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**Voltage security assessment and control in electric power
systems**

Cote, James William, Jr., Ph.D.

University of Washington, 1992

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Voltage Security Assessment and Control in Electric Power Systems

by

James W. Cote, Jr.

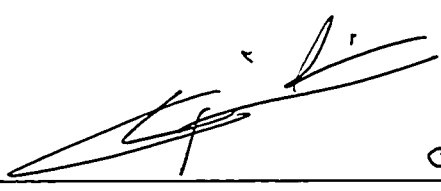
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of the requirements for the degree of

Doctor of Philosophy

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1992

Approved by


(Chairperson of Supervisory Committee)

C.-C. Liu

Program Authorized
to Offer Degree

ELECTRICAL ENGINEERING

Date

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Abstract

**Voltage Security Assessment and Control
in Electric Power Systems**

by James W. Cote, Jr.

Chairperson of the Supervisory Committee : Professor Chen-Ching Liu
Department of Electrical Engineering

Due to the increase in load demand and lack of major transmission or generation expansions, electric power systems are facing the risk of severe voltage problems. This research addresses two aspects of voltage security in electric utility transmission systems. First, the efficient assessment of steady state security with respect to all plausible single and double line contingencies is investigated. Second, detection and avoidance of a dynamic voltage collapse event is investigated.

This dissertation develops an expert system called SEEKS to assess steady state voltage security. SEEKS must intelligently select line outages likely to cause steady state voltage violations. The contingency selection process assesses outages in the context of the local topology and operating condition, using heuristics derived from operational planning experience. Information about the local topology is captured by grouping buses and branches into neighborhoods (structures). These structures are used for comparing the impact of an outage relative to other outages connected to the same structure. The worst outages are evaluated by running fast decoupled power flows. When voltage violations are found, remedial action is investigated. The remedial action set is limited to adjustment of capacitors, tap changing transformers, and generators connected to the same structure as the buses with voltage violations. The resulting control action provides a sufficient but non-optimal set of controls for removing the violations.

SEEKS uses an uncommon criterion for determining the success of the contingency selection process. Following the same process used by operational planning engineers, SEEKS tries to identify only the worst case or most severe outage amongst sets of outages in the same neighborhood. This assumes that remedial control used to

compensate for the most severe outage will correct the violations caused by other outages in the same neighborhood.

In the area of voltage security assessment, this research contributes a qualitative approach to line contingency selection based on generalized operational planning knowledge. The proposed method deals with both single and double line outages by considering possible relay and breaker failures. Outages are grouped into sets such that the most severe outages can be evaluated. The remedial action search is limited to control devices near the violations by using the identified local topology.

This dissertation also develops an algorithm for detection and remedial control of an imminent dynamic voltage collapse in real-time. The detection scheme monitors each load bus voltage and reactive load demand in the time domain, looking for an indication of imminent collapse at each bus. Once a collapse is detected at a bus, the remedial control scheme calculates the amount of control necessary to steer the system voltages away from the collapse.

The detection scheme is based on continuously updated Thevenin equivalences at each load bus which approximate the network's ability to supply reactive power. The stability of the first order system consisting of the load bus reactive demand and the equivalence is continuously evaluated. When this system approaches instability, the remedial control scheme is triggered. Each iteration of remedial control forces the voltage derivative to become positive at the collapsing bus, i.e., the voltage recovery region for the collapsing bus captures the current system state. The control set consists of switchable capacitors (both at and nearby the collapsing load bus) and load shedding. The remedial scheme attempts to minimize the amount of load shedding by using all capacitors first, while also minimizing the total amount of control applied. This is accomplished by iteratively applying remedial control, rather than forcing the system into a known stability region with one large set of control actions.

In the area of dynamic voltage collapse research, this work contributes a localized real-time detection scheme for predicting an imminent collapse and a real-time remedial control scheme for calculating the amount of capacitor switching and load shedding required to steer the system voltages away from the collapse. This work is a logical extension of the research into constructing stability regions for the voltage collapse time frame.

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Chapter 1. Introduction

Utilities have found the current economic and political environment such that the addition of major new facilities is more difficult and therefore less frequent. This places a burden on existing generation and transmission facilities, exhibited by increasingly large power transfers across long transmission corridors for long durations. When transmission corridors carry large transfers between systems or areas, voltage control problems are created. The impact of these transfers on the receiving area can range from low steady state bus voltages to poor voltage control properties and exposure to possible voltage collapse. Transmission line series compensation has been commonly used to enhance inter-area transfer capability while continuing to meet transient stability requirements. However, while series compensation has increased the ability to load transmission lines, the bus voltage performance of these systems has not been addressed.

This dissertation will address two aspects of the voltage performance problem. First, from the steady state viewpoint, the problem of efficiently assessing the security of the transmission system with respect to all plausible single and double line contingencies is investigated. Specifically, the task is to select line contingencies which create post-disturbance steady state voltage violations. Once selected, the impact of the most severe line contingencies must be evaluated. Second, from the dynamics viewpoint, the problem of detecting and avoiding a voltage collapse event is investigated. Specifically, an algorithm is developed for detecting an imminent dynamic voltage collapse and for determining the remedial control necessary to avoid the collapse. The algorithm must account for the effects of equipment known to have a significant impact on the system's dynamic performance during a collapse. In addressing each of these voltage performance problems, the variation or behavior of bus voltages under extreme system conditions or disturbances must be incorporated, and remedial control to improve the system's voltage characteristics must be determined.

1.1 Static Voltage Security Assessment

On-line assessment of static voltage phenomena can provide an economic benefit during real-time operation. Normally, operating guidelines are developed from off-line studies. These off-line studies are based on estimates of future operating conditions. The error inherent in estimating the operating point forces engineers to add margin to the study results before producing operational guidelines. In contrast, accurate real time data is

available when performing on-line assessment, thereby allowing the use of less margin during actual operation.

Approximate methods for quickly estimating steady state real power flows and bus phase angles after a disturbance have exhibited much success due to the accuracy of linearized methods. As a result, many algorithms capable of assessing line overload problems in an on-line environment have been implemented. Fast voltage estimation has proved more difficult. The dependence of bus voltage magnitudes on reactive power flow is less accurately modeled using linearized methods than the dependence of bus voltage angles on real power flow.

Efficient algorithms for on-line voltage assessment have remained a research challenge. Contingency ranking through the use of a performance index (PI) is a common approach to static security assessment (SSA) which has met with much success in dealing with the line overload problem. However, PI masking problems for the voltage problem have proven more complex to overcome. Contingency screening is another popular approach to SSA. However, most methods use local or approximate power flow algorithms to compute the impact of outages, a method prone to failure when dealing with voltage problems.

In general, the common approaches to static voltage security assessment do not provide insight into the characteristics of the operating point which allow contingencies to cause violations. This is in contrast to the approach used by the utility's operational planning engineers. The engineer identifies those aspects of the system topology and operating point which indicate that certain outages will likely create operational violations. From this insight, the engineer selects only the outages most likely to cause violations for further analysis. This selection process greatly reduces the total number of power flow cases to be computed.

This dissertation presents an expert system called SEEKS which assesses the steady state bus voltage security of the system with respect to single and double line outages. The most difficult task SEEKS must accomplish is the intelligent selection of line contingencies likely to cause steady state voltage violations. The contingency selection process assesses the impact of outages in the context of the local topology and operating

condition, using heuristics generalized from operational planning experience. Information about the local topology is captured by grouping buses and branches into neighborhoods (structures). These structures are used for comparing the impact of an outage relative to other outages connected to the same structure. These comparisons result in a final ordering of local groups of outages based on anticipated severity.

The final evaluation of the impact of the worst outages (those with highest order) is done by running fast decoupled power flows. Because power flow evaluation is computationally expensive, the selection process must greatly reduce the list of contingencies to be evaluated, for the assessment to be efficient.

When the power flow evaluation of an outage yields steady state voltage violations, remedial action is investigated. The remedial action considered by SEEKS is limited to control devices (capacitors, tap changing transformers, and generator reference voltages) connected to the same neighborhood as the buses with voltage violations. This reduces the available control set such that remedial action investigates only those controls likely to relieve the violations. The remedial action task does not try to choose an optimal set of controls, but rather tries to find a sufficient set of controls to remove the violations. An elaborate remedial action algorithm is not time effective in the context of real-time security assessment.

All SSA algorithms are evaluated by their ability to efficiently select only those outages which cause violations, and to accurately estimate the impact of these outages. SEEKS uses a power flow algorithm to evaluate each selected outage, such that accurate impact estimation is not an issue. However, from the selection viewpoint, SEEKS uses a different criterion for determining the success of the contingency selection process. Following the same process used by operational planning engineers, SEEKS tries to identify only the worst case or most severe outage amongst sets of outages in the same neighborhood. This criterion is based on assuming that remedial control or operating point modification used to compensate for the most severe outage will correct the violations caused by other outages in the same neighborhood of the worst outage. Therefore, only the worst case outage is important from an assessment point of view.

The contributions made by SEEKS in the area of voltage security assessment are :

- 1) A heuristic approach to the selection of line contingencies is developed which uses generalized operational planning knowledge in addition to superposition principles for determining the impact of outages on bus voltages.
- 2) A method for identifying local bus and branch structures to assist in the assessment is proposed.
- 3) Both single and double line outages are included in the plausible contingency set by considering possible relay and breaker failures.
- 4) Outages are grouped into collections such that only the most severe outage in each collection need be evaluated by the power flow and remedial action tasks.
- 5) The remedial action search is performed, but limited to control devices near the violations by using local bus and branch structures.

1.2 Dynamic Voltage Security Control

In addition to steady state voltage control problems, inter-area transfers increase the system exposure to voltage collapse events. The phenomenon of voltage collapse did not receive much attention until recent system blackouts from uncontrolled voltage depression, such as those in France [1] and Japan [2]. These events were caused by an inability to control bus voltages under the influence of large inter-area transfers or extreme load changes. Voltage collapse events have been difficult to study because traditional power system stability tools are tailored for transient time frame phenomenon (0 to 10 seconds), emphasizing the angular separation of generators. The models developed for transient stability analysis do not adequately represent the response of equipment during the time frame of dynamic voltage collapse.

Popular approaches to voltage collapse assessment use steady state models for detecting unacceptable operating points or the disappearance of a stable equilibrium point. These approaches analyze the power flow solution as the system slowly moves toward a

collapse. Indicators such as failure of the power flow to converge, bifurcation of the power flow equations, or singularity of the power flow Jacobian matrix have been proposed to detect a collapse.

When, however, the transient behavior of a system during a disturbance is significant, collapse assessment must be based on the system dynamics. This is true even though both the pre-disturbance and post-disturbance operating points may be acceptable from the steady state viewpoint. The effects of generator excitation limits, dynamic load characteristics, and on-load tap changing transformers (LTCs), to name a few, are known to significantly impact the system dynamic performance during a collapse. A dynamic model of a collapse event including these mechanisms provides a complete picture of the trajectory of system variables during the collapse.

Recently, research attention has focused on the dynamic voltage response to disturbances and small variations in the operating point. This effort has analyzed the stability of the operating point and developed stability regions, based on the mechanisms mentioned above. The next step along this line of research is to develop methods for real-time calculation of remedial control for avoiding the collapse, while considering system dynamics.

This dissertation presents an algorithm for detection and remedial control of an imminent voltage collapse in real-time. The detection scheme monitors each load bus voltage and reactive load demand in the time domain, looking for an indication of imminent collapse at each bus. Once a collapse is detected at a bus, the remedial control scheme calculates the amount of control necessary to steer the system voltages away from the collapse region.

The detection scheme is implemented at each load bus by constructing an approximate Thevenin equivalence which can be used to evaluate the network's ability to supply reactive power to the load bus. The equivalence is continuously updated to reflect the current system state. From the equivalence, the stability of the first order system consisting of the load bus reactive demand dynamic can be evaluated. When the first order system approaches instability, the remedial control scheme is triggered.

The goal of each remedial control iteration is to drive the voltage derivative positive at the collapsing bus. This is accomplished by forcing the voltage derivative at the bus where collapse was detected to become positive, i.e., the voltage recovery region for the collapsing bus captures the current system state. A proof that this remedial scheme is guaranteed to eventually force the system state into a stability region is provided.

The remedial control set consists of switchable capacitors (both at and nearby the collapsing load bus) and load shedding. The remedial scheme attempts to minimize the amount of load shedding by using all capacitors first, while also minimizing the total amount of control applied. This is accomplished by iteratively applying remedial control, rather than forcing the system into a known stability region with one large set of control actions.

The contributions made by the voltage collapse detection and remedial control algorithm to the area of dynamic voltage collapse research are :

- 1) A localized real-time detection scheme for predicting an imminent voltage collapse is developed.
- 2) A real-time remedial control scheme for calculating the amount of capacitor switching and load shedding required to steer the system voltages away from a collapse is proposed.

Chapter 2. Static Voltage Security Assessment

Static Security Assessment (SSA) is the task of estimating or evaluating the steady state impact of all plausible contingencies or outages on the current operating point. The assessment must determine whether the operating point is secure with respect to the set of outages and some set of post-disturbance steady state limits. In this context, a system is secure whenever all plausible post-outage static operating points contain no bus voltage and no line flow violations. When possible, controls able to remove post-outage violations should also be identified.

The dimension of modern power systems results in a long list of contingencies to be considered during SSA. Present technologies do not allow exhaustive power flow evaluation of a long list of outages in a real-time environment. Off-line SSA has few computational time constraints, allowing many outages to be examined. Nevertheless, operational planners performing off-line assessment select only a small fraction of the plausible outages for power flow analysis. These outages are expected to create the most severe changes in the operating point. Power flows are run to determine the post-outage static operating points for the selected outages. Remedial action is investigated whenever violations are present in the post-outage operating point.

Typical operation of the transmission system usually results in only minor violations occurring for outages of one component. Major violations are usually caused by multiple component outages. Often these outages begin as single component outages which, coupled with breaker or relay failures, evolve into double component outages. To improve SSA, the impact of these multiple outages must be included in the SSA task. However, evaluating these double contingencies is difficult because of the number of outages to be considered.

