Long-term Voltage Stability in Power Systems

Alleviating the Impact of Generator Current Limiters

Stefan Johansson

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Department of Electric Power Engineering
School of Electrical and Computer Engineering
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Abstract

The main issues in this dissertation are the behaviour of current limiters protecting synchronous generators, and the interactions that occur with other components in the power system during a voltage instability. The importance of these limiters for the voltage stability is shown both in the analysis of small models and in the simulations of larger networks.

Voltage stability of a power system can be improved by a proper current limiting equipment for generators situated in load areas which have a deficit in power production. Two different remedial actions alleviating the impact of the current limiters are analysed. These are:

- the optimum use of the generators field winding thermal capacity by including temperature measurements into the control.
- the use of mechanical power production increases or decreases as a way to avoid a too high current in the generator.

The system can then be supported locally until both field and armature currents are at their respective maximum steady-state levels, the maximum capability for the system is attained or constraints in the mechanical power production are reached. The dissertation analyses the consequences of active power rescheduling and its significance for field and armature current limiter operation. Aspects as the size of active power changes and its variation in time are discussed on the basis of simulation results.

Long-term voltage stability is also decided by other interactions occurring in the power system. In particular the load behaviour and tap changer control are analysed. The importance of proper modelling of these components and using correct values are discussed.

Keywords: Long-term power system dynamic stability, Voltage stability, Overexcitation limiter, Field current limiter, Armature current limiter, Rotor thermal overloading, Dynamic load modelling, Active power rescheduling

LIST OF PUBLICATIONS

This thesis is based on work reported in the following papers, referred by Capital letters in the text:

A S. G. Johansson, F. G. A. Sjögren, D. Karlsson, J. E. Daalder, "**Voltage Stability Studies Using PSS/E**", Bulk Power System Phenomena III, pp. 651-661, Davos, Switzerland, 1994.

B F. G. A. Sjögren, S. G. Johansson and J. E. Daalder, "**Behaviour of generator current limiters near the point of voltage collapse**", Stockholm Power Tech, STP PS 07-06-0492, pp. 221-226, Sweden, 1995.

C S. G. Johansson, D. Popović, D. J. Hill and J. E. Daalder, "**Avoiding Voltage Collapse by fast Active Power Rescheduling**", International Journal of Electrical Power and Energy Systems, Vol. 19, No. 8, pp. 501-509, 1997.

D S. G. Johansson, "**Mitigation of Voltage Collapse caused by Armature Current Protection**", Accepted for publication in IEEE Power Engineering Society Transactions, Paper Number: 98 SM 094, 1998.

E S. G. Johansson and J. E. Daalder, "**Maximum Thermal Utilization of Generator Rotors to avoid Voltage Collapse**", International Power Engineering Conference -97, Singapore, pp. 234-239, 1997.

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Paper A Voltage stability studies with PSS/E

Contents

Chapter 1 Introduction

Voltage stability issues are of major concern worldwide. One reason is the significant number of black-outs which have occurred and which frequently have involved voltage stability issues. Major regions (like half of France, 1978) or smaller (as Israel, 1996 and Tokyo, 1987) have been exposed to voltage instability problems. These kinds of blackouts will undoubtedly occur also in the future. It is also believed among professionals that the existing transmission systems will become more and more utilized due to environmental concern which makes it difficult to build new power plants and/or transmission lines. As a result the stress on the existing system will increase. Two examples in Sweden, which are quite much in the news these days, which will influence the load on the existing transmission system, are the ongoing process of a possible shut down of nuclear power plants and a prospective HVDC connection between Sweden and Poland. The government has decided that nuclear power production shall be closed down and the first plant is to be shut down on July 1, 1998. For the HVDC-line, local authorities is concerned of environmentally aspects of the sea floor grounding electrode of the HVDC connection.

The continuing deregulation of the electricity market now occurring in many countries will change the way power systems will be operated. The deregulation will introduce an economical competition between companies. A high utilization of the system may then be beneficial from an economical point of view. There is also a possibility that certain information is kept restricted within the companies due to the competition. The sharing of information between the companies have so far been an advantage from the system operating and stability point of view. These reasons will make the operation of the system as a whole more difficult and hence increases the possibility of stability problems. Much research work is therefore going on worldwide covering many different aspects of system operation where voltage stability is an important feature.

Voltage stability deals with the ability to control the voltage level within a narrow band around normal operating voltage. The consumers of electric energy are used to rather small variations in the voltage level and the system behaviour from the operators point of view is fairly well known in this normal operating state. Equipment control and operation are tuned towards specified setpoints giving small losses and avoids power variations due to voltage sensitive loads.

Once outside the normal operating voltage band many things may happen of which some are not well understood or properly taken into account today. A combination of actions and interactions in the power system can start a process which may cause a completely loss of voltage control. The system will experience a voltage collapse and this results in a rapid loss of electrical supply in wide areas, sometimes affecting millions of people.

The origin of a significant voltage deviation is in most cases some kind of contingency where a generator in a vital power plant shuts down or an important transmission line is disconnected from the power grid. This initiates a voltage change and alters the system characteristics. The system is normally designed to withstand these kind of single contingencies occurring many times a year. However, abnormal operating conditions, several independent contingencies occurring almost simultaneously in time or a completely unexpected phenomena may violate the normal design conditions. This leads to an insecure operating condition threatening the voltage stability of the system. The goal is therefore to try to understand the course of events after such a contingency and propose remedial actions when the control of voltage is insecure.

The main part of this dissertation consists of work presented in 5 papers, all dealing with long-term voltage stability aspects in power systems. Long-term voltage stability is connected with phenomena in the power system which have time constants from a couple of seconds to minutes and even tens of minutes. An important issue in this time frame is the behaviour of current limiters which protect synchronous generators from too high temperatures due to overloading. Generators are *generating* voltage and current and are thus the first link in the voltage control chain from production to load consumption. Several types of interaction can occur between limiter operation and other components in the power system which may disturb or upset the voltage control. The limiters will also impose operating restrictions on the generator which are important to understand.

A generator has two types of windings: the field winding carrying the current which creates the magnetization in the rotor; and the armature winding situated in the stator and carrying the produced power to the grid.

The field winding is protected by a limiter which controls the magnetization (i.e. the field current) of the generator to avoid a too high field current. Normally, the field current is controlled in such a way that the voltage is controlled on the generators terminal and an overloading of the generator is avoided by reducing the field current to its maximum steady state value. The use of a limiter allows the generator to stay connected to the grid, though with a reduced output. The power system demand can then not be fulfilled when the generator becomes limited and a voltage decrease occurs. An overcurrent relay may be used as a backup protection disconnecting the generator if the limiter is unsuccessful.

The armature winding is either protected by an overcurrent relay or an armature current limiter. The overcurrent relay disconnects the generator from the grid when the maximum current limit is violated and all production from that generator is lost instantaneously. An example where the armature winding is protected by a limiter function are the generators of the nuclear power plants in Sweden. The armature current limiter will influence system behaviour and play a major role in system stability.

Excessive winding temperatures will lead to a fast degradation of the insulation material and thereby a decreased life span of the generator. Most likely, limiter operation occurs in situations when the power system is in a need of the production that the limiters obstruct. A trade off between the life span of the generator and system stability must therefore be accomplished to avoid solutions that may become unnecessarily complex or expensive.

The main purpose of this research project is to investigate how to attain an improved support from the generators to the power system in case of a current limiter operation without endangering the generators economical lifetime.

In this dissertation it is often possible to substitute the influence of the armature current limiter action with a tripping of that generator instead, the latter however, is more severe for the power system and therefore a more restricted situation than a mere limitation. The analysis of the armature current limitation may be of general interest despite the fact that not all generators are equipped with such a protection. Certain phenomena are common between the limiter setting and the overcurrent relay setting. In the text, the expression armature current limiter is used extensively and the reader should interpret the analysis as either limitation or tripping of the generator depending on his own prerequisites for that particular study. The term armature current protection is also used implying either a limiter action or an overcurrent relay action.

Several other aspects of voltage stability are discussed in this dissertation. In particular, the relation between load behaviour and tap changer control of transformers is analysed. The dynamic behaviour of this combination is frequently a key factor in the understanding of voltage stability. Due to the introduction of new technology the load characteristics are slowly changing. Examples are new air conditioning equipment and semi-conductor based motor drives. A continuous work is therefore required if voltage stability is to be maintained.

A major part of the dissertation is based on computer simulation of power systems. Both small networks, where the models are kept as simple as possible, and larger, more complex networks are studied. The larger networks often uses as accurate models of the existing components as is possible. Network data is then chosen to correspond with known values. Some analysis have been performed for the small system.

1.1 Background and realization of the project

This dissertation is an extension of a licentiate thesis work [1] which I undertook together with Fredrik Sj gren in 1995. The licentiate project started in 1992 and treated different aspects of important components in a power system. One interesting point presented in that thesis was the behaviour of the generator influenced by its field and armature current limiters. A research project was therefore granted by Elforsk AB within the Elektra research program titled Voltage collapse caused by interaction between generator protection systems and electrical power systems for a further study of this behaviour.

The project started with a half year visit at the Systems and Control group at Sydney University, Australia where the work was concentrated on a radial system with a large generation area and a smaller generator located in the load area. Different operating modes were introduced determined by the behaviour of the current limiters in the system. The small generator was exposed to changes in the active power input for different modes and the system capability as seen in the load point was established for these active power changes.

This analysis was extended by studying the field current limiter where system capability was (temporarily) increased by utilizing the rotor thermal capacity.

To verify the previous results, simulations were performed in a larger network. The analysis was then concentrated on the armature current limiter and system aspects of its behaviour.

1.2 Outline of the dissertation

This dissertation consists of five papers together with supplementary chapters. References are made to the papers with a capital letter together with the corresponding figure number or paragraph.

Chapter 1 gives a brief introduction to the dissertation where the background and motivation to the project are discussed.

Chapter 2 gives a general background to the phenomenon Voltage Stability and is based on a similar chapter in the licentiate thesis [1].

A general overview of the papers is given in Chapter 3, where common issues and important sections are pointed out. The analysis is also extended somewhat concerning the importance of the position of transformers in the grid. The literature for a particular area covered in this dissertation is discussed based on the presented results. Finally, some more background information is given which has not been presented in the papers. The reader may choose to read the papers before Chapter 3 since these can be read as independent contributions and then return to Chapter 3 for a brief summary.

Chapter 4 gives the most important conclusions of this study and Chapter 5 contains suggestions for future work. Finally the papers are presented as separate sections.

1.3 References

[1] S. G. Johansson and F. G. A. Sj gren, VOLTAGE COLLAPSE IN POWER SYSTEMS - The influence of generator current limiters, on-load tap changers & load dynamics , Technical report No. 192L, Dept. of Electrical Power Systems, Chalmers University of Technology, ISBN 91-7197-119-X, Sweden, 1995.

Chapter 2 Voltage stability and voltage collapse

2.1 Introduction

This research area concerns disturbances in a power system where the voltage becomes uncontrollable and collapses. The voltage decline is often monotonous and small at the onset of the collapse and difficult to detect. A sudden and probably unexpected increase in the voltage decline often marks the start of the actual collapse. It is not easy to distinguish this phenomenon from angle (transient) stability where voltages also can decrease in a manner similar to voltage collapse. Only careful post-disturbance analysis may in those cases reveal the actual cause.

