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CLARIFY BASIC VOLTAGE COLLAPSE IN POWER SYSTEM

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This Report Is Submitted In Partial Fulfillment Of Requirements For The Degree of Bachelor In Electrical Engineering (Industry Power)

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March 2005

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Ir. Rosli Omar, for his engagement, support, encouraging attitude, coursed and editorial advise in preparation during this project. I also express my thanks to my panel Dr. Musse. Also a very sincere thanks to the Final Year Project Coordinators Faculty of Electric for their guidance and help. Also not forgetting, my grateful thanks to my beloved, my colleagues for providing me support, advise in preparing this project and for creating a cheerful atmosphere.

Thank you all.

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ABSTRACT

This report aims to give a approach to the problem of voltage instability and collapse. The main symptoms of voltage collapse are- low voltage profile, heavy reactive power flows, inadequate reactive support, and heavily loaded system. The collapse is often cause by low-probability single or multiple contingencies. The consequences of collapse often require long system restoration, while large groups of customers are left without supply for extended period of time. Voltage stability analysis methods such as the PV-analysis, and in particular the QV-analysis, will be used along with simulations in order to determine the test system proximity to a system voltage collapse. All the simulations are to be done with a constant load model, in other words, a static model is assumed throughout the simulations. The software used to do the simulations is Power World Simulator.

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ABSTRAK

Laporan ini bertujuan untuk memberi penjelasan bagi masalah terhadap " Voltage instability and Collapse". Kesan utama bagi masalah ini adalah kerana profil voltan yang rendah, 'heavy reactive power flows', 'inadequate reactive support' and sistem yang diberi beban yang lampau. Collapse ini terjadi kerana kebarangkalian rendah secara siri dan selari. Kesinambungan collapse ini memerlukan sistem 'restoration' yang lama. Analisa kestabilan voltan seperti analisis PV dan analisis QV, akan digunakan secara kesinambungan dengan simulasi untuk mengenalpasti ujian terhadap kebarangkalian system collapse voltan. Kesemua simulasi ini perlu dijalankan dengan beban yang stabil dengan penggunaan beban static perlu dijangkakan dengan penggunaan simulasi. Perisian yang digunakan bagi tujuan simulasi adalah 'Power World Simulator'.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Overview

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

In this section, most of the discussion here is based on power system voltage stability. The ability of a power system to maintain steady acceptable voltages at all busses in the system under normal operating conditions. The power system is considered voltage stable if voltages after a disturbance are close to optimum voltages i.e. 0.95 – 1.05 pu during normal operation.

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

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reflect that there is not enough knowledge about the phenomenon itself to establish a generally accepted definition at this stage.

According to CIGRÉ [1] voltage collapse happens if the post-disturbance equilibrium voltages are below acceptable limits. Voltage collapse may be total (blackout) or partial. According to Hill et al [2], 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 nonviable. A definition according to IEEE [3] Voltage Collapse is the process by which voltage instability leads to loss of voltage in a significant part of the system.

Voltage instability in a system often occurs where there is an increase in load demand or change in system operating condition. This will cause a progressive drop in voltage at the bus. As the power system networks get more and more heavily loaded and increasingly more complex, there is possibility of voltage instability, or even voltage collapse occurring, due to any severe disturbances such as voltages of transmission lines, generators etc.

There are many methods currently in use to keep in the analysis of voltage instability such as QV analysis, FVSI (Fast Voltage Stability Index) and Modal analysis. In this project, two main methods of analysis were used on the test system, namely the PV analysis and QV analysis.

The PV analysis is mainly used to determine the proximity to a system to a system voltage collapse in term of variation of bus voltages with real power transfer. The QV analysis is mainly used to determine the proximity to voltage collapse in terms of operational voltages, Q-margin and collapse voltage.

Power World Simulator is another software used to simulate the 5-bus test system and 9-bus test system. This Power World Simulator is used because it is user friendly and easy to be used.

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1.2 Optimal Power Flow Incorporating Voltage Collapse

As open-access market principles are applied to power systems, sign cant changes in their operation and control are occurring. In the new marketplace, power systems may be operated under higher loading conditions as market influences tend to demand greater attention to operating cost versus stability margin, increasing the emphasis on the use of a variety of new optimal power flow tools.

There have been several voltage collapse events throughout the world in recent years, as system are being operated with less stability margins, e.g., [4][5]. Thus, the incorporation of voltage stability criteria in the operation of power systems has become essential [6]. In recent years, the application of optimization techniques to voltage stability problems has been gaining interest. It is possible to restate many voltage collapse problems as optimization problems. Although, bifurcation methods are numerically well developed, the use of optimization based techniques has many advantages, including their ability to incorporate limits [7][8]. This issue becomes even more important when considering limit induced voltage collapse [9], which can not be easily dined using some of the traditional bifurcation-based computational techniques.