Various methods for achieving fast and accurate SSA have been proposed. Numeric algorithms for contingency ranking based on calculating the change in a performance index have shown success in quickly capturing line overloads [3,4]. Contingency screening is also a popular method for eliminating those outages whose impact can be predicted without the use of power flows. In [5], a rule-based approach was proposed which screens contingencies by applying power system structural information to overload evaluation. The relationship between system topology and line overloads is also investigated in [6], in which MW flow re-routing is considered. The expert system

proposed in [7] incorporates line flow, voltage, and stability criteria into a hybrid rule-based/algorithmic environment. The coupling of a symbolic approach with numerical algorithms for security assessment is not uncommon [8,9]. Empirical rules for alleviating line MW overloads and for applying other operational guidelines are included in an expert system prototype presented in [10]. Other references in this area are given in [11-14].

This chapter presents an expert system (ES), called SEEKS, for SEcurity Evaluation Knowledge-based System. SEEKS selects the worst case single and double contingencies for power flow evaluation, based on the network structure and operating point. Specifically, SEEKS selects contingencies which are expected to create post-outage steady state bus voltage violations. The contingency list is not fixed, but rather is adapted to the current operating condition. SEEKS achieves rapid and accurate SSA by combining a knowledge base for selecting severe outages with accurate operating point information and fast power flow algorithms.

SEEKS is designed to assess voltage security as opposed to line MW overload problems. SEEKS does not address the issue of voltage collapse. Nevertheless, for comparison, voltage collapse proximity results are presented to provide another perspective of the system voltage performance under outage conditions. Voltage security remains an area of considerable concern; existing approaches to this problem have not achieved the same level of accuracy and performance as in the line overload problem. The development of fast algorithms for on-line static voltage security is an active area of research [15].

SEEKS analyzes specific network structures (radials, loops, and clusters) along with the current operating point to quickly identify the critical contingencies. All other contingency scenarios are eliminated from further analysis. A fast decoupled power flow is used to evaluate the post-outage operating point. Any violations found in the power flow results are examined by a remedial action rule base to determine possible control action. The network structures are also used during the remedial action task to help identify local controls.

2.1 Expert System Development

The SEEKS expert system was developed by identifying the generic knowledge used by operational planners during system security assessment. During this knowledge acquisition phase, a software prototype was built to evaluate the quality of the acquired knowledge. The knowledge acquisition and the software environment are described below.

2.1.1 Knowledge Acquisition

The development of the knowledge base for SEEKS presented a challenge. Usually, the knowledge engineer who builds the system software consults with a human expert in the problem domain. Together they synthesize the knowledge applied to solve or analyze specific problems. The knowledge engineer questions the detailed and usually system specific knowledge the human expert uses in solving each problem. In the process, specific knowledge is generalized to broaden its applicability. These generalized rules may often have exceptions, leading to the specialization of some of the rules.

For this prototype, the author, who has 5 years of operational planning experience with the Los Angeles Department of Water and Power (LADWP), is serving as both the domain expert and the knowledge engineer. This often complicated the task of extracting the generic knowledge from the detailed, system specific knowledge. The generalization of system-specific experience was non-trivial because the resulting generic concepts often seemed to lead to many exceptions. A balance had to be struck between the level of generality in the rule base and the number of allowable exceptions.

The knowledge acquisition was achieved by repeatedly using operational planning experience to select contingencies expected to lead to violations. Post-outage power flows were calculated, and the results were compared to an exhaustive evaluation of all outages. Rules were formed by analyzing the components of the operational planning reasoning process which led to the selection of worst case outages. Whenever the outages selected by SEEKS differed from those selected by the operational planner, the offending rules were identified. The basis for each of these rules was questioned, and new rules were added, or old rules were modified.

2.1.2 Software Environment

SEEKS was developed on a VAXstation 3100 platform running VAX/VMS version 5.3. The software environment contains a rule-based system written in OPS83 and a fast decoupled power flow written in FORTRAN 77. Meta-rules (or control rules) were developed to control the task flow in the problem solving process.

The SEEKS software communicates with a power flow program during execution. This interaction is implemented using the mailbox feature of VAX/VMS. Messages are passed between the power flow and ES as needed, allowing the power flow and ES to run concurrently. The input to SEEKS is a power flow data file representing the current operating condition and a data file describing the controllers available for remedial action. For real-time use of SEEKS, state estimation results can represent the current operating point.

2.2 Knowledge Base

The knowledge base contains a number of rule modules, each handling a separate task. Meta-rules control the separate tasks. The structure and control of SEEKS is illustrated in figure 2.1. The rule modules are discussed in the following sections.

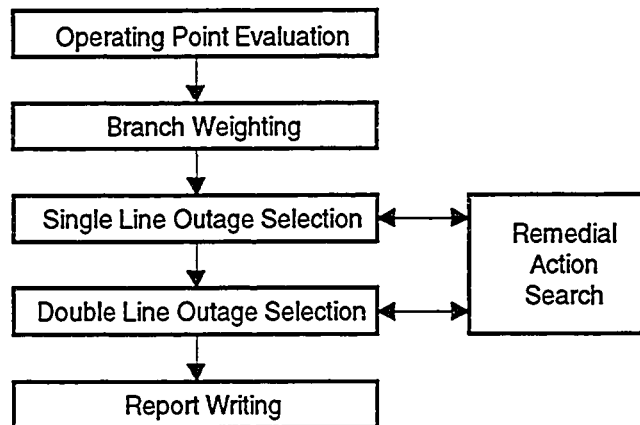


Figure 2.1 SEEKS Functional Diagram

2.2.1 Operating Point Evaluation

The operating point evaluation task consists of a security evaluation of the base case operating point without considering contingencies. SEEKS accesses the power flow solution of the base case operating point (actual voltages, etc.) and searches for bus voltage violations. If violations are found, a search for remedial control action is begun. Barring base case violations, SEEKS proceeds with the security assessment by considering branch contingencies.

In preparation for the remaining phases of the assessment, SEEKS relies on search algorithms built into the power flow to identify the bus/branch structures identified below. SEEKS will use this network structural information along with the current operating point to select worst case outages. The identification of these structures emulates the operational planner's grouping of buses into subsets, allowing closer examination of the branches which tie these subsets to the remaining system. The structure identification is implemented inside the power flow to achieve the best execution speed. Definitions and search algorithms for each structure type follow. Examples of each structure appear in figure 2.2.

Radial : a collection of single branches in series such that any radial branch outage islands some buses in the structure. The search algorithm begins by finding a bus incident to exactly one line. The bus and line are added to a new radial. Next, the bus at the opposite end of the most recently added line is tested. If this tested bus is incident to exactly two lines, the tested bus and the new line (not already in the radial) are added to the radial. The search ends when no new buses or lines can be added.

Loop : a path of single branches which begins and ends at buses connected to the remaining system. Each line outage internal to the loop creates two radial structures. The search algorithm begins by finding a line and the two incident buses, where both buses must be incident to exactly two lines. This yields three lines and two buses which create a new loop. Next, any bus incident to exactly one loop line and one non-loop line is added to the loop, along with the non-loop line. The search ends when no new buses or lines can be added.

Cluster : a collection of several buses interconnected by low impedance lines. Low impedance is defined as less than the average impedance of all other lines at the same nominal voltage class. The search algorithm begins by finding a low impedance line and the two incident buses. Starting from an incident bus, additional lines and buses are added to the cluster if the line is low impedance and is incident to a bus in the cluster. When no more low impedance lines are found, a second stage of the search begins. Any bus connected to exactly one line in the cluster is removed from the cluster together with the line. These lines are not included in the cluster because outages inside a cluster are required to have little impact. This condition is met by requiring all cluster buses to be incident to at least two internal, low impedance lines.

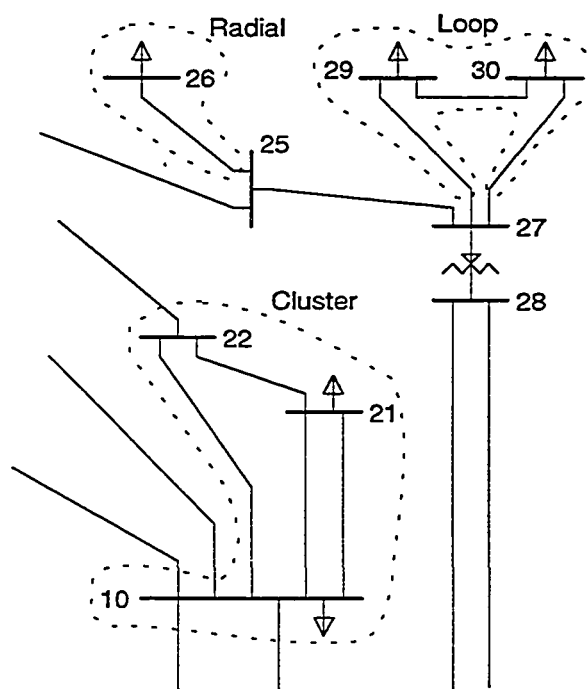


Figure 2.2 Structure Examples
(Partial IEEE 30 Bus System)

2.2.2 Branch Weighting

The impact of each branch outage is ranked by assigning weights to branches. The selection of branch outages for power flow evaluation will be based on these weights. The operational planner selects branch outages for power flow evaluation by comparing the impact of different branch outages. This comparison is dependent on the operating point, local topology, and heuristics derived from experience solving power flows. The branch weight adjustment made by each rule is dependent on the assumptions built into each heuristic comparison.

When comparing branch outages, operational planners do not identify a list of all contingencies which create limit violations. Rather, the worst case outages amongst sets of outages are identified. These "consistent" sets of outages represent groups of outages impacting the same local areas in the power system and result in violations because of the same deficiencies in the operating point. Examples of such deficiencies might be heavy loading of a group of buses with limited reactive support, or heavily loaded, weak transmission corridors. Provided that outages are grouped into consistent sets, only the impact of the worst case contingency in each set need be investigated. This consistent set concept implies that all other outages in the set have a less severe impact on the operating point. In addition, a successful remedial action search for each worst case outage implies the success of a remedial action search for all other outages in the same consistent set. From the SEEKS point of view, a consistent set consists of all branches in the same structure. Structure identification and branch weighting together filter away many branch outages from power flow analysis.

The branch weighting rules increment and decrement integer weights assigned to each branch, based on the expected impact of the branch outage on the operating point. All branches (lines and transformers) are initially assigned a weight of zero. The rule base modifies branch weights by identifying branches most important to the voltage profile, based on topology and operating point. A discussion of the branch weighting rules follows. (Note : the term flow refers to real power unless otherwise indicated.)

Radials : An outage of any radial branch creates out-of-service buses correctable only through switching action. SEEKS does not consider switching action during the

remedial action search. Therefore, each radial branch outage is effectively a loss of load or generation from the system viewpoint. Radial branches which carry flow from the system into the radial will not depress voltages outside the radial when removed. These branches are decreased in weight. The interesting scenarios are those where generation exists inside the radial structure. Line outages under these scenarios can lead to the loss of system generation. Therefore, a radial branch carrying generation into the remaining system is incremented in branch weight. Also, the outage of a radial branch connecting two generation buses will interrupt less generation (from the system viewpoint) than the outage of the radial branch one node closer to the system. In addition, if a radial supplies net generation to the system, the boundary branch must be considered a generation source from both the bus and the system viewpoint. Rules for weighting radial branches follow.

- R1** if a branch is inside a radial, and both end buses are load or both are generation, then decrease its weight by two.
- R2** if a radial's boundary branch carries real and reactive flow into the radial, then decrease its weight by two.
- R3** if a radial contains both load and generation, and an internal branch carrying flow toward the system has larger flow than all other internal branches, then increase its weight by one.
- R4** if a radial's boundary branch is the largest generation source at a bus, then increase its weight by one.
- R5** if a radial's boundary branch is the largest generation source in the system, then increase its weight by two.

Loops : Usually, the significant branches in a loop structure are the two boundary branches which connect the loop to the remaining system. The outage of either boundary branch forces the remaining boundary branch to carry all the flow into or out of the now radial loop. The boundary branch which carries the largest flow into or away from the loop, depending on loop load and generation, is incremented in weight. Likewise, an outage of the lower impedance boundary branch forces the displaced flow on to the higher impedance boundary branch. The lower impedance boundary branch is therefore incremented in weight. If a loop contains both generation and load and an internal branch carries the largest line flow, this branch outage will displace the most flow, and is

incremented in weight. Otherwise, internal branches are decremented in weight. Lastly, if a boundary branch is incident to and carries reactive flow to the lowest voltage bus in the loop, its weight is incremented because this outage forces reactive flow into the opposite end of the loop. Rules for weighting loop branches follow.

- L1** if a branch is inside a loop, and both end buses are load or both are generation, then decrease its weight by two.
- L2** if a net load/generation loop has a boundary branch carrying more MW/MVAR flow into/away from the loop than the other boundary branch, then increase its weight based on the branch flow. (The actual weight change is dependent on the magnitude of the MW/MVAR flow.)
- L3** if a loop has a boundary branch with lower impedance than the other boundary branch, then increase its weight by one.
- L4** if a loop has a boundary branch connected to the lowest voltage bus in the loop and carrying reactive flow into the bus, then increase its weight based on the flow.

Clusters : Cluster analysis is performed much like loop analysis. Boundary branches carry the largest change in flow whenever another boundary branch is removed. Therefore, the boundary branches with the largest flow and lowest impedance are increased in weight. Branches inside the cluster, by definition, should minimally impact the operating point if removed, and are decreased in weight. Boundary branches which carry reactive flow into the lowest voltage bus are also incremented in weight, since their outage will require reactive flow to be provided along another, less direct path.

- C1** if a branch is inside a cluster, then decrease its weight by two.
- C2** if a net load/generation cluster has a boundary branch carrying more MW/MVAR flow into/away from the cluster than its other boundary branches, then increase its weight based on the branch flow.
- C3** if a cluster has a boundary branch with lower impedance than its other boundary branches, then increase its weight by one.
- C4** if a cluster has a boundary branch connected to the lowest voltage bus in the cluster and carrying reactive flow to the bus, then increase its weight based on the flow.

Extra : Extra branch weighting rules exist for buses and branches not inside a structure. These rules identify conditions local to single buses where the impact of branch outages can be easily compared. For example, at a generating station or at a transmission transformer, the branch carrying the largest flow away from this location creates the largest displacement of flow and is expected to most impact the voltage profile. These branches are therefore increased in weight. In addition, at one transmission transformer bus, if all incident branches other than the transformer carry flow away from the bus, the transformer weight is increased because an outage of the transformer creates a large displacement of flow on all incident branches. Also, if a branch has nearly zero flow ($<20\%$ of the line rating), the branch weight is decreased because the outage has little impact. The extra branch weighting rules follow.