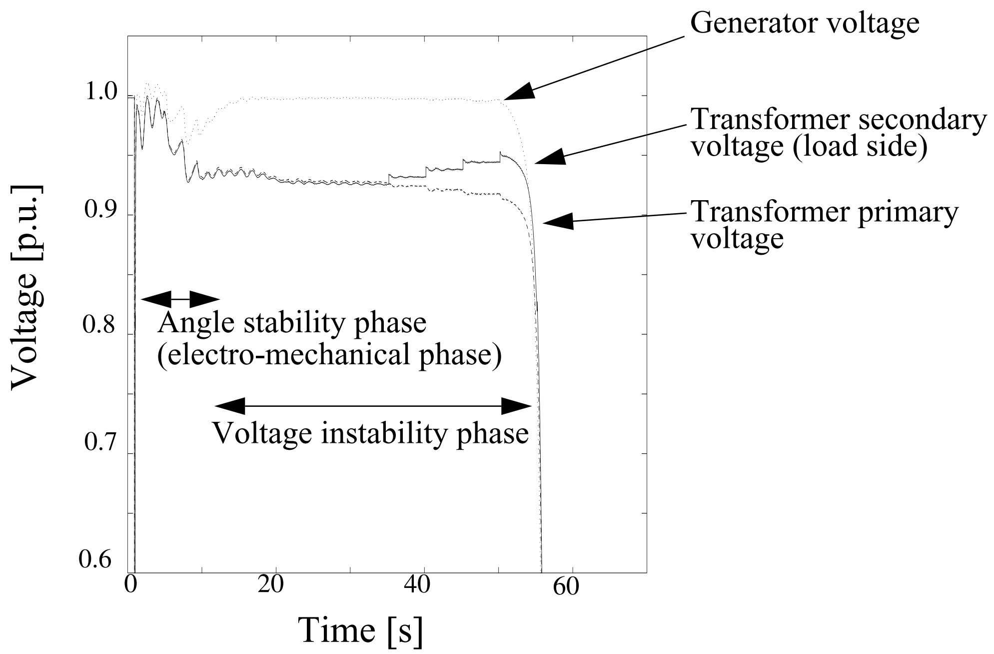

Figure 2.1 Example of a collapse simulation which is transient (angle) stable followed by a voltage decline and a fast voltage drop leading to a collapse. (See Figure A.18).

During the last decades there have been one or several large voltage collapses almost every year somewhere in the world. The reason is many times a higher degree of utilization of the power system leading to a decreasing system security. Also, load characteristics have changed. Two examples are the increased use of air conditioners and electrical heating appliances which may endanger system stability radically. The incidents that lead to a real breakdown of the system are rare, but when they occur they have large repercussions on society.

It is the opinion of many professionals that in the future power systems will be used with a smaller margin to voltage collapse. There are several reasons for this: the need to use the invested capital efficiently, difficulties in supervising a deregulated market and the public opposition to building new transmission lines and new power plants. Voltage stability is therefore believed to be of greater concern in the future.

Nearly all types of contingencies and even slow-developing load increases could cause a voltage stability problem. The time scale for the course of events which develop into a collapse may vary from around a second to several tens of minutes. This makes voltage collapse difficult to analyse since there are many phenomena that

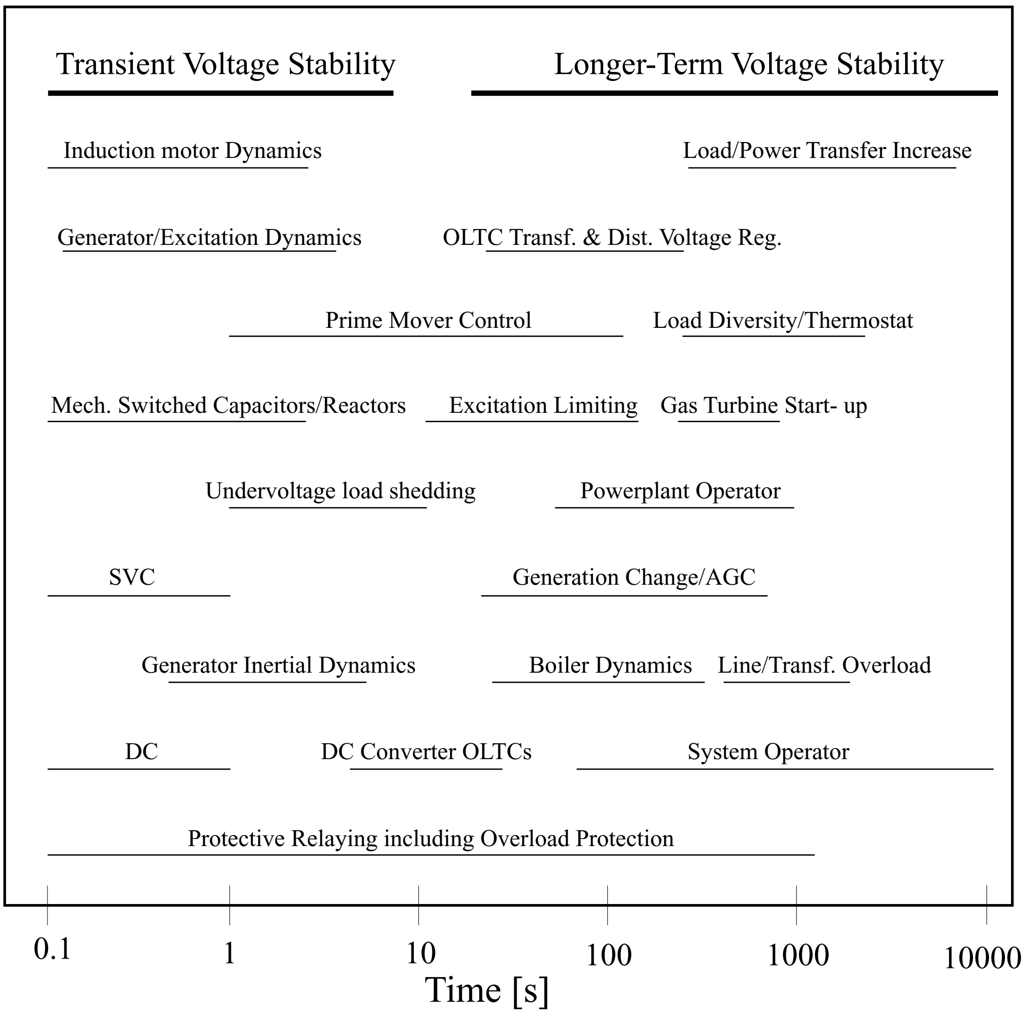

Figure 2.2 Different time responses for voltage stability phenomena [19].

interact during such a time span (see Figure 2.2). Important processes that interact during a voltage decline lasting (several) minutes are among others: generation limitation, behaviour of on-load tap changers and load behaviour. The actions of these components are often studied in long-term voltage stability studies.

An interesting point is that some researchers discard voltage magnitude as a suitable indicator for the proximity to voltage collapse, although this is in fact the quantity that collapses [6, 9].

An ongoing discussion is whether voltage stability is a static or dynamic process. Today it is widely accepted as being a dynamic phenomenon. However, much analysis can be made and insight can be obtained by the use of static models only.

Voltage instability is only one kind of stability problem that can arise in a power system. A typical property of voltage instability is that the system frequency usually is fairly constant until the very end of the collapse. This indicates that the balance is kept between production and active load demand. Power oscillations between different areas in the system can be a limiting phenomenon on its own but may also appear during a voltage instability mixing voltage instability issues with electro-mechanical oscillations.

2.2 Voltage collapses worldwide

Much can be learnt from observed voltage collapses or incidents. Detailed information of the most well known occurrences can be found in [2] and [7].

Analysing real collapses involves two problems. Firstly, the lack of event recorders in relevant locations causes a lack of information about the disturbance. Secondly, it is sometimes difficult to distinguish between voltage stability and angle (transient) stability. There may also be other actions which make the system more difficult to understand, such as human interaction, frequency deviation etc.

Below examples are given of some important events which ended in voltage collapse. Some properties common in many disturbances are pointed out.

•***Transmission system limitations***

The tripping of fairly small generators if situated in areas that need voltage support, could cause a large increase of reactive power loss in the transmission network. Voltage drops results which can initiate stability problems. Examples are the 1970 New York disturbance [7] and the disturbance in Zealand, Denmark in 1979 [2]. In the New York disturbance, an increased loading on the transmission system and a tripping of a 35 MW generator resulted in a post-contingency voltage decline. In Zealand, a tripping of the only unit in the southern part of the island and producing 270 MW caused a slow voltage decline in that area. After 15 minutes the voltages were 0.75 p.u., making the synchronization of a 70 MW gas turbine impossible. Both systems were saved by manual load shedding.

The Belgian collapse in August 4, 1982 was also due to problems with the transmission capacity. The collapse was initiated by a fortuitous tripping of one of the (relatively few) operating production sources. The low load made it economically advantageous to use only a few power plants operating close to their operating limits. When the generator tripped, the surrounding area was exposed to a lack of reactive power and several generators were field current limited. After a while the generators tripped one after another due to the operation of the protection system. The transmission system was unable to transmit the necessary amount of reactive power to the voltage suppressed area and cover the reactive power loss that were produced in the tripped generators. This caused a continuous voltage decline. When the fifth generator was tripped some four and a half minutes after the first tripping, the transmission-protective relays separated the system and a collapse resulted [10].

The collapse in Canada, in B. C Hydros north coast region in July 1979 is also interesting in this respect [7]. A loss of 100 MW load along a tie-line connection resulted in an increased active power transfer between the two systems. The generators close to the initial load loss area were on manual excitation control (constant field current), which aggravated the situation. When voltages started to fall along the tie-line due to the increased power transfer, the connected load decreased proportionally to the voltage squared. This increased the tie-line transmission even more since there was no reduction in the active power production. About one minute after the initial contingency, the voltage in the middle of the tie-line fell to approximately 0.5 p.u. and the tie-line was tripped due to overcurrent at one end and due to a distance relay at the other.

Also Czechoslovakia experienced a similar collapse as B. C. Hydro in July 1985 but on a much shorter time-scale [2]. Before the disturbance, there were three interconnected systems, two strong ones, I and II and one weak system, III, between I and II as can be seen in Figure 2.3. A large amount of power was delivered from I to III, while II was approximately balanced. When the connection between I and III was lost, the II-III connection was expected to take over the supply of power to III. However, one of the overhead lines between II and III tripped due to overcurrent and the remaining transmission capacity was too low and the voltage collapsed in III within one second after tripping of the other line.

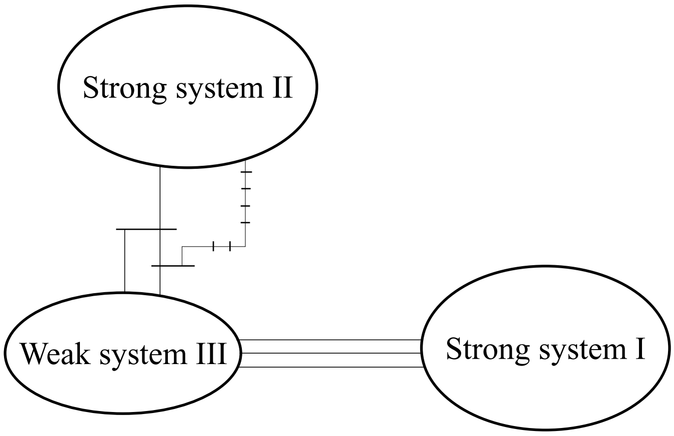

Figure 2.3 The Czechoslovakian network during the collapse.

•*Load behaviour including on-load tap changers*

On 23 July 1987, Tokyo suffered from very hot weather. After the lunch hour, the load pick-up was ~1%/min. Despite the fact that all the available shunt capacitors were switched on, the voltages started to decay on the 500 kV-system. After 20 minutes the voltage had fallen to about 0.75 p.u. and the protective relays disconnected parts of the transmission network and by that action shed about 8000 MW of load. Unfavourable load characteristics of air conditioners were thought to be part of the problem [21].

In the collapse in Sweden, on 27 December 1983, the load behaviour at low voltage levels was also a probable cause leading to a collapse [22]. Transmission capacity from the northern part of Sweden was lost due to an earth fault. Virtually nothing happened during the first ~50 seconds after the initial disturbance when the remaining transmission lines from the northern part of Sweden were tripped. Since these lines carried over 5500 MW, the power deficit in southern Sweden was too large for the system to survive. The cause of the cascaded line trippings was a voltage decline and a current-increase in the central part of Sweden. The on-load tap changer transformers contributed to the collapse when they restored the customer voltage level. Field measurements performed afterwards in the Swedish network have also shown inherent load recovery after a voltage decrease [5, 16]. This recovery aggravated the situation when voltages started to decline. The cause of this load recovery in the Swedish network is believed to be due to the particular behaviour of electrical heating appliances in connection with OLTC response.

