Voltage Stability – Modelling and System Protection Scheme

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Abstract

This report describes power system component and system modelling for voltage stability studies, as well as a protection system against voltage collapse installed in Sweden. The importance of detailed and accurate models for dynamic loads, tap changer control, generator current limiters and distribution systems is demonstrated in the paper. The necessity to go into details and to do experiments is also emphasised and illustrated.

Introduction

Voltage stability, as a phenomenon, has been studied for some decades now. There is however no generally accepted stringent definition of voltage stability or voltage collapse. Both IEEE and CIGRÉ have their respective definitions [1,2]. Voltage stability can be interpreted as the capability of the power system to maintain voltage equilibrium at reasonable voltage levels. There are essentially three types of voltage collapse:

1) Transient voltage collapse, time scale of a few seconds, which occurs immediately after a very severe disturbance. In this case it is not possible to find any equilibrium point after the disturbance. The typical example is a brush fire, across a number of parallel transmission lines. Example: South Florida, May 1985 [1].
2) Longer term voltage collapse, time scale of 10 seconds to 10 minutes. The system survives the initial disturbance, e. i. an equilibrium point is reached immediately after the disturbance, but due to load recovery and control system actions (such as on-load tap changer operation) the power demand is increased and the weak system will finally collapse. Example: Sweden, December 1983 [3,4], France January 1987 [5].
3) Longer term voltage collapse due to load growth, time scale tens of minutes. Without any initial disturbance a rapid load growth can slowly bring the system to a collapse. Example: Tokyo, July 1987 [6].

Beside the phenomenon of voltage stability and collapse itself, stability margins and indices have been defined and methods to derive such quantities have been developed [7]. Some researchers in the field use simulations in order to include the dynamics of load, tap changers, and generator reactive power capacity limits in the voltage collapse studies [8,9,10]. Good surveys of the voltage stability discipline can be found in references [1,4,11], where theory as well as analytical tools and industrial experience are presented. The phenomenon of voltage stability is very often illustrated by the so called nose-curve, see Figure 1, where the receiving end voltage in a transmission system is plotted against the receiving end real power (the power factor or the reactive power is often used as a parameter).

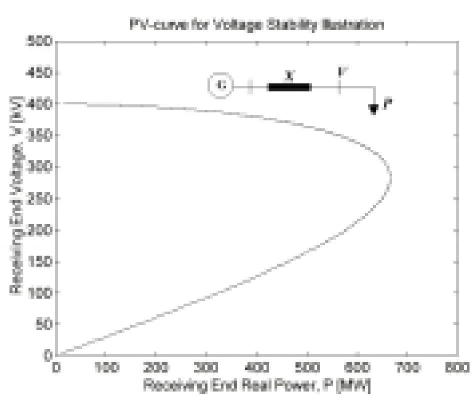

Figure 1. Nose-curve for voltage stability illustration.

It has to be remembered that the nose-curve is a static description of the transmission system capability. If dynamic aspects are taken into consideration, which is necessary for a complete analysis, the nose-curve has to be modified.

As the demands concerning return on investment for power systems around the world increases, different ways to utilise the system harder and closer to its limits are studied. Since the risk of voltage collapse is the limiting factor for the transmission capacity in many power systems, detailed studies, based on accurate models are requested. On-line real-time simulation tools to keep track of the operational risks have been developed, as well as protection systems against voltage collapse [10,12]. Having a protection system against voltage collapse installed, the operational requirements could be changed from "the system should withstand the most severe single fault" to "the system should withstand the most severe single fault *followed by protective actions from the voltage collapse protection system*".

Load Modelling

The modelling of power system loads has been shown to be extremely important for voltage stability studies. For transient angular stability studies, impedance characteristic load models are mostly accurate enough. For long term planning and loadability, studies constant power load models are used. The phenomenon of voltage stability is in the time scale from just a few seconds to tens of minutes. Therefore accurate load models for the entire time frame are necessary. Depending on the type of load, degree of reactive power compensation and load control system a corresponding load model has to be chosen. Sometimes even on-load tap changers and shunt capacitors in the distribution system are included in the load. For longer term voltage stability studies (longer than a few seconds) induction machines can be regarded as constant power load objects. For shorter term studies a short load relief, a few seconds, can be achieved. Special attention has however to be paid to reactive power compensation close to the motors, the capacitors will behave like constant impedances. Therefore low voltage in induction motor dominated load areas will keep the real power close to the nominal value, but additional reactive power have to be transmitted from neighbouring areas, with further voltage drop and perhaps a collapse as a consequence.