- E1** if a branch carries the largest real/reactive flow away from a net generation bus, then increase its weight based on the flow.
- E2** if a branch carries the largest real/reactive flow away from a transformer, then increase its weight based on the flow.
- E3** if a transformer is the only branch carrying flow into a bus, then increase the transformer weight by one.
- E4** if a branch has nearly zero flow, then decrease its weight by one.

The branch weight adjustments are chosen based on the assumptions in each heuristic rule. Each rule independently compares the impact of various outages based on some aspect of the operating point and topology. The weighting rules do not estimate numeric deviations in bus voltages. Rather, they try to select the worst case outages by anticipating the relative impact of each outage on bus voltage deviations. The result of these comparisons is accumulated in the branch weights. The net effect of these comparisons is a ranking of branch outages based on weights. All weighting rules are applied before any contingencies are investigated by power flow.

To illustrate the branch weighting rules, refer back to figure 2.2 (IEEE 30 bus test system). For the given operating point, SEEKSS selects branch 27-30-1 as the worst case outage in the loop formed around buses 29 and 30. Branch 27-30-1 receives a weight of 3 as follows. The initial branch weight is 0. Rule L2 increases the weight by 1 because branch 27-30-1 carries more MW flow into the loop than branch 27-29-1. Rule L4

increases the weight by 1 because bus 30 is the lowest voltage bus in the loop and branch 27-30-1 carries reactive flow into bus 30. Rule E2 increases the weight by 1 because branch 27-30-1 carries the largest real flow away from transformer 28-27-1. Branch 27-30-1 has the highest weight in the local area, which eventually causes this branch to be selected for power flow evaluation.

2.2.3 Single Contingency Selection

After branch weighting is completed, single contingency scenarios are selected and power flows are run. Each contingency is selected based on branch weight, actual flow, and branch voltage class. Voltage class refers to the nominal design voltage (500kV, 345kV, 230kV, etc.). To minimize the computation time used for power flows, the selection process must evaluate only the worst case outage from each consistent set of outages. The single contingency selection process is illustrated in figure 2.3.

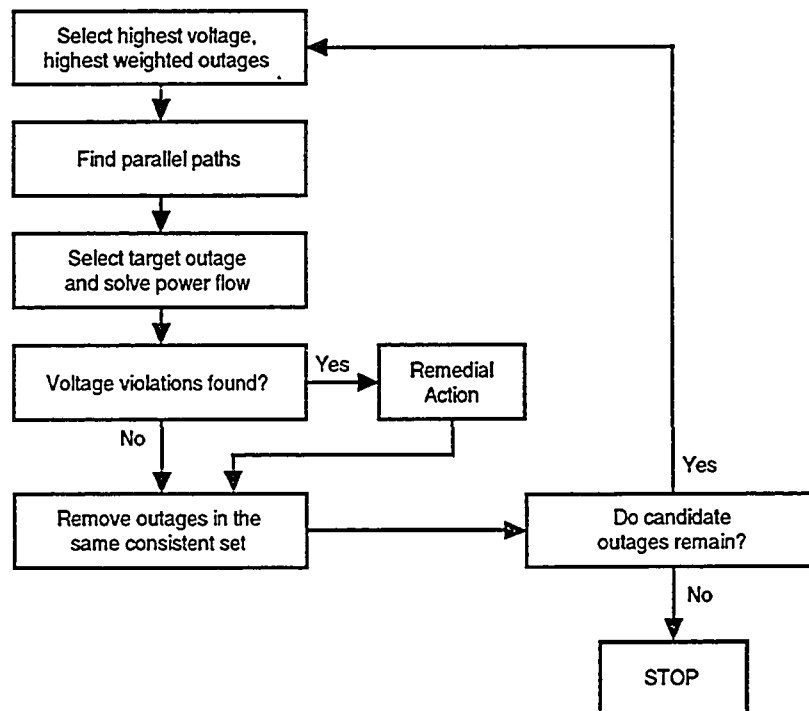


Figure 2.3 Single Contingency Selection

Control rules first select the highest nominal voltage branches as candidates for power flow evaluation. Within this current voltage class, those branches with the maximum weight are considered first.

There may be several branches with the same weight at each voltage class. To introduce more filtering of the contingency list, SEEKS uses another operational planning concept. An operational planner can assess the impact of a outage by searching the local network for an easily identified path for the displaced flow. SEEKS uses the power flow to examine the local network of each proposed outage for any low impedance path in parallel with the proposed outage. This path is expected to carry the majority of any flow interrupted on the outaged branch, if the series impedance is small. (Line reactance is used for these calculations.) The following definitions are useful.

Actual Parallel Path : another branch incident to the same two buses as the candidate branch.

Effective Parallel Path : a branch path (several branches in series) which is incident to the candidate branch and has a total series reactance approximately equal (defined as less than 125%) to the candidate branch.

Candidate branches with neither effective nor actual parallel paths are ordered highest, followed by those with effective parallel paths, and then those with an actual parallel path, when selecting between outages of equal weight. Using superposition principles, the parallel path indicates a less severe outage because the displaced flow will create smaller deviations in voltages. If several candidate branches with the same parallel path status remain, the branch with the largest flow is finally chosen as the target outage.

The target outage is then evaluated by the power flow and the result is scanned for bus voltage violations. Whenever violations exist, a remedial action search is begun. Each target outage is tagged with the number of violations found in the power flow results and with the result of the remedial action search (success or failure). The remedial action (RA) task sends only a success or failure message back to the selection task. A success message indicates that sufficient remedial control was found to remove all violations. A failure message indicates that the RA task could not find sufficient control to remove all violations.

After the target outage has been evaluated and remedial action has been identified, other outages can be removed from the selection process. From the operational planners viewpoint, other outages in the same consistent set as the target outage can be removed from consideration. From the SEEKS viewpoint, branches connected to the same structure as the target outage, and branches which share an incident bus with the target outage are considered to be in the same consistent set, and are therefore removed. This filtering based on consistent sets greatly limits the total number of contingencies sent to the power flow for evaluation.

Single contingencies continue to be selected until no candidate branches remain at the current nominal voltage. Lower voltage classes are successively searched for candidate outages until no lower voltage classes remain.

2.2.4 Double Contingency Selection

A multiple component outage is frequently initiated by a single event such as a faulted line. This single event can evolve into a double outage through protection miscoordination or the failure of relays and/or breakers. From a network or power flow viewpoint, the end result of this scenario may be the removal of two power carrying components from the network.

SEEKS incorporates this possible failure of coordination, relays, and breakers with single branch outages to produce double branch outages. In figure 2.4(a), only a stuck middle breaker in this breaker-and-a-half scheme can cause a double outage, and the line pair is unique. For the double breaker scheme in figure 2.4(b), no single stuck breaker will cause a double outage. In 2.4(c), any stuck breaker will cause a double outage. Relay failures, i.e., failure to trip or inadvertent tripping, can be viewed as breaker misoperations for security assessment purposes. Overreaching protective zones can result in the loss of any combination of two branches sharing the same bus in figure 2.4. The worst case double contingency scenario can be captured by defining a plausible double outage as a pair of branches which share a common bus scheme.

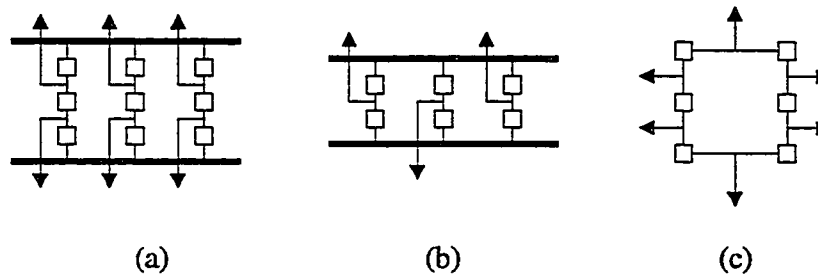


Figure 2.4 Typical Breaker Schemes

The selection of double contingency scenarios for power flow evaluation proceeds much like the selection of single contingencies. The highest voltage class is chosen first and all possible double outages are generated. Each candidate outage consists of two branches which share a common bus, and has weight equal to the sum of the two branch weights.

After selecting the maximally weighted double outages, each branch in these double outages is examined for parallel paths. The double outages are next ordered based on the parallel status of the component branches as follows : 1) those outages where neither branch has any parallel path, 2) those containing one or two branches with effective parallel paths, and 3) those containing any branch with an actual parallel path.

A target double outage is then selected, breaking any ties by comparing branch flows. An outage of two branches which carry flow in the same direction (both into or away from the common bus) is considered before other outages. The target outage is evaluated by the power flow, scanned for bus voltage violations, and passed to the remedial action task if violations are found. Other double outages which connect to the same structure or bus as the target outage's common bus are removed from consideration based on the consistent set concept.

Each voltage class is exhausted of outages before the next lower voltage is considered. The double contingency selection phase ends when no voltage classes remain. The organization of the double contingency selection task mirrors that of the single contingency selection task, which was shown in figure 2.3.

2.2.5 Remedial Action

Contingencies which create violations removable by applying remedial action should be considered less severe than outages where no remedial action can be found. To this end, target outages which exhibit violations are analyzed by a simple remedial action search task. Each target outage is tagged with the number of voltage violations found by the power flow and with the success or failure result of the remedial action task.

The grouping of buses and branches into radial, loop, and cluster structures is useful during the remedial action search. The remedial action rules examine structures which contain voltage violated buses and look for available reactive resources internal to these structures. At present, SEEKS only searches inside the local structure of the violated bus. Limiting the search to local controllers saves processing time. In addition, violations which cannot be removed by these local controllers are an indication of a more severe voltage problem. These conditions should be brought to the attention of the operator and require the use of a more sophisticated remedial control algorithm.

The controllers available to the remedial action task consists of switchable capacitors, generator voltage reference points, and remotely adjustable transformer tap positions. These controllers are adjusted by the remedial action rule base as follows :

Capacitors : If available in the same structure as the violated bus, use the capacitor's sensitivity factor to determine the change in compensation. The sensitivity is calculated once off-line for a typical operating point.

Generators : If available in the same structure as the violated bus, increase the terminal voltage by an amount greater than the violation.

Transformers : If incident to the violated bus or to the structure containing the violated bus, change the tap by an amount greater than the voltage violation.

The remedial action task does not try to calculate the optimal control action for relieving violations. Instead, the goal is to quickly scan the available controllers and validate the

existence of sufficient controls for removing the violations. Voltage violations which cannot be corrected in this manner are identified for further analysis outside of SEEKS.

The structure of the remedial action task is shown in figure 2.5. The remedial action search begins by trying to remove the worst voltage violation. If available controllers are found, the power flow is solved for the new operating point. If violations remain, the task is repeated. If no violations remain, a success message is returned to the contingency selection task. If no control action can be found for remaining violations, a failure message is returned. The contingency selection task will tag the outage for further review outside SEEKS. The control set associated with each execution of the remedial action task is stored for easy retrieval.

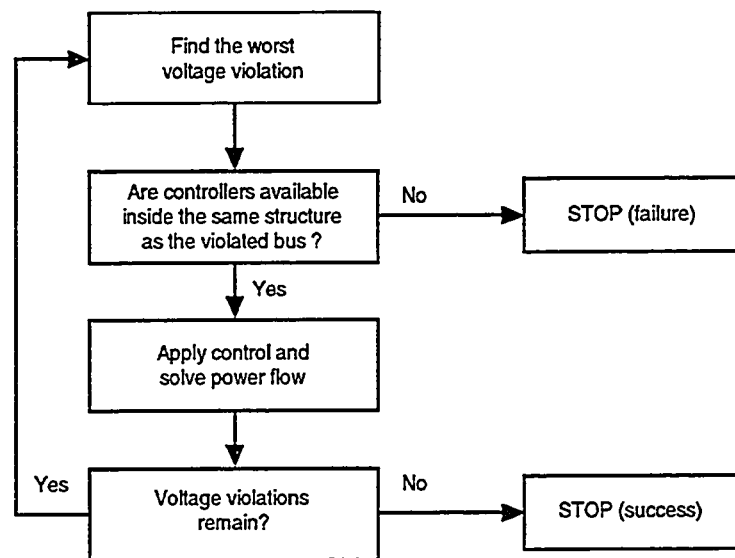


Figure 2.5 Remedial Action Task

2.2.6 Rule Base Details

The SEEKS rule base contains 86 rules. These rules can be broken into four classes as follows.

- **Branch Weighting** : these rules increment and decrement the branch weights.

- Contingency Selection : these rules control the selection of single and double line outages for power flow evaluation (figure 2.3).
- Remedial Action : these rules search the local network for possible control action to remove voltage violations (figure 2.5).
- Miscellaneous Rules : these rules provide task control, initialization, user input/output, power flow communication, etc.

2.3 Knowledge Base Validation

The SEEKS rule base was evaluated by comparing the ES results to a power flow evaluation of all plausible branch outages. The testing was performed on the IEEE 30 bus system and the LADWP 182 bus system.

2.3.1 IEEE 30 Bus System

A modified version of the IEEE 30 bus system was used as a base case. Power flows were run for all 41 single branch outages. Power flows were also run for all 102 double branch outages, using the double contingency definition given earlier. This exhaustive search of all possible outages revealed 27 outages which created violations. Bus voltage violations are defined to be voltages less than 0.95 p.u. These 27 scenarios are shown in table 2.1.

The outages in table 2.1 are grouped into seven consistent sets (A through G) by the author, based on the topology of the network and the results of the post-outage power flows. Each set contains outages in one local area, centered around one or two key buses or branches. Each set corresponds to one deficiency in the operating point. This deficiency must be addressed to eliminate the violations created by outages in the set. The author's selection of groups was tested by manually evaluating remedial control. Ideally, SEEKS would select only the worst case outage in each consistent set. However, this is difficult because SEEKS must build these consistent sets before obtaining any post-outage power flows results.

