Transmission system reconfiguration for corrective control

Wei Shao
Iowa State University

Follow this and additional works at: https://lib.dr.iastate.edu/rtd
Part of the Electrical and Electronics Commons

Recommended Citation
Shao, Wei, "Transmission system reconfiguration for corrective control " (2006). Retrospective Theses and Dissertations. 1304.
https://lib.dr.iastate.edu/rtd/1304

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.
Transmission system reconfiguration for corrective control

by

Wei Shao

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Major: Electrical Engineering

Program of Study Committee:
Vijay Vittal, Major Professor
James D. McCalley
Venkataramana Ajjarapu
Wolfgang Kliemann
Degang Chen
David A. Hennessy

Iowa State University
Ames, Iowa
2006

Copyright © Wei Shao, 2006. All rights reserved.
INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.
Graduate College
Iowa State University

This is to certify that the doctoral dissertation of
Wei Shao
has met the dissertation requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program
To
the Memory of My Grandparents
and
To My Parents
TABLE OF CONTENTS

LIST OF FIGURES ......................................................................................................................... ix

LIST OF TABLES ............................................................................................................................ xi

ACKNOWLEDGEMENT .................................................................................................................. xiii

ABSTRACT ...................................................................................................................................... xiv

CHAPTER 1 : INTRODUCTION......................................................................................................... 1

1.1 Power System Reliability and Control .................................................................................... 1

1.2 Transmission System Reconfiguration ................................................................................... 2

1.3 Optimal Power Flow ................................................................................................................ 5

1.3.1 Nonlinear Programming (NLP) Methods ........................................................................... 5

1.3.2 Quadratic Programming (QP) Method .............................................................................. 6

1.3.3 Linear Programming (LP) Method .................................................................................... 6

1.3.4 Interior Point (IP) Method ................................................................................................ 7

1.4 Problem Statement .................................................................................................................. 8

1.5 Dissertation Organization ....................................................................................................... 10

CHAPTER 2 : AN OVERVIEW ON TRANSMISSION SYSTEM RECONFIGURATION ............................................. 12

2.1 Corrective Switching ................................................................................................................ 12

2.1.1 Purposes of Corrective Switching ..................................................................................... 13

2.1.2 Switching Elements and Their Models ............................................................................ 13

2.1.2.1 Line Switching Model ................................................................................................. 13

2.1.2.2 Bus-bar Switching Model .......................................................................................... 14

2.1.2.3 Shunt Switching Model .............................................................................................. 15

2.1.3 Corrective Switching Algorithms (CSAs) ........................................................................ 15

2.1.3.1 Problem Reduction ..................................................................................................... 15

2.1.3.2 Search Techniques ...................................................................................................... 16

2.1.3.3 Feasible and Optimal Solution ..................................................................................... 17

2.1.3.4 Power Flow Calculation .............................................................................................. 18

2.1.4 Security Assessment of Corrective Switching .................................................................... 18
CHAPTER 3 : LINE AND BUS-BAR SWITCHING ALGORITHM FOR
RELIEVING OVERLOADS AND VOLTAGE VIOLATIONS  

3.1 Introduction ............................................................................. 23
3.2 Line Switching Model ................................................................. 24
  3.2.1 Network Matrix Modification .................................................. 24
  3.2.2 Post Compensation Method .................................................... 25
3.3 General Bus-bar Switching Model ............................................... 25
  3.3.1 Bus-bar Layouts ................................................................... 25
  3.3.2 Bus-bar Switching Constraints ............................................... 27
  3.3.3 Bus-bar Switching Modeling Process .................................... 27
3.4 Proposed Line and bus-bar Switching Algorithm .......................... 29
  3.4.1 Fast Decoupled Power Flow with Limited Iteration Count ......... 29
  3.4.2 Performance Index of Security Margin ................................. 29
  3.4.3 Proposed Line and Bus-bar Switching Algorithm .................... 31
3.5 Case Studies ........................................................................... 33
  3.5.1 The New England 39-bus System ........................................... 33
    3.5.1.1 Line Switching Solution .................................................... 33
    3.5.1.2 Bus-bar Switching Solution .............................................. 35
  3.5.2 The WECC 179-bus System ................................................... 37
    3.5.2.1 Bus-bar Switching Solution .............................................. 38
3.6 Summary .............................................................................. 39

CHAPTER 4 : SHUNT ELEMENT SWITCHING ALGORITHM FOR
CORRECTIVE VOLTAGE CONTROL ............................................. 41
4.1 Introduction ............................................................................ 41
4.2 Voltage Distribution Factor ...................................................... 42
  4.2.1 First Iteration Based Voltage Distribution Factor ..................... 43
  4.2.2 Multiple Iteration Based Voltage Distribution Factor ............... 45
4.3 Corrective Voltage Control Algorithm by Shunt Element Switching .... 48
  4.3.1 Switching Cost and Maximum Switchable Shunt Banks ............. 48
4.3.2 System Voltage Security Margin (SVSM) ................................................................. 48
4.3.3 Proposed Corrective Voltage Control Algorithm ....................................................... 49
4.5 Case Studies .................................................................................................................. 51
   4.5.1 The New England 39-bus System .......................................................................... 51
   4.5.2 The WECC 179-bus System ................................................................................... 53
4.6 Summary ......................................................................................................................... 56

CHAPTER 5 : INTEGRATION OF LINE SWITCHING, BUS-BAR SWITCHING, AND SHUNT SWITCHING ALGORITHMS ........................................... 57

5.1 Introduction ................................................................................................................... 57
5.2 Ordering of Successful Switching Actions ................................................................. 57
5.3 The Proposed Corrective Switching Algorithm ......................................................... 58
5.4 Case Studies ................................................................................................................. 60
5.5 Summary ....................................................................................................................... 64

CHAPTER 6 : LP-BASED OPF FOR CORRECTIVE FACTS CONTROL TO RELIEVE OVERLOADS AND VOLTAGE VIOLATIONS ................. 65

6.1 Introduction ................................................................................................................... 65
6.2 Power Flow Models of FACTS Devices ..................................................................... 66
6.3 LP-based OPF for UPFC Control................................................................................ 69
   6.3.1 System State Variables and Control Variables ..................................................... 69
   6.3.2 Objective Function ............................................................................................... 70
   6.3.3 Equality Constraints ........................................................................................... 71
   6.3.4 Inequality Constraints ......................................................................................... 72
   6.3.5 Sensitivities ......................................................................................................... 73
6.4 Algorithm Implementation ............................................................................................ 74
6.5 Case Studies ................................................................................................................. 76
   6.5.1 The New England 39-bus System ....................................................................... 76
       6.5.1.1 Case 1: The UPFC Is Installed at Bus 16 to
               Control Power Flow on Line 16-17 ................................................................. 77
       6.5.1.2 Case 2: The UPFC is Installed at Bus 15 to
               Control Power Flow on Line 15-16 ................................................................. 78
6.5.1.3 Case 3: The UPFC is Installed at Bus 4 to Control Power Flow on Line 4-14 ......................................................... 80

6.5.2 The WECC 179-bus System .............................................................................................................................. 82

6.5.2.1 Case 1: The UPFC is Installed at Bus 81 to Control Power Flow on Line 81-99 ................................................................. 83

6.5.2.2 Case 2: The UPFC is Installed at Bus 28 to Control Power Flow on Line 28-29 ................................................................. 84

6.6 Summary .................................................................................................................................................. 86

CHAPTER 7 : BINARY INTEGER PROGRAMMING BASED OPF FOR LINE AND BUS-BAR SWITCHING .......................................................................................... 87

7.1 Introduction ............................................................................................................................................... 87

7.2 A New Model for Line Switching .................................................................................................................. 87

7.2.1 Switching out a Transmission Line .............................................................................................................. 88

7.2.2 Switching in a Transmission Line ............................................................................................................... 92

7.3 A New Model for Bus-bar Switching ............................................................................................................ 93

7.4 Binary Integer Programming Based OPF for Line and Bus-bar Switching ...................................................... 94

7.4.1 System State Variables ............................................................................................................................... 94

7.4.2 Control Variables ....................................................................................................................................... 95

7.4.3 Objective Function ..................................................................................................................................... 95

7.4.4 Equality Constraints .................................................................................................................................. 95

7.4.5 Inequality Constraints ............................................................................................................................... 96

7.4.6 Algorithm .................................................................................................................................................. 97

7.5 Case Studies .......................................................................................................................................... 98

7.5.1 The New England 39-bus System .................................................................................................................. 98

7.5.1.1 Line Switching Solution .......................................................................................................................... 98

7.5.1.2 Bus-bar Switching Solution .................................................................................................................. 99

7.5.2 The WECC 179-bus System .......................................................................................................................... 102

7.5.2.1 Bus-bar Switching Solution .................................................................................................................. 102

7.5.2.2 Line and Bus-bar Switching Solution .................................................................................................. 105

7.6 Summary ............................................................................................................................................... 107

CHAPTER 8 : CONCLUSIONS AND FUTURE WORK ......................................................................................... 109
8.1 Conclusions ................................................................. 109
8.2 Specific Contributions .................................................. 109
8.3 Future Work ............................................................. 112

REFERENCES .................................................................... 114
LIST OF FIGURES

Figure 1-1: Corrective Control Strategies and Relevant System Operating States ...........................................4
Figure 2-1: The Simplest Bus-bar Diagram .......................................................................................................14
Figure 2-2: Bus-adding Model of Bus-bar Switching .....................................................................................15
Figure 2-3: Security Enhancement by Corrective Switching ........................................................................19
Figure 3-1: The Structure of a Bus-bar with Four Lines .................................................................................26
Figure 3-2: The Structure of a Bus-bar Layout of Breaker-and-a-half with Six Lines ....................................27
Figure 3-3: The Model Diagrams of a Bus-bar with Four Branches ..............................................................29
Figure 3-4: Flowchart of the Proposed Line and Bus-bar Switching Algorithm ...........................................32
Figure 3-5: Line 1 is Recommended to Be Switched out .............................................................................34
Figure 3-6: Bus-bar 2 is Recommended to Be Split off ..............................................................................36
Figure 3-7: One-line Diagram of the WECC 179-bus System .............................................................37
Figure 3-8: The Relevant Portion of the WECC 179-bus System .............................................................39
Figure 4-1: Flowchart of the Proposed Corrective Voltage Control Algorithm ...........................................49
Figure 4-2: Shunt Capacitor Banks at Bus 12 are Recommended to Be Switched in ..................................52
Figure 4-3: One-line Diagram of the WECC 179-bus System .............................................................54
Figure 5-1: Flowchart of the Proposed Corrective Switching Algorithm ....................................................59
Figure 5-2: The Relevant Portion of the WECC 179-bus System .............................................................61
Figure 5-3: Generator Rotor Angles after Switching out Line 81-99 ..........................................................63
Figure 5-4: Generator Rotor Angles after Splitting off Bus-bar 83 ..............................................................63
Figure 6-1: The Schematic Diagram of UPFC ...............................................................................................67
Figure 6-2: The Equivalent Model of UPFC ...............................................................................................67
Figure 6-3: Connection of a UPFC with the Power System ......................................................................68
Figure 6-4: UPFC Model in Power Flow Calculation ...................................................................................69
Figure 6-5: Flowchart of the proposed LP-based OPF Algorithm for UPFC Control ....................................75
Figure 6-6: One Line Diagram of the New England 39-bus System ............................................................76
Figure 6-7: One-line Diagram of the WECC 179-bus System ...................................................................82
Figure 7-1: Line Outage Model Using Injections .........................................................................................88
Figure 7-2: Diagrams of Switching out a Transmission Line .....................................................................88
Figure 7-3: Diagrams of Switching in a Transmission Line .........................................................................92
Figure 7-4: The Model Diagrams of a Bus-bar with Four Branches ...........................................................94
Figure 7-5: Line 1 is Recommended to Be Switched out.................................................................100
Figure 7-6: Bus-bar 2 is Recommended to Be Split off..................................................................102
Figure 7-7: One-line Diagram of the WECC 179-bus System.............................................................103
Figure 7-8: The Relevant Portion of the WECC 179-bus System.......................................................105
Figure 7-9: The Relevant Portion of the WECC 179-bus System.......................................................107
LIST OF TABLES

TABLE 3-1: Contingency Analysis Results for Outage of Line 7 .............................................. 33
TABLE 3-2: Power Flow Results after Switching out Line 1 ...................................................... 34
TABLE 3-3: Contingency Analysis Results for Outage of Line 7 .............................................. 35
TABLE 3-4: Power Flow Results after Splitting off Bus-bar 2 .................................................. 36
TABLE 3-5: Contingency Analysis Results for Outage of Line 170-171 ...................................... 38
TABLE 3-6: Power Flow Results after Splitting off Bus-bar 83 ................................................... 38
TABLE 4-1: Contingency Analysis Results for Outage of Line 16-17 ....................................... 51
TABLE 4-2: Available Shunt elements for the New England 39-bus System ............................. 51
TABLE 4-3: Simulation Results after Switching in the Shunt Capacitor Banks at Bus 12 .......... 52
TABLE 4-4: Available Shunt elements for the WECC 179-bus System ....................................... 53
TABLE 4-5: Contingency Analysis Results for Outage of Line 170-171 ...................................... 54
TABLE 4-6: Simulation Results after Switching in Shunt Capacitors at Buses 60 and 105 ....... 55
TABLE 5-1: Contingency Analysis Results for Outage of Line 170-171 ...................................... 60
TABLE 5-2: Power Flow Results after Corrective Switching Actions ....................................... 61
TABLE 5-3: Power Flow Results after Switching out Line 81-99 ............................................... 62
TABLE 6-1: Contingency Analysis Results for Outage of Line 4-5 .............................................. 77
TABLE 6-2: Operational Limits of UPFC .................................................................................... 77
TABLE 6-3: Comparison of UPFC’s Variables before and after Control (Case 1) ................. 78
TABLE 6-4: Control Targets of UPFC before and after Control (Case 1) ................................. 78
TABLE 6-5: Power Flow Results after UPFC Control (Case 1) .................................................. 78
TABLE 6-6: Comparison of UPFC’s Variables before and after Control (Case 2) ................. 79
TABLE 6-7: Control Targets of UPFC before and after Control (Case 2) ................................. 79
TABLE 6-8: Power Flow Results after UPFC Control (Case 2) .................................................. 79
TABLE 6-9: Comparison of UPFC’s Variables before and after Control (Case 3) ................. 80
TABLE 6-10: Control Targets of UPFC before and after Control (Case 3) .............................. 81
TABLE 6-11: Power Flow Results after UPFC Control (Case 3) ............................................... 81
TABLE 6-12: Contingency Analysis Results for Outage of Line 170-171 .............................. 83
TABLE 6-13: Operational Limits of UPFC .................................................................................. 83
TABLE 6-14: Comparison of UPFC’s Variables before and after Control (Case 1) ................. 84
TABLE 6-15: Control Targets of UPFC before and after Control (Case 1) .............................. 84


<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-16</td>
<td>Power Flow Results after UPFC Control (Case 1)</td>
<td>84</td>
</tr>
<tr>
<td>6-17</td>
<td>Comparison of UPFC's Variables before and after Control (Case 2)</td>
<td>85</td>
</tr>
<tr>
<td>6-18</td>
<td>Control Targets of UPFC before and after Control (Case 2)</td>
<td>85</td>
</tr>
<tr>
<td>6-19</td>
<td>Power Flow Results after UPFC Control (Case 2)</td>
<td>85</td>
</tr>
<tr>
<td>7-1</td>
<td>Contingency Analysis Results for Outage of Line 7</td>
<td>98</td>
</tr>
<tr>
<td>7-2</td>
<td>Power Flow Results after Switching out Line 1</td>
<td>99</td>
</tr>
<tr>
<td>7-3</td>
<td>Contingency Analysis Results for Outage of Line 7</td>
<td>100</td>
</tr>
<tr>
<td>7-4</td>
<td>Power Flow Results after Splitting off Bus-bar 2</td>
<td>101</td>
</tr>
<tr>
<td>7-5</td>
<td>Contingency Analysis Results for Outage of Line 170-171</td>
<td>103</td>
</tr>
<tr>
<td>7-6</td>
<td>Power Flow Results after Splitting off Bus-bar 83</td>
<td>104</td>
</tr>
<tr>
<td>7-7</td>
<td>Contingency Analysis Results for Outage of Line 170-171</td>
<td>105</td>
</tr>
<tr>
<td>7-8</td>
<td>Power Flow Results after Splitting off Bus-bar 83</td>
<td>106</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENT

I would like to express my most sincere gratitude to my major advisor, Dr. Vijay Vittal, for the opportunity, as well as for his sustained support, patience, and guidance throughout the course of this research. His professional accomplishments and dedication are a tremendous source of inspiration to every aspiring student, and I am fortunate to have had the opportunity to work under his supervision.

