Static voltage stability analysis in power systems engineering essay

Voltage stability, one of the principal aspects of power system stability, has been the main reason for many of major power system blackout incidents over the last few decades. It is acknowledged universally that voltage stability is and will remain a challenge in the 21st century, even likely to increase in importance. Therefore a better understanding of voltage stability in power systems is necessary for power engineers, who might participate in the planning, designing, and operation of modern power systems. This report talks about a relevant engineering thesis project: Static Voltage Stability Analysis in Power Systems, which is carried out for 2 semesters from July 2009 to June 2010.

The aim of this thesis project is to conduct a more comprehensive study into the theory of static voltage stability, and investigate a new approach for power flow analysis: 3-dimension P-Q-V curve. First of all, the basic knowledge of static voltage stability is reviewed, and analysis on an elementary power system, radial system, is carried out including power flow study, P-V and Q-V curve analysis. Based on the 2- dimension P-V and Q-V plotting, the relationship of P, Q, and V is studied and a new method for static voltage stability analysis is tried: P-Q-V curve.

The second part of this project focuses on the analysis of WSCC three-generator-nine-bus system. Simulation of the system is carried through by means of UWPFLOW and POWERWORLD. Direct power flow method and continuation power flow method are applied and the weakest bus is studied. Last but not least, curves are obtained and results are discussed.

Keywords: Static Voltage Stability; Radial System; Power Flow Method; Continuation Power Flow Method; P-V Curve; Q-V Curve; P-Q-V Curve.

CONTENTS

CHAPTER 1 INTRODUCTION

An Overview of Modern Power System

A power system is a network of conductors and devices which allows electrical energy to be transferred from the generating power stations to load centers through transmission network. Since the first electric network in the United States was established at the Pearl Street Station in New York City by Thomas Edison in 1882 [1], power systems have been experiencing more than 100 years' development and improvement. Nowadays, modern power system has developed to be a complex interconnected network, which can be subdivided into four parts:

Generation

Private and publicly owned generators produce the electricity that feeds into high voltage grids.

Transmission

High voltage transmission grids transport power from generating units at various locations to distribution systems which ultimately supply the load.

Distribution

Distribution systems deliver the power from local bulk supply points to the consumers’ service-entrance equipments.

Loads

Loads of power systems are composed of industrial, commercial, and residential load.

Figure 1. 1 Modern Power System [2]

Power System Stability

A power system is said to be stable if it has the property that it retains a state of equilibrium under normal operating conditions and regains an acceptable state of equilibrium after being subjected to a disturbance. Of all the complex phenomena on power system, power system stability is the most intricate to understand and challenging to analyze [3]. Damage to power system stability may cause the system to blackout or collapse as well as other catastrophic incidents, leading to enormous social and economic losses.

Classification of Power System Stability

Based on the system’s different properties, network structures and operation modes, the system instability can behave in many different ways. Accordingly power system stability study is divided mainly into three fields: angle stability, frequency stability and voltage stability. The diagram below shows visually the classification of power system stability.

Figure 1. 2 Classification of Power System Stability

History of Study on Power System Stability

Initially, angular stability was firstly paid attention to and studied since power transmission capability had traditionally been limited by either rotor angle (synchronous) stability or by thermal loading capability. And the blackout problems had been associated with transient stability, which were diminished by fast short circuit clearing, powerful excitation systems and varies special stability controls [3]. In other words, nowadays the theory and methods on angular stability are relatively more complete.

Meanwhile, study on voltage stability had been quite slow, which mainly attributed to two reasons:

Incidents caused by voltage instability or voltage collapse occurred relatively late, not until which did people paid attention to voltage instability problems.

Understanding of voltage instability was not so profound as other kinds of instability problems in the early days. Varies of issues arose during the study on voltage stability such as load-based modeling, dynamic behaviors of different components as well as their interaction, and so on.