A third example of the importance of load behaviour and OLTC actions was the collapse in western France 1987, a disturbance which is interesting due to the fact that the system operated stable at 0.5 p.u. voltage for a considerable time [14] and where operators had to shed 1500 MW of load to restore control of voltage.

Load behaviour is considered to be so important that some researchers define the voltage stability phenomenon as a load stability phenomenon.

•***The influence of protection and control systems***

The protection of the generator plays a major role during voltage instabilities. Often limiters are used as part of the generator protection. These take over control of the generator and try to avoid a tripping of the whole unit when the generator becomes overloaded. The significance of these limiters can be seen in several of the cases presented.

Almost all voltage instability processes are interrupted by protective relays which are disconnecting parts of the system causing a definite collapse. The Swedish power system and the Tokyo network finally collapsed due to (proper) protective relay operations. The collapse in France in 1987 was aggravated by the fact that many generators were tripped by maximum field current protective relays instead of being field current limited [14]. These examples illustrate the importance of taking protection systems into account in the system security analysis. It also implies the necessity of having a well-tuned control and protection system.

The control-systems of a HVDC-link can also affect voltage stability. The Nelson River HVDC-system in Canada and the Itaipu HVDC-link have experienced collapses [19]. In both cases the control-systems affected the cause of collapse. At Nelson River there was a System Undervoltage Protection-system out of service. At Itaipu several disturbances led to a number of DC-control changes.

In virtually all known collapses there is one contingency (or a series of related contingencies) that triggers a sequence of events causing voltage collapse or an insecure operating situation. Every part of the power system, generation, transmission and distribution (including load demand) can initiate, be involved in or interact with the other parts during voltage instabilities. The protection and control systems holds a unique position since it works as an ‘overlay’ or coating to the power system introducing other aspects than mere ‘power flow’ aspects. These systems are also a source of unexpected fortuitous events. The French collapse 1987 and the ones in Itaipu are two examples where equipment have been working inappropriate and aggravating the situation.

2.3 Definitions of voltage collapse

In the literature several definitions of voltage stability can be found. The definitions consider time frames, system states, large or small disturbances etc. The different approaches therefore reflect the fact that there is a broad spectrum of phenomena that could occur during a voltage instability. Since different people have various experiences of the phenomenon, differences appear between the definitions. It could also reflect that there is not enough knowledge about the phenomenon itself to establish a generally accepted definition at this stage. References [17 and 20] reflects the present status in these discussions.

2.3.1 Definitions according to Cigré

Cigré [3] defines voltage stability in a general way similar to other dynamic stability problems. They define:

- A power system at a given operating state is *small-disturbance voltage stable* if, following any small disturbance, voltages near loads are identical or close to the pre-disturbance values.

- A power system at a given operating state and subject to a given disturbance is *voltage stable* if voltages near loads approach post-disturbance equilibrium values. The disturbed state is within the region of attraction of the stable post-disturbance equilibrium.

- A power system undergoes *voltage collapse* if the post-disturbance equilibrium voltages are below acceptable limits.

2.3.2 Definitions according to Hill and Hiskens

Another set of stability definitions is proposed by Hill and Hiskens [6]. The phenomenon is divided into a static and a dynamic part. For the static part the following must be true for the system to be stable:

- The voltages must be viable i.e. they must lie within an acceptable band.

- The power system must be in a voltage regular operating point.

A regular operating point implies that if reactive power is injected into the system or a voltage source increases its voltage, a voltage increase is expected in the network.

For the dynamic behaviour of the phenomenon, Hill and Hiskens propose the following concepts:

- *Small disturbance voltage stability:* A power system at a given operating state is small disturbance stable if following any small disturbance, its voltages are identical to or close to their pre-disturbance equilibrium values.

- *Large disturbance voltage stability:* A power system at a given operating state and subject to a given large disturbance is large disturbance voltage stable if the voltages approach post-disturbance equilibrium values.

- *Voltage collapse*: A power system at a given operating state and subject to a given large disturbance undergoes voltage collapse if it is voltage unstable or the post-disturbance equilibrium values are non-viable.

Hill and Hiskens [6] present different methods to detect these different criteria. These definitions have common properties with the Cigré definitions.

2.3.3 Definitions according to IEEE

A third set of definitions is presented by IEEE [7]. The following formal definitions of terms related to voltage stability are given:

- *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 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.

- A system enters a state of *voltage instability* when a disturbance, increase in load, or system changes causes 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 minutes. If the decay continues unabated, steady-state angular instability or *voltage collapse* will occur.

These definition are more restricted than the others presented above. Only operating points on the upper side of the PV curve are allowed with these definitions (see Chapter 2.4.1).

2.3.4 Definitions according to Glavitch

Another approach is presented by Glavitch [18]. In this approach different time frames of the collapse phenomenon are illustrated:

- *Transient voltage stability* or collapse is characterized by a large disturbance and a rapid response of the power system and its components, e.g. induction motors. The time frame is one to several seconds which is also a period in which automatic control devices at generators react.

- *Longer-term voltage stability* or collapse is characterized by a large disturbance and subsequent process of load restoration or load change of load duration. The time frame is within 0.5-30 minutes.

Glavitch also proposes a distinction between *static* and *dynamic* analysis. If differential equations are involved, the analysis is dynamic. “Static does not mean constant, i.e. a static analysis can very well consider a time variation of a parameter.”

Of these definitions, Hill seems to be the closest to control theory and the IEEE-definition is related to the actual process in the network. The framework in these definitions on voltage stability include mainly three issues: *the voltage levels must be acceptable; the system must be controllable in the operating point; and it must survive a contingency or change in the system.*

2.4 The small system

A small system is generally used to demonstrate particular properties of voltage stability. The system is equipped with a generator, a transmission link and a load as can bee seen in Figure 2.4.

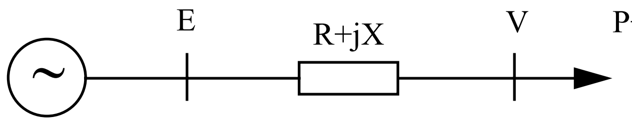

Figure 2.4 A simple model of a transmission system. E and V are the voltages at the generator and the load end, respectively. The transmission link has the impedance Z=R+jX and the load consumes the power S=P+jQ.

More components can be added to the system (transformers, capacitors etc.) and more details included (generator current limitation, on-load tap changer-relays etc.) to study the behaviour during different classes of disturbances.

2.4.1 The PV- and the VQ-curves for the small system

The active power-voltage function for the small system has a characteristic form usually called the ‘PV-curve’ (see Figure 2.5). As can be seen there is a maximum amount of power that can be transmitted by the system. Another property of the system is that a specific power can be transmitted at two different voltage levels. The high-voltage/low-current solution is the normal working mode for a power system due to lower transmission losses. One way to write the equations describing this power-voltage relation is:

$$V = \sqrt{\alpha \pm \sqrt{\alpha^2 - \beta}} \text{ where} \tag{2.1}$$

$$\alpha = \frac{E^2}{2} - RP - XQ \text{ and } \beta = (P^2 + Q^2)Z^2 \tag{2.2}$$

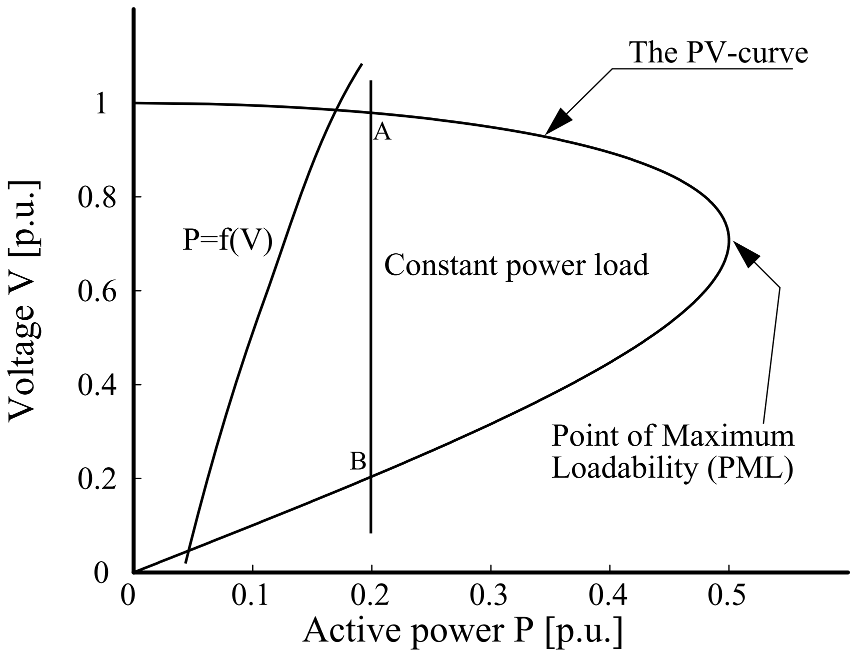

Figure 2.5 The PV-curve in per-unit with different load characteristics added. (E=1.0 p.u., R=0, X=1.0 p.u. and Q=0 p.u.)

The important "Point of Maximum Loadability" (maximum power transfer capability) is indicated in Figure 2.5. This point can be calculated by either solving 'PML' from the relation $\alpha^2=\beta$ from equation 2.1, by implicit derivation of dP/dV=0 in equation 2.1 or by evaluating the load-flow Jacobian singularity.

Another possibility to demonstrate the capacity of the small system is to show the V-Q relation. The necessary amount of reactive power in the load end for a desired voltage level V is plotted in Figure 2.6.

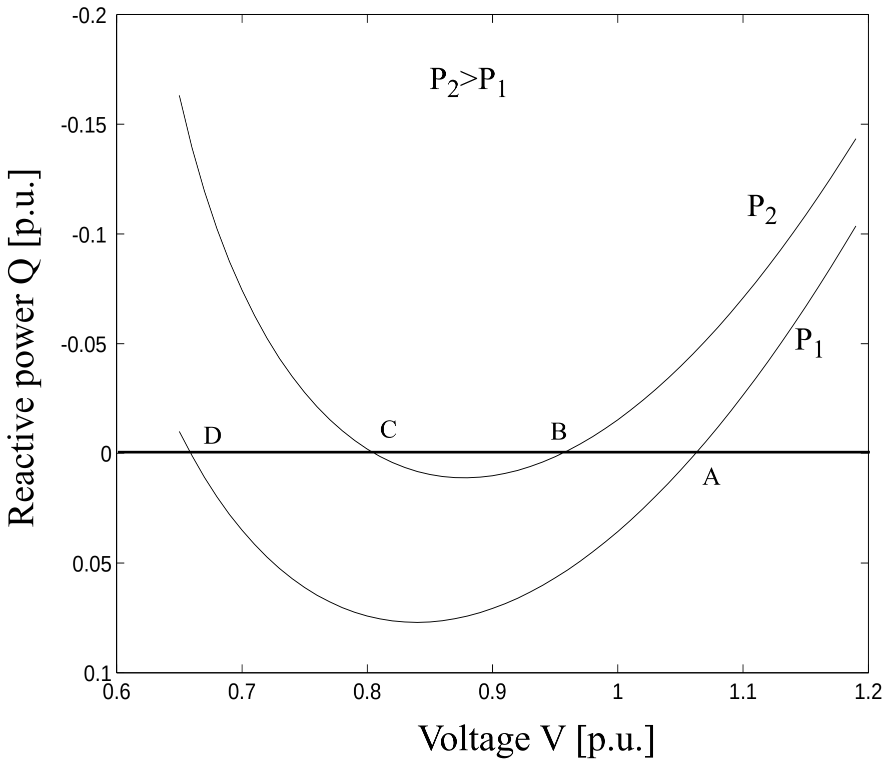

Figure 2.6 The QV curve in per-unit for two different active loads, showing the amount of reactive power to be injected at the load end to achieve a specified voltage. Without any reactive support in the load end, the system will be stable in the working points A and B and unstable in case of constant power loads in C and D [12, appendix 3]. Observe the common practice to 'flip' the Q-axis, i.e. a negative Q means injected reactive power in the load end.

