UNDERSTANDING VOLTAGE STABILITY

Matthew Clifford Johnson
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A Project

by

Matthew Clifford Johnson

Approved by:

Mohammad Vaziri, Ph.D., P.E., Committee Chair

Fethi Belkhouche, Ph.D., Committee Member

Harrison Clark, P.E., Committee Member

Date
Student: Matthew Clifford Johnson

I certify that this student has met the requirements for format contained in the University format manual, and that this project is suitable for shelving in the Library and credit is to be awarded for the project.

__________________________, Graduate Coordinator  ___________________
Preetham B. Kumar, Ph.D.               Date

Department of Electrical and Electronic Engineering
Abstract

of

UNDERSTANDING VOLTAGE STABILITY

by

Matthew Clifford Johnson

This report explains and documents the dynamics of voltage instability on large power systems at a basic and intuitive level. The project will outline the voltage instability phenomenon and leave the specific details for individual investigation. Understanding what causes voltage instability and why this may cascade into a voltage collapse requires knowledge of how key components of the power system are affected by low voltage. Power System components will respond at different time frames, contributing to faster transient voltage instability, and/or slower, long term voltage instability. Simulations will show how the components of voltage instability contribute to cause low voltage conditions. Popular power flow methods such as PV and QV curves are used to show how a system can be analyzed for voltage stability. Finally, several possible solutions that could help stabilize voltage for large power systems will be discussed.

Mohammad Vaziri, Ph.D., P.E.

Date
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TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Acknowledgments</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>vi</td>
</tr>
<tr>
<td>List of Figures</td>
<td>vii</td>
</tr>
</tbody>
</table>

Chapter

1. INTRODUCTION .......................................................... 1
2. A REVIEW ............................................................... 2
3. SOURCES OF REACTIVE POWER AND LIMITATIONS .............. 7
4. SOURCES OF REACTIVE POWER LOSS .............................. 15
5. LOAD TAP CHANGERS CAN AFFECT THE LOAD............... 26
6. TRANSIENT VOLTAGE COLLAPSE .................................. 32
7. SLOW DYNAMICS OF VOLTAGE INSTABILITY .................. 34
8. SIMULATION ........................................................... 36
9. METHODS FOR CALCULATING VOLTAGE STABILITY .......... 42
10. CONCLUDING REMARKS AND RECOMMEND POSSIBLE SOLUTIONS | 48

References ................................................................. 50
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Table 1 Typical Surge Impedance Loading (SIL)</td>
<td>12</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1.</td>
<td>Figure 1 Phasor Diagrams</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Figure 2 Simple Transmission Circuit</td>
<td>4</td>
</tr>
<tr>
<td>3.</td>
<td>Figure 3 Simple Generator Capability Curve</td>
<td>8</td>
</tr>
<tr>
<td>4.</td>
<td>Figure 4 Generator Capability Curves</td>
<td>9</td>
</tr>
<tr>
<td>5.</td>
<td>Figure 5 Pi Model of a Transmission Line</td>
<td>10</td>
</tr>
<tr>
<td>6.</td>
<td>Figure 6 Load Characteristics</td>
<td>19</td>
</tr>
<tr>
<td>7.</td>
<td>Figure 7 Typical Speed Torque Curve for an Induction Motor</td>
<td>21</td>
</tr>
<tr>
<td>8.</td>
<td>Figure 8 Reduced Voltage effect on Speed Torque Curve</td>
<td>22</td>
</tr>
<tr>
<td>9.</td>
<td>Figure 9 Slow Dynamics of Thermostats</td>
<td>25</td>
</tr>
<tr>
<td>10.</td>
<td>Figure 10 LTC Tap and Deadband</td>
<td>27</td>
</tr>
<tr>
<td>11.</td>
<td>Figure 11 Model of an Ideal Transformer</td>
<td>28</td>
</tr>
<tr>
<td>12.</td>
<td>Figure 12 LTC Load Restoration</td>
<td>30</td>
</tr>
<tr>
<td>13.</td>
<td>Figure 13 Extended time frame for LTC action</td>
<td>31</td>
</tr>
<tr>
<td>14.</td>
<td>Figure 14 Dynamic Model for Motors</td>
<td>33</td>
</tr>
<tr>
<td>15.</td>
<td>Figure 15 Slow Dynamics of Voltage Instability</td>
<td>34</td>
</tr>
<tr>
<td>16.</td>
<td>Figure 16 Simulation Step 1</td>
<td>37</td>
</tr>
<tr>
<td>17.</td>
<td>Figure 17 Simulation Step 2</td>
<td>37</td>
</tr>
<tr>
<td>18.</td>
<td>Figure 18 Simulation Step 3</td>
<td>38</td>
</tr>
<tr>
<td>19.</td>
<td>Figure 19 Simulation Step 4</td>
<td>38</td>
</tr>
<tr>
<td>20.</td>
<td>Figure 20 Simulation Step 5</td>
<td>39</td>
</tr>
<tr>
<td>21.</td>
<td>Figure 21 Simulation Step 6</td>
<td>39</td>
</tr>
<tr>
<td>22.</td>
<td>Figure 22 Simulation Slide 7</td>
<td>40</td>
</tr>
</tbody>
</table>
23. Figure 23 Normalized P-V Curves ................................................................. 44
24. Figure 24 Normalized Q-V Curves................................................................. 46
Chapter 1

INTRODUCTION

Understanding voltage stability is becoming more important as the frequency of outages caused by voltage instability increases. There has been a lot of new research in the area of voltage stability analytical methods, though it is not nearly as developed as frequency or angular stability. It is all very exciting and confusing on which method will prevail. An understanding of the basic components of voltage instability is important to grid reliability. Key concepts should be applicable to any large power systems, despite the use of analytical method for solving the voltage instability problem. The basic components of any power system are generation, transmission, and load. Transmission in this case includes all connecting network components that connect the generation to the load. Reactive power is needed in order to transfer real power across the transmission system to the customers. Without reactive power, voltage cannot be maintained, and losses on the system would cause voltage collapse and blackout.

Power systems are in constant state of change as the load fluctuates and the generation adjusts to meet the load. The goal here is to have a balanced system of generation and load. If there is a sudden increase or decrease in available generation or load, instability could result depending on the severity of the sudden change. An example of this would be the loss of a generator, faulted transmission line or sudden large increase in load. For the most part, voltage instability has to do with insufficient reactive power on the power system. This project will explain how reactive power is related to voltage and what might cause a further reduction in reactive power or voltage that could lead to voltage collapse. Although the project attempts to start at a basic level, the reader is expected to understand vectors, power flow, and be familiar with how power system elements are modeled.
There is fundamental relationship between voltage (V) and reactive power (Q). Reactive power can be injected into a system via capacitors or absorbed by inductors. This can be easily seen with review of the principle for power factor correction. Figure 1 shows an example of reactive power injection and how it affects the receiving end voltage (\(V_R\)). The figure shows that adding a reactive power source, in this case a capacitor, increases the magnitude of the receiving end voltage (\(V_R\)).