Table 2.1 Exhaustive Search (IEEE 30 Bus)

Outage Type	Branch 1			Branch 2			Vios	RA?	Set	L values	
	From	To	ID	From	To	ID				Max	Bus
double	1	2	1	1	2	2	diverged		A		
double	1	3	1	1	2	1	diverged		A		
double	2	5	1	2	6	1	diverged		A		
double	2	4	1	2	5	1	25	No	A	0.84	5
double	2	5	1	1	2	1	10	No	A	0.74	5
single	2	5	1				3	Yes	A	0.62	5
double	2	4	1	2	6	1	2	Yes	A	0.56	30
double	6	28	1	6	8	1	diverged		B		
double	4	12	1	4	6	1	25	Yes	C	0.96	14
double	2	4	1	3	4	1	25	Yes	C	0.80	30
double	2	6	1	4	6	1	22	Yes	C	0.93	30
double	4	12	1	12	13	1	16	No	C	0.64	14
double	4	12	1	3	4	1	9	Yes	C	0.69	14
double	6	7	1	4	6	1	1	Yes	C	0.34	7
double	8	28	1	6	28	1	6	Yes	D	0.40	30
double	28	27	1	27	29	1	5	Yes	D	0.52	29
double	28	27	1	27	30	1	5	Yes	D	0.56	30
double	28	27	1	8	28	1	5	Yes	D	0.40	30
double	28	27	1	6	28	1	5	Yes	D	0.38	30
single	28	27	1				5	Yes	D	0.38	30
double	25	27	1	27	29	1	1	Yes	D	0.19	29
double	25	27	1	27	30	1	1	Yes	D	0.21	30
single	27	29	1				1	Yes	D	0.22	29
single	27	30	1				1	Yes	D	0.24	30
double	12	15	1	12	14	1	2	No	E	0.33	14
double	23	24	1	22	24	1	2	No	F	0.30	24
double	9	10	1	6	10	1	2	No	G	0.48	21
Branch labels are from bus, to bus, and circuit identifier. Vios = number of buses with voltage violations (before remedial action). RA? = Was the remedial action task able to remove all voltage violations? Set = consistent set partitioning (by authors). Lmax = voltage collapse indicator. Lbus = bus with largest L value.											

The analysis by SEEKS, shown in table 2.2, resulted in 7 single and 13 double contingencies being selected for power flow evaluation. Five of these outages exhibited voltage violations and required execution of the remedial action task. One outage caused the fast decoupled power flow algorithm to diverge (indicated by "diverged" in the

tables). The SEEKS execution sequence for the IEEE 30 bus system is as follows. First, the base case operating point was obtained from the power flow and no violations were found. Second, the branch weighting rules made 47 adjustments in branch weights. Third, 7 single contingencies were selected for power flow evaluation. Two of these created violations and required remedial action. Both outages were successfully corrected. Fourth, 13 double contingencies were selected. Three of these created violations, and one contingency, the outage of branch 1-2-1 and branch 1-2-2, diverged when solved by the power flow. From the SEEKS viewpoint, a divergent power flow result signifies an abnormal operating condition which must be brought to the attention of the operator or operational planner. The SEEKS remedial action algorithm is not capable of handling non-convergent operating points, and is therefore not executed.

Table 2.2. SEEKS Results (IEEE 30 Bus)

Outage Type	Branch 1			Branch 2			Vios	RA?	Set
	From	To	ID	From	To	ID			
single	2	5	1				3	Yes	A
single	3	4	1				0		
single	6	8	1				0		
single	6	9	1				0		
single	10	17	1				0		
single	12	15	1				0		
single	27	30	1				1	Yes	D
double	6	7	1	6	9	1	0		
double	1	2	1	1	2	2	diverged		A
double	4	12	1	4	6	1	25	Yes	C
double	1	2	1	2	5	1	10	No	A
double	2	5	1	5	7	1	0		
double	28	27	1	6	28	1	5	Yes	D
double	8	28	1	6	8	1	0		
double	9	10	1	6	9	1	0		
double	9	10	1	10	17	1	0		
double	12	16	1	12	15	1	0		
double	27	29	1	27	30	1	0		
double	12	15	1	14	15	1	0		
double	10	17	1	16	17	1	0		

The SEEKS knowledge base is evaluated by comparing the results in table 2.2 to the exhaustive search results in table 2.1. Success is measured by the ability of SEEKS to

select only the worst outage in each consistent set. The exhaustive search revealed three consistent sets (A,B,C) with divergent or near divergent power flow results for at least one outage. SEEKS selected the worst case outage in two of the three critical sets (sets A and C). Three of the outages in set A were selected, including one of the divergent outages. The worst outage in set C is also found (double outage of 4-12-1 and 4-6-1). However, SEEKS missed the one divergent outage in consistent set B. Set B contains only one outage (double outage of 6-8-1 and 6-28-1) due to the unique network structure local to this outage. A detailed analysis of the network and a long explanation by the operational planner is required to explain the power flow divergence. The IEEE 30 bus test system is shown in figure 2.6. When the double outage of 6-8-1 and 6-28-1 occurs, the load area around buses 29 and 30 becomes much more difficult to serve, because the transmission corridor from the generation resources (buses 1, 2, 5, and 8) to these load buses is severed. The only transmission corridor remaining is along the branch from bus 24 to bus 25. In addition, bus 24 is itself far away from generation resources. The SEEKS knowledge base is not yet sophisticated enough to capture this outage. These results indicate some need for system specific knowledge in the branch weighting rule base. For this prototype, the use of any system specific knowledge is explicitly excluded.

The exhaustive search results revealed four other consistent sets (sets D through G). SEEKS selected two outages in set D, one of which is nearly the worst case based on the number of violations. The remaining three consistent sets (E,F,G) are missed by SEEKS. These sets contain outages which exhibit at most two minor bus voltage violations, each no more than 0.01 p.u. below the acceptable voltage range. The missed contingencies indicate a sensitivity problem with some of the branch weighting rules. Note however that all three sets contain only double outages.

The remedial action task is invoked for those outages which exhibit a convergent, post-outage operating point with bus voltage violations. In the tables, "Yes" indicates the remedial action task was successful and "No" indicates failure. SEEKS was successful in finding remedial action for all but one of the outage scenarios. The number of controllers available in the IEEE 30 bus system is limited. A sophisticated remedial action algorithm is needed to handle the severe and divergent scenarios.

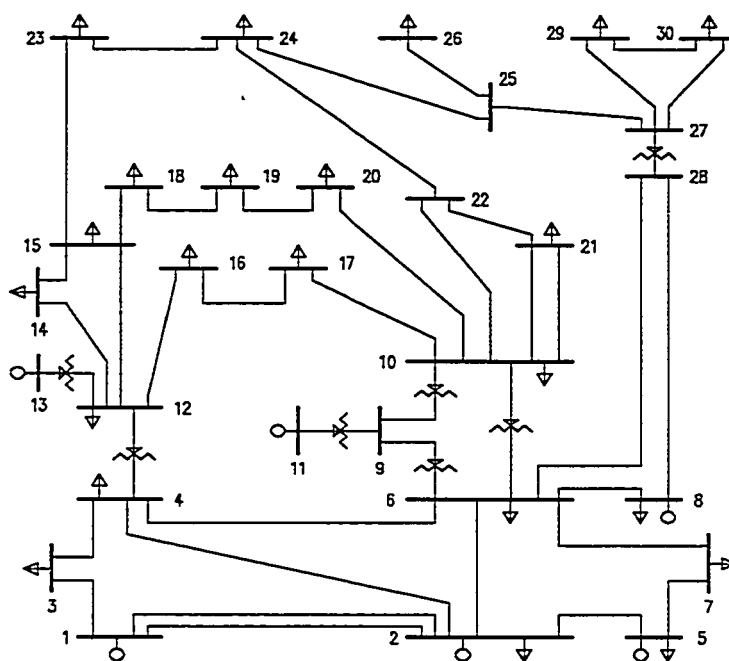


Figure 2.6 IEEE 30 Bus Test System

Table 2.1 also includes the calculation of a voltage collapse indicator which approximates the distance of the operating point to the voltage collapse boundary [16]. This indicator varies from 0 to 1 as the operating point moves from no-load to the disappearance of power flow solution, respectively. In table 2.1, this index is provided as another measure of outage severity. The L index tracks the ranking of outages based on number of violations reasonably well. The index could not be calculated for the divergent cases because no post-outage operating point existed (L would be greater than 1.0). For each outage in the tables, the buses with voltage violations always included the bus where the maximum L value was obtained. The base case has a maximum L value of 0.15 at bus 30.

2.3.2 LADWP 182 Bus System

The SEEK knowledge base was also evaluated using a 182 bus model of the LADWP bulk transmission system. The operating point represents a hypothetical peak load

condition. No modification to SEEKS was necessary to switch from one system model to another. No system dependent rules exist in the rule base.

The exhaustive search evaluated 121 single and 420 double contingencies, revealing 22 contingencies which created violations. These are shown in table 2.3. A low voltage limit of 0.95 p.u. was used. Table 2.3 also includes a partitioning of outages into four consistent sets (A through D) performed by the author, and a calculation of the voltage collapse index for each outage.

Table 2.3 Exhaustive Search (LADWP 182 Bus)

Outage Type	Branch 1			Branch 2			Vios	RA?	Set	L values	
	From	To	ID	From	To	ID				Max	Bus
double	28	322	1	7	28	1	7	Yes	A	0.43	87
double	28	30	2	28	30	1	5	Yes	A	0.49	28
double	6	7	H	7	28	1	2	Yes	A	0.40	87
double	6	7	G	7	28	1	2	Yes	A	0.40	87
double	28	30	2	7	28	1	2	Yes	A	0.40	87
double	28	30	1	7	28	1	2	Yes	A	0.40	87
double	6	7	H	6	7	G	2	Yes	A	0.39	87
single	7	28	1				2	Yes	A	0.40	87
double	12	21	3	12	49	2	4	No	B	0.47	87
double	49	112	U3	12	49	2	1	Yes	B	0.41	87
double	12	13	E	12	49	2	1	Yes	B	0.42	87
double	12	13	F	12	49	2	1	Yes	B	0.42	87
double	12	13	E	12	13	F	1	Yes	B	0.39	87
single	12	49	2				1	Yes	B	0.41	87
double	8	25	1	1	25	1	3	No	C	0.38	91
double	8	25	1	25	50	1	1	Yes	C	0.35	91
double	50	105	U2	50	109	U6	1	Yes	D	0.45	91
double	8	50	1	1	50	1	1	Yes	D	0.39	91
double	50	109	U6	50	104	U1	1	Yes	D	0.45	91
double	50	109	U6	50	106	U3	1	Yes	D	0.45	91
double	1	50	1	25	50	1	1	Yes	D	0.40	91
double	8	50	1	25	50	1	1	Yes	D	0.40	91

Table 2.3 also includes the calculation of the voltage collapse index for all outages. The L index reasonably tracks the ranking of outages based on the number of violations. For

each outage in table 2.3, the bus with the maximum L value also exhibits a voltage violation. The base case maximum L is 0.32 at bus 87.

The SEEKS results are shown in table 2.4. Six single branch outages and fourteen double branch outages were selected for power flow evaluation. Five of these outages produced violations and all violations were removable by remedial action. SEEKS selected the three outages in set A, including the worst case outage based on number of violations. In set B, SEEKS missed the worst case outage but did select an outage nearby. Both the selected outage and the worst case outage are centered at bus 12. In set D, one outage is selected and all outages in this set are similar in severity. The only set missing from the SEEKS assessment is C. The worst outage in set C exhibits only slight voltage violations (1-3%). Again SEEKS has a problem detecting outages which exhibit slight violations.

Table 2.4 SEEKS Results (LADWP 182 Bus)

Outage Type	Branch 1			Branch 2			Vios	RA?	Set
	From	To	ID	From	To	ID			
single	7	28	1				2	Yes	A
single	55	255	1				0		
single	29	203	1				0		
single	22	26	1				0		
single	12	13	E				0		
single	58	226	1				0		
double	28	322	1	7	28	1	7	Yes	A
double	30	31	1	31	33	H	0		
double	7	28	1	6	7	H	2	Yes	A
double	29	303	2	29	203	1	0		
double	43	55	1	55	255	1	0		
double	29	203	1	203	3	F	0		
double	12	13	F	12	13	E	1	Yes	B
double	226	26	G	22	26	1	0		
double	22	26	1	22	41	1	0	Yes	D
double	25	50	1	8	50	1	1		
double	22	41	1	27	41	1	0		
double	13	221	1	12	13	E	0		
double	3	24	1	3	24	2	0		
double	226	26	G	58	226	1	0		

2.3.3 Execution Details

The number of power flows evaluated by SEEKS, 20 for the IEEE system and 22 for the LADWP system, remained nearly constant even though the number of buses increased from 30 to 182. The execution times for the two SEEKS cases differ because of the difference in database size and because the LADWP power flows take longer to compute. On a multi-user VAXstation 3100, the SEEKS prototype took 51 seconds to assess the IEEE 30 bus system, and 268 seconds to assess the LADWP 182 bus system. These times encompass data initialization, communication with the power flow, user input / output, etc., and provide a comparison based on network size only.

2.4 Comparison to 1P-1Q Algorithm

SEEKS performance was also compared to results generated by a 1P-1Q contingency scanning algorithm. The 1P-1Q algorithm performs one P-THETA and one Q-V iteration of a fast decoupled power flow for each plausible outage, starting from the base case solution.

The 1P-1Q results for the IEEE 30 bus system are shown in table 2.5. The algorithm captured an outage from each consistent set except set A, which contains the most severe outages. The 3 divergent outages in consistent set A did not exhibit any violations after 1 P-THETA and 1 Q-V iteration. The 1P-1Q algorithm captures the outages with slight violations (sets E, F, and G), and the divergent outage in set B, which SEEKS failed to capture.

The LADWP 1P-1Q results are shown in table 2.6. The 1P-1Q algorithm captured the most severe outage in each set. One double outage (22-222-G and 22-322-H) was falsely identified by the 1P-1Q algorithm as creating violations. Recall that SEEKS captured all sets except C.

