Voltage collapse in power systems
–
The influence of generator current limiter, on-load tap-changers and load dynamics

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Abstract

Voltage stability in power systems is influenced by generator field-, and armature current limiters, on-load tap changers and load dynamics. This dissertation analyses possible interactions between these system components by computer simulations of long-term power system dynamics.

The different modes of *generator current limiter* operation are analysed and it is shown that possible transitions between these modes can cause voltage instability. The importance of the armature current limiter behaviour is emphasized since this protection system causes the generator to lose all of its voltage support when trying to keep the armature current on a constant level.

During a voltage decline in the transmission network, the *on-load tap changers* try to maintain a constant load voltage. This will cause a higher current demand in the transmission system which increases the voltage drop even more.

It is shown how *dynamic load characteristics* can have a strong influence on the outcome of a disturbance. A load recovery in combination with on-load tap changers may cause an overshoot in power demand leading to a higher stress on the system compared to a constant power load. The system is also sensitive to the static load dependence where a small variation in characteristics may cause a completely different outcome of a disturbance.

The phenomena mentioned were studied in a small power system with special attention to the current behaviour. That voltage stability can be treated as a ‘current problem’ is best shown by the on-load tap changer behaviour and the armature current limiter actions. These components have a strong influence on the currents in the system. A clear indication that the system sooner or later will approach voltage instability is therefore an increasing current combined with a decreasing voltage. This current versus voltage relation is briefly studied through the parameter $\Delta I/\Delta U$.

Keywords

Voltage collapse, voltage instability, armature current limiter, field current limiter, load dynamics, current-voltage trajectory.

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Without our colleagues at the department of Electrical Power Systems things would have been much harder (and more boring).

Thanks!

Kort sammanfattning på svenska:

Vi löser
"Ickelinjära, diskontinuerliga samt styva differential-algebraiska ekvationssystem med både explicita och implicita lösningsmetoder"

Så att säga...

List of Abbreviations

AGC	Automatic Generation Control
DSL	Dynamic Simulation Language
ETMSP	Extended Transient/Midterm Stability Program
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
LTC	Load Tap Changer
LTSP	Long Term Stability Program
OLTC	On-Load Tap Changer
PML	Point of Maximum Loadability
PSS/E	Power System Simulator for Engineering
RMS	Root Mean Square
VCPI	Voltage Collapse Proximity Indicator

The symbols used for quantities and units coincide with the IEC recommendations, except for the decimal sign which in this dissertation is represented by a dot.

Contents

Chapter 1 Introduction

This licentiate's dissertation treats certain aspects of voltage stability in power systems. The approach has a practical point of view, where computer simulations and analysis are based on accurate models of real components. Two different models for on-load tap changer relays and a generator field and armature current limiter model have been implemented into the simulations. Also a dynamic load model based on field measurements has been included. With these models long-term dynamics of power systems have been analysed. Finally a qualitative study of the current limiter behaviour of generators is presented together with a study of the current-voltage trajectory during a voltage instability.

The project began with a preliminary study in October 1992. The usefulness of the power system simulation software PSS/E as a simulating tool for long-term models was investigated. It was concluded that the ability to develop user models in PSS/E was sufficient for the purpose of investigating voltage collapse.

Two papers have been written during this project. They are the scientific basis for this dissertation which also includes chapters with background information on voltage stability and software used.

The first paper is reprinted as chapter 4 in this dissertation. It was presented at the conference on "Bulk Power System Phenomena III, Voltage stability, Security and Control" in Davos, Switzerland in August 1994. The paper treats four implemented models: a generator current limiting model, two different on-load tap changer models and a dynamic load model. All of them are based on real components or field measurements. Their behaviour are exemplified by simple simulations. The significance of the current limiters, OLTC and the load dynamics is demonstrated.

The second paper, reprinted as chapter 5, has been accepted for publication at Stockholm Power Tech, International Symposium on Electric Power Engineering June 1995. This paper analyses the behaviour of generator current limiters. It is shown in which manner different current limiting modes interact with the power system and may cause a voltage collapse. The variable $\Delta I/\Delta U$ is introduced, which gives information on the state of the system. Simulations with $\Delta I/\Delta U$ on a larger network are presented in chapter 6 together with a discussion about the meaning of $\Delta I/\Delta U$ from a physical point of view.

Chapter 2 is an introduction to the voltage stability phenomenon. Experiences from real collapses and incidents are presented together with ongoing research in this field. Definitions and other important properties are also introduced.

Since much of the simulations in this project have been executed using PSS/E software, chapter 3 describes this program in some detail.

The two final chapters contain conclusions and describe proposals to future work.

Voltage instability and voltage collapse

There is a lack of clear definitions and vocabulary in this area when not using strict mathematical expressions (see chapter 2.3). Since the presented simulations have not been analysed with mathematical methods the use of terminology may be imprecise. In this dissertation, the phrase “Voltage collapse” implies a non-viable voltage which magnitude is decreasing fast in time. The term “Voltage instability” is more vague. During a disturbance leading to a voltage collapse, there is a point in time where the voltage becomes uncontrollable. A voltage instability has occurred but the actual collapse may occur later (due to load recovery, OLTCs or other phenomena). The difference is best studied in figure 2.1. The voltage collapse point in that simulation occurs at 55 s whereas the voltage instability phase might be taken from the onset of the disturbance and onwards (a slow voltage decline leading to OLTC-regulations causing a collapse). At some instant during the simulation there is a situation where the system has not a stable working point.

This naturally leads to a subjective treatment of these terms but hopefully it will be made clear in the context what is meant.

Chapter 2 The voltage stability phenomenon

2.1 Introduction

This research area concerns disturbances in a power system network where the voltage magnitude becomes uncontrollable and collapses. The voltage decline is often monotonous in the beginning of the collapse and difficult to detect. A sudden increase in the voltage decline often marks the end of the collapse course. It is not easy to distinguish this phenomenon from 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.

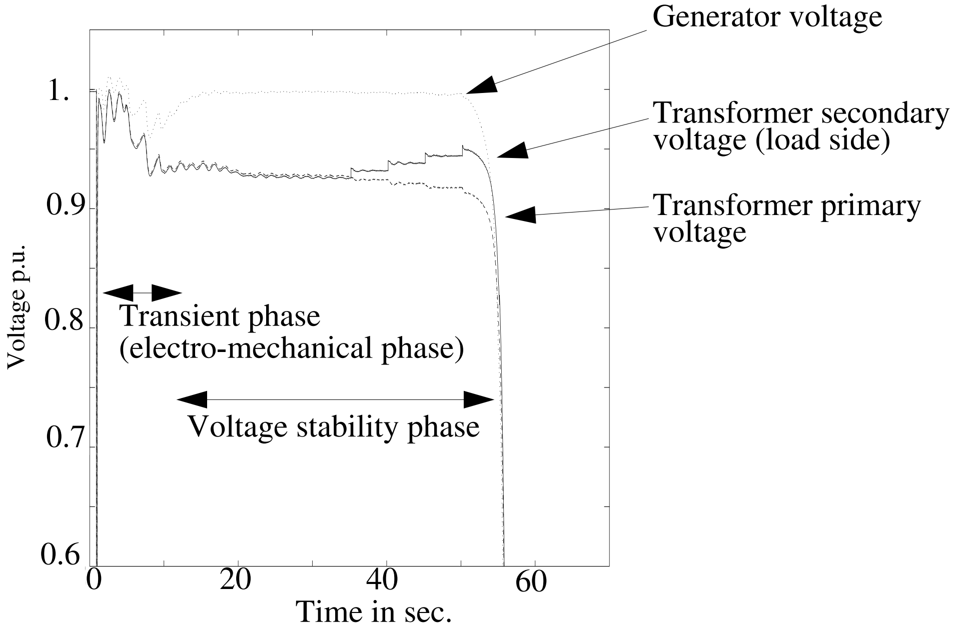

Figure 2.1 Example of a collapse simulation with a stable transient stability phase, a voltage decline and a fast voltage drop. (See chapter 4, figure 18).

During the last twenty years there have been one or several large voltage collapses almost every year somewhere in the world. The reason is the increased number of interconnections and a higher degree of utilization of the power system. 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 the stability of power systems.

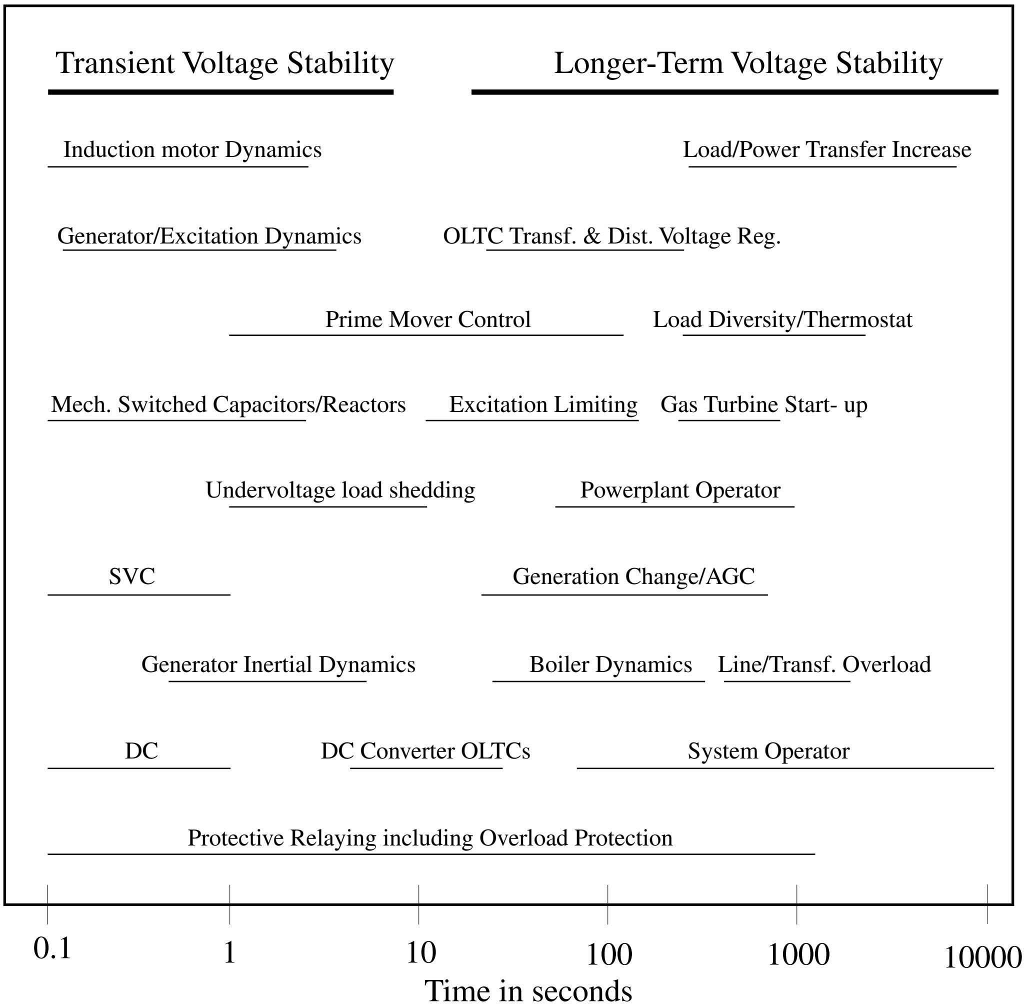

Figure 2.2 Different time responses for voltage stability phenomena [16].

It is believed by many professionals that the power system will be used with a smaller margin to voltage collapse in the future. The reasons are twofold: the need to use the invested capital efficiently, and the public resistance 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 varies from seconds to several tens of minutes. This makes voltage collapse difficult to analyse since there are many phenomena that interact during this time (see figure 2.2). Important factors that cause interaction during a voltage decline are among others: generation limitation, behaviour of on-load tap changers, and load behaviour.

An interesting point is that many researchers discard voltage magnitude as a suitable indicator for the proximity to voltage collapse, although this is in fact the quantity that collapses, [4] and [7].

One question that has been discussed is whether voltage stability is a static or dynamic process. Today it is widely accepted as a dynamic phenomenon but much analysis is performed using static models.

2.2 Experiences gained from the real world

Much can be learnt from real voltage collapses or incidents. Detailed information of the most well known occurrences can be found in [2] and [5].

Analysing real collapses involves two problems. Firstly, the lack of event recorders in the “right” places causes lack of information about the disturbance. Secondly, it is sometimes difficult to distinguish between voltage stability and transient stability. There might be other reciprocal actions which make the system more difficult to understand, such as human interaction, frequency deviation etc.

We would like to present the following experiences gained from real collapses. They point out several important properties that are common in many different disturbances.

•***Transmission system limitations***

The tripping of fairly small generators could, if they are placed in positions that need voltage support (voltage weak positions), cause a large increase of reactive power losses in the transmission network. This causes large voltage drops which can generate stability problems. Two examples are the 1970 New York disturbance [5] and the disturbance at Zealand in Denmark 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. At Zealand, a tripping of the only unit in the southern part of the island producing 270 MW caused a slow voltage decline in that part. After 15 minutes the voltages had declined to 0.75 pu, 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 also had 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 just a few plants for production. This resulted in that they were operating quite 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. During this period, the transmission system was unable to transmit the necessary amount of reactive power to the voltage suppressed area and this caused a continuous voltage decline. When the fifth generator was tripped, the transmission-protective relays separated the system and a collapse resulted [8].

The collapse in Canada, in B. C Hydros north coast region in July 1979 is also interesting in this respect [5]. 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 pu 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. Before the disturbance, there were three interconnected systems, two strong ones, I and II and one weak system, III, in the middle of I and II (see 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 within one second on the other line.

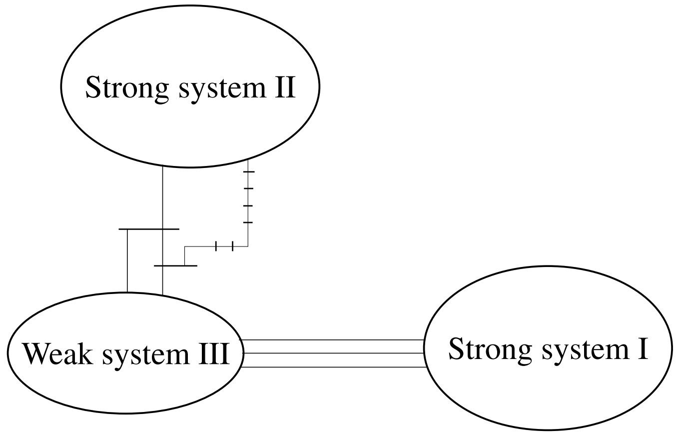

Figure 2.3 The Czechoslovakian network during the collapse.

•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 put into the system, the voltages started to decay on the 500 kV-system. In 20 minutes the voltage had fallen to about 0.75 pu 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 [17].

In the collapse in Sweden, on 27 December 1983, the load behaviour at low voltage levels was also a probable source leading to a collapse [18]. Transmission capacity from the northern part of Sweden was lost due to an earth fault. Virtually nothing happened 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 the inherent load recovery after a voltage decrease [14]. 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 electrical heating appliances.

A third example of the importance of load behaviour and OLTC actions was the collapse in western France 1987 [12].

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***

Almost all voltage instability courses are interrupted by protective relays which are disconnecting parts of the system causing a definite collapse. The Swedish and 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 [12]. This points out the importance of taking protection systems into account in the 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 [16]. 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.

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 stability course. 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.

2.3.1 Definitions according to CIGRÉ

CIGRÉ [2] 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. (Small-disturbance voltage stability corresponds to a related linearized dynamic model with eigenvalues having negative real parts. For analysis, discontinuous models for tap changers may have to be replaced with equivalent continuous models).
- 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.
- Following voltage instability, a power system undergoes *voltage collapse* if the post-disturbance equilibrium voltages are below acceptable limits. Voltage collapse may be *total* (blackout) or *partial*.
- Voltage instability is the absence of voltage stability, and results in progressive voltage decrease (or increase). Destabilizing controls reaching limits, or other control actions (e.g., load disconnection), however, may establish global stability.

2.3.2 Definitions according to Hill et al.

Another set of stability definitions is proposed by Hill et al. [4]. 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.

Here Hill et al. use two forms of regularity. One could say 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 et al. 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 et al. [4] present different methods to detect these different criteria. These definition have common properties with the CIGRÉ definitions.

2.3.3 Definitions according to IEEE

A third definition of this phenomenon is presented by IEEE [5]. 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.

This definition is more restricted then the others presented above. Only operating points on the upper side of the U-P curve are allowed with this definition (see chapter 2.4.1).

2.3.4 Definitions according to Glavitch

Another approach is presented by Glavitch [15]. 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 mathematics 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 simple system

A small system is generally used to show some properties of voltage stability. This system must be equipped with a generator, a transmission link and a load (figure 2.4).

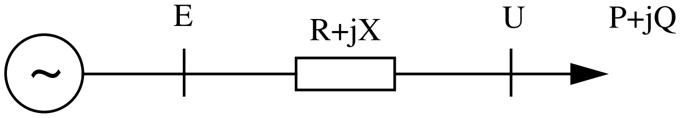

Figure 2.4 A simple model of a transmission system. E and U are the voltages at the generator and the load end, respectively. The transmission link has the impedance Z=R+jX and the load consumes the power S=P+jQ.

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

2.4.1 The U-P and the Q-U curves for the small system

The active power-voltage function for the basic small system has a characteristic form usually called the 'U-P 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 point for a power system due to lower transmission losses. One way to write the equation describing this power-voltage relation is:

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

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

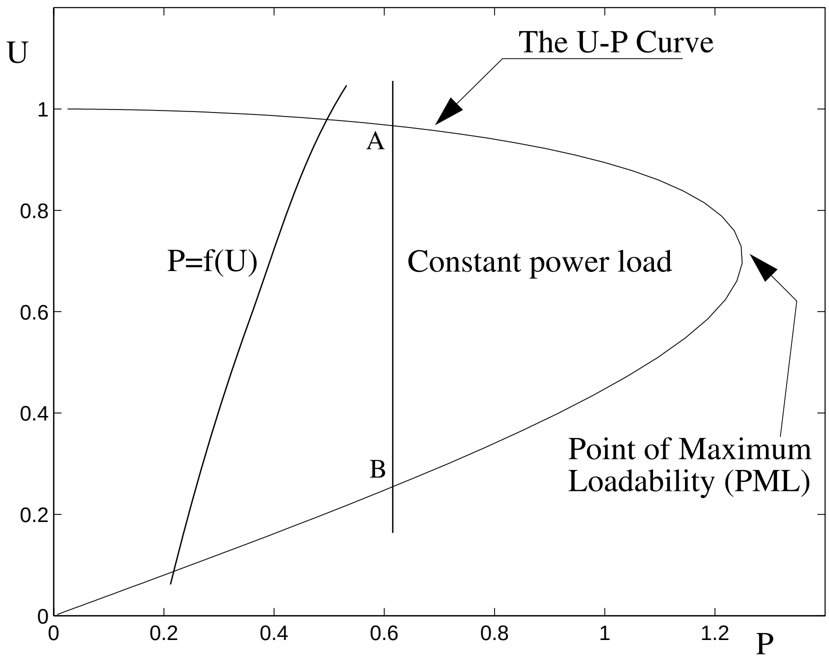

Figure 2.5 The U-P curve in per-unit with different load characteristics added.

The important property “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/dU=0 or by evaluating the load-flow Jacobian singularity.

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

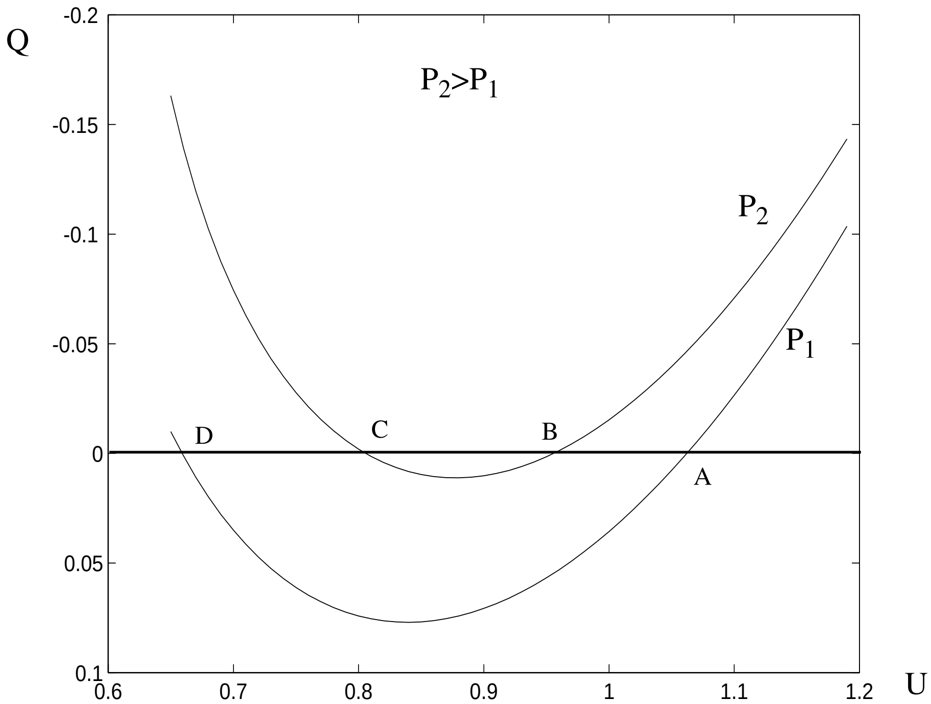

Figure 2.6 The Q-U-curve in per-unit for two different active loads, showing the amount of reactive power to be injected at the load end to achieve a specified voltage. Without any reactive support in the load end, the system will be stable in the working points A and B and unstable in case of constant power loads in C and D [10, 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 loads

The system should supply the loads at all times. Consequently, the system must manage all load-voltage dependencies without restraints. All types of electrical loads behave differently. One possible way to describe the static voltage-power relation is to use the relations:

$$P = P_0\left[a_0\left(\frac{U}{U_0}\right)^0 + a_1\left(\frac{U}{U_0}\right)^1 + a_2\left(\frac{U}{U_0}\right)^2\right]$$

and (2.3)

$$Q = Q_0\left[b_0\left(\frac{U}{U_0}\right)^0 + b_1\left(\frac{U}{U_0}\right)^1 + b_2\left(\frac{U}{U_0}\right)^2\right]$$

where P and Q are active and reactive power load respectively while P_0 and Q_0 are the powers at voltage U_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 both equal to 1. It is also possible to use an exponential load model:

$$P = P_0\left(\frac{U}{U_0}\right)^{\alpha} \text{ and } Q = Q_0\left(\frac{U}{U_0}\right)^{\beta} \qquad (2.4)$$

Values for the parameters for different types of loads can be found for instance in [16, page 73] or [13, chapter 3].

Electrical loads can also have a dynamic voltage dependence. Motor loads often have some sort of dynamic dependence due to the mechanical load they are connected to. This often implies a nearly constant active power load when the mechanical slip has been adjusted to the new operating point. For motor loads the time constants are quite small and they are in the same time-frame as the voltage regulation from generators. Transient voltage stability is therefore mainly connected to motor load dynamics. There are also loads with slower dynamics where the dynamic behaviour comes from control-systems regulating the dissipated power. Electrical heating appliances, controlled by 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 [14] and chapter 4.2.1):

$$T_{pr}\frac{dP_r}{dt} + P_r = P_0\left(\frac{U}{U_0}\right)^{\alpha_s} - P_0\left(\frac{U}{U_0}\right)^{\alpha_t}$$

and (2.5)

$$P_m = P_r + P_0\left(\frac{U}{U_0}\right)^{\alpha_t}$$

P_m is the active power load demand and P_r describes the part of the load that recovers. Here, the voltage dependence is divided into one transient, α_t and one static, α_s, term. The voltage dependence varies over time from α_t to α_s as a first order differential equation with a time constant T_{pr}. Field measurements have shown that α_t can be 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.

Voltage independent loads as 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 type of loads can be unstable in a quasi-stationary sense if they are operating on the lower side of the U-P-curve. This can be shown in the following way. If the present working point is located to the left of the desired power 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 U and the working point moves to A. For the remaining part of the U-P-curve from the origin to B the dissipated power is too low and the control-system add more conductance which decrease U even further and lower the dissipated power. Therefore will B be unstable [11]. 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 [13] and [14].

2.5 Different methods of analysis

Today the analysis of voltage stability could be divided into several points of attack. One approach is analytical analysis on small networks with mathematical bifurcations as the 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 be used on large networks. A second approach is to find the extremes of either the U-P-curve or the Q-U-curve by some type of load-flow calculations, where the "distance" between the current 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 analysis

The analytical approach is usually dependent on continuous mathematical models of the components of interest. Today these models are not as detailed as the models used in computer simulation [9], and it is difficult for the analytical methods to explain all events during a computer collapse simulation. The analyst often work 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 try 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):

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

The trajectory of the eigenvalues then decides the system behaviour in the bifurcation points. Schlueter et al. [9] indicate more than 10 different bifurcations existing in a power system depending on which models are included in (2.6) and the complexity of the models.

The Point of Collapse (PoC) is the point where 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 in the PoC [11].

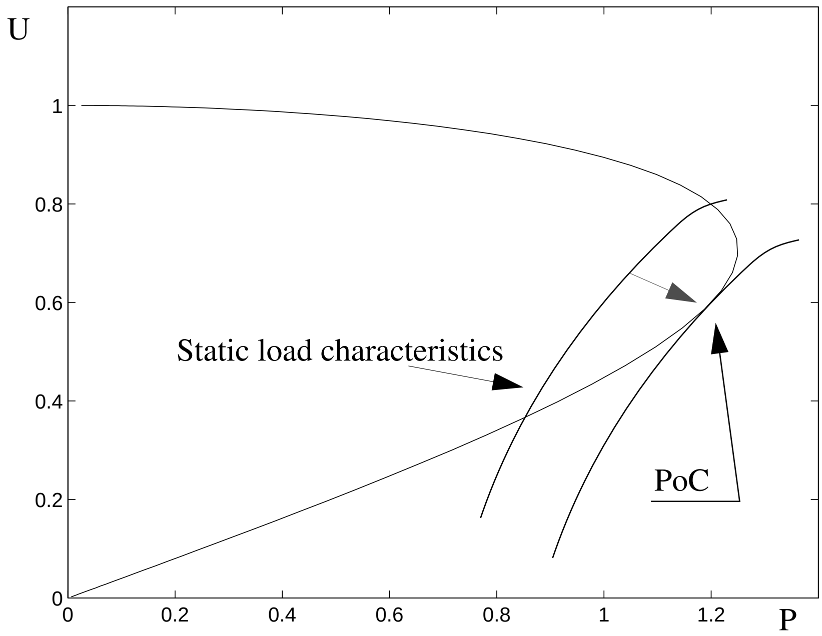

Figure 2.7 A UP-curve and a load characteristic where the load demand is increased. The indicated point of collapse (PoC) comes from Hill and Hiskens, [4] and is also described by Pal [11].

2.5.2 Indexes and sensitivity methods for voltage stability analysis

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

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

where the incremental changes in active and reactive power are related to incremental changes in angle and voltage. If the Jacobian matrix is singular (non-invertable), 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. is included (extended Jacobian matrix) the singularity will indicate the point of collapse (see figure 2.5).