In power flow equations, there is additional demonstration that reactive power is coupled with voltage. The power flow equations are:
\[ P_i = \sum_{j=1}^{n} |V_i||V_j| [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] \quad (2.1) \]
\[ Q_i = \sum_{j=1}^{n} |V_i||V_j| [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] \quad (2.2) \]

Where \( P_i \) and \( Q_i \) are the real and reactive power injected into bus \( i \) respectively. Since these are non-linear equations, a numerical method called Newton-Raphson is employed to solve for voltages and their angles at each bus. Although power flow is not the emphasis of this project, its basic concepts are essential to understanding of voltage stability and they would be reviewed as needed. The power flow equations show a strong tie between reactive power (\( Q \)) and the bus voltages (\( V \)). This relationship is evident in the decoupled method of Newton-Raphson where a few legitimate assumptions are made for simplification. These assumptions are based on the facts that transmission lines are mostly inductive, voltage magnitudes are close to unity at all buses and that the differences in the voltage angles at adjacent buses are relatively small. Eventually, the result is a set of decoupled equations where the real power flows are mainly dependant on the voltage angles and the reactive power flows are mainly dependant on voltage magnitudes.

\[- B[\Delta \delta] = [\Delta P^-] \quad (2.3)\]
\[- B[\Delta |V'|] = [\Delta Q^-] \quad (2.4)\]

In 2.3 and 2.4, \( P^- \) and \( Q^- \) are scaled versions of \( P \) and \( Q \). Detailed proof and justification of these equations can be found in the study of power flow analyses. The goal here is simply to recognize the dependence of voltage magnitudes on reactive power for better understanding of voltage stability.
Known limitations to transfer reactive power across transmission lines is a fundamental problem with voltage stability. Analysis of the simple system in figure 2 results in the equations below.

\[
\begin{align*}
\bar{S}_R &= P_R + jQ_R = \bar{E}_R I^* \\
&= \bar{E}_R \left[ \frac{E_S \cos \delta + j E_S \sin \delta - E_R}{jX} \right] \\
&= \frac{E_S E_R \sin \delta}{X} \cos \delta + j \left[ \frac{E_S E_R \cos \delta - E_R^2}{X} \right]
\end{align*}
\]

\[
\Rightarrow P_R = \frac{E_S E_R}{X} \sin \delta \quad (2.5)
\]

\[
Q_R = \frac{E_S E_R \cos \delta - E_R^2}{X} \quad (2.6)
\]

Writing equation 2.6 in terms of voltages at the buses, as in part (a) of figure 2, results in:

\[
Q_R = \frac{V_S V_R \cos \theta - V_R^2}{X} = \frac{V_R (V_S - V_R)}{X} \quad (2.7)
\]

Similar to the assumptions in decoupled power flow, for two adjacent buses \( \theta \approx 0 \Rightarrow \cos \theta \approx 1 \).

\[
Q_R = \frac{V_S V_R - V_R^2}{X} = \frac{V_R (V_S - V_R)}{X} \quad (2.8)
\]
From equation 2.8, it is clear that the received reactive power \( Q_R \) depends mainly on the difference in voltage magnitudes between the sending \( V_S \) and receiving \( V_R \) ends. If there is a large difference, the reactive power flow over the transmission lines is increased. In an actual power system the magnitudes of the busses must be kept close to 1 per unit, leaving little voltage differential between the busses for the transfer of reactive power.

If there is a large angular difference in the sending and receiving ends, as there may be in long lines, then there is a lot of real power flowing through the connecting transmission line(s). Transfer of real power through the predominantly inductive transmission lines creates a large reactive power demand on the system. Even with higher angles and a large voltage differential, the inductive losses tend to drain reactive power from the sending end to the point where there is essentially no reactive power left for the receiving end. Limitations in transfer of reactive power and reactive losses are well known facts of transmission systems. These are the minimum constraints, which govern voltage stability.

So far, by the foregoing analysis we have:

1) Voltage magnitude fluctuations are directly related to reactive power. That is, as reactive power increases so does the magnitude of voltage. 2) Reactive power cannot be transferred efficiently over the transmission lines while holding acceptable voltage magnitudes at sending and receiving buses.

Reactive power is not “lost” in power systems. Reactive power is absorbed by inductors and released by capacitors over each half cycle, manifesting as the stored energy in their magnetic and electric fields respectively. Unlike Real power losses that are truly lost in the form of heat,
reactive power is simply transferred between the capacitive and inductive components of the power system. By the industry jargon, the word “loss” is used even when talking about reactive power. Though reactive power “demand” is a better description than “losses”, both terms will be synonymously employed in this project.
Chapter 3

SOURCES OF REACTIVE POWER AND LIMITATIONS

In power systems, there is a constant balancing act between generation and load. The same can be said for reactive power. The inductive losses in the lines, transformers and the load combine to create reactive power demands. That reactive power demand varies with load and with transmission line loading. The different sources of reactive power must meet these varying demands or the voltage will deviate from its nominal value. Thusly it is important to understand the main contributors to both loading and supplying the reactive power to the system. Sources of reactive power are listed below, some of which will be explained further.

1) Generation
2) Line Charging
3) Capacitors
4) Static Var Compensators (SVC)
5) STATCOMS
6) Synchronous Condensers

Previously listed reactive power sources will now be analyzed on how well they contribute to voltage instability during low voltage conditions. Sources of reactive power have limitations. Additionally, some sources become less effective under low voltage situations. Understanding these limitations will enable the planners to assess the vulnerability of a particular area to voltage collapse.

**Generators**

Most limitations in power systems usually come down to heat and spacing. Heat relates to the amount of current allowed through a device before the device is damaged. Spacing considers
voltage, and how far away from a lower voltage a device has to be in order to be safe from flash over. The limitations of generators are no different. The reactive power produced by generators is limited by the current rating of the generators excitation or field windings. Exciter winding produces a field when current flows through it. The exciter field is coupled with the stator field, so the stator field increases with increased excitation. This increases the generators internal flux or voltage, which increases the reactive power output of the generator. If more or less reactive power is need by the system, the generators Automatic Voltage Regulator (AVR) will adjust the excitation current to produce the needed reactive power for the pre-specified voltage or power factor levels. Again there are limits to how much current or heat the exciter winding can take before the winding insulation is damaged. This limitation results in the reactive power limitation of the generator. A simple capability curve for a generator can be seen in figure 3.

Figure 3: Simple Generator Capability Curve [2]
Figure 3 is a simplified case and there is generally more to a capability curve than what is represented here. However the diagrams explain the essential elements. The field limit rating is based on the amount of current the field windings can accept before failure. The armature heating limit is similar, and represents the amount of current the armature windings can accept before failure. Their intersection results in the rating of the generator at that particular power factor. There may be additional limits to generators such as under excitation limitations and mechanical power limitations that also contribute to the composition of the capability curves. If the windings can be cooled, the capability of the generator can be expanded as suggested by figure 4.

