the armature current limited system from the very moment the ACL is activated. This results in a faster collapse than in the previous case.

It is important to notice that the collapse cannot be explained or predicted by looking at the PV-curves in the actual load-nodes (node 3 and 4). One can be suspicious about the low voltages in these nodes, but the induction motor load has quite a distance to the critical point of the PV-
curve where it would stall, and the constant resistance load is itself sta-
ble for every voltage. But in node 2, one can recognize the characte-
ristic of the armature current limited system, and with knowledge of the
load characteristic in this node, analyse the voltage stability situation.

*This emphasizes the importance of accurate load models at buses
where important generators are connected.*

### 7.1.2 Field current limitation

In this section, the load conditions are exactly the same as in the previous
section. However, here, the field current limit is set to be activated at
about the same load as was the case with the armature current limiter in
7.1.1.

In Figure 7.4, the resistive load is ramped. When the FCL is activated
and the resistive load continues to increase, the operating point for
node 2 moves along the new PV-curve, see Chapter 4.5.1. When all
available resistive load is connected, the load characteristic (dotted
line) still has an intersection with the system characteristic. Hence, the
system remains stable.

![Figure 7.4 PV-curves for node 2, 3 and 4 in Figure 7.1 with ramped resistive load and
constant active power drawn by the induction motor. Dotted line: load
current limit is exceeded
characteristic for the active load in node 2.](image-url)
In the last case in this section (see Figure 7.5), the induction motor load is increased until the motor stalls. This happens when the operating point for the induction motor node (node 4) reaches the critical point of the PV-curve (see Chapter 4 and 5) for the field current limited system.

The active power load characteristic in node 2 at the moment the induction motor stalls is drawn with a dotted line. By looking at the PV-curve and the load characteristic at node 2, it can be concluded that at the same time as the motor stalls at node 4, the load characteristic and the system characteristic in node 2 no longer intersect, and the system collapses.

The conclusions after these measurements on the three-node system are that previous results on current limiters and load characteristics are valid even for this system if the system is studied from an aggregate load-node. It is not possible to analyse voltage stability in multi-node systems by looking at load-nodes only.
Chapter 7: Current limitation in larger systems

7.2 Two generator nodes and one load-node

In this section, it is shown how current limiters impact the system when there are more generators feeding the load. The model was connected to the utility grid according to Figure 7.6. No line capacitance is included. The network connection is much weaker than the generator connection. The load consists of a constant resistance load and a shunt-compensated motor load. Both current limiters were investigated. The motor power was increased slowly until the current limits were reached.

![Laboratory setup with two generator nodes and one load node.](Figure 7.6)

7.2.1 Armature current limitation

The armature current limiter (ACL) was tested and the limit was set to 0.5 pu. The voltages, currents and powers are shown in Figure 7.7 - 7.10. When the current limit is reached, it implies that the motor stability limit is reached, and the system collapses. The collapse is quite slow for a load incorporating a stalling motor. At the point of current limitation, the resistance load power is 0.47 pu and the motor power is 0.355 pu. (Rated motor power = 0.45 pu).

![System voltages. The load voltage decreases due to the load increase. When the current limit is reached, the generator voltage is decreased in order to limit the current.](Figure 7.7)
Figure 7.8 Network and generator power. The active power increase is taken only from the network since the generator active power is constant. The reactive load demand from the generator increases and causes the current limitation. The network power then decreases due to decreasing load demand.

Figure 7.9 System currents. The current limit is reached at point a. The current increase at point b is a consequence of the fast current increase at the end of the motor stalling. The excitation control is too slow to keep the current under the limit.