Detailed load model studies have been performed in Swede, where quite extensive field measurements were included [13,14,15]. Two substations, each one feeding about 10,000 households, were used. One substation fed a pure residential area with dominating household load, while the other substation fed a small town and a rather large industry. The recordings, to find out the dynamic behaviour of the load with respect to the applied voltage, were made during winter, spring and summer as well as for different times of the day. No on-load tap changers were activated in the load area and no shunt compensation was connected. For the excitation of the dynamic load response different shapes of the applied voltage magnitude were used, such as step, ramp, sine (staircase approximation) and pseudo random binary sequence. The voltage variations were achieved by quick manual operation of the tap-changer on the feeding transformer (ramp and sine) and by switching the transformer circuit-breaker on one out of two parallel transformers with tap changers at different positions, see Figure 2.

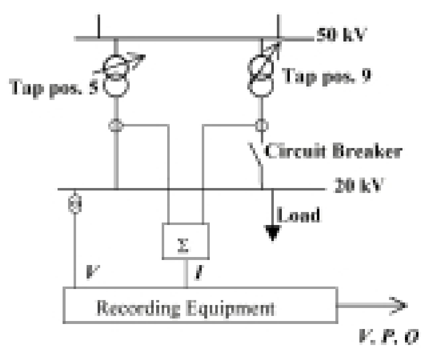

Figure 2. Arrangement for the voltage step-change recordings. The two tap changers were set at different tap positions. The circuit-breaker for one of the transformers was used to create the step.

The analysis was concentrated to the voltage step change. Results from the recordings are shown in Figure 3. The basic behaviour of the load was similar, irrespective of the time of the year and the day. It was also similar for both load areas. The amount of load recovered, the time constant, etc. differed however between the recordings.

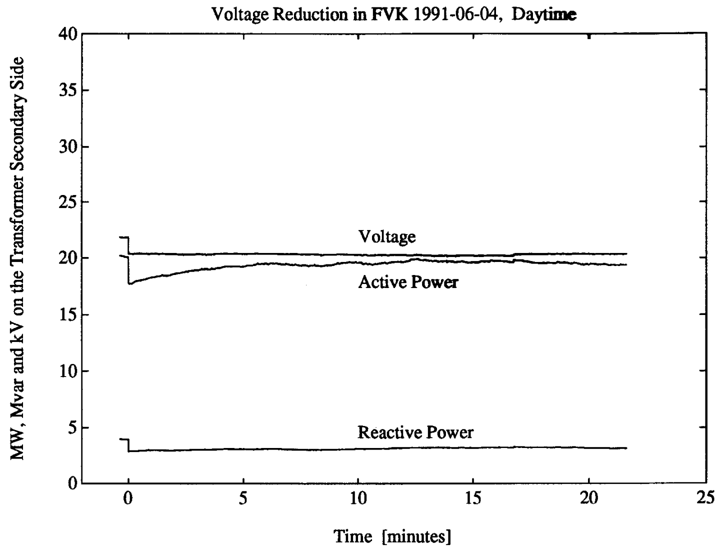

Figure 3. Active and reactive power recording from the pure residential area; June; daytime.

From Figure 3 we see that a voltage drop of about 10% (from 22 to 20 kV) cause an initial drop in real power of about 20%, which corresponds to the impedance load model. But after about 5 minutes the real power has recovered to a level that is just slightly below the pre-disturbance level, which corresponds to the constant power load model. The initial drop in reactive power is larger than for the real power, but the recovery is less pronounced. For both real and reactive power, it seems reasonable to assume that a dynamic load model comprising the transient and steady state level, combined with a time constant, according to Equation 1.

$$T_{pr} \cdot \frac{dP_r}{dt} + P_r = P_0 \cdot \left(\frac{V}{V_0}\right)^{\alpha s} - P_0 \cdot \left(\frac{V}{V_0}\right)^{\alpha t} \; ; P_{\text{model}} = P_r + P_0 \cdot \left(\frac{V}{V_0}\right)^{\alpha t} \tag{1}$$

The load area contained a great deal of electric heating, therefore a time constant of about half an hour was expected for the recovery, due to house insulation. The very short recovery time was a bit surprising, until the most common space heating thermostat, the bimetallic thermostat, was studied. This thermostat is equipped with an acceleration element, which is energised during the on-period and heats the bimetal, to switch off the heater a bit earlier in order to avoid temperature overshoot due to remaining heat in the radiator at switch off. To improve the capabilities of the thermostat a compensation element that is energised during off-periods is added, see Figure 4. Of course the voltage dependence of these resistors, acting directly on the “controller” of the load object, has a great impact on the overall behaviour of the load. Tests were also performed in an apartment, which showed that if the supplying voltage was decreased, the temperature in the apartment increased [16].