Figure 4: Generator Capability Curves. (Left) Generator capability curve with hydrogen cooling at different psi and power factors. (Right) A three dimensional graph of a generators capability polyhedron as a function of network voltage. [2]
Capacitance of Transmission Lines

Once energized, transmission lines themselves have a certain amount of capacitance or charge that is a source of reactive power. In figure 5, a traditional pi model of a transmission line is shown. It is very similar to the model presented in figure 2. The resistance was neglected in figure 2 since resistance is low in comparison to inductive components in transmission lines.

\[ \frac{V^2}{X_C} \quad \frac{I^2 X_L}{I^2 R} \quad \frac{V^2}{X_C} \]

Figure 5: Pi model of a Transmission line

\( X_C \) is the capacitive reactance, and \( X_L \) is the inductive reactance of the line. If the line is energized, voltage exists on the line. The line will then produce reactive power due to the natural capacitance in the line, which is proportional to the square of the voltage. Current flowing through the line results in reactive losses known as \( I^2 X \). Therefore, the line both produces and absorbs reactive power during operation. There is a point at which the absorption and production is balanced. This point is called the Surge Impedance Loading (SIL). Restated, given a voltage level, capacitance, and inductance of a system, there is a point at which the reactive losses due to current flow will balance with the reactive power produced by the natural capacitance of that system. If the line is loaded under the SIL, the line produces reactive power that can be used elsewhere on the grid (to the extent it can be transmitted). If the line is loaded above the SIL, than the line is will absorb reactive power, which must be provided from other elements of the system. The higher the voltage of the line the more reactive power can be produced by the capacitance of the line. SIL is normally calculated by using the following equations.
\[ SIL \approx \frac{|kV_{R(L-L)}|}{Z_c}^2 \text{ MW} \quad (3.1) \]

\[ Z_c = \sqrt{\frac{R + jwL}{G + jwC}} \Omega \quad (3.2) \]

\( Z_c \) is the characteristic impedance of the line in ohms

\( kV_{R(L-L)} \) is the magnitude of the line-to-line receiving-end voltage in kilovolts

R and G are the Resistance and Conductance of the line respectively

L and C are the Inductance and Capacitance of the line respectively

Again, since inductance is primarily responsible for the reactive power losses of the lines, R and G are assumed to be zero. The current at which the SIL is reached can be calculated using equation 3.3 for a lossless line. Some typical values of SIL are listed in table 1.

\[ |I_L| = \frac{|kV_{R(L-L)}|}{\sqrt{3} \sqrt{L/C}} \text{ A} \quad (3.3) \]

The natural capacitances of the lines are an important source of reactive power.

Transmission lines are often loaded much higher than their SIL; thusly the lines normally act as “sinks” of reactive power, contributing to lower voltages at the receiving ends of the lines. As shown in figure 5 the reactive power produced from the line is proportional to the square of the voltage magnitudes. When the voltage drops, the reactive power produced by the line drops as well, making the natural capacitance less effective as voltage decays. For example: if at \( V=1 \) p.u. the reactive power produced by the line is 1 MVAR. If the voltage drops by 10% resulting in \( V=0.9 \) p.u., then the reactive power produced by the line will drop to \( 0.9^2 = 0.81 \) p.u. This is a 19% drop!
<table>
<thead>
<tr>
<th>Nominal System Voltage (kV)</th>
<th>Line Type</th>
<th>Phase Conductor Diameter (in)</th>
<th>Conductor per Phase</th>
<th>Phase Spacing (ft)</th>
<th>SIL Capability (MVA)</th>
</tr>
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<tbody>
<tr>
<td>345</td>
<td>Horizontal</td>
<td>1.76</td>
<td>1</td>
<td>24.6</td>
<td>325</td>
</tr>
<tr>
<td>345</td>
<td>Horizontal</td>
<td>1.11</td>
<td>2</td>
<td>24.6</td>
<td>418</td>
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<tr>
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<td>2</td>
<td>29.5</td>
<td>421</td>
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<td>1.76</td>
<td>2</td>
<td>32.8</td>
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<tr>
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<td>1.60</td>
<td>12</td>
<td>73.8</td>
<td>10000</td>
</tr>
</tbody>
</table>

Table 1: Typical Surge Impedance Loading (SIL) [5]

**Capacitors**

Capacitors are also sources of reactive power. Similar to the line charging the reactive power produced varies with the square of the voltage, as suggested by equation 3.4.

\[
Q_c = \frac{V^2}{X_c}
\]  

(3.4)

\(Q_c\) is the reactive power produced by the capacitor

\(X_c\) is the capacitive reactance of the capacitor

Again, using shunt capacitors will increase the available reactive power, but become less affective as the voltage drops. Relying only on shunt capacitors and line charging to maintain
voltage can be deceiving with some false sense of security. This is because as the voltages begin to drop, the shunt capacitors will inject less MVArs to support the voltage drops and the system may collapse into a blackout. There are both mechanically and thyristor controlled capacitors. The mechanically switched capacitors (MSC) are slower to respond to low voltage than the thyristor controlled units. When enabled, both types of capacitors are either on or off.

Series capacitors behave somewhat differently. Not only does series capacitance help with production of reactive power, the reactive power injected also depends on the current flow, and not the voltage as shown by equation 3.5. [6]

\[
Q_c = I^2 X_c
\]  

(3.5)

This means that under increased loading, the series capacitors produce more reactive power. Additionally, series capacitors reduce the overall series impedance of the transmission lines, thus lowering the limitations on transfer of reactive power from one area to another. Series compensated lines are more resilient against outage contingencies as compared to shunt compensated lines and less susceptible to the risk of rapid voltage collapse. Sub-Synchronous Resonance or (SSR) can be a problem with series compensation and should be researched when adding series compensating capacitors near generators. Series compensating capacitors also complicate distance relay protection as adding or bypassing them changes the apparent “length” of the line as detected by the relay.

**Other Reactive Power Sources**

A Static Var Compensator (SVC) is a dynamic reactive power source that can both produce and absorb reactive power. In general, SVC can be perceived to acts like a capacitor with “taps”, increasing or decreasing the reactive power as needed. The SVC produces or absorbs reactive power that is proportional to the voltage squared, just as capacitors do. For
example when the SVC “tap” is at its highest limits, it can no longer produce reactive power, and the voltage decays further, similar to the behavior of capacitors.