Overview of Power System Voltage Stability

Voltage Instability Incidents in the World

Power system voltage stability was firstly introduced in 1940s, but failed to draw people's attention until 1970s, since which voltage instability and collapse had resulted in several major system failures or blackouts throughout the world, as listed below [4, 5, 22]:

August 22, 1970, Japan, 30 minutes;

September 22, 1970, New York, several hours;

September 22, 1977, Jacksonville, Florida, few minutes;

December 19, 1978, France, 26 minutes;

August 4, 1982, Northern Belgium, 4. 5 minutes;

September 2, November 26, December 28 & 30, 1982, Florida, 1-3 minutes;

May 21, 1983, Northern California, 2 minutes;

December 27, 1983, Sweden, 55 seconds;

June 11, 1984, Northeastern USA, several hours;

May 17, 1985, South Florida, 4 seconds;

April 1986, Winnipeg, Canada Nelson River HVDC links, 1 second;

May 20, 1986, England, 5 minutes;

November 1986, SE Brazil, Paraguay, 2 seconds;

January 12, 1987, Western France, 6-7 minutes;

July 20, 1987, Illinoisand India, several hours;

July 23, 1987, Tokyo Japan, 20 minutes;

August 22, 1987, Western Tennessee, 10 seconds;

July 2, 1996, Western System Coordination Council (WSCC), Northern USA;

August 1996, Malaysia;

August 14, 2003, USA & Canada;

September 28, 2003, Italy.

Progress of Study on Voltage Stability

The large numbers of worldwide voltage collapse incidents made it become the focus of world's attention to study voltage stability of power system. In the 1982's researching list of Electric Power Research Institute (EPRI) in USA, voltage stability was considered as the most significant issue. Over the last thirty years, and especially over about the last twenty years, utility engineers, consultants, and university researchers have intensely studied voltage stability. Hundreds of technical papers have resulted, along with conferences, symposiums, and seminars. Utilities have developed practical analysis techniques, and are now planning and operating power systems to prevent voltage instability for credible disturbances [6].

Importance of Voltage Stability in Future

In a foreseeable future, the global fast-growing power consumption will require more intensive use of available transmission facilities, which means an operation of power systems closer to their voltage stability limits. The increased use of existing transmission is made possible, in part, by reactive power compensation [6]. Undoubtedly, voltage stability is and will remain a challenge in the 21st century, even likely to increase in importance. Therefore a better understanding of voltage stability in power systems is necessary for power engineers, who might participate in the planning, designing, and operation of modern power systems.

Topic Definition and Scope

The topic of this project is Static Voltage Stability Analysis in Power Systems, which mainly focuses on the following:

Overview of the phenomena of static voltage stability;

Analysis associated with the phenomena;

Reasons why voltage collapse happens;

Measures to improve static voltage stability.

In consideration of restrictions on the simulation, a three-generator-nine-bus case is used throughout the whole project while a typical two-bus (one-generator-one-load) case is used for the P-Q-V curve analysis.

Aims and Objectives

The main objective of this project is to get a wider and deeper understanding of static voltage stability in power systems, which can be reduced into sub-objectives:

To conduct a more comprehensive study into the theory of static voltage stability;

To look for reasons why voltage collapse happens;

To investigate a new approach for power flow analysis: 3-dimension P-Q-V plotting;

To propose proper measures of improving static voltage stability in power systems;

To conclude generation direction and load direction for the analyzed power system.

CHAPTER 2 POWER SYSTEM VOLTAGE STABILITY

Basic Concepts of Voltage Stability

IEEE Definitions

IEEE [7] provided a formal definition of voltage stability and relative concepts as given below:

Voltage Stability: 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: Voltage collapse is the process by which voltage instability leads to very low voltage profile in a significant part of the system.

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

CIGRE Definitions

Nevertheless, the above definitions of voltage stability conditions were not directly compatible with the general IEEE definition for stability concept. Hence new definitions were given in CIGRE report [8], which are as following:

Voltage Stability: A power system, at a given operating state and subjected to a given disturbance, is voltage stable if voltages near loads approach post-disturbance equilibrium values. The disturbed state is within the region of the stable post-disturbance equilibrium.