Table 2.5 1P-1Q Results (IEEE 30 Bus)

Outage Type	Branch 1			Branch 2			Vios	RA?	Set
	From	To	ID	From	To	ID			
double	4	12	1	12	13	1	7	No	C
double	8	28	1	6	28	1	6	No	D
double	6	8	1	6	28	1	5	No	B
double	28	27	1	27	29	1	5	No	D
double	27	30	1	28	27	1	5	No	D
double	28	27	1	8	28	1	5	No	D
double	6	28	1	28	27	1	5	No	D
single	28	27	1				5	No	D
double	9	10	1	6	10	1	3	No	G
double	12	15	1	12	14	1	3	No	E
double	22	24	1	23	24	1	2	No	F
single	27	29	1				2	No	D
double	27	30	1	25	27	1	1	No	D
double	25	27	1	27	29	1	1	No	D
single	27	30	1				1	No	D

Table 2.6 1P-1Q Results (LADWP 182 Bus)

Outage Type	Branch 1			Branch 2			Vios	RA?	Set
	From	To	ID	From	To	ID			
double	28	30	2	28	30	1	2	No	A
double	7	28	1	28	322	1	2	No	A
double	322	22	H	222	22	G	2	No	
double	1	25	1	8	25	1	2	No	C
double	50	105	U2	50	109	U6	1	No	D
double	6	7	H	7	28	1	1	No	A
double	25	50	1	8	25	1	1	No	C
double	28	30	2	7	28	1	1	No	A
double	12	21	3	12	49	2	1	No	B
double	50	104	U1	50	109	U6	1	No	D
double	50	109	U6	50	106	U3	1	No	D
double	8	50	1	25	50	1	1	No	D
single	7	28	1				1	No	A

2.5 Conclusion

An expert system called SEEKS has been developed which uses operational planning knowledge to provide insight into power system voltage behavior. The approach adopted in SEEKS does not provide a numerically precise description of voltage performance in terms of a direct ranking of contingencies. Rather, operational planning knowledge is used to select the worst case contingencies which may cause voltage violations.

The plausible contingency set contains both single and double branch outages. SEEKS collects contingencies into sets and selects the worst case outage from amongst these sets. Remedial control is also identified using a knowledge based approach.

Performance comparisons for the IEEE and the LADWP systems show that SEEKS is capable of selecting the worst case outages, while greatly reducing the number of power flow runs. The contingency list is capable of changing based on the operation condition. The SEEKS rule base selects outages without the use of system dependent knowledge. Augmenting the SEEKS rule base with system specific knowledge may allow SEEKS to capture additional voltage phenomenon. The benefit system specific rules provide to SEEKS performance will be investigated during future testing of SEEKS using the Puget Sound Power and Light system.

Chapter 3. Remedial Control for Dynamic Voltage Collapse

Voltage collapse events have generated much recent interest. Initially, research effort focused on identifying the mechanisms responsible for causing a voltage collapse and on developing models which describe these mechanisms [17]. Two different analytical viewpoints evolved to describe the collapse mechanism, namely the steady state models approach and the dynamic models approach. The steady state approach is useful when the system dynamic response to changes in the operating point is small when compared to the overall change in the operating point. Most of these approaches investigate the characteristics of the power flow solution as the system slowly moves toward a collapse [18-27]. Other approaches study the small signal stability of the current operating point, such as [28]. Broad spectrum load disturbances are investigated in [29]. Energy methods for evaluating the operating point stability are developed in [30]. However, if the transient behavior of the system during a disturbance is significant, dynamic models are needed to evaluate the transition of the operating point. A method for determining the system dynamics after bifurcation of the power flow equations is given in [31]. In [32], voltage instability is investigated using singular perturbation theory.

Load dynamics, on-load tap changing transformers (LTCs), and generator excitation limits are known to be primary contributors to the system's dynamic response during a collapse event [33-37]. In [37], the concept of a voltage recovery "leaf" explains the evolution of a collapse event as the gradual shrinking and disappearance of the voltage recovery region. This recovery region is dynamically reduced in size when LTCs attempt to regulate load bus voltages and when generators reach steady state excitation limits or rotor current limits. Any reduction in the size of the recovery region may cause the system voltage trajectory to exit the recovery region, leading to a collapse. The concept of a voltage recovery region was generalized to multiple bus systems in [38].

Remedial control schemes for avoiding a voltage collapse are given in [38,39,44]. In [39], the remedial scheme sheds load whenever bus voltages fall below some threshold value for a fixed time duration. A hybrid load shedding expert system is presented in [44] for correcting low voltage areas. Remedial action based on tap changer locking is proposed in [38]. When all bus voltage derivatives are positive, the system trajectory must be inside the voltage recovery region. Reference [38] states that locking of all LTCs at this point will result in stabilization of the complete system. Clearly, the criterion of positive voltage derivatives at all buses at an instant in time can rarely be

met. This paper will propose a localized method for detecting an imminent voltage collapse and will develop two remedial control schemes for calculating the amount of control necessary to avoid the collapse. The proposed detection scheme improves upon the scheme used in [39] by using both the reactive power demand and the bus voltage at each load bus for determining when a collapse is imminent. The remedial control scheme extends the results of [38] by providing an approach which does not require all load bus voltage derivatives to be positive simultaneously.

3.1 System Modeling

To accurately investigate a dynamic voltage collapse event, the system modeling must include the contributions made by load dynamics, LTCs, and generation excitation limits. Algebraic equations describe items such as the transmission system, the steady state operating point, and generator excitation limits, while differential equations describe the continuous load dynamics and difference equations describe the discrete LTC dynamics. The system modeling, discussed in the following sections, is based on the generalized system model shown in figure 3.1.

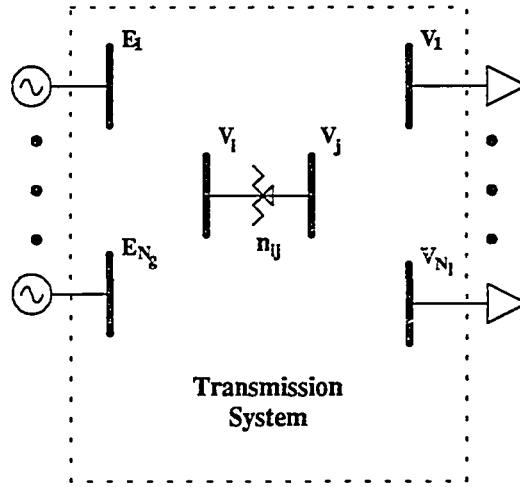


Figure 3.1 General System Model

In figure 3.1, N_g is the number of generators, N_l is the number of buses with dynamic load, and n_{ij} is the per unit turns ratio of the transformer connecting bus i to bus j .

3.1.1 Steady State

The steady state equations consist of the standard real and reactive power flow equations for each bus. Three additional equations exist for each non-slack generator bus. These equations are used to calculate the generator's internal voltage magnitude and angle (E_i) and the terminal current magnitude (I_i). The time frame of voltage collapse events allows the swing equations to be ignored and steady state angular and frequency conditions to be assumed. The internal voltage magnitude $|E_i|$ is limited due to excitation limits and the current magnitude $|I_i|$ is limited due to stator current limits. At a slack generator, the terminal voltage and angle are always constant and no excitation limits exist. The internal voltage calculation adds one real and one reactive power equation per generator. The terminal current is calculated from

$$|V_i|^2 |I_i|^2 = P_{g,i}^2 + Q_{g,i}^2 \quad (3.1)$$

where $P_{g,i}$ and $Q_{g,i}$ are the generator real and reactive outputs at bus i and V_i is the terminal voltage magnitude. The generator limit equations are

$$E_i \leq E_{\max,i} \quad (3.2)$$

$$I_i \leq I_{\max,i} \quad (3.3)$$

where $E_{\max,i}$ is the maximum internal voltage at generator i , representing the maximum steady state excitation, and $I_{\max,i}$ is the maximum steady state current for generator i .

The LTC regulating action is modeled using a discrete tap changer model. For a LTC between buses i and j , a discrete per unit tap value (n_{ij} in figure 3.1) is found which satisfies

$$|V_s^* - V_s| \leq V_{DB,s} \quad (3.4)$$

$$n_{ij} \leq n_{\max,ij} \quad (3.5)$$

$$n_{ij} \geq n_{\min,ij} \quad (3.6)$$

where V_s^* is the bus s reference voltage which LTC ij tries to regulate, V_s is the actual voltage at bus s , $V_{DB,s}$ is the voltage deadband, and $n_{\max,ij}$ and $n_{\min,ij}$ are the maximum

and minimum turns ratios, respectively. The regulated bus s is usually bus i or bus j , but does not need to be.

The steady state load is modeled with ZIP characteristics (constant impedance, current, and MVA terms). The real and reactive steady state loads at each load bus i are given by

$$P_{ss,i}(V_i) = P_{a,i} * V_i^2 + P_{b,i} * V_i + P_{c,i} \quad (3.7)$$

$$Q_{ss,i}(V_i) = Q_{a,i} * V_i^2 + Q_{b,i} * V_i + Q_{c,i} \quad (3.8)$$

respectively, where V_i is the load bus voltage. The ZIP parameters are assumed constant over the voltage range of interest for each load bus.

3.1.2 Dynamic

To capture the voltage trajectories during a collapse event, the dynamics of the reactive load demand and the discrete tap changers are modeled. The complete reactive load model approximates the terminal characteristics of a composite load consisting of many elements including induction motors. This model is presented in [40,41] and a comparison to a third order induction motor model is investigated in [42]. The total reactive load at each load bus is given by

$$Q_{l,i}(V_i) = Q_{ss,i}(V_i) + K_{q,i}(V_i) * dV_i/dt \quad (3.9)$$

where $Q_{l,i}$ is the total reactive demand supplied by the network as given by the reactive power flow equations. $K_{q,i}$ is a composite term capturing the effect of all load dynamics, and is assumed constant in these studies.

The discrete dynamics of each tap changer are given by

$$n_{k+1} = n_k + \Delta n * f(V_i - V_i^*) \quad (3.10)$$

where

$$f(x) = \begin{cases} -1 & \text{if } x > V_{DB}, \\ 0 & \text{if } |x| < V_{DB}, \\ 1 & \text{if } x < -V_{DB} \end{cases} \quad (3.11)$$

where Δn is the tap step size in per unit, k represents the transition between discrete states, V_i and V_i^* are the actual and reference voltages at the regulated bus respectively, tap changing can only occur at discrete times, and the tap position honors upper and lower tap limits.

The complete dynamic system has one continuous state variable V_i for each dynamic load bus and one discrete state variable n_{ij} for each LTC. In addition, each non-slack generator is modeled in one of three states, constant terminal voltage, constant internal voltage, or constant current.

3.2 Detection and Control

The remedial scheme posed in [38] is not usable when all load bus voltage derivatives are not simultaneously positive. A new scheme which is always applicable and is as localized as possible, both in the detection of an imminent collapse and in the application of control, is more desirable.

3.2.1 Strategy

Consider first a two bus system (a generator bus connected to a load bus by one line with a LTC) as given in [37], where E is the generator terminal voltage, V is the load bus voltage, and n is the LTC tap position. The internal generator voltage E_i is subject to excitation limits, and the generator current I is subject to stator current limits. Assume for the moment that the tap changing action of the LTC is continuous rather than discrete. The two state variables are V and n . As derived in [37], the voltage recovery leaf and stability boundary change or move, depending on the state trajectory. A stationary voltage recovery leaf and stationary stability boundary can also be derived, as shown in figure 3.2. The voltage recovery leaf is shown by the solid line, the stability boundary is shown by the dashed line, and the voltage reference for the LTC is shown by

the dotted line. The term stationary means the boundaries are fixed, independent of the state trajectory. For example, the stationary leaf is the solution of

$$\begin{aligned} dV / dt &= 0 \\ E(V,n) &\leq E_{\max} \\ I(V,n) &\leq I_{\max} \end{aligned} \quad (3.12)$$

where E_i is the generator internal voltage behind transient impedance. The stationary stability boundary is found by integrating backward in time from a point very near the unstable equilibrium point U [43], while including the effects of the generator limits. If the stationary boundaries can be easily computed, the shift in the stability boundary needed to correct a collapsing voltage trajectory can be easily found. Remedial control only needs to create an expanded stability region which just captures the current state. Also, a collapse trajectory can be detected immediately because the system state will be outside the stability region after the disturbance.

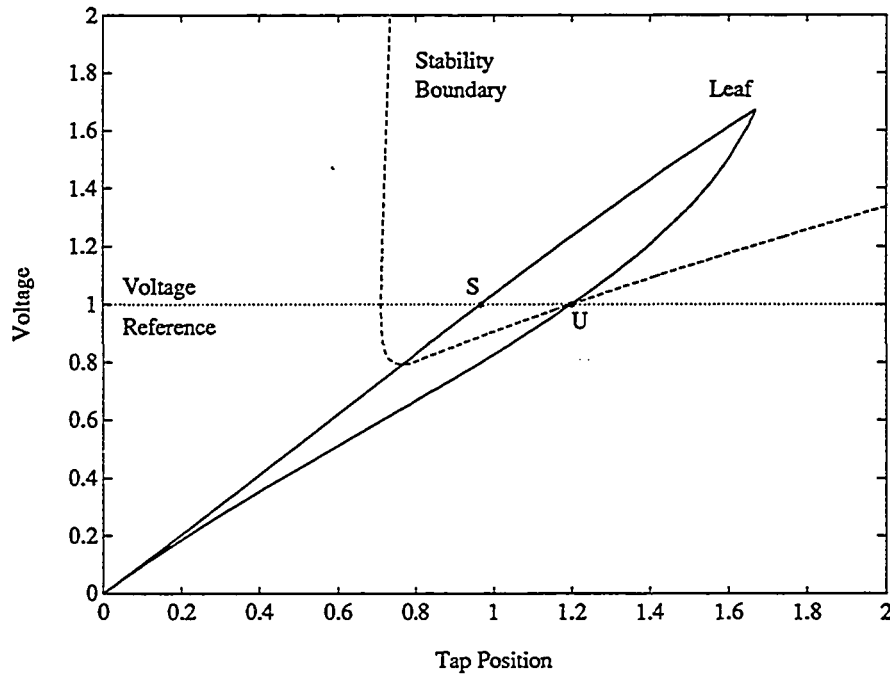


Figure 3.2 Two Bus Stationary Leaf and Stability Region

However, it is unlikely that the stability boundary can be easily computed. Given only the voltage recovery leaf, the results in [38] indicate that tap changer locking while the state is inside the leaf will guarantee stability. This result can be used to develop a simple remedial control scheme for stabilizing a collapsing voltage trajectory. For example, if the state exits the leaf while below the voltage reference line in figure 3.2, the appropriate remedial control is tap changer locking combined with an expansion of the stationary recovery leaf such that the new leaf just captures the current state. Figure 3.3 shows such an example. The state trajectory is shown by the dotted line. Assume some disturbance has moved the system state to point a. At point b, the state trajectory has left the original voltage recovery leaf, and a capacitor is added to the load bus. The capacitor switching creates a new, expanded leaf shown by the dashed lines. The tap changer is locked, causing the system state to follow a vertical trajectory of increasing voltage to a new steady state equilibrium, point c.