If $\Delta\mathbf{P}=\mathbf{0}$, the relation between incremental 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 [7] 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 U-P 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 for constant power loads). This is, however, difficult and special continuation load flow methods for calculating the UP-curve near PML have been developed [6].

There are two indices called $VCPI_{Pi}$ and $VCPI_{Qi}$ (Voltage Collapse Proximity Indicator) presented in [3] 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 Simulations of voltage stability analysis

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 2.5.2). Certain continuation load-flow methods have been developed to avoid singularity problems [6].

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 things that motivate long-term dynamic simulations. The conclusions in [1] are enlightening in this matter. The following is taken from [16, appendix D] or [6]:

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

2.5.5 Other approaches

As long as the OLTC in the distribution network, load dynamics and generator field current protection or limitation 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 [6] 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.

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Chapter 3 The PSS/E program

3.1 Introduction

In order to simulate voltage collapse it is important to have suitable software since dynamic effects can be both of a fast and a slow nature. Voltage collapse can occur not only as the immediate consequence of a contingency, but can also be the result of changes in system conditions due to restoration of loads, limitation of generator currents or capacitor/reactor switching etc. These varying conditions will increase the demands on the solution algorithms used in the program. It is also important to be able to implement user-written models of the equipment used in the system since there is no model library that covers all details or models of the equipment used in power systems.

According to the requirements mentioned above, this project was started with a preliminary study [9] aimed to verify if the PSS/E[1] program was suitable for voltage collapse simulations. The outcome of the study showed that PSS/E met the requirements regarding long-term dynamic simulation and model implementation, though it has to be mentioned that comparison with other software was not made. Consequently, the simulation results shown in this report are all obtained by using the PSS/E program.

This chapter deals with the structure and the dynamic solution methods as used by the PSS/E program. User-written models are briefly mentioned as well as other software programs which are available for similar studies.

3.2 Structure

PSS/E is an integrated, interactive program for simulating, analysing and optimizing power system performance. The program contains a set of modules which handle a number of different power system analysis calculations. All the modules operate from the same set of data whose structure is divided into four different “working files”, shown in figure 3.1. These working files are set up in a way that optimizes the

1. PSS/E: Power System Simulator for Engineering, developed by Power Technologies Inc. (U.S.A)

computational aspects of the key power system simulation functions: network solution and equipment dynamic modelling. The user has a variety of ways of operating PSS/E, depending upon the type of study being performed. However, he never needs to address these working files by name, though he must be aware that he is processing these files every time he uses PSS/E. The modules used for voltage collapse simulations are *Power flow*, *Dynamic simulation* and *Extended term dynamic simulation* [2].

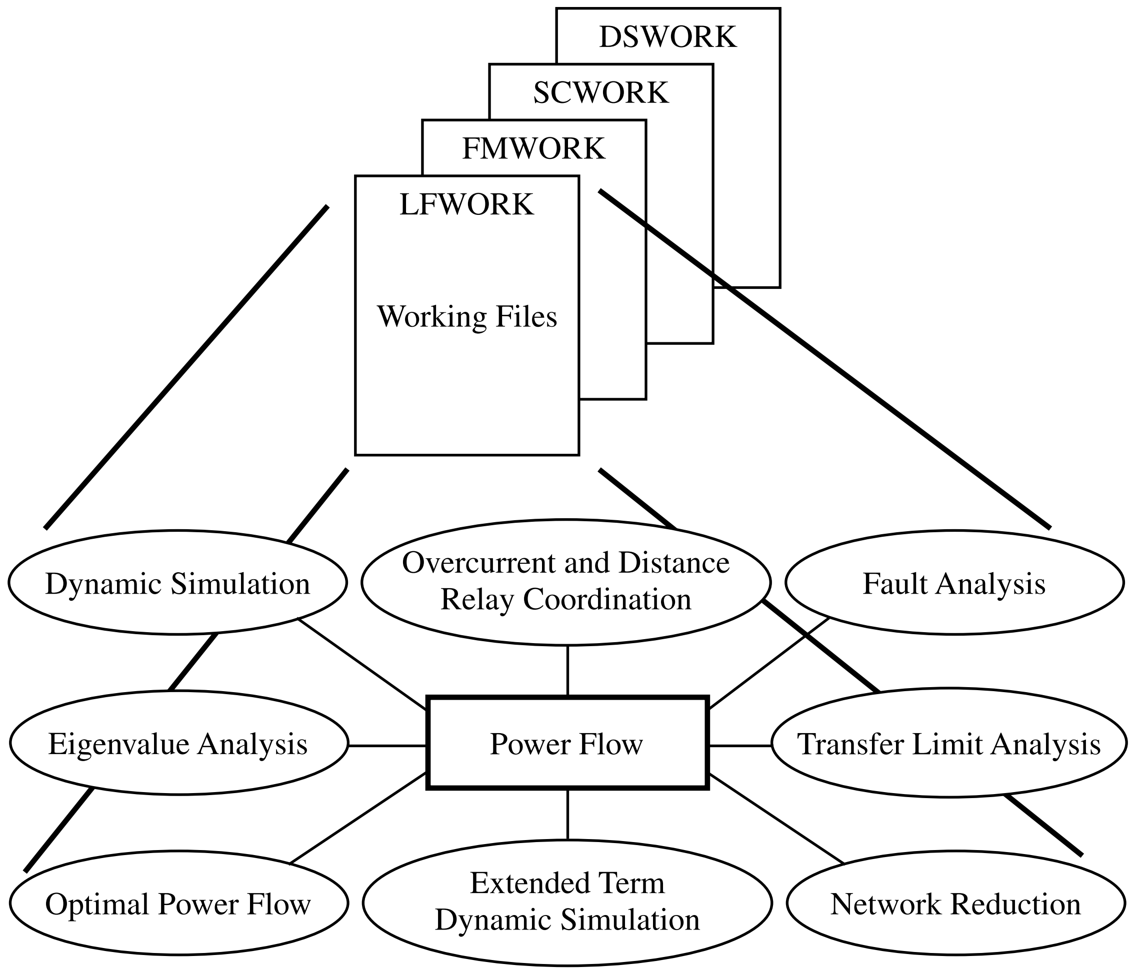

Figure 3.1 Structure: PSS/E integrates the modules into a single package centred on the power flow case. Furthermore, the modules operate on the same set of data through the working files.

The four working files have the following names and general functions:

LFWORK Contains a complete set of power flow data (Load Flow WORKing file).

FMWORK Working file for all operations involving the factorized system admittance matrix (Factorized Matrix WORKing file).

SCWORK Working file for fault analysis (Short Circuit WORKing file).

DSWORK Scratch file for dynamic simulation activities (Dynamic Simulation WORKing file).

3.3 Load flow

To calculate a steady state solution in PSS/E, one can use either the Gauss-Seidel or the Newton-Raphson algorithm. PSS/E allows the user to choose from five different ac power flow iteration schemes. These are:

- Gauss-Seidel iteration
- Modified Gauss-Seidel iteration suitable for series capacitors
- Fully coupled Newton-Raphson iteration
- Decoupled Newton-Raphson iteration
- Fixed slope Decoupled Newton-Raphson iteration

There are many problems which are difficult or impossible to solve with a single iterative method but which can readily be solved by successive application of more than one method. Therefore, it may be noted that: a) The Gauss-Seidel methods are quite tolerant of poor starting voltage estimates but converge slowly as the voltage estimate gets close to the true solution. b) The Newton-Raphson methods are prone to failure if given a poor starting voltage estimate, but are usually superior to the Gauss-Seidel methods once the voltage solution has been brought close to the true solution.

3.4 Dynamic simulation

To simulate voltage collapse, it is important to choose a numerical integration method which combines reasonable computational time with good precision. There are several methods of which PSS/E uses the modified Euler method (explicit integration) and the trapezoidal method (implicit integration) [4]. In the case where explicit integration is used, the source voltages (or their equivalent Norton current sources) are fixed both in magnitude and angle at each time step. The use of trapezoidal integration or implicit integration, on the other hand, requires inclusion of the flux, rotor speed, and rotor angle calculations within the load flow iterations. With explicit integration numerical instability would arise if the time step exceeds the smallest time constant (figure 3.3), usually the subtransient rotor time constant. Implicit methods are more stable numerically for a large time step Δt. The effect of an increasing time step is to lose fidelity of high frequency transients, and the system would essentially yield its steady state response as the time step is increased to infinity (figure 3.4). Therefore, depending on whether transient or long-term dynamics is to be studied, the dynamic simulations in PSS/E could roughly be divided in two parts, namely the transient dynamic simulation, using an explicit integration algorithm (chapter 3.4.2), and the long-term dynamic simulation, using an implicit integration algorithm (chapter 3.4.3).

In dynamic simulation the network solution at each time step (figure 3.2) is of the form **I=Y•E** where **I** is a vector of complex source currents and **E** is a vector of complex bus voltages, [1]. In the case of a network of pure impedance elements, including loads, the solution is a straightforward algebraic operation without iterations. More realistically, load characteristics are nonlinear and the network load flow solution involves iterations with nonlinear load effects introduced as current injections.

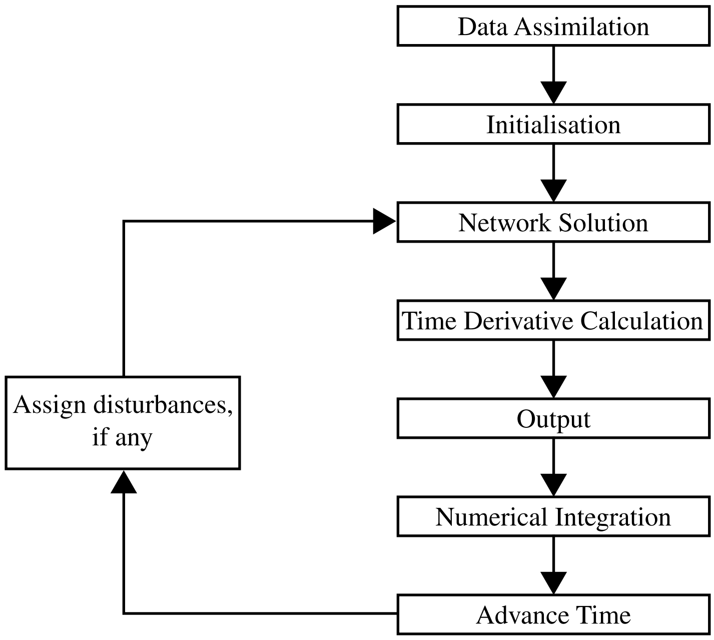

Figure 3.2 Basic logic flow for dynamic simulation. The network solution is of the form **I** = **Y·E**, while either the Euler or the trapezoidal algorithm is used in the numerical integration.

3.4.1 Basic dynamic simulation

The process of dynamic simulation is quite straightforward conceptually and is principally based upon repeated calculations of steady state solutions. At an instant time "t", it is known "where you are". From "where you are" and using the differential equations describing the behaviour of the system, it can be determined "where you are going". Then "go there", advance time to "t+Δt" (where Δt is the time step or integration step), and repeat the process until $t = T_{end}$.

Stated in slightly more formal terms, the behaviour of a system is described by a set of differential equations. At every time step of the simulation, the time derivative of each state variable in the system is calculated, using the constant and variable parameters which describe the system condition at that time instant as initial conditions. The state variable values at the next time step ($state_{new}$) are determined from the present value of each state variable ($state_{old}$) and its rate of change (i.e., its time derivative). Simulation time is advanced and the process is repeated. In the form of a formal equation the procedure mentioned above will be:

$$state_{new} = state_{old} + \frac{d(state_{old})}{dt} \cdot \Delta t \tag{3.1}$$

The user of the dynamic simulation section of PSS/E requires a working knowledge of the dynamics modelling structure. The principal steps of dynamic simulation as applied to electric power systems are shown in figure 3.2. The dynamic simulation procedure outlined above is complicated by the presence of the electrical network, which is described by a large set of simultaneous algebraic equations. The activities, which initialize a dynamic simulation and calculate the instantaneous state of the system at each time step, contain the basic elements of a general purpose dynamic simulation calculation (e.g. numerical integration, time stepping, output). The following calculation phases are required to extend this dynamic simulation control structure to that required for the simulation of electric power systems [2] and [3]:

1) The solution of the electric network given the machine internal flux linkages and the load boundary conditions.

2) The calculation of the time derivative of each state variable used in modelling equipment, given the present values of all state variables and of all generator armature currents. This phase includes calculating the values of algebraic variables needed in the course of obtaining numerical values of the state variable derivatives.

3) The modelling of equipment in which there is an algebraic relationship between the voltage at a bus and the current drawn by the device. These include such devices as induction motors and thermostatic loads.

3.4.2 Transient dynamic simulation

During its period of evolution as a simulation tool for power system dynamics, PSS/E was designed principally to model transients over a period of a few to several seconds following disturbances. Among power system engineers these phenomena have been broadly labelled transient stability simulation. The bandwidth of the effects being modelled in this time frame is limited to about 10 Hz at the high end with typical integration time steps of 10 milliseconds (1/2 cycle for 50 Hz system) [2].

The explicit numerical integration algorithm used to solve the differential equations for these phenomena is the modified Euler algorithm. This is the ordinary algorithm used in PSS/E. The advantage of the simplicity of the explicit algorithm is partly offset by numerical stability considerations which require integration time steps smaller than the smallest time constant describing the process. Figure 3.3 shows how the time step affects numerical stability.

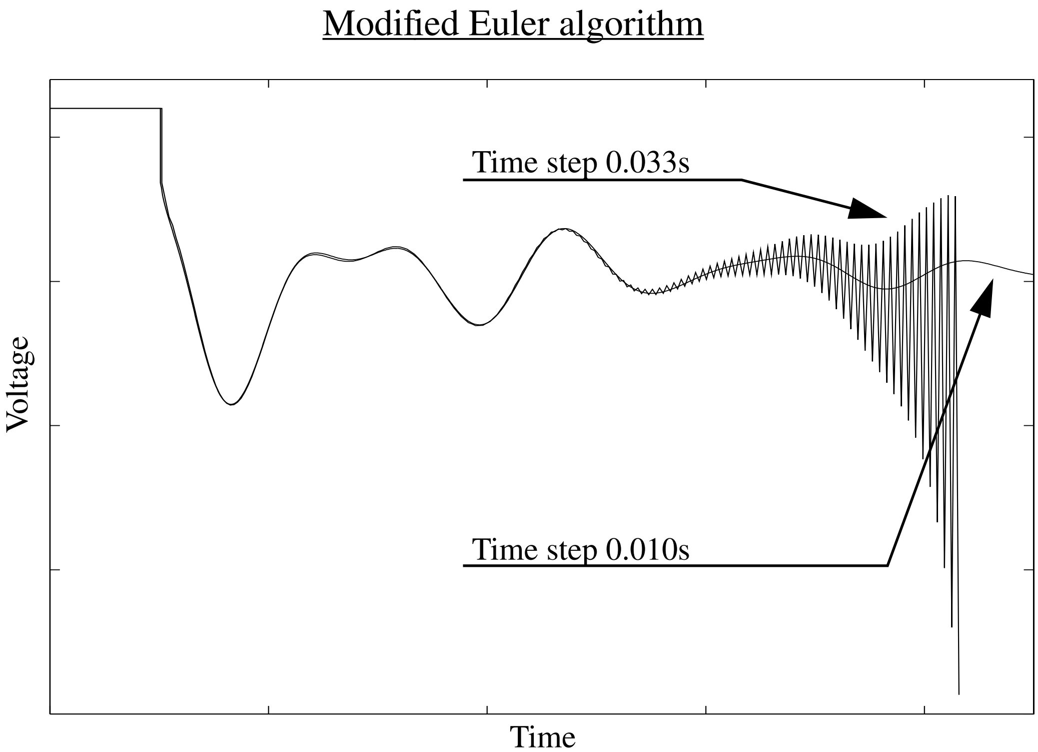

Figure 3.3 The explicit solution method becomes numerically unstable when the time step exceeds the smallest time constant in the system.

3.4.3 Long-term dynamic simulation

In many cases where the system survives the initial disturbance, the higher frequency effects (i.e., rotor angle swings) subside after a few seconds and then the transition to a new post contingency state occurs over minutes. While this process can be solved by extending the stability run through minutes with 1/2 cycle time step using the explicit integration method, the computation time can be very excessive.

The extended term option of PSS/E (figure 3.1), was created to analyse system behaviour over the period of many seconds to minutes following disturbances where the load restoration, excitation limiters, tap changing transformers, switching of capacitors and reactors etc., come into account. This is the situation when studying long-term voltage stability. A more efficient algorithm in these cases is the implicit trapezoidal integration method [4]. As mentioned before, this algorithm is numerically stable. But with larger time steps, high frequency modes and transients are filtered out and only the solutions for the slower modes are accurate. Figure 3.4 shows the effect when the time steps are increased.

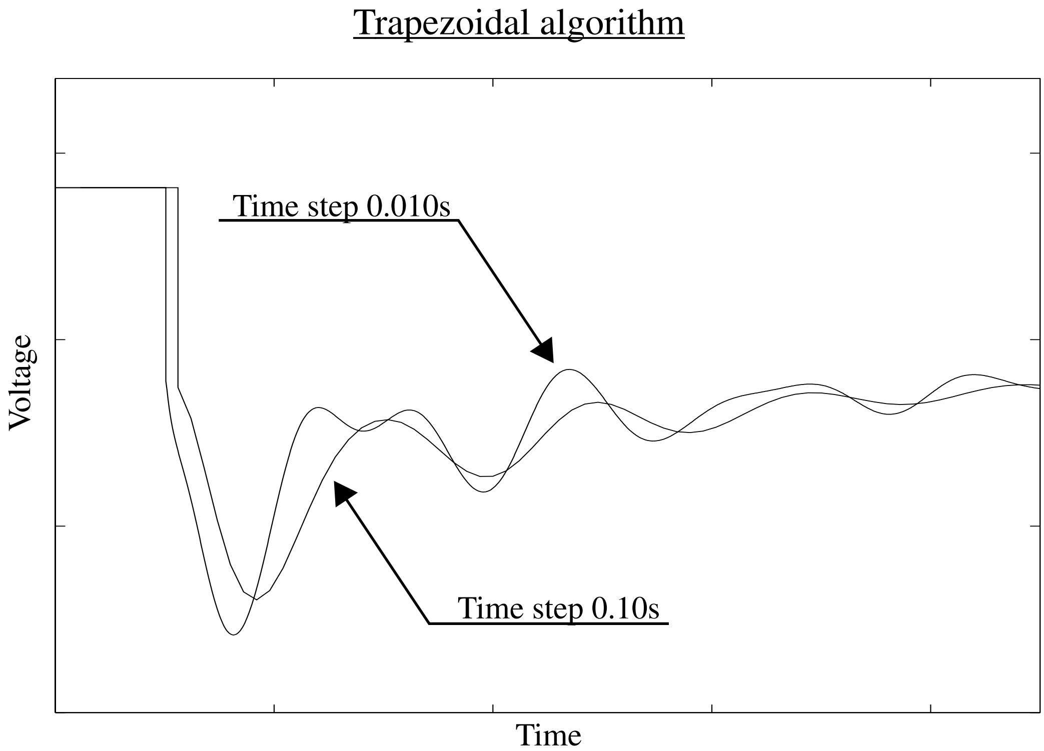

Figure 3.4 As the time steps increase the solution loses fidelity for high frequency transients and the system will essentially yield its steady state response.

3.5 User-written models

The objective of dynamic simulation is to accurately predict the response of a physical system to some event. This, in turn, requires that each component affecting the response has to be strictly modelled over the time frame of interest. In PSS/E terms, this means that, for all the equipment represented, models must be supplied which implement the differential equations describing the dynamic behaviour of each component. The PSS/E Model Library contains a variety of equipment models which satisfy this requirement for the most types of power system equipment. However, situations may arise in which there is no library model which corresponds to the differential equations needed to model a given piece of equipment. To handle this situation, the PSS/E user can write his own model which accurately models the equipment. One should keep in mind when creating models if they are to be used only with the Euler algorithm or also with the trapezoidal algorithm. The mathematical expressions will be quite different whether only the Laplace or also the Z-form representation is to be used. In reference [10] there is a list of suggested models, suited for long-term dynamic simulation, where user-defined modelling is desirable for most of them.

This project, where one of the main tasks has been to develop models aimed for voltage collapse simulations, has led to the development of three user-written models, all representing equipment commonly used in the Swedish network. A detailed description of the three models is given in chapter 4.

3.6 Other softwares

Beside the PSS/E program there are other programs frequently applied in voltage stability simulation studies. A brief description of these programs is given below. Reference [5] gives a more complete description of different simulation tools and in addition some simulation comparisons between different programs.

3.6.1 EUROSTAG

The EUROSTAG program, jointly developed by Tractabel and EdF covers the domains of transient, mid-term, and long-term stability by means of an automatically and continuously variable step size integration algorithm. It allows a complete simulation of voltage stability phenomena and includes models for transformer on-load tap changing, dynamic loads, field current limiters, etc. The implicit method used for the numerical solution is based on the backward differentiations' algorithm treated according to the GEAR implementation, see [6], [7] and [8].

3.6.2 EXSTAB

The EXSTAB program, developed by Tokyo Electric Power Company and General Electric, allows for dynamic simulation over an extended range of the time domain. Explicit as well as implicit integration technique is used. The program includes detailed models of AGC with frequency and interchange control, power plants, dynamic and thermostatically controlled loads, OLTC's, and many protective functions. Simulation modes allow for automatic continuously variable time step integration, as well as a fast algebraic quasi-steady state mode for slowly varying system conditions [11].

3.6.3 SIMPOW

SIMPOW (simulation of power systems), developed by ABB Power Systems AB, covers dynamic simulations in a wide range of time. The program is used for all types of static and dynamic simulations of electrical power systems: long term, short term and fast transients caused by switching and lightning, etc. SIMPOW has models of most power system elements but the user-oriented Dynamic Simulation Language (DSL), allows implementation of power system elements which are not available in the standard library of models.

3.6.4 ETMSP

ETMSP (Extended Transient/Midterm Stability Program), developed by Ontario Hydro, has been enhanced to meet the modelling requirements for dynamic analysis of voltage stability. These include representation of transformer LTC action, generator field current limits, dynamic loads, constant energy loads, special relaying, and undervoltage load shedding.

3.6.5 LTSP

LTSP (Long Term Stability Program) is capable of simulating fast as well as slow dynamics of power systems and is based on the ETMSP program. In addition to all the features of ETMSP, LTSP includes detailed models for fossil-fuelled, nuclear, and combustion turbine plants. The basis for and the details of modelling and solution techniques used in these programs can be found in [4].

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Chapter 4 Voltage stability studies with PSS/E

Paper published at "Bulk Power System Voltage Phenomena III, Voltage Stability, Security & Control", Aug. 1994, pp 651-661.

Abstract

A study of simulations of voltage stability phenomena using the PSS/E program (Power System Simulator) is presented. The objective is to explain how the interaction of different components, such as on-load tap changers, field and armature current limiters and dynamic loads, can endanger the voltage stability of a system. Special attention is given to the user-written models that have been implemented in PSS/E.

A computer model has been designed for a voltage regulator combined with field and armature current limiters. This combination is used for nuclear power plant generators in Sweden. Two different models for an on-load tap changer control unit commonly used have also been implemented in the program. The dynamic load model with load recovery is based on field measurements. Furthermore, some problems in using simulation tools are discussed, as well as the importance of parameter determination for some of the models implemented. The simulations highlight the importance of the generator current limiter and its interaction with the on-load tap changer and the type of load model chosen.

Keywords

Voltage stability, simulation, dynamic load model, on-load tap changer, armature current limiter.

4.1 Introduction

The problem of voltage stability and voltage collapse has been under consideration for 10 to 20 years. The approach to the phenomenon ranges from power system recording analyses, simulations of voltage collapses and incidents experienced by the power companies, to thorough theoretical mathematical studies. Researchers in the field have not yet been able to agree upon definitions of voltage collapse and voltage stability. Concordia defines voltage stability in a straightforward way, using words well known to utility companies: "...in terms of the ability to maintain voltage so that when load is increased, load power will increase, and so that both the power and voltage are controllable" [4]. Kwatny, on the other hand, uses static bifurcation theory for voltage collapse definition [12]. The authorities in this field also continue to discuss whether the voltage collapse and stability phenomenon is a static or a dynamic problem [15]. Researchers in close co-operation with power companies often view voltage collapse as a static problem, since it can be analysed with ordinary load flow programs. In the academic world, where the bifurcation theory is predominant, voltage collapse is regarded as a dynamic problem.

In addition to study of the phenomenon of voltage stability and collapse itself, stability margins and indices have been defined and methods to derive such quantities have been developed [13]. Some authors in the field use simulation in order to include the dynamics of load, tap changer and generator reactive power capacity limits in the voltage collapse studies [5, 16]. A good survey of the voltage stability discipline can be found in reference [9], where both analytical tools and industrial experience are presented.

A voltage collapse can be initiated by either a primary fault or an unexpected load demand increase, in combination with insufficient reactive power reserves or transmission capacity. In order to avoid collapse, a detailed knowledge of the reactive power capacity in stressful situations, for large generators close to load centres, is essential.

The aim of this report is to provide models for load devices, on-load tap changer control systems and generator reactive power output capacity limits, based on data and experiments, and to compare our models with previous ones in simulation technique for voltage stability studies. The methods and models used in the report are designed to be easily accepted, both within the power industry and in the academic world. The simulation technique is well accepted in the power industry, and many of the dramatic simplifications sometimes necessary for analytical studies are avoided. Furthermore, well established and tested programs can be used to hold and solve the load flow case.

We believe that more attention should be directed to the importance of load dynamics, on-load tap changer control dynamics and generator limits in research on voltage collapse. In the variety of papers already published, detailed transfer limits, stability indices, etc., have been derived, while omitting, or only roughly modelling such important aspects as load recovery, tap-changer control systems and generator field and armature current limiters. While there is value in developing advanced mathematical tools based on simple system component models, we have to keep in mind that the voltage levels in the post-fault load flow case and the static nose curves (P/V and Q/V curves) are still used as criteria for power transfer limit settings within many power companies. To be accepted by power companies and used as practical tools for system design and operation, research results must be related to the data and methods used within the power industry today. The results reported here are intended to be suitable for use as refined methods for voltage collapse studies within power companies.

4.2 Computer model implementation

In order to simulate the dynamic events that cause voltage instability, it is important to know how to specify relevant models of the equipment that affects the long-term voltage stability. A survey of components affecting the long-term voltage stability is given in [3]. It is also important to balance sufficient accuracy in the models against unreasonably long simulating time for large power systems. The test systems that have been used in this paper include dynamic load models, generator voltage controllers with field and armature current limiters, and on-load tap changing transformers. These models are all based on field and laboratory measurements.