I would also like to thank Dr. James D. McCalley, Dr. Venkataramana Ajjarapu, Dr. Wolfgang Kliemann, Dr. Degang Chen, and Dr. David A. Hennessy, for serving on my program of study committee. Their advice and patience is highly appreciated.

I want to thank Dr. Wenzheng Qiu, Dr. Xiaoming Wang, Shu Liu and Qian Liu, for their advice, help, support, and encouragement throughout my study and research.

I am also indebted to the alumni and graduate students in the power group at Iowa State University, Dr. Qiming Chen, Dr. Kun Zhu, Dr. Zhong Zhang, Dr. Jiang Huang, Dr. Xiaoyu Wen, Dr. Zheng Zhou, Dr. Wang Yu, Dr. Badri Ramanathan, Yong Jiang, Haifeng Liu, Licheng Jin, Weiqing Jiang, Bo Yang, Feng Gao, Yuan Li, Fei Xiao, Sheng Yang, Gang Shen, Ashutosh Tiwari, Cheng Luo and many others. Their great friendship accompanied me throughout my school years and made my life in Ames so happy and meaningful. These memories will never be forgotten.

Finally, I would like to thank my mother and my father, for their endless support and encouragement in every one of my endeavors. I would also like to thank my sister and brother who have been extremely supportive all along.
When a power system is in the alert state, a severe contingency may bring the system into the emergency state, resulting in overloads, voltage violations, cascading failures, or even loss of stability, and force system operators to take appropriate corrective control actions. It is widely known that transmission system reconfiguration (TSR), including transmission line switching, bus-bar switching, shunt element switching, transformer tap changing, and FACTS control, may change the states of the power systems, and consequently, affect the distribution of power flows, transmission losses, short circuit currents, voltage profiles as well as the transient stability of power systems. Under the restructured environment of the power industry, TSR has a great advantage in economy compared with other corrective control methods, such as load shedding and system islanding, since it almost has no effect on generation and load, and thereby, becomes a very attractive research topic for on-line corrective control.

Focusing on line and bus-bar switching, shunt element switching, and corrective FACTS control, this dissertation has proposed a general framework for employing TSR actions to relieve overloads and voltage violations caused by system contingencies. In this dissertation, a new line and bus-bar switching algorithm for relieving overloads and voltage violations is proposed based on fast decoupled power flow with limited iteration count. A novel shunt switching algorithm is also presented for corrective voltage control based on the newly derived voltage distribution factor. These two algorithms are then integrated into one corrective switching algorithm. Furthermore, an LP-based OPF algorithm is developed for corrective FACTS control based on the newly derived parameter sensitivities of FACTS devices such that the operational constraints of FACTS devices can be considered during optimization. In order to improve computation speed, a general power compensation model is proposed for line and bus-bar switching, and a BIP-based OPF algorithm is developed for line and bus-bar switching on the basis of the proposed model. All the developed algorithms are implemented with MATLAB and tested on the New England 39-bus system.
and the WECC 179-bus system. The simulation results obtained indicate that the developed approaches could effectively solve the problems of overloads and voltage violations and significantly reduce the computational time.
CHAPTER 1: INTRODUCTION

1.1 Power System Reliability and Control

The function of an electric power system is to convert energy from one of the naturally available forms into electrical energy and to transport it to the points of consumption. The advantage of electrical energy is that it can be transported and controlled with relative ease and with a high degree of efficiency and reliability [1]. A properly designed and operated power system should meet the requirement of reliability, which consists of two components as defined by the North American Electric Reliability Council (NERC) planning standards, a) adequacy of supply, and b) transmission security.

Adequacy is the ability of electric power systems to supply the aggregate electrical demand and energy requirements of customers at all times, taking into account scheduled and reasonably expected unscheduled outage of system elements.

Security is the ability of electric power systems to withstand sudden disturbances such as electrical short circuits or unanticipated loss of system elements.

Power system control, therefore, can be divided into two categories, a) normal control, implemented during system operation under normal conditions, and b) security control, implemented during system operation under abnormal conditions.

In order to analyze power system security and design appropriate control strategies, the power system can be conceptually classified into five operating states: normal, alert, emergency, in extremis, and restorative [1].

In the normal state, all system variables are within normal range. The system operates in a secure manner and is able to withstand a contingency without violating any of the constraints.

In the alert state, all system variables are still within acceptable range and all constraints are satisfied. However, the security level of the system has been weakened and a
contingency may cause violations of some system variables.

The system enters **emergency state**, if a sufficiently severe disturbance occurs when the system is in the alert state, such that some system variables violate their constraints.

The system is **in extremis**, if the system security level continuously deteriorates, which will result in cascading failures and possibly a blackout of a major portion of the system.

The **restorative state** represents a condition in which control action is being taken to reconnect all the facilities and to restore system load.

Based on the different levels of system security, there are generally two kinds of security controls, a) preventive control and b) corrective control.

The **preventive control** actions, such as generation rescheduling or increasing reserve margins, are usually taken to restore the system from the alert state back to the normal state.

The **corrective control** actions, which sometimes are also called **emergency control** actions, are usually employed to restore the system from the emergency state back to the alert state.

Secure operation of the electric power infrastructure is very crucial for a flourishing economy. The cost of major blackouts is immense, in human and financial terms. In a recent study, the total economic cost of the August 2003 Northeast blackout has been estimated to be near 10 billion dollars [2]. There occur numerous shorter and localized power outages in various areas that have the potential to develop into major blackouts without timely control actions being taken. Therefore, maintaining reliability of power systems is always the most important target of power system planning and operation.

### 1.2 Transmission System Reconfiguration

The bulk power grid is the largest and most complex interconnected network ever devised by man, which makes control of the grid an extremely difficult task. The task of controlling the grid become even more complex since the electric power industry is
undergoing worldwide restructuring and deregulation. Economy-oriented power system operation makes control of the system more challenging than ever. When the system is in the alert state, a severe contingency may bring the system into the emergency state, resulting in overloads, voltage violations, cascading failures, or even loss of stability and force system operators to take appropriate corrective control actions.

It is widely known that transmission system reconfiguration (TSR) may change the states of the power systems, and consequently, affect the distribution of power flows, transmission losses, short circuit currents, voltage profiles as well as the transient stability of power systems. Generally, TSR can be classified into two categories: one is the so-called corrective switching, including transmission line switching, bus-bar switching, transformer tap changing, and shunt element switching (including shunt capacitors and shunt reactors), and the other one is corrective FACTS control, i.e. power flow and voltage control and dynamic control using FACTS devices, such as static Var compensator (SVC), thyristor-controlled series capacitor (TCSC), interline power flow controller (IPFC), static synchronous series compensator (SSSC), static synchronous compensator (STATCOM), and unified power flow controller (UPFC). In these TSR operations, transformer tap changing and shunt element switching have been used as common control maneuvers in power systems. Although many studies have been conducted dealing with line and bus-bar switching since this idea was first proposed in early 1980’s [3]-[16], line and bus-bar switching is still not widely employed as an effective means of control. The reasons for this mainly lie in the possibility of reduction of system security by switching actions and the discrete performance of switching actions, which makes it very difficult to model and design a systematic search method. On-line corrective control needs both speed and accuracy, and with the continued growth of modern power systems, the speed requirement becomes more and more important. Moreover, there are few instances of practical on-line applications of TSR algorithms [13],[17]. Therefore, more research is needed to find fast and accurate on-line TSR algorithms.
There are other corrective control methods, such as generation rescheduling (GR), load shedding (LS), and system islanding (SI). However, under the restructured environment of the electric power industry, these operations result in other costs that need to be considered. Nevertheless, for TSR actions, no additional costs are needed since they are only operational actions and almost have no effects on generation and load demands. Therefore, system reconfiguration has a great advantage in economy compared with other corrective control methods. Furthermore, TSR can change the power flow distribution very quickly such that it can be also employed as a fast corrective control approach under emergency situations. Therefore, there is a need for detailed studies on TSR. From the economic point of view, when the system enters the emergency state, TSR should be first considered as a corrective control option. Only when TSR cannot relieve all of the violations, should more aggressive corrective control strategies, such as generation rescheduling, load shedding, or even system islanding, be executed to prevent catastrophic failures [19]. Figure 1-1 illustrates the relationship of these corrective control strategies and corresponding system operating states.

![Figure 1-1: Corrective Control Strategies and Relevant System Operating States](image-url)
1.3 Optimal Power Flow

In recent years there has been increasing interest in the application of optimization techniques to power system planning and operation problems. The optimal power flow (OPF) is a generic term that describes a broad class of problems in which we seek to optimize a specific target while satisfying a set of system operational and/or security constraints. The OPF has been studied for decades and has become a successful and flexible analytical tool that could be applied in everyday use. The OPF has many applications including generation cost minimization, system loss minimization, voltage-Var optimization, available transfer capability (ATC) calculation, and security-constrained OPF, etc. [20].

The OPF is a large and complex mathematical programming problem. Almost every mathematical programming approach that can be applied to this problem, each with its particular mathematical and computational characteristics, has been attempted and significant efforts have been made to solve the OPF problem reliably. The methods employed to solve the OPF problem can be generally classified as follows:

1. Nonlinear programming (NLP) methods
2. Quadratic programming (QP) method
3. Linear programming (LP) method
4. Interior point (IP) method

1.3.1 Nonlinear Programming (NLP) Methods

The nonlinear programming methods deal with problems involving nonlinear objective functions and constraints. The NLP methods are the most essential and commonly used approaches for OPF problems since power systems behave nonlinearly. Many NLP techniques have been applied since OPF was first discussed and studied and their attributes can be summarized as follows [20]-[28]:
- **Lagrange multiplier method**: The basis of many standard on-line economic dispatch programs.

- **Gradient methods**: Slow in convergence and difficult to handle inequality constraints.

- **Newton’s methods**: Fast in convergence but may give problems with inequality constraints.

- **P-Q decomposition method**: decompose real power and reactive power during optimization.

- **Evolutionary and Genetic algorithm**: Good for finding the global optimal solution.

- **Penalty function method**: make it easy to handle inequality constraints.

### 1.3.2 Quadratic Programming (QP) Method

Quadratic programming is a special form of nonlinear programming, which treats the problems with quadratic objective functions but with linear constraints. The QP methods have been employed to solve such special OPF problems as system loss minimization, voltage control and economic dispatch [29]-[32].

### 1.3.3 Linear Programming (LP) Method

Although the NLP-based OPF works very well in many cases, especially for the loss minimization problem, it has difficulties in detecting and handling infeasibility, and is inefficient for the enforcement of complicated constraints such as contingencies [33]. Moreover, the NLP-based OPF is very time-consuming since a power flow calculation has to be conducted at every iteration. Therefore, it is not suitable for on-line operation and control. These reasons encourage the concentration of efforts on the linear programming (LP) based approach [33]-[37].

The LP approach only deals with linear objective functions and constraints. Therefore, linearization is necessary for LP-based OPF since power systems behave nonlinearly. Although it may not be as accurate as the NLP-based OPF, convergence to engineering
accuracy is rapid and acceptable when the changes in the control variables are small.

There are several main advantages of the LP approach [33]. One is the reliability of optimization. Another is its ability to recognize problem infeasibility quickly. A third is that it can easily handle complicated constraints such as contingencies. However, the most attractive issue is the very high speed of the calculation. In many cases, especially in emergency situations, there is no need to converge very accurately to obtain a meaningful or optimal result. This offers greater flexibility for trade-offs between computing speed and convergence accuracy than is possible with most NLP approaches.

Another attraction of LP approach is its capability to consider integer variables using mixed integer linear programming (MILP) technique. The MILP approach is mainly used for the unit commitment problem [38]-[40]. However, it eventually becomes a powerful technique for corrective switching and transmission planning [37],[41]-[42], since many power system control actions involve discrete variables, such as transmission line switching, shunt element switching, and transformer tap changing.

1.3.4 Interior Point (IP) Method

For conventional LP approach, the optimal solution is solved by following a series of points on the "constraints boundary". However, a new solution algorithm was proposed in the 1980s' for linear programming problems that found the optimal solution by following a path through the interior of the constraints directly toward the optimal solution on the constraints boundary [43]-[44]. This method, which thereby was called interior point method, featured the choice of a good starting point and fast convergence compared with the conventional LP algorithms and has become the basis for many OPF solutions [45]-[46]. The extension of IP method to NLP and QP problems has shown superior convergence qualities and promising results.
1.4 Problem Statement

This work is aimed at developing fast TSR algorithms for line and bus-bar switching, shunt element switching and corrective FACTS control, with enough accuracy to relieve overloads and voltage violations caused by system contingencies and prevent the occurrence of cascading failures.

Most of the past studies for line and bus-bar switching either only considered line switching [3]-[6],[14]-[16],[41] or only dealt with very simple bus-bar switching [7]-[13]. However, in practice, the bus-bar switching in substations is more complicated as it involves several breaker switching actions simultaneously and is preferred to line switching because it will cause smaller disturbances in power systems. Therefore, it is necessary and important to establish a general bus-bar switching model that can simulate any kind of bus-bar switching scenario.

Furthermore, most of past studies on corrective switching either only took into account the MW overload problem and ignored the voltage violation problem [3]-[13], or only considered the voltage control problem [18],[47]-[52]. However, for power system operation and control, the overload problem and the voltage violation problem are often involved together, and an integrated consideration of both overload problem and voltage violation problem will significantly improve system security.

It is well known that the power flow calculation is the bottleneck for on-line corrective voltage control. Some attempts have been made with voltage distribution factors to avoid power flow calculation in the last twenty years. A reactive power distribution factor formulation was developed in [53]-[54], based on the S-E (complex power - complex voltage) model of the power network and linearization of the Q-V relationship. Reference [55] presented a method to calculate a set of distribution factors for the reactive power flow based on decoupled power flow and network sensitivities. Furthermore, a new approach for calculating voltage and reactive power distribution factors using the sensitivity property of
the Newton-Raphson power flow Jacobian at a base operating point was proposed in [56]. However, their accuracy is not satisfactory.

Unlike corrective switching, FACTS control is a continuous variable problem. Therefore, the OPF becomes the first choice for FACTS control. Over the past 20 years, many techniques, such as genetic algorithm [57]-[60], Newton's method [61]-[64], augmented Lagrange multiplier [65], decomposed OPF algorithm [66], sequential quadratic programming [67]-[68], and Han-Powell algorithm [69], have been employed to solve OPF with FACTS devices. However, the requirement of high computational speed for on-line corrective control points to the need for further research efforts directed towards LP-based OPF algorithms for FACTS control due to their inherent robustness and high computational speed [20],[33].

A very important issue for OPF with FACTS devices is consideration of the operational constraints of FACTS devices during optimization. Otherwise, a practically unreachable solution could be obtained. This aspect is easily handled in NLP-based OPF. However, it is quite difficult to incorporate it in an LP-based OPF. Reference [70] did not consider the operational constraints for FACTS devices and [71] only took into account the thermal limits for FACTS devices.

Based on the above problems that need to be overcome for on-line application of TSR algorithms, this research will focus on the following aspects:

1. Development of a general model for complicated bus-bar switching actions that could simulate any kind of bus-bar switching scenario.
2. Development of a new line and bus-bar switching algorithm that would be able to solve the overload problem as well as the voltage violation problem. The algorithm would be fast enough for on-line corrective control with acceptable accuracy.
3. Development of a new set of voltage distribution factors (VDFs) for shunt element switching with better accuracy than conventional VDFs.
4. Development of a novel algorithm for corrective voltage control by shunt element switching based on the newly derived VDFs in order to improve computational speed for on-line voltage control by avoiding repetitive power flow calculations.

5. Development of an LP-based OPF algorithm for corrective FACTS control. This algorithm would take into account the operational constraints of FACTS devices during optimization.

6. Development of a power injection model for line and bus-bar switching based on the network sensitivities, and a binary integer programming based OPF algorithm to find the best line and bus-bar switching action for relieving overloads and voltage violations.

Automation is our goal for on-line corrective TSR control. The TSR algorithms should be powerful enough to give the operator a reasonable solution without much human interaction. However, it should also be able to acquire and utilize information from human evaluation and prediction to improve the performance.