2.4.2 The load demand

The system should supply its load demand at all times. Consequently, the system must manage all load-voltage dependencies without restraints. Electrical loads will behave differently. One way to describe the static voltage-power relation is to use the relations:

$$P = P_0\left[a_0\left(\frac{V}{V_0}\right)^0 + a_1\left(\frac{V}{V_0}\right)^1 + a_2\left(\frac{V}{V_0}\right)^2\right]$$

and (2.3)

$$Q = Q_0\left[b_0\left(\frac{V}{V_0}\right)^0 + b_1\left(\frac{V}{V_0}\right)^1 + b_2\left(\frac{V}{V_0}\right)^2\right]$$

where P and Q are active and reactive power load respectively while P_0 and Q_0 are the powers at voltage V_0. The relations in equation (2.3) are called a polynomial load model. The three terms correspond to a constant power fraction, a constant current fraction and a constant impedance fraction. The sum of $a_0+a_1+a_2$ and $b_0+b_1+b_2$ are equal to 1 but there is a choice to restrict each component to the interval [0,1] or let them vary freely. It is also possible to use an exponential load model:

$$P = P_0\left(\frac{V}{V_0}\right)^{\alpha} \text{ and } Q = Q_0\left(\frac{V}{V_0}\right)^{\beta} \qquad (2.4)$$

Values for the parameters of these static load models can be found for instance in [19, page 73] or [15, Chapter 3].

Electrical loads may also have a dynamic voltage dependence. Motor loads have a mechanical dynamic dependence due to the applied load torque but since this load demand depends on the frequency this will have little influence for decreasing voltages as long as the motor can develop the necessary torque. Motors are sensitive to voltage changes and electrodynamic couplings will arise within the winding when voltage changes but the time constants are quite small (one second or less) and they are in the same time-frame as the voltage regulation of generators. This often implies a nearly constant active power load when the mechanical slip has been adjusted to a new operating point after a contingency whereas the reactive power demand may change. Motor load dynamics is therefore mainly connected with transient voltage stability.

There are also loads with slower dynamics where the dynamic behaviour comes from control-systems regulating the dissipated power. Electrical heating appliances controlled by electromechanical thermostats is one example.

Dynamic loads are often composed of a transient and a stationary part. One way to describe these two conditions is (see [16] and Paper A.2.1):

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

and (2.5)

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

P_m is the active power load demand and P_r describes the part of the load that recovers. Here, the voltage dependence is given by a transient term denoted by the exponent α_t and a static term, denoted by the exponent α_s. Field measurements have shown that α_t is around 2 and α_s can, for certain types of loads, be 0.5. The same relation could be applied to reactive power demand but there has not yet been a relevant physical explanation for a reactive load recovery on its own and it is believed that reactive power recovery is a consequence of active power recovery during longer term voltage stability [16].

Electrical heating appliances can be composed of discrete conductances and a control-system that connects the appropriate amount of conductance to achieve the desired power demand. This gives in the long time-frame a constant power load. This type of load can be unstable in a quasi-stationary sense if it is operating on the lower side of the PV-curve. This can be shown in the following way: If the present working point is located to the left of the desired power demand A (set-point value) in Figure 2.5, the control-system will increase the conductance G and the dissipated power will increase until the working point reaches A. On the curve A-PML-B the dissipated power is too large and the control-system will therefore decrease G which increases the voltage V and the working point moves to A. For the remaining part of the PV-curve from the origin to B the dissipated power is too low and the control-system add more conductance which decrease V even further and lower the dissipated power. Therefore B will be unstable [13]. Note that there are no problems to “pass” PML with this type of controlled load because the load characteristic is transiently a conductance.

More about loads can be found in [15] and [16].

2.5 Different methods of analysis

The analysis of voltage stability can be done using different methods. One approach is the analysis of small networks with mathematical bifurcations as a stability criterion. A special case of this method is the analysis of the smallest singular value or the minimum eigenvalue. Modal analysis, the eigenvectors of the system representation, is also used sometimes. The smallest singular value and modal analysis can also be used on large networks. A second approach is to find the extremes of either the PV-curve or the VQ-curve by some type of load-flow calculations, where the "distance" between the actual working point and the extremes is a stability criterion. Time domain simulations are yet another approach to analysis. Sometimes these different methods are mixed so that two different methods are presented simultaneously to gain further insight into the phenomenon.

It is also possible to divide the different methods in static and dynamic ones. Much work is being done on static load flow models which could be compared with other methods of analysis. In the following some of the different methods are introduced.

2.5.1 Analytical methods

The analytical approach is usually based on continuous mathematical models of the components of interest. Today these models are not as detailed as the models used in computer simulation [11], and it is therefore difficult to explain all events during a computer collapse simulation. The analyst often works with the following system description:

$$\begin{aligned} \dot{x} &= f(x, y, \lambda) \\ 0 &= g(x, y, \lambda) \end{aligned} \tag{2.6}$$

From this set of equations the analyst tries to figure out in which points the time solution changes its behaviour qualitatively. These points are called bifurcation points and are associated with eigenvalues of the Jacobian matrix J of (2.6):

$$J = \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} \end{bmatrix} \tag{2.7}$$

The trajectory of the eigenvalues then decides the system behaviour in the bifurcation points. Schlueter et al. [11] indicate more than 10 different bifurcations existing in a power system depending on which models are included in (2.6) and the degree of complexity of the models.

The Point of Collapse (PoC) is a point where a bifurcation occurs and is indicated in Figure 2.7. If the power is increased for the load in Figure 2.7 there will be a bifurcation in the system Jacobian matrix when reaching the PoC [13].

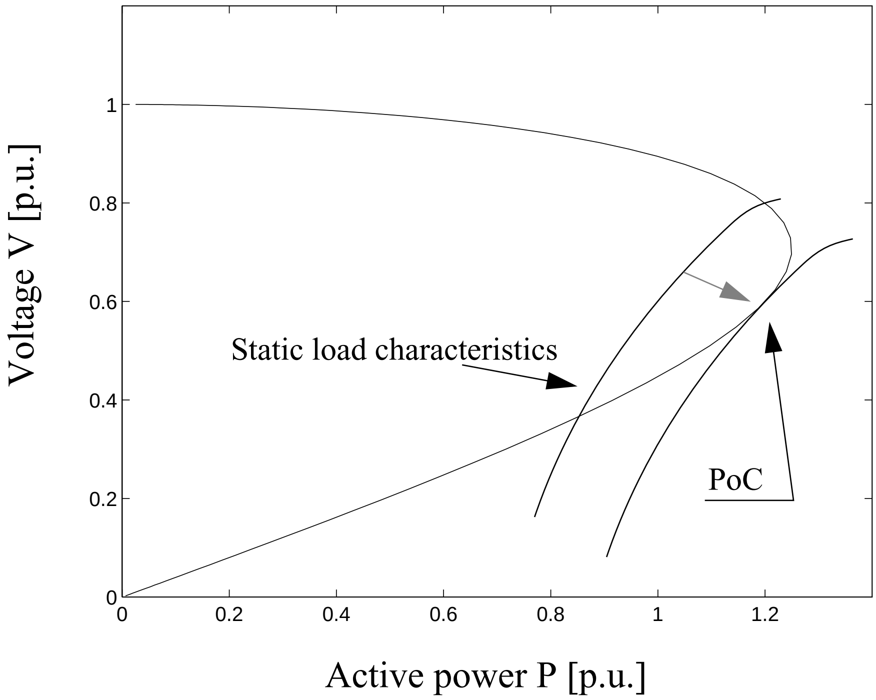

Figure 2.7 A PV-curve and a load characteristic where the load demand is increased. The indicated point of collapse (PoC) comes from Hill and Hiskens, [6] and is also described by Pal [13].

2.5.2 Indexes and sensitivity methods for voltage stability analysis

A bifurcation called the saddle-node bifurcation, is of special interest. It is connected to the singularity of the power-flow Jacobian matrix,

$$\begin{bmatrix} \Delta\mathbf{P} \\ \Delta\mathbf{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{P\theta} & \mathbf{J}_{PV} \\ \mathbf{J}_{Q\theta} & \mathbf{J}_{QV} \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta\mathbf{V} \end{bmatrix} \tag{2.8}$$

where the changes in active and reactive power are related to changes in angle and voltage. If the Jacobian matrix is singular (non-invertible), the system has reached a point where it has no solution i.e. a saddle-node bifurcation. The minimum singular value or the smallest eigenvalue of the Jacobian matrix, can be used as a "distance" or proximity indicator to this limit.

If the Jacobian matrix models the power flow equations, this singularity will coincide with the point of maximum loadability. But if load behaviour etc. are included (extended Jacobian matrix) the singularity will indicate the point of collapse.

If $\Delta\mathbf{P}=\mathbf{0}$, the relation between voltage change and reactive power change can be written as:

$$\Delta\mathbf{Q} = [\mathbf{J}_{QV} - \mathbf{J}_{Q\theta}\mathbf{J}_{P\theta}^{-1}\mathbf{J}_{PV}]\Delta\mathbf{V} = \mathbf{J}_R\Delta\mathbf{V} \tag{2.9}$$

This matrix $\mathbf{J}_R$ is used as a state space matrix in the analysis. Efficient algorithms [9] have been developed to calculate the minimum singular value for the reduced matrix $\mathbf{J}_R$ which can be used as a voltage stability index.

Modal analysis, calculation of eigenvalues and eigenvectors of the Jacobian matrix can be used to derive weak voltage nodes in the system. If an extended Jacobian matrix (where generators, loads etc. are modelled into the matrix) is used, the participation factors of the states in the models are presented with modal analysis.

2.5.3 Other indexes

Sometimes the distance in MW or MVAr to the maximum transfer point on the PV-curve is used as an index for vulnerability to voltage collapse. The point of maximum loadability can be calculated in many ways. A conventional load flow program can be used if it is capable of capturing the system behaviour near the bifurcation point (the same point as PML when applying constant power loads). This is, however, difficult and special continuation load flow methods for calculating the PV-curve near PML have been developed [8].

There are two indices called $VCPI_{Pi}$ and $VCPI_{Qi}$ (Voltage Collapse Proximity Indicator) presented in [4] that may be useful. They relate the total change of reactive power output to a change in either active or reactive power in a node i:

$$VCPI_{Pi} = \frac{\sum \Delta Q_g}{\Delta P_i} \tag{2.10}$$

$$VCPI_{Qi} = \frac{\sum \Delta Q_g}{\Delta Q_i} \tag{2.11}$$

At off-peak load the indexes are near 1 and grow to infinity at the collapse point.

2.5.4 Voltage stability simulation

Simulations in the voltage stability area are usually computer calculations in the time domain where the computer tries to solve the differential-algebraic equations describing the power system. Voltage stability phenomena put standard computer algorithms at new numerical problems. The differential equations are usually stiff, i.e. the time constants vary over a broad spectrum. This sometimes forces the user to choose which phenomena the models should represent. Some algorithms adapt their time-step to reduce simulation time and capture all the modelled phenomena with the same accuracy. Another problem is the way the computer solves the load flow. This could be done in several ways. Some software uses the admittance matrix with current injections and other uses the Jacobian matrix approach. If the software solves the network with a Jacobian matrix, it will have singularity problems near the collapse point but it will have the opportunity to calculate some indexes (see Chapter 2.5.2). Certain continuation load-flow methods have been developed to avoid singularity problems [8].

When the models used in the simulation have a known degree of accuracy, it is possible to simulate very complex systems with these models. The main problem is then to collect relevant input data. Usually, a time simulation only indicates if a disturbance is stable or unstable but, by calculating indexes and sensitivities, this drawback can be reduced. There are other reasons that motivate long-term dynamic simulations and the conclusions in [1] are enlightening in this matter. A summary of arguments for long term dynamic simulations follows here [8, 19 appendix D]:

- Time coordination of equipment where the time frames are overlapping.