The load node PV-curve is plotted in Figure 7.10. The steady state load characteristic does not intersect the characteristic for constant generator current and the system collapses. The two characteristics run in parallel down to rather low voltages, with only a slight power difference. This explains the “slow” collapse. The connection from the utility network is apparently too weak to contribute to the stability. We have also run tests with a stronger connection to the network and even then the system collapsed when the armature current limit was reached, at least for the mixed load type and the generator data used here.
Chapter 7: Current limitation in larger systems

Since the generator active power is constant, the reactive power increase causes the current limitation. This means that the current limit is reached at exactly the same load voltage no matter how strong the network connection is. If the power flow on the network connection is close to the critical power when the current limit is reached for one connection, it will be for a stronger connection as well.

Figure 7.10 Solid line: PV-curve at the load node. Dotted line: Load characteristic, 
\[ P = P_\text{IM} + P_\text{R}, \quad P_\text{IM} = \text{const} = 0.355 \text{ pu}, \quad P_\text{R} = 0.635^*V^2. \]

The capability diagram for this case looks different when compared to the one-generator case, see Chapter 6.3.1. Since the generator has a constant power input, only the reactive power is variable. The reactive power is decreased when the generator is current limited.

Figure 7.11 Capability diagram for armature current limitation, with constant power input.
In this case, the generator is tripped at a terminal voltage 0.8 pu, but if the reactive power reaches zero before that, the generator is also tripped. The reason is that the voltage regulator is equipped with underexcitation protection that operates when the ACL is active.

More tests have to be made before general conclusions can be drawn about the effects of armature current limitation in large systems. It seems, however, that the connections from the surrounding network do not improve the stability once the limiter is activated. The load composition and its dynamics are also contributing factors, as shown in Chapter 4 and 6.1.1.

### 7.2.2 Field current limitation

The field current limit does not cause any stability problems in this system. The load is increased until the field current limit is reached, and is then further increased with the current limiter active.

![Figure 7.12 System voltages. When the limit is reached the generator voltage $V_1$ is decreased in order to keep the field current under the limit.](image)

The PV-curve is similar to the one-generator case. When the limit is reached, the operating point is transferred to a new PV-curve, due to the fact that the voltage control is moved behind the synchronous reactance. The equivalent transmission reactance is higher in the current limiting case, causing a new PV-curve with a “shorter nose”.

*It can be concluded that the shift of voltage control from the terminals to the internal voltage, behind the synchronous reactance, always weakens the system.*
Chapter 7: Current limitation in larger systems

The capability diagram in Figure 7.14 shows how the FCL affects the power output. As long as the ACL is not affected, there is no reactive power limit. The left circle segment shows the limit at $V_t = 1.0$ pu. When the current limiter decreases the voltage, the limitation boundary moves to the right. The reactive power can obviously increase even though the FCL is activated.

The conclusions from this section with two generator nodes are: Armature current limitation is detrimental to the system even if there are strong connections to other generators.
Field current limitation affects the system in the same way as in the one-generator case: the voltage control is moved behind the synchronous reactance and weakens the system.

7.3 Reduction of the generator active power at current limitation

In large power systems, a large number of generators are connected to the network. A selected number of them regulate the frequency, and the rest of them has a constant active power output. At current limitation, only the reactive power can change for the latter category as shown earlier.

7.3.1 Armature current limitation

At armature current limitation, the voltage is decreased to keep the current under the limit. Since the active power is constant, the reactive power has to decrease. The reactive power supply is very important for the system, therefore armature current limitation is bad for the voltage stability. One possibility to escape from the current limitation state could be to decrease the active power immediately after a current limit is reached, in order to re-establish voltage control. This has been tested in the laboratory.

The same load case as shown in Figure 7.7 - 7.10 was run again, but this time the generator active power was decreased slightly when the current limit was reached. As seen in Figure 7.15 - 7.17, the voltage control was retained and a stable steady state equilibrium was reached. In order to see what would have happened if the power was decreased more, a further reduction was made. At $P_{\text{gen}} = 0.25$ pu, the load angle has increased so much that transient instability occurs. Oscillations amplified by the current limiter start to develop.
Chapter 7: Current limitation in larger systems

Figure 7.15 System voltages when the generator active power is decreased. At the first active power decrease, the load voltage decreases slightly, but at the same time the generator voltage control is retained. The second power decrease implies oscillations and, finally, loss of synchronism.