1.5 Dissertation Organization

This dissertation consists of 8 chapters. **CHAPTER 1** provides the introduction, background, and motivation for this work as well as a general summary of the techniques used. The rest of the dissertation is organized as follows:

**CHAPTER 2** gives a detailed overview of TSR. The first part of the overview deals with corrective switching. In this part, based on the review of the relevant literature, the following issues are discussed: purposes of corrective switching, switching elements and their models, corrective switching algorithms (CSAs), and security assessment of corrective switching. The second part is a literature review of FACTS control. The effort needed to implement TSR is also summarized at the end of this chapter.

**CHAPTER 3** presents a new line and bus-bar switching algorithm for relieving
overloads and voltage violations based on the fast decoupled power flow with limited iteration count and the sparse inverse technique. A general model for bus-bar switching that could simulate any kind of bus-bar switching scenario is also proposed in the chapter.

**CHAPTER 4** derives a new set of voltage distribution factors for shunt element switching with better accuracy than the conventional VDFs and presents a novel shunt switching algorithm for corrective voltage control based on the concept of voltage change matrix.

**CHAPTER 5** integrates the line switching algorithm, bus-bar switching algorithm, and shunt switching algorithm into an integrated corrective switching algorithm.

**CHAPTER 6** proposes an LP-based OPF for corrective FACTS control to relieve overloads and voltage violations with the objective of minimizing average loadability on highly loaded transmission lines. This corrective FACTS control algorithm considers the operational constraints of FACTS devices during optimization based on the newly derived parameter sensitivities for FACTS devices.

**CHAPTER 7** proposes a new power injection model for line switching and bus-bar switching based on the network sensitivities and develops a binary integer programming based OPF algorithm for line and bus-bar switching. The optimization objective is still chosen to minimize the average loadability on highly loaded transmission lines.

**CHAPTER 8** summarizes the specific contribution of the research work and discusses the future work that needs to be done.
CHAPTER 2: AN OVERVIEW ON TRANSMISSION SYSTEM RECONFIGURATION

2.1 Corrective Switching

Transmission line switching, bus-bar switching, shunt element switching, and transformer tap changing, are usually classified as corrective switching actions. Many studies dealing with line and bus-bar switching have been conducted since this idea was first proposed in early 80’s [3]-[17],[41], and shunt element switching for voltage control have also been studied for decades [14]-[15],[18],[49]-[52]. These attempts mainly focused on the development of corrective switching algorithms (CSAs). However, only few implementations of CSAs on practical on-line energy management systems (EMS) were reported [13],[18]. CSAs should be extremely fast since an on-line decision must be made following a severe contingency. Corrective switching is a multi-variable discrete programming problem, which is very hard to solve. Many different and powerful approaches have been employed, such as the linear programming (LP) based network topology optimization [7],[9]-[12],[49], the MW distribution factor [8], the Z-matrix method [6], the “D” vector approach [18],[50]-[51], the Benders decomposition algorithm [16], the local power flow method [52], and the mixed-integer programming approach [41], etc. These CSAs go along two different directions in dealing with the simplification of the corrective switching problem, one approach is to simplify the mathematical model, and the other approach is to reduce the search space since not all transmission lines or shunt elements can be considered as switchable. These algorithms will be discussed in detail in the following sections.
2.1.1 Purposes of Corrective Switching

The purposes of corrective switching can be summarized as follows:

- Relieving transmission line overload [3]-[4],[6]-[10],[13]-[16]
- Alleviating voltage violation [9],[14]-[16],[18],[49]-[52]
- Control of short circuit current [7]
- Security enhancement [10]-[12]
- Improving transient stability [5]

Most of the references shown in this dissertation only considered either relieving transmission line overload or alleviating voltage violation as their research goal. Only [14] and [15], took into account an integrated solution.

2.1.2 Switching Elements and Their Models

The switching elements used in the reviewed papers can be listed as follows:

- Transmission lines [3]-[16]
- Bus-bars [4],[7]-[9],[13]
- Shunt elements (capacitors and reactors) [14]-[15],[18],[49]-[52]
- Transformer taps [9]

For bus-bar switching, which is usually implemented at substations, several breakers may need to be switched simultaneously to achieve the desired control function.

2.1.2.1 Line Switching Model

There are basically two kinds of line switching models used in the reviewed references.

a) Computational Index Model [6],[8]: Line switching candidates were selected
without using the network topological parameters but by using indices, such as the MW distribution factor [8], where the line impedances and the bus impedance matrix (Z-Matrix) were the only needed data [6]. This kind of model was fast and allowed for simplified calculation. However, the AC power flow was still needed to check the effects of switching actions and to see if the switching actions would result in new overloads or voltage violations.

b) Current Compensation Model [7],[9]-[10],[15],[41]: In this model two current sources are added to the two terminal nodes of the switched line so that the current on the switched line was compensated to zero. Thus, the distribution of power flow was still the same after switching. With this model, the system would be considered to behave in a linear manner such that a linear programming approach could be applied to solve the power flow problem. One of the advantages of this model was that it allowed the formulation of multiple switching operations.

2.1.2.2 Bus-bar Switching Model

The simplest bus-bar composes of two buses and a breaker connecting them. The network topology will be changed when the breaker is opened or closed as shown in Figure 2-1.

![Figure 2-1: The Simplest Bus-bar Diagram](image)

A bus-adding model was described in [8]. The basic idea was to represent each breaker involved in the bus-bar switching as a zero impedance circuit made up of two circuits connected to a newly added intermediate bus in series with equal but opposite reactance. This is shown schematically in Figure 2-2. Thus, switching either circuit will result in the breaker itself being switched.
2.1.2.3 Shunt Switching Model

The difficulty of modeling shunt elements (capacitors or reactors) lies in their discrete nature. A continuous model for shunt elements was proposed in [14]. In this model, the shunt elements were initially considered as continuous control variables, and then the optimization problem was solved to obtain the values of continuous variables. Subsequently, a penalty factor algorithm was introduced to determine if the shunt elements should be switched in or out. Another model was presented in [15], where the switching of shunt elements was determined by the injected reactive power mismatch vectors.

2.1.3 Corrective Switching Algorithms (CSAs)

2.1.3.1 Problem Reduction

During the last 20 years, many techniques and algorithms have been developed for corrective switching. There are basically two different approaches to problem simplification: one is model reduction – simplifying the models of switching actions such that some methods other than power flow calculation can be used, and the other one is search space reduction – reducing and sorting the switchable elements by some heuristic techniques.

Reference [3] only considered the branches electrically close to the overload. References [7],[9]-[10] imbedded the switching actions into a linear programming algorithm, and reduced the possible switching cases by constraints, such as bus voltages and short circuit current, etc. However, no detailed constraints were presented in [7],[9]-[10]. References [6]
and [8] did not use heuristic techniques to eliminate possible switching actions, but introduced the Z-matrix [6] or the MW distribution factor [8] to select the switching candidates without using power flow calculation. Reference [14] used a performance index to rank the line switching operations. Reference [15] applied the active and reactive power mismatch vectors to sort the switching candidates, and then tested each candidate in a power flow calculation until a desired solution was obtained. Reference [16] adopted Benders decomposition to divide the optimal transmission system reconfiguration problem into an OPF subproblem with only continuous variables subject to the stability constraints and a coordinate master problem with discrete variables. A “D” vector was defined to indicate the problematic buses (with non-zero D elements) and an echelon-based algorithm was developed to find corrective shunt switching actions in [18],[50]-[51].

2.1.3.2 Search Techniques

Different search techniques have been employed to find switching solutions. These techniques can be divided into two categories:

- Linear programming [7],[9]-[12]
- Brute force search after search space reduction [3]-[4],[6],[8],[13]-[15]

With the linearized current injection model, reference [7] presented a linear programming method to find the optimal solution for switching actions. The size of the system analyzed would not be a limitation for this method since sparse techniques were available. References [9] and [10] also employed linear programming to find the “optimal” network which met all constraints and differed from the original network by one elementary switching operation only. In [16], for the OPF subproblem, starting from the initial solution, if an infeasible solution was found, then the primal and dual solutions were transferred to the master problem to make a new Benders cut. If a feasible solution was found, the primal and dual solutions were transferred to the master problem to make
another new Benders cut. For the master problem, an augmenting linear programming with a simple rounding-up logic was employed.

Reference [8] selected circuits with negative distribution factors in the row as switching candidates, which corresponded to the worst overloaded line in the distribution matrix, and ordered them by the absolute values of distribution factors, then tested them with power flow calculation to see if other overloads or violations would be caused. Although this method was fast, it could only deal with one overloaded line in one distribution factor calculation. Reference [14] used different search techniques for different switching elements. For continuous variables and shunt elements (modeled as continuous variables), linear programming was adopted. For line switching, the switching candidates were ranked first by performance index, and then checked sequentially until the optimal objective was found. Reference [6] modified the Z-matrix for each switching action, and compared the elements of the modified Z-matrix with the original Z-matrix. The switching candidates were selected by ranking the lines with negative impedance difference and checked by power flow calculation. Reference [15] dealt with voltage violation and overloads in two steps. First the switching candidates (shunt elements and branches) were ranked by reactive mismatch vectors and checked by power flow calculation for alleviating voltage violations. Second, the switching candidates were sorted by reactive and active mismatch vectors and checked by power flow calculation for relieving overloads.

2.1.3.3 Feasible and Optimal Solution

The feasible solution is a solution that does not violate constraints. The optimal solution is a solution where the objective can reach its optimal value under the constraints. Corrective switching algorithms must be fast since an on-line decision needs to be made. Therefore, there is a dilemma between the optimal solution and time constraint. In some earlier work, the CSAs only aimed at finding a feasible solution as time constraint was the dominant issue due to the limitations on computer speed. Thus, any solution that could
relieve the system was adequate.

2.1.3.4 Power Flow Calculation

Although many studies have been done on the problem reduction and search techniques and some good results could be obtained by these methods, it must be realized that the results from reduced methods have to be checked by AC power flows in order to ensure that the effects of the selected switching actions are valid and no other overloads or variable violations will be caused.

2.1.4 Security Assessment of Corrective Switching

Corrective switching may affect the system security - static and transient stability. Intuitively, switching out a transmission line will decrease the security of the power system, especially when the system is heavily loaded. Therefore, a security assessment needs to be done before a corrective switching action can be carried out. Furthermore, whenever necessary, the transmission line that is switched out should be returned to operation as soon as possible after the fault is cleared. A switching action that may reduce the security of the system under the security limit will not be accepted as a feasible solution.

In most references reviewed, the security problem was not considered [3],[6]-[8],[15]. The only constraints were that no new overloads and voltage violations occurred. Reference [14] and [16] embedded the corrective switching into the optimal transmission system reconfiguration problem, where the system security was regarded as a constraint on the optimization problem. In reference [3], only the branch whose terminal nodes were connected to the rest of the network with at least two other links could be switched out.

However, corrective switching can also contribute to security enhancement. Reference [11] and [12] systematically proposed the idea of security enhancement by corrective switching. A strong opinion was presented in [12] that feasibility is more important than economy of the solution for corrective switching. A method of security enhancement was
presented based on the current compensation model in [10], where the control variables in system equations were replaced by injected currents of those elements to be switched. The graphical representation of security enhancement is shown in Figure 2-3.

![Diagram showing security enhancement before and after corrective switching](image)

**Figure 2-3: Security Enhancement by Corrective Switching**

### 2.2 Corrective FACTS Control

It is well known that flexible AC transmission systems (FACTS) technology can significantly improve the steady-state as well as the transient performance of power systems, including power flow and voltage control, available transfer capability (ATC) enhancement, oscillation damping, and transient stability improvement [72]-[76].

Generally, FACTS operation can be divided into two steps: the first step is to determine the operational goals of FACTS control, and the second step is to implement the operational goals using certain control strategy, i.e. controller design. Corrective FACTS control only focuses on the first step – determining the operational goals.

Unlike corrective switching, FACTS control is a continuous variable problem. Therefore, the OPF becomes the first choice for FACTS control [77], although other approaches, such as sensitivity method [80]-[85], genetic-based algorithm [57], and maximum flow algorithm [78]-[79], were attempted. Over the past 20 years, many techniques, such as genetic algorithm [57]-[60], Newton's method [61]-[64], augmented Lagrange multiplier [65], decomposed OPF algorithm [66], sequential quadratic programming [67]-[68], and
Han-Powell algorithm [69], have been employed to solve OPF with FACTS devices. However, the requirement of high computational speed of on-line corrective control points to the need for further efforts on LP-based OPF algorithms for FACTS control due to the robustness and high computational speed of the LP algorithm [20],[33],[70]-[71].

A very important issue for OPF with FACTS devices is consideration of the operational constraints of FACTS devices during optimization. Otherwise, a practically unreachable solution could be obtained. This aspect is easily handled in NLP-based OPF. However, it is quite difficult to incorporate it in an LP-based OPF. Reference [70] did not consider the operational constraints for FACTS devices and [71] only took into account the thermal limits for FACTS devices.

Maximum flow algorithm was employed to solve the power flow reconfiguration problem in [78]. The idea of decentralized (distributed) reconfiguration control, which implemented parallel algorithms by assuming that processors existed at the FACTS devices and at the power generation sites, was also proposed to reduce computational cost and to avoid the possible hardware failures of communication network in centralized control. Then a framework for developing fault tolerance approaches for transmission system reconfiguration with FACTS devices was presented. Furthermore, this idea was extended for locating UPFCs in [79].

Reference [66] decomposed the OPF problem into an active power OPF (APOPF) subproblem and a reactive power OPF (RPOPF) subproblem, and then introduced the active power control variables and their equations, and reactive power control variables and their equations into the APOPF and RPOPF subproblems respectively. Finally, the LP-based algorithm and the quadratic programming algorithm were employed to solve the APOPF and RPOPF subproblems respectively.

A new genetic algorithm method was presented to solve the OPF problem with FACTS devices in [59]. The case studies showed that the operational cost of OPF with FACTS devices might be even higher than that of the conventional OPF without FACTS devices.
since FACTS devices needed more constraints. However, this approach could increase the controllability of the system and provide wider operating margin and higher voltage stability limits with higher reserve capacity.

Based on the real power flow performance index sensitivity factors and power injection model of UPFC, an optimal power flow control approach was proposed in [67] to find the minimum cost in an open power market using a sequential quadratic programming (SQP) algorithm. This method was suitable for suggesting the candidate lines and installation locations for UPFCs, especially in a congested system.

Reference [68] used the power injection model and generation shift distribution factors to represent security constraints of transmission device outage (contingency analysis). Then the SQP algorithm was employed to solve the optimization problem. Furthermore, the economic efficiency of FACTS devices in loss reduction and system loadability enhancement was shown by case studies.

All of these studies revealed the high potential of FACTS devices in corrective control. However, in practical applications, the problems of identifying the sizing and placement of FACTS devices and how to coordinate their actions still need more research.

2.3 Summary

Corrective switching and FACTS devices have been studied as control options for many years. Although transformer tap changing, shunt elements switching, and some FACTS devices, such as SVC, TCSC, and STATCOM, have been used widely in power systems, line and bus-bar switching are still not commonly accepted and employed in practical applications. The reasons lie not only in the difficulties in modeling and algorithm development for discrete control variables, but also in the possible side effects of switching actions, such as transient responses which may cause damages to electrical equipments. These issues need more detailed research, especially when multi-switching actions are allowed.
Many different algorithms and approaches have been proposed to find the feasible or optimal solutions for corrective switching and corrective FACTS control. Although these methods differed in their objectives, models, and search processes, the final objectives were to reduce the problem and find a solution with acceptable computational time and accuracy. However, most current studies only focused on the steady-state analysis of TSR and in the future transient stability constraints also need to be included.

Corrective switching and corrective FACTS control both have their own advantages and disadvantages. Line and bus-bar switching can implement fast control, but may produce some side effects. Corrective FACTS control does not have to change the network topology, but the sizing, placement and coordination of FACTS devices are still challenging issues. Therefore, any approach that will combine corrective switching and corrective FACTS control, and even the conventional OPF, could be very valuable. It can not only enlarge the control range of TSR but also overcome these shortcomings. TSR is a very valuable control maneuver for power systems, further studies, however, are still needed.
CHAPTER 3: LINE AND BUS-BAR SWITCHING ALGORITHM FOR RELIEVING OVERLOADS AND VOLTAGE VIOLATIONS

3.1 Introduction

Although many studies have been conducted dealing with line and bus-bar switching since this idea was first proposed in early 1980’s [3]-[17],[41], line and bus-bar switching are still not widely employed as an affective means of control. The main reasons for this are the possible reduction of system security due to switching actions and the discrete performance of switching actions that makes it very difficult to model and design a systematic search method.