- Clarification of phenomena and prevention of overdesign. Time domain simulations forces more careful analysis and modeling.

- Confirmation of less computationally intensive static analysis.

- Improved simulation fidelity especially near stability boundaries.

- Simulation of fast dynamics associated with the final phases of a collapse.

- Demonstration and presentation of system performance by easy-to-understand time-domain plots.

- Education and training.

In analytical modelling, it is difficult to implement protective relaying. In time simulations on the other hand, one can include these relays that may interact at any time during the voltage instability. It is therefore possible to coordinate between automatic regulation, limitation and protection in a time simulation.

There are many software packages available which can be used for long time simulation in power systems. A comparison between several different softwares applied to different test networks can be found in [1]. In this project a software called PSS/E from PTI Inc. has been used. This software is well recognized at power companies worldwide and has also started to be used among universities. PSS/E can be used for load flow calculations as well as short circuit analysis. The dynamic simulation utility in PSS/E can apply both explicit and implicit integration methods on the data set. Especially for long term dynamics implicit integration methods have been found favourable and are recommended to be used.

Some simulations on small networks has been performed in Matlab which is a versatile mathematical tool.

2.5.5 Other approaches

As long as load dynamics, generator current protection or limitation and OLTC-behaviour dominate the system response, is it possible to divide the voltage collapse course into several static phases and solve the load flow for each step. In [8] the system response is divided into the following phases:

1 **T=0 to 1 second**

Voltage excursions due to transient decay in generator flux and changes in motor slip. At the end of the period, voltage regulating equipment is affecting the voltage levels.

2 **T=1 to 20 seconds**

Generator terminal voltage output levels are restored if not limited by VAR-limits. Loads are modelled with transient models.

3 **T=20 to 60 seconds**

Current limiters may affect the output capacity of generators.

4 **T=1 to 10 minutes**

Load tap changers in the distribution network restore customer load.

5 **T=10+ minutes**

Automatic Generation Control (AGC), operators etc. affect the behaviour of the system.

If phase-angle regulators, Automatic Generation Control, combustion turbine starting etc. come into action during the same time-frame, simulations could be necessary to reveal the system behaviour. Governor response on the turbines should also be taken into account if they affect the distribution of power production.

2.6 References

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Chapter 3 Alleviating the impact of generator current limiters

This chapter aims to summarize certain important aspects presented in the papers and will pursue some further thoughts.

3.1 Organization

The papers which are a part of this thesis are organized as follows:

Paper A, **Voltage stability studies with PSS/E**; analyses the behaviour of dynamic load demand, current limiters and on-load tap changers. The implementation of these components into the PSS/E software is discussed. Different aspects of component behaviour are shown by simulations.

Paper B, **Behaviour of generator current limiters near the point of voltage collapse**; concentrates on the behaviour of the current limiters and discusses the capability diagram of the generator ‘as seen by the generator’, i.e. treats the generator as a stand-alone component.

Paper C, **Avoiding Voltage Collapse by fast Active Power Rescheduling**; tries to establish a ‘system capability’ as seen by the load demand for a small system equipped with current limiters. Different ‘modes’ of operation are introduced corresponding to the operation of different current limiters in the system. Here the view is shifted from the generator to the load point. The controlled parameter is the active power input to the generator during current limitation.

Paper D, **Mitigation of Voltage Collapse caused by Armature Current Protection**; continues the analysis in Paper C with simulations performed for a more extensive network.

Paper E, **Maximum thermal utilization of generator rotors to avoid voltage collapse**; investigates the use of the specific thermal capacity of a generator on system voltage stability.

Paper A and paper B are mainly dealing with inherent component behaviour, whereas papers C, D and E investigate system aspects and different actions that can be beneficial for the system in case of an impending collapse.

The following sections are a short description of important issues presented in the papers together with some additional information not presented elsewhere.

3.2 The field current limiter

The main issue in this dissertation is the general behaviour of a limiter and not its detailed implementation of which there exists many examples. However, two examples of field current limiter implementations are given in Section A.2.2 and Section E.2. For discussion of the qualitative behaviour of the field current limiter, see Section B.2 and Section E.2.1. More information about field current limiters can also be found in references [6, 7 and 9].

3.3 The armature current limiter

As stated in the introduction, the armature current limiter is not a common component worldwide. However in this dissertation the armature current limiter may in many instances be considered to be equivalent with an overcurrent relay. It is not difficult to implement an armature current limiter in a computerized voltage control/over-current protection device since all quantities are available together with the means of controlling it through the magnetization of the generator. The implementation of the armature current limiter used in Sweden follows closely that of the field current limiter (see Section A.2.2). Armature current limiters will allow generators to produce power in a stressed network for a longer time than an overcurrent relay. This will give other remedial actions more opportunity to support the system.

3.4 The interaction between the limiters

One interesting conclusion from the capability diagram of the generator (Figure B.3) is that a field current limited generator will become armature current limited if it is exposed to a continuously decreasing voltage (Figure B.4). Since virtually all voltage collapses contain a phase with decreasing voltage this transition between the limiters will happen if nothing else occurs before. Events as the activation of protection equipment (cf. distance relays) or the stalling of induction motors will initiate a new phase of the voltage instability creating new conditions which has to be dealt with accordingly. Note however that there are examples of generators where the reactive power decreases for a decreasing voltage during field current limitation. Figure 5.17 in reference [11] and figure 1 in reference [15] indicates such a situation which is very severe for the system. In such a case the influence of field and armature current limiter operation becomes similar. This situation occurs for generators having a high synchronous reactance and/or a low degree of saturation.

Several other constraints will be present in the generator capability diagram besides the two presented here. Reference [1] indicates a max/min generation limit, an auxiliary bus high/low voltage limit, a generator high/low voltage limit, a max/min voltage regulator output, a stator core end heating and a minimum excitation limit as probable sources of restricted operation of the generator. These constraints must also be included in a complete analysis of the generator. Practical aspects and field assessment of generator capability curves can be found in [16, 17] which are of particular interest for utilities and power plant operators. A general observation made during this study is how important the regular maintenance and tuning of the *existing* generator equipment is. Defects and anomalies in the field current protection/control have contributed to several voltage instability problems [21, page 263 and 25, page 30]. Also, short circuits in the field winding due to ageing may arise which will have repercussions on the reactive power capability [16]. Utilities should also update their modelling during security analysis to take into account improved computational resources available today.

3.5 The interaction between the transmission system and the limiters

One way to show the interaction between the generator current limiters and a transmission line is to plot a PV-curve (e.g. Figure B.2). The field current limiter decreases the point of maximum loadability but voltage is still in a sense controlled since the constant field current will keep a controlled voltage within the generator. Armature current limiting is more severe for the system since the voltage will not be controlled any longer and is solely dependent on the loads in the system. Different control mechanisms and certain voltage dependent loads will continuously change the load connected to the generator terminals and hence voltage levels.

For an armature overcurrent relay all operating points to the right of the straight line in Figure B.2 are prohibited and will cause a tripping of the generator. Note that the slope of the armature current in the PV-plane may vary (cf. Section 3.7) and the crossing between the valid PV-curve and an armature current limit can be above or under the point of maximum loadability.

3.6 The interaction between the load and the current limiters

System behaviour is very dependent on load behaviour which in its own is difficult to model. Sometimes the influence of the on-load tap changers is included in the load model [5, 13] or explicitly represented. This must then be taken into account when analysing the system.

A field current limiter will not change the general behaviour of the PV-curve but it will decrease the maximum power transfer and will make the voltage support weaker (Figure B.5). The analysis in the PV-plane of the system will therefore not differ that much between for instance a line tripping and a field current limiter action. However, in case of field current limitation one has to address the non-linearity of the introduced reactance and the saturation in the generator to achieve correct results.

The interaction between the armature current limiter and load behaviour is completely different. The system will become unstable if the load as seen by the armature current limited generator requires more current than the limit value. Figure A.15 demonstrates this performance for a few load models and Section B.2.4 discusses the key aspect to this behaviour. This property is also discussed in Section D.4.

3.7 The interaction between on-load tap changers and the current limiters

In general, tap changers will restore the voltage level and thereby the active power demand. It will also influence the network impedance as seen by the generator [14, page 76]. Since transformers are placed in different positions in the power system relative to generation and load demand the analysis must also take the location into account. Here follows an analysis of a small network containing a transformer as shown in figure 3.1. The model can represent any transformer in the

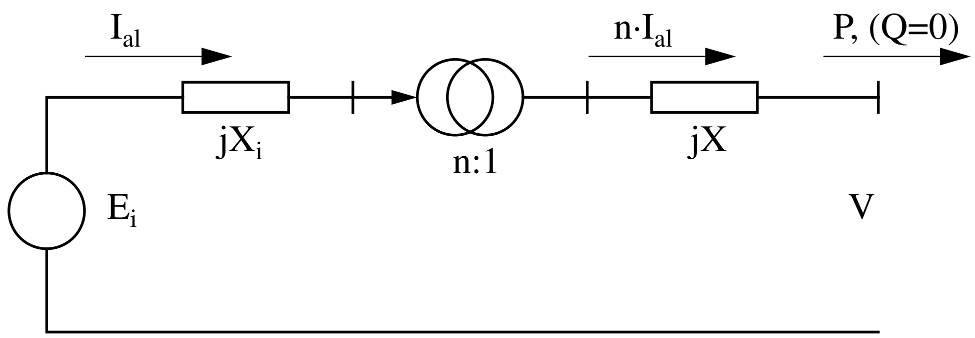

Figure 3.1 The studied system for establishing the interaction between OLTC:s and current limiters. In these examples are $X+X_i=0.1$ p.u.

power system. The load voltage V can be written as

$$V = \sqrt{\frac{1}{2}\left(\frac{E_i}{n}\right)^2 \pm \sqrt{\frac{1}{4}\left(\frac{E_i}{n}\right)^4 - \left(X + \frac{X_i}{n^2}\right)^2 P^2}} \tag{3.1}$$

A qualitative understanding of the interaction can be studied by examining the point of maximum power transfer P_{max} (or Point of Maximum Loadability). Equation (3.1) can be used to establish

$$P_{max} = \frac{\frac{1}{2}E_i^2}{(n^2X + X_i)} \tag{3.2}$$

The active power P_{max} will be a function of the reactances n^2X and X_i. By studying the transformer's relative position in the network one can distinguish between two different cases: the transformer is either close to the generator or close to the load.

Case 1: A transformer close to the generator ($X >> X_i$ and $n \approx 1$)

An approximate expression of P_{max} is then

$$P_{max} \approx \frac{\frac{1}{2}E_i^2}{n^2 X} \tag{3.3}$$

The family of PV-curves in this case is shown in Figure 3.2 and they illustrate how different tap steps alters the system capability. The load characteristics plotted in the figure show an improved system condition by tap changing operation. P_{max} will increase quadratic with the tap step. Therefore, the system will remain above the PML for all loads with a voltage dependence less than squared for (in this case) a decreasing tap step which increases the secondary voltage level.