Figure 7.16 Active and reactive power from the generator and from the network. The first active power decrease brings the AVR back to voltage control, which is desirable. The second power decrease causes transient instability through amplified power oscillations which, in turn, cause loss of synchronism and a breakdown.
7.3.2 Field current limitation

The same test was made for the field current limiter. The load was increased until the limit was reached and then a little further, and an equilibrium point was reached. The generator power was then decreased, but that implied decreasing load voltage since the power flow from the network increased. The generator reactive power then increased and caused harder limitation with even lower terminal voltage. Consequently, there are no benefits from a power decrease in this case. It would be better to increase the active power instead if there is no risk of armature current limitation.

Figure 7.17 System currents. When the limit is reached, the active generator power is decreased to keep the current under the limit. This is done successfully, but with the second power decrease, the limiter is activated and oscillations start to develop. The currents oscillate around the current limit and the limiter amplifies the oscillations and causes a breakdown.

Figure 7.18 Voltages for field current limitation.
The conclusions from this section are: When an ACL has become active, a slight reduction of the active power might retain the voltage control and avoid a collapse. There is a risk, however, that the active power reduction causes transient instability since the decreased active power must be taken from other parts of the system.

There are no similar benefits with a power decrease at field current limitation. The only effect of the power decrease is an increased reactive generator power since the load voltage decreases.
Chapter 8  Conclusions

In this thesis, basic phenomena concerning voltage stability and voltage collapse have been investigated and explained using a power system model and theoretical analysis.

In contrast to opinions found in literature, the point of collapse does not coincide with the critical point of the PV-curve. It is possible to run the system on the lower solution of the PV-curve with a constant impedance load as well as with a mixed load.

In our opinion, armature current limitation is a main issue when studying voltage stability. Once an armature current limiter has become active, generator tripping is very hard to avoid. This seems to be valid even when there is a strong connection to other production plants. Field current limitation is not by far that critical for the voltage stability.

A combination of load dynamics and OLTC regulation might tend to cause a power/current overshoot which could endanger the voltage stability. In order to avoid this overshoot, OLTCs must be tuned according to the specific load behaviour.

Cascaded OLTCs might also cause a current overshoot. OLTCs must therefore be coordinated as well. Additionally, it is not a general stabilizing measure to block OLTCs. A blocking must be anticipated by a careful analysis of the load situation.

A system with decreasing voltage, operating on the lower side of the PV-curve, can be rescued by decreasing the transformer ratio and/or switching in additional capacitor banks, or by load shedding. If the load has a large portion of induction motor load, very fast automatic action has to be taken such as, for example, by using an SVC.

A reduction of the generator active power output could be beneficial if the armature current limiter has become active. However, if the power output is drastically decreased, transient instability may follow.

An exponential load model for reactive power must be considered as unsuitable for voltage stability studies.

In voltage stability studies, proper modelling of induction motor loads should at least include the non-linear behaviour of their magnetic circuits. In addition the reactive load should be modelled as a function of
Chapter 8: Conclusions

the fraction of motor loads, the active load power behaviour and the characteristics of the network between the point where the load is modelled and the load objects.

It is extremely important to understand dynamic load behaviour in order to predict voltage instability. Field measurements in important buses on different voltage levels and further load model identification as made in [7] could be strongly beneficial.
Chapter 9 Future work

Voltage stability and collapse have been subject to intense research for many years. Still, many questions remain to be answered. The lack of clear definitions is good proof of that.

This thesis has answered some questions. But it has also generated new ones and pointed out some of them as more important than others.

9.1 Future work in general

The impact of different components, such as current limiters and OLTCs, on voltage stability is, in most cases, determined by the load behaviour. In our opinion, it is not sufficient to model the load at load buses only. Accurate load models as seen from nodes where important generators are connected must also be developed.