4.2.1 Dynamic load model

The dynamic model proposed by Karlsson [10] is a special case of a dynamic load model given by Hill [8]. The model implemented is described by the following equations:

$$T_{pr}\frac{dP_r}{dt} + P_r = P_0\left(\frac{V}{V_0}\right)^{\alpha_s} - P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \qquad (4.1)$$

$$P_m = P_r + P_0\left(\frac{V}{V_0}\right)^{\alpha_t} \qquad (4.2)$$

where

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

$$T_{qr}\frac{dQ_r}{dt} + Q_r = Q_0\left(\frac{V}{V_0}\right)^{\beta_s} - Q_0\left(\frac{V}{V_0}\right)^{\beta_t} \qquad (4.3)$$

$$Q_m = Q_r + Q_0\left(\frac{V}{V_0}\right)^{\beta_t} \qquad (4.4)$$

where

- Q_0 = reactive power consumption at pre-fault voltage [Mvar],
- Q_m = reactive power consumption model [Mvar],
- Q_r = reactive power recovery [Mvar],
- β_s = steady state reactive load-voltage dependence,
- β_t = transient reactive load-voltage dependence, and
- T_{qr} = reactive load recovery time constant [s].

When there is a voltage drop of 5-10% on load nodes, field measurements show that α_t is around 2. This means that the transient behaviour of the load can be regarded as a constant impedance. In most of the measurements, α_s is well below 1, which indicates a changed voltage dependence for the active power, and the load characteristic tends to be more like constant power (figure 4.1). The time constant T_{pr} for this changing phase is around some hundred seconds. This phenomenon has been explained by the power characteristic in electrical domestic heating [11].

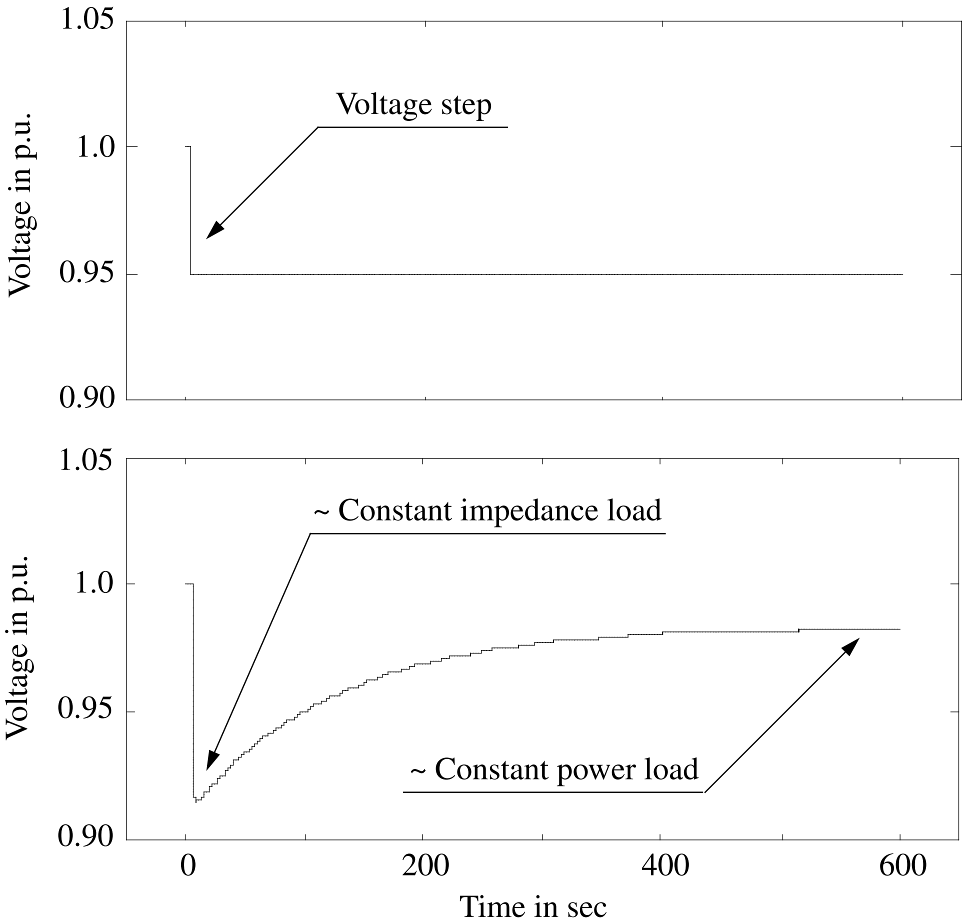

Figure 4.1 The active power recovery caused by a voltage step.

An important experience when implementing the load model was finding that the voltage dependence had to be included during the iterations. Since the time step in the integration procedure is several thousand times smaller than the time constants in the dynamic model, the voltage dependence during load flow iterations was not taken into account in the beginning. This did not work well all the time; numerical instabilities occurred and it was necessary to expand the implementation to include voltage dependence during the load flow calculations, see figure 4.2. A delay of one time step between the iterated voltage and the corresponding load demand was eliminated by the implementation.

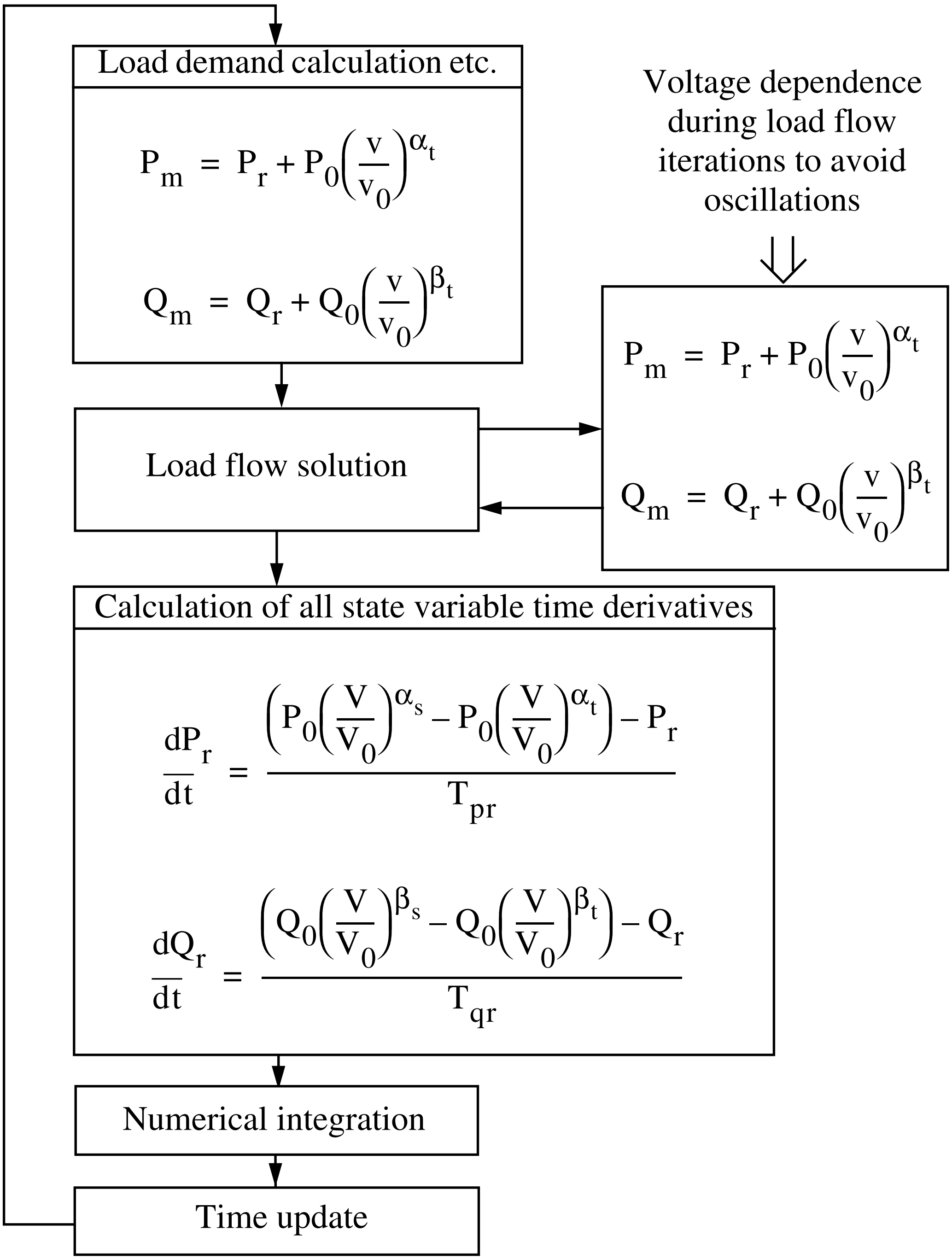

Figure 4.2 The solution algorithm for the dynamic load.

4.2.2 Voltage regulator, including field and armature current limiters

A model program for the FREA[1] excitation system has been written, based on a graduation thesis [6] in which the dynamics of the system were measured and identified. The FREA system consists of different units, among which the voltage regulator represents the basic one. The

1. Manufactured by ABB

model of the FREA system used in the simulations contains two units, a basic one for voltage control, illustrated in figure 4.3, and an another for field and armature current limitation, illustrated in figure 4.4.

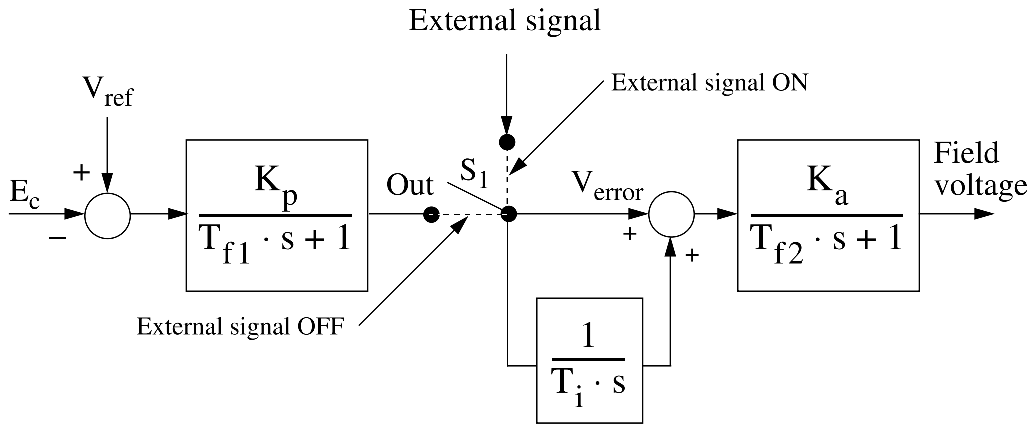

Figure 4.3 Block diagram of the voltage regulator.

The external signal is the connection between the two units.

Typical parameters for the model are:

K_p = 10-100, T_{f1} = 25 ms, T_i = 2-5 s, K_a = 1-40 and T_{f2} = 1-40 ms.

Since the limitation of the field or the armature currents affect the reactive power generation, it is important to simulate these.

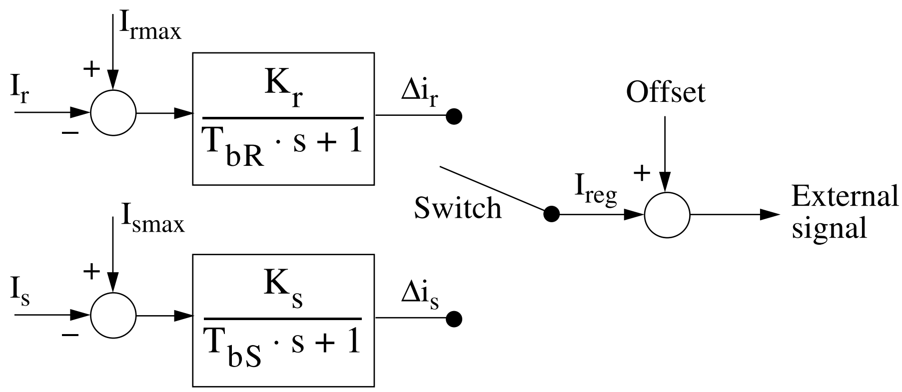

Figure 4.4 Block diagram of the field and armature current limiters.

Typical parameters for the model are:

K_r = 2–10, T_{bR} = 25 ms, T_{bS} = 25 ms and K_s = 2–10.

Using the two units above provides a model with the following functions. The regulated field voltage is normally controlled by the difference signal V_{ref}-E_c. When one of the currents exceeds its permitted maximum, a timer that controls the switch S_1 starts and the current limiter takes control over the field voltage after a delay of t_1 seconds. The timer delay is a protection against undesired limiter functions i.e. short-circuits. When the timer value is greater than the delay time t_1, the limiter controls the field voltage instantaneously when an overcurrent occurs. This condition is maintained for at least t_2 seconds or until the timer is reset.

The two conditions that activate the current limiters are:

1. $I_s > I_{smax}$ or $I_r > I_{rmax} \Rightarrow$ timer starts, and
2. Timer value > t_1

The two conditions to reset the timer are:

1. $I_s < k*I_{smax}$ and $I_r < k*I_{rmax}$, and
2. Timer value > t_2

Figure 4.5 illustrates the course of events when I_r is outside its limit. The sequence when I_s is outside its limits is analogous. When I_r and I_s are both outside their limits, the external signal will be assigned the largest value of $|\Delta i_r|$ and $|\Delta i_s|$.

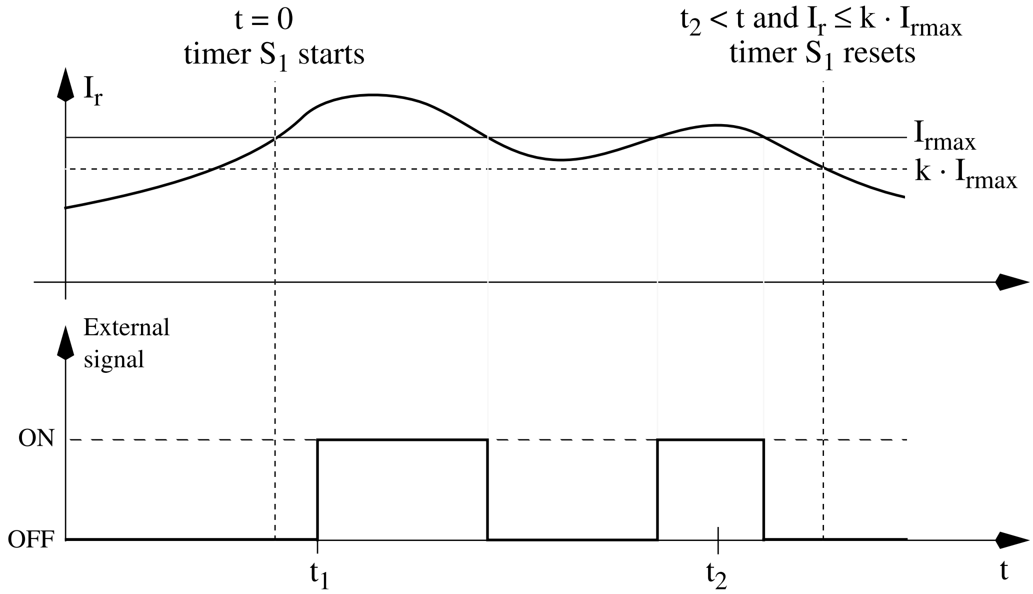

Figure 4.5 Conditions that control the blocking of the external signal when $I_r > I_{rmax}$.

Since the generator is permitted to operate only in an over-excited mode when the current limiters are active, it was necessary to implement a blocking signal. This signal also blocks the limiter when the terminal voltage falls below a permitted value. If this were not done, the simulations showed that the regulated field current changed sign and the generator became more and more underexcited. This blocking of the current limiter is important in order to prevent underexcitation and to avoid incorrect regulation. It was noticed that the blocking was the source of large moment steps in mechanical power. Consequently, it is unlikely that this running condition can be allowed for more than a short time.

4.2.3 On-load tap changer models

Two different types of OLTC-relays (On-Load Tap Changer) commonly used in the Swedish utility network have been modelled [1]. The purpose of these relays is to keep the secondary voltage within a specific dead band around a set-point value. The time from the point at which the voltage deviation exceeds the dead band until the relay triggers the tap changer mechanics on the transformer is called the functional time of the relay. This time interval depends mainly on two things: a) the basic setting time of the relay, chosen by the operator, and b) whether the relay is working in constant time mode or inverse time mode.

When the voltage deviation is large and one step change on the transformer is not sufficient to restore the voltage, then two other things must be taken into account. One is the time it takes to reenergize the tap changer mechanics after a changing. The other is whether the mechanics use a pulse or a constant control signal from the relay to trigger the tap changer. The effects of these conditions will be discussed later on. As the operation time needed for an energized tap changer to change step is within a few periods of the network frequency, it is considered negligible in these models. When the relays are exposed to a large voltage step (~several dead bands/second), the functional time becomes reduced for reasons unknown. More identification of the relays is necessary to model this phenomenon. The two relays modelled are the RXCE41[1] and RV902[2].

1. Manufactured by ABB
2. Manufactured by Siemens

4.2.4 Description of the RXCE41

The RXCE41 relay has several settings that control its behaviour. On the front panel of the relay, the operator has to tune in one of the basic setting times: 15, 30, 60, 90 or 120 seconds. All actual time delays are scaled to one of these basic settings. Also the voltage set-point value and the deadband on the relay must be tuned. Finally, one of the four working modes of the relay has to be chosen.

I) Constant time mode and pulsed control signal

The functional time is independent of the amount of the voltage deviation. A short pulse of approximately 1 second triggers the tap changer, after which the relay is restarted. This means that this mode is the slowest way to restore voltage.

II) Constant time mode and constant control signal

The functional time is independent of the amount of the voltage deviation. If several tap changing steps are necessary to restore the voltage, the reenergizing time delay of the tap changer mechanics controls the speed with which the voltage is restored.

III) Inverse time mode and pulsed control signal

The functional time is dependent on the amount of the voltage deviation. When large deviations are present and several tap changing steps are necessary in order to restore the voltage, the time delay of the first steps is controlled by the delay in the transformer. When the voltage approaches the desired voltage, the time between tap changings is controlled by the relay. The functional time of the relay, in this mode, may be shorter than the reenergizing time of the tap changer mechanics. If this is so, trigger pulses will be lost due to the fact that the mechanics have no memory. Although the voltage will be restored (if possible without running the tap changer into an end stop), but it will take a longer time.

IV) Inverse time mode and constant control signal

The functional time is dependent on the amount of the voltage deviation. A larger deviation means a shorter functional time of the relay. If several tap changing steps are necessary, the steps following the first are controlled by the mechanical delay. This is the fastest way to restore the voltage deviation.

The different characteristics of these modes are shown in figure 4.6. It can be seen from the figure that the relay settings affect the time constants of the voltage restoration. This is important when a dynamic load is connected to the transformer.

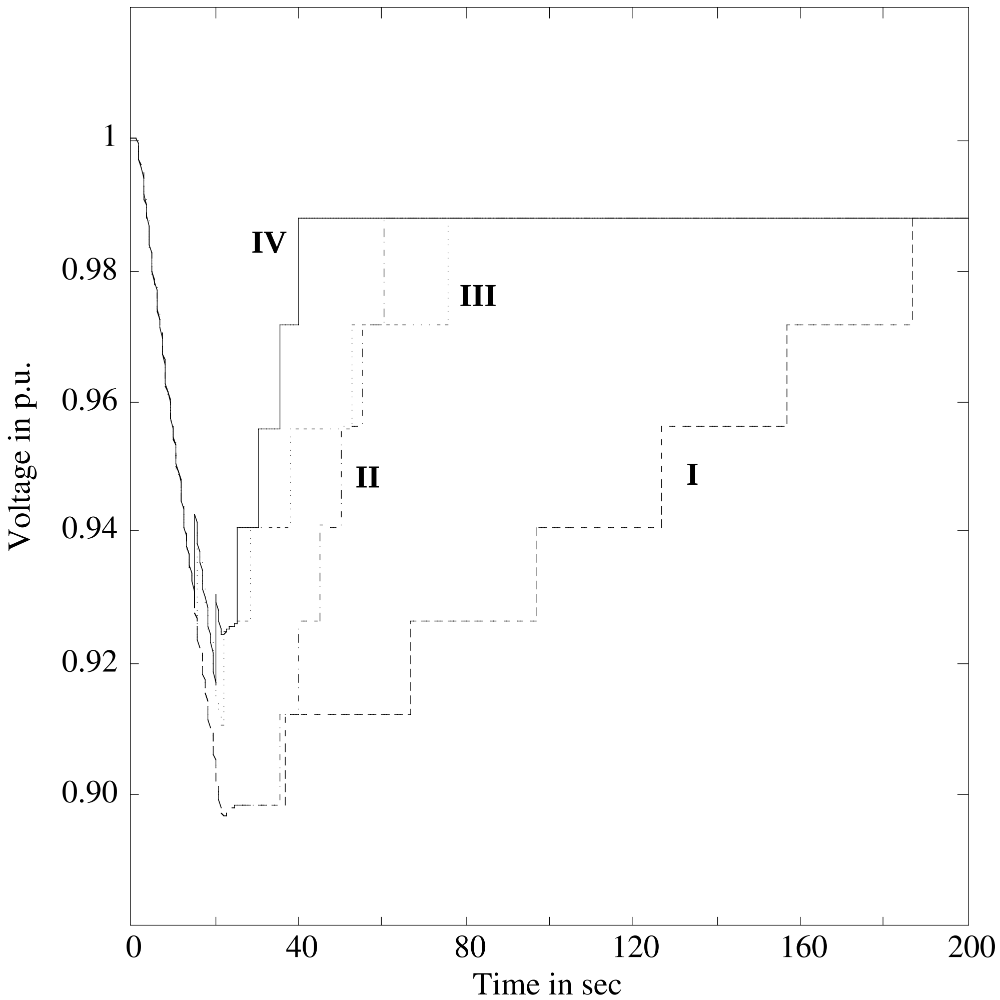

Figure 4.6 Different modes for the RXCE41 relay.
I) Constant time mode and pulsed control signal,
II) Constant time mode and constant control signal,
III) Inverse time mode and pulsed control signal,
IV) Inverse time mode and constant control signal.

The relay timer is started when the voltage exceeds the dead band, and reset when the voltage deviation is less than the return ratio multiplied by the dead band. A hysteresis effect on the function of the relay is thus achieved.

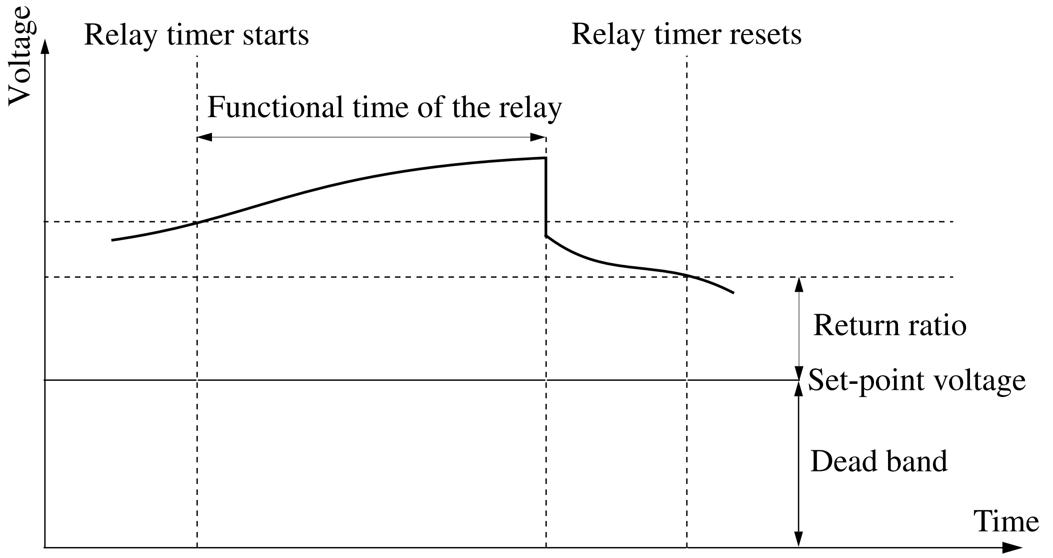

Figure 4.7 One tap changing manoeuvre and the corresponding timer actions. The return ratio is around 0.75 times the deadband.

In inverse time mode, the deviation is not integrated in the usual sense. It is the voltage deviation that actually gives a functional time. If the relay time is greater than this functional time, the tap changer receives an order to change. The voltage deviation divided by the dead band is defined as δ and calculated for every time step. If δ is greater than 1, the voltage is outside the dead band and the relay timer is running. When δ is below the return ratio the timer is reset. The five different basic setting times offer different functional times, T_{ds}. If the operator has chosen the basic functional time ΔT to 15 seconds, the model calculates the functional time from

$$T_{ds} = (\Delta T - 2) \cdot e^{\frac{-(\delta - 1)}{1.25}} + 2 \qquad (4.5)$$

If the voltage is just outside the deadband ($\delta = 1$), it will take 15 seconds for the relay to operate. Note that the formula is also valid for $1 > \delta >$'return ratio', when the timer is running. Therefore, it is possible to have quite long delays even in the inverted time mode. Similar formulas are valid for the other basic functional times.

The calculated functional times have a maximum discrepancy of 1.5 seconds (3 seconds for T = 120 s) between the model and the relay.

4.2.5 Description of the RV902

The RV902 relay works as an inverse time relay. It does not use a constant control signal to the tap changer. It has no timer-function and the voltage deviation is integrated all the time.

The model integrates the voltage deviation in the following way. First, δ is calculated as the deviation from the set-point value divided by the dead band. This gives a value greater than 1 (or less than -1) when the voltage is above (or under) the dead band. Two other constants are calculated,

$$m = 1.4 \cdot (\text{deadband}) \text{ , and} \tag{4.6}$$

$$k = 1.014 \cdot (1 - e^{-(1.2 \cdot (\text{dead band})^{1.5})}) \tag{4.7}$$

and the model sums up the level with the following formulas:

$$\Delta\text{level} = (\delta - k \cdot \text{level}) \cdot m \cdot \frac{\text{time step}}{\text{delay time}} \tag{4.8}$$

$$\text{level} = \text{level} + \Delta\text{level} \tag{4.9}$$

When this level value is greater than the top level, the relay is functioning.The top level is usually chosen as 0.98. The function of the RV902 is similar to the RXCE41 when working in inversed time mode and pulsed control signal. Therefore the RV902 essentially works as in the III curve in figure 4.6.

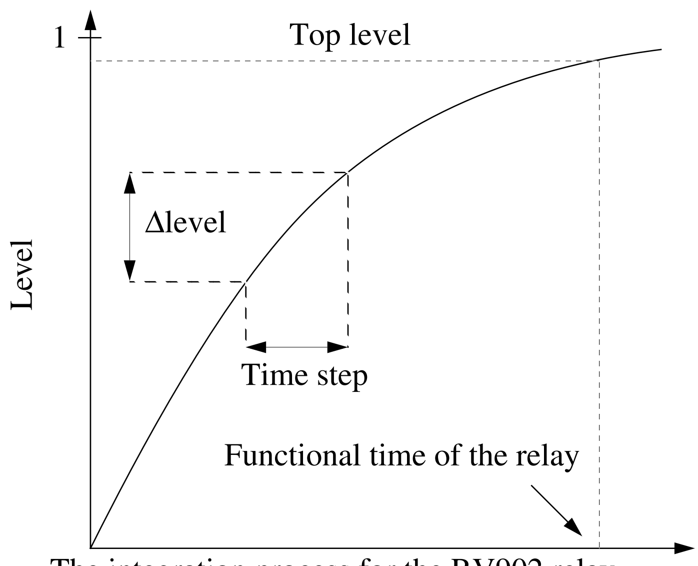

Figure 4.8 The integration process for the RV902 relay.