New voltage stability analysis techniques are being introduced using optimization methods that determine optimal control parameters to maximize load margins to a voltage collapse. In [10], optimal shunt and series compensation parameter settings are calculated to maximize the distance to a saddle-node bifurcation, which can be associated in some case with voltage collapse. In [11], a voltage collapse point computation problem is formulated as an optimization problem, allowing the use of optimization techniques and tools. In [12], the reactive power margin from the point of view of voltage collapse is determined using interior point methods; the authors used a barrier function to incorporate limits. In [13], the authors determine the closest bifurcation to the current operating point on the hyperspace of bifurcation points.

In [12], the maximum load ability of a power system is examined using interior point methods. In [8], an interior point optimization technique is used to determine the optimal PV generator settings to maximize the distance to volt- age collapse. Furthermore,

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the algorithm presented in [8] includes constraints on the present operating conditions. Possible applications of optimization techniques to voltage collapse analysis are discussed in [9].

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CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Methods for voltage stability analysis

Voltage stability studies are performed with a number of different methods. Johansson and Sjögren [15] give a thorough description of the most common methods. A short summary of these methods is given below.

2.1.1 PV-curves and QV-curves

The most basic and commonly used method is to use the system's theoretical PV-curve or QV-curve together with the load characteristic. These curves are also called "nose curves" due to their characteristic shape. The nose-curve is a graph of the active or reactive power in a node as a function of the node voltage. The point on the nose-curve where the maximum power occurs is called the "critical point" and in literature is often considered to be the voltage stability limit [16].

2.1.2 Analytical methods

The analytical methods use continuous models of the system components, and describe the system with a set of differential-algebraic equations. These equations are used

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to find bifurcation points in the system solution. Bifurcation points are common to more than one branch of solutions. Therefore it is possible for the system solution to change branch and thereby behaviour at such a point. Methods that use the eigen values of the Jacobian matrix can then be applied to determine how the system will behave at these points [16].

2.1.3 Index and sensitivity methods

Another method is to calculate a "distance" to the point where the system will collapse. The minimum singular value of the power-flow Jacobian matrix is one such value that is used as a stability index. The distances in MW or MVAr to the critical point of the nose curves are other examples of indexes for this purpose [16].

2.1.4 Time domain simulations

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

The simulations are mostly performed with a computer program that uses detailed models of the system components. Both the simulation program and the models used must be adapted to the demands of long term dynamic simulations to be useful in voltage stability studies. These demands are not always the same as for the more common transient stability simulations with a much shorter time perspective. Time domain simulation can be used to investigate basic aspects in small power systems as well as more complex phenomena in larger systems.[3]

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2.2 Definitions

2.2.1 Voltage stability and collapse

The research area of voltage stability lacks unambiguous definitions. There are various definitions presented by different organisations, groups and individuals. Here we may mention the definitions by [1], [3], [17], [18].

All these definitions are presented and discussed in [15]. The definitions according to IEEE are the most suitable for the analysis presented in this thesis and are as follows:

- *Voltage stability* is the ability of a system to maintain voltage so that when load admittance is increased, load power will increase, and so that both power and voltage are controllable.

- *Voltage collapse* is the process by which voltage instability leads to loss of voltage in a significant part of the system.

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

- The system enters a state of *voltage instability* when a disturbance, increase in load, or system change causes the voltage to drop quickly or drift downward, and operators and automatic system controls fail to halt the decay. The voltage decay may take just a few seconds or ten to twenty of minutes. If the decay continues unabated, steady-state angular instability or voltage collapse will occur. The meaning of the first paragraph is that a power system can not operate on the lower side of the PV-curve and still be voltage stable.

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2.2.2 Power system load

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

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

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

2.3 Examples of voltage collapse

Several voltage collapses have occurred around the world during the last decades. The contingencies have different reasons, but mostly the collapses are triggered by a fault situation or a component malfunction. Heavy load can also cause voltage instability and collapse. A few examples of voltage collapses are given below, [2] [15] [19] [20].

2.3.1 Belgium, August 4, 1982

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

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Wednesday, August 4 was characterized by a low load situation. Less than half of the installed capacity was operative. Prior to the incident, the major load was industrial, mainly consisting of motor load. The load consequently demanded a considerable amount of reactive power. A number of generation plants and transmission lines, including the western link to France, were disconnected due to maintenance work. In order to save fuel, a minimum of the oil fired plants were in operation. In the Doel nuclear power station, all three units were running. About half of the production was generated by the nuclear power stations and the pumping station. The rest was produced by fossil fuel plants[22].