Most of past studies on line and bus-bar switching only considered the MW overload problem and ignored the voltage violation problem [3]-[13], which sometimes is more severe and needs more attention. Although the algorithm developed in [16] could solve both overload and voltage violation problems, it was so time-consuming that it was very difficult to realize for practical power systems. In addition, these studies either only took into account the line switching [3]-[6],[14]-[16],[41] or only dealt with very simple bus-bar switching [7]-[13]. However, in practice, the bus-bar switching in substations is more complicated as it involves several breaker switching actions simultaneously and is preferred to line switching because it will cause smaller disturbances in the power systems.

In this chapter, a new algorithm is developed to find the best line and bus-bar switching action for relieving both overloads and voltage violations. In the new algorithm, the fast decoupled power flow is employed so that reactive power and voltage can also be considered but the convergence tolerance is enlarged and iteration count is limited to obtain a tradeoff between accuracy and computing time. A general model of bus-bar switching action is also proposed such that any kind of complicated bus-bar switching action can be simulated. The algorithm is implemented with MATLAB and tested on the New England
39-bus system and the WECC 179-bus system.

3.2 Line Switching Model

3.2.1 Network Matrix Modification

The system model with network modification can be described as

$$(Y + \Delta Y) \cdot V = I$$

(3-1)

Where, $Y$ is a sparse network admittance matrix.

$\Delta Y$ is the modification matrix.

$V$ and $I$ are the network voltage and current matrices.

The methods discussed in [80] are adopted to find the solution after network modification. For full AC power flow, the node-oriented modification is employed: switching on or switching out a branch ($\pi$-equivalent model) between nodes $f$ and $t$ means an admittance change $\Delta y_{\text{series}} + \Delta y_{\text{shunt}}/2$ between nodes $f$ and $t$ is added to self-admittance elements $Y_{ff}$ and $Y_{tt}$, and an admittance change $\Delta y_{\text{series}}$ is added to mutual-admittance elements $Y_{ft}$ and $Y_{tf}$, as shown in (3-2).

$$\Delta Y = M \cdot \delta y \cdot M^T$$

$$= f \begin{bmatrix} +1 & 1 \\ t +1 & 1 \end{bmatrix} \begin{bmatrix} \pm \left( \Delta y_{\text{series}} + \Delta y_{\text{shunt}} \right)/2 & \mp \Delta y_{\text{series}} \\ \mp \Delta y_{\text{series}} & \pm \left( \Delta y_{\text{series}} + \Delta y_{\text{shunt}} \right)/2 \end{bmatrix} \begin{bmatrix} +1 & 1 \\ f & t \end{bmatrix}$$

(3-2)

When $m$ nodes are involved in the modification simultaneously, the matrix $\delta y$ is of size $(m\times m)$, and the matrix $M$ has $m$ columns.

For the fast decoupled power flow, the branch-oriented modification is employed.
\[ \Delta Y = M \cdot \Delta y \cdot M^T = \begin{bmatrix} +1 \\ t \end{bmatrix} \left[ \pm \Delta y_{\text{series}} \right] \begin{bmatrix} +1 & -1 \\ f & t \end{bmatrix} \] \quad (3-3) \]

When \( m \) branches are modified simultaneously, the diagonal matrix \( \Delta y \) is of size \((m \times m)\), and the matrix \( M \) has \(2m\) elements with \(+1\) and \(-1\) in corresponding rows.

### 3.2.2 Post Compensation Method

Applying the inverse matrix modification lemma (IMML),

Where \( C = (\Delta y^{-1} + Z)^{-1} \) and \( Z = M^T \cdot Y^{-1} \cdot M \).

Since the system solution is obtained from a contingency analysis, the post-compensation method should be employed to find the solution after the network modification, which is shown below:

a) Obtain solution: \( \hat{V} = Y^{-1} \cdot I \)

b) Calculate compensating vector: \( \Delta V = -Y^{-1} \cdot M \cdot C \cdot M^T \cdot \hat{V} \)

c) Perform compensation: \( V = \hat{V} + \Delta V \)

### 3.3 General Bus-bar Switching Model

#### 3.3.1 Bus-bar Layouts

There are six types of substation bus-bar layouts commonly used in substations [81]-[82]:

- single bus
- double-bus-double breaker
- main-and-transfer-bus
- double-bus-single-breaker
- ring bus
- breaker-and-a-half

A good model for simple bus-bar switching was proposed in [8], as shown in Figure 2-2 (See Section 2.1.2.2). Modeling the layout of a ring bus has been discussed in [13].
However, these models cannot simulate all kinds of possible switching scenarios of bus-bar switching.

The double-bus-double-breaker, main-and-transfer-bus, and double-bus-single-breaker layouts all have similar configuration and can be represented as shown in Figure 3-1. The differences among them are only the location and number of breakers. For these three bus-bar layouts, every line can be switched onto either bus of the bus-bar, where loads and shunt elements at the bus-bar are also considered as lines. Thus, there are many kinds of switching scenarios when the bus-bar is split.

![Figure 3-1: The Structure of a Bus-bar with Four Lines](image)

The layout of a breaker-and-a-half scheme, as shown in Figure 3-2, can also be represented as shown in Figure 3-1. However, some additional switching constraints must be imposed.

In Figure 3-2, the additional bus-bar switching constraints are that lines L1 and L4 cannot be in the same switching group, lines L1 and L6 cannot be in the same switching group, lines L1, L4 and L6 cannot be in the same switching group, lines L2 and L3 cannot be in the same switching group, lines L3 and L6 cannot be in the same switching group, lines L2, L3 and L6 cannot be in the same switching group, lines L2 and L5 cannot be in the same switching group, lines L4 and L5 cannot be in the same switching group, and line L2, L4, and L5 cannot be in the same switching group.
3.3.2 Bus-bar Switching Constraints

There are several constraints for bus-bar switching with regard to the function and purpose of bus-bar switching.

a) There should be at least four lines (including load and shunt elements) connected to a bus-bar. If the number of lines connected to the bus-bar is less than four, the switching action of bus-bar splitting will provide the same result as line switching.

b) When the bus-bar is split, it is required that there should be at least two lines (including load and shunt elements) connected to each of the split buses.

c) When the bus-bar is split, the lines connected to each of the split buses cannot all be loads and shunt elements since this situation would correspond to load-shedding.

d) Bus-bar switching cannot result in islands in the system.

3.3.3 Bus-bar Switching Modeling Process

The process of modeling bus-bar switching is as follows:
a) Find all lines connected to the bus-bar, including load and shunt elements which are also considered as lines.

b) Generate a new node for each line connected to the bus-bar, and the lines are connected to their corresponding nodes. This step will add \( n \) new nodes into the system, where \( n \) is the number of lines connected to the bus-bar.

c) Connect every two generated new nodes with a breaker which is modeled as a line with very small impedance such as 1.0e-6. Simulation results show that these small impedance lines will not affect the power flow of the system. This step will add \( \binom{n^2}{2} - n \cdot (n - 1)/2 \) new branches into the system.

d) Find all possible results to divide the new nodes into two groups under the constraints of bus-bar switching. Thus each grouping result represents one possible bus-bar switching scenario. The most number of possible switching scenarios is 
\[ C_n^2 + C_n^3 + \cdots + C_n^{n-1} \] for odd \( n \) or 
\[ C_n^2 + C_n^3 + \cdots + \frac{C_n^n}{2} \] for even \( n \). This step can be done off-line and the results can be stored in the system database.

e) For each grouping result, disconnect all breaker lines connected to the nodes in the first group except the breaker lines connecting them to each other.

f) The breaker line switching can be modeled as line switching.

For a typical bus-bar with 6 lines (including load and shunt elements) connected to it, the number of new added nodes is 6, the number of new added breaker lines is 15 and the number of possible switching scenarios is at most 25. Hence, it is not a big computational burden.

The model diagrams of a bus-bar with four lines connected to it are shown in Figure 3-3.
3.4 Proposed Line and Bus-bar Switching Algorithm

3.4.1 Fast Decoupled Power Flow with Limited Iteration Count

Fast Decoupled Power Flow (FDPF) is employed to obtain voltage and reactive power information. In order to obtain a trade off between the convergence accuracy and the computational time, the convergence criteria for FDPF are set as the iteration errors being less than 10 MW for real power and 10 MVar for reactive power and the iteration count being not more than 3. Furthermore, the post-contingency power flow is set as the initial power flow for switching action selection so as to increase the probability of convergence of FDPF. Simulation results show that all the FDPF calculations would be convergent after 2 iterations.

3.4.2 Performance Index of Security Margin

For a branch between bus $i$ and bus $j$, it is known that (all the following equations are in p.u.)
Hence,

\[
\tilde{S}_y = P_y + jQ_y = V_i^* I_y^* = \frac{V_i^* - V_j^*}{R_y - jX_y} \approx \frac{|V_i| \cdot |V_j| \cdot \sin(\theta_y)}{X_y} + j\frac{|V_i|^2 - |V_i| \cdot |V_j| \cdot \cos(\theta_y)}{X_y}
\]

(3-5)

Thus,

\[
|S_y| = \frac{1}{X_y} \sqrt{|V_i|^2 \cdot |V_j|^2 \cdot \sin^2(\theta_y) + (|V_i|^2 - |V_i| \cdot |V_j| \cdot \cos(\theta_y))^2}
\]

(3-6)

\[
d|S_y| \left| \frac{d}{d|V_i|} \right| = \frac{1}{X_y} \cdot \frac{2 |V_i| \cdot |V_j|^2 + 4 |V_i|^3 - 6 |V_i|^2 \cdot |V_j| \cdot \cos(\theta_y)}{2|V_i|^2 \cdot |V_j|^2 + 4 |V_i|^2 - 2 |V_i| \cdot |V_j| \cdot \cos(\theta_y)}
\]

(3-7)

Usually, in a transmission system, the voltage magnitude difference between two adjunct buses is about 0.03–0.05 p.u., and the reactance of the transmission lines are 0.01–0.05 p.u.. Therefore,

\[
|\Delta S_y| = 10 - 50 \cdot |\Delta V_i|
\]

(3-8)

In security analysis, it is presumed that voltage related problems are of greater concern than overload ones. Therefore, \(|\Delta S_y| = 50 \cdot |\Delta V_i|\) is used, which means that the security
margin associated with the voltage is equivalent to only two percent security margin in line apparent power.

Thus, we define the Performance Index of Security Margin (PISM) for line and bus-bar switching actions as follows:

\[ PISM = \min_i \left( \min_j \frac{|S_{\text{max}}| - |S_i|}{S_{\text{BASE}}} \right) \left( 50 \times \min_j \left( V_j \left| V_j - V_{j\text{min}} \right| \right) \right) \tag{3-9} \]

Where, \( |S_{\text{max}}| \) and \( |S_i| \) are the rated maximal and actual apparent power in MVA on line \( i \).

\( S_{\text{BASE}} \) is the system MVA base.

\( V_{j\text{max}}, V_{j\text{min}} \) and \( |V_j| \) are the rated maximal, minimal and actual voltage magnitude at bus \( j \), respectively.

\( i=1, \ldots, n, \ j=1, \ldots, m \). \( n \) and \( m \) are the line number and bus number of the system.

The line and bus-bar switching actions will be ranked by PISM, and the switching action with maximum PISM is considered as the "best" switching action. In addition, bus-bar switching action is always preferred to line switching action since it would cause smaller disturbances in the system.

3.4.3 Proposed Line and Bus-bar Switching Algorithm

In the algorithm developed, it has been presumed that only one transmission line or one bus-bar can be switched at one time because too many switching actions could reduce the security of the system to an unacceptable level.

There are also some restrictions for line switching candidates, i.e., line switching cannot cause isolated buses or islands.

Another important issue regarding line and bus-bar switching is that in an emergency situation, finding a feasible solution is more important than finding the optimal solution when an on-line decision is needed. Therefore, the line and bus-bar switching algorithm does not necessarily guarantee the optimal solution and a feasible and approximate optimal solution is sufficient.
The flowchart of the line and bus-bar switching algorithm is shown as in Figure 3-4.

**Figure 3-4: Flowchart of the Proposed Line and Bus-bar Switching Algorithm**
3.5 Case Studies

The algorithm is implemented with MATLAB and is tested on the New England 19-bus system and the WECC 179-bus system on a DELL PC (2.79 GHz CPU). Since the contingency selection algorithm is not the main thrust of this research, the full AC power flow is used for contingency analysis.

3.5.1 The New England 39-bus System

3.5.1.1 Line Switching Solution

The outage of line 7 (from bus 4 to bus 5) is selected to test the proposed line and bus-bar switching algorithm, and the contingency analysis results are shown in TABLE 3-1.

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 17</td>
<td>10</td>
<td>13</td>
<td>569.26 MVA</td>
<td>550.0 MVA</td>
<td>19.26 MVA</td>
</tr>
<tr>
<td>LINE 18</td>
<td>13</td>
<td>14</td>
<td>575.43 MVA</td>
<td>550.0 MVA</td>
<td>25.43 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.94977 pu</td>
<td>( V_{\text{min}} = 0.95 ) pu</td>
<td>- 0.00023 pu</td>
</tr>
</tbody>
</table>

The output results of the line and bus-bar switching program are as follows:

- Bus-bar switching cannot relieve all the overloads and voltage violations.
- Overloads and voltage violations have been relieved by line switching action.
- The best switching action is to switch out line 1 (from bus 1 to bus 2).
- The minimal PISM is 0.166.
- The CPU time is 0.29 seconds.

The power flow results after switching out line 1 are shown in TABLE 3-2, and the system diagram for the switching action is shown in Figure 3-5.
From TABLE 3-2, it can be seen that the voltage at bus 4 is still the bottleneck with regard to system security. In this case, if the voltage violation problem is not considered,
the results of the line and bus-bar switching program show that there is also one bus-bar switching action which can relieve all the overloads. Thus, this bus-bar switching action will be selected as the best switching action since bus-bar switching actions are always preferred to line switching actions. However, this is a mis-operation due to voltage violation. It is shown that it is very important to consider both overload problem and voltage violation problem in line and bus-bar switching. Otherwise some mis-operations may occur.

3.5.1.2 Bus-bar Switching Solution

The system operation conditions are modified in order to test the bus-bar switching algorithm. The outage of line 7 (from bus 4 to bus 5) is still selected for analysis. The contingency analysis results are shown in TABLE 3-3.

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 17</td>
<td>10</td>
<td>13</td>
<td>561.61 MVA</td>
<td>550.0 MVA</td>
<td>11.61 MVA</td>
</tr>
<tr>
<td>Line 18</td>
<td>13</td>
<td>14</td>
<td>569.86 MVA</td>
<td>550.0 MVA</td>
<td>19.86 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>1.05044 pu</td>
<td>$V_{max} = 1.05$ pu</td>
<td>+0.00044 pu</td>
</tr>
</tbody>
</table>

The buses 2, 8, 16, and 26 are selected as bus-bar switching candidates. The output results of the line and bus-bar switching program are as follows:

- Overloads and voltage violation have been relieved by bus-bar switching.
- The best switching action is to split off bus-bar 2 with line 1-2 and line 2-3 being switched on one split bus-bar (bus $2'$), and line 2-25 and line 2-30 being switched on the other split bus-bar (bus $2''$).
- The minimal PISM is 0.114.
- The CPU time is 0.13 seconds.
The power flow results after splitting bus-bar 2 are shown in TABLE 3-4 and the system diagram for splitting bus-bar 2 is shown in Figure 3-6.

**TABLE 3-4: POWER FLOW RESULTS AFTER SPLITTING OFF BUS-BAR 2**

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 17</td>
<td>10</td>
<td>13</td>
<td>537.50 MVA</td>
<td>550.0 MVA</td>
<td>12.50 MVA</td>
</tr>
<tr>
<td>Line 18</td>
<td>13</td>
<td>14</td>
<td>538.59 MVA</td>
<td>550.0 MVA</td>
<td>11.41 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>1.0382 pu</td>
<td>( V_{\text{max}} = 1.05 ) pu</td>
<td>0.0118 pu</td>
</tr>
</tbody>
</table>

**Figure 3-6: BUS-BAR 2 IS RECOMMENDED TO BE SPLIT OFF**
From TABLE 3-4, it can be seen that the apparent power on line 18 (from bus 13 to bus 14) is the bottleneck with regard to system security.