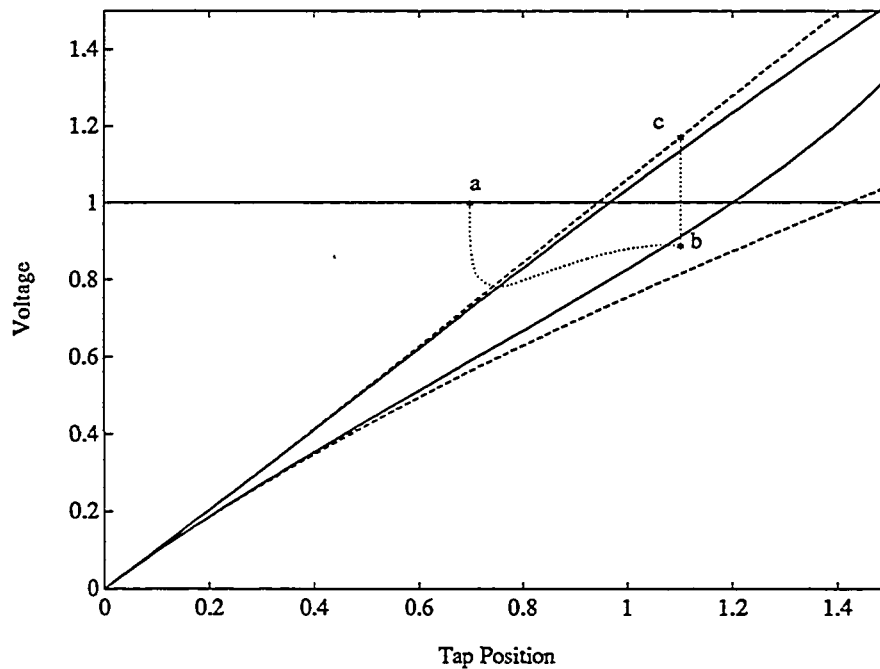


Figure 3.3 Two Bus Remedial Control Scheme

Even for this two bus system, the stability region and stationary voltage recovery leaf are time consuming to find. With a multiple bus system, construction of these stationary

leaves and stability boundaries is impractical. Therefore, an alternate detection and remedial control approach must be developed which is based on generic characteristics of the voltage trajectory, and is not dependent on explicit knowledge of the complete leaf boundary or stability region. The central issues to be resolved are the detection of imminent collapse and the calculation of the appropriate amount of remedial control.

One approach to collapse detection is to determine when the system state exits a stability region. Assuming the tap changer to be discrete, some sense of voltage stability can be examined for the instantaneous value of bus voltage between tap changing events. If the tap changer is assumed to be locked, the voltage equilibrium point can be found from equation 3.9. The boundary of the voltage recovery leaf is the point at which the voltage derivative goes to zero, i.e., an equilibrium point. Equation 3.9 relates the steady state and total load demand to the voltage derivative. To achieve a voltage derivative of zero, the steady state demand must equal the total load demand. In the proposed model, the steady state demand is not a function of the network. However, the total reactive load demand is a function of the network.

To investigate this equilibrium, consider again the two bus model. Figure 3.4 shows a sample steady state reactive load demand, Q_{ss} , as a function of voltage. Also shown is an approximation to the total load demand, Q_l , i.e., the network reactive power supplied to the load bus. This approximation assumes a fixed tap position for the LTC, the line impedance to be 0.280 p.u., the source voltage E to be fixed, and no generator limits are enforced. Q_l , shown for three different values of E , is given by

$$Q_l = \frac{V(E - V)}{X} \quad (3.13)$$

where V is the load voltage and X is the line impedance. The bus voltage angles are assumed to be constant, allowing the $\cos(\delta)$ term normally found in equation 3.13 to be absorbed into E .

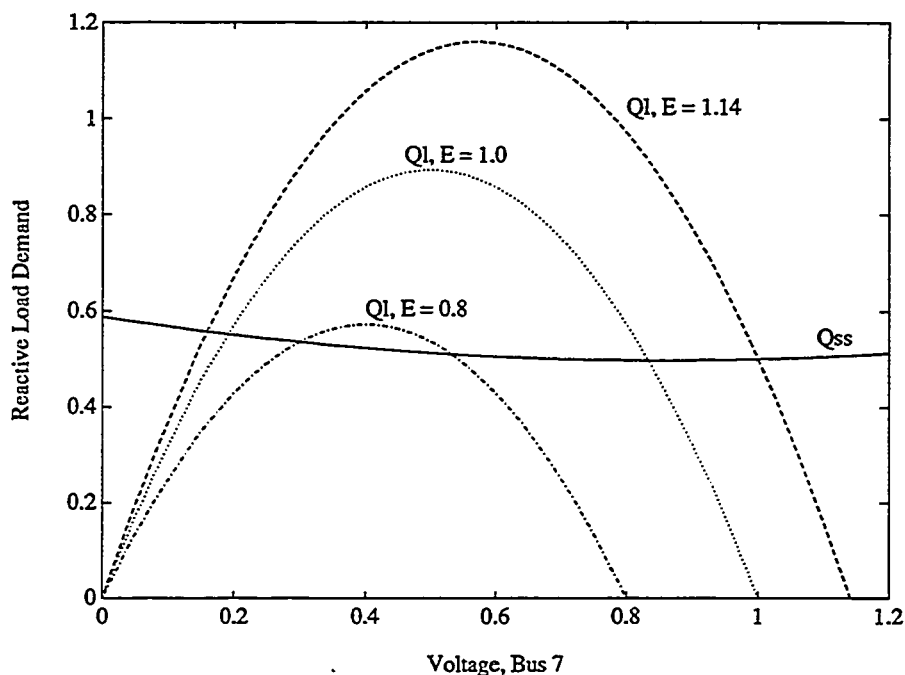


Figure 3.4 Steady State and Total Load Demands

For a fixed value of E , the stable voltage equilibrium point is the larger voltage intersection of the Q_{ss} and Q_l curves. The stability region in the voltage space is the set of all voltages greater than the smaller voltage intersection, if this point exists. However, this analysis is based on a fixed voltage source. In reality, the effective or Thevenin voltage seen at a load bus looking into a network of any size varies as system generator limits are reached, tap changers move, and other load bus voltages dynamically change. During a collapse event, the Thevenin voltage seen at a load bus decreases as the collapse evolves. From figure 3.4, this means the true stability region becomes smaller along with the $dV/dt \geq 0$ region. Nonetheless, one indicator of imminent voltage collapse is the disappearance of an intersection between the Q_{ss} and Q_l curves, if the Q_l curve can be explicitly calculated or dynamically updated as the disturbance evolves.

Once detected, the collapse must be avoided through the application of control. One approach to remedial control is to determine the amount of control necessary to expand the voltage recovery leaf enough to capture the current state, i.e., the control amount forces the voltage derivative to be positive (enters the leaf). This condition is derived

from proposition 11 in [38] which guarantees stability for multiple bus systems if tap changers are locked when all bus voltage derivatives are positive. Therefore, the remedial control scheme should apply sufficient control to force all bus voltage derivatives positive while locking all tap changers. A formulation of this control scheme is

$$\begin{aligned}
 &\text{minimize :} && \text{the total control taken} \\
 &\text{subject to :} && \text{the power flow equations} \\
 &&& \text{any controller limits} \\
 &&& \text{all voltage derivatives} \geq \text{zero}
 \end{aligned} \tag{3.14}$$

For a multiple bus system, it may be impractical to apply remedial control to all load buses, especially if control can be taken sequentially at individual buses while still guaranteeing overall voltage stability. Also, simulations have shown the constraint that all voltage derivatives be simultaneously made non-negative to be overly stringent, i.e., more control is taken than is necessary. Therefore, in a multiple bus system, an intuitive approach to control is to handle the worst case voltage derivatives sequentially. Ideally, sequential control will lead to a smaller total control set, while still ensuring stability.

In summary, an imminent voltage collapse can be detected based on determining the intersections of localized Q_{ss} and Q_l curves in the voltage space. The non-existence of these intersections indicates an imminent collapse. When a collapse is detected, the objective of the remedial control scheme will be to sequentially calculate the amount of local control needed to drive the collapsing bus voltage into the voltage recovery leaf, i.e., the bus voltage derivative becomes positive.

3.2.2 Collapse Detection

In order to minimize the total control taken to avoid a collapse, the detection scheme must identify the need for control as quickly as possible. If the detection scheme is based on approximate models, then a balance must be struck in the design to minimize false triggering, while guaranteeing no collapse events are missed and that the detection scheme triggers quickly when needed.

Extrapolating from the two-bus model, a variable Thevenin equivalence based detector is proposed for each bus with dynamic load. The Thevenin equivalence parameters must continuously be adjusted as the disturbance evolves. The post-disturbance Thevenin impedance is likely to increase due to line and generator outages. More significantly, the Thevenin source voltage is likely to decrease as some of the system generation reaches its excitation and stator current limits. The detector estimates the reactive power supplied by the equivalence to the load using equation 3.13, where E and X are the Thevenin equivalence parameters. As E decreases and X increases, the ability of the equivalence to supply reactive power to the load is decreased. E is dynamically updated such that the equivalence always agrees with the actual reactive demand Q_1 at the current value of load bus voltage. The proposed detection scheme monitors the reactive demand seen at each load bus, Q_1 . From the actual value of Q_1 , the pre-disturbance estimate of Thevenin impedance, and the actual bus voltage, an on-line estimate of E is calculated from equation 3.13. The total reactive load demand curve is then constructed.

The equivalence approximates the actual network response to load bus voltage changes. The post-disturbance Thevenin impedance is in general larger than the pre-disturbance value, but is difficult to determine on-line. As an approximation, the pre-disturbance Thevenin impedance X at each load bus is calculated by standard network reduction techniques assuming a linear network. The impedance X in the equivalence is held constant, and E is continuously adjusted such that the actual reactive demand from the equivalence is accurate. This results in the estimated total demand curve having a larger peak value than actual, causing the stable intersection point with the steady state curve to be larger than actual. A detection scheme based solely on the existence of a stable equilibrium point will therefore trigger later than desired. To compensate, an additional detection criterion is introduced. This criterion requires the stable equilibrium point, V_{EQ} , to be greater than a threshold value V_{thres} (say 0.85 p.u.). V_{thres} is chosen as a minimum acceptable post-disturbance equilibrium voltage. When $V_{EQ} < V_{thres}$, remedial control is triggered. This criterion can be quickly checked by computing the steady state and total demands at V_{thres} . If the steady state demand exceeds the total demand, the voltage derivative at that point will be negative, and remedial control is triggered.

The steady state demand curve is stationary while the total demand curve moves as the disturbance evolves. The detection scheme is easily shown to trigger at a load bus voltage not less than V_{thres} , and usually at a voltage greater than V_{thres} . This provides a predictive capability to the detection scheme. This is an improvement over any scheme which only monitors the load bus voltage because remedial control is initiated earlier. The advantage of taking control as early as possible is that the total control required is usually less.

3.2.3 Remedial Control

At the Load Bus

Independent detectors reside at each load bus, and when triggered, initiate control. The set of potential control devices consists of switchable capacitors at the load bus where the detector triggered (collapsing bus), switchable capacitors at buses nearby the collapsing bus, and load shedding at the collapsing bus. Initially, consider only control available at the collapsing load bus (local capacitor switching and load shedding). The control objective is to expand the voltage recovery leaf for the collapsing bus, such that the new leaf captures the present state. The formulation becomes :

$$\begin{aligned}
 &\text{minimize :} && \text{total switched capacitors (or load shed)} \\
 &\text{subject to :} && \text{power flow equations} \\
 &&& \text{controller limits} \\
 &&& \text{local bus voltage derivative} \geq \varepsilon > 0
 \end{aligned} \tag{3.15}$$

where ε is introduced as margin. The minimum amount of reactive power added via shunt capacitors or lost via load shedding is found using equation 3.9. This reduces the formulation in equation 3.15 such that only the reactive power flow equation for the local bus need be solved, subject to controller limits. If the reactive power supplied by the network to bus i is changed by $\Delta Q_{l,i}$, the magnitude of dV_i/dt must change. The local dV_i/dt term is driven to ε by letting

$$\Delta Q_{l,i} = K_{q,i} * (\varepsilon - dV_i/dt) \tag{3.16}$$

or

$$\Delta Q_{l,i} = Q_{ss,i} - Q_{l,i} + K_{q,i} * \varepsilon \quad (3.17)$$

Recall that the load bus voltages cannot change discontinuously because they are determined from the differential equations for each load. Therefore the $Q_{ss,i}$ term does not change when switchable capacitors are added to the system. The dV_i/dt term changes to compensate for the additional reactive flow into the load bus. $\Delta Q_{l,i}$ represents the change in the reactive demand supplied by the network, necessary to move inside the voltage recovery leaf. The minimum value of capacitance ΔC to be switched in at the load bus is given by

$$\Delta C_i = \Delta Q_{l,i} / V_i^2 \quad (3.18)$$

where V_i is the instantaneous load voltage. If load shedding is the only available control, it is represented by $\Delta Q_{ss,i}$, a change in the steady state load characteristics, evaluated at the actual load voltage. $\Delta Q_{ss,i}$ is solved for in a manner analogous to equations 3.16 and 3.17.

The voltage stability criterion in [38] requires locking of all tap changers when all load voltage derivatives are positive. From the Thevenin equivalence model, a stable equilibrium will be reached if the external system remains stationary and if no tap changers move. As this is not true, tap changing action will negatively effect the voltage stability. Therefore, tap changer locking is combined with the local remedial control calculation to provide a additional stabilizing effect.

The remedial scheme where control is taken at the collapsing bus is 1) calculate the switchable capacitors to be added or the reactive load to be shed, and 2) lock all tap changers. Of course, switchable shunt capacitors at buses nearby the collapsing bus should also be considered as possible control before load shedding is initiated. The next section discusses the calculation of nearby remedial control.