A disturbance then occurred in the nuclear power plant in Doel. Unit 3 tripped as a result of the fortuitous operation of a turbine protection device. The voltage decreased in the region due to the loss of 449 MVAr reactive power production. The AVRs in Doel 1 and 2 intervened in order to raise the voltage. The field currents started to increase in both units, and reached their upper limits. The current limiters were then activated and prevented further voltage recovery. On-load tap changers in the network started tapping and caused a further field current limitation that lowered the voltages even more [22].

Decreasing voltages implied increasing currents, and due to protection relay operation, 5 units in the region successively tripped, including the nuclear power units in Doel. The loss of this production in the northern and central parts of the country lead to an increased power flow and one of the lines from the south tripped due to overload. Oscillations started between the north and the south of the country, and a considerable lack of both active and reactive power in the north and the central parts caused a disconnection of these parts from the 380 kV network. The collapse became a fact.

There were mainly two network components that caused the collapse. The *field current limiters* and the *on-load tap changers* interacted and caused low voltages and consequently high currents. In the Swedish nuclear power plants, the generator excitation controllers have *armature current limiters* in addition to the field current limiters. In the Belgian collapse, the nuclear power generators were tripped due to overcurrent, and if the AVRs had been equipped with armature current limiters, these would have been activated instead. In the Swedish power system, it is therefore also important to study the armature current limiter [22].

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2.3.2 Sweden, December 27, 1983

The Swedish collapse occurred on a cold winter's day, when the system was heavily loaded. The power transfer from the north to the south was 5600 MW, compared to the recommended maximum of 5800 MW [19].

An earth fault occurred in an important 400 kV switchyard in eastern Sweden about 150 km from Stockholm. Because of special circuit breaker arrangements, the whole station tripped. Consequently, the 220 kV connection to Stockholm and the transmission route from the north were interrupted. The supply to Stockholm and the eastern part of Sweden was then weakened. Power oscillations that followed from the fault died out quickly and the frequency remained unchanged since no generators were tripped. But the voltage in the south-eastern part of Sweden decreased due to the weakened transmission system [19].

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

Initial calculations showed that the system should have been stable after the initial fault, and the cascaded tripping could not be explained. Further studies showed interesting phenomena that had occurred in the system [16].

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

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

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

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

2.3.3 France, January 12, 1987

The western part of the French system, in the Brittany region, suffered from a major disturbance on January 12, 1987. This region has a substantial generation capacity, mostly nuclear power, connected to the national 400 kV system. January 12 was a rather cold day. The power consumption on the national level was 52,000 MW and the power margin was 6,000 MW. The transmission voltage was normal in the Brittany area [21].

Between 10.55 a.m. and 11.41 a.m. three nuclear power units failed for unclear reasons and the region control centre ordered the start-up of gas turbines. Thirteen seconds after the last of the three units tripped, the fourth unit tripped due to maximum field current protection. The sudden loss of generation led to a sharp voltage drop. The voltage drop spread to adjacent areas and caused tripping of nine conventional and nuclear generation units within a few minutes. A loss of about 9,000 MW was recorded between 11.45 and 11.50 a.m. The voltage in the 400 kV system then stabilized at extremely low values: 300 kV was the average value in the Brittany area. The lowest value was 180 kV in the La Martyre sub-station, which is the most remote station in Brittany. The system "survived" in the sense that no lines were tripped. After load shedding, the voltages

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returned to normal again. The extremely low voltage levels indicate that the system was operating on the lower side of the PV-curve, and it seems that a stable equilibrium was reached before the load shedding took place. By our definition, there was no real collapse in Brittany, just a period of voltage instability that ended up in a stable operating point.

Harmand et. al., EdF [2] carried out a simulation analysis based on recordings from the incident, in order to understand the mechanisms that caused the incident. The *load behaviour*, the *on-load tap changers*, and *field current limiters* were given special attention.

- The voltage dependence of the load was determined from recordings during the incident and a linear dependency was found. However, no conclusions regarding the contributions to the voltage decay were made.

- The on-load tap changers were very much blamed for causing the instability. When the voltage dropped, the OLTCs tried to restore the voltage and thereby increased the load. Simulations were made with the tap changers on the highest voltage levels blocked. The system then remained stable.

- The role of the generator voltage control and its protection devices was also examined. Two phases can be distinguished in the incident. The EdF version is given first, and a comment is given by the authors (italics) as an alternative explanation.

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

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