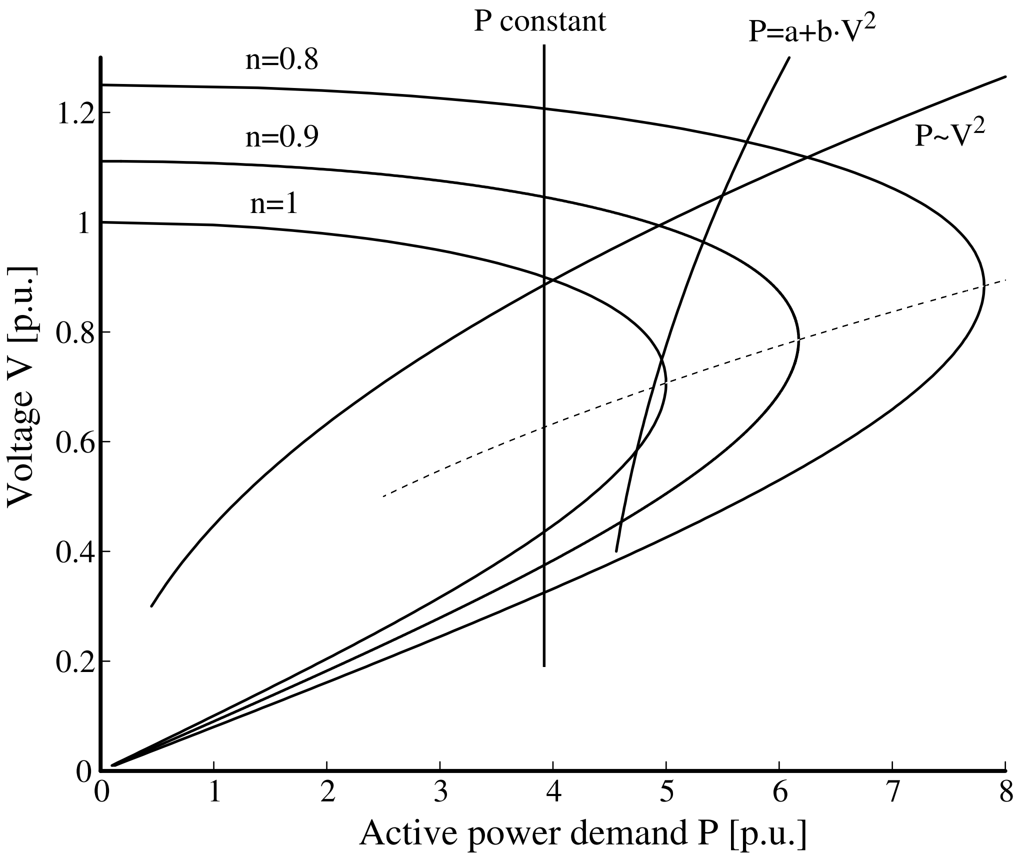

Figure 3.2 Different PV-curves for a transformer close to the generator.

Case 2: A transformer close to the load ($X \ll X_i$ and $n \approx 1$)

Now one can approximate P_{max} from (3.2) to

$$P_{max} \approx \frac{\frac{1}{2}E_i^2}{X_i} \tag{3.4}$$

i.e. P_{max} will be independent of the tap step. The family of PV-curves in Figure 3.3 clearly indicates that the system can become unstable due to the static characteristics of the load. Also, as discussed in Section 2.4.2, thermostatically controlled load may become unstable on the lower side of the PV-curve. A transformer close to the load may shift the PV-curve in such a way that the latter occurs. The tap changing

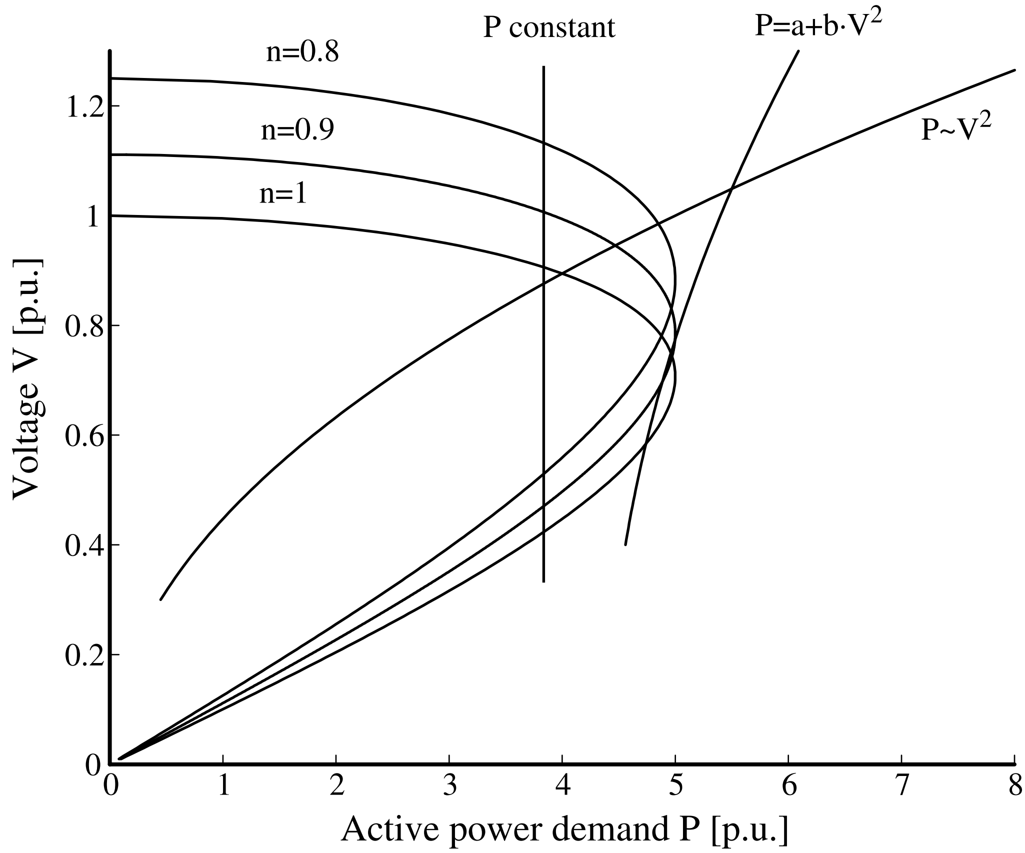

Figure 3.3 Different PV-curves for a transformer close to the load.

control equipment may also initiate an instability when the working point enters the lower side of PML. For certain load types the voltage will then decrease instead of increase for (in this case) a decreasing tap step.

In reality no transformer has a negligible impedance on either side and the response of a specific transformer on different system actions will be a mixture of these two extremes. The following observation can be made concerning the field current limitation:

- A field current limiter in operation will increase the reactance X_i and thereby decrease the maximum power transfer shown in (3.2). As the two cases above indicate, the field current limitation will also move the operation for this small system towards a ‘Case 2’ operation since X_i relatively increases if compared with X. The tap changing action will then be less beneficial for system stability.

From these two cases concerning tap changing actions the following general observations can be made:

- Step-up transformers close to generators are beneficial to ”increase” the tap ratio to avoid voltage stability problems. Usually however they are not equipped with on-load tap changers and can not be used as a countermeasure. If they are equipped with tap changers, the voltage drop might be too small for a control action based on local criteria only. Also, the maximum operating voltage of the transmission system may ‘prohibit’ this action.
- The importance of the load characteristics can not be underestimated. Case 2 shows a situation where both a conductance load and a constant power load are stable whereas a mixture of them might become unstable. The behaviour of dynamic loads such as thermostatically controlled load devices will complicate this (static) analysis even more.

For an armature current limit the tap changer will have a different impact. The most likely tap-changer operation during a voltage instability process is to try to increase the voltage on the secondary side in figure 3.1 by reducing the tap ratio n. This means that the current ratio of the transformer must go in the opposite direction i.e. the current at the secondary side will be $n \cdot I_{al}$. The armature current limit will then decrease for every tap step as seen by the load since I_{al} is fixed. The armature current capability will therefore change in the PV-plane as indicated in figure 3.4. The load demand will be as important as before since it may or may not trigger the limiter.

An example of this process can be seen in Figure A.12 and Figure A.14 where the current on the primary side increases considerably which causes a collapse in the second figure. Load characteristics in combination with the tap changer operation triggers the armature

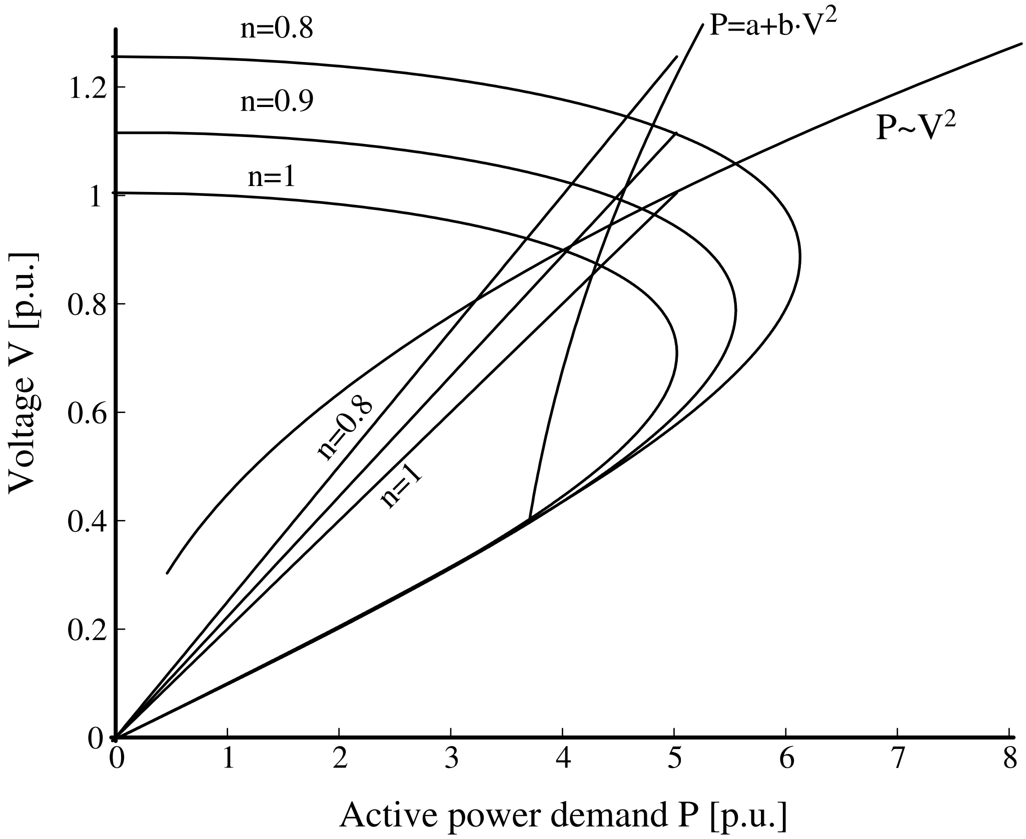

Figure 3.4 The interaction between the armature current limit and tap changings. The PV-curves represents a case when $X=X_i$.

current limiter and the system changes its performance completely leading to a voltage collapse.

The relative position of the transformer in the system is also important in this case. For a transformer close to the load ($X<<X_i$, Case 2) the tap changing causes a power invariant shift in the PV-plane whereas a transformer closer to the generator will increase the maximum capability of the system.

The behaviour of the tap-changer can also be seen as being a part of the load behaviour. One will then have dynamics originating from the tap changer control in the load characteristics instead. Field measurements performed in the south of Sweden [5] show examples of this.

3.8 Remedial actions

Any activation of a current limiter is a serious threat to system voltage stability and should be avoided as long as possible. The armature current limiter appears to be the most critical one even though the field current limiter can cause a collapse on its own.

Papers C, D and E are focused on two possible remedial actions alleviating the impact of current limiters during a voltage instability. The first remedial action aims *to utilize the thermal capacity in the field winding*. The pre-disturbance conditions do not always have to be rated conditions and by introducing temperature controlled current limits will the bias of different pre-disturbance temperatures disappear which can cause unnecessarily strict limitation of the generator.

The other remedial action is *to make small changes in local active power production* during current limitation in order to *increase the system capability* locally. This rescheduling of power will give the generator protection another degree of freedom to set aside too high currents.

In particular, the interaction of the limiters with the rest of the power system is considered when these remedial actions are performed. Both remedial methods are based on a radial system with a comparatively small generator feeding a load with a gross import of active power.

3.8.1 The use of the thermal capacity in the field winding

Many contingences leading to voltage stability problems occur under circumstances where generators are not fully loaded from a thermal point of view. Paper E investigates this aspect during field current limitation. Rather few measurements of the temperature rise in the field winding seems to be available and it is the authors opinion that this aspect has been neglected. Some values are given in [4] and in [19] in addition to [E.9]. These references also discuss the approach to keep field current as high as possible until maximum rotor temperature is reached. Reference [19] indicates decreasing time constants for increasing generator sizes. The settings of protection should therefore vary between different sized generators to make them equally loaded (compared to their respective rated conditions) during contingencies.