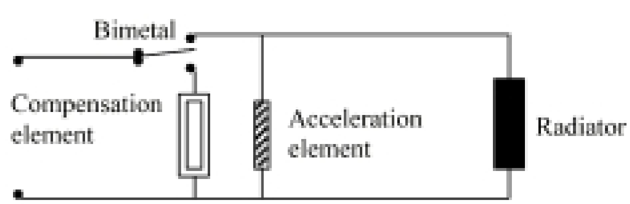

Figure 4. Bimetallic thermostat equipped with acceleration and compensation elements.

The experience referred above raises of course the very important question: - What other control systems acting on the main load devices do we have in our power systems that significantly will affect the behaviour of the system during abnormal operation conditions. From the study above we learned that we have to do experiments, both in the laboratory and in the field, and we do have to go into details. During this load model project we had a very fruitful co-operation between the Swedish universities and the power industry – the field measurements were performed within the industry and the main part of the analysis was made at the university.

On-Load Tap Changer Control

The purpose of on-load tap changer control in electric distribution systems is to keep the voltage on the low voltage side of the step-down transformer within certain limits. Figure 5 shows the corresponding nose-curve when the tap changer keeps the voltage at the receiving at a constant value.

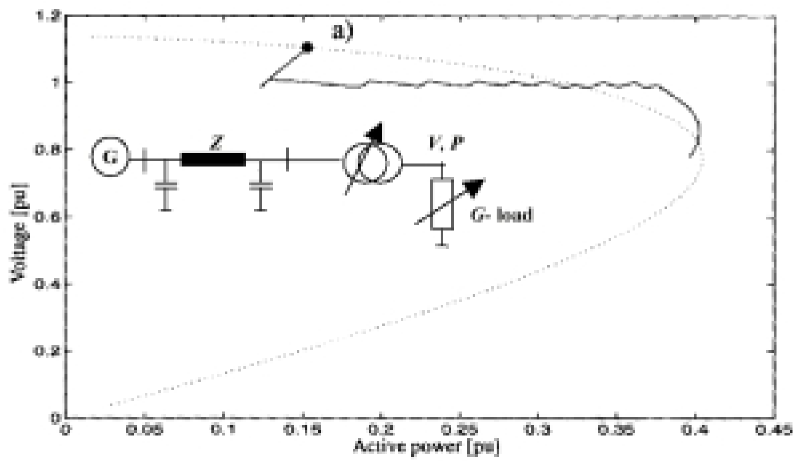

Figure 5. Nose-curve at tap changer control for slow load increase, from [17].

The tap changer control is operating on local criteria only. In Sweden up to four levels of cascaded tap changers can occur (e. g. 400/130, 130/50, 50/20, 20/10). After a large voltage reduction on the 400 kV transmission level, which is the most likely initial consequence of a disturbance that might develop to a voltage collapse, all the tap changer controllers in the system try to re-establish their low voltage side voltage level. With many cascaded tap changers there is a risk for voltage and power overshoot on the load connection level, which might collapse the system. The blackout in Sweden 1983, was found out to be caused by tap changer actions, that slowly re-established the voltage on the load level and thereby ruined the, already weak, transmission system. The collapse appeared about 50 seconds after the initial disturbance. Many countries, such as France and Japan, only use two levels of cascaded tap changers, which makes these systems easier to handle. An experiment was performed in the very south-west of Sweden, where the 130 kV subtransmission voltage was manually decreased by about 6%, using the tap changer of the nearby 400/130 kV transformer. Three levels down stream (130/50, 50/20, and 20/10) on the load level, a temporary voltage overshoot of about 2% was experienced for about 2 minutes, around 5 five minutes after the initial voltage reduction.

With co-ordinated tap changer control would it be possible to use the tap operations to “help the system”, during stressed voltage conditions. The voltage on load level could for example be kept reduced in a residential system after a disturbance in the transmission system, but could be re-established in industrial areas and in systems with a high degree of shunt compensation. Co-ordinated tap changer control would also reduce the wear and maintenance of the tap changer and improve the voltage profile. Field tests including 3 levels of cascade tap-changers in the very south-east end of Sweden showed a potential to reduce the total amount of tap operations by about 50%, if communication between the substations is available [18]. Even without communication a tuning strategy, with the shortest delay time for tap operations in the feeding end and the delay time increased a factor 2.2 for each level towards the load, will provide good stability for transmission level voltage reduction as well as for normal operational conditions.