Voltage Instability: Voltage instability is the absence of voltage stability, and results in progressive voltage decrease (or increase). Destabilizing control reaching limits, or other control actions (e. g. load connection), however, may establish global stability.

Voltage Collapse: Following voltage instability, a power system undergoes voltage collapse if the post-disturbance equilibrium voltages near loads are below acceptable limits. Voltage collapse in the system may be either total (blackout) or partial. Voltage collapse is more complex than simple voltage instability leading to a low-voltage profile in a significant part of the power system.

Other Relative Concepts

Large-disturbance Voltage Stability: Large-disturbance voltage stability is concerned with a system’s ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. The study period of interest may extend from a few seconds to tens of minutes. Therefore, long-term dynamic simulations are required for analysis.

Small-disturbance Voltage Stability: Small-disturbance voltage stability is concerned with a system’s ability to control voltages following small perturbations such as incremental changes in system load. For such case, static analysis is effectively used.

Relation of Voltage Stability to Rotor Angle Stability

Voltage stability and rotor angle (or synchronous) stability are more or less interlinked. Transient voltage stability is often interlinked with transient rotor angle stability, and slower forms of voltage stability are interconnected with small-disturbance rotor angle stability.

Voltage Stability is concerned with load areas and load characteristics. For rotor stability, we are often concerned with integrating remote power plants to a large system over long transmission lines. Voltage stability is basically load stability, and rotor angle stability is basically generator stability [6].

In a large interconnected system, voltage collapse of a load is possible without loss of synchronism of any generators. Transient voltage stability is usually closely associated with transient rotor angle stability. Long-term voltage stability is less interlinked with rotor angle stability. We can consider that if voltage collapses at a point in a transmission system remote from loads, it is an angle instability problem. If voltage collapses in a load area, it is possibly mainly a voltage instability problem.

CHAPTER 3 STATIC VOLTAGE STABILITY ANALYSIS OF ELEMENTARY POWER SYSTEM

Introduction of an Elementary Model: Radial System

Simple radial system network is used to develop most of the concepts of the static voltage stability. Once basic concepts are understood, we can represent as much as appropriate in computer simulation, which will be carried out in Chapter 4. Figure 3. 1 shows an equivalent circuit of the power system, and a model called radial system is formed to represent such power system, as shown in Figure 3. 2.

Figure 3. 1 Equivalent Circuit of Power System

Figure 3. 2 Radial System Model

The sending-end and receiving-end voltages are assumed to be fixed and can be interpreted as points in large systems where voltages are stiff or secure. The sending end and receiving end are connected by an equivalent reactance.

Basic Analysis of Radial System

Active Power Transmission

Applying the radial system in Figure 3. 2, the relations can be easily calculated:

Similarly, for the sending end:

The familiar equations for and are equal since we assume a lossless system, and maximum power transferred is at a power load angle equal to 90 degree. Note that the 90-degree maximum power angle is nominal, in other words, maximum power occurs at a different angle if we apply transmission losses or resistive shunt loads. And the case with impedance load at the receiving end will be discussed in section 3. 2. 2.

Reactive Power Transmission

In the study of the static voltage stability in power system, the transmission of reactive power is especially of interest. Usually we are interested in variable voltage magnitudes. Particularly, we are interested in the reactive power that can be transmitted across a transmission line, or a transformer as the receiving-end voltage sags during a voltage emergency or collapse. Considering the reactive power flow over the transmission line alone, we can write approximate formulas for Equations (3. 3) and (3. 5) in terms of small angles by using :

From Equations (3. 6) and (3. 7), it can be observed that reactive power transmission depends mainly on voltage magnitudes and flows from the higher voltage to the lower voltage. Such observation, however, cannot be applied in the case of high stress, i. e. high power transfers and angles, where the angle is large enough and no longer approaches 1. This is important as voltage stability problems normally happen during highly stressed conditions.