A STATCOM is another dynamic source that can both produce and absorb reactive power. STATCOMs have a DC component, which in contrast to the SVC will provide nearly constant current despite the reduction in voltage. This is helpful since the STATCOM’s reactive power output, when at maximum, will drop in proportion to voltage rather than with the square of voltage as is the case with a capacitor-based SVC. Both the SVC and the STATCOM also have the advantage of reacting to voltage reduction quicker than mechanically switched capacitors. This will respond to an outage contingency much faster. Both the SVC and the STATCOM are more expensive than the shunt capacitors. For this reason alone, the purchase of one STATCOM could supply the funding for multiple capacitor banks with a greater overall reactive power capability. Hence, capacitor installations are much more common than SVCs or STATCOMs.
Chapter 4
SOURCES OF REACTIVE POWER LOSS

Several components contribute to voltage instability through reactive power demands. Some of these components contribute more to the fast or transient voltage instability while others dominate the slow voltage instability phenomenon. Two main components control both transient and slow voltage stability. These two components are at the heart of the voltage stability problem. They are:

1) The inductive reactive power losses in the system \( I^2 X \),

2) The effects of low voltage magnitudes on the loads

The first on this list was covered earlier when discussing the limitations on the transfer of reactive power through the lines. Since the power system is primarily inductive, the more current sent through the system the more reactive power losses occur. These reactive losses bring down the magnitudes of the voltages at the receiving ends or at the loads. The main components that contribute to the reactive losses are the transmission lines, transformers, and the loads.

The second on this list is the load. When the voltage gets low, how does that affect the load? Under low voltage conditions, is the load drawing more or less current from the bulk power system? Here, the bulk power system refers to the transmission system on the source side of the LTC transformer. If the load draws more current, it will simply cause more reactive losses. When more reactive power is lost, the voltage decays further.

Additional Components of voltage instability

If there were a third member of this list of primary contributors, most likely it would be some type of outage contingency. An outage “Contingency” refers to the loss of any element of the power system. This can be caused from a fault, generator tripping offline, or a sudden loss of
reactive power near the load. If “N” represents the number of power system elements without any contingencies, then the loss of a single equipment is called an “N-1” contingency scenario. Similarly, loss of two elements is known as; “N-2” scenario. A contingency is often the catalyst that begins the voltage problem. Though voltage instability is not always dependant on contingencies to occur, they are often the starting point that can lead to voltage collapse of a fragile system. For example if systems transmission lines are near peak loading to the point that the line sags excessively, the line could touch a tree and create an electrical fault. This fault could start a voltage instability condition since the system was highly stressed prior to the fault.

Although these are the primary reasons for voltage instability, there are also others. For slow voltage instability, additional factors are; Load Tap Changers (LTCs) on transformers, and thermostat controlled loads. For transient voltage instability, the fault duration is a deciding factor. If faults are not cleared quickly, a transient voltage collapse could occur. For example, if a breaker is stuck and cannot clear a faulted line, the fault stays on the system too long and a voltage collapse may follow.

**Types of Load**

The main factors for voltage instability have been discussed above. The next observation is to see how the above factors combine to create voltage instability. This is best done by looking at the load types. Additionally where these different types of loads are connected to the system plays a pivotal role. Different load types, depending on where they are connected, may offer load relief, or increased load or reactive demand under low voltage situations. If low voltage increases the load current, from the perspective of the bulk power system, then that type of load is contributing to a voltage collapse. Remembering that increasing the current means increasing the reactive losses, and increasing the reactive losses means decreasing the voltage magnitudes.
Load is the most dynamic portion of the power system, and the most complex to model accurately due to its changing nature. There is a static load model and a dynamic load model. The static model uses voltage to describe the power at each instant of time, while the dynamic model uses past instances to describe the power consumed. The static model is typically used for long-term voltage collapse studies, while the dynamic is used for transient voltage collapse studies. Though load seldom follows any of these approximations exactly, there are traditionally three different types of static load models as follows;

1) Constant Impedance
2) Constant Current
3) Constant Power

Load could be more accurately modeled as a composite of two or more of these different types. For many power flow programs these load types are labeled as Residential (Constant Impedance), Commercial (Constant Current), and Industrial (Constant Power). Again, these models are only approximations of how the loads will respond in actuality. Below is a simple mathematical equation that shows how power consumption is related to voltage. Note that these mathematical models are only accurate within \( \pm 10\% \) voltage fluctuations from its nominal value.[3]

\[
P = P_0 \left( \frac{V}{V_0} \right)^\alpha \tag{4.1}
\]

\[
Q = Q_0 \left( \frac{V}{V_0} \right)^\beta \tag{4.2}
\]

For equations 4.1 and 4.2, different values of \( \alpha \) and \( \beta \) represent either constant impedance, constant current, or constant power. If \( \alpha \) and \( \beta \) are equal to 2, this is indicative of a constant impedance load. If \( \alpha \) and \( \beta \) are equal to 1, this is a constant current load. If \( \alpha \) and \( \beta \) are
equal to 0, than it is a constant power load. A constant power load is also called a constant MVA load. \( V_0 \) is the rated voltage of the load and \( P_0 \) and \( Q_0 \) are the power consumed by the load at the rated voltage. \( P \) and \( Q \) are the power consumed by the load at the new voltage \( V \).

Since most loads are a combination of these static loads, a more accurate description of loads would be:

\[
P = P_0 \left[ p_1 \left( \frac{V}{V_0} \right)^2 + p_2 \left( \frac{V}{V_0} \right) + p_3 \right]
\]

(4.3)

\[
Q = Q_0 \left[ q_1 \left( \frac{V}{V_0} \right)^2 + q_2 \left( \frac{V}{V_0} \right) + q_3 \right]
\]

(4.4)

Where \( p_1, p_2, p_3, q_1, q_2, q_3 \) are all constant coefficients that represent the amount of each type of load. Since these equations describe the composite of a single load, \( p_1 + p_2 + p_3 = 1 \) and \( q_1 + q_2 + q_3 = 1 \) to represent the entire load described.

Figure 6 is a graph that shows how the current drawn from the system is affected by voltage for the different static loads.
Figure 6 shows that as the voltage gets lower on a purely constant power load, current will increase. In contrast, less current is drawn by a constant impedance load as the voltage drops. Remember the relations discussed, more current means more reactive losses, so as voltage drops further, constant power loads contribute to further voltage collapse while constant impedance loads offer some load relief. The voltage drop across the bulk power system is the most important. That is, if these static loads are connected to the bulk power system, than the previous assertions hold. However, if these loads are connected on the load side of the Load Tap changers
(LTCs), then the results are entirely different and will depend on the type of load connected. Again, it depends on which type of load connected where in the system, and how that load affects the voltage on the bulk power system. LTCs are discussed later.

**Load Characteristics**

Beyond the mathematical modeling, several other load characteristics and data can be observed and explored about static loads. This data is particularly important to know when the voltage deviates beyond the threshold of a 10% voltage drop. This data serves as a record on how loads react to further decrease in voltage. Below is a list of some loads and devices and the highly approximate characteristics usually assigned to them.