Current Limiters on Large Generators

Large generators connected to transmission systems are equipped with field current limiters affecting the AVR, to keep the field current below a certain upper level. Some large turbo generators also have armature current limiters, which control the AVRs in such a way that the armature current is limited to a certain level. The impact on the nose curve of these limiters is very clearly shown in Figure 6. If no limiter is activated the load admittance increase follows the characteristic of the transmission system. When the field current limit is hit, (there is a small overshoot, due to a time delay in the limiter), the load characteristic follows another characteristic. This field current limited characteristic curve is similar to the original one, but with different parameters. The point of sending end constant voltage has been moved for the generator terminal to a point behind the synchronous reactance of the generator. When the armature current limit is hit, there is a similar overshoot, but the shape of the characteristic for increased load admittance is significantly different. A constant load current is maintained, and when the load admittance is increased the load voltage as well as the load power are decreased.

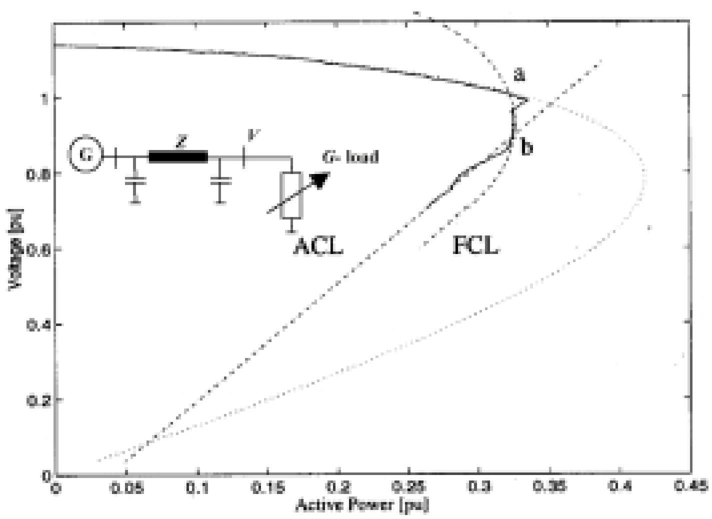

Figure 6. Effects of the armature (ACL) and field (FCL) current limiters on the nose-curve, from [17].

Distribution System Modelling

Radial system model aggregation is necessary to be able to perform full scale simulations for adequate voltage stability studies on large transmission systems. The aim of this model reduction project [19] was to reduce a radial distribution system, without any significant generation, to a simple branch model (Π-link), reflecting the lines, transformer impedances and shunt devices in the network, a tap-changer model, reflecting the behaviour of the parallel and cascaded tap changers, and a dynamic load model. Extensive simulations showed that the distribution system model in Figure 7, was able to capture the essential behaviour of the entire distribution system (as modelled in detail) for voltage stability studies.

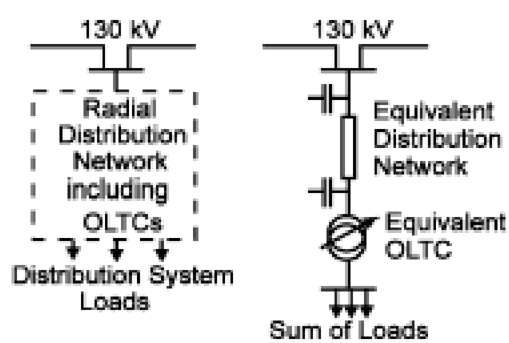

Figure 7. The distribution system and its equivalent model.

Full scale voltage reduction test in a 2000 MW system

Based on the detailed studies of aggregated loads and specific load objects, the impact of on-load tap changers in distribution systems and current limiters on generators, a full scale transmission system voltage reduction test was performed in the entire South of Sweden, with a total load of about 2000 MW [20]. The tap changers on ten 750 and 500 MVA transformers, connecting the 400 kV transmission system to the 130 kV subtransmission system in the South of Sweden, were used to manually lower the 130 kV voltage with up to 5%, as fast as possible. Real and reactive power, as well as voltages, on the transformers and tie lines were recorded during the experiments. The idea was to get the total response from the underlying system due to a voltage reduction in the transmission grid; including load dynamics, tap changer operations and local generation. The results could then be compared to simulations using detailed models of each type of power system component and load. The essential results from the recordings are shown in Figure 8.