Difficulties with Reactive Power Transmission

Reactive Power Transmission Behavior in Different Cases

First of all, take an example of the radial system in Figure 3. 2, assuming X= 0. 2 p. u. with varied values of voltage magnitude and angles, i. e. varied loading conditions. Applying Equations (3. 3) and (3. 5), and can be calculated as listed in the following table:

Conditions	**(p. u.)**	**(p. u.)**	**(degree)**	**(p. u.)**	**(p. u.)**
Lightly loaded	1. 10	1. 00	10	0. 634	0. 416
Moderately loaded	1. 05	0. 90	20	1. 072	

0. 390

Heavily loaded

1. 00

0. 80

50

2. 429

-0. 629

Table 3. 1 Reactive Power Transmission in varied conditions

From the table, it is clear that at higher loading, transmission lines are more difficult to transfer reactive power and reactive power cannot be transmitted across large power angles (the value of becomes negative in the case with a power angle of 50 degree).

Minimizing Transfer of Reactive Power

High angles are due to long lines and high real power transfers. It is therefore required to maintain voltage magnitude profiles with voltages of approximately 1 p. u.. Compared with real power transfers, reactive power cannot be transmitted across long distances. It has been observed that the greater distance of the reactive power sources from the reactive demand will lead to: [9]

greater voltage gradient on the lines supplying the reactive power greater amount of required reactive power compensation

more difficult to control the voltage level

Another reason to minimize the transfer of reactive power is minimizing the real and reactive losses. The purpose to reduce real losses is due to economic reasons while minimizing the reactive losses can reduce investment in reactive devices such as shunt capacitors.

As we know, the losses across the series impedance of a transmission line are and . For , we have:

and

Obviously, to minimize losses, we should minimize reactive power transfer and keep voltage high at the same time. Keeping voltage high to minimize reactive losses helps maintain voltage stability. In other words, reactive power should be generated close to the receiving end.

Power Flow Analysis

In a power system, powers are known rather than currents. Thus power flow analysis is backbone of static voltage stability studies. Power flow analysis, also known as load flow analysis, involves the calculation of power flows and voltages of a transmission network for specified terminals or bus conditions.

Bus Classification

In solving a power flow problem, a power system is supposed to be operating under balanced conditions and a single-phase model is used. Associated with each bus are four quantities: active power P, reactive power Q, voltage magnitude , and voltage angle.

The following types of buses (nodes) are represented, and at each bus two of the above four quantities are specified:

Voltage-controlled (P-V) buses: These buses are the generator buses. They are also known as regulated buses or P-V buses. For such kind of buses, the real power P and voltage magnitude are specified, while the reactive power Q and the voltage angle are unknown.

Load (P-Q) buses: Load buses are also called P-Q buses as their real power P and reactive power Q are specified. The voltage magnitude and angle are to be determined.

Slack (Swing) bus: Such bus is taken as reference of the whole power system. For a slack bus, the voltage magnitude and voltage angle are specified. As the power losses in the system are not known a priori, at least one bus must have unspecified P and Q. Thus the slack bus is the only bus with known voltage. This bus makes up the difference between the scheduled loads and generated power that are caused by the losses in the network [1]. Traditionally while analyzing, the voltage magnitude of slack bus is assumed to be 1 p. u. and the voltage angle is assumed to be 0 degree.

Transmission Line Modeling

The transmission line is traditionally represented with two types of models: nominal model and nominal T model, as shown in Figure 3. 3 and Figure 3. 4

where Z is the series impedance and Y is the shunt admittance due to the line charging capacitance. Neither nominal T or nominal Ï€ exactly represent the actual line, however, they brings great convenience in the power flow analysis, especially in the application of NEWTON-RAPHSON method, which will be discussed in the coming section.

Figure 3. 3 Nominal Model

Figure 3. 4 Nominal T Model

NEWTON-RAPHSON Power Flow Method

In order to include all the three types of buses (P-V bus, P-Q bus and slack bus as introduced in 3. 3. 1) at the same case, a 3-bus power system is considered as shown in Figure 3. 5, where

Bus 1 is the slack bus, i. e. and are specified as .