- Motors – Constant Power Loads (actually behave somewhat less than constant power)
- Discharge Lighting – Constant Current or Constant Power (depending on age/design)
- Incandescent Lighting – Constant Impedance or Constant Current (usually half way between the two)
- Thermostat Controlled
  - Air Conditioners – Constant Power (behave somewhat less than constant power)
  - Heating devices – Constant Impedance
- Electronic Devices with Regulated Power Supplies – Constant Power
- Adjustable Speed Drives – Constant Power

This list is not inclusive, and load characteristics are changing as technology changes. However, this at least gives an idea on which types of loads are on the system. Though all of these load characteristics can contribute to voltage stability, Load Tap Changers (LTC) and thermostat controlled loads play a more important role in slow voltage decay, while motor stalling and fault duration are the primary concern in Transient Voltage Collapse (TVC).
either scenario, motor stalling can be devastating, as it is also considered the final stage in slow voltage decay.

**Load Characteristics of Motors**

Motors are around 70% of the electrical load in the United States, 90% of the energy consumed by the motor loads is attributed to induction motors.[3,2] Understanding how and why motors can affect voltage boils down to understanding torque and stalling conditions. When motors stall, they can draw 600% or more of their rated current.[1] Moreover, the added current is heavily lagging with poor power factor. This creates large reactive losses and therefore lowers voltage significantly. Figure 7 shows a typical speed torque curve of an induction motor.

![Speed Torque Curve](image)  

**Figure 7**: Typical Speed Torque Curve for an induction motor. The normal operating point is shown for a constant torque load. [1]

In figure 7, there is an operating point at which the mechanical torque demanded by the mechanical load is exactly matching the electrical torque supplied by the motor. The small green circle in figure 7 shows this normal operating point. When an operating point is achieved, the
motor will not stall. When the voltage goes down, the torque goes down with the square of the voltage as suggested by figure 8 below.

Figure 8 shows the another prominent kind of mechanical torque load which is proportional to the speed squared. These types of loads include fans and centrifugal compressor or pump. Examples of constant torque loads are constant displacement pumps, compressors, and conveyors. It should be noted that since the maximum electric torque of the motor is proportional to the square of the supplied voltage, then as the voltage drops, the electrical torque supplied by the motors also drops rapidly. If the torque decreases enough, there will not be a point of intersection between the mechanical load (green lines) and the electrical supplied torque as shown by the red torque curve in figure 8. This will result in the motor stalling. Visually, the blue (motor torque) lines drop below the green (load torque) lines resulting in a torque curve.
resembling the red line. That is, the maximum torque or “breakdown torque” is lower than the mechanical torque load. It should be noted, even after restoration of the voltage, it is not possible for certain motors to operate at pre-stalling torque until their starting circuits have been reset. Air Conditioning motors specifically have this problem. There are also “under voltage” protective relays built into the majority of the larger industrial motors. This protection will disconnect the motor offline when voltage gets low a pre-set value. However, these are primarily to avoid thermal damage and depending on their settings may not help with voltage instability. Larger industrial motors are also typically connected through “starters” that contain a contactor. These contactors will open in the range 50% to 70% voltage to disconnect the motor under low voltage conditions.[1]

Besides knowing when a motor stalls and why voltage plays a role in the stall, the size of the motor also plays a significant role in Transient Voltage Collapse. Large motors have large rotating masses. The large rotational inertia associated with the rotating mass, resists sudden changes in rotational speed. The larger the motor, the more rotational inertia the motor possesses. Therefore, motors with larger inertia constants (H) will slow down less quickly than smaller motors with smaller inertia.

The duration of the low voltage is also important to motor stalling. If the voltage is significantly low for a short period of time, inertia from the motor may be sufficient to ride through the low voltage. If the voltage is not restored fast enough, the motor will stall. Conversely, if the voltage is barely low enough for stalling for a longer period, the energy stored in the rotating mass will diminish slowly to supply the mechanical torque of the load. The motor can resists stalling for a longer period. However, the voltage needs to be restored or the motor will eventually stall. The stall point depends on the breakdown torque relative to the load torque. Most motors will stall when voltage drops into the range of 70% to 80%.[1,3] Motors driving
pulsating torque loads may stall at voltages above 80% and are often among the first to stall.[1] Motors served at voltages below their rated value will also be among the first to stall.

**Load Characteristics of Thermostat Controlled Loads**

Besides motor stalling, the other load characteristic that makes a significant contribution to voltage instability is thermostat controlled loads. Thermostats control the load on the power system by turning the load on or off depending on the temperature and the settings. The basic problem here is that thermostats tend to keep the load “ON” for a longer time during low voltage conditions. A large penetration of thermostat controlled loads means that more load is on than normal. This decreases the load diversification. Again, larger loads translates to more reactive power losses lower voltages.

Heaters closely model constant impedance loads during short duration changes in voltage. When voltage drops for a period, the energy radiated from the heater also drops measurably, enough to trigger thermostat action. Noting that the real power drawn for a constant impedance or resistive load is proportional to the square of the voltage, equation 4.1, when \( \alpha=2 \). The thermostat will sense the energy dropped and thusly will extend the “on” cycle longer than would normally be needed to maintain the set temperature. A long enough period of extended “on” cycle (about 20 minutes on the average) helps the thermostat to restore the energy consumed to the previously set amount. Noting that the voltage is still low, to keep the energy constant it will require the same average current as at normal voltage. Figure 9 shows this phenomenon graphically.
The result is that after the load restoration period of about 20 minutes, the thermostat controlled load tends to act more like a constant power load. In summary, under low voltages, more thermostat controlled loads are on longer and draw less current than normal but more of them are connected to the system. All this contributes to increase reactive power loss and further reduce voltage.
Load Tap Changers are typically part of the step-down transformer to distribution voltages, though there are some at the transmission or sub-transmission level. The purpose of these LTCs is to regulate the voltage on the secondary (lower voltage) side by changing the winding ratio within the transformer. Therefore, if the voltage goes down on the secondary side of the LTC, the tap will change so that the voltage is maintained. In order to trigger a tap change, the voltage (or current) levels must go outside a pre-set band of values and remain there for a period of time. The band is a range of voltage or current in which no changes to the tap will be initiated. This range of values is referred to as the deadband. For example: if the secondary voltage drops below a value (or the current level increases above a level even if the voltage is at the same level) for 45 seconds, then the LTC will automatically change the tap to increase the voltage to the secondary side. It should be noted that the changes in the tap values due to current level increases (or decreases) are more prevalent than the changes due to voltage changes at constant current levels. This is the main reason for the name Load Tap Changers as “Load” refers to “Current”. The tap changing action is mainly to compensate for voltage drops along the distribution feeder. The discussion about the parameters and the settings for the “Line drop Compensation” is beyond the scope of this project. Typical LTCs have a buck or boost limit of around 10%.[1]
Figure 10: LTC Tap and Deadband. (Left) A capacitor is on the low side or load side of the LTC. (Right) The voltage drops out of the deadband for the programmed duration and the tap will automatically change to restore the voltage. [1]

An important question with LTCs is; what type of load is on the load side of the LTC and where are the capacitors in reference to the LTC. If the capacitors are on the high side bus of the transformer then the low side voltage restoration produced by the LTC will have no effect on the capacitor voltage or its reactive power output. That is, the reactive power output of the capacitor will continue to decrease as the high side voltage drops down. On the other hand, if the capacitor is on the low side bus, then as the LTC restores the voltage on the low side, the capacitors reactive output will also increase.