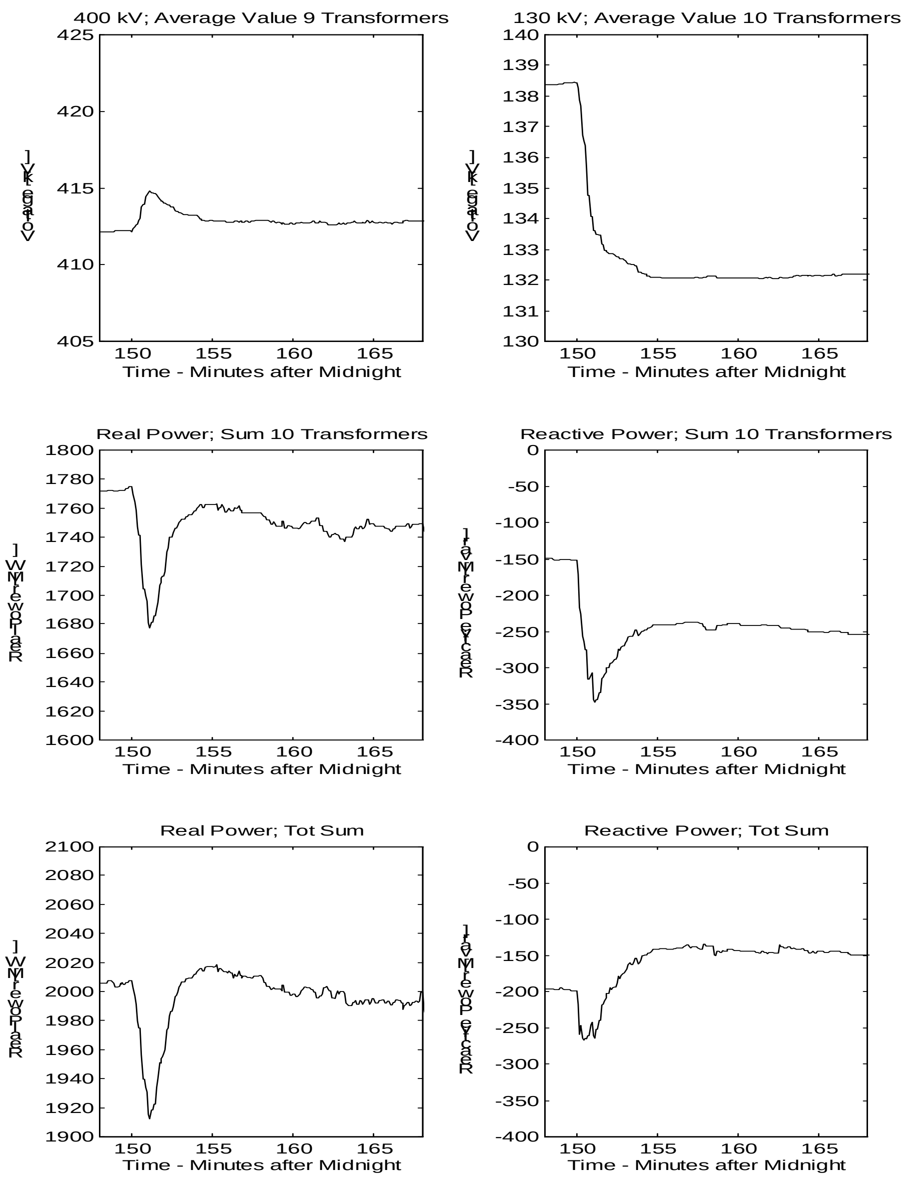

Figure 8. Results from voltage reduction test; voltages in the 400 and 130 kV system; real and reactive power through the 400/130 kV transformers, and total import of real and reactive power to the area of voltage reduction.

It is obvious that there will be a real power load relief, immediately after the voltage reduction, which is recovered to a large extent after a few minutes. There is, however, much time for automatic remedial actions to counteract a collapse. Concerning the reactive power, the reactive power flow from the transmission system to the 130 kV grid through the transformers is reduced, while the total reactive power consumption in the 130 kV system increases. The deficit is supplied by the 130 kV tie lines into the area.

System protection scheme against voltage collapse in the South of Sweden

The objective of the system protection scheme is to avoid a voltage collapse after a severe fault in a stressed operation situation. The system can be used to increase the power transfer limits from the North of Sweden or to increase the power system security or to a mixture of both increased transfer capability and increased security. The system protection scheme was commissioned in 1994 and is designed to be in continuous operation and independent of system operation conditions such as load dispatch, switching state, etc [21].