4.3 Simulations

The computer program used for all the dynamic simulations is the PSS/E program[1] which has the modelling capacity to account for the important dynamics of voltage stability analysis.

4.3.1 Description of the test systems

To demonstrate dynamic analysis techniques and to illustrate the basic phenomenon of voltage instability, two test systems were used. One was a very simple radial network, System 1, and the other a meshed 27-node network, System 2. System 1, shown in figure 4.9, consists of 4 buses, 4 branches and 1 generator. Most of the important factors influencing system voltage stability are readily identified in this simple system. One of the two lines in parallel has twice the reactance of the other, in order to show distinct results.

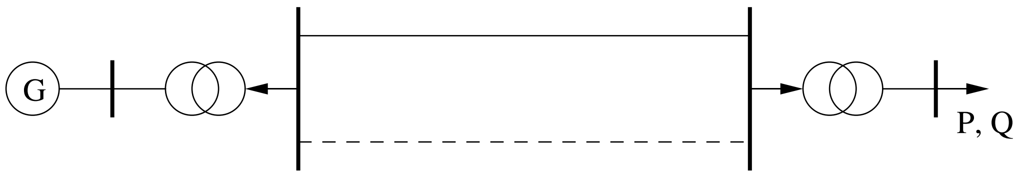

Figure 4.9 Test system 1

System 2, shown in figure 4.10, consists of 27 buses, 33 branches and 17 generators. The simulations conducted using this representation give a better picture of the dynamics of voltage stability in a large power system.

When the simulations are initiated, the parameters of the different components decide the behaviour of the system. The parameters used in the following simulations are taken from field measurements [10]. Some parameters for the small network are given in the appendix.

1. Manufactured by Power Technologies, Inc

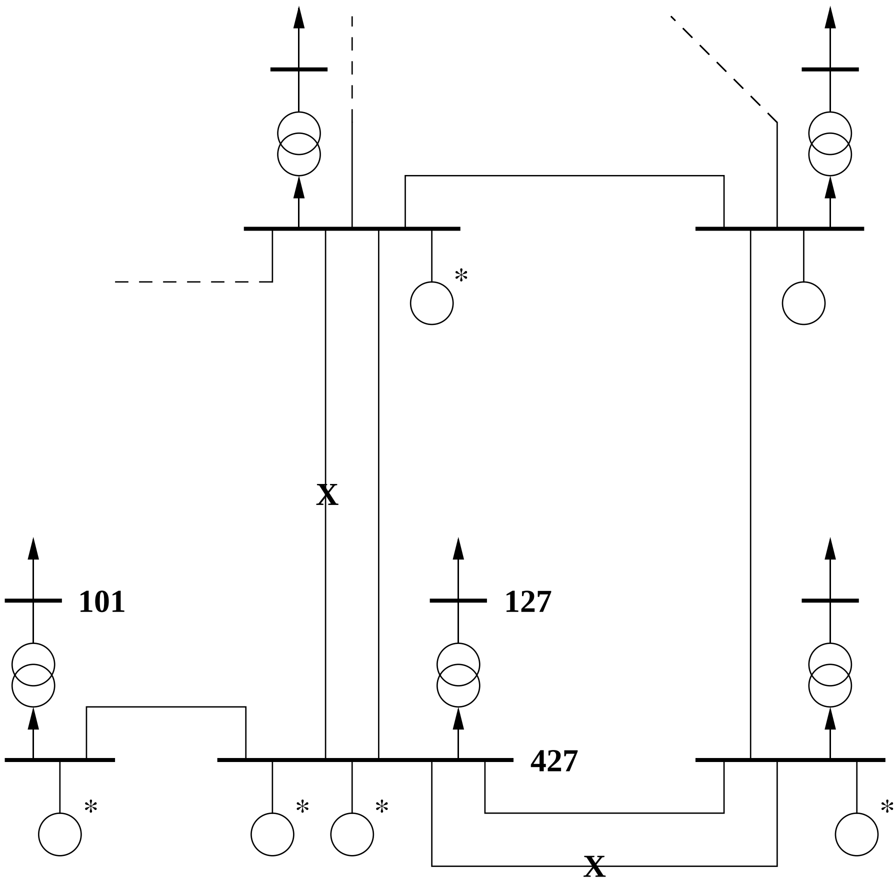

Figure 4.10 Part of test system 2, showing where the simulated fault was applied. The X-marked lines and one of the two identical generators at node 427 were disconnected. The asterisk (*) marks a generator with a current limiter.

4.3.2 Response of the dynamic load including the OLTCs and current limiters: System 1

A disturbance initiated by opening the line with the lowest reactance was studied for two cases, A and B. The simulations were conducted for up to 350 seconds, using the models described for dynamic load, OLTC transformers and generator current limiters.

Case A demonstrates the combined effects of one OLTC and a dynamic load. In figure 4.11 it can be seen that system voltage stability is maintained though there is a low voltage level on the primary side of the transformer at the load end. The voltage level at the secondary side is restored by the transformer in a few minutes. For every tap changing step, power demand increases, which gives a current increase on the load side of the transformer (figure 4.12). This increased current is amplified on the generator side by the transformer tap changings and gives an increased voltage drop over the line.

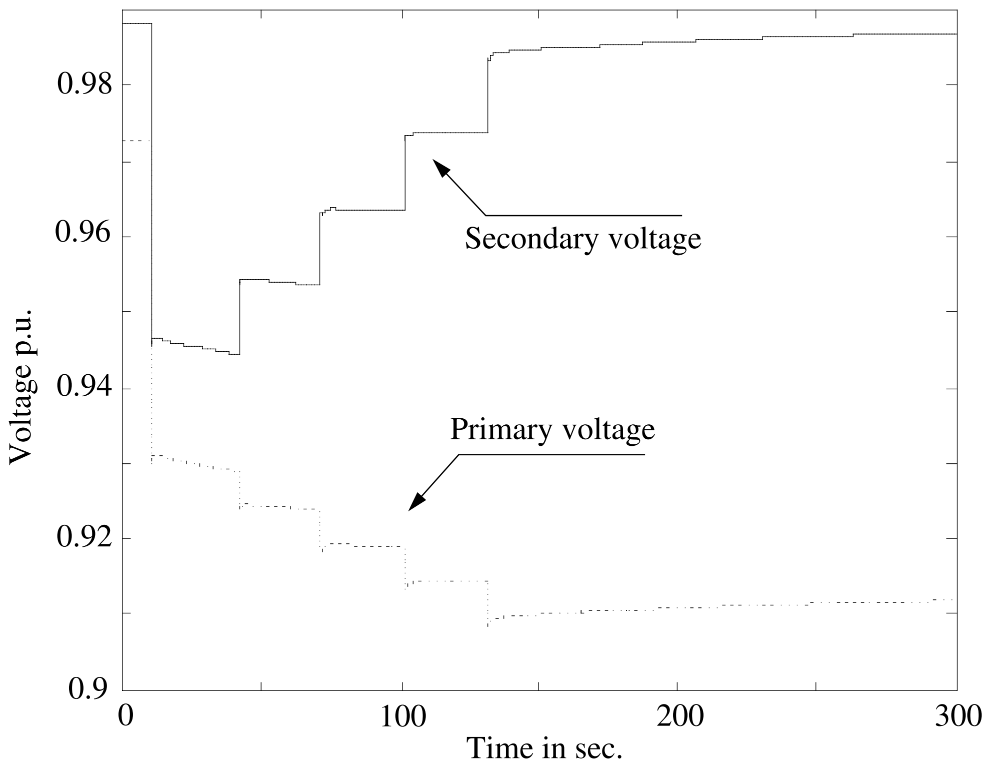

Figure 4.11 Case A: The voltage on both sides of the transformer at the load end.

When the time needed to restore the voltage level by the regulating transformer and the time constant of the load recovery are in the same time domain, an overshoot in power demand can appear. In figure 4.13 one can see the combination of these effects.

Case B is similar to case A except that the current is higher than the settings of the current limiter. The generator is limited in order to study the effects of the armature current limiter (figure 4.14). It can be seen that as soon as the armature current limiter is operating the load voltage starts to decline, due to the tap changing manoeuvres and the armature current limitation. Since the delayed operation of the current limiters is usually a few seconds, just a short period of overcurrent is sufficient to activate one of them, which puts the system into a very critical situation.

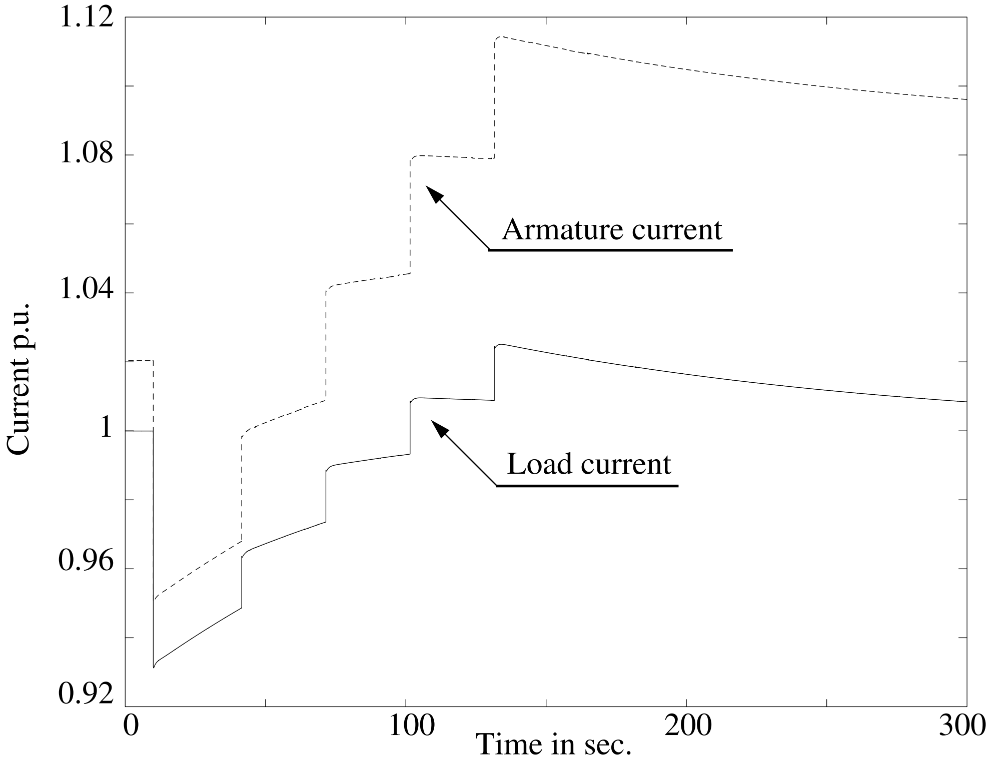

Figure 4.12 Case A: The armature and load current. Note the significantly larger armature current during the recovery.

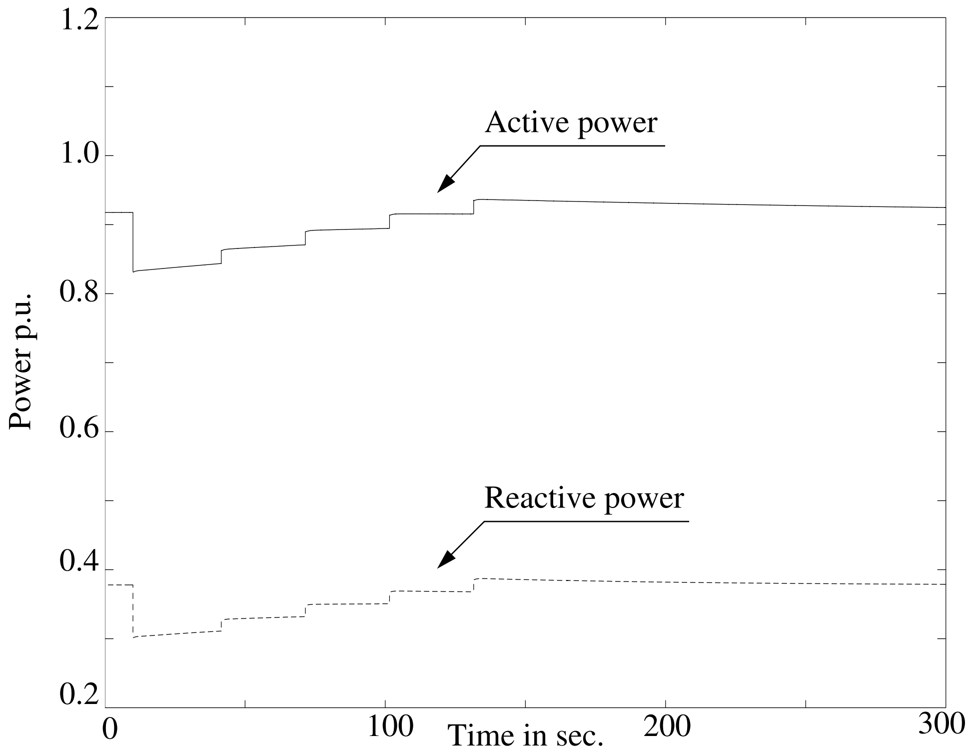

Figure 4.13 Case A: Active and reactive power demand for the dynamic load.

When there is a disturbance in a large meshed network, this overshoot may not occur. Variation in the parameters of both transformers and loads spread out the overshoot. However, the generator current is increased due to the tap changers and load recovery, and this can, in a system under stress, cause the limiter to activate. The outcome of the current limiter action depends on the generator size and the network around the generator. An example of a collapse where the current limiters had a major impact is the French collapse of 1987 [7]. The importance of the current limiters is also mentioned in [3].

For a network without load recovery, one could get the effects described above from several levels of voltage regulating transformers, working unselectively. This could be the source of large armature currents, when a voltage disturbance is not restored sufficiently fast by the transformers near the origin of the disturbance.

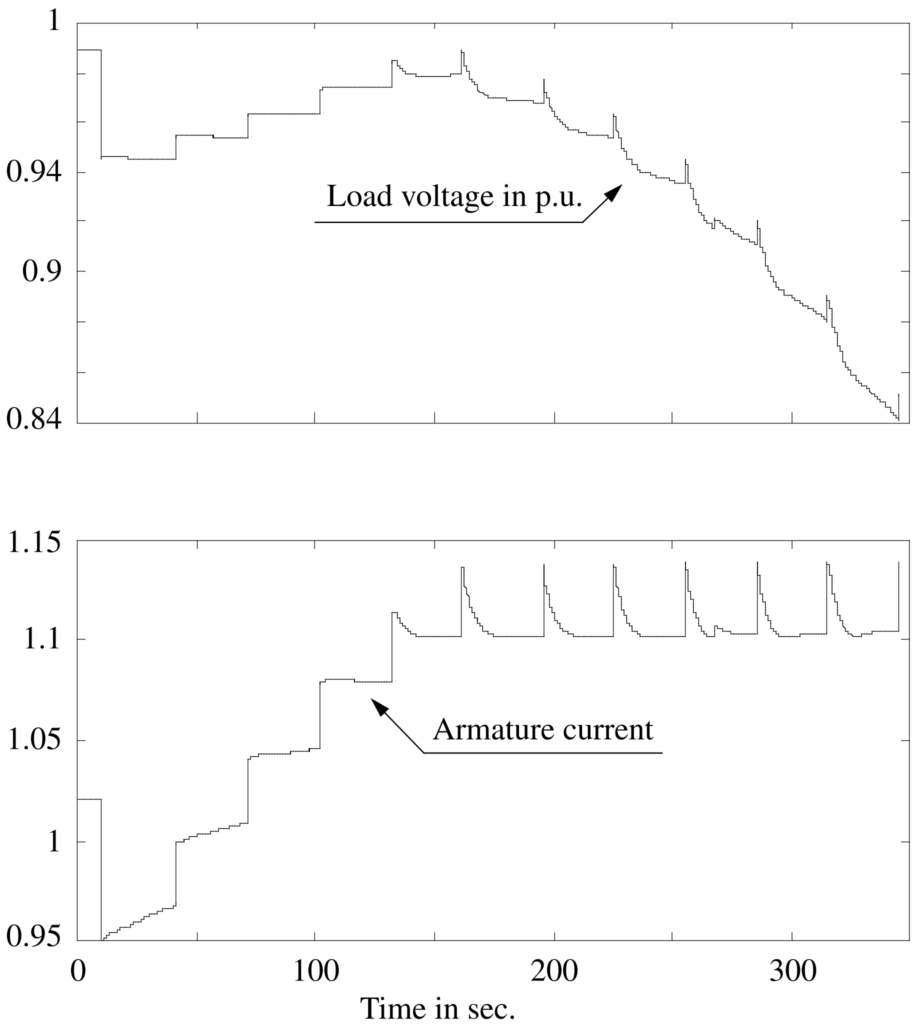

Figure 4.14 Case B: Voltage and armature current where the current is limited to 1.1 p.u. It can be seen that the tap changer tries to restore the voltage while the current limiter decreases the current within a few seconds to the limiting value.

4.3.3 The importance of the load model chosen: System 1

In the event of a disturbance, power systems, depending on their load representation, can respond with completely different characteristics.

The following simulations, on System 1, illustrate the statement above. The limiting factor in these simulations is the armature current limiter. The system is disturbed by a 5% voltage step down on the generator set-point (i.e. disconnecting reactive support at the generation end). figure 4.15 shows four simulations with different load models; in figure 4.16 there are the same simulations with the OLTC transformer relay at the load end activated. After the disturbance, the small system is not able to supply power to the constant power model at all (curve a in figure 4.15). There is no stable operating point for the voltage. As the voltage decreases, the current would increase if it were not prevented form doing so by the current limiter.

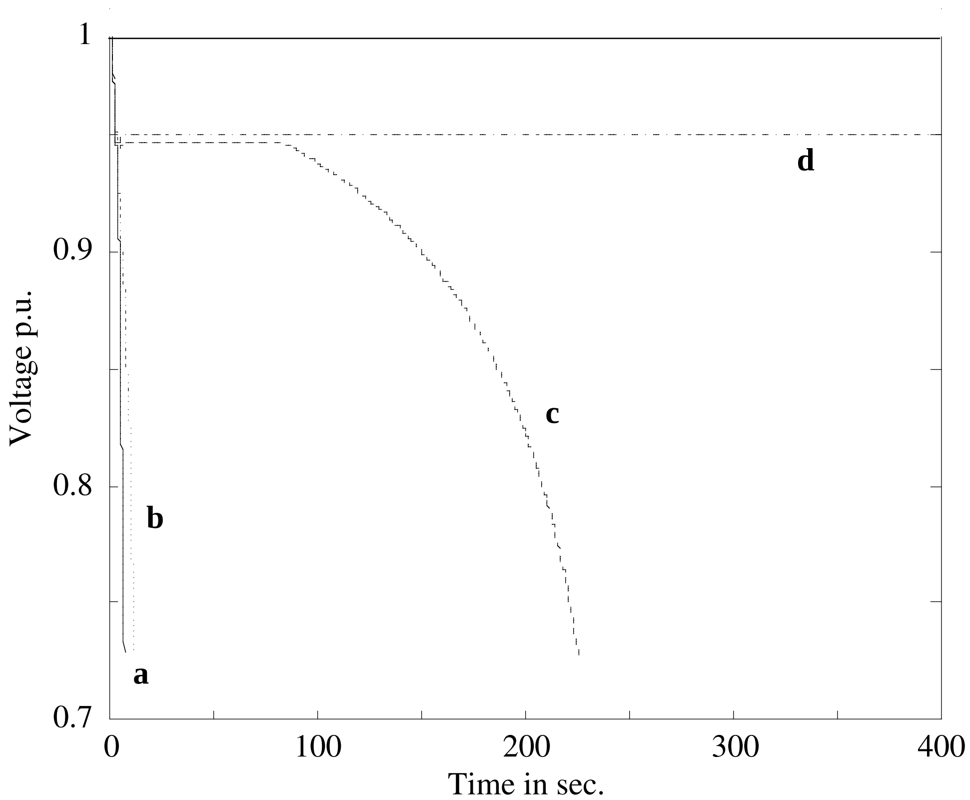

Figure 4.15 Four different load models and their interaction with a current limited generator. The reactive power demand is independent of the voltage in simulations a, b and d.
a) Constant power model for P.
b) $P=P_0 \cdot (V/V_0)^{0.8}$
c) A dynamic load model according to Section 4.2.1
d) Constant impedance model for active power

If the active power demand is nearly proportional to the constant current, the system responds nearly the same way (b in figure 4.15). Curve d shows that when the load is more voltage dependent, the system is stable. With this model, current demand decreases when the voltage decreases and the current limiter is not activated. Thus, a stable working point can be found.

The dynamic load model, described in Section 4.2.1, has two voltage phases in time (curve c in figure 4.15). At first, the load is principally a constant impedance and follows the d curve. With time, the load recovers (figure 4.1) and becomes more like a constant power load. The voltage starts to decline as for curve a and b in figure 4.15. Neither of the three static load models (a, b and d), could be used to emulate the behaviour of the field measured dynamic load model.

One can also see in figure 4.16 that the transformer actions increase the speed of the voltage decline. All of the models chosen have an unstable voltage when the tap changer of the transformer starts to restore the voltage.

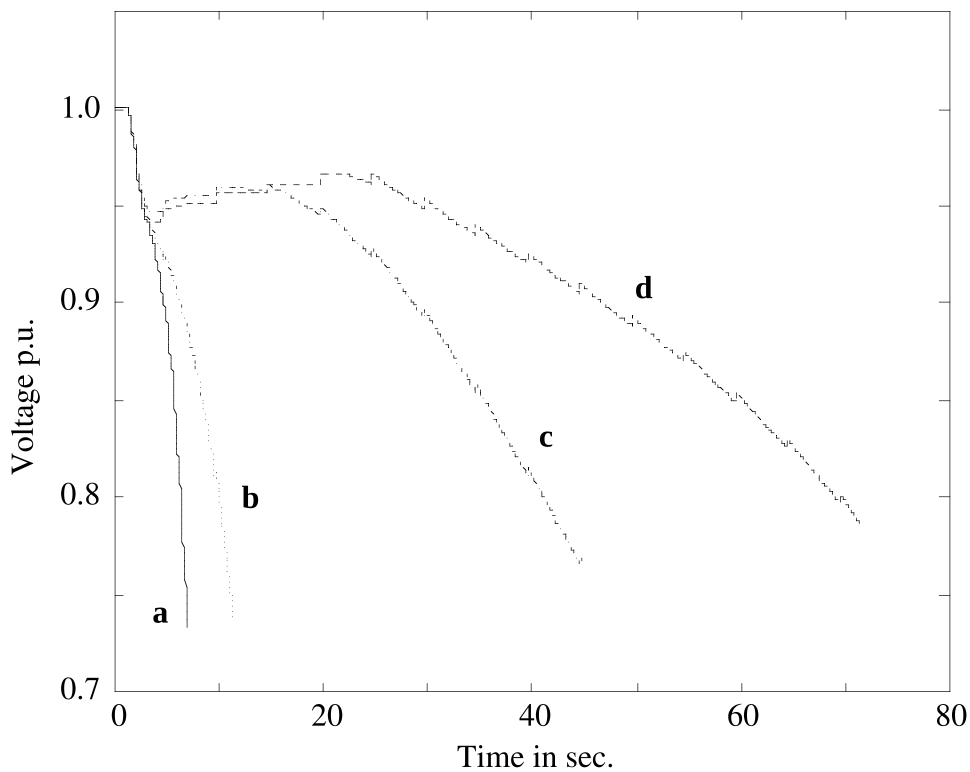

Figure 4.16 The same load models as in figure 4.15 but with one OLTC relay active. Note the shorter time scale. The tap changings accelerate the voltage decline.

If the transformer is omitted in order to decrease the computer simulation times and the constant power load is used with the motivation of restoring the voltage, the result could be a too pessimistic simulation (curve a). If a load model that is proportional to the voltage squared is used, a completely different response is possible (curve d). By choosing models that lie between a and d, a simulation of the voltage somewhere between these could be utilized.

4.3.4 Response of dynamic loads including OLTCs and current limiters: System 2

To demonstrate the long term voltage phenomenon in a large power system, a short-circuit causing two lines and one generator to trip was simulated (figure 4.10). Two cases were studied: C and D. In case C all the tap changers in the system were locked and in case D they were active.

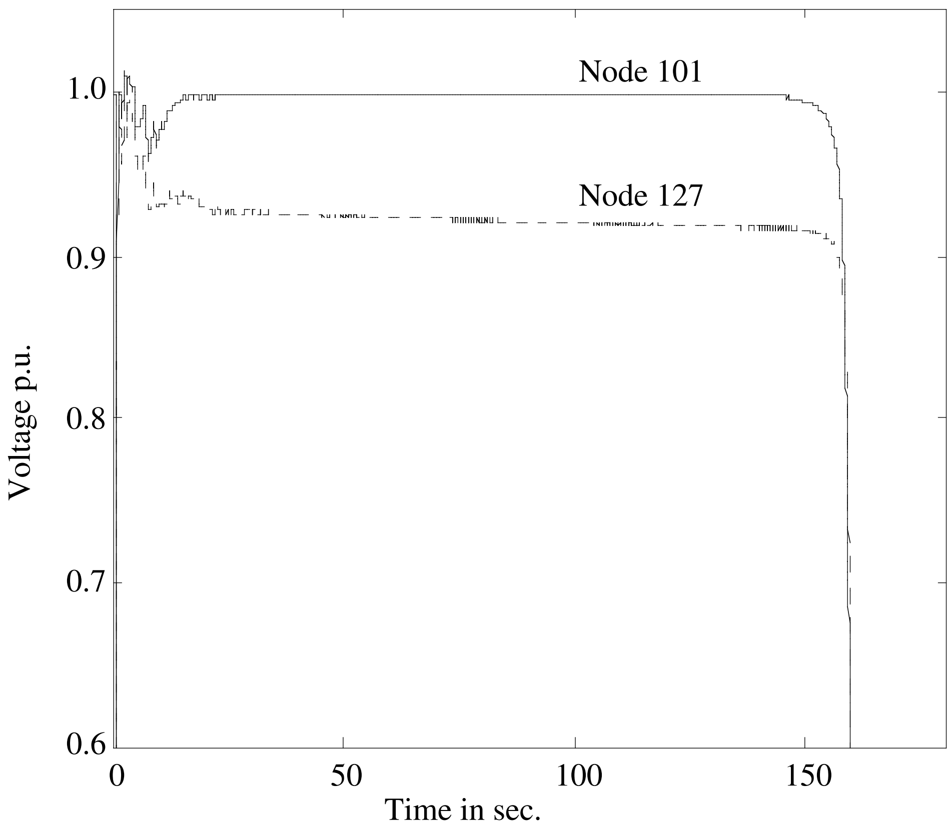

Figure 4.17 Voltages in System 2. After the short-circuit the voltage is rather stable in node 101 but it slowly drops due to load recovery in node 127. After 160 seconds the voltage collapses.

Case C: When the short-circuit occurs, the generators with armature current limiters are activated and they continue to operate during the whole simulation. After the transient oscillations have died out, the delayed operation of the armature current limiters decrease the voltage. While the voltage level becomes acceptable in node 101, it is low in node 127 and slowly decreasing. After 160 seconds the load recovery in the nodes with depressed voltages pulls the voltages down, i.e. the dynamic in load characteristics causes the system to collapse. This simulation is analogues to curve c in figure 4.15.