3.5.2 The WECC 179-bus System

The one-line diagram of the WECC 179-bus system is shown in Figure 3-7.

![One-line diagram of the WECC 179-bus system](image-url)
### 3.5.2.1 Bus-bar Switching Solution

The outage of line 170-171 is selected to test the proposed line and bus-bar switching algorithm, and the contingency analysis results are shown in TABLE 3-5.

#### TABLE 3-5: Contingency Analysis Results for Outage of Line 170-171

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 168-169</td>
<td>1818.60 MVA</td>
<td>1700 MVA</td>
<td>118.60 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 84</td>
<td>1.06121 pu</td>
<td>$V_{max} = 1.06$ pu</td>
<td>+0.00121 pu</td>
</tr>
</tbody>
</table>

The output results of the line and bus-bar switching program are as follows:

- Overloads and voltage violations have been relieved by bus-bar switching.
- The best switching action is to split off bus-bar 83 with lines 83-94, 83-98, 83-172, and load at bus 83 being switched on one split bus (bus 831) and lines 83-89 and 83-168 being switched on the other split bus (bus 832).
- The minimal PISM is 0.0636.
- The CPU time is 5.09 seconds.

The power flow results after splitting bus-bar 83 are shown in TABLE 3-6 and the system diagram for the switching action is shown in Figure 3-8 (The arrows represent the directions of power flow.).

#### TABLE 3-6: Power Flow Results after Splitting Off Bus-bar 83

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 168-169</td>
<td>1574.34 MVA</td>
<td>1700 MVA</td>
<td>125.66 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 84</td>
<td>1.05863 pu</td>
<td>$V_{max} = 1.06$ pu</td>
<td>0.00147 pu</td>
</tr>
</tbody>
</table>
3.6 Summary

Under the environment of restructuring in the power industry, line and bus-bar switching has a great advantage of economy compared with other corrective control methods, such as generation re-scheduling, load shedding, and system islanding. The following work has been done in this chapter regarding line and bus-bar switching:

- A general model for bus-bar switching is proposed. It can deal with any kind of bus-bar switching scenarios.
- The idea of evaluating switching actions by maximizing the minimal system security margin is proposed.
- A new algorithm for relieving overloads and voltage violations by line and bus-bar switching is developed. The FDPF with limited iteration count in order to get a tradeoff between accuracy and calculation speed.

Simulation studies on the 39-bus New England system and the WECC 179-bus system indicate that the proposed algorithm is able to effectively solve the problems of overloads
and voltage violations and the computing time is also satisfactory.

However, in the simulation studies, it is also found that line and bus-bar can only work for a portion of severe contingencies. When the system is heavily loaded, the effect of line and bus-bar switching is very limited. Therefore, further studies on combining line and bus-bar switching with other corrective controls, such as shunt element switching and optimal power flow should be considered.
CHAPTER 4 : SHUNT ELEMENT SWITCHING ALGORITHM FOR CORRECTIVE VOLTAGE CONTROL

4.1 Introduction

Voltage stability is one of the requirements of power system security. In some European countries, voltage control is organized in three levels (primary, secondary and tertiary) [47]-[48]. At the secondary level, adjusting reactive generation is employed as the main corrective voltage control means based on the concepts of “pilot” node and voltage control zone. However, due to inability to transmit reactive power and the flexibility and economy provided by shunt elements (including capacitors and reactors), shunt element switching is still one of the most widely used voltage control methods.

Shunt element switching for voltage control have been studied for decades. Many techniques have been employed, including linear programming, non-linear programming, and mixed integer programming, etc. Reference [49] incorporated shunt capacitor switching into a two-step optimal power flow (OPF). First, control variables were optimized as if the shunt capacitors were continuous variables, then the discrete elements were reset to their nearest actual settings and the remaining continuous control variables were re-optimized. However, this method was mainly used for shunt capacitor planning and placement and it is not suitable for on-line corrective voltage control since OPF is time-consuming. In [18],[50]-[51], a “D” vector was defined to indicate the problematic buses (with non-zero D elements) and an echelon-based algorithm was developed to find corrective actions. However, this method may cause too many shunt switching actions at different locations (10 different locations in [18]) as a result of which system operators may hesitate to adopt it. A local power flow based voltage control approach was presented in [52]. However, the authors did not discuss how to determine the local areas when more than one bus had a voltage violation problem and did not specify the method for multiple
shunt switching.

On-line corrective voltage control needs both speed and accuracy. However, these constraints result in contrasting control requirements as a result of which precise and rapid control of voltage is not possible [83]. It is well known that the power flow calculation is a bottleneck for on-line corrective voltage control. Some attempts to develop a voltage distribution factor have been made in the last twenty years. A reactive power distribution factor formulation was developed in [53]-[54], based on the S-E (complex power - complex voltage) model of power network and linearization of Q-V relationship. Reference [55] presented a method to calculate a set of distribution factors of reactive power flow based on the decoupled power flow and network sensitivities. Furthermore, a new approach for calculating voltage and reactive power distribution factors using the sensitivity property of Newton-Raphson power flow Jacobian at a base operating point was proposed in [56]. However, the accuracy obtained is not satisfactory.

In this chapter, a new voltage distribution factor for shunt switching is proposed, which considers multiple iterations in the fast decoupled power flow. Furthermore, based on the voltage change matrix, a shunt switching algorithm for corrective voltage control is developed to keep the voltages within security requirements with switching cost minimization and system voltage security margin maximization. The algorithm is implemented with MATLAB and tested on the New England 39-bus system and the WECC 179-bus system.

4.2 Voltage Distribution Factor

In order to reduce the computational burden of the power flow calculation, the voltage distribution factor was suggested to obtain the system voltage profile by shunt switching. In this section, the first iteration based voltage distribution factor is derived. References [53]-[56] however show that this may cause big errors in some cases. Hence, a multiple iteration based voltage distribution factor is presented in detail.
4.2.1 First Iteration Based Voltage Distribution Factor

The reactive power at bus $i$ is given by

$$Q_i - Q_i^0 = V_i \sum_{j=1}^{n} V_j (G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij}) - Q_i^0$$

$$= V_i^2 B_{ii} + V_i \sum_{j=1}^{n} V_j (G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij}) - Q_i^0 = 0 \quad (4-1)$$

Where $Q_i$ — reactive power of bus $i$

$Q_i^0$ — initial injective reactive power of bus $i$

$V_i$ — voltage magnitude of bus $i$

$(G_{ij} - jB_{ij})$ — admittance between bus $i$ and bus $j$ with $G_{ij}, B_{ij} > 0$

$\theta_{ij}$ — difference of voltage angles of bus $i$ and bus $j$

$n$ — the number of system buses

From the post-contingency power flow solution, the initial bus injective reactive power can be obtained as follows

$$Q_i^0 = V_{i0} \sum_{j=1}^{n} V_{j0} (G_{ij} \sin \theta_{ij0} + B_{ij} \cos \theta_{ij0})$$

$$= V_{i0}^2 B_{ii} + V_{i0} \sum_{j=1}^{n} V_{j0} (G_{ij} \sin \theta_{ij0} + B_{ij} \cos \theta_{ij0}) \quad (4-2)$$

Where the subscript "0" represents the post-contingency quantities.

When one shunt element at bus $k$ with equivalent admittance $j b_k$ is switched in (or out), the reactive power mismatch equation is given by

$$\Delta Q_i^{(1)} = Q_i^1 - Q_i^0$$

$$= V_{i0} \sum_{j=1}^{n} V_{j0} (G_{ij} \sin \theta_{ij0} + B_{ij} \cos \theta_{ij0}) - V_{i0} \sum_{j=1}^{n} V_{j0} (G_{ij} \sin \theta_{ij0} + B_{ij} \cos \theta_{ij0}) = 0 \quad (4-3)$$

for $i = 1, \ldots, k-1, k+1, \ldots, n$

and
\[ \Delta Q_k^{(1)} = Q_k^{(1)} - Q_k^0 = V_{ko}^2 (B_{kk} - b_k) + V_{ko} \sum_{j \neq k}^n V_{j0} (G_{kj} \sin \theta_{j0} + B_{kj} \cos \theta_{j0}) \]

\[ = -V_{ko}^2 b_k + V_{ko} \sum_{j \neq k}^n V_{j0} (G_{kj} \sin \theta_{j0} + B_{kj} \cos \theta_{j0}) \]  (4-4)

Hence, the reactive power mismatch vector after the first iteration (The subscript “1” represents the iteration count) is

\[ \Delta Q^{(1)} = [0...V_{ko}^2 b_k...0]^T \quad \text{and} \quad \Delta \tilde{Q}^{(1)} = \Delta Q^{(1)}/V_0 = [0...V_{ko}^2 b_k...0]^T = -b_k D V_0 \]  (4-5)

Where \( V_0 \) — post-contingency bus voltage magnitude vector

\( D \) — an \( n \times n \) sparse matrix with only one element 1 at the \( k^{th} \) row and the \( k^{th} \) column

The symbol “./” represents the element-wise vector divide.

From the fast decoupled power flow,

\[ \Delta V^{(1)} = -[B^*]^{-1} \Delta \tilde{Q}^{(1)} = b_k [B^*]^{-1} D V_0 \]  (4-6)

Note: In the above equation, the system matrix \( B^* \) should be the matrix after the shunt element is switched. By the Inverse Matrix Modification Lemma (IMML) [80]

\[ (B^* + \Delta B^*) \cdot \Delta V = (B^* + b_k \cdot D) = -\Delta \tilde{Q} \]  (4-7)

\[ \Delta V = -([B^*]^{-1} - c \cdot [B^*]^{-1} \cdot D \cdot [B^*]^{-1}) \cdot \Delta \tilde{Q} \]

\[ = -[B^*]^{-1} \cdot \Delta \tilde{Q} + c \cdot [B^*]^{-1} \cdot D \cdot [B^*]^{-1} \cdot \Delta \tilde{Q} \]  (4-8)

Where \( c = (1/b_k + X_{kk})^{-1} \approx b_k \)

\( X_{kk} \) — the \( k^{th} \) diagonal element of the matrix \([B^*]^{-1}\).

For power systems, all the elements in matrix \([B^*]^{-1}\) are very small (less than 0.08). Therefore, the second term on the right hand side in (4-8) may be ignored. That is, the matrix modification effect of shunt switching on matrix \( B^* \) could be neglected.

All the past studies on reactive power/voltage distribution factor only considered the first iteration in the power flow calculation [53]-[56]. However, this could result in big voltage
errors. Therefore, for improving the calculation accuracy it is necessary to take into account more iterations.

### 4.2.2 Multiple Iteration Based Voltage Distribution Factor

Shunt switching mainly affects bus voltage magnitudes and reactive power on transmission lines on associated buses. However, the changes in bus voltage angles $\theta_j$ by shunt switching are very small (For the IEEE 39 bus system and the WECC 179 bus system, the changes in bus voltage angles are less than 1 degree). In addition, for realistic power systems, $\cos \theta_j$ is approximately equal to 1 and $G_j \sin \theta_j$ is much less than $B_j \cos \theta_j$. Therefore, the change in term $(G_j \sin \theta_j + B_j \cos \theta_j)$ is very small (less than 1%). Thus, the following assumption can be made for shunt switching.

**Assumption 1:** The term $(G_j \sin \theta_j + B_j \cos \theta_j)$, denoted by $C_j$, can be regarded as a constant before and after switching action.

Let $\Delta V = \Delta V^{(1)}$. Based on Assumption 1

$$\Delta \tilde{Q}_j^{(2)} = \frac{\Delta Q_j^2}{V_{i_0} + \Delta V_i} = \frac{Q_j^2 - Q_{i_0}^2}{V_{i_0} + \Delta V_i} = \frac{Q_j^2}{V_{i_0} + \Delta V_i} - \frac{Q_{i_0}^2}{V_{i_0} + \Delta V_i} \quad \text{for } i = 1, \ldots, k-1, k+1, \ldots, n \quad (4-9)$$

By Taylor series expansion,

$$\frac{Q_j^0}{V_{i_0} + \Delta V_i} = \frac{Q_j^0}{V_{i_0}} - \frac{Q_{i_0}^0}{V_{i_0}^2} \Delta V_i + \frac{Q_j^0}{V_{i_0}^3} \Delta V_i^2 + \ldots \approx \frac{Q_j^0}{V_{i_0}} - \frac{Q_{i_0}^0}{V_{i_0}^2} \Delta V_i \quad (4-10)$$

$$\Delta \tilde{Q}_j^{(2)} \approx \frac{Q_j^2}{V_{i_0} + \Delta V_i} - \frac{Q_j^0}{V_{i_0}} + \frac{Q_{i_0}^0}{V_{i_0}^2} \Delta V_i$$

$$\approx \sum_{j=1}^{n} (V_{j_0} + \Delta V_j) C_{j_0} - \sum_{j=1}^{n} V_{j_0} C_{j_0} + \frac{\Delta V_j \sum_{j=1}^{n} V_{j_0} C_{j_0}}{V_{i_0}} \quad (4-11)$$

$$= \sum_{j=1}^{n} \Delta V_j C_{j_0} + \frac{\Delta V_j \sum_{j=1}^{n} V_{j_0} C_{j_0}}{V_{i_0}}$$
\[\Delta \tilde{Q}^{(2)}_i = \frac{\Delta Q^{(2)}_i}{V_{k0} + \Delta V_k} = \frac{Q^i - Q^0}{V_{k0} + \Delta V_k} + (V_{k0} + \Delta V_k) \sum_{j=1}^{n} (V_{j0} + \Delta V_j)C_{yj0} - V_{k0} \sum_{j=1}^{n} V_{j0}C_{yj0} \]

\[\approx \sum_{j=1}^{n} \Delta V_j C_{yj0} + \frac{\Delta V_k}{V_{k0}} \sum_{j=1}^{n} V_{j0}C_{yj0} - b_k V_{k0}\]

Define a new vector as \(\Delta \tilde{V} \equiv \Delta V / V_0\), then

\[\Delta \tilde{Q}^{(2)} = \Delta Q^{(2)} / (V_0 + \Delta V) \approx C_0 \Delta V + (C_0 V_0) * \Delta \tilde{V} - b_k \Delta \tilde{V}_0\]

\[\Delta V^{(2)} = -[B^*]^{-1} \Delta \tilde{Q}^{(2)}\]

Where \(C_0\) is an \(n \times n\) matrix with the element \(C_{ij} = G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij}\).

The symbol ".*" represents the element-wise vector multiplication.

Let \(\Delta V = \Delta V^{(1)} + \Delta V^{(2)}\), from (4-13) and (4-14), \(\Delta V^{(3)}\) can be obtained, and so on, until the tolerance requirement can be met. Actually, three iterations are sufficient in order to save computational time. Thus the bus voltage distribution vector corresponding to a single shunt element switching can be defined as follows:

\[a_k = \Delta V / b_k = \frac{(\Delta V^{(1)} + \Delta V^{(2)} + \Delta V^{(3)})}{b_k}\]

It can be observed that each term in \(\Delta V^{(1)}, \Delta V^{(2)},\) and \(\Delta V^{(3)}\) includes the coefficient \(b_k\), therefore, in (4-5)-(4-14), we can just drop the coefficient \(b_k\) in all terms, and directly obtain \(a_k\) which depends only on the system configuration and post-contingency operating point. The equations for computing voltage distribution factor for single shunt element switching are then rewritten as follows:

\[\Delta V^{(1)} = [B^*]^{-1} \Delta V_0 = V_{k0} \cdot [B^*]_k^{-1}\]

Where \([B^*]_k^{-1}\) is the \(k^{th}\) column of the matrix \([B^*]^{-1}\).
Let $\Delta V = \Delta V^{(i)}$, $\Delta \tilde{V} = \Delta V / V_0$, and $X = [B']^{-1} C_0$, then

$$\Delta V^{(2)} \approx -X \Delta V - (X V_0)_o \cdot \Delta \tilde{V} + \Delta V^{(1)} \quad (4-17)$$

Let $\Delta V = \Delta V^{(i)} + \Delta V^{(2)}$, and $\Delta \tilde{V} = \Delta V / V_0$, then

$$\Delta V^{(3)} \approx -X \Delta V - (X V_0)_o \cdot \Delta \tilde{V} + \Delta V^{(1)} \quad (4-18)$$

$$\alpha_k = \Delta V^{(1)} + \Delta V^{(2)} + \Delta V^{(3)} \quad (4-19)$$

The bus voltage magnitudes after shunt element switching can then be obtained from:

$$V = V_0 + b_k \alpha_k \quad (4-20)$$

From (4-16)–(4-18), it can be noted that the elements of the matrix $[B']^{-1}$ have significant influence on the voltage distribution factor. If all the elements of the matrix $[B']^{-1}$ are very small, then $\Delta V^{(i)}$ is small so that $\Delta V^{(2)}$ and $\Delta V^{(3)}$ are also very small. Thus, considering multiple iterations will not greatly improve the accuracy of the voltage distribution factor. However, it is possible that not all the elements of the matrix $[B']^{-1}$ are very small. Therefore, for those buses whose corresponding elements in the matrix $[B']^{-1}$ are very large, $\Delta V^{(i)}$ is large so that $\Delta V^{(2)}$ and $\Delta V^{(3)}$ will also be large. Thus, multiple iterations must be taken into account in order to improve the accuracy of the voltage distribution factor.