The type of load on the low side of the LTC is also very important. Examining a few scenarios, shows how the effects of the LTC operations can restore (increase) the load or offer load relief (decrease the load current) as seen by the bulk power system. See figure 6 for a review of how changes in voltage affect the current drawn by different loads. Using the classic model of
an ideal transformer it will be demonstrated that changing the windings \( N_2 \) can have an affect on the primary current \( I_1 \).

\[
\begin{align*}
  I_1 & \quad \bullet \quad I_2 \\
  V_1 & \quad \downarrow \\
  N_1 : N_2 & \quad \downarrow \\
  V_2 & 
\end{align*}
\]

Figure 11: Model of an ideal transformer. Assume the load (Secondary Side) is on the right and the source (Primary Side) is on the left.

For an ideal transformer shown by figure 11, there are no real power losses. That is the input power is equal to the output power.

\[
S = V_i I_i^* = V_2 I_2^* \quad (5.1)
\]

\[
\frac{V_1}{V_2} = \frac{N_1}{N_2} \quad (5.2)
\]

\[
\Rightarrow N_1 = I_2 \Rightarrow \left( \frac{N_1}{N_2} \right) I_1 = I_2 \quad (5.3)
\]

\[
V = IZ \Rightarrow \frac{V}{I} = Z \quad (5.4)
\]

We will consider the following different cases of loading for this ideal transformer;

1. **Constant power load after LTC** – When grid voltage goes down, a constant power load will draw more current to keep constant power \( S = VI^* \). Since power is conserved through transformers, neglecting some small losses, a constant power load on the load side of an LTC affects the bulk system similarly to if the constant power load was on the
source side of the LTC. Either way the bulk system sees a constant power load. Tap changing, on the LTC, does not affect the constant power aspect of the load. Thusly, the dominating concern with constant power load is when the voltage goes down, the current increases. The LTC has little effect on how the bulk system responds to constant power loads on the load side of the LTC.

2. **Constant Current load after LTC** – When the primary and the secondary voltages go down, the LTC will change the tap to restore the secondary voltage. To increase $V_2$ it is necessary to increase $N_2$, as suggested by equation 5.2. From equation 5.3, when $N_2$ increases $(N_1/N_2)$ decreases. Since $I_2$ must remain constant for a constant current load, $I_1$ must increase to compensate for the drop in primary voltage. That is, when the LTC changes the tap to increase the secondary voltage, more current is drawn from the primary source and power drawn from the grid increases. LTCs contribute to load restoration for constant current loads by increasing the current on the primary side of the LTC, which causes further drop on the primary voltage.

3. **Constant Impedance loads after LTC** – When the primary and the secondary voltages go down, a constant impedance load will draw less current based on Ohms law and as suggested by equation 5.4. Thusly, the load is initially decreased. The LTC senses that voltage reduction on the secondary and changes the tap to restore voltage. When voltage is restored, current drawn from the constant impedance load increases. LTCs contribute to load restoration for constant impedance loads by increasing the current on the primary side of the LTC.

Figure 12 shows a time graph of how constant impedance or constant current loads on the secondary side of an LTC transformer will affect the primary voltage as the tap changer of the
LTC moves to restore the secondary voltage. Figure 13 shows the cumulative effect on the subtransmission voltage as the LTC taps are changed until the maximum value is reached. LTCs will usually reach their maximum tap values when the voltage drops to around 5-7%. After this point, the LTCs no longer have any effects on the system voltage. During heavy loading LTCs normally operate at a few percent boost.

Figure 12: LTC Load Restoration. The graph above shows the affect of load restoration that a LTC transformer has on the primary voltage given a constant impedance type of load. [1]
Figure 13: Extended time frame for LTC action. [1]

Multiple LTC transformers can be connected to the same primary bus within a substation. When the primary bus voltage is reduced due to load restoration by an LTC, other connected LTCs will begin to sense the low primary voltage and also change their taps. This causes a ripple effect that starts with a single LTC, at a particular substation, and ultimately affects other LTCs connected to other stations in the area.
In contrast to the slow voltage collapse, where lack of reactive power is the driving force, the transient voltage collapse (TVC) is about longer duration faults that may cause motors to slow sufficiently that the system is unable to re-accelerate them. Faults that cause TVC are usually multiphase faults that are usually sustained well beyond 5 cycles.[1] Other factors include the stiffness of the grid, proximity of generators, characteristics of the motor and non-motor loads. There have been examples of TVC that lasts from 10 to 25 second and it is generally accepted that TVCs can lead to cascading and widespread grid blackouts.

It is well known that partial depression or full collapse of system voltage is associated with electrical faults. This voltage depression is sustained until the fault is cleared and isolated. The degree of voltage collapse at a bus is inversely proportional to the electrical distance of that bus to the fault location. Motors located within the affected area slow down, especially the ones with low inertia and close to the fault. The slowed motors draw more current and their power factor drops thus demanding more reactive power than is available in the area. This causes further voltage drops on motors in the surrounding area causing further speed reductions. This continues until either the fault is cleared in time and the system is recovered, or a blackout occurs.

For Air Conditioning (AC) and refrigeration units, there is an additional complication. When the motor on an AC or refrigeration unit slows excessively, or fully stalls, it cannot restart even after voltage is restored. The pressure in the condenser needs to bleed out of the release valve before the motor can be restarted. This keeps the stalled motors on the system for longer periods. This means that if areas have a large penetration of AC or refrigeration units they are
more prone for TVC. In some areas, reports have indicated that around 50% of the motor summer load can be AC or refrigeration.[3]

Almost all sizable motors have some type of overload protection that will disconnect them from the system. Feeder protection can also drop the stalled motors along with other loads. It can take up to twenty seconds for the overload protection to operate. If the grid does not experience angular instability due to low voltage and cascade of the stalled motors, then the voltage will recover after the fault is cleared and all stalled motors have been dropped by overload protection. The dynamic modeling of the motors is different from the modeling of the statics loads previously shown for slow voltage collapse. Figure 14 shows a traditional dynamic modeling for these motors. Unfortunately, this model is just a generic representation of motor dynamics, and does not represent the vast spectrum of different types of motor loads accurately. This makes it very difficult to be precise to calculate sensitive values such as critical clearing times for transient voltage collapse. To calculate the critical clearing times, the necessary load data would have to include the types of motors are on all the buses in the system. Without this information, it is difficult to create an accurate model for calculation of critical clearing times or test any solutions other than faster clearing. There could always be a pessimistic assumption of the load characteristics, which would require a faster clearing time.