Bus 2 is a voltage-controlled bus, i. e. and are known while and are unknown.

Bus 3 is a load bus, i. e. and are known while and are unknown.

Figure 3. 5 3-bus Power System

The network performance equation of such a sample is:

where

Applying the bus-loading equations:

Now NEWTON-RAPHSON Power Flow Method can be approached as:

P-V Curve Analysis

P-V curve is useful for conceptual analysis of static voltage stability and for study of radial system, where P is the load in an area and V is the voltage at a critical or representative bus. Besides, P can also be the power transferred across a transmission interface or interconnection. Voltage at several busses can be plotted.

Consider the radial system as shown in Figure 3. 2. The receiving-end active power can be expressed as in the Equation 3. 2. Then a P-V cueve can be plotted as in Figure 3. 6, which shows relationship between P and V at the receving end for different values of load power factor and the locus of the critical operting point is shown by the dotted line. Nornally, only the operting points above the locus of the critical points represent satisfying operating condition. A sudden reduction in power factor or increase in Q can thus cause the system to change from a stable operating condition to an unsatisfactory and possibly unstable [10].

Figure 3. 6 V versus P for different power factors [10]

Q-V Curve Analysis

Q-V curve is presently the workhorse method of voltage stability analysis at many utilities [6]. Considering the system in Figure 3. 2, we can obtain reactive power both at sending end and receiving end, or and by means of Equation (3. 5) and Equation (3. 3). Then a Q-V cueve can be plotted as in Figure 3. 7, which shows relationship between Q and V. The reactive power margin is the MVAr distance from the operating point to either the bottom of the curve, or to a point thaere the voltage squared characteristic if an applied capacitor is tanfent to the V-Q curve [6]. Additionally, the slope of the V-Q curve indicates the stiffness of the bus.

Figure 3. 7 Typical Q – V Curve

A New Method for Static Voltage Stability Analysis: P-Q-V Curve Analysis

Introduction of MATLAB Software

MATLAB is a numerical computing environment and fourth generation programming language. Developed by The MathWorks, MATLAB allows matrix manipulation, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs in other languages [18]. An additional package, Simulink, adds graphical multi-domain simulation. This project greatly benefits from MATLAB to handle 3-dimension curve drawing for P-Q-V curve study, as well as the matrix manipulation associated with power flow analysis, 2-dimension curve plotting for P-V/Q-V curve study in the analysis of WSCC nine-bus system, which will be described in details in CHAPTER 4.

P-Q-V Curve

In this section, for convenience of forming an ideal voltage source, we assume the angle of the to be zero while the angle of to be degree. Then Equation 3. 2 and 3. 3 become:

Noting that

We can eliminate in Equations 3. 16 and 3. 17, which obtains

or

Obviously, with specified , and , Equation 3. 19 shows relationship of , and . To work out such relationship visually, MATLAB is applied and a P-Q-V curve is obtained as below, where P stands for , Q stands for V stands for and E stands for . Refer to Appendix A for details on MATLAB codes, with the assumsion that E = 1 , X= 0. 2 and the values of tan are chosen randomly as [-0. 41, -0. 2, 0, 0. 2, 0. 41, 1, 10, 100, 1000].

Figure 3. 8 P – Q – V Curve

CHAPTER 4 STATIC VOLTAGE STABILITY ANALYSIS OF WSCC NINE-BUS SYSTEM

Introduction of WSCC Nine-bus System

WSCC nine-bus system is a typical testing system develped by Western Systems Coordinating Council. It is commonly uesd in jornals and papers for power system studying. Figure 4. 1 shows an overview of the WSCC nine-bus system. Refer to Appendix H for parameters of this system.