If an ACL is activated, it is very hard to avoid tripping of the generator. Under conditions leading to armature current limitation, tripping can be devastating for the system stability. Therefore, much effort must be made to find methods to prevent the ACL from being activated, or to find other algorithms for a better operation of the ACL.

9.2 Future work with the laboratory power system model

Load modelling is also an issue for future work with the laboratory power system model. A method to make an aggregate motor load out of a number of induction motors of different sizes is one possible subject. Another matter is to develop both a static and a dynamic load model for reactive power based on the results in Chapter 5. This model should include the low-voltage and medium-voltage networks between the bus from which the load is modelled and the load objects.

A few tests with more than one generator and one load have been presented in this thesis. Larger systems should be further studied by adding more generators, preferably of different sizes, to the model. With more generators, the voltage stability, in the case of current limitation on one generator or more, can be studied.
Chapter 9: Future work

If the system enters a state of voltage instability, actions have to be taken to prevent a voltage collapse. If the instability is caused by a current limited generator, the speed of the voltage decrease can vary from slow to very fast. Therefore, time constants involved in current limitations ought to be analysed to determine how much time there is left to take preventive actions. This could determine if actions should be taken automatically or by an operator.

The power system model has recently been equipped with an SVC. Preliminary tests show that, in some cases, the SVC by its fast action can prevent the system from entering a state of voltage instability. Further investigations on how the SVC can be used to enhance the voltage stability and how it can be used in emergency situations could be carried out with the power system model.
# Errata

<table>
<thead>
<tr>
<th>location</th>
<th>Now.....</th>
<th>Should be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title page</td>
<td>Electrical Power....</td>
<td>Electric Power.....</td>
</tr>
<tr>
<td>page 2-8 line 8 from end</td>
<td>...e.g small induction...</td>
<td>...that is small induction....</td>
</tr>
<tr>
<td>page 3-21</td>
<td>.. to control speed.</td>
<td>.. to measure speed.</td>
</tr>
<tr>
<td>page 1-2 line 3, page 3-1 line 6 from end</td>
<td>masked network</td>
<td>meshed network</td>
</tr>
<tr>
<td>page 5-7, 5.4.1 line 3</td>
<td>in section 5.3.2 in.</td>
<td>in section 5.3.2.</td>
</tr>
<tr>
<td>Fig. 5.14</td>
<td>Dotted lines: static torque.</td>
<td>Dotted lines: torque curves for constant voltages.</td>
</tr>
<tr>
<td>Fig. 5.20</td>
<td>...system trajectories</td>
<td>...system characteristics</td>
</tr>
<tr>
<td>Fig. 5.21</td>
<td>switching to late</td>
<td>switching too late</td>
</tr>
<tr>
<td>page 5-23 ref 5</td>
<td>ETEP</td>
<td>European Transactions on Electrical Power Engineering</td>
</tr>
<tr>
<td>page 5-24 ref 17</td>
<td>.....Systems.</td>
<td>...Systems, vol. 15, pp 221-228</td>
</tr>
<tr>
<td>Fig 6.7</td>
<td>$V_1 &lt; 1$</td>
<td>$V_1 = 0.8$ pu</td>
</tr>
<tr>
<td>Fig 6.11</td>
<td>Voltage $V_2$</td>
<td>Voltage $V_3$</td>
</tr>
<tr>
<td>page 6-16, ref 6</td>
<td>...on Power Systems.</td>
<td>..on Circuits and Systems.</td>
</tr>
<tr>
<td>Fig. 7.7</td>
<td>AC limit</td>
<td>armature current limit</td>
</tr>
<tr>
<td>page 8-2, last line</td>
<td>in [7] could</td>
<td>in [7], Chapter 4, could</td>
</tr>
</tbody>
</table>
Errata:

<table>
<thead>
<tr>
<th>location</th>
<th>Now.....</th>
<th>Should be</th>
</tr>
</thead>
</table>

Errata-2