At Nearby Buses

Because local capacitor control may not be sufficient to avoid a collapse, switchable capacitors near the collapsing bus are also investigated. As before, the objective of the

remedial control is to drive the voltage derivative positive at the collapsing bus, i.e., get inside the leaf. For nearby switchable capacitors, the remedial control formulation is simplified as follows :

- 1) order the available capacitors such that only one capacitor is adjusted at a time,
- 2) decouple the real and reactive power flow equations, i.e., solve only the reactive equations,
- 3) assume bus voltages remote from both the control devices (capacitors) and the collapsing bus to be fixed, i.e., create a local neighborhood, and
- 4) force only the voltage derivative at the collapsing bus to zero.

The resulting set of non-linear equations must be solved for each capacitor switching event. If the voltage derivative at bus k is being controlled, and capacitors at bus m are available for control, the amount of control is determined from

$$\sum_{\substack{j=1 \\ j \neq i}}^n (V_i V_j \cos(\theta_{ji}) B_{ij} - V_i^2 B_{ij}) - V_i^2 (B_{ii} + \Delta C_i) + Q_{ss,i}(V_i) + K_{q,i} * \varepsilon = 0 \quad (3.19)$$

where

$i \in \{ \text{all buses inside the local neighborhood, except generator buses and dynamic load buses, plus bus } k \},$

B_{ji} = per unit susceptance from bus j to bus i , (assume $G_{ij} = 0$)

θ_{ij} = voltage angle from bus i to bus j (assumed to be constant)

ΔC_i non-zero only when $i = m$,

$Q_{ss,i}(V_i)$ and $K_{q,i}$ non-zero only when $i = k$.

The unknowns are the bus voltages at non-load buses inside the local neighborhood, and ΔC_m . The following items are implied in equation 3.19 : 1) the capacitors at bus m will be used completely before other capacitors are used, 2) the voltage angles (θ_{ij}) are

constant, 3) bus voltages at the boundary of the neighborhood, generator terminal voltages, and load bus voltages are instantaneously constant, and 4) dV_k/dt equals ϵ . Keeping voltage angles constant and decoupling the real and reactive power calculations is commonplace. The generator terminal voltages are not constant, but will increase as the reactive support from ΔC_m is introduced. If the effect of increasing generator voltages is included, the resultant value of ΔC_m will be smaller because generators will supply a larger portion of the total reactive power to the load. Therefore, when the control found by equation 3.19 is executed, the actual dV_k/dt result is greater than ϵ .

The Complete Scheme

The complete remedial control scheme is fabricated by combining local and nearby control. Control is taken in the following order:

- 1) On the first detection of collapse at any bus, lock all on-load tap changing transformers, and
- 2) Calculate and switch in the required number of capacitors at the bus where the detector has triggered (collapsing bus). If insufficient control is available to force the voltage derivative positive, then switch in all capacitors and
- 3) Calculate and switch in the required number of additional capacitors nearby the collapsing bus. Capacitors are used one nearby bus at a time, moving to the next bus with available capacitors, as needed. If sufficient control is still not found, then
- 4) Calculate and shed the required amount of load at the collapsing bus. Note that if all the load is shed at the collapsing bus, the differential equation for the collapsing bus voltage disappears, reducing the dynamic order of the system by one.

3.2.4 Sufficiency of Control

The complete remedial control scheme along with the detection scheme must guarantee that a collapse will be avoided. Load shedding is only used when both local and nearby control action is insufficient to force the local voltage derivative to become positive. If the constraint that all voltage derivatives be positive is included in the remedial

strategies, the stability of the resultant system would be guaranteed. However, the positive derivative constraint is known to be too stringent, i.e., more control than necessary is used. To avoid the larger control set, the remedial scheme sequentially controls only those load bus voltages which have triggered their collapse detectors. A proof of system stability is needed under this new control strategy.

Consider the $dV_i/dt = 0$ contours in the state space. Figure 3.5 shows an example of a voltage state space in two variables, i.e., two dynamic load buses. The $dV_i/dt = 0$ contours are calculated by assuming that tap changers are locked (which is true after the first iteration of remedial control), or are in between tap changing events, and that all system constraints such as generator limits are enforced. Because all system constraints are included in the calculation of the contours, the contours are stationary, i.e., they do not move as a function of the state, unlike the contours developed in [38].

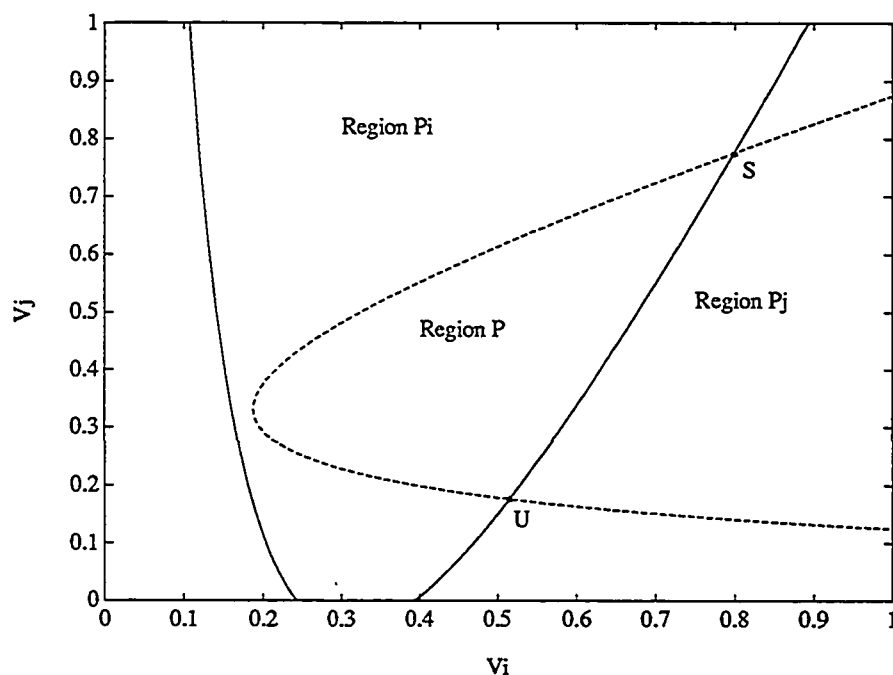


Figure 3.5 Voltage State Space, 2 Variables

Let P_i be the region in the voltage space where $dV_i/dt \geq 0$. In figure 3.5, P_i is the region inside the solid curve. Let P be the intersection of all P_i regions, i.e., a region where all

load bus voltage derivatives are non-negative. P may consist of multiple disconnected components. The stable equilibrium point (S in figure 3.5) in the voltage space must reside on the boundary of one of the components of P . If at any time the system state x enters P , stability is ensured from Lemma 4 in [38]. Therefore, a collapse can only arise if the state never enters P .

Several useful items can be established using the mild assumption that the load model is convex. For the ZIP load model, this assumption holds when $Q_{c,i} > 0$, a common load characteristic. Appendix B in [38] establishes the uniqueness of the stable equilibrium point as follows. A convex load model at bus i results in the region P_i being convex. If all P_i 's are convex, P must be convex. From the convexity of P , it follows that there is only one stable equilibrium point, S, and it lies at the largest coordinates in P .

Let A be the allowable voltage region such that $V_i \geq V_{\text{thres}}$, $i=1, \dots, n$. Note that the state x is always confined to A by the detection scheme, which forces each $dV_i/dt \geq 0$ whenever V_i nears V_{thres} (the boundary of A). Therefore, for the state x to reach the stable equilibrium point S, S must eventually enter A following remedial control. If x diverges, i.e., voltage collapse occurs, x must exit A , causing some collapse detector to trigger remedial control.

When the detector at bus i causes remedial control to be executed, P_i must get larger. This can be seen by looking at any cross section of P_i where only V_i is varied and all other voltages are held constant. This cross section is equivalent to the picture in figure 3.4. Control will either cause the $Q_{ss,i}$ curve to decrease or the $Q_{l,i}$ curve to increase, both of which cause the positive dV_i/dt region (line segment) to expand. Also note that P_i must include x after control, whereas P_i did not include x before control. Other regions such as P_j , $j \neq i$, expand if the control is taken at non-load buses. This is because when control is taken at a load bus, the load bus voltage must instantaneously remain constant. Therefore, looking at any point in the state space, control at a load bus has no effect on the network reactive power flow equations. Control at the load bus only impacts the load bus voltage derivative (equation 3.9). Therefore, the reactive demand supplied to bus j from the network is independent of the control. So P_j does not change. However, if control is taken at a non-load bus (say bus k), the reactive power flow into bus j from bus k will increase as expected from the reactive power flow equations.

Therefore, P_j expands. The intersection of all P_i 's, i.e., P , must expand, along with movement of the stable equilibrium S to higher coordinates. This is because S lies on the boundary of P_i and P_i expands. S must eventually enter A because S always increases in coordinates with each iteration of remedial control.

After S enters A , the worst scenario is where remedial control continues. Remedial control always expands P , such that the origin of A ($V_i = V_{\text{thres}}, i=1, \dots, n$) must eventually be captured by P . From Proposition 6 in [38], A then becomes a subset of the stability region for S , x will converge to S , and no more remedial control is required.

The rate at which each P_i is expanded by remedial control is dependent on the magnitude of ϵ . ϵ controls the distance with which the expansion of P_i captures the present state. Larger values of ϵ cause 1) a larger expansion of P_i and P per control action, 2) decrease the number of remedial control iterations, and 3) increase the probability that more control than necessary will be taken. Therefore, ϵ should be chosen to balance between using a smaller number of control iterations with possible overshoot in the control, versus using more control iterations but implementing less total control.

This discussion has given sufficient conditions under which the stability of x is guaranteed. It should be noted that these conditions are not necessary conditions. In fact, it can be argued that the remedial scheme minimizes the amount of control taken for the following reasons.

- 1) Load shedding is used only as the last resort.
 - 2) Control is only taken for load buses where the detection scheme has identified a possible collapse condition.
 - 3) Control only expands the specific P_i region where the collapse was identified.
- In addition, P_i is expanded just enough to capture x .

Note that the remedial scheme is founded on the concept of voltage recovery regions, i.e., P_i , because the true stability region is clearly impractical to calculate. The region P is the only known region where a stability guarantee exists, and where the region is in some sense obtainable (can be calculated or detected).

3.3 Simulation Results

In [38], a seven bus, three generator model of parts of central and western Washington is presented to demonstrate a multiple bus voltage collapse event. This 7 bus system will be used to demonstrate the proposed detection and remedial control schemes. A one-line diagram of the 7 bus system is shown in figure 3.6. The model represents the Puget Sound basin (buses 3 through 7), five major 500 kV lines which cross the Cascade mountains (lines from bus 2 to bus 4), and some major generation on the eastern side of the Cascade mountains (buses 1 and 2). Steady state and dynamic system data for the 7-bus system are given in table 3.1. The system base is 5000 MVA.

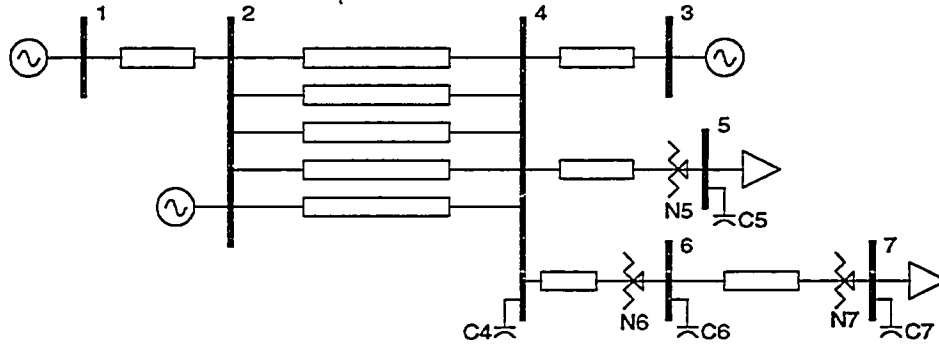


Figure 3.6 7 Bus Test System

The 7 bus system is subjected to the following disturbance :

- at 2.0 seconds, C_7 is changed from 0.3 to 0.1 p.u.,
- at 3.5 seconds, X_{24} is changed from 0.2 to 0.33 p.u.

This disturbance scenario is taken from [38] and represents a loss of local reactive support at bus 7 followed by the loss of two of the "across the mountain" lines (X_{24}) which carry significant generation from east of the Cascade mountains west into the Puget Sound basin. Figure 3.7 shows the resulting dynamic voltage collapse.

Table 3.1 System Parameters

Node	Data
1	Slack node, $V = 1.02$, $X_{12} = 0.2$
2	$V = 1.01$, $P_{\text{gen}} = 0.3$, $X_{\text{gen}} = 0.2$, $E_{\text{max}} = 1.11$, $I_{\text{max}} = 0.602$
3	$V = 1.01$, $P_{\text{gen}} = 0.2$, $X_{\text{gen}} = 0.15$, $E_{\text{max}} = 1.075$, $I_{\text{max}} = 0.502$
4	$X_{24} = 0.2$, $X_{34} = 0.2$, $C_4 = 0.65$
5	$X_{45} = 0.005$, $C_5 = 0.0$, $K_{q5} = 5$, $P_a = 0.070$, $P_b = -0.112$, $P_c = 0.742$, $Q_a = 0.090$, $Q_b = -0.153$, $Q_c = 0.513$
6	$C_6 = 0.0$, $X_{46} = 0.0700$, $X_{67} = 0.0815$
7	$C_7 = 0.3$, $K_{q7} = 5$, $P_a = 0.060$, $P_b = -0.090$, $P_c = 0.630$, $Q_a = 0.125$, $Q_b = -0.2125$, $Q_c = 0.5875$
LTCs (nodes 5,7)	delay = 5.0 secs., deadband = 0.005, tap size = 0.005, tap range = 0.8 - 1.2

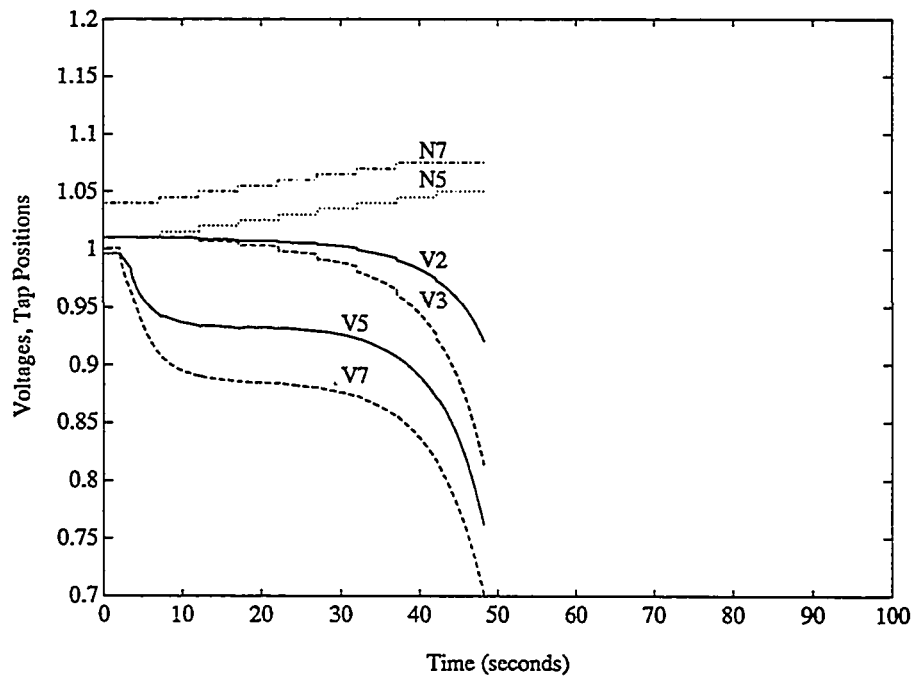


Figure 3.7 Disturbance Without Remedial Control

In [38], tap changer locking is shown to be sufficient remedial control for avoiding the collapse if the tap locking can be done when all load bus voltages are rising (i.e., the voltage derivatives at all load buses are positive). In figure 3.7 there does not exist any time after the disturbance when both bus 5 and bus 7 exhibit positive voltage derivatives. In figure 3.8, the same disturbance scenario was simulated along with locking of the tap changers at buses 5 and 7 at 0.0 seconds to investigate the effect of locking the taps. Note that the voltages still collapse, but the collapse occurs roughly 20 seconds later, providing additional decision time for other remedial control to be found.