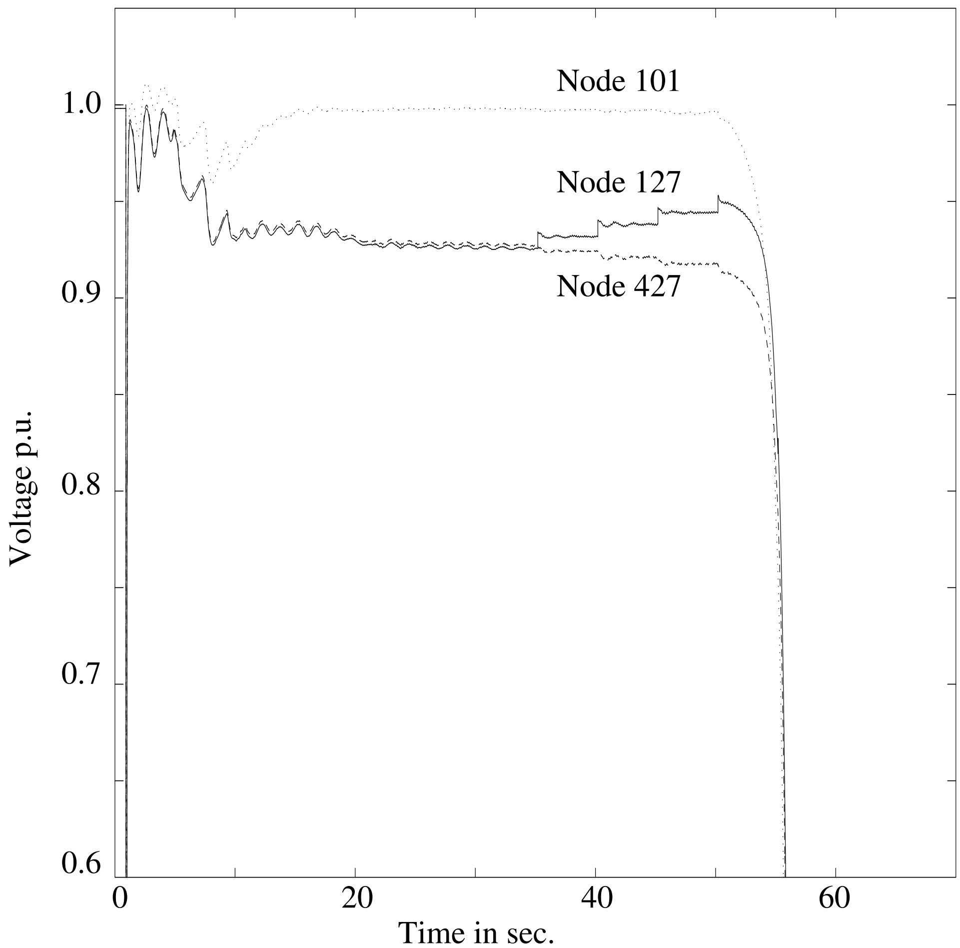

Figure 4.18 Voltages in System 2. The same divergence of the voltage on the different sides of the transformers can be seen in figure 4.11.

Case D: When one level of voltage regulating transformers is active the progression will go much faster. Up to the point when the first transformer changes tap position, the simulation is the same as above. After just a few tap movements of the transformers in the area, the voltage collapses. Note that the primary voltage at node 427 shows the same behaviour as the primary voltage in figure 4.11. We have also seen that the transformer actions speed up the process in the simple system (figure 4.16). A simulation with a similar behaviour could be found in [14].

4.3.5 Discussion of the simulations

In a weakened network with generators having limited voltage regulation capabilities, the regulating transformer behaviour is important when the generators become current limited. When a voltage level falls below the transformer dead band, the voltage will be restored by the OLTC. Every tap changing increases load voltage and thereby increases load demand. This also increases the current on the primary side, see figure 4.12. The step up transformers near the generators can not cope with the load transformer tap changings due to the larger voltage drops in the network, which affect the load transformers more than the step up transformers. The current increase, therefore must be taken from a generator that is not current limited, probably far away from the critical area, since the mechanical power to the limited generators is virtually unchanged. If this is not possible or is very difficult due to line losses in the transmission system, the voltage starts to decrease, sometimes very fast (figure 4.14, 4.17 and 4.18). In these simulations it appeared to us that the OLTC-regulation speeded up the voltage decline when the armature current limiters came into action (figure 4.16 and 4.18). In several French regions an automatic OLTC blocking system has been installed to prevent voltage collapse [2].

The system operator should be presented with the actions of the current limiters, due to their influence on the system. Therefore, this presentation is going to be implemented at the Sydkraft utility company.

4.4 Conclusions

The authors believe that it is important to model components with a high degree of accuracy. Many phenomena that were not expected to have an effect on voltage stability simulations turn out to be important when included. One thing that was found important was the blocking of the activated current limiter when there was a risk that the generator would become under-excited.

Accurate simulation can be a complement to more theoretical/mathematical treatment of voltage stability phenomena. These simulations can also be used to verify general theories developed on small, easier-to-understand networks.

However, it must kept in mind that the simulation results depend on the quality of the input data. Several parameters in the load model used here are difficult to extract from a real network. The simulations reported here show clearly how different load models affect the outcome of a simulation. The lack of information in this area should be remedied.

The simulations highlight the importance of the generator current limiter and its interaction with the on-load tap changer and the type of load model chosen.

4.5 Acknowledgements

The authors would like to thank Sydkraft company and Sydkraft Research Foundation for their engagement in this research area and for their financial support.

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4.7 Appendix

Primary data for the simple test system:

The dynamic load model:

$\alpha_s = 0.38$
$\alpha_t = 2.26$
$\beta_s = 2.68$
$\beta_t = 5.22$
$P_0 = 0.10$ p.u.
$Q_0 = 0.04$ p.u.
$T_{pr} = 127.6$ s
$T_{qr} = 75.3$ s.

Line parameters:

The short line: x = 0.75 p.u.

The long line: x = 1.5 p.u.

The transformers:

$x_k = 0.1$ p.u.
voltage set-point = 1.0 p.u.
deadband = 0.02 p.u.
tap step = 0.015 p.u.

Chapter 5 Behaviour of generator current limiters near the point of voltage collapse

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Abstract

Voltage instability and system collapse could be ascribed to the inability of a power system to sustain the load. Analysis of the problem over the years has strongly focused on the significance of reactive power and its repercussions on voltage. This paper has a different approach where the collapse phenomenon is treated as a current problem and is related to the current limiter behaviour of generators. The effect on the system differs drastically depending on whether the field or the armature current limiter becomes active. An illustration of how a field current limited generator exposed to a voltage drop will reach the armature current limit is made. It will also be shown that the relation between changes in current and voltage (ΔI/ΔU) as a function of different disturbances gives valuable information on the onset of voltage collapse.

Keywords

Voltage instability, voltage collapse, armature current limiter, field current limiter, current-voltage trajectory.

5.1 Introduction

There are several approaches to voltage stability problems. One approach might be to divide the power system into three parts: the transmission system, the distribution system which includes the electrical load demand, and the generation system. These three sub-systems interact with each other and voltage stability problems can originate in any of these sub-systems. For transmission systems, increased reactive power demand can cause a voltage stability problem. In distribution networks, stalling asynchronous motors, airconditioning systems and electrical heating appliances are examples of dynamic loads that can give rise to voltage stability problems. Voltage problems can also be due to generators. A well known example is the field current limiter (over-excitation limiter) [7]. However, the armature current limiter affects the power system in an even more drastic way. The armature current limiter is quite often neglected in the analysis because it is not commonly used. However, there are reasons to include it as an overcurrent protection system. This paper analyses current limiter behaviour and its significance for system stability.

5.2 Generator current limiters

The interaction between the current limiters and the network is studied using the following model of the synchronous generator (figure 5.1):

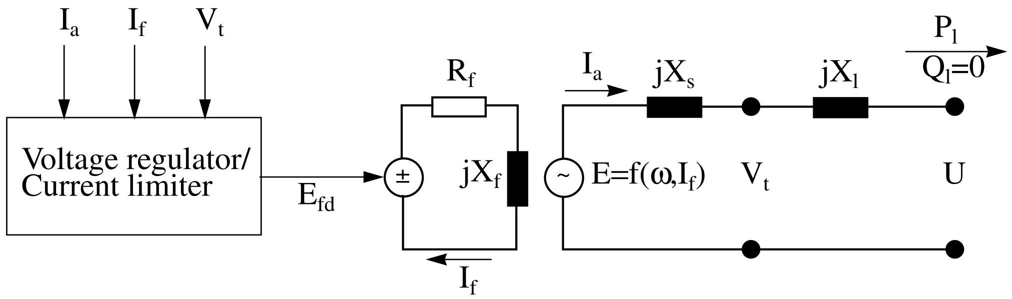

Figure 5.1 The synchronous round rotor generator with a transmission link and an active load demand.

The Voltage regulator/Current limiter[1] (see chapter 4.2.2) may operate in one of three regulating modes:

- Regulating terminal voltage V_t at a given set-point. This is the normal operating condition.
- The field current I_f may be limited to avoid overheating of the field winding. This corresponds to a constant voltage E and the voltage regulation point V_t disappears. The "synchronous reactance" X_s can now be considered as a part of the transmission system. The value of X_s is not trivial. It depends on armature reaction, self-inductance (and resistance) of armature coils and the pole shapes of the rotor and

1. FREA manufactured by ABB.

stator. The value of X_s is therefore difficult to predict quantitatively (see ref. [5]).

Note that the relation between E and I_f is nonlinear due to saturation, which is evident when the machine is light loaded. For a machine connected to a lagging load, the armature reaction will decrease the field and makes the relation more linear.

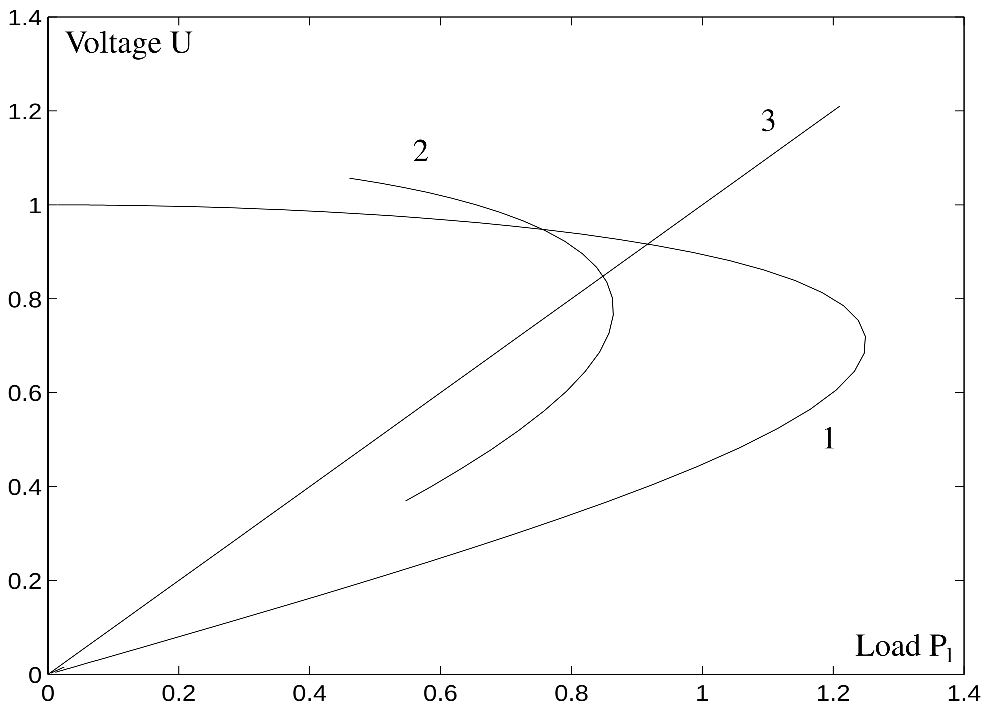

Figure 5.2 Possible system characteristics as seen by the load (constant power factor), depending on which mode the generator is working in. The shapes and slopes will vary with the power factor of the load (Symbols from figure 5.1).
1: Voltage regulating mode (V_t constant)
2: Field current limited mode (E constant)
3: Armature current limited mode (I_a constant)

- The armature current I_a is limited if it exceeds a specified level. This protection system avoids overheating of the armature windings. In that case the generator loses all voltage regulating capabilities and becomes a constant current source. The only way the protection system now can decrease a too high I_a is by decreasing E. This certainly stresses the voltages in a system.

If the generator is not equipped with an armature current limiter, the generator is usually tripped by an overcurrent relay and all production is lost from that source, i.e. an even worse situation for the system. Some large hydro-power stations in Sweden use this configuration whereas nuclear power plants use armature current limiters.

If the regulator is working in a limiting mode, the most severe limitation is valid. The system characteristics as seen by the load are shown in figure 5.2 for the three modes.

5.2.1 The capability diagram for the generator

A capability diagram displays possible operating areas where the generator thermal limits are not violated [1]. The small circle in figure 5.3 corresponds to the MVA-rating of the generator, and the circle-segment is the boundary due to field current limitation.

If the generator becomes field current limited and is exposed to a decreasing voltage V_t, it will end up as armature current limited. In the capability diagram this can be seen since the small circle "shrinks" and the large circle segment "moves" to the right.

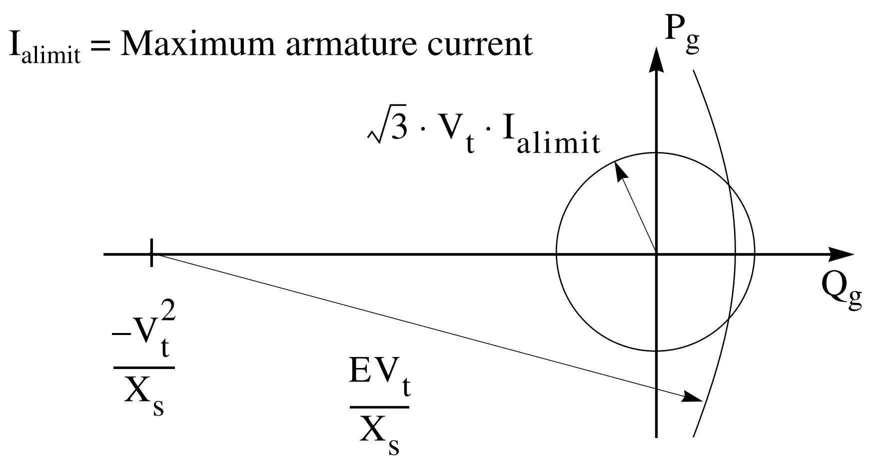

Figure 5.3 The capability diagram for a generator. The working point must be inside both circles. Only the thermal constraints of the generator are indicated. Prime mover restrictions may be added to the capability diagram. (For symbols: see figure 5.1).

5.2.2 The interaction between the current limited generator and the load characteristics

If the load P_l in figure 5.1 is increased from zero, one of the following sequences will occur:

- The voltage V_t is kept at the given set-point until the transmission system will be unable to transmit the power over X_l at a viable voltage U and comes into voltage stability problems due to lack of transmission capacity.
- The field current limiter is activated after further load increase. The reactance in the system increases and this might cause a voltage collapse in the same way as the tripping of a line in the network can cause a collapse. The system may also survive with this increased reactance but at a lower voltage U. The load increase causes a lower voltage V_t at the terminal. This may activate the armature current limiter (figure 5.5) or causes an non-viable voltage U.
- The armature current limiter becomes activated before the field current limiter. At this point the outcome depends only on the load characteristics (see chapter 5.2.4).

Usually, generators are designed such that they are field current limited before they reach maximum armature current. However, efficiency improvements on the turbine side may increase the active power output and thereby move the generator working point closer to the armature current limit. This is valid for several of the Swedish nuclear power plants.

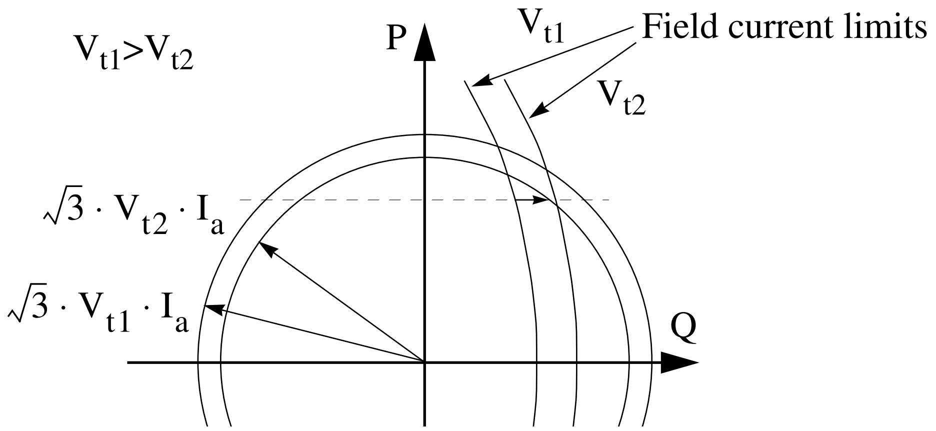

Figure 5.4 The capability diagram for two different voltages $V_{t1}>V_{t2}$ for a field current limited generator. The dotted line is active power delivered from the turbine to the generator. The small arrow indicates how the working point can become armature current limited when the terminal voltage decreases. Note that the reactive power out from the generator increases for a field current limited generator exposed for a voltage drop.

5.2.3 The influence of the field current limiter

It is interesting to consider a real field current limiter (see chapter 4.2.2) with delayed operation and to study how it is interacting with a dynamic load. By including delayed operation the transient load characteristics appear when the limiter drastically changes its operating mode (figure 5.5).

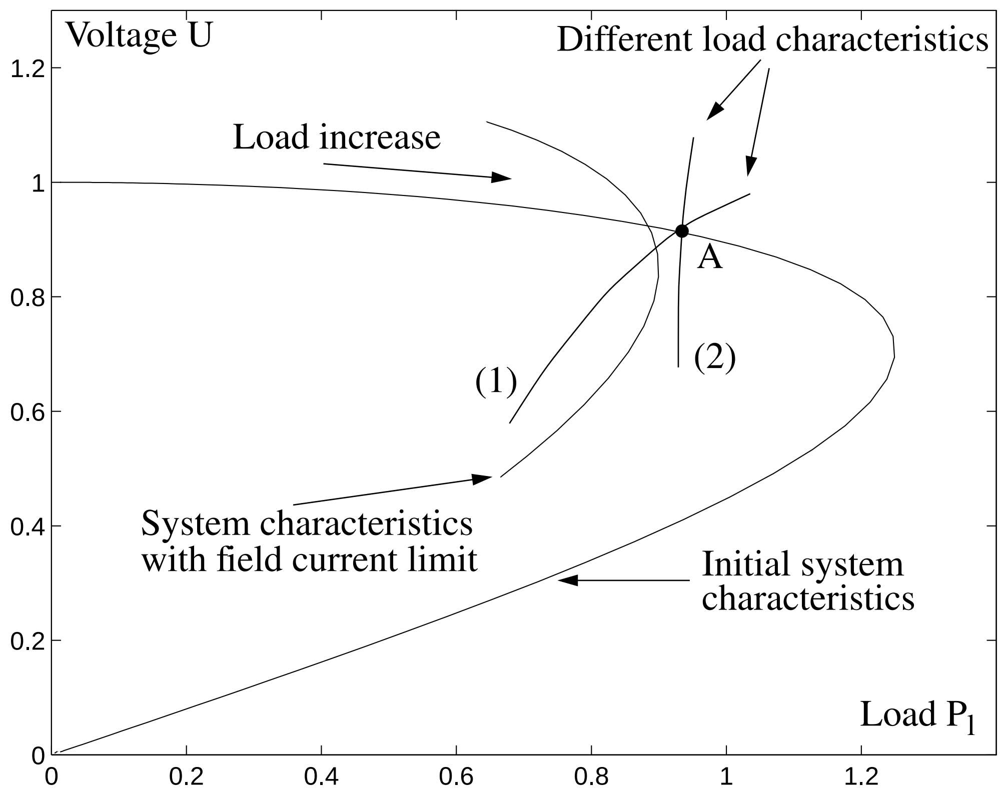

Figure 5.5 A load increase with a delayed field current limiter. In point A the limiter comes into action and a continuous transition to the new system characteristics will occur. It then depends on the load characteristics if the system will find a stable operating point (1) or become unstable (2).

Depending on the values of the systems components, it is possible for the system to be unstable due to the fact that the working point is on the lower side of the UP-curve. Certain types of loads can be unstable on the lower side of the UP-curve (See ref. [2] and [6]).

5.2.4 The influence of the armature current limiter

When the armature current limiter becomes activated, the load behaviour is important and is going to decide if the small system will be stable or not. In figure 5.6, two possible load characteristics, I and II are shown.

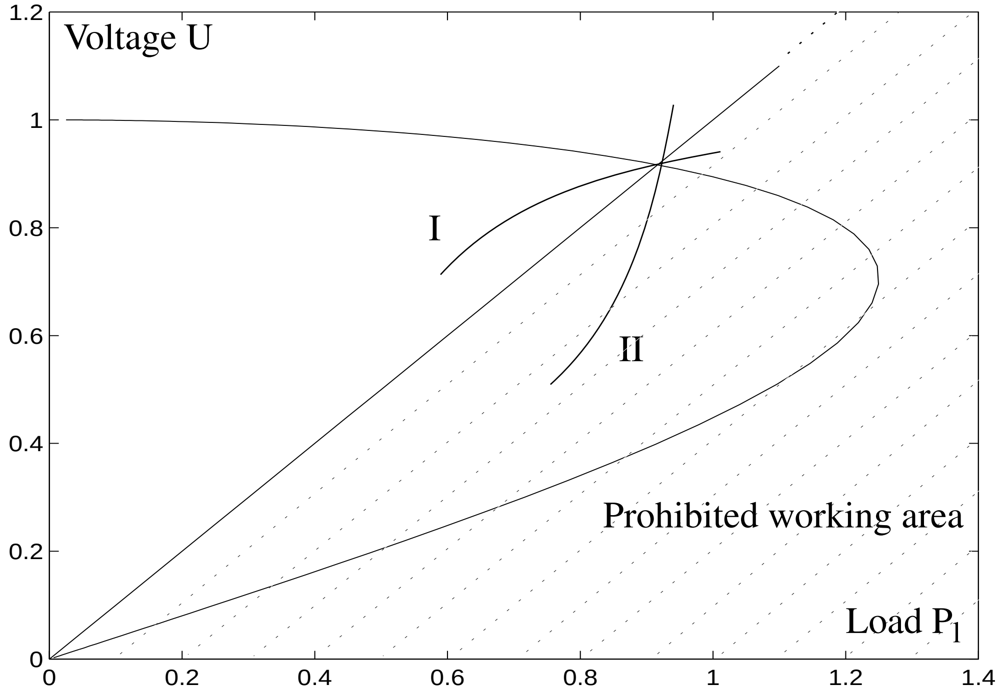

Figure 5.6 Armature current limiter and load interaction. Two possible load characteristics I and II are indicated.

A general expression for the load can be given by:

$$P = P_0 \left(\frac{U}{U_0} \right)^{\alpha} \tag{5.1}$$

Here the value of α is of particular significance in case of armature current limitation and will be analysed further on. The armature current limiter divides the UP-plane in two zones, where the right one is not a possible stable operating area with regard to thermal heating of the generator. The output power from the generator into the load follows the relation $P_l = \sqrt{3} \cdot U \cdot I_s$ i.e. a straight line in the UP-plane (in case of no reactive load as in figure 5.1). If the operating point enters the unstable half, the only possible protection action of the current limiter to decrease I_a is to decrease E (i.e. decrease the field current I_f).

Case A: An increase of load demand and α>1:

We will have the following situation:

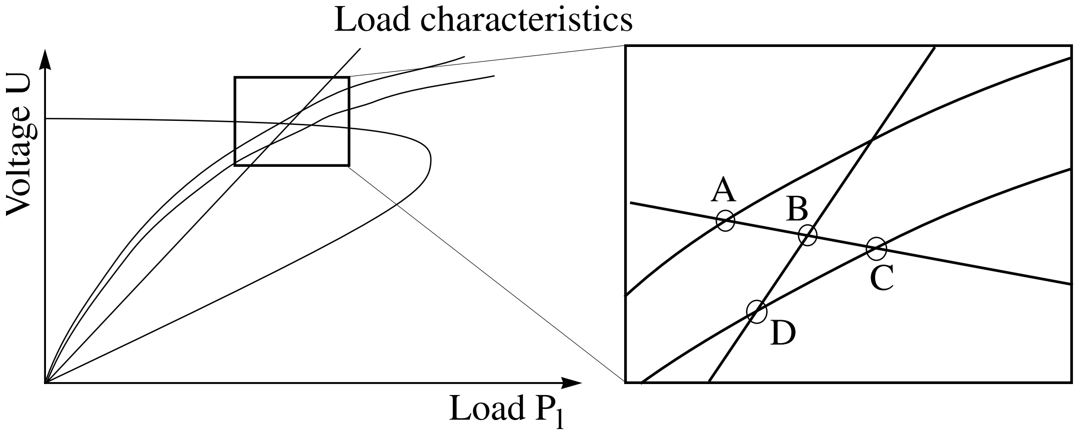

Figure 5.7 Armature current limiter and load interaction when α>1.

A load increase where the character of the load does not change (same α) can be expressed as an increase of P_0 in equation (5.1). At the beginning the system is located at point A in figure 5.7. After the load increase the system moves to C. The stator current limiter either prohibits that movement in B or starts its timer for a delayed operation (see chapter 4.2.2). The armature limiter then forces the system operating point to D, which is a stable operating point.

Case B: An increase of load demand and α<1:

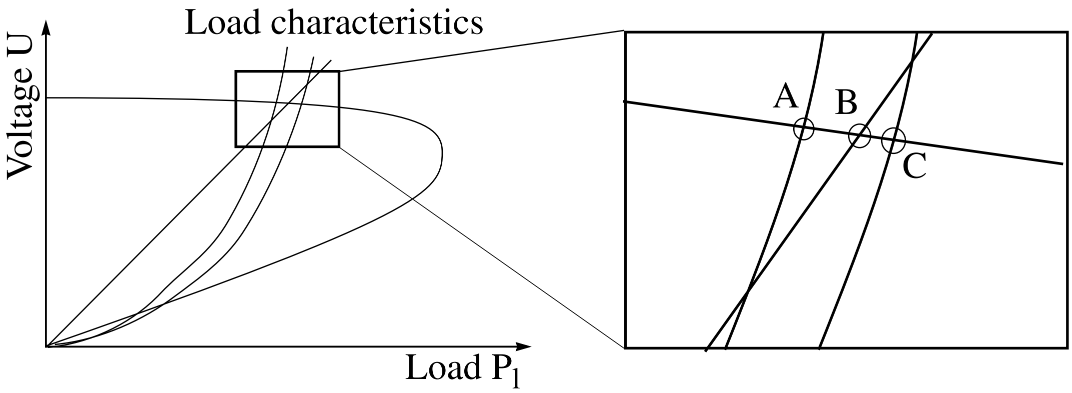

Figure 5.8 Armature current limiter and load interaction when α<1.