A number of indicators such as low voltage level, high reactive power generation and generator current limiters hitting limits are used as inputs to a logical decision-making process implemented in the Sydkraft SCADA system. Local actions are then ordered from the SCADA system, such as switching of shunt reactors and shunt capacitors, start of gas turbines, request for emergency power from neighbouring areas, disconnection of low priority load and, finally, load shedding. Shedding of high priority load also requires a local low voltage criterion in order to increase security.

The system protection scheme is designed to have a high security, especially for the load-shedding, and a high dependability. Therefore a number of indicators are used to derive the criteria for each action. The logical system is designed in such a way that a faulty indicator should neither cause an unwanted operation nor a missed operation by the system protection scheme.

Simulations with the PSS/E program have been used to find relevant set-point values of the indicators. Detailed user-written models for the load dynamic, the on-load tap changer control and the generator current limiters have been used. Even the actions of the system protection scheme have been included in the PSS/E simulations. The simulations show that the collapse in Southern Sweden will occur at quite low voltage values in the 400 kV system. It was also found that a collapse always occurred if the armature current limiter at Barsebäck nuclear power plant reached its limit, and no preventive actions were taken. According to the simulations, the system protection scheme has turned out to be very efficient.

The voltage levels in six 400 kV stations are used as indicators together with the reactive power output from five generator units and the current limiters from two large turbo generators.

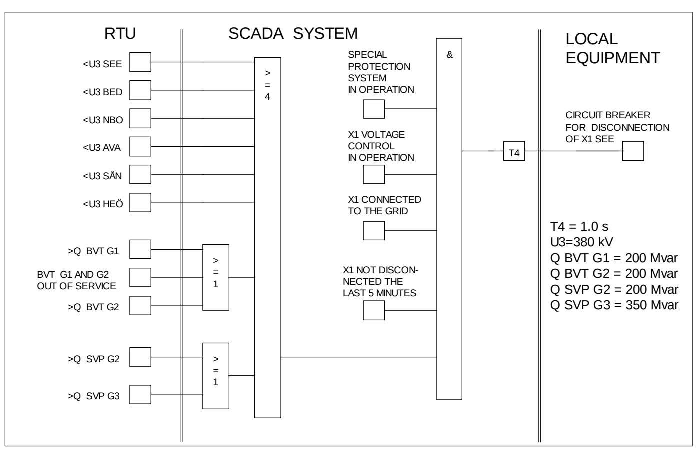

Figure 9. System protection scheme using system wide data for local action.

All the shunt reactors connected to the 400 kV grid and most of the shunt capacitors in the 130 kV system are affected by the system protection scheme. Emergency power is requested from Germany by the Baltic Cable HVDC link. A certain amount of low priority heating load will be disconnected. The same load areas as for the underfrequency load shedding system are used for this system protection scheme. The basic structure for the actions by the protection scheme is shown in Figure 9.

Discussion

The research and development work described in this paper might be regarded as first steps towards, increased knowledge about the voltage stability phenomenon, simulation methods and protection strategy against voltage collapse. In Sweden, we enjoyed a very fruitful co-operation between the power industry and the Swedish universities, and we are still surprised that this working practice is still quite unique in the world. The next steps will probably be to design more intelligent protection systems that are more flexible and adaptive to actual situations. We will probably soon get a more intense discussion about tools for control centres and the way that emergency control actions are divided between operators and automatic functions. There is still a lot to learn about voltage stability and collapse, especially concerning the cause and development of the collapse as well as detailed component and control system behaviour. There also remain a large amount of research to be done in the area of *preventive* planning and operation as well as in the area of *curative* emergency control and protective actions.

Based on the work reported in this paper, it is the ambition of the author, that other researchers in the field of voltage stability get encouraged to continue the work in this important area. Recent incidents and blackouts confirm that there is still a lot of work to do [22,23].

Conclusions

The area of voltage stability and voltage collapse has been addressed in this report. Detailed load modelling for voltage stability studies based on field and laboratory measurements, as well as theoretical work has been reported. Accurate modelling methods for tap changer control, generator current limiters and distribution systems has been referred and described. The properties of an entire, meshed 2000 MW subtransmission system have been studied in a full scale voltage reduction test. Finally the description of the first generation of protection scheme against voltage collapse in Sweden, has been given. It has been shown in the paper that it is necessary to do experiments and it is necessary to go into details.

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