![Dynamic Model for Motors](image_url)

Figure 14: Dynamic Model for Motors
Chapter 7

SLOW DYNAMICS OF VOLTAGE INSTABILITY

The slow dynamic of voltage instability will be analyzed in this chapter. Figure 15 shows the chronology of a sample of the slow dynamics for voltage instability.[1]

Figure 15: Slow Dynamics of Voltage Instability [1]

Figure 15 shows the order and the time in which the different components play their role in slow voltage instability. Again the main reason here is insufficient reactive power supply for prevailing system conditions. First, there is the contingency, which causes loss of a line or generation. This will initially drop the voltage. Shortly after, the generators will attempt to meet
the reactive power demand by increasing excitation current to the field windings. Often, the field windings are over their limits at this point. The voltage is initially restored, but cannot be maintained at this level since the field windings cannot stay at the over rating for a long period. Approximately, after 20 seconds of over rating, protective relays restore the generators field windings to the rated current, which drops the voltage again. As voltage drops, the LTCs will begin to change their taps to restore the load voltage. Load recovery further lowers the voltage. LTC taps reach their maximum values after around 10 minutes. Voltage continues to drop. Some capacitors may switch on, but their outputs are diminishing as the voltage continues to drop. About 20 minutes into the event, thermostats have extended the “on” cycle of their loads. This creates a loss of diversity and further restores load on the weakened system thus causing the voltage to even lower values. At this point, there is little time for the dispatchers to take action and if the load is not shed in a timely manner, the voltage could drop below 90% where there is the danger of motor stall or angular instability. If motors stall, they can draw up to 600% of their rated current, which can cause cascading effects and ultimately blackouts.
Chapter 8
SIMULATION

The following simulation is taken from source [1] using Power World software. The simulation is a good example of slow voltage collapse on a step-by-step analysis. Power flow is used to solve each system for the factors shown. Here is a quick synopses of how this example progresses. Loss of a local generation unit causes a reactive power strain on the other generators. These generators will adjust to maintain the voltage at the load and go beyond their excitation limits. When some of the generators protection restricts the excitation to their continuous reactive limit, the voltage will continue to drop. Low voltage provides some load relief, predominantly for constant impedance loads, and tends to slow or halt the voltage decay process. Then the LTCs will respond to support distribution voltage, thus restoring some of the load, causing further voltage drop as previously discussed. Other generators increase their excitation until their limits are reached. This will of course widen the affected area. After the exciters of the local generation units reach their maximum limits, the sending end generators are the only sources for voltage regulation. LTCs will continue to change their taps to further restoring load.

The process continues until; 1) voltage stabilizes under the control of remote generators and the intervening lines; 2) angular instability ensues from low voltage; or 3) motors stall possibly causing cascading effects from additional motor stalling and angular instability.

Additional simulations are performed for a deeper understanding of the concepts. In this simulation, there are five generators and two loads as shown by figures 16-22. For naming purposes, the local generators are those that are closest to the load buses. The load buses are on the far right of the simulation. The load on the upper load bus is a constant power load, and the load on the lower load bus is a constant current load. The constant current load is on the load side
of an LTC transformer. There is only one LTC transformer in this simulation. There are 7 steps to this simulation as follows;

Figure 16: Simulation Step 1. Normal Conditions [1]

Step 1 - This is the normal state of the system without any contingencies. Note the local generators are the primary suppliers of the reactive power, and thus the voltage levels.

Figure 17: Simulation Step 2 [1]

Step 2 - The generator on bus two is tripped offline as the initiating contingency. Almost instantly, the Automatic Generation Controls (AGCs) on the other generators will try to support the power flow and the voltage levels on the system to cover the tripped generator. Despite the
effort of the remaining generators, there is still a 3% voltage reduction on high side of the LTC load bus and on the distribution system. Note that most of the reactive power is still supported by the local generators. These generators have gone beyond their excitation limits and cannot stay in such position for a long period.

Figure 18: Simulation Step 3 [1]

Step 3 – The Protective scheme for the generator on bus number 1 has limited the reactive power output to its rated continuous limits. This reduction in MVARs transfers more of the reactive load on the other generators especially the remaining local generator.

Figure 19: Simulation Step 4 [1]
Step 4 – The LTC tap changes to restores the load. The voltage has been in the dead band on the LTC transformer long enough for the tap to change. By restoring the load, higher current levels on the transmission lines places more reactive demand on the system. Again, the generators will attempt to keep up.

Step 5 – The last local generators’ reactive power outputs will be limited due to their protection actions. The loss of the reactive power leaves the sending end generators as the primary support. This is not effective, and the voltage in the load area suffers dramatically.
Step 6 – The LTC tap changes again. This restores more load, which drops area voltage further.

![Simulation Step 7](image)

Figure 22: Simulation Step 7 [1]

Step 7 – The LTC will continue changing taps until its limit is reached. When this occurs, the distribution voltage falls and thermostats begin compensating for the low voltage condition thus restoring more of the load. The voltage on the high side is now reaching “stall” level conditions for motors that see the primary side voltage. Many industrial plants are served without LTC and their motors are subjected to this lower the sub-transmission voltage. These are the motors with least torque margin and the ones likely be stalled. Other issues such as pulsating loads also tend to stall.

The results of the simulation are to show the dynamics of slow voltage decay to include:

- Large reactive power demand due to real power flows. Compare the total reactive power contributions from the generators in step 1 (194.4 MVAr) to slide 7 (1430 MVAr).
- Inability for reactive power transfer over longer distances. Compare the reactive power received by the load on the load side of the LTC from step 1 (603 MVAr) to step 7 (452 MVAr).
• LTCs combined with restorative loads can collapse the voltage of a fragile system under contingency operation as shown in step 7 when high side voltage drops to .85 p.u.
Chapter 9

METHODS FOR CALCULATING VOLTAGE STABILITY

Calculating stability for TVC is different from calculating for slow voltage instability. Both will be analyzed in this chapter. Transient Voltage Stability must be simulated with detailed motor loading data, which can accurately model the dynamics of motor stalling and recovery resulting in voltage collapse or stability respectively. Voltage recovery or collapse for post contingency is the primary concern in TVC analysis. Transient conditions are usually analyzed over a few seconds. The voltage magnitude at each bus can be plotted against time to show the collapse or recovery. Motors need to be modeled in detail with inertia, contact dropouts, etc. to accurately simulate how these motors respond to low voltage conditions.

Simulations for transient resemble a trial and error type of analysis. Given existing fault clearing times, does a fault clear fast enough so that enough motors recover from the low voltage or does the voltage continue to drop stalling more motors. If not, faster clearing times or some other solution may be needed. Again, dynamic modeling of the motor loads are the critical portions.