The system is located in A in figure 5.8 (stable operating point between the UP-curve and the load characteristic). We increase P_0. The system wants to move to C. When it passes B the current limiter either stops the armature current increase or starts its timer for a delayed action (see chapter 4.2.2). The only possible direction for the system is to decrease the voltage but this means an even larger violation of the armature current and an even lower voltage E. The voltage collapses since there is no intersection between the system characteristic and the load characteristic. This also indicates that the voltage decline during a collapse can be very fast in the final phase.

The condition for returning to a stable situation is that the load current ($=I_a$) decreases below I_{alimit}. For the load end we can calculate the current in figure 5.1:

$$I_a = \frac{P_l}{U} \qquad \text{and using equation (5.1)} \qquad (5.2)$$

$$\frac{\partial I_a}{\partial U} = \frac{P_0}{U_0^{\alpha}} \cdot (\alpha - 1) \cdot U^{\alpha - 2} \qquad (5.3)$$

The system will find a stable operating point at I_{alimit} when $\alpha>1$ and it will be unstable for $\alpha<1$. This should be compared with the cases A and B, respectively. It can be seen that the combination of an armature current limiter and a negative $\partial I_a/\partial U$ can be interpreted as a stability criterion for the simplified system in figure 5.1. A $\partial I_a/\partial U>0$ gives a stable situation while $\partial I_a/\partial U<0$ leads to an unstable situation.

Since the property of $\partial I/\partial U$ seems to contain valuable information on an impending voltage collapse in a small system, a simulation study has been made to analyse the $\partial I/\partial U$ relation in a more general sense. The simulated quantity in this paper is

$$\frac{\partial I}{\partial U} \approx \frac{\frac{\Delta I}{\Delta t}}{\frac{\Delta U}{\Delta t}} = \frac{\Delta I}{\Delta U} \qquad (5.4)$$

A similar study (see chapter 6) has been made using the CIGRÉ Swedish test system [4].

5.3 Simulations

The simulations are made on a simple power system consisting of one dynamic load, two generators, and four transmission lines connected as shown in figure 5.9, (see appendix for network data). Generator G1 is to be regarded as an infinitely strong power source, while G2 is a small generator. The dynamic load is based on parameters taken from field measurements [3].

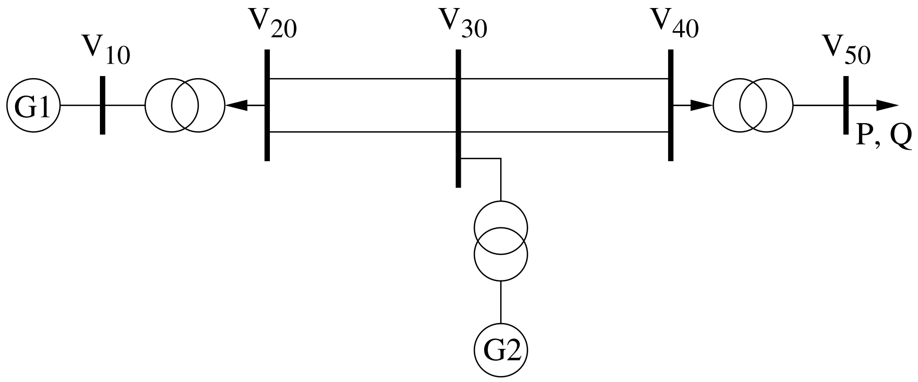

Figure 5.9 A simple power system

The model used to analyse the ΔI/ΔU signal is implemented as a "user-written" model in the PSS/E[1] program. As shown in figure 5.10 there are two possible outputs: one continuous output named ΔI/ΔU value, and a discrete one named ΔI/ΔU signal. The latter is used in these studies. The values of ΔI/ΔU are calculated for each current flow at each node.

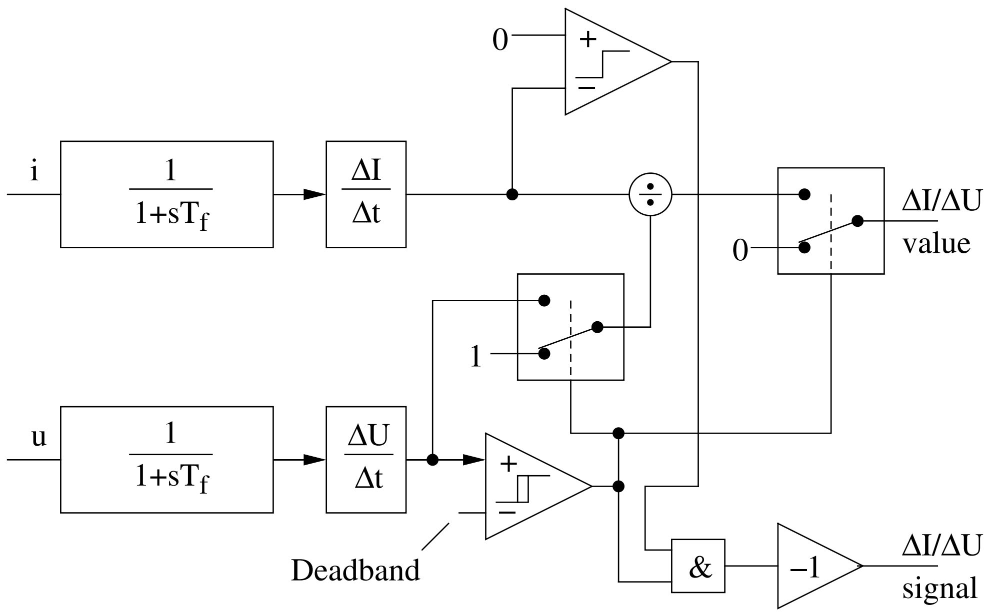

Figure 5.10 The ΔI/ΔU model. There are two possible outputs: A continuous one named ΔI/ΔU value, and a discrete one named ΔI/ΔU signal.

1. Power System Simulator for Engineers, by PTI (U.S.A)

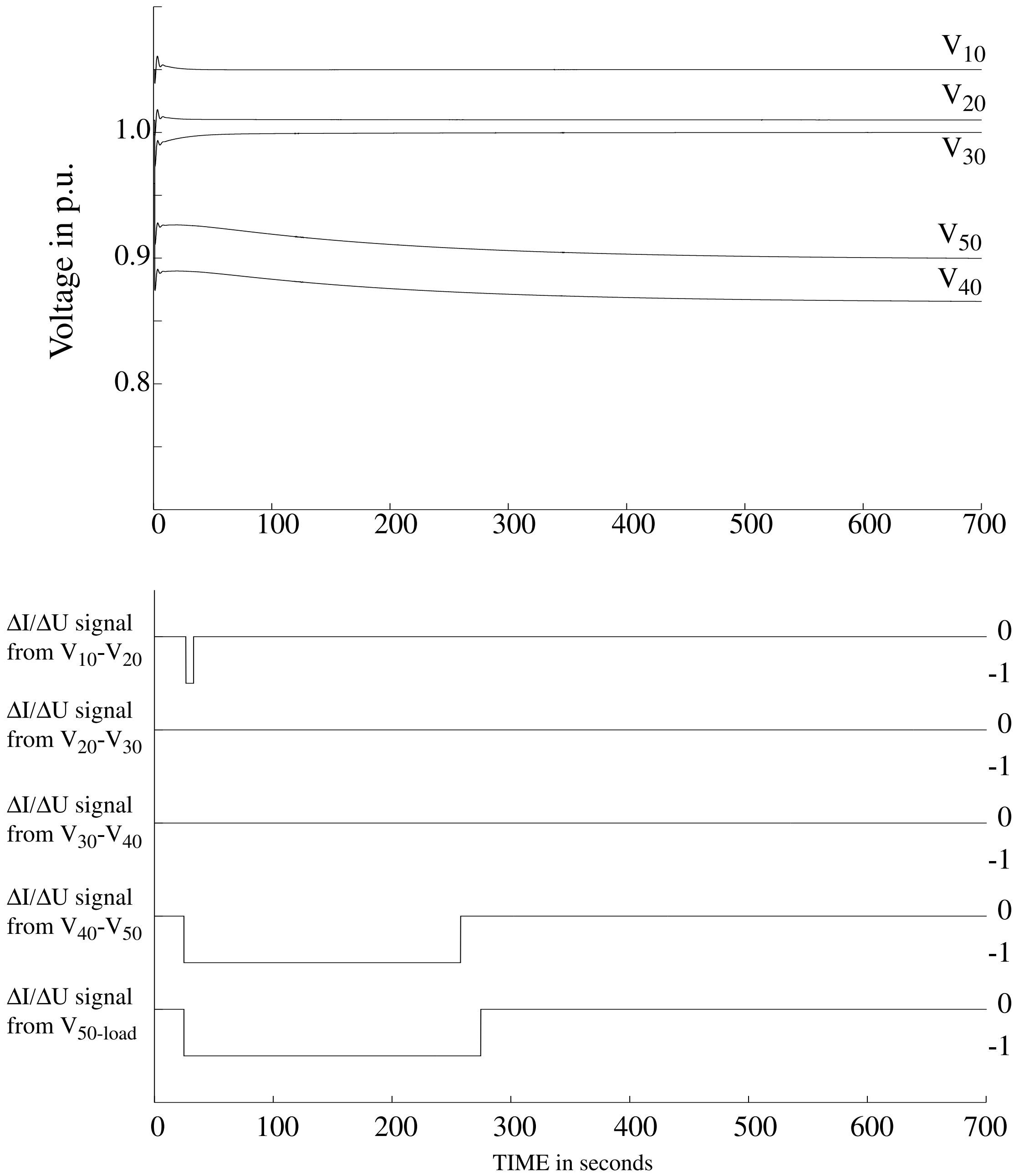

Figure 5.11 Case 1: Voltages and ΔI/ΔU signals.

Case 1: One of the two lines between V_{30} and V_{40} is disconnected after 1 s and the voltages decrease instantaneously. Then a dynamic process starts where the generators quickly try to restore the voltages whereas the load dynamics restore the load in the time frame of 4-5 minutes. After about 6 minutes the system has found a new stable operating point. The course of events can be studied in figure 5.11 where the discrete ΔI/ΔU signals in combination with the node voltages are shown. The current limiters and the dynamics in the OLTCs are not activated. In this case the ΔI/ΔU signals give a warning at three nodes after about 25 s. At the V_{10} node there is just a short dip depending on the voltage oscillations in combination with the load recovery. But at the other two nodes, V_{40} and V_{50}, there are negative ΔI/ΔU signals as long as the dynamic load is in the recovering phase. This means that these two nodes are weakened but the system survives and the ΔI/ΔU signals return to their original zero level.

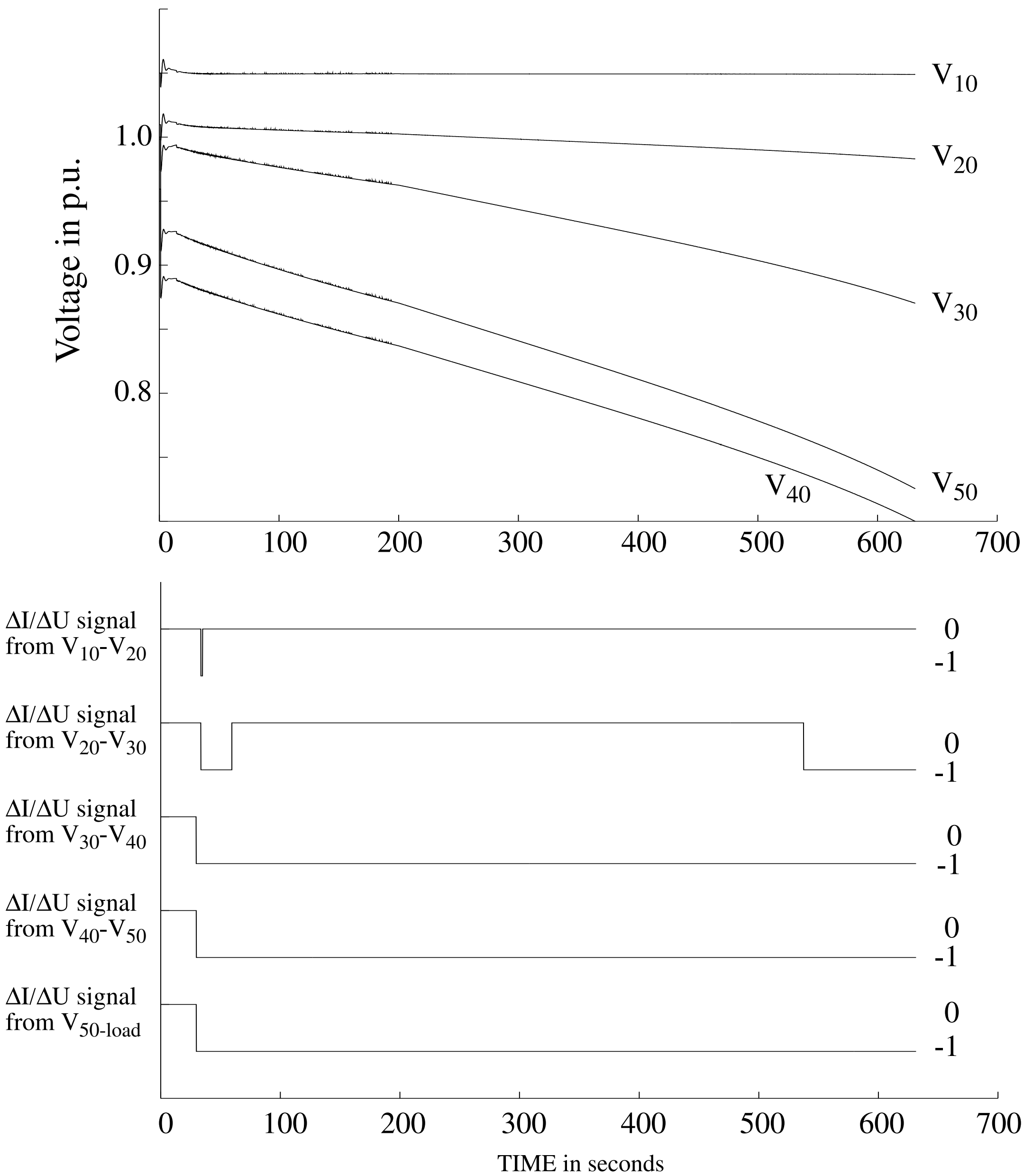

Figure 5.12 Case 2: Voltages and ΔI/ΔU signals.

Case 2: This case has exactly the same conditions as the first case except that the field current limiter of G2 is activated after 14 s. After 200 s the armature current limiter becomes activated. In this case, the system will not find a stable operating point and the ΔI/ΔU signals become negative at every node. A close look at figure 5.12 shows a spreading in time in which the ΔI/ΔU signals become negative. The nodes close to the load are 'voltage weak' which means that here the ΔI/ΔU signals become negative there first. The ΔI/ΔU signals near the strong generator become negative a few seconds later, but they will return to the original zero level since generator G1 sustains the voltages. After 200 s the armature current limiter at G2 becomes activated and the voltages at the weak nodes V_{30}, V_{40}, and V_{50} decline even more until the simulation is stopped at 0.7 p.u.

5.4 Discussion about the IU-trajectory

It is generally agreed that the frequency is stable to a point very close to the occurrence of a voltage collapse. Therefore we can assume that the load is satisfied with respect to the active power demand. Hence the limiting parameter will be the load current which is supplied from the generators and the reactive sources in the system. There are two scenarios that limit the current in an impending collapse situation: a) The transmission lines are not able to sustain the load and relays will trip the current overloaded lines and a voltage collapse may occur. b) Generators reach their thermal limits and become current limited. It is obvious in these cases that, as long as the currents increase and the voltages decrease, the system will run into trouble sooner or later. By following the direction of the trajectory of I and U it is possible to gain more information about the systems state. In other words, a continuously negative sign of ΔI/ΔU predicts that we are moving towards a voltage collapse.

A power system which load are increased will naturally have a decreasing voltage. In order to avoid ΔI/ΔU signals during normal load conditions there is a voltage deadband in time. The voltage must decrease faster than a certain amount or in other words ΔU/Δt must exceed the deadband as shown in figure 5.13, indicating a stressed system. If this is valid, the current change is studied. If the current has decreased this might indicate a voltage fluctuation and should not be dangerous for the system. But if the current has increased this indicates a load increase or some sort of limitation in the system which is dangerous, especially as the voltage support is weak already.

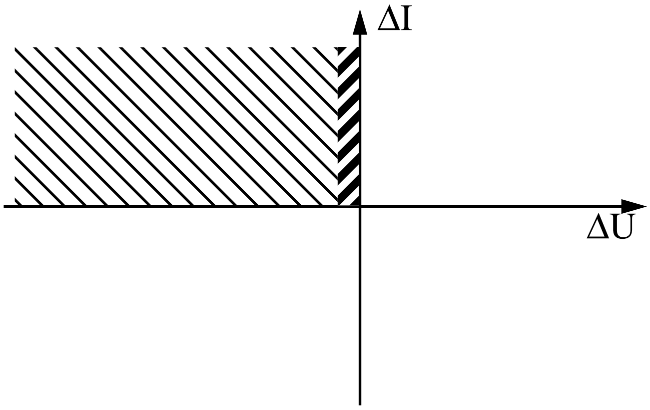

Figure 5.13 The marked area symbolizes a dangerous direction for the system and the marked line symbolizes the dead band used in the simulations.

Another interesting observation is the geographical spreading of the negative ΔI/ΔU signal. Simulations show how an increased number of nodes receive negative signs of ΔI/ΔU after an initial disturbance which ends up with a collapse. These observations indicate where the network has been weakened and where reactive support is needed.

In combination with other indicators, the ΔI/ΔU signal could be a valuable indicator of an emerging voltage collapse. A suitable application would be in a system emergency protection scheme. In addition, currents and voltages are easy to measure in a power system.

Issues that have to be studied more are appropriate dead bands and time constants for the filters to avoid that transients from generator swings causing too much signals. No attention is given to the ΔI/ΔU-value (i.e. the amplitude). This will be an objective for future work. An extended discussion about ΔI/ΔU can be found in chapter 6.2.

5.5 Conclusions

When studying voltage collapse phenomena it is important to notice how generator current limiters may affect the characteristics of the system. It is worth to notice that a field current limited generator becomes armature current limited if the terminal voltage declines. This implies that it is necessary to model the armature current limiter, since this limitation is more severe for the system. Current limiters can, in combination with load dynamics, explain why the voltages have decreased so fast in several collapse situations. Another current limiting aspect of the collapse problem is the decreasing transmission ability in the case of declining voltages in combination with recovering loads. This situation can lead to erroneous trippings of lines and in that way cause a voltage collapse. In combination with other criteria the sign of $\Delta I/\Delta U$ might be a valuable indicator of an imminent voltage collapse.

5.6 Acknowledgements

The authors would like to thank the Sydkraft company and the Sydkraft Research Foundation for their engagement in this research area and for their financial support.

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[7] CIGRÉ TF 38-02-10, "Modelling of Voltage Collapse Including Dynamic Phenomena", 1993.

5.8 Appendix

Network data

Dynamic load data [3]:	α_s=0.38, α_t=2.26, β_s=5.22, β_t=2.68, P_0=0.8 p.u., Q_0=0.03 p.u., T_{pr}=127.6 s, T_{qr}=75.3 s.
Line data:	R_{10-20}=0.08 p.u., X_{10-20}=0.8 p.u., B_{10-20}=0.1 p.u., R_{20-30}=0.04 p.u., X_{20-30}=0.4 p.u., B_{20-30}=0.05 p.u.
Transformer data:	X_{10-20}=0.1 p.u., X_{40-50}=0.1 p.u., X_{G2} included in generator G2
ΔI/ΔU-Data	Filter time constant 5s, Deadband -0.00004 pu/s, Δt=1s

Chapter 6 ΔI/ΔU simulations

This chapter is an extension of the previous chapter where the ΔI/ΔU signal was introduced and analysed in a small network. Here the purpose is to analyse the significance of ΔI/ΔU in a larger network. The network used is the Swedish test system, shown in figure 6.1 and described in [1]. This power system is fictitious but has dynamic properties that are similar to the Swedish power system. The system is used to study voltage stability phenomena in a small network modelling a large system.

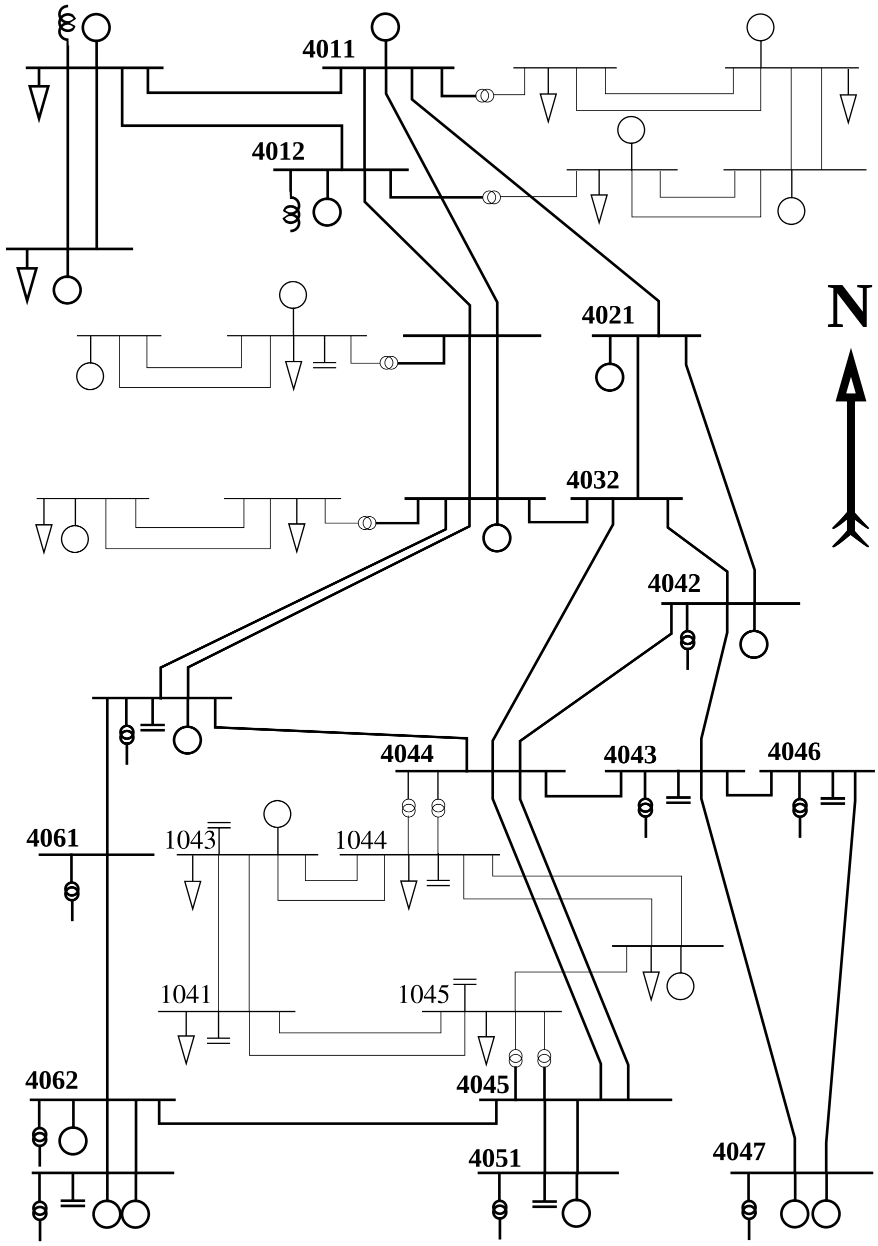

Figure 6.1 The Swedish test system (CIGRÉ Nordic 32A test network). The bold lines represent 400 kV and the thin lines represent 130 kV and 220 kV.

6.1 Check of the load level dependence

An analysis has been made where the same disturbance was applied for four different load cases. Using the network, as shown in figure 6.1, the loads were scaled to 80%, 90%, 100% and 105% of the nominal load. This gives four different load conditions, which all were subjected to the same disturbance consisting of an increased load demand during 50 s. The increased load demand is shown in the figure below.

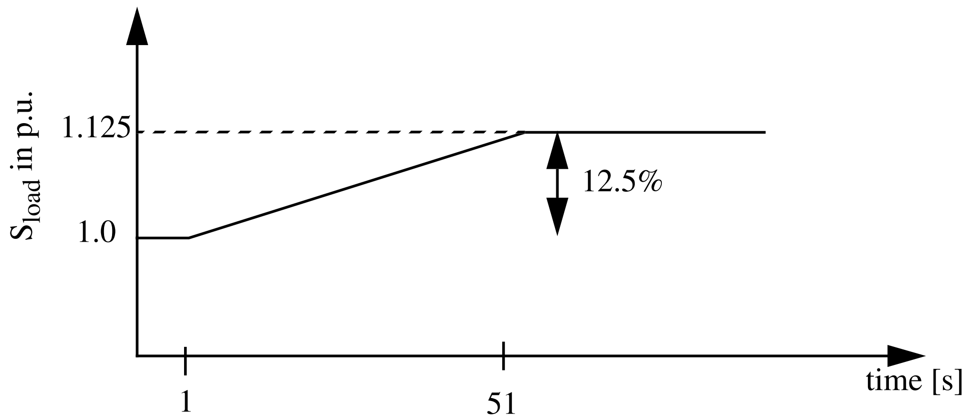

Figure 6.2 The disturbance in node 1041 consists of an increasing load of 15%/minute in active and reactive power during 50 s. S_{nom}= 600 MW+200 MVAr for the nominal case.

6.1.1 General comments to the simulation study

The nominal load level (100%) represents a stressed network and the disturbance is located at node 1041 (figure 6.1). In order to keep the tap changer ratios at the same level, it was necessary to connect some reactors in the case of 80% load.

Long-term dynamics from turbine regulators, on-load tap changers and generator current limiters are included in the simulations. The loads have a static voltage dependence where the active power is modelled as a constant current load and the reactive power is modelled as a constant impedance load. This is the most commonly accepted static representation for active and reactive power [2].

The discrete ΔI/ΔU-signals are shown in figures 6.5 - 6.15 for the four different load levels, and measured as described in figure 6.3. Every ΔI/ΔU-signal corresponds to a transmission line in figure 6.1, where a continuous negative signal implies that the system is moving towards voltage instability, but it does not specify if or when a voltage collapse may occur.

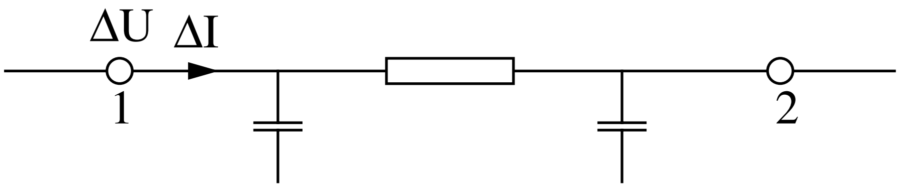

Figure 6.3 The ΔI/ΔU-signal between node 1 and node 2 is written as ΔI/ΔU 1-2, which has to be interpreted as the ΔI and ΔU measured at node 1.