This observation could also provide some suggestion on placement of shunt elements: when the shunt element is installed at the bus whose corresponding element in the matrix $[B']^{-1}$ is relative large, less capacity is needed to achieve the same voltage regulation objective.

It is well known that shunt switching can significantly change bus voltages only in a very small area whose center is at the bus at which that shunt element is located. Another fact is shunt elements cannot be installed at buses which are very close to each other. That means
shunt switching at one bus will not significantly change the operating points of other buses with shunt elements. Therefore, for multiple shunt switching at different locations, the voltage distribution factors can be computed regardless of shunt switching actions at other places. Thus, the total voltage change due to multiple shunt switching at different locations can be obtained by the linear combination of voltage changes due to single shunt element switching.

4.3 Corrective Voltage Control Algorithm by Shunt Element Switching

4.3.1 Switching Cost and Maximum Switchable Shunt Banks

In this research, it is assumed that the switching cost is the same for each shunt bank regardless of bank capacity and location. From the operators’ point of view, it is important to minimize the switching cost and over-voltage problem caused by multiple shunt switching. Therefore, the less shunt banks are switched, the better the operational viability. If switching one shunt bank can solve the voltage problem, switching more banks is not needed, and if switching two shunt banks can solve the voltage problem, switching more is not needed, and so forth. In practice, however, system operators will hesitate to switch too many shunt banks simultaneously. Hence, it is assumed that at most three shunt banks can be switched simultaneously.

4.3.2 System Voltage Security Margin (SVSM)

A system voltage security margin index is proposed to evaluate shunt switching actions, and is defined as follows:

\[
V_{SM} = \min _i \{ \min (V_{max} - V_i, V_i - V_{min}) \} \quad \text{for } i = 1, 2, \ldots, n \tag{4-21}
\]

Where \(V_i\) — voltage magnitude at bus \(i\).

\(V_{max}\) — the maximum voltage limit

\(V_{min}\) — the minimum voltage limit
The bigger the SVSM, the better the effect of the corresponding shunt switching action.

4.3.3 Proposed Corrective Voltage Control Algorithm

The flowchart of the proposed corrective voltage control algorithm by shunt element switching is shown in Figure 4-1.
The detailed description of the approach is given below:

1. Data Input.
2. Contingency Analysis.
3. If there is voltage violation, find the available shunt elements and their bank numbers and capacity per bank.
4. Compute voltage distribution factor of each shunt element.
5. Build voltage change matrix with voltage change vectors per bank (bank capacity times corresponding voltage distribution factor vector) as columns. Thus, any linear combination of the columns represents the final voltage change vector corresponding to multiple shunt switching.
6. Find successful single switching actions by searching if any single column in the voltage change matrix is within the desirable voltage change range. If yes, go to step 9, else single shunt switching cannot solve the voltage problem, and go to step 7.
7. Find successful double switching actions by searching if combination of any two columns in the voltage change matrix is within the desirable voltage change range. If yes, go to step 9, else double shunt switching cannot solve the voltage problem, and go to step 8.
8. Find successful triple switching actions by searching if combination of any three columns in voltage change matrix is within the desirable voltage change range. If yes, go to step 9, else shunt switching cannot solve the voltage problem, and go to step 11.
9. Rank the successful shunt switching actions by system voltage security margin.
10. For the ranked successful switching actions, run full AC power flow for all candidate switching actions until a best switching action is found which can actually solve the voltage problem and will not cause any other voltage problem.
11. Stop and print results.
4.5 Case Studies

The algorithm is implemented with MATLAB and is tested on the New England 39-bus system and the WECC 179-bus system on a DELL PC (2.79 GHz CPU).

4.5.1 The New England 39-bus System

The outage of line 16-17 is selected to test the proposed shunt switching algorithm. The contingency analysis results are shown in TABLE 4-1 and the available shunt elements are listed in TABLE 4-2.

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>4</th>
<th>12</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Voltage (p.u.)</td>
<td>0.9465</td>
<td>0.9379</td>
<td>0.9449</td>
</tr>
<tr>
<td>Violation Amount (p.u.)</td>
<td>-0.0035</td>
<td>-0.0121</td>
<td>-0.0051</td>
</tr>
</tbody>
</table>

**TABLE 4-1: CONTINGENCY ANALYSIS RESULTS FOR OUTAGE OF LINE 16-17**

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>24</th>
<th>27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bank Capacity (p.u.)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Number of Banks</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**TABLE 4-2: AVAILABLE SHUNT ELEMENTS FOR THE NEW ENGLAND 39-BUS SYSTEM**

The output results of the shunt switching program are as follows:

- Voltage violations have been relieved by shunt element switching.
- The best switching action is to switch in the shunt element at bus 12.
- The number of bank to be switched in is 2 at bus 12.
- The total switched capacity is 160 MVar.
- The system voltage security margin is 0.00205.
- The CPU time is 0.031 seconds.

The simulation results after switching in the shunt capacitor banks at bus 12 are shown in TABLE 4-3, and the system diagram for the switching action is shown in Figure 4-2.
TABLE 4-3: SIMULATION RESULTS AFTER SWITCHING IN THE SHUNT CAPACITOR BANKS AT BUS 12

<table>
<thead>
<tr>
<th>Bus</th>
<th>(V_{\text{POST}})</th>
<th>Voltage(^{\text{PF}})</th>
<th>Voltage(^{\text{1st}})</th>
<th>Voltage(^{\text{3rd}})</th>
<th>Error(^{\text{1st}})</th>
<th>Error(^{\text{3rd}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.04110</td>
<td>1.04220</td>
<td>1.04190</td>
<td>1.04250</td>
<td>0.00030</td>
<td>0.00030</td>
</tr>
<tr>
<td>4</td>
<td>0.94651</td>
<td>0.95941</td>
<td>0.95652</td>
<td>0.95736</td>
<td>0.00289</td>
<td><strong>0.00205</strong></td>
</tr>
<tr>
<td>5</td>
<td>0.96644</td>
<td>0.98008</td>
<td>0.97714</td>
<td>0.97845</td>
<td>0.00294</td>
<td>0.00163</td>
</tr>
<tr>
<td>6</td>
<td>0.97402</td>
<td>0.98795</td>
<td>0.98508</td>
<td>0.98653</td>
<td>0.00287</td>
<td>0.00142</td>
</tr>
<tr>
<td>7</td>
<td>0.95632</td>
<td>0.96957</td>
<td>0.96650</td>
<td>0.96767</td>
<td>0.00307</td>
<td>0.00190</td>
</tr>
<tr>
<td>8</td>
<td>0.95512</td>
<td>0.96789</td>
<td>0.96486</td>
<td>0.96591</td>
<td>0.00303</td>
<td>0.00198</td>
</tr>
<tr>
<td>10</td>
<td>0.99545</td>
<td>1.01300</td>
<td>1.01050</td>
<td>1.01240</td>
<td>0.00250</td>
<td>0.00060</td>
</tr>
<tr>
<td>11</td>
<td>0.98583</td>
<td>1.00470</td>
<td>1.00200</td>
<td>1.00340</td>
<td>0.00270</td>
<td>0.00130</td>
</tr>
<tr>
<td>12</td>
<td><strong>0.93793</strong></td>
<td><strong>1.02240</strong></td>
<td>1.01800</td>
<td>1.02410</td>
<td><strong>0.00440</strong></td>
<td><strong>0.00170</strong></td>
</tr>
<tr>
<td>13</td>
<td>0.98314</td>
<td>1.00260</td>
<td>1.00000</td>
<td>1.00130</td>
<td>0.00260</td>
<td>0.00130</td>
</tr>
<tr>
<td>14</td>
<td>0.96182</td>
<td>0.97685</td>
<td>0.97417</td>
<td>0.97509</td>
<td>0.00268</td>
<td>0.00176</td>
</tr>
</tbody>
</table>

Contingency:
Outage of Line 16-17

Shunt Capacitor at Bus 12 is Recommended to Be Switched on

FIGURE 4-2: SHUNT CAPACITOR BANKS AT BUS 12 ARE RECOMMENDED TO BE SWITCHED IN
In TABLE 4-3, \( V^{\text{POST}} \) is the post-contingency bus voltages. Superscript “PF” represents the voltage results obtained from a full AC power flow, superscript “3rd” represents the voltage results obtained from the proposed shunt switching algorithm using multiple iteration based voltage distribution factor, and superscript “1st” represents the voltage results obtained from the same algorithm but using the traditional first iteration based voltage distribution factor.

From TABLE 4-3, it can be seen that all voltage errors by multiple iteration based voltage distribution factor algorithm are much less than voltage errors by first iteration based voltage distribution factor algorithm, especially for the bus where the shunt capacitor is switched on and the largest voltage error is reduced from 0.0044 to 0.00205.

4.5.2 The WECC 179-bus System

As shown in Figure 4-3, outage of line 170-171 is selected for analysis. The available shunt elements for the WECC 179-bus system are listed in TABLE 4-4 and the contingency analysis results are shown in TABLE 4-5.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Bank Capacity (p.u.)</th>
<th>Number of Bank</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>37</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>44</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>60</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>68</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>71</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>72</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>76</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>78</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>80</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>105</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>119</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>145</td>
<td>2.0</td>
<td>2</td>
</tr>
<tr>
<td>150</td>
<td>2.0</td>
<td>2</td>
</tr>
</tbody>
</table>
TABLE 4-5: CONTINGENCY ANALYSIS RESULTS FOR OUTAGE OF LINE 170-171

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>61</th>
<th>105</th>
<th>106</th>
<th>134</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Voltage (p.u.)</td>
<td>0.9436</td>
<td>0.9374</td>
<td>0.9404</td>
<td>0.9489</td>
</tr>
<tr>
<td>Violation Amount (p.u.)</td>
<td>-0.0064</td>
<td>-0.0126</td>
<td>-0.0096</td>
<td>-0.0010</td>
</tr>
</tbody>
</table>

FIGURE 4-3: ONE-LINE DIAGRAM OF THE WECC 179-BUS SYSTEM

The output results of the shunt switching program are as follows:

- Voltage violations have been relieved by shunt element switching.
- The best switching action is to switch in the shunt elements at buses 60 and 105.
The number of banks to be switched in is 1 at bus 60 and 2 at bus 105.

The total switched capacity is 200 MVar at bus 60 and 100 MVar at bus 105.

The system voltage security margin is 0.00210.

The CPU time is 0.125 seconds.

The simulation results for the buses whose voltage errors are larger than 0.0025 p.u. are listed in TABLE 4-6.

From TABLE 4-6, it can be observed that the voltage error by first iteration based voltage distribution factor is 0.0128 at bus 105, which is too large to be acceptable. The reason is that the corresponding element of bus 105 in the matrix \([B']^{-1}\) is large, therefore, the voltage change at bus 105 is also large and the first iteration based voltage distribution factors will not be effective. However, by multiple iteration based voltage distribution factors, the voltage error can be greatly reduced, from 0.0128 to 0.046, which is in the acceptable error range.

**TABLE 4-6: SIMULATION RESULTS AFTER SWITCHING IN SHUNT CAPACITORS AT BUSES 60 AND 105**

<table>
<thead>
<tr>
<th>Bus</th>
<th>(V^{\text{POST}})</th>
<th>(V^{\text{pF}})</th>
<th>(V^{\text{1st}})</th>
<th>(V^{\text{2nd}})</th>
<th>(\text{Error}^{\text{1st}})</th>
<th>(\text{Error}^{\text{2nd}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>1.00290</td>
<td>1.01440</td>
<td>1.01170</td>
<td>1.01170</td>
<td>0.00270</td>
<td>0.00270</td>
</tr>
<tr>
<td>41</td>
<td>0.95506</td>
<td>0.96538</td>
<td>0.96266</td>
<td>0.96273</td>
<td>0.00272</td>
<td>0.00265</td>
</tr>
<tr>
<td>47</td>
<td>0.95693</td>
<td>0.96936</td>
<td>0.96660</td>
<td>0.96667</td>
<td>0.00276</td>
<td>0.00269</td>
</tr>
<tr>
<td>48</td>
<td>0.95364</td>
<td>0.96647</td>
<td>0.96360</td>
<td>0.96367</td>
<td>0.00287</td>
<td>0.00280</td>
</tr>
<tr>
<td>55</td>
<td>0.95333</td>
<td>0.96422</td>
<td>0.96142</td>
<td>0.96149</td>
<td>0.00280</td>
<td>0.00273</td>
</tr>
<tr>
<td>56</td>
<td>0.97321</td>
<td>0.98305</td>
<td>0.98035</td>
<td>0.98042</td>
<td>0.00270</td>
<td>0.00263</td>
</tr>
<tr>
<td>58</td>
<td>0.95841</td>
<td>0.96827</td>
<td>0.96563</td>
<td>0.96571</td>
<td>0.00264</td>
<td>0.00256</td>
</tr>
<tr>
<td>59</td>
<td>0.95150</td>
<td>0.96422</td>
<td>0.96134</td>
<td>0.96141</td>
<td>0.00288</td>
<td>0.00281</td>
</tr>
<tr>
<td>60</td>
<td>0.95080</td>
<td>0.96516</td>
<td>0.96213</td>
<td>0.96220</td>
<td>0.00303</td>
<td>0.00296</td>
</tr>
<tr>
<td>61</td>
<td>0.94361</td>
<td>0.95660</td>
<td>0.95379</td>
<td>0.95386</td>
<td>0.00281</td>
<td>0.00274</td>
</tr>
<tr>
<td>62</td>
<td>0.95182</td>
<td>0.96398</td>
<td>0.96111</td>
<td>0.96118</td>
<td>0.00287</td>
<td>0.00280</td>
</tr>
<tr>
<td>100</td>
<td>0.99939</td>
<td>1.01150</td>
<td>1.00890</td>
<td>1.00890</td>
<td>0.00260</td>
<td>0.00260</td>
</tr>
<tr>
<td>101</td>
<td>0.98583</td>
<td>1.00700</td>
<td>1.00320</td>
<td>1.00380</td>
<td>0.00380</td>
<td>0.00320</td>
</tr>
<tr>
<td>105</td>
<td>0.93742</td>
<td>1.02560</td>
<td>1.01280</td>
<td>1.02100</td>
<td>0.01280</td>
<td>0.00460</td>
</tr>
<tr>
<td>106</td>
<td>0.94041</td>
<td>0.95700</td>
<td>0.95260</td>
<td>0.95282</td>
<td>0.00440</td>
<td>0.00418</td>
</tr>
</tbody>
</table>
It can be also found that, in most situations, the voltage errors cannot be greatly reduced. The reason is that the voltages at those buses will not change very much and the first iteration based voltage distribution factors are sufficient.

4.6 Summary

Shunt element switching is still one of the most widely used voltage control methods due to its flexibility and economy. For on-line corrective voltage control, it is a tradeoff between accuracy and speed. In this chapter, the following work has been done for corrective voltage control by shunt element switching:

- A new voltage distribution factor is proposed which considers multiple iterations in power flow calculation. With this voltage distribution factor, the voltage error caused by the traditional first iteration based voltage distribution factor can be greatly reduced.
- A corrective voltage control algorithm by shunt element switching is developed which uses voltage change matrix to compute voltage change results by single shunt switching action or multiple shunt switching actions without power flow calculation but with acceptable accuracy. The computation speed is also extremely fast.
- Simulation results on the IEEE 39 bus system and the WECC 179 bus system indicate that the proposed corrective voltage control algorithm is very effective in deciding shunt element switching.
CHAPTER 5 : INTEGRATION OF LINE SWITCHING, BUS-BAR SWITCHING, AND SHUNT SWITCHING ALGORITHMS

5.1 Introduction

In some situations, line and bus-bar switching can successfully relieve all overloads and voltage violations. However, for some severe contingencies, line and bus-bar switching may only be able to solve the overload problem but the system may still be suffering from the voltage violation problem since the main function of line and bus-bar switching is to change power flow distribution and its ability to alter voltage profile is limited. However, shunt element switching in comparison can only change voltage profile and has almost no influence on line flow, especially the real power flow. Therefore, in order to enlarge the solution space for corrective control, line switching, bus-bar switching, and shunt switching should be integrated together such that problems of overloads and voltage violations could be solved more effectively.