A cost effective way to improve voltage stability seems to be the use of existing generators and loading them until they reach their maximum steady-state level from a thermal point of view. A thermal model, temperature measurements of the winding and a field current limiter control equipment based on temperature data are the basic requirements. The cost of upgrading the exciter, if necessary, should also be compared with other methods as capacitive support. Since the thermal capacity is a finite ‘resource’ the limiter must use it carefully. Communication with neighbours indicating a severe situation and asking for support may be useful to implement to keep in view the limited capability.

Some problems encountered in measuring the field winding temperature are described in [18]. The environment is extreme due to a large temperature range with sometimes very high mechanical stresses (considerably above 3000 rpm for the fastest rotating machines) in a highly electrically-noisy environment. The field voltage and current measurements have to be transferred from the rotating shaft. These values give the present field resistance which is indirectly a measure of the temperature of the winding. Reference [18] reports that a temperature accuracy of ±1.5° C can be achieved by existing equipment. This method gives an average temperature of the winding so the problem of so called ‘hot spots’ must also be addressed.

It is tempting to propose a similar approach for armature windings. There are in this case no problems in transferring temperature measurement data from a rotating shaft and the possible problem of exciters having a too low transient rating does not exist as for the field circuit (even though a maximum utilization of the armature may be obstructed by too small power resources). Also, the temperature of the cooling media in the armature winding (if any) will influence the rating which is something a temperature based current limiter can take into account.

3.8.2 Rescheduling of active power production

The second remedial method proposed is an increase or a decrease of mechanical power input to the generator shaft when any of the current limits are violated. In certain cases power plants have this control ability.

Voltage stability problems are many times regarded as a lack of reactive power locally. This causes a declining voltage in that area which increases the reactive power deficit further due to increasing transmission losses. The voltage continues to decrease. If a generator, exposed to this voltage drop becomes **armature current limited** it is impossible to increase the reactive power output from that generator. In fact, the opposite will occur. When voltage declines the active power production will take an increasingly larger fraction of the available armature current. The reactive power output from the generator must decrease which escalates the voltage drop further. By decreasing the mechanical power input during armature current limitation the reactive power production can be held constant or may even increase and keep voltage levels higher. The transmission system uses this extra reactive support and imports the rescheduled active power until a certain (rather low) power factor is reached for the generator.

On the other hand, if the generator exposed to the voltage drop becomes **field current limited** and can not supply enough reactive power, an increase of mechanical power in that generator will ease the transmission losses into the depressed area. This will improve the voltage level somewhat. Reference [8] on the other hand states, based on the capability diagram, that one can generate less active power in favour of reactive power at critical locations. This may be true but not necessarily the best action from the systems point of view at all times. Figure 3.5 indicates two possible positions for the small generator in the network. Case A shows a generator 'surrounded' with other generators. If a limitation is initiated in the small generator the system is in this case similar to the one presented in papers C, D and E. Figure C.7 indicates a possible capability curve for the load point. An active power decrease during field current limitation will in that case be an *extra* stress for the system.

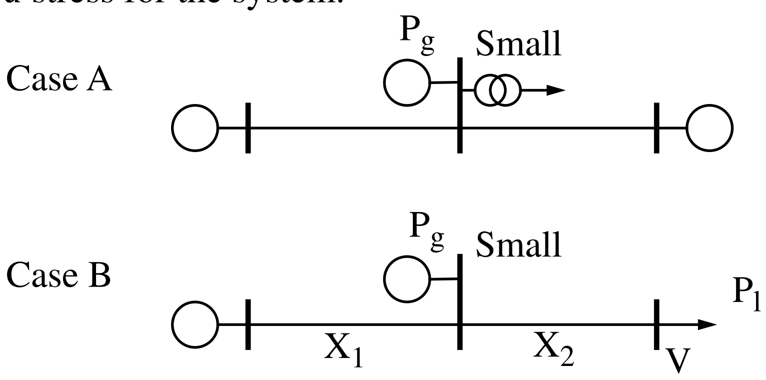

Figure 3.5 Different generator positions.

Also for Case B in figure 3.5 where the load demand has been moved away from the generator node and fed through a transmission line will an active power decrease in the small generator be a burden in certain situations. An example is given in figure 3.6. Two different kinds of PV-curves are plotted in the figure. The first one, where the small generator is keeping its voltage at its set point, indicates the PV-curve for the system containing the reactance X_2. The other three curves represent different levels of active power production in the small generator when it is field current limited. An increase of active power production will push the interception between the two ‘modes’ of operation of the small generator (i.e. the field current activation point) to a higher load demand level. The system will be able to deliver more active power before system characteristics are changed by the field current limiter.

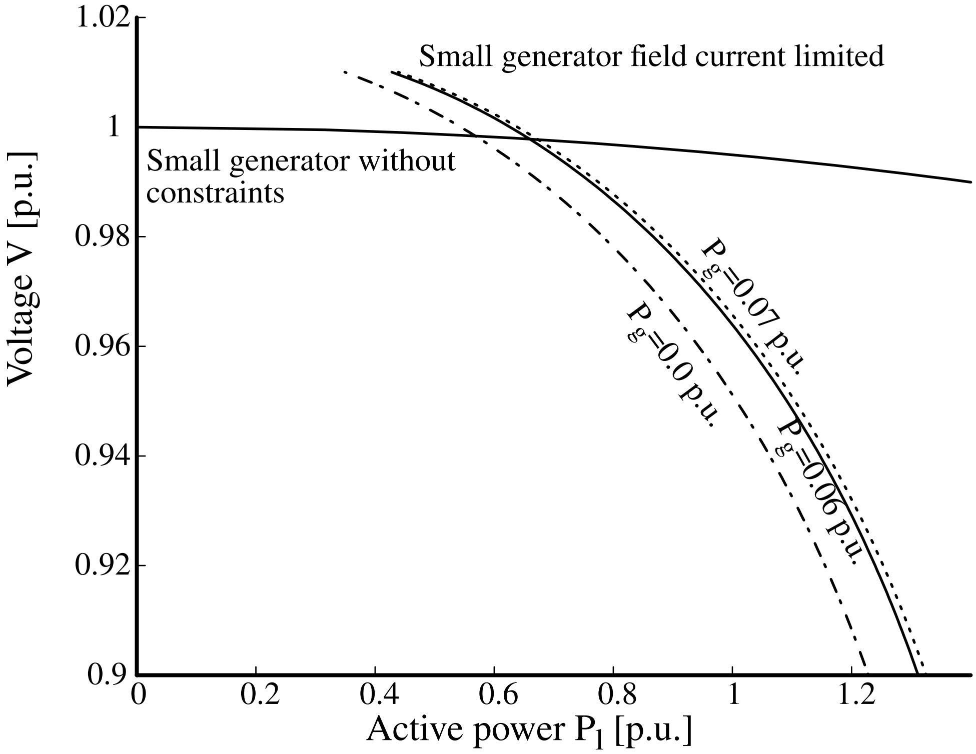

Figure 3.6 The PV-curve for different levels of active power production in the small generator for case B in figure 3.5.

Active power rescheduling as a means of relieving the system during current limitation is hardly discussed in the literature. The idea is mentioned by Taylor [21, page 116] but the concept is probably meant to be implemented as an operator control and can be seen as a slower control mechanism working through EMS/SCADA systems. The concept seems to operate mostly from relieving the transmission system by increasing power transfer to the exposed area on lightly loaded lines. Also Kundur et al. [12] mentions that the generator capabilities changes due to modified active outputs and this has to be taken into account during longer time frames although no further analysis is made.

Another source which mentions active power changes during current limitation is [3]. The capability diagram of the generator is discussed together with a strategy of how to increase system voltages during a load pick up.

The Cigré report [4] is one of the most extensive descriptions of generation based countermeasures during long term voltage stability published so far. Several aspects are discussed including active power decrease during armature current limitation and thermal utilisation of the windings.

In reference [23] active power dispatch is used to alleviate voltage instability. As a criterion for instability a static index is used based on [10]. The index identifies the Point of Maximum Loadability and adjusts active power production to increase the distance to the point of maximum loadability. Another example is reference [20] where optimal power flow is used to reschedule active power production. The criteria used for minimization is either total cost of generation, transmission losses, maximizing of the minimum singular value or minimization of slack reactive injection. A comparison between these criteria is made. A few similar approaches are available but all those seem to be based on off-line calculations.

In Paper D, an Active Power Rescheduler, APR is introduced. The purpose is to try to implement ideas about the influence of a decrease in mechanical power input during armature current limitation and thereby improving the reactive power balance locally. The difference between this approach and the ones presented above is that it is based on local control and work in a time frame comparable to the field and armature current limiters.

It was found in paper D that a rather slow APR giving small decreases of active power production was beneficial. At first, this behaviour was not understood but if figure C.13 is studied a hypothesis can be given. Figure C.13 shows the local system capability when the local generator is armature current limited (Mode 3) and when both generators are limited (Mode 8). When Mode 8 becomes activated the maximum capability of the system is shifted to a higher relative level of local active power production as compared to Mode 3. If the same shift of system capability is applied to the large system the system will only benefit from rather small decreases (i.e. slow) and if the decrease becomes too large there will be a reduced system capability. During the simulated contingencies in the large network one or several generators will become armature current limited and for those cases where voltage collapse occurred the number of limited generators increased during time. This can be seen as a transition from different modes to more complex ones such as in Section C.6.3. A sketch of the system capabilities is made in Figure 3.7.

One can also argue that for every generator that becomes limited in the large system the effective reactance will increase between the load demand and the infinite generation point which gives, if it is translated to the small system, a higher angle δ in equation (C.17) and hence a higher power factor at maximum system capability.

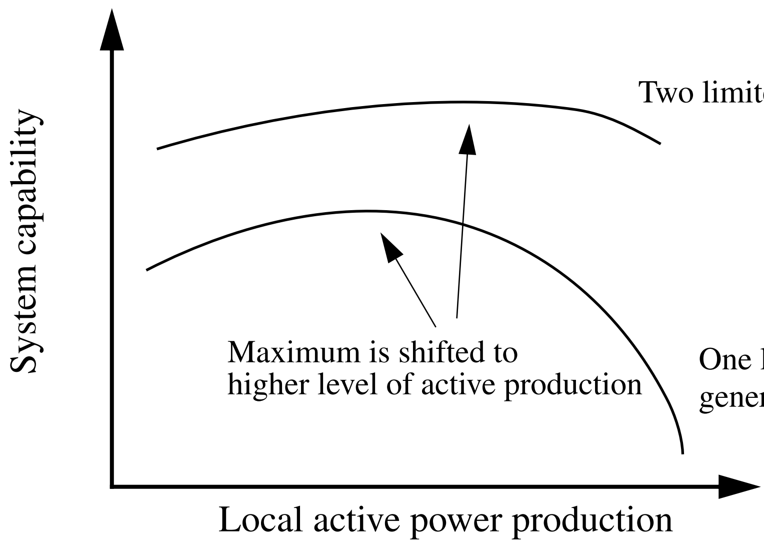

Figure 3.7 The system capability maximum is shifted to the right for increased numbers of limited generators.

Another interesting connection between the more complex simulation performed in paper D and the analysis of the smaller network (paper C) can be studied in figures C.10 and D.12. The total load power demand for the case with and without APR in the voltage depressed area is almost the same in figure D.12 but the dynamic load/tap changer control operates as in C.10 so the maximum energy deficit is reduced and the load excess region is increased for the case with APR. The example is not stable but shows the importance of keeping a high load voltage. A slight decrease of the pre-disturbance situation would have been enough for the APR case to become stable in figure D.12.