The load disturbance at node 1041 starts after 1 s and is active during a time period of 50 s. The active power flow will then increase in the north-to-south direction because of the frequency regulation in the hydro power plants up in the north, see figure 6.1.

Finally, the first three simulations are stable while the last case ends up with a voltage collapse.

6.1.2 80% and 90% of base load

These two cases show a low activity regarding ΔI/ΔU-signals which means that the system still has reactive power margins and as soon as the disturbance is discontinued and the voltages are stable, the activity stop. In spite of the low activity it is possible to see a geographical spreading in the onset and duration time for the different ΔI/ΔU-signals; roughly from the source of the disturbance and further out. Far away from the disturbance there is no activity at all. Neither the tap changers nor the generator current limiters are activated during these two simulations.

6.1.3 Base load 100%

This case shows an increased activity in the ΔI/ΔU-signals. Compared to the previous cases, the negative ΔI/ΔU-signals appear earlier and the duration time is longer. After 30 s the armature current limiter at node 1043 is activated. This causes the OLTCs, at nodes 1044-4044 and 1045-4045, to restore the voltages on the 130 kV side 50 s later and in this connection there is a negative ΔI/ΔU response at every 400 kV line in the system. A few seconds later all ΔI/ΔU-signals are stabilized due to the new steady state situation, but the system is now on the very border of a voltage collapse.

6.1.4 105% of base load

At this load level the system is not able to withstand the disturbance by an increased load demand and the activity of the negative ΔI/ΔU-signals increases dramatically when the system approaches the stability limit. After 20 s the armature current limiters at nodes 1043 and 4042 are activated and the voltages decline in the entire system, figure 6.4. After 65 s the OLTCs start to restore the low voltages on the 130 kV sides. This voltage restoring process ends up after 180 s when the two generators at node 4047 becomes armature current limited and after another 20 s the armature current limiter at node 4051 is activated and then the voltage collapse occur at 201 s. The trend in this case is the same as in the previous cases, the heavier load the earlier we get negative ΔI/ΔU-signals and the more activity is registered.

6.1.5 Simulation summary

The simulations confirm our earlier thesis of the ΔI/ΔU signal (see chapter 5.4). There is an imbalance in reactive power as long as we have negative ΔI/ΔU signals and additionally the system is moving in a dangerous direction regarding voltage stability. If the situation becomes worse the negative ΔI/ΔU signals tend to be more widely spread and the closer we get to a voltage collapse the more activity is registered. It is also obvious that the more stressed the system is the faster response of the ΔI/ΔU-signals we have.

These negative ΔI/ΔU signals seem to be an unmistakable sign for a declined voltage stability in the system. But only using the information from these negative ΔI/ΔU signals does not make it possible to predict if a voltage collapse is impending or not. Therefore it is also necessary to have an opinion about the resources of reactive power; a combination of ΔI/ΔU signals and reactive power reserves may be a suitable tool.

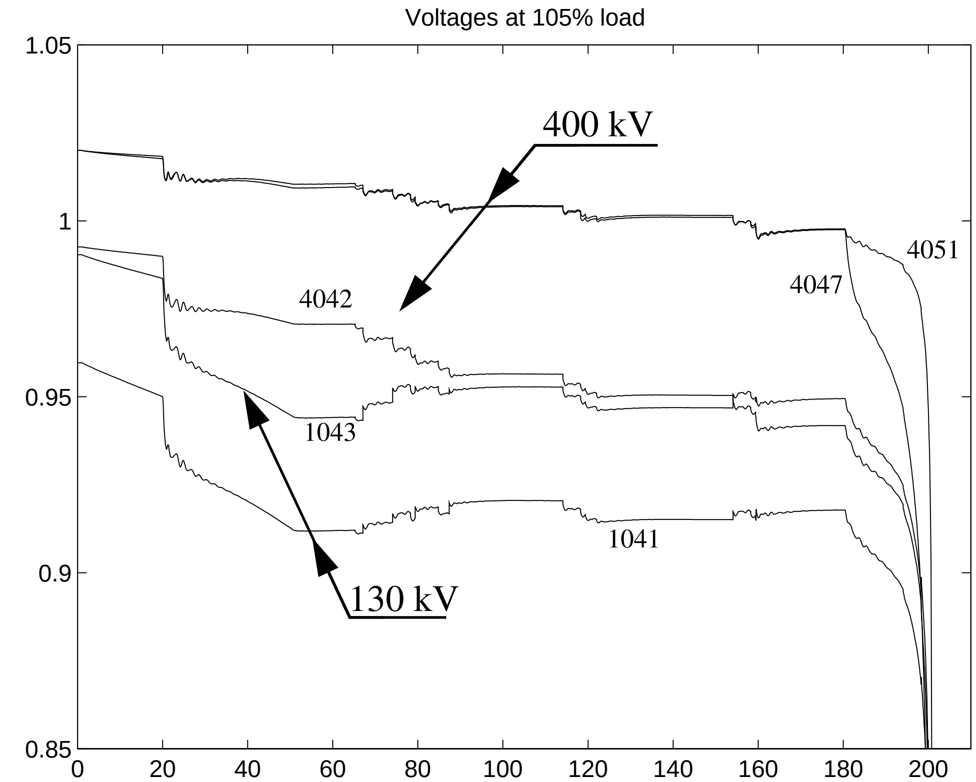

Figure 6.4 Different node voltages during the collapse course.

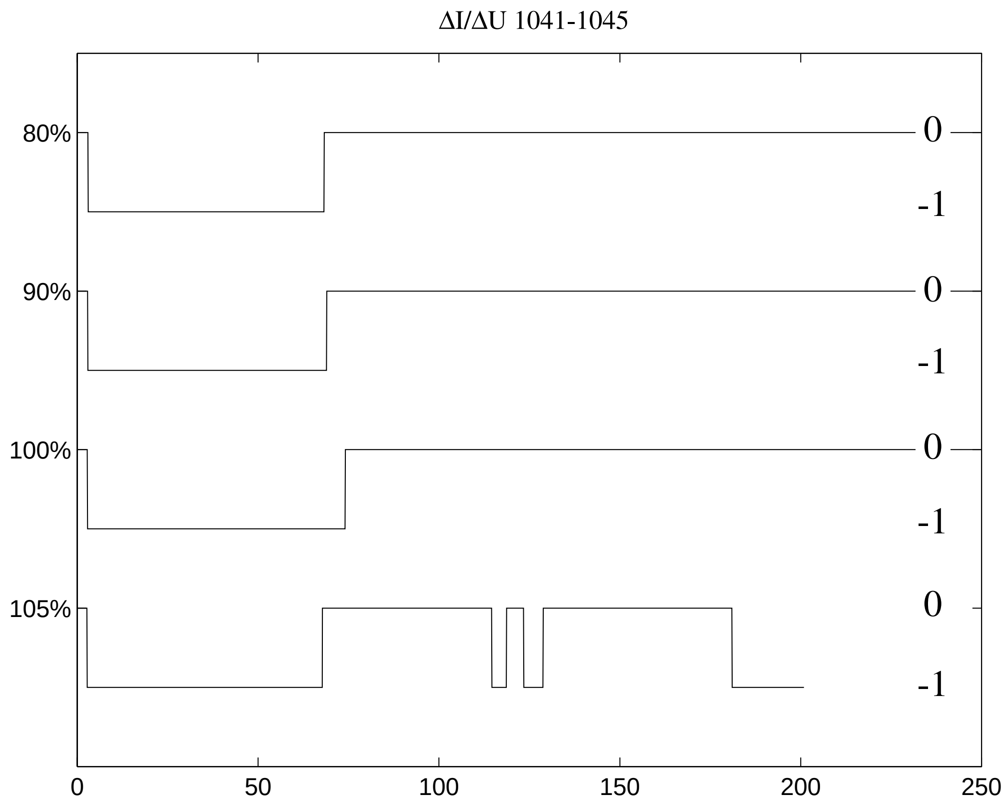

Figure 6.5 The ΔI/ΔU-signals as a function of time between 1041-1045. The current is measured from 1041 to 1045 and the node voltage is measured at 1041.

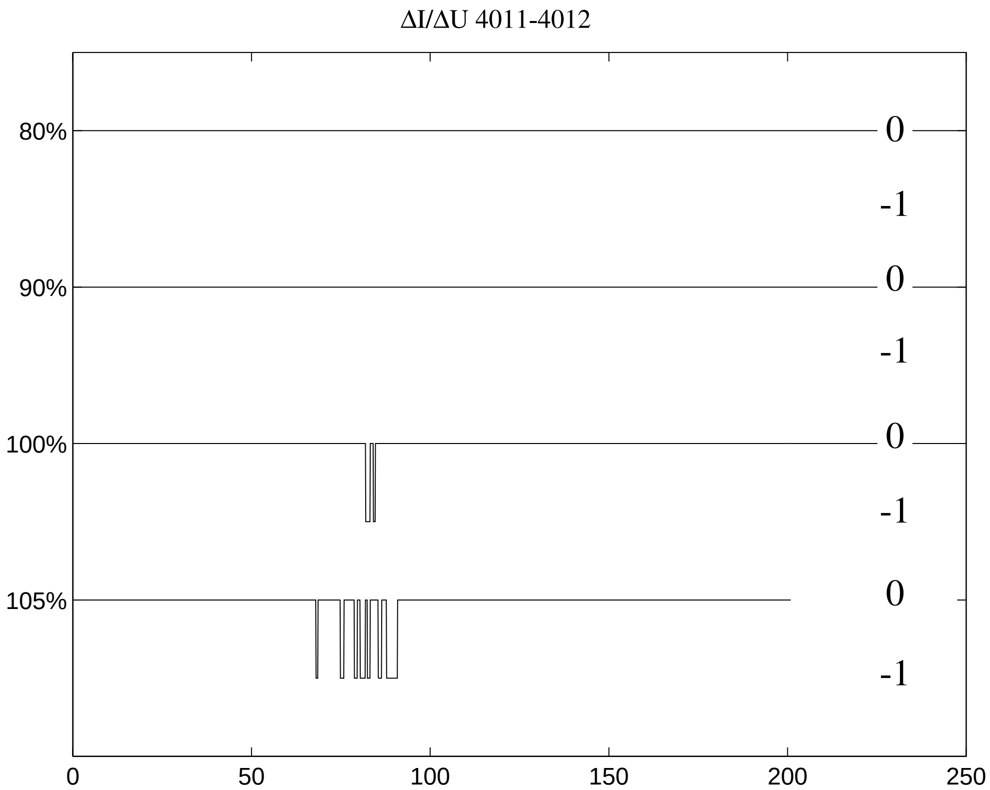

Figure 6.6 The ΔI/ΔU-signals as a function of time between 4011-4012. The current is measured from 4011 to 4012 and the node voltage is measured at 4011.

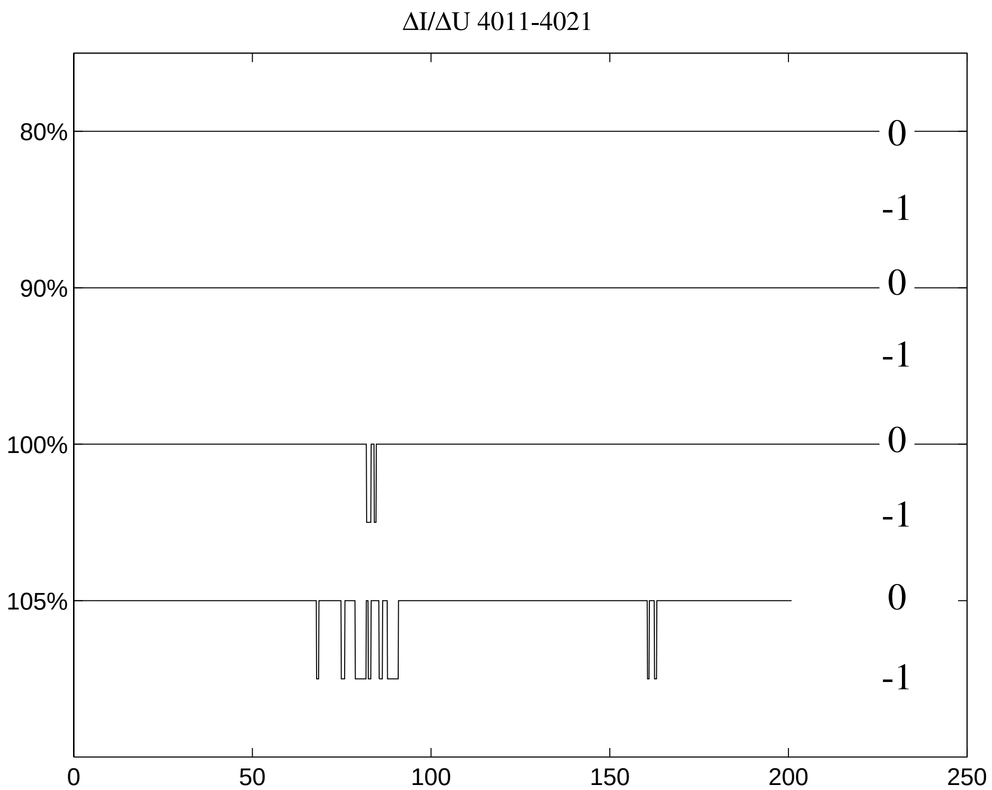

Figure 6.7 The ΔI/ΔU-signals as a function of time between 4011-4021. The current is measured from 4011 to 4021 and the node voltage is measured at 4011.

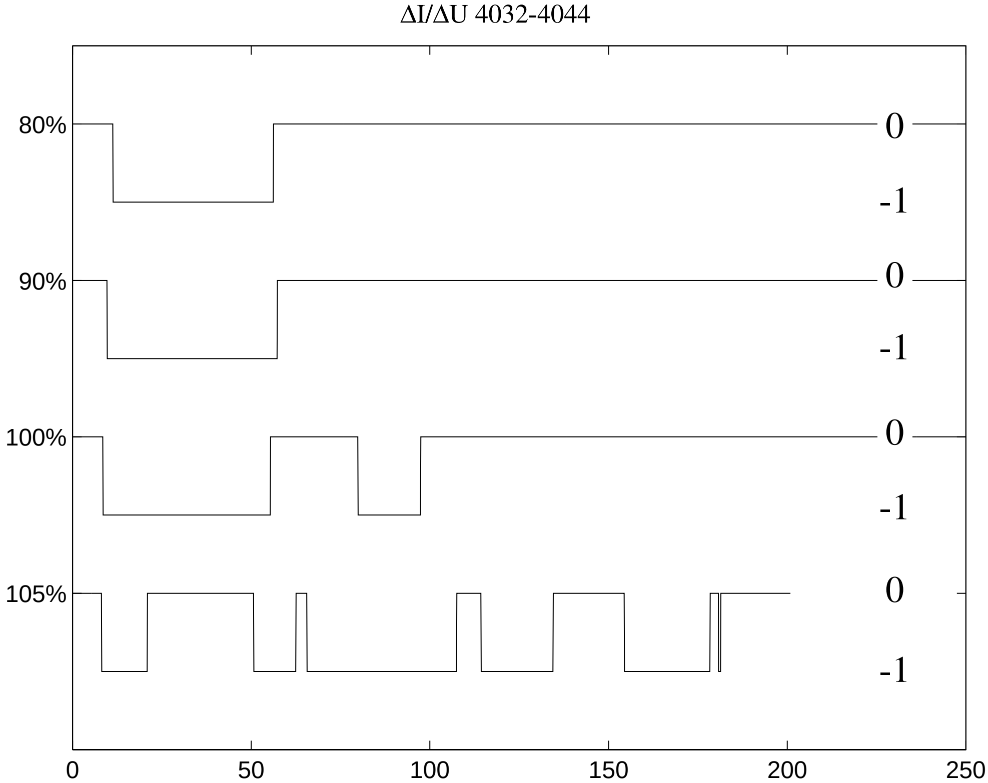

Figure 6.8 The ΔI/ΔU-signals as a function of time between 4032-4044. The current is measured from 4032 to 4044 and the node voltage is measured at 4032.

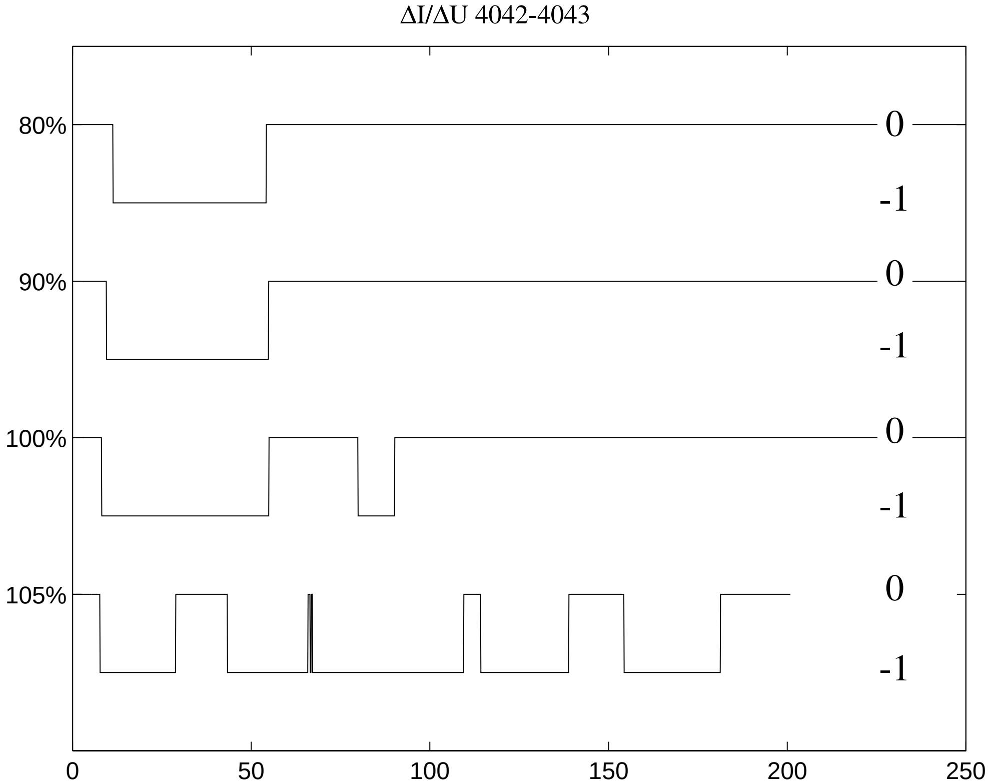

Figure 6.9 The ΔI/ΔU-signals as a function of time between 4042-4043. The current is measured at from 4042 to 4043 and the node voltage is measured at 4042.

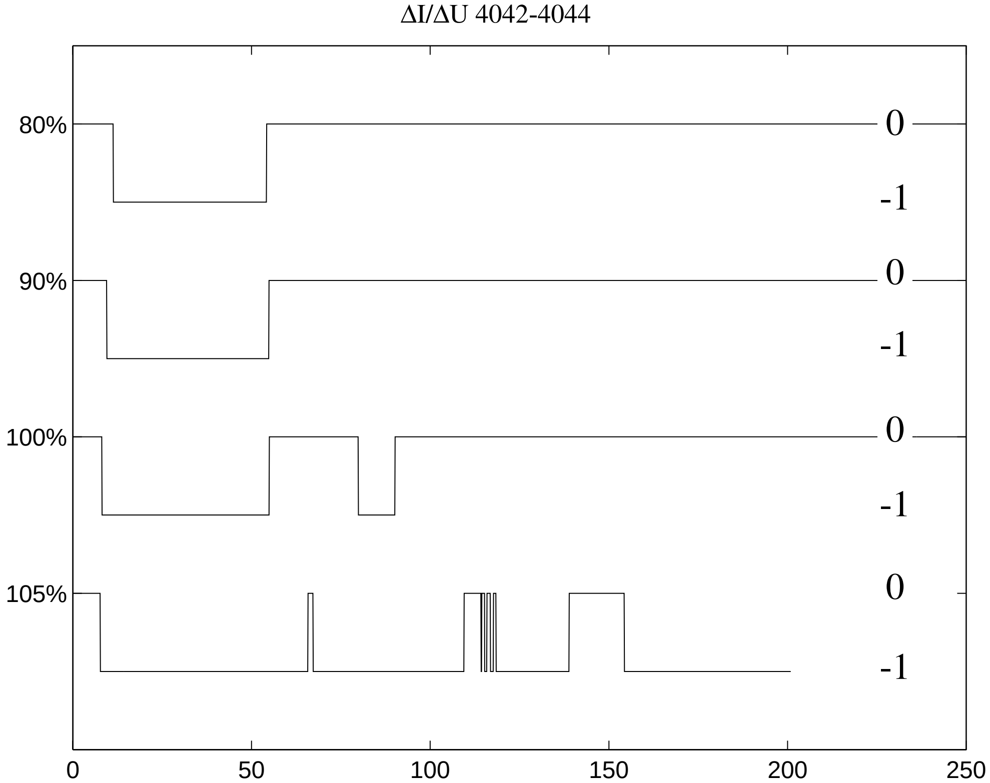

Figure 6.10 The ΔI/ΔU-signals as a function of time between 4042-4044. The current is measured from 4042 to 4044 and the node voltage is measured at 4042.

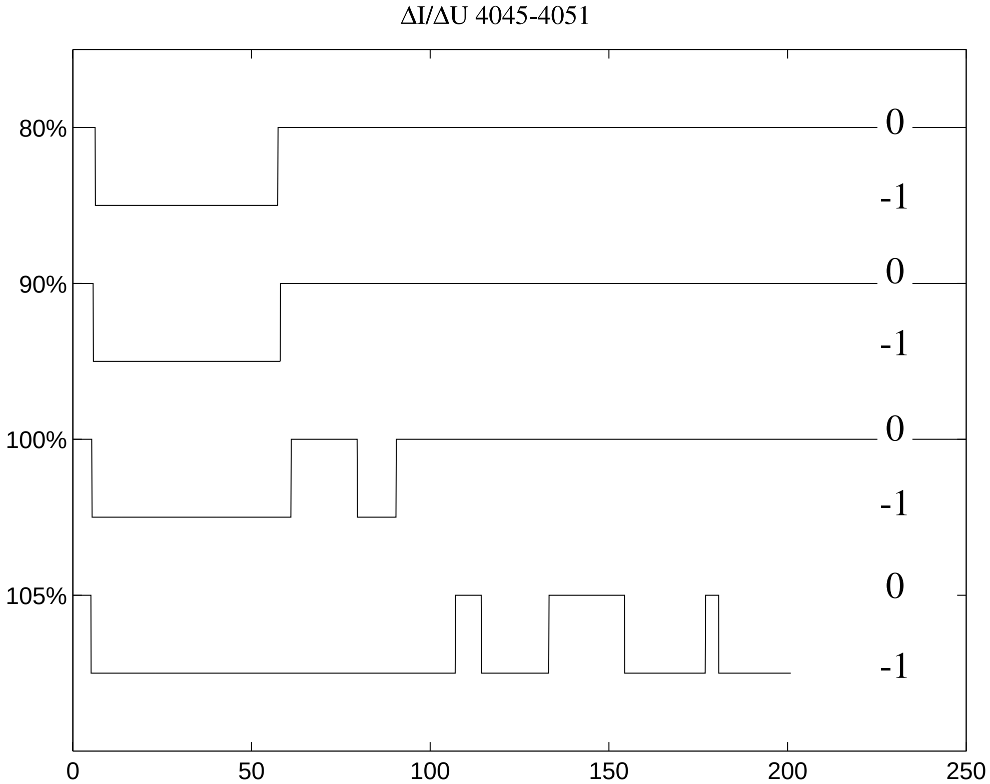

Figure 6.11 The ΔI/ΔU-signals as a function of time between 4045-4051. The current is measured from 4045 to 4051 and the node voltage is measured at 4045.

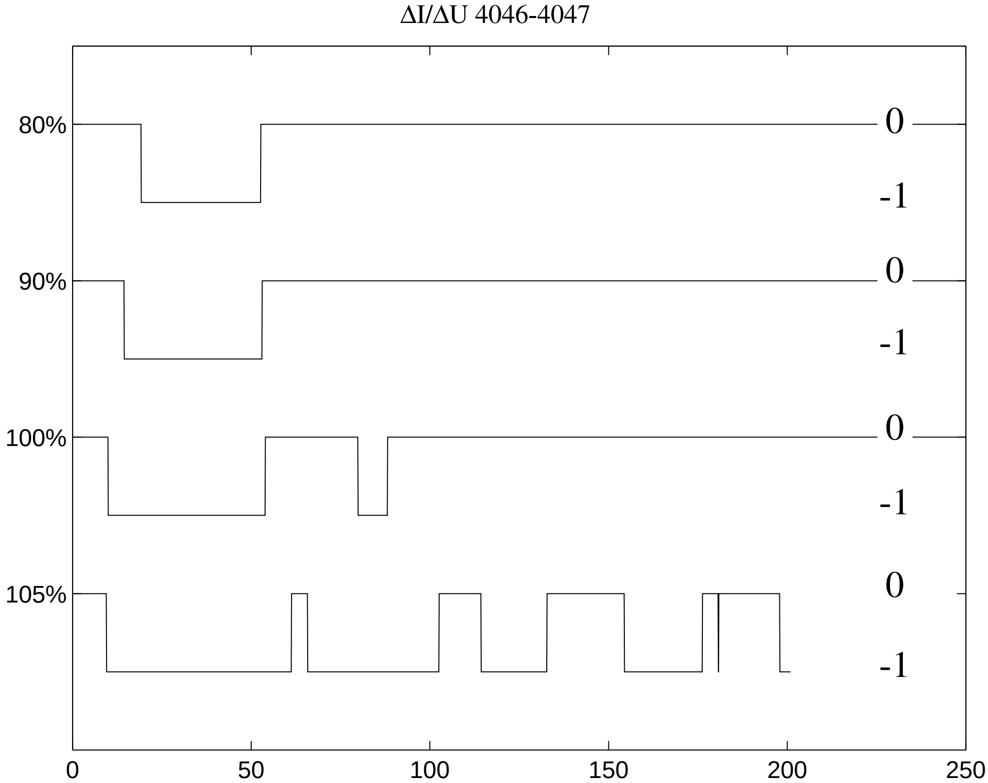

Figure 6.12 The ΔI/ΔU-signals as a function of time between 4046-4047. The current is measured from 4046 to 4047 and the node voltage is measured at 4046.