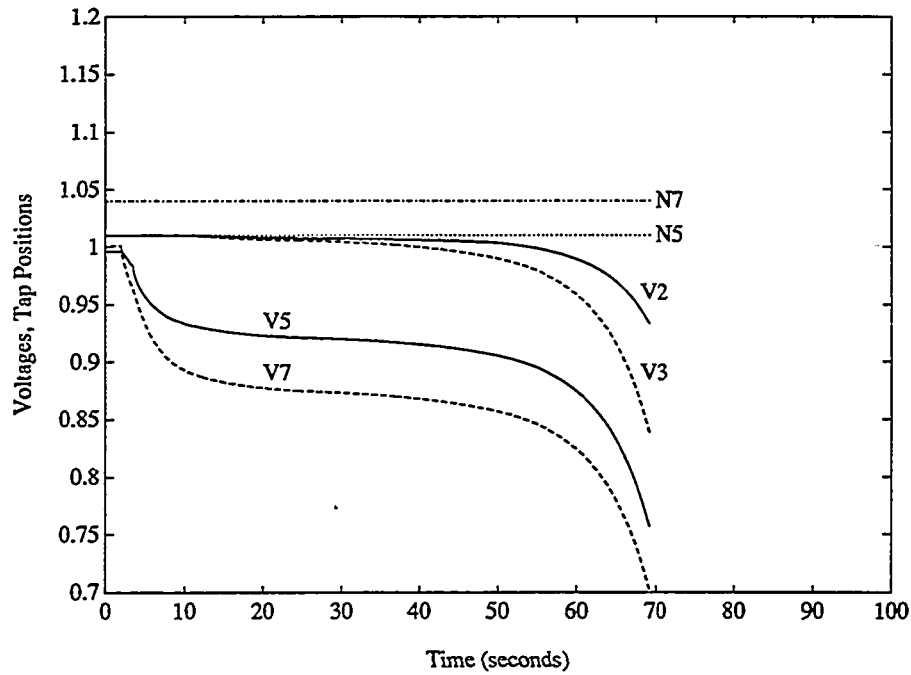


Figure 3.8 LTCs locked at 0.0 seconds

The detection and remedial control schemes are evaluated using the collapse event shown in figure 3.7. In the simulations, switchable capacitors are available at buses 4, 5, 6, and 7 in 0.02 p.u. increments (100 MVAR each). Voltage collapse detectors are implemented at buses 5 and 7. The pre-disturbance Thevenin impedances at buses 5 and 7 are 0.116 p.u. and 0.280 p.u., respectively.

3.3.1 Remedial Control - At the Load Bus

Figure 3.9 shows the results of using load bus remedial control to avoid the collapse. The detection scheme at bus 7 triggers remedial control at 36.5 seconds, when V_7 equals 0.8581 p.u. The approximate Thevenin voltage at 36.5 seconds is 1.0136 p.u. The detection scheme triggers because at $V_7 = 0.85$ p.u., the estimated value of $Q_{1,7}$ (0.4966 p.u.) is less than the computed value of $Q_{ss,7}$ (0.4972 p.u.). This implies that if a stable voltage equilibrium point exists for bus 7, it exists at a voltage less than 0.85 p.u. Using equation 3.16, the required change in $Q_{1,7}$ is 0.0710 p.u., achievable by switching in a capacitor of value $C_7 = 0.096$ p.u. Equation 3.18 yields a minimum value for C_7 . Because the switchable capacitors are discrete in value, a total of 0.100 p.u. (500 MVAR) is added at bus 7. In addition, all tap changers are locked. After control is taken, the voltage at buses 5 and 7 continue to change dynamically. The voltage at bus 7 begins to recover, freeing up reactive support for bus 5, resulting in a recovery of the voltage at bus 5 also. Note that the steady state values of V_5 and V_7 are well inside region A ($V_5 = 0.956$ p.u., $V_7 = 0.979$ p.u.).

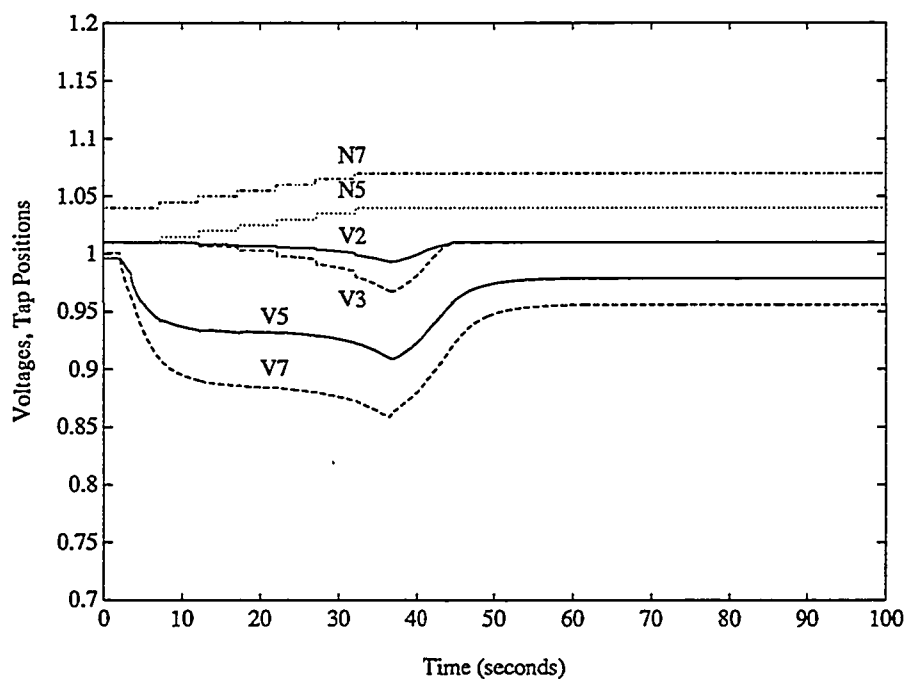


Figure 3.9 Remedial Control at Bus 7

3.3.2 Remedial Control - At Nearby Buses

Figure 3.10 shows the results of initiating remedial control at controllers nearby the collapsing load buses. The detection scheme at bus 7 again triggers remedial control at 36.5 seconds, when V_7 equals 0.8581 p.u. The nearby remedial scheme is tested by using switchable capacitors at bus 6 to control the voltage derivative at bus 7. Equation 3.19 yields a value of 0.216 p.u. for ΔC_6 . The discrete capacitor value actually added at bus 6 is 0.22 p.u. (1100 MVAR). Again, all tap changers are locked. After control is taken, the voltage at buses 5 and 7 continue to dynamically change. The capacitor addition provides enough reactive support to allow the voltages at buses 5 and 7 to recover. The post-disturbance steady state voltages are $V_5 = 1.000$ p.u. and $V_7 = 0.980$ p.u., which are well inside region A. As expected, a larger amount of control is required when nearby capacitors are used instead of local capacitors.

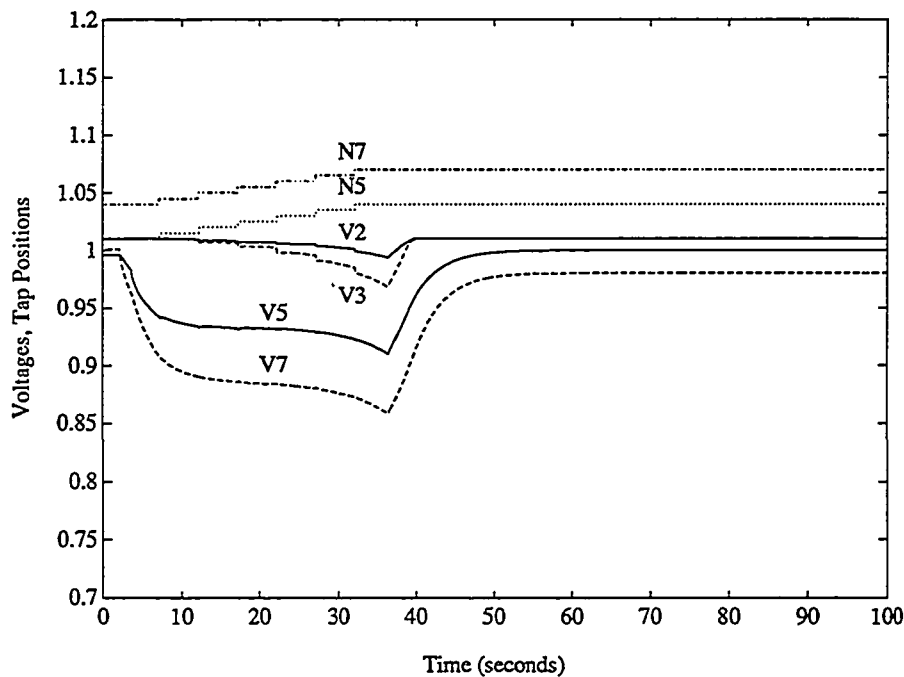


Figure 3.10 Nearby Remedial Control at Bus 6

3.4 Conclusions

This chapter has presented a decentralized detection scheme for voltage collapse events, based on the dynamic load model. The detection scheme uses a continuously updated Thevenin equivalence at each load bus to model the ability of the network to supply reactive power to each load bus. The detection scheme triggers remedial control whenever the localized stable balance between the steady state and total load demands falls below an acceptable voltage threshold.

This chapter has also presented a remedial control formulation for voltage collapse prevention. Two remedial control schemes have been proposed, depending on the location where control is to be taken. The first scheme is used to calculate the amount of control to take at each collapsing load bus so that the voltage derivative at the load bus will become positive. The second scheme is used to calculate the amount of control to be taken at controllable devices near each collapsing load bus. Each scheme forces the voltage derivative at the collapsing load bus to become positive, by an amount ϵ . A proof is developed to show that localized control of those load bus voltages which are nearing a collapse is sufficient to guarantee that a global collapse will be avoided.

The simulations shown in figures 3.9 and 3.10 show the system voltages recovering from an imminent collapse using local and nearby remedial control, respectively. As expected, local control is more effective at stabilizing the bus voltages than control taken at buses near the collapsing bus. In both simulation cases, only one control iteration was necessary to avoid the collapse. While one iteration is not guaranteed to be sufficient to avoid the collapse, these simulations show two scenarios where only one iteration is required. The proposed remedial control schemes attempt to reduce the required amount of control, while still guaranteeing that the collapse will be avoided.

Chapter 4. Conclusions and Recommendations

Two power system voltage performance issues have been addressed by this research. First, an expert system called SEEKS was developed to perform the static voltage security assessment task normally performed by operational planners. Second, a detection and remedial control algorithm was developed for dynamic monitoring and control of load bus voltages, so as to avoid the occurrence of a voltage collapse.

The SEEKS expert system assesses the impact of the most severe line outages on the steady state bus voltage profile, and determines remedial control for removing these voltage violations. This approach is different from other approaches because of the generalized operational planning strategy used by SEEKS. Two interesting aspects of this strategy are the analysis of non-trivial collections of buses and branches when prioritizing outages, and the goal of evaluating only the most severe outage in these collections, rather than all outages which cause voltage violations.

The voltage collapse detection and remedial control algorithm controls load bus voltages during an imminent collapse in order to steer the bus voltages away from the collapse. The algorithm is an extension of the research into the mechanisms of a dynamic voltage collapse. In particular, this research effort grew out of the work reported in [37] where voltage recovery regions or leaves were derived. This dissertation provided two extensions, namely a localized or bus by bus detection of collapse conditions, and a localized formulation for remedial control calculations.

SEEKS could be improved in the following ways. First, the results of power flows run by SEEKS during an assessment should be used during the selection of outages later on during the assessment. In particular, when outages are evaluated during the single contingency selection process, the results of these power flows should be factored into the double contingency selection process. Also, previous assessment results and previous operating point information is valuable to the operational planning engineer when assessing the current operating point. This historical information should be accommodated in the SEEKS knowledge base.

The following issues concerning detection and control require further work. First, the detection scheme should provide a greater predictability of imminent collapse than shown in the simulation results. However, the detection should not require a wealth of

information or require lengthy calculation. Second, from the remedial control side, more research into the relationship between the localized control strategy and the global stability region is needed. This should lead to a theoretical foundation on how to strictly minimize load shedding while avoiding a collapse.

The practical application of both the SEEKS expert system and the detection and remedial control algorithm for voltage collapse need to be investigated. Testing of SEEKS using Puget Sound Power and Light data has already begun.

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