3.8.3 Power plant response to a change of active power production

Hydro power plants are fairly easy to control and are often used for frequency regulation. Walve [24] states that the loading from synchronisation to full load takes between 20 and 100 seconds for a hydro power plant. In case of thermal power plants the situation will be more complex. An increase of power may be considered as being a response to a frequency drop and a thermal power plant can accomplish an increase rather fast when steam is available. Baldwin et al. [2] indicates that a transient increase of 25-30% of nominal power is allowed for major frequency drops. For even larger frequency deviations there will be a restriction in the order of 10% of rated load per minute though higher values may be possible. The reference also indicates that for a transient power change of 20%, 5.4% will be accomplished within 3.25 s and the remaining 14.6% within 50 seconds. A power decrease may be achieved by closing the control valve which has a slew rate of typical 40% per second.

For thermal power plants working in constant power mode the available power increase capacity will be more restricted since it takes longer time to change the primary power production in this case. However, Termuehlen and Gartner [22] shows several ways to obtain a fast sustained power increase. The methods used are bypassing of heaters and water injection into the superheater.

Walve [24] gives ‘typical’ response times for mechanical power changes showed in Table 3.1.

Type of change	Unit	Speed
Step response	Oil-fired	2.5% within 5 s 5% within 30 s
	Coal-fired	2.5% within 5 s 5% within 30 s
Continuous frequency control		±2% within 30 s
Ramp (applies within 50-90% of operating range)	Oil-fired condensing	8%/minute Total 30%
	Coal-fired condensing	4%/minute Total 20-30%
	Gas turbines	10%/minute Total 30%

Table 3.1 Response times for power plants [24].

Walve [24] also states that tests show that nuclear boiling water reactors can vary their output by 20% with a time constant of 10 to 20 seconds whereas pressurized water reactors are slower.

The given figures clearly indicate that most power plants will be able to accomplish active power changes deemed by current limit restrictions. Insufficient control equipment and/or opposing operating strategies may obstruct this possibility.

3.9 References

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Chapter 4 Conclusions

A necessary requirement when making computer simulations is to use accurate models and enter correct parameters into these models. The user must also understand the general behaviour of the system in order to verify and validate the results. The modeling aspects are illustrated through the detailed implementation of several different components in this dissertation. Field and armature current limiters, dynamic load model and on-load tap changer relays all show more aspects than a “straightforward” model would give. Armature current limiter models must prohibit the transition from overmagnetization to undermagnetization and tap changer relays may have a completely different response time depending on the characteristic chosen. The choice between constant or inverse time operation and constant or pulsed control signal can give a variation in response time of several multiples for the same time setting on the tap changer relay. Given also the fact that the impact of a tap changer operation on the system depends to a high degree on the relative position of the transformer in the grid, the response to a disturbance may vary considerably. Tap changing actions electrically close to generators are better from a voltage stability point of view than tap changings close to the load demand. Without a general understanding of such phenomena on their own some simulation results would be difficult to understand.

All papers presented in this dissertation conclude to the importance of the load behaviour and the necessity to implement accurate load models to achieve proper quantitative results. The interaction between an armature current limited generator and a load demand having a voltage dependence around constant current can be used as an example. The outcome is very sensitive to the load behaviour and a voltage dependence slightly larger than constant current will give a stable case whereas a collapse will occur for a load dependence slightly less than constant current. Tap changer relay operations and load demand also show a considerable coupling and may interact in such a way that an overshoot in power demand occurs. Since the system is already stressed due to the initial voltage drop this overshoot in power demand can make a considerable burden on the system.

It is also shown that the field and armature current limiters do not work independently. A voltage stressed situation where the generator is not able to keep the voltage from decreasing due to a field current limitation will eventually lead to the maximum steady state armature current where an armature current limiter operation/overcurrent relay tripping may result. Both kind of limiters have a major impact on system stability and it is important to try to avoid their activation.

Given the major influence that the two different current limiters have on voltage stability the question can be raised on how to alleviate their influence. The way they interact with the system indicates that a limitation of reactive power from the generator is severe and therefore a study was made of how active power changes could relieve a stressed system. A small system with models of current limiters, dynamic load and tap changer operation was used to investigate ‘Active Power Rescheduling’ during current limitation. By dividing the operation of the system into different ‘modes’ corresponding to different combinations of activated current limiters, the system capability in the load point can be calculated. Already for two generators the system capability becomes a complex function of these modes.

It was found that the local system capability depends on the active power production during both field and armature current limitation in the local generator. The results show that the system benefits from a local active power *decrease* when the local generator is **armature current limited** i.e. when extra reactive power becomes available and is injected into the system. For **field current limiting operation** an *increase* of active power is beneficial. Sometimes these reschedulings can result in a situation where the generator becomes both field and armature current limited i.e. the generator is then fully loaded.

The local system capability characteristics in case of armature current limitation in the local generator shows a maximum. The question can then be stated as follows: Which power factor should a constant current source have to support the system capability as much as possible? The answer shows a relation between the power factor and the power angle (the angle between the voltages) to the remote generation area.

The derived system capability is based on a static analysis. In order to investigate the dynamic response of the system to an active power rescheduling a dynamic load fed through a tap changing transformer was simulated and analysed for a particular case when the local generator was armature current limited. It was found that active power rescheduling changes the dynamic response of this on-load tap changer/dynamic load combination. The energy deficit in the load demand that occurs after a contingency was decreased and the load excess region increased in the state space plane when an active power rescheduling was performed. This has two advantages. The power overshoot in load demand would not be as severe as without an active power rescheduling and the region in the state space plane where the system has a possibility to recover to a steady state operating point is increased.

A simple controller was implemented which took advantage of the derived relation for the maximum system capability and was found to be very efficient in the small system.

More complex combinations of current limiter operations were then investigated and it was found that local active power rescheduling also can support other generators further away. A rather uncommon situation was shown where a voltage *decrease* actually led to a stable case. The reason for this was a starting operating point on the abnormal side of the maximum of the system capability curve. The simulation showed that the system can make use of the active power rescheduling also going in the opposite direction.

Given the promising results in the small system a large system was simulated. A simple Active Power Rescheduler, APR, was implemented operating during armature current limiter operation and the outcome of a number of disturbances was analysed.

One empirically learned experience in the larger system was that a rather slow and small APR was most beneficial for a broader spectrum of contingencies. This is attractive from the view of power plant operation where slow active power changes appear to be more easily incorporated but this also restricts the type of contingencies which can be alleviated with APR to longer term voltage instabilities.

It was shown that the APR can be used either to increase the transmitted power over a critical transfer corridor or prolong the time before collapse for the same active power transfer. A combination of these benefits can also be achieved. Two kinds of load models were used and the static one was found to be generally more stable than the dynamic one. The time to collapse was also generally longer for the simulations with the static load model.

The next remedial action studied was to exploit the generators field winding thermal capacity by including on-line temperature measurements. This will allow the generator to feed more reactive power into the grid and keep voltages higher until the field winding reaches its maximum temperature. The benefits that could be gained when fully utilizing the thermal capacity of the generator are dependant on the pre-disturbance loading of the generator and the thermal time constants of the rotor. Since many voltage collapses start with a contingency not necessarily occurring at maximum generator power output there will be cases where this extra capacity is available. This is a limited resource and measures must be taken to cover this fact. One way may be to use communication to neighbouring 'voltage resources' and inform that the voltage is 'boosted' and that an overloading will occur shortly. Today a field current limitation will show up as a voltage depression around the generator which will inform the surrounding area about the critical situation through the grid voltage. As before, a voltage drop will increase the energy deficit due to the load/tap changer response and also decrease the load excess region.

A general observation made during this study is how important the regular maintenance and tuning of the *existing* generator equipment are. Defects and anomalies in the field current protection/control have contributed to several voltage instability problems.

Chapter 5 Future work

The generator is one of the most controlled and protected components in a power system. It is connected mechanically through a shaft to a thermal-mechanical system which is very complex regarding operation, control and protection. On the other side the generator is a part of the power system which also is quite complex and not fully understood on its own. To propose changes in the control of the generator is therefore some challenge; on the other hand the advantages obtained from a coordinated analysis can become substantial.

A coordinated field-and-armature limiter is proposed which is a part of the normal generator controller responsible for voltage regulation and other features as power system stabilization. The limiter has inputs such as the temperature of the windings and the ”mode of operation” of generators which are, electrically seen, neighbours. Another input is information about the active power transmission through nearby located ”critical tie-line sections”. As output signals the current limiter uses field voltage and mechanical power control. In case of a contingency which violates the capability of the generator the limiter evaluates the situation according to the following rules:

- All thermal capacity in the rotor and stator should, if necessary, be used within a certain time (say one minute) after which only maximum stationary levels of the violating current (and hence winding temperature) are allowed.
- If possible, power plant active power production should be increased until it reaches either armature current limit or maximum power plant production.
- Power plant active power production should be decreased either until it runs the risk of becoming field current limited; maximum system capability is reached; or the angle over the transmission tie-line section becomes too large initiating power oscillations.
- The limiter should inform its generator neighbours and if required, apply for support. Both active and reactive power might be supplied by the neighbours if they are not under any kind of restriction. This will prevent that an overloaded generator will keep voltage levels within its dead band until its resources are completely exhausted without its neighbours being aware of this. The communication does not need to be fast. Regular Supervisory Control And Data

Acquisition/Energy Management Systems (SCADA/EMS) are probably sufficient communication channels since the likelihood of both current limitation and an inoperable SCADA system is relatively low. The neighbours must naturally be equipped with similar controllers and have the potential of rescheduling power.

- The limiter should make sure that input signals from power system stabilizers are fed through the complete control system in a proper way. It is no use saving the system from a voltage collapse if a power oscillation arises causing a collapse due to ‘blocked’ power system stabilizers when needed most in a voltage weak situation. Since this proposal already contains active power control during current limitation, this feature may also be used for damping (the slowest) power oscillations. This leads into a parallel and completely different research area [e.g. 1]. Maybe the combined benefits can motivate the implementation of new control equipment including active power control.

Many interesting aspects of this coordinated limiter are still to be investigated. In particular is the phase when the thermal capacity is used up interesting. A decreased voltage will relieve the system load demand initially but the system will, as load recovery starts and continues, be more and more strengthened by a high voltage. One implication which needs more attention are those generators with a high synchronous reactance and a relatively low degree of saturation as discussed in Section 3.4. For example, will the system response change when a field current limited generator works ‘below’ Point of Maximum Loadability?

The restoration process after a voltage collapse is, at least in Sweden, dependent on the success or failure of changing to household operation of the major power plants. Assuming that a generator becomes armature current limited, can an Active Power Rescheduler be tuned in such a way that the probability of a successful household operation increases? An effective APR-function will keep the local voltage higher and is able to decrease the steam production somewhat. The higher voltage level will decrease the risk of a generator tripping or that auxiliary equipment within the plant stalls or switches off due to low voltage. A reduced steam production will decrease the turbine overspeed in case of a grid isolation and hence lower the risk of an emergency shut down. Both these aspects are worth considering in a future work.

Depending on the future of electrical energy storage such as Superconducting Magnetic Energy Storages or fuel cells some analysis presented here may be beneficial to implement in Flexible AC Transmission System-devices. In particular is an armature current limit and maximum rated current for semiconductor valves comparable. In situations when the output current of such valve is limited by its maximum level the controller has to choose the mixture of active or reactive power supplied to the system. This is roughly the same problem as presented here but probably with another time delay. Such devices may have a comparable small active power capability (small active power storage units will be the ones most likely to be available first) and hence working with rather low power factors. Situations will then occur when an active power increase will be beneficial for the system during maximum rated output current (cf. Figure C.6). Quite interesting system responses are in such cases ”forecasted” (cf. Figure C.12) during long term voltage instabilities.

The load model mostly used in this dissertation can be extended by taking the voltage dependency for lower voltages into account. Since the parameters used here are based on field measurements rather close to normal voltages the power demand will not be correctly represented during low voltage levels and during the fast voltage drop of a collapse.

The external system around a limited generator is in the small system represented as a Thevenin source in this dissertation. It is shown that the limiter operation depends somewhat on the Thevenin source. Reference [2] shows a way to estimate the voltage stability limit locally by means of the impedance in the Thevenin source. One could pose the question if the coordinated limiter proposed here can make use of the information gained from reference [2].

5.1 References

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