The most popular method for calculating voltage stability limits for slow voltage decay utilizes PV and QV curves. This method uses static loads, as is typical with power flow problems. The static load model is chosen to match load conditions at the end of the period of slow decay. Constant power model is used as it accounts for LTC action and load self-restoration from thermostats. Because some loads do not self-restore, a constant power model is somewhat more conservative and thus provide a safety margin beyond that shown in the PV or VQ curve. A snapshot of a system can be used as data and solved using power flow. Typically, this is done through a computer program that can perform complicated calculations and handle thousands of buses. The power flow solution will provide the voltage magnitude and angle at each bus,
necessary generation within limits, and the real and reactive power flows on the lines. Additionally, power flow analysis should be done with some contingencies in mind so that worst-case scenarios can be identified.

As the line currents during various power flow conditions increase, the reactive losses increase. When reactive losses increase, the voltage magnitude decreases. Therefore, as the real power flow increases the voltage magnitudes tend to decrease. There is a point that the system can no longer support the real power flow on the lines and maintain a stable voltage. Thusly the voltage collapses. Let us refer to figure 23 for an example of a theoretical PV curve. Static loads normally have fixed power factors. This PV figure simply shows how different power factors result in different PV curves. Plotting multiple curves for a particular bus is similar to comparing several contingencies to find the worst-case scenario. The lower halves of the PV curves are theoretical since these points on the curve refer to conditions for which the power flow program will not converge (unable to find a solution). Additionally, actual PV curves tend to be flatter on top since generators tend to control the voltage better under light loading conditions.
Analysis using PV curves is based on increasing the real power flow by increasing the load or power transfer. Loads should be steadily increased while a power flow solution is executed at each load increment. Each bus will have its own PV curve, where the bus voltage is represented per the power flow solution. Systematic analysis will likely reveal a weak point- or a group of critical buses in the system where the voltages drop more than at other buses. Critical busses are often those farthest from reactive power sources. Once these critical buses are determined, additional PV analysis can be applied to the critical buses to determine the available
active margins. Other limitations on lines or equipment might come into play as power flow increases.

The QV curve relates the voltage on a bus to the reactive power available at that bus. As voltage increases on a bus, more reactive power flows from that bus to the rest of the system. Similarly, as the voltage on a bus drops, reactive power is directed from the system to that bus. At lower voltages, where the curve flattens there is no reactive power available at the bus due to a balance between inductive and capacitive reactance of the transmission lines. Past this point, reactive power must flow into the QV test bus as voltage is lowered further.

The analysis of QV curves is based on an unlimited fictitious reactive power source that controls the voltage at the QV test bus by either supplying or absorbing reactive power to force the voltage up or down at that bus. This fictitious device is simply a condenser with real power set to zero and the reactive power limits opened wide. The power flow is solved at each incremental change of voltage and the resulting reactive power to or from the condenser on the bus is plotted against the bus voltage. The only thing a user needs to change is the voltage at the test bus via the fictitious generator and then allow the other system elements to respond to this voltage via power flow. Each bus will have its own QV graph. Figure 24 shows an example of a set of QV curves for a system at different load levels. Note that the voltage is the independent variable. Other reactive sources, such as capacitors, should be included in the model and set at normal switching criteria so that accurate reactive power margins can be ascertained.

The QV curves shown have some theoretical elements to them that are not traditionally present in QV curves. Normal QV curves are only plotted from 90% to 105% voltage. Voltages outside of this range are not feasible. Also, the family of curves should be from around 95% to 110% of expected load. The QV curves are plotted for all credible and potential limiting contingencies. The “p=” in the graphs represents the fixed normalized real power of the loads.
Figure 24: Normalized Q-V Curves. Modeled for fixed (infinite) source and reactance network with constant power loads. [2]

Buses that allow less reactive power to be drawn from the QV test bus are in a weak area of the system. Generally, a reactive power margin criterion is set, for instance 150 MVar at 230 kV. Of course, the margin should be sufficient to cover the most severe contingency in the area being studied. Often some margin will be mandated during that worst contingency.

Here are some additional notes on PV and QV curves. The instability points on the PV curves are at the tip or the “nose”. Hence, these curves are sometimes referred to as the “nose” curves. The instability point of the QV curve is at the bottom of the curve. This is when the reactive power on the bus no longer increases as the voltage decreases. Reactive power margins
can be seen from the QV curves. The reactive power margin is negative if the curve does not pass below the 0 MVAr axis. The lower the curve drops below the 0 MVAr axis, the more reactive power margin exists in the area around that bus.[1] However, since operation below about 90% voltage puts the system at high risk of angular instability or motor stalling, any reactive margin below that voltage is of no value. In figure 24, the lower two curves have a usable reactive margin only slightly below the 0 MVAr axis when voltage is at 90%.
Chapter 10

CONCLUDING REMARKS AND RECOMMEND POSSIBLE SOLUTIONS

In most of the voltage instability issue presented above, there are possible solutions that can help maintain voltage stability. It was discussed that the basic problem with the slow voltage decay is the lack of reactive power. If there is a way to decrease the reactive power losses or increase the reactive power then this could help with voltage stability. As with any solution, the economic benefits need to be weighed against the cost. Here is a list of some of the problems with their recommended solutions, followed by any concerns with the solutions.

1. Reactive Power sources for the system
   a. Solution 1: Reactive sources such as condensers or capacitors may be added near the high reactive loss areas. Series capacitors work well to compensate for long transmission lines but may be an SSR hazard if installed near generation. Shunt capacitors work well but their outputs drastically decrease as the voltage drops.
   b. Solution 2: Additional transmission lines may be built. The key here is not to increase the amount of power transferred with the extra lines in place. Lightly loaded lines can be a good source of capacitance and can ease congestion. If new lines are added, then heavily loaded to take advantage of this new capacity, the system may be in a worse situation. Also with a system that is more interconnected, faults affect a greater area, which can lead to Transient Voltage Collapse. Adding lines is an expensive solution.

2. Load Shedding:
a. Solution 3: – Operators usually shed load as the last resort. Under Voltage Load Shedding (UVLS) schemes, drops load when the voltage gets too low. The dropping of load will alleviate the system by eliminating the current flowing to the dropped load. UVLS usually triggers distribution feeders to open when voltage on the bulk electric system is around 90%. Definite time relays usually act when all three phases show low voltage for around 10 seconds. At 90% voltage, this would be after some of the LTCs have acted. Good candidates for UVLS are loads that would have been restored by these LTCs (constant impedance and constant current loads). In addition, any constant power loads would be a good candidate for UVLS. Certain critical customers cannot be dropped from load despite the help it may present to the system. Critical customers include hospitals or customers that would loose lots of revenue from being dropped.

b. Solution 4:– The way load reacts to low voltages may be modified. If there were an industry standard for motors and thermostatic loads to trip under low voltage, it could help maintain the voltage stability. More under-voltage protective schemes may be added to motors or thermostatic loads to sense when the voltage is low and trip the unit offline. This may not be economically feasible, but it is possible. Since most loads are on the load side of an LTC, a region where voltage is maintained longer, the under-voltage schemes may have to trip load at around 95% voltage to make a better impact.
REFERENCES