Figure 4. 1 Single Line Diagram of WSCC Nine-bus System

Introduction of UWPFLOW Software

For determining the static voltage stability of the WSCC nine-bus system, UWPFLOW software is used. This software has been developed by University of Waterloo, Canada, and distributed free on the Power Globe. It was written in C and runs under DOS and UNIX enviroments. It has no limitation on the system size other than those imposed by memory limitation in the corresponding enviroment, i. e. RAM and swap space in the UNIX and exrended memory in DOS [16, 20].

UWPFLOW is a research tool that has been designed to calculate local bifurcation characterized by a singularity in the power system Jacobian. This was developed based on power flow method. This software also generates a series of output files that allow further analysis. UWPFLOW reads AC power flow data in WSCC format [11] or IEEE common format [12], DC data in ETMSP format [13], FACTS devices data in s special format described in [14], and steady state load model data in OH format [15]. However in the present study IEEE common format data is used. Additional UN format data is required for bifurcation analysis, such as direction of generation change, direction of load change and maximum genertion limit [10]. The software assumes that one parameter the loading factor, is allowed to change. All steady state system controls remain operational unless otherwise specified by means of the software option.

Introduction of POWERWORLD Software

POWERWORLD Simulator is an interactive power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days [17]. POWERWORLD provides a linear programming based optimal power flow package Simulator OPF, which ideally suits to do power flow analysis. What’s more, the planning-mode tool Simulator PVQV fulfills the need of Q-V curve drawing. Throughout the project, PowerWorld Simulator will be used to carry out power flow analysis and Q-V curve study of the twelve-bus case.

Analysis of WSCC Nine-bus System

Direct Method: Repeated Power Flow

First of all, the WSCC nine-bus system in Figure 4. 1 is built in UWPFLOW software. By running the system and increasing the loading level of step by step, attention will be focused on getting convergence and the maximum loading level. For loading “ direction”, assume all the loads are increased by the same ratio, and only generator at Bus-1 is allowed to dispatch required additional real power.

With the load P and Q increased simultaneously with the ratio of 10%, in the same loading direction, the bus voltages in per unit measurement are tabulated in Table 4. 1. Couples of data points are collected near the system divergence point. Table 4. 1 has shown that the system started to collapse (or diverge) at the point where all loads at the 3 load buses are increased in the same direction till 116%. Note that in Table 4. 1, the starting point is denoted as 0% as there is no additional loads added, which is named as basic load. Then we can conclude from Table 4. 1 that the maximum loading level for the WSCC nine-bus system is at additional of 116% loading direction on all 3 load buses.

Load Increment (%)

Bus5

Bus7

Bus9

P (MW)

Q (Mvar)

V (p. u.)

P (MW)

Q (Mvar)

V (p. u.)

P (MW)

Q (Mvar)

V (p. u.)

0

90

30

1. 0129

100

35

1. 0162

125

50

1. 0261

10

99

33

1. 0069

110

38. 5

1. 0105

137. 5

55

0. 9886

20

108

36

1. 004

120

42

1. 0053

150

60

0. 981

30

117

39

0. 9928

130

45. 5

0. 999

162. 5

65

0. 972

40

126

42

0. 9846

140

49

0. 993

175

70

0. 9625

50

135

45

0. 9753

150

52. 5

0. 9862

187. 5

75

0. 9516

60

144

48

0. 9648

160

56

0. 979

200

80

0. 9394

70

153

51

0. 953

170

59. 5

0. 9711

212. 5

85

0. 9257

80

162

54

0. 9396

180

63

0. 9626

225

90

0. 9102

90

171

57

0. 9242

190

66. 5

0. 9532

237. 5

95

0. 8923

100

180

60

0. 9061

200

70

0. 9428

250

100

0. 8714

110

189

63

0. 881

210

73. 5

0. 9239

262. 5

105

0. 84

112

190. 8

63. 6

0. 8737

212

74. 2

0. 9167

265

106

0. 83

114

192. 6

64. 2

0. 8657

214

74. 9

0. 9087

267. 5

107

0. 8191

115

193. 5

64. 5

0. 86

215

75. 25

0. 9024

268. 75

107. 5