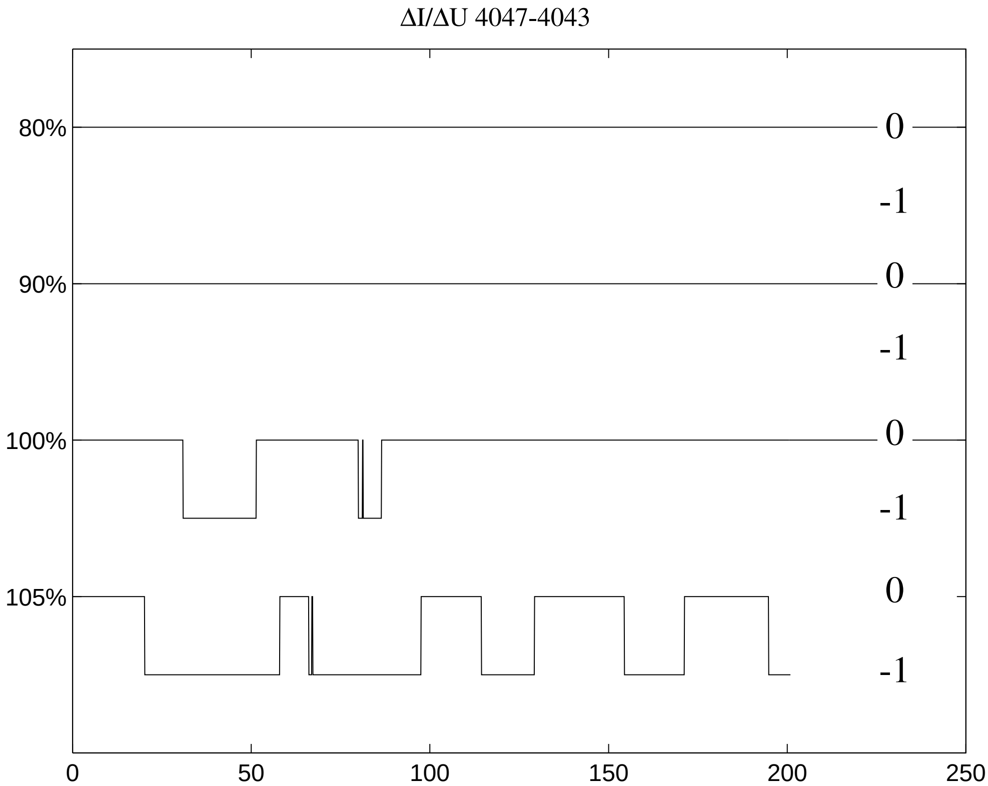

Figure 6.13 The ΔI/ΔU-signals as a function of time between 4047-4043. The current is measured from 4047 to 4043 and the node voltage is measured at 4047.

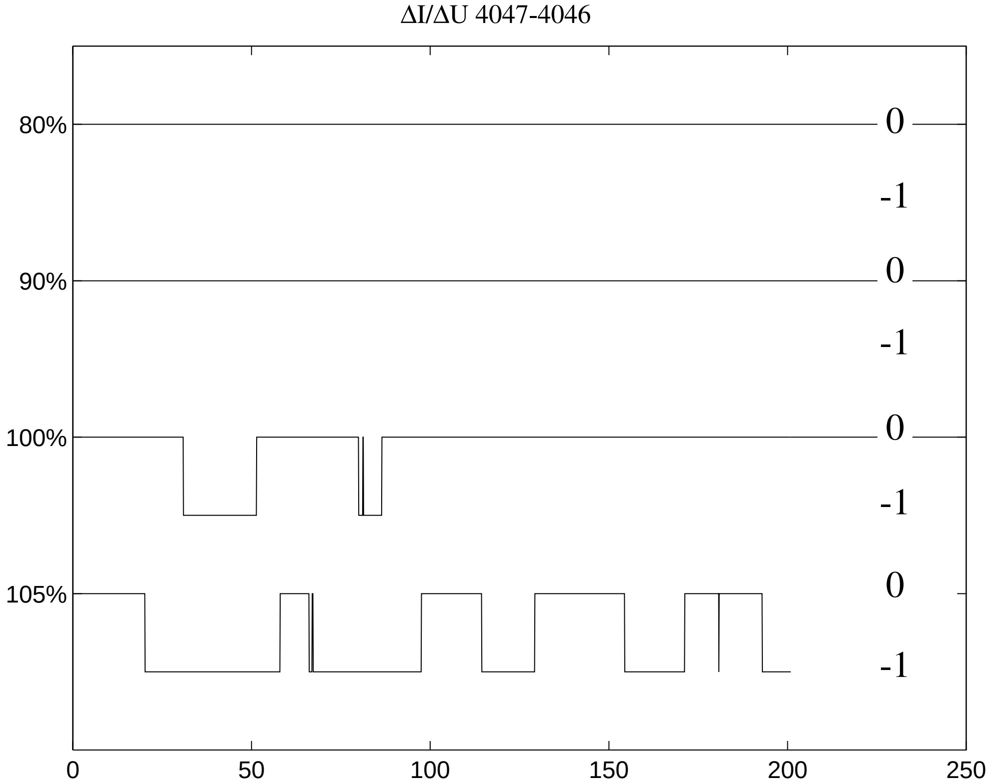

Figure 6.14 The ΔI/ΔU-signals as a function of time between 4047-4046. The current is measured from 4047-4046 and the node voltage is measured at 4047.

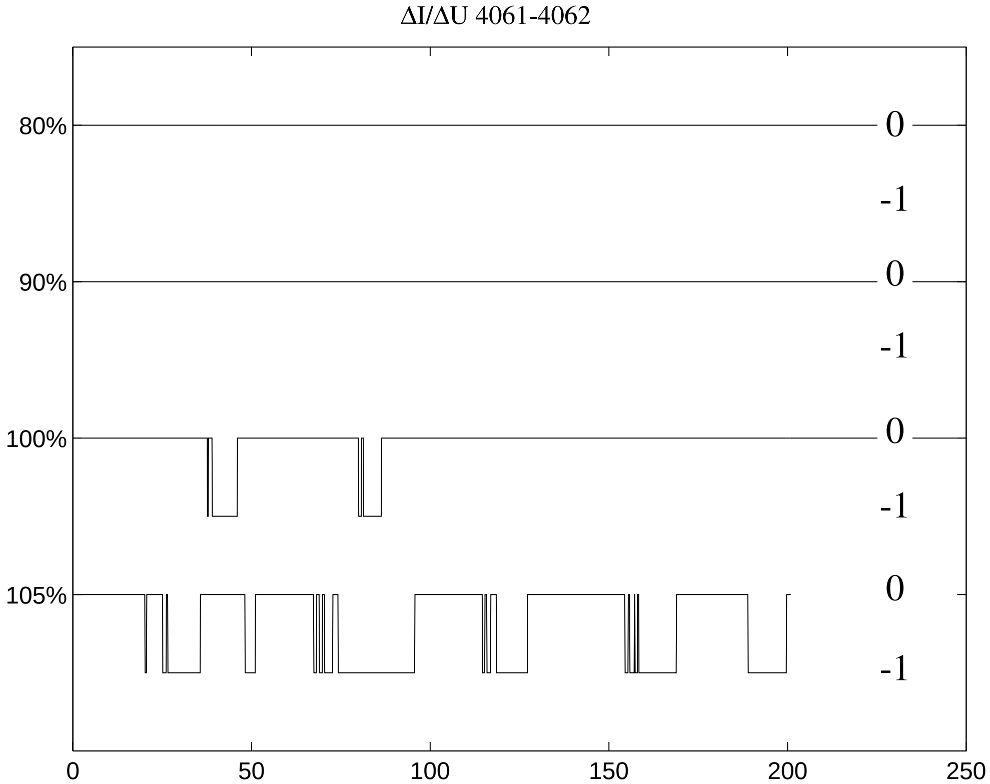

Figure 6.15 The ΔI/ΔU-signals as a function of time between 4061-4062. The current is measured from 4061 to 4062 and the node voltage is measured at 4061.

6.2 Discussion on ΔI/ΔU

The simulated ΔI/ΔU relation is nothing but the dynamic trajectory of the working point in the IU-plane. Similar thoughts with an analogous intention are studied in [3]. In order to explain the physical meaning of the negative ΔI/ΔU signal the following definitions have to be granted:

$$\text{Admittance: } Y(t) = \frac{I_{rms}(t)}{U_{rms}(t)} \tag{6.1}$$

$$\Delta I/\Delta U = \frac{I_{rms}(t_1 + \Delta t) - I_{rms}(t_1)}{U_{rms}(t_1 + \Delta t) - U_{rms}(t_1)} \quad \text{where } \Delta t = 1 \text{ s} \tag{6.2}$$

Observe that

$$\Delta I/\Delta U \neq Y(t_1 + \Delta t) - Y(t_1) = \frac{I_{rms}(t_1 + \Delta t)}{U_{rms}(t_1 + \Delta t)} - \frac{I_{rms}(t_1)}{U_{rms}(t_1)} \tag{6.3}$$

If the admittance is plotted as a function of time it may appear as in figure 6.16. The system can sustain an increased load admittance as long as the voltage regulation can preserve the voltage within a certain dead band. But as soon as the system does not manage to keep the voltage under control the ΔI/ΔU signal functions as an indicator and tells if the system is moving in a critical direction or not.

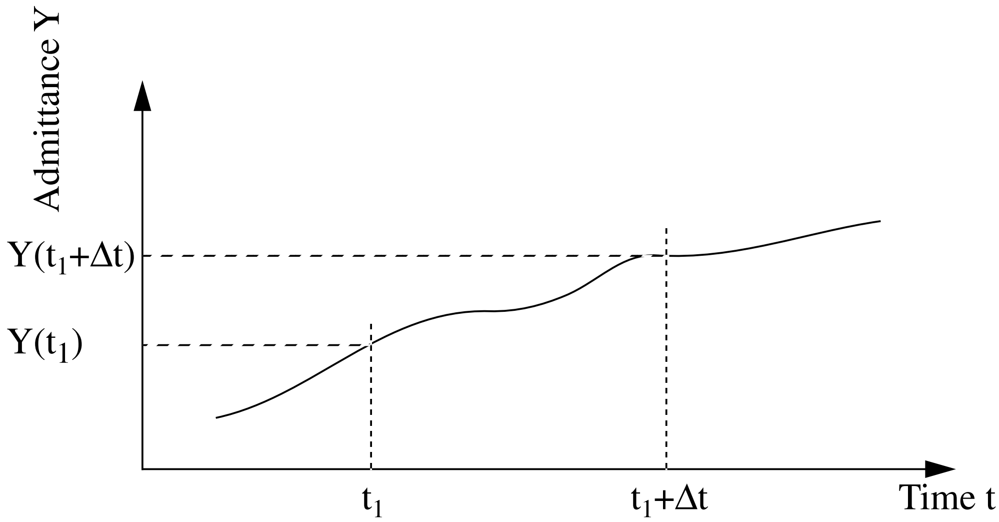

Figure 6.16 An admittance variation as a function of time.

6.2.1 The IU-trajectory in Cartesian coordinates

Each time step of the simulation gives a working point for all nodes in the entire system. Plotting the working points W(I(t),U(t)) in the IU-plane, will form a trajectory as in figure 6.17. Adding the conditions $U_{rms}(t_1)>U_{rms}(t_1+\Delta t)$ and $I_{rms}(t_1)<I_{rms}(t_1+\Delta t)$ to equation 6.2 gives the negative ΔI/ΔU signal which have been the subject of interest in the simulations. This negative slope of the IU-trajectory or negative ΔI/ΔU signal, describes a hazardous movement for a working point in the network.

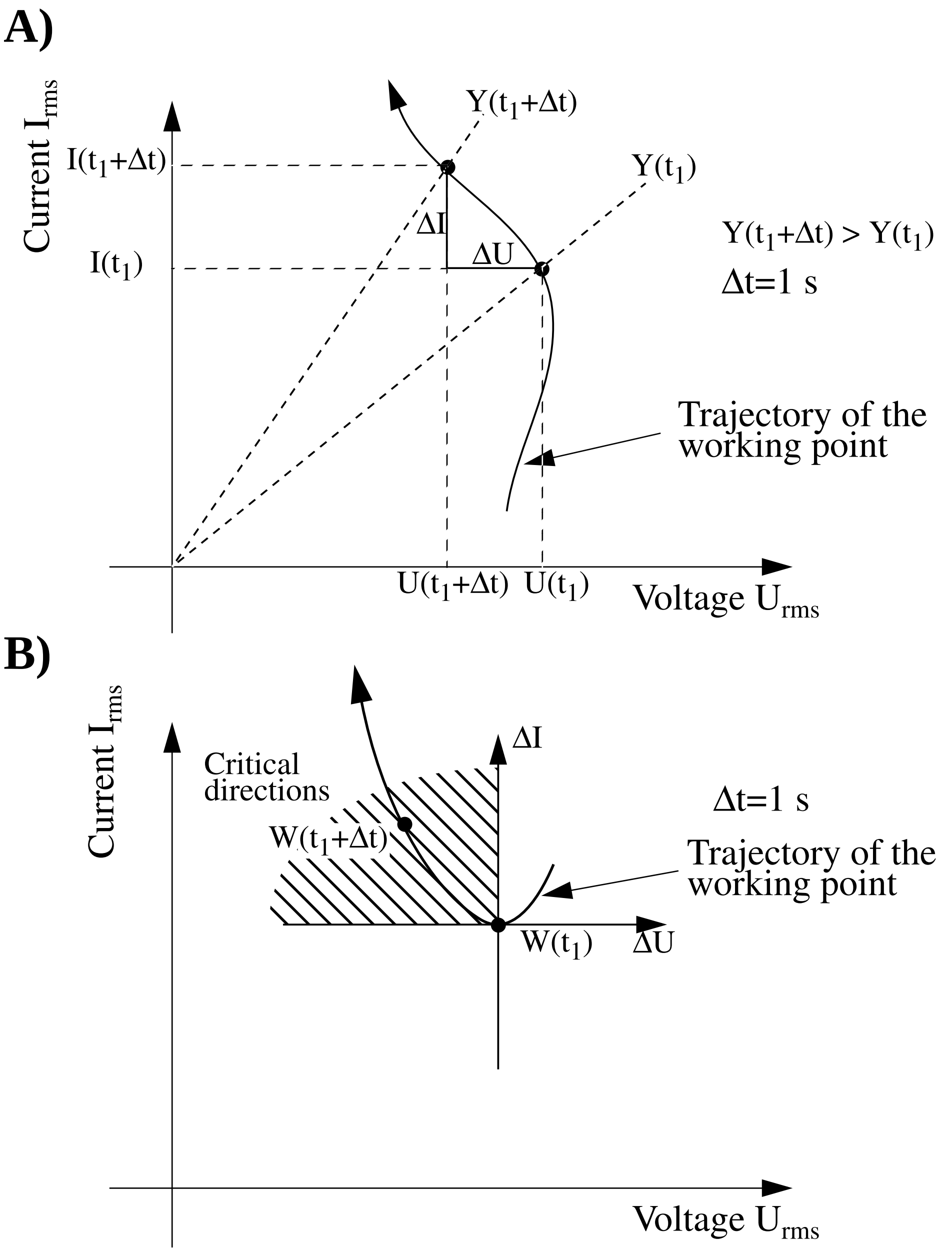

Figure 6.17 A: The IU-trajectory and two different working points. The ΔI/ΔU is negative in this case. B: The marked area symbolizes a dangerous direction in which the working point $W(t_1)$ can move.

For different load characteristics the IU-diagram will have the appearance as in figure 6.18. Assume the intersection between the load characteristics in the figure to represent the working point. If the working point moves in a direction that implies increased current and decreased voltage, it is quite obvious that we get a negative ΔI/ΔU and obtain load characteristics which are dangerous for the power system, for example constant power load.

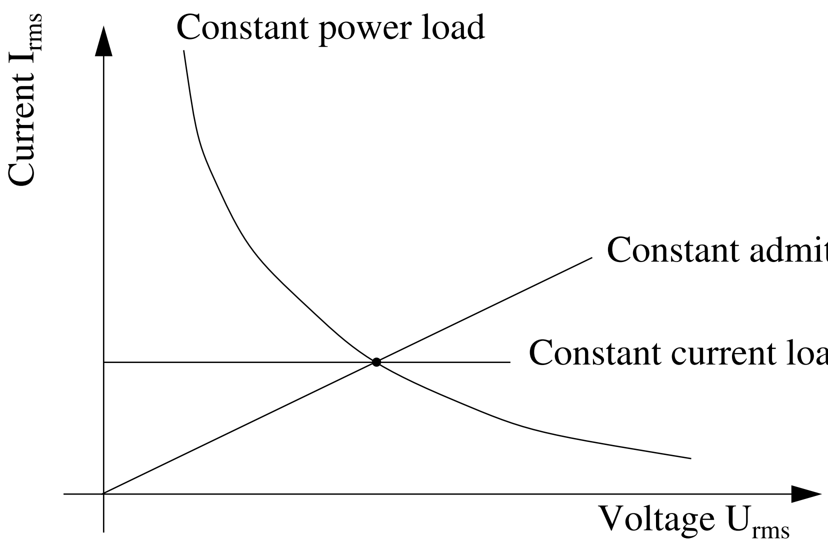

Figure 6.18 Different load characteristics in the IU-plane.

6.2.2 The IU-trajectory in plane polar coordinates

In order to get an other view of the IU-trajectory, a similar trajectory has been plotted which also includes the load angle (cosø). Figure 6.19 describes a passive linear network with a constant voltage source connected to a resistive load (cosø=1,0). If we change the relation U/I_b as illustrated in the figure and compare this change with the trajectory movement $W(t_1) \rightarrow W(t_1+\Delta t)$ in figure 6.17, we obtain the same negative ΔI/ΔU direction. Moving from the reference case $(U_1,I_{b1}) \rightarrow (U_3,I_{b3})$ in the figure below will be equivalent with the trajectory movement in figure 6.17.

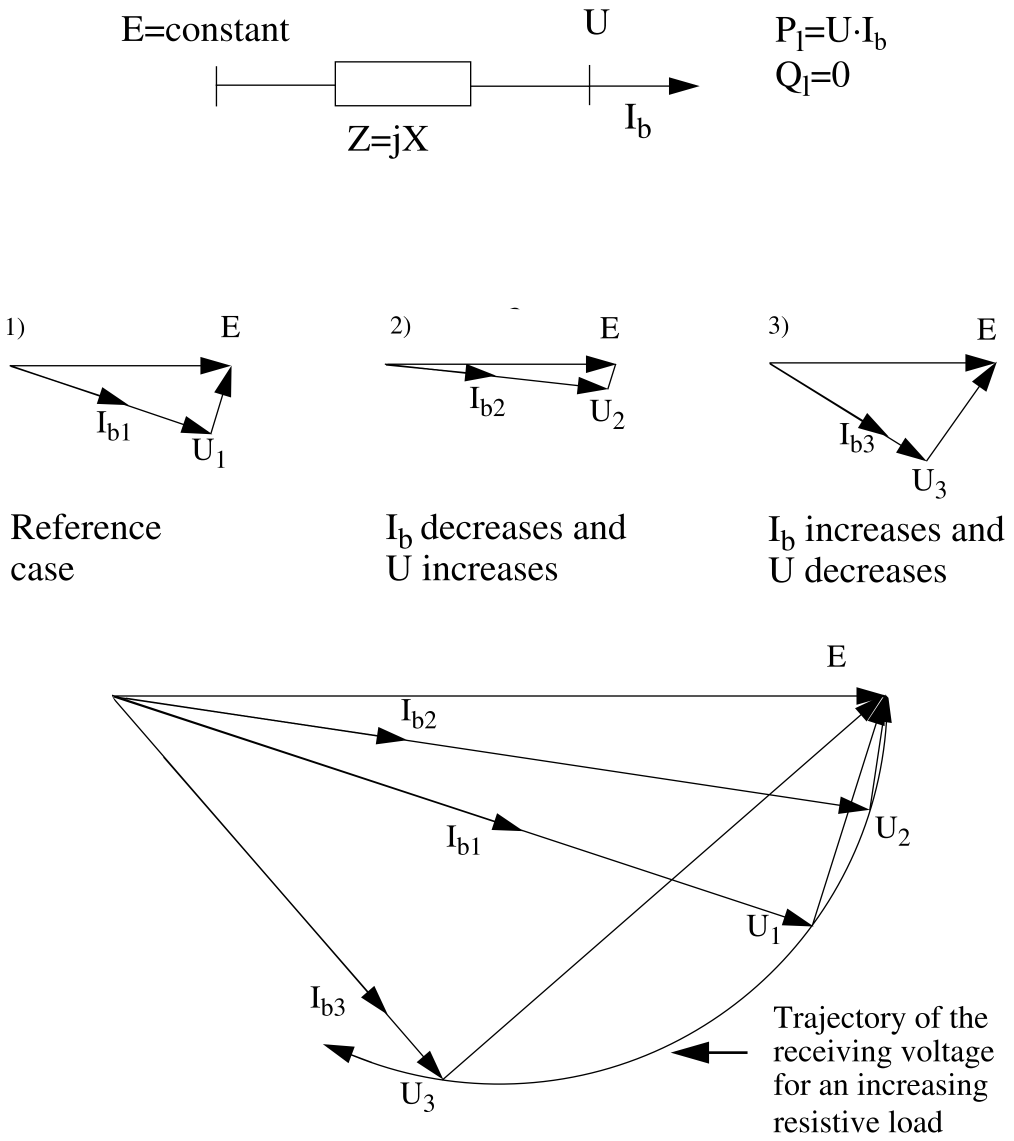

Figure 6.19 ΔI/ΔU in plane polar coordinates for a simple network with resistive load. Moving from U2⟶U1⟶U3 gives a negative ΔI/ΔU.

6.3 References

[1] CIGRÉ TF 38-02-08, ”Long Term Dynamics Phase II”, 1995.

[2] IEEE TF, “Load Representation for Dynamic Performance Analysis”, Transactions on Power Systems, Vol. 8, No. 2, May 1993.

[3] B.K. Johnson, “Voltage Collapse and Maximum Power Transfer Analyzed Using Current vs. Voltage Plots”, IEEE, NTUA Joint International Power Conference, Athens Power Tech, September 5-8, 1993

Chapter 7 Conclusions

There are two different kinds of issues that has to be taken into account during voltage stability studies. Firstly, there are physical laws which dictate what the power system does. Secondly, there are many different control and protection systems which regulate the system both continuously and discretely in a way that has been decided by the user. Sometimes conflicts occurs between these objectives. Voltage stability is to understand how everything works together.

7.1 Three sub-systems

The power system can be divided into three sub-systems: The generating part, the transmission part and, the distribution part with the load demand. Voltage stability problems can arise in any of these sub-systems and can be studied separately or in combination. In this dissertation, the following aspects have been studied:

The generation part
Field and armarture current limiters have a major impact on the generator capability. The transition between different control modes of the generator seems to be non-reversible from a system point of view if not radical control actions are taken.

The distribution part including the load demand
Load characteristics of asynchronous motors and dynamic load recovery due to electrical heating appliances may set the voltage stability limit for the system. The load characteristics are very important for the system behaviour. One significant boundary of this characteristic is a load behaving as a constant current load. For loads responding as an impedance, a voltage drop will unload the system whereas the opposite is valid for a constant power load. Note the strong coupling between dynamic loads and OLTCs. If the time constants are in the same order, an overshoot in power demand can arise.

Interaction between the generation and the transmission system
In case of field current limitation, the generator "synchronous reactance" is included into the transmission system. This alone can cause a collapse, force load voltages to a low value due to the increased reactance of the system. The field current limiter may force the working

point to the lower side of the U-P-curve which is an unstable operating point for certain loads.

Interaction between the generation and the distribution system
The armarture current limiter causes the generator to be very sensitive to the voltage characteristics of the load. If the load increases its current demand for a decreasing voltage, a severe voltage stability problem occurs. The on-load tap changer may also play an important role causing high currents in the generator.

Interaction between the transmission system and the distribution system
Transformers with on-load tap changers are usually located between the transmission system and the distribution system. The system response of a tap changing step is not obvious and depends on the load behaviour and the strength of the transmission system. A whole range of different responses is possible when OLTCs and loads interact.

The generator protection system together with OLTCs makes a voltage instability hard to reverse. The system might become stressed with low voltages in the transmission system and restored load voltages due to OLTCs. This restoration of the load voltage may cause a significantly higher primary current drawn from the transmission system. It is then difficult to restore the voltage in the transmission system. The reason is that the generator current limiters might prohibit an increase of reactive power output necessary to restore the tap changers to normal operating points and by this decrease the primary currents.

7.2 The voltage stability phenomenon related to current flows

We will emphasize the importance of studying the current flows due to the following reasons:

- On-load tap changers may amplify the load currents considerably.
- Armarture current limiters prohibits high currents out from the generator (or the generator is disconnected by overcurrent protection relays).
- Increasing currents (and decreasing voltages) might initiate transmission protective relays (distance relays) causing a voltage collapse. An increasing voltage-current angle may also initiate these relays due to their characteristics.

- Motor loads often show an increased current demand for decreasing voltage. This causes an increased voltage drop in the distribution system which may affect other components (e.g. other motors) in the surrounding area.

Our experience so far indicates that much knowledge and insight about voltage stability can be gained by studying the current flows in the network. Particularly the last phase in the collapse course is often affected by the current behaviour of loads and the system components.

It is shown that the trajectory of the current-voltage relation ($\Delta I/\Delta U$) can give new information about the system behaviour. In combination with other criteria the direction of $\Delta I/\Delta U$ might be an early indicator of an imminent voltage collapse.

Chapter 8 Future work

There is an international tendency to increase the power transfer limits in the networks and to improve the efficiency of existing power plants. The reasons are on the one hand the huge economical costs for new investments and the growing environmental concern, and on the other hand the considerable economic benefits to be gained. This will raise the requirements for more sophisticated computer programs and models and there will be ongoing efforts to maintain and to improve the reliability in the power systems. Therefore the need to improve planning and operation in power systems, underlines the importance of future work in the voltage stability field.

8.1 Load modelling

Today power system operators have access to a large number of dynamic models which quite well can illustrate a voltage collapse in a computer environment. But there is one important exception regarding certainty in dynamic load models. The reliability in these models is still too low, particularly as the dynamic load behaviour seems to be one of the major reasons for voltage collapse in power systems. It is therefore necessary to improve our knowledge of the load dynamics considered from the transmission level. The existing load models are more based on measurements and theoretical analyses of individual load devices than on field measurements, and the few measurements that have been made are mainly done on the distribution level. This is the reason why the dynamic voltage dependency of the aggregated load representation is hard to define. The dynamic load models that exist are certainly general enough, but all of them contain key parameters which have not been verified. The lack of field measurements on higher voltage levels and the economical benefits of using more accurate load models implies that dynamic load models is an important issue for further research and development.

8.2 Improvements of generator capability

When studying current limitation in large generators it is evident that current limiting causes a strong reduction of the voltage stability margin in the area near the generator. This reduction in voltage stability or reactive power generation is a contributive factor to voltage collapse in power systems. Since both the armature and the field current limiters are intended to protect the generator from exceeding its thermal limit, it is necessary to analyse the possibility to use the thermal capacity in a more efficient way. A strategy could be to use the remaining thermal capacity in the generator windings in order to provide a stressed network with extra reactive power. It might be feasible to exceed the thermal limits over a period of minutes in order to start gas turbines, but this approach needs an analysis of the pay-off between an acceptable ageing and the consequences of a collapse. A better utilization of the thermal capability of existing generators might be an economical way to improve voltage stability in a power system.

8.3 System protection scheme

Increasing the transfer limits in a network without endangering voltage stability requires a detailed knowledge on the voltage sensitivity of the system and a fail-safe system protection scheme. The development work of these system protection schemes has proceeded for a couple of years and a general strategy of how to obtain relevant information of an impending voltage instability is slowly growing. The most commonly used indicators of an impending voltage collapse are: decreasing reactive power reserves, declining voltages, and combinations of these two. As only a few of them are in operation there is still much research to do in the network protection field. It has been shown, that the $\Delta I/\Delta U$ variable is an interesting parameter which might be used as an indicator for an imminent collapse. Further analysis and probably field measurements has to be done in order to judge the value of the $\Delta I/\Delta U$ variable as an operational quantity.