In the previous two chapters, a new line and bus-bar switching algorithm and a novel shunt switching algorithm are presented separately. In this chapter, these two algorithms are integrated into one corrective switching algorithm in order to enlarge the solution space for relieving overloads and voltage violations. All the successful switching actions are evaluated by a security threshold criterion. The proposed integrated corrective switching algorithm is implemented with MATLAB and tested on the WECC 179-bus system.

5.2 Ordering of Successful Switching Actions

Both operational cost and system security need to be taken into account when corrective switching actions are evaluated. The PISM defined in (3-9) is still used to calculate system security margin after switching actions. The assumption that the operational cost
for each shunt bank is the same regardless of bank capacity and location still holds and the operational cost for single line switching action and single bus-bar switching action are assumed to be the same. Then a security threshold criterion for ordering of corrective switching actions is used as follows:

1. The threshold of system security is defined as 0.2, which may vary depending upon the system and operating conditions.
2. The switching actions that can improve the system security above the system security threshold are defined as successful switching actions.
3. The switching actions that can relieve all overloads and voltage violations but cannot improve the system security above the system security threshold are defined as the useful switching actions.
4. The successful switching actions are sorted by switching cost and the one with the minimum switching cost is selected as the best switching action.
5. If there is no successful switching action, the useful actions are ranked by performance index of security margin (PISM) and the one with the maximum PISM is selected as the best switching action.

5.3 The Proposed Corrective Switching Algorithm

Simulation results and practical experience show that there are only a few successful line or bus-bar switching actions for relieving overload problem, usually, no more than 5. Furthermore, the shunt switching algorithm is extremely fast since no power flow calculation is involved and shunt switching almost has no influence on line flow. Therefore, line and bus-bar switching can be implemented first to see if all overloads and voltage violations will be relieved. If there are still voltage violations after line and bus-bar switching actions, shunt switching will be applied but only based on the successful line and bus-bar switching actions which can relieve all overloads.
The flowchart of the proposed corrective switching algorithm is shown in Figure 5-1, which integrates line and bus-bar switching algorithm, and shunt switching algorithm.
5.4 Case Studies

The algorithm is implemented with MATLAB and is tested on the WECC 179-bus system on a DELL PC (2.79 GHz CPU). Since the contingency selection algorithm is not the main thrust of this research, the full AC power flow is used for contingency analysis.

The outage of line 170-171 is still selected to test the proposed corrective switching algorithm but the operating point is altered by adjusting the output power of generators. The contingency analysis results for the outage of line 170-171 are shown in TABLE 5-1.

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 168-169</td>
<td>1814.74 MVA</td>
<td>1700 MVA</td>
<td>114.74 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 105</td>
<td>0.94477 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>-0.00523 pu</td>
</tr>
<tr>
<td>Bus 106</td>
<td>0.94115 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>-0.00885 pu</td>
</tr>
<tr>
<td>Bus 134</td>
<td>0.94799 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>-0.00201 pu</td>
</tr>
</tbody>
</table>

The output results of the corrective switching program are as follows:

- Overloads and voltage violations have been relieved by corrective switching actions.
- The best bus-bar switching action is to split off bus-bar 83 with lines 83-94, 83-98, 83-172, and load at 83 being switched on one split bus (bus 831) and lines 83-89 and 83-168 being switched on the other split bus (bus 832).
- The best shunt switching action is to switch in shunt elements at buses 105 and 119.
- The number of banks to be switched in is 1 at bus 105 and 2 at bus 119.
- The total switched capacity is 50 MVar at bus 105 and 400 MVar at bus 119.
- The minimal PISM is 0.1089.
- The CPU time is 8.29 seconds.
The power flow results after the switching actions are shown in TABLE 5-2 and the system diagram for the switching actions is shown in Figure 5-2 (the arrows represent the directions of power flow.).

![System Diagram](image)

**Figure 5-2: The Relevant Portion of the WECC 179-Bus System**

**TABLE 5-2: Power Flow Results after Corrective Switching Actions**

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 168-169</td>
<td>1573.73 MVA</td>
<td>1700 MVA</td>
<td>126.27 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 105</td>
<td>0.99551 pu</td>
<td>$V_{\text{min}} = 0.95$ pu</td>
<td>0.04551 pu</td>
</tr>
<tr>
<td>Bus 106</td>
<td>0.95703 pu</td>
<td>$V_{\text{min}} = 0.95$ pu</td>
<td>0.00703 pu</td>
</tr>
<tr>
<td>Bus 134</td>
<td>0.96641 pu</td>
<td>$V_{\text{min}} = 0.95$ pu</td>
<td>0.01641 pu</td>
</tr>
</tbody>
</table>
However, if bus-bar 83 is not selected as a bus-bar switching candidate, the output results of the corrective switching program are as follows:

- Bus-bar switching CANNOT relieve all overloads and voltage violations.
- Overloads and voltage violations have been relieved by line switching.
- The best line switching action is to switch out line 81-99.
- No shunt switching is needed.
- The minimal PISM is 0.00559.
- The CPU time is 9.86 seconds

The power flow results are shown in TABLE 5-3.

TABLE 5-3: POWER FLOW RESULTS AFTER SWITCHING OUT LINE 81-99

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 168-169</td>
<td>1543.67 MVA</td>
<td>1700 MVA</td>
<td>156.33 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 105</td>
<td>0.95404 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>0.00404 pu</td>
</tr>
<tr>
<td>Bus 106</td>
<td>0.95012 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>0.00012 pu</td>
</tr>
<tr>
<td>Bus 134</td>
<td>0.95699 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>0.00699 pu</td>
</tr>
</tbody>
</table>

It seems that switching out line 81-99 is also a useful solution for relieving overloads and voltage violations. However, transient stability simulation reveals that switching out line 81-99 will cause the system to lose its stability, as shown in Figure 5-3, as a result line 81-99 should be removed from the line switching candidate list. The switching action of bus-bar 83, however, has almost no impact on system stability, as shown in Figure 5-4.
Simulation of WECC 179 Bus System

**FIGURE 5-3:** GENERATOR ROTOR ANGLES AFTER SWITCHING OUT LINE 81-99

Simulation of WECC 179 Bus System

**FIGURE 5-4:** GENERATOR ROTOR ANGLES AFTER SPLITTING OFF BUS-BAR 83
It can be shown from this case that it is very important to choose the switching candidates carefully. Some heuristic methods must be employed for selection of switching candidates since it is impossible to do transient simulation for each switching action.

5.5 Summary

In this chapter, the proposed line switching, bus-bar switching, and shunt switching algorithms are integrated into one corrective switching algorithm for relieving overloads and voltage violations. Simulation studies on the WECC 179-bus system show that the proposed corrective switching algorithm is able to effectively solve the problems of overloads and voltage violations and significantly reduce the computing time.

One important issue that needs further analysis is the selection of switching candidates. In this study, only steady states analysis, i.e. power flow calculation is conducted. However, switching actions sometimes may cause transient stability problem. Therefore, an approach to account for transient stability in the corrective switching algorithm is one of the issues that need further analysis.
CHAPTER 6 : LP-BASED OPF FOR CORRECTIVE FACTS
CONTROL TO RELIEVE OVERLOADS
AND VOLTAGE VIOLATIONS

6.1 Introduction

Generally, FACTS operation can be divided into two steps: the first step is to determine the operational goals of FACTS control, and the second step is to implement the operational goals using a particular control strategy, i.e. controller design. Corrective FACTS control only focuses on the first step – determining the operational goals.

Unlike corrective switching, FACTS control is a continuous variable problem. Therefore, the OPF becomes the first choice for FACTS control [77], although other approaches, such as sensitivity method [80]-[85], genetic-based algorithm [57], and maximum flow algorithm [78]-[79], have been attempted. Over the past 20 years, many techniques, such as genetic algorithm [57]-[60], Newton's method [61]-[64], augmented Lagrange multiplier [65], decomposed OPF algorithm [66], sequential quadratic programming [67]-[68], and Han-Powell algorithm [69], have been employed to solve OPF with FACTS devices. However, the requirement of high computational speed of on-line corrective control points to the need for further efforts on LP-based OPF algorithms for FACTS control due to the robustness and high computational speed of the LP algorithm [20],[33],[70]-[71].

A very important issue for OPF with FACTS devices is the consideration of the operational constraints of FACTS devices during optimization. Otherwise, a practically unreachable solution could be obtained. This aspect is easily handled in NLP-based OPF. However, it is quite difficult to incorporate it in an LP-based OPF. Reference [70] did not consider the operational constraints for FACTS devices and [71] only took into account the thermal limits for FACTS devices.
In this chapter, a new LP-based OPF algorithm is presented to find the optimal parameter settings for FACTS devices to relieve overloads and voltage violations caused by system contingencies. The optimization objective is chosen to minimize the average loadability on highly loaded transmission lines. A new set of parameter sensitivities of FACTS devices are derived such that the operational constraints of FACTS devices can be included during optimization. Finally, the algorithm is implemented with MATLAB and tested on the New England 39-bus system and the WECC 179-bus system.

6.2 Power Flow Models of FACTS Devices

The thyristor-controlled FACTS devices, such as static Var compensator (SVC) and thyristor-controlled series capacitor (TCSC), are usually modeled as controllable impedance [72]-[73],[84]-[85],[62]-[63],[86]. However, voltage source converter (VSC) based FACTS devices, including series devices like interline power flow controller (IPFC) and static synchronous series compensator (SSSC), shunt devices like static synchronous compensator (STATCOM), and combined devices like unified power flow controller (UPFC), are more complex and usually modeled as controllable sources [72]-[73],[62]-[63],[70]-[71],[86]-[92].

The UPFC can control bus voltage as well as the real and reactive power flow on the transmission line, and thereby, is considered the most versatile FACTS device. This chapter, therefore, focuses on the UPFC for corrective FACTS control. The equivalent bus model for the UPFC discussed in [86]-[87] is adopted. The schematic diagram and equivalent model of the UPFC are shown in Figure 6-1 and Figure 6-2.
If the shunt and series transformers are assumed to be lossless, the following equations can be derived:

\[ P_{se} = V_{se} \left[ V_j \sin(\delta_{se} - \delta_j) - V_i \sin(\delta_{se} - \delta_i) \right] / X_{se} \]  

(6-1)

\[ Q_{se} = V_{se} \left[ V_i \cos(\delta_{se} - \delta_i) - V_j \cos(\delta_{se} - \delta_j) - V_{se} \right] / X_{se} \]  

(6-2)

\[ MVA_{se} = \sqrt{P_{se}^2 + Q_{se}^2} \]  

(6-3)

\[ P_{sh} = -V_{sh} V_i \sin(\delta_{sh} - \delta_i) / X_{sh} \]  

(6-4)

\[ Q_{sh} = V_{sh} \left[ V_i \cos(\delta_{sh} - \delta_i) - V_{sh} \right] / X_{sh} \]  

(6-5)

\[ MVA_{sh} = \sqrt{P_{sh}^2 + Q_{sh}^2} \]  

(6-6)
\[ P_{se} + P_{sh} = 0 \]  
(6-7)

\[ P_j = V_j[V_{se} \sin(\delta_j - \delta_{se}) - V_i \sin(\delta_j - \delta_i)]/ X_{se} \]  
(6-8)

\[ Q_j = V_j[V_i \cos(\delta_j - \delta_i) - V_{se} \cos(\delta_j - \delta_{se}) - V_j]/ X_{se} \]  
(6-9)

\[ P_i = P_j \]  
(6-10)

\[ Q_i = Q_{ij} + Q_{sh} \]
\[ = V_i[V_i + V_j \cos(\delta_i - \delta_j) - V_{se} \cos(\delta_i - \delta_{se})]/ X_{se} + [V_i - V_{sh} \cos(\delta_i - \delta_{sh})]/ X_{sh} \]  
(6-11)

Where the subscripts "se" and "sh" represent the variables of the series VSC and the shunt VSC, respectively.

It is observed that the UPFC is connected to the power system only through bus \( i \) and bus \( j \), as shown in Figure 6-3. If the UPFC is regarded as a black box, then all the variables needed to solve for the internal parameters of the UPFC can be obtained from the power flow calculation. Let the series VSC be operated at automatic power flow control mode, then bus \( j \) can be set as a PQ bus, and let the shunt VSC be operated at automatic voltage control mode, then bus \( i \) can be set as a PV bus, as shown in Figure 6-4. Thus, all the external variables, such as \( Q_i, V_j, \delta_i, \) and \( \delta_j \), can be obtained from ordinary power flow calculation by setting \( P_j = P_{desired}, \ Q_j = Q_{desired}, \) and \( V_i = V_{desired}, \) and the internal variables of the UPFC, \( V_{se}, V_{sh}, \delta_{se}, \) and \( \delta_{sh}, \) can be obtained from (6-12), which can be solved by an iterative numerical approach.

![Figure 6-3: Connection of a UPFC with the Power System](image)
FIGURE 6-4: UPFC MODEL IN POWER FLOW CALCULATION

\[
\begin{align*}
V_j[V_e \sin(\delta_j - \delta_{se}) - V_{\text{desired}} \sin(\delta_j - \delta_i)]/X_{se} - P_{\text{desired}} &= 0 \\
V_j[V_e \cos(\delta_j - \delta_i) - V_{\text{desired}} \cos(\delta_j - \delta_{se}) - V_j]/X_{se} - Q_{\text{desired}} &= 0 \\
V_j[V_e[V_{\text{desired}} \sin(\delta_{se} - \delta_j) - V_{\text{desired}} \sin(\delta_{se} - \delta_i)]/X_{se} - V_{\text{sh}}]V_{\text{desired}} \sin(\delta_{sh} - \delta_i)/X_{sh} &= 0 \\
V_{\text{desired}} [(V_{\text{desired}} + V_j \cos(\delta_i - \delta_j) - V_{\text{se}} \cos(\delta_i - \delta_{se})]/X_{se} + [V_{\text{desired}} - V_{\text{sh}} \cos(\delta_i - \delta_{sh})]/X_{sh}] - Q_i &= 0
\end{align*}
\]

(6-12)

Equation (6-12) can be rewritten in vector form as follows:

\[
Fx_{\text{upfc}},xp = 0
\]

(6-13)

Where \(x_{\text{upfc}} = [V_{\text{sh}}, V_{\text{se}}, \delta_{sh}, \delta_{se}]\) is the parameter vector of the UPFC.

\(xp = [V_j, \delta_i, \delta_j, Q_i, V_{\text{desired}}, P_{\text{desired}}, Q_{\text{desired}}]\) is the system state variable vector obtained from power flow calculation.

\(X_{se}\) and \(X_{sh}\) are the reactance of the series and shunt transformers.

6.3 LP-based OPF for UPFC Control

6.3.1 System State Variables and Control Variables

In optimal power flow, the system state variables are bus voltage magnitudes and angles, and the control variables are the real power and reactive power of generators. Therefore, the total number of the system variables is \(2(nb + ng)\), where \(nb\) is the number of buses
and \(ng\) is the number of generators.

It is presumed that the target of corrective FACTS control is to only relieve overloads and voltage violations by FACTS control without changing the real power and reactive power outputs of generators. Therefore, the system state variables are the voltage magnitudes at bus \(i\) and all PQ buses (including bus \(j\)), and voltage angles at all buses except the reference bus. The control variables are the real power and reactive power injections of buses \(i\) and \(j\). For a system with \(m\) UPFCs, the total number of the system variables is \(nb + npq + 4m\), where \(npq\) is the number of PQ buses.

### 6.3.2 Objective Function

Under emergency situations, the system security is the most important concern. Therefore, the control target of corrective FACTS control should be to maximize system security after relieving all overloads and voltage violations. Since the primary function of the UPFC is power flow control, the optimization objective for the UPFC control is chosen to minimize the average loadability on all transmission lines, as shown in (6-14).

\[
\text{Min } z = \frac{1}{nl} \sum_{i=1}^{nl} \frac{MVA_i}{MVA_{i,\text{max}}} \tag{6-14}
\]

where \(nl\) is the number of transmission lines.

- \(MVA_i\) is the apparent power on line \(i\).
- \(MVA_{i,\text{max}}\) is the maximum apparent power on line \(i\).

The objective function can be linearized as follows:

\[
\text{Min } \Delta z = \frac{1}{nl} \sum_{i=1}^{nl} \frac{\partial MVA_i}{\partial x} \Delta x \tag{6-15}
\]

where \(x\) is the system state variable vector.

In fact, the apparent power on transmission line \(i\) includes the apparent power from the sending end to the receiving end, \(MVA_{i,f}\), and the apparent power from the receiving end
to the sending end, \( MVA_y \). Therefore, in the objective function, it is defined as

\[
MVA_i = \frac{1}{2}(MVA_y + MVA_i)
\]  

(6-16)

Thus, the linearized objective function can be rewritten as follows:

\[
\text{Min } \Delta z = \frac{1}{2n_l} \left\{ \sum_{i=1}^{n_l} \left( \frac{\partial MVA_y}{\partial \Delta x} + \frac{\partial MVA_i}{\partial \Delta x} \right) \Delta x \right\}
\]  

(6-17)

However, it is found that although there are some highly loaded lines whose loadabilities are nearly 1 in power systems, there are also many lightly loaded lines whose loadabilities are small, usually less than 0.5. The power flow changes on these lightly loaded lines will not affect the system overload security margin. Moreover, if all lines are taken into account to minimize the average system loadability, it could sometimes happen that although the average system loadability is lowered, (which usually results from big decreases in loadabilities on lightly loaded lines) small increases in loadabilities on highly loaded lines could occur. Therefore, only highly loaded lines should be considered in maximizing the system security by minimizing the average loadability on transmission lines. The objective function (6-17) then becomes:

\[
\text{Min } \Delta z = \frac{1}{2nh} \left\{ \sum_{i=1}^{nh} \left( \frac{\partial MVA_y}{\partial \Delta x} + \frac{\partial MVA_i}{\partial \Delta x} \right) \Delta x \right\}
\]  

(6-18)

where \( nh \) is the number of the highly loaded lines whose loadabilities are larger than the loadability index.

Usually, the loadability index can be set as 0.5.

6.3.3 Equality Constraints

The equality constraints include bus real power balance (for all PV buses and PQ buses), bus reactive power balance (for all PQ buses and bus \( i \)), and UPFC real power balance.
constraints. The linearized equality constraints are as follows:

\[
\frac{\partial P}{\partial \delta} \Delta \delta + \frac{\partial P}{\partial V} \Delta V + \frac{\partial P}{\partial P_g} \Delta P_g + \frac{\partial P}{\partial Q_g} \Delta Q_g = 0 
\]  
(6-19)

\[
\frac{\partial Q}{\partial \delta} \Delta \delta + \frac{\partial Q}{\partial V} \Delta V + \frac{\partial Q}{\partial P_g} \Delta P_g + \frac{\partial Q}{\partial Q_g} \Delta Q_g = 0 
\]  
(6-20)

\[
P_{g,i} + P_{g,j} = 0 
\]  
(6-21)

where \( P \) and \( Q \) are the bus real and reactive power injection vector, \( \delta \) and \( V \) are the bus voltage angle and magnitude vector, \( P_g \) and \( Q_g \) are the bus real and reactive generation vector, \( P_{g,i} \) and \( P_{g,j} \) are the real power injections at bus \( i \) and bus \( j \).

### 6.3.4 Inequality Constraints

The inequality constraints include system security constraints, i.e. line flow constraints (including receiving end flow and sending end flow) and bus voltage constraints, and the operational constraints of the UPFC. As discussed in [73],[90]-[92], a UPFC has 6 operational constraints:

- Maximum real power exchanged between two VSCs
- MVA rating of shunt VSC
- MVA rating of series VSC
- Minimum voltage magnitude of shunt VSC
- Maximum voltage magnitude of series VSC
- Maximum voltage magnitude of shunt VSC

There are no limits for voltage angles of the two VSCs, and they can be chosen to be any value between -180 and 180 degrees.

The linearized system security constraints are as follows:

\[
MVA_f(x^0) + \frac{\partial MVA_f(x^0)}{\partial x} \Delta x \leq MVA_{i,\text{max}} 
\]  
(6-22)
The linearized operational constraints of the UPFC are:

\[
MVA_{sh}(x^0) + \frac{\partial MVA_{sh}(x^0)}{\partial x} \Delta x \leq MVA_{sh,\text{max}}
\]  

(6-23)

\[
V_{j,\text{min}} \leq V_j(x^0) + \Delta V_j \leq V_{j,\text{max}}
\]  

(6-24)

where \( i = 1, 2, \ldots, nl \), and \( j = 1, 2, \ldots, npq+1 \).

The linearized operational constraints of the UPFC are:

\[
P_{sh,\text{min}} \leq P_{sh}(x) + \frac{\partial P_{sh}(x)}{\partial x} \Delta x \leq P_{sh,\text{max}}
\]  

(6-25)

\[
MVA_{sh}(x) + \frac{\partial MVA_{sh}(x)}{\partial x} \Delta x \leq MVA_{sh,\text{max}}
\]  

(6-26)

\[
MVA_{se}(x) + \frac{\partial MVA_{se}(x)}{\partial x} \Delta x \leq MVA_{se,\text{max}}
\]  

(6-27)

\[
V_{sh,\text{min}} \leq V_{sh}(x) + \frac{\partial V_{sh}(x)}{\partial x} \Delta x \leq V_{sh,\text{max}}
\]  

(6-28)

\[
V_{se,\text{min}} \leq V_{se}(x) + \frac{\partial V_{se}(x)}{\partial x} \Delta x \leq V_{se,\text{max}}
\]  

(6-29)

### 6.3.5 Sensitivities

For the equality constraints (6-19)-(6-20), \( \frac{\partial P}{\partial \delta}, \frac{\partial P}{\partial V}, \frac{\partial Q}{\partial \delta}, \frac{\partial Q}{\partial V} \) are the Jacobian submatrices in the power flow equations, and \( \frac{\partial P}{\partial g}, \frac{\partial Q}{\partial g} \) are sparse matrices with 1 at corresponding locations, and \( \frac{\partial Q}{\partial P}, \frac{\partial P}{\partial Q} \) are zero matrices.

For the inequality constraints (6-22)-(6-23), the sensitivities can be calculated as discussed in [20]. They are not shown here in order to save space.

The inequality constraints of UPFC can be obtained as follows:

Take the derivative of both sides of (6-13) with respect to \( x_p \),
\[
\frac{\partial F}{\partial x_{\text{upfc}}} \frac{\partial x_{\text{upfc}}}{\partial x_p} + \frac{\partial F}{\partial x_p} = 0
\]  (6-30)

Then

\[
\frac{\partial x_{\text{upfc}}}{\partial x_p} = -\left[\frac{\partial F}{\partial x_{\text{upfc}}}\right]^{-1} \frac{\partial F}{\partial x_p} 
\]  (6-31)

From (6-31), \( \frac{\partial V_{sh}}{\partial x_p} \) and \( \frac{\partial V_{sc}}{\partial x_p} \) can be obtained.

Let

\[
H = \begin{bmatrix}
p_{sh} \\
MVA_{sh} \\
MVA_{sc}
\end{bmatrix} = \begin{bmatrix}
-V_{sh}V_i \sin(\delta_{sh} - \delta_t)/X_{sh} \\
\sqrt{P_{sh}^2 + Q_{sh}^2} \\
\sqrt{P_{sh}^2 + Q_{sh}^2}
\end{bmatrix} 
\]  (6-32)

Then

\[
\frac{\partial H}{\partial x_p} = \frac{\partial H}{\partial x_{\text{upfc}}} \frac{\partial x_{\text{upfc}}}{\partial x_p} + \frac{\partial H}{\partial x_p} = -\frac{\partial H}{\partial x_{\text{upfc}}} \left[\frac{\partial F}{\partial x_{\text{upfc}}}\right]^{-1} \frac{\partial F}{\partial x_p} + \frac{\partial H}{\partial x_p} 
\]  (6-33)

From (6-31)-(6-33), the sensitivity matrix for UPFC's variables can be assembled,

\[
\frac{\partial \text{upfc}_\text{var}}{\partial x_p} = \begin{bmatrix}
\frac{\partial P_{sh}}{\partial x_p}, & \frac{\partial MVA_{sh}}{\partial x_p}, & \frac{\partial MVA_{sc}}{\partial x_p}, & \frac{\partial V_{sh}}{\partial x_p}, & \frac{\partial V_{sc}}{\partial x_p}
\end{bmatrix}^T 
\]  (6-34)

### 6.4 Algorithm Implementation

The UPFC can control power flow on the transmission line over a large range. Therefore, the sensitivities based on the original operating point may not always be sufficiently accurate during optimization. Therefore, it is necessary to update the sensitivities during optimization so as to reduce the effect of errors due to linearization.

Another issue of importance with regard to computational time under an emergency situation is that, finding a feasible solution is more important than finding an optimal
solution. Therefore, if an LP solution is feasible when checked by the AC power flow, it is acceptable for corrective control.

The flowchart of the proposed LP-based OPF algorithm for UPFC control is shown in Figure 6-5.
6.5 Case Studies

The LP-based OPF for corrective FACTS control is implemented in MATLAB and tested on the New England 39-bus system and the WECC 179-bus system.

6.5.1 The New England 39-bus System

The one line diagram of the New England 39-bus system is shown in Figure 6-6.
The outage of line 4-5 is selected as the study case. The contingency analysis results for line 4-5 outage are shown in TABLE 6-1 and the operational limits of the UPFC are shown in TABLE 6-2.

**TABLE 6-1: CONTINGENCY ANALYSIS RESULTS FOR OUTAGE OF LINE 4-5**

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 10-13</td>
<td>568.55 MVA</td>
<td>550 MVA</td>
<td>18.55 MVA</td>
</tr>
<tr>
<td>Line 13-14</td>
<td>574.90 MVA</td>
<td>550 MVA</td>
<td>24.90 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.94878 pu</td>
<td>(V_{\text{min}} = 0.95 \text{ pu}) (V_{\text{max}} = 1.05 \text{ pu})</td>
<td>-0.00122 pu</td>
</tr>
</tbody>
</table>

**TABLE 6-2: OPERATIONAL LIMITS OF UPFC**

<table>
<thead>
<tr>
<th>(V_{\text{sh}})</th>
<th>(V_{\text{se}})</th>
<th>(P_{\text{sh}})</th>
<th>(MVA_{\text{sh}})</th>
<th>(MVA_{\text{se}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>1.2 pu</td>
<td>0.3 pu</td>
<td>50 MW</td>
<td>200 MVA</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.8 pu</td>
<td>0.0 pu</td>
<td>-50 MW</td>
<td>-</td>
</tr>
</tbody>
</table>

### 6.5.1.1 Case 1: The UPFC Is Installed at Bus 16 to Control Power Flow on Line 16-17

The output results of the UPFC control program are as follows:

- Overloads and voltage violations have been relieved.
- The desired voltage at bus 16 is 0.98481 pu.
- The desired real power on line 16-17 is -12.632 MW.
- The desired reactive power on line 16-17 is 28.456 MVar.
- The average loadability on highly loaded lines is 0.6478.
- The iteration count of LP-based OPF is 1.
- The CPU time is 0.175 second.

The UPFC's state variables and control targets before and after UPFC control are shown in TABLE 6-3 and TABLE 6-4 respectively and the power flow results after corrective
UPFC control are shown in TABLE 6-5.

**TABLE 6-3: COMPARISON OF UPFC'S VARIABLES BEFORE AND AFTER CONTROL (CASE 1)**

<table>
<thead>
<tr>
<th></th>
<th>$V_{sh}$</th>
<th>$V_{se}$</th>
<th>$\delta_{sh}$</th>
<th>$\delta_{se}$</th>
<th>$P_{sh}$</th>
<th>$MVA_{sh}$</th>
<th>$MVA_{se}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.898 pu</td>
<td>0.085 pu</td>
<td>-17.2</td>
<td>-86.2</td>
<td>-0.34 MW</td>
<td>129.0 MVA</td>
<td>17.4 MVA</td>
</tr>
<tr>
<td>After</td>
<td>0.902 pu</td>
<td>0.185 pu</td>
<td>-12.9</td>
<td>80.2</td>
<td>4.61 MW</td>
<td>148.8 MVA</td>
<td>5.78 MVA</td>
</tr>
</tbody>
</table>

**TABLE 6-4: CONTROL TARGETS OF UPFC BEFORE AND AFTER CONTROL (CASE 1)**

<table>
<thead>
<tr>
<th></th>
<th>$V_i$</th>
<th>$P_j$</th>
<th>$Q_j$</th>
<th>Average loadability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.96952 pu</td>
<td>187.37 MW</td>
<td>-71.54 MVar</td>
<td>0.6618</td>
</tr>
<tr>
<td>After</td>
<td>0.98481 pu</td>
<td>-12.632 MW</td>
<td>28.456 MVar</td>
<td>0.6478</td>
</tr>
</tbody>
</table>

**TABLE 6-5: POWER FLOW RESULTS AFTER UPFC CONTROL (CASE 1)**

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 10-13</td>
<td>528.03 MVA</td>
<td>550 MVA</td>
<td>21.97 MVA</td>
</tr>
<tr>
<td>Line 13-14</td>
<td>532.53 MVA</td>
<td>550 MVA</td>
<td>17.47 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.95672 pu</td>
<td>$V_{min} = 0.95$ pu</td>
<td>0.00672 pu</td>
</tr>
</tbody>
</table>

From TABLE 6-3, it is seen that $\delta_{se}$ undergoes a big change before and after UPFC control, from -86.2 to 80.2. The reason being that before UPFC control, the real power flows from bus 16 to bus 17, however, after UPFC control, the real power flow on line 16-17 reverses direction. Therefore, the firing angle of the series VSC has to change sign.

**6.5.1.2 Case 2: The UPFC is Installed at Bus 15 to Control Power Flow on Line 15-16**

If the operational constraints of the UPFC are chosen as in TABLE 6-2, the output results of the UPFC control program will indicate that the UPFC control cannot relieve overloads and voltage violations. However, if the operational limits of the UPFC are reset as $0 \leq V_{se} \leq 0.4$ and $MVA_{se}, MVA_{sh} \leq 250$ MVA, then the output results of the UPFC
control program are as follows:

- Overloads and voltage violations have been relieved.
- The desired voltage at bus 15 is 1.01277 pu.
- The desired real power on line 15-16 is -424.972 MW.
- The desired reactive power on line 15-16 is 2.204 MVar.
- The average loadability on highly loaded lines is 0.6457.
- The iteration count of LP-based OPF is 1.
- The CPU time is 0.231 second.

The UPFC’s state variables and control targets before and after UPFC control are shown in TABLE 6-6 and TABLE 6-7 respectively and the power flow results after corrective UPFC control are shown in TABLE 6-8.

TABLE 6-6: COMPARISON OF UPFC'S VARIABLES BEFORE AND AFTER CONTROL (CASE 2)

<table>
<thead>
<tr>
<th></th>
<th>$V_{sh}$</th>
<th>$V_{sc}$</th>
<th>$\delta_{sh}$</th>
<th>$\delta_{sc}$</th>
<th>$P_{sh}$</th>
<th>$MVA_{sh}$</th>
<th>$MVA_{sc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.859 pu</td>
<td>0.103 pu</td>
<td>-18.4</td>
<td>50.5</td>
<td>-0.53 MW</td>
<td>170.0 MVA</td>
<td>26.0 MVA</td>
</tr>
<tr>
<td>After</td>
<td>0.879 pu</td>
<td>0.350 pu</td>
<td>-15.5</td>
<td>63.5</td>
<td>10.78 MW</td>
<td>235.6 MVA</td>
<td>152.4 MVA</td>
</tr>
</tbody>
</table>

TABLE 6-7: CONTROL TARGETS OF UPFC BEFORE AND AFTER CONTROL (CASE 2)

<table>
<thead>
<tr>
<th></th>
<th>$V_i$</th>
<th>$P_j$</th>
<th>$Q_j$</th>
<th>Average loadability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.95836 pu</td>
<td>-224.97 MW</td>
<td>-97.8 MVar</td>
<td>0.6618</td>
</tr>
<tr>
<td>After</td>
<td>1.01277 pu</td>
<td>-424.972 MW</td>
<td>2.204 MVar</td>
<td>0.6457</td>
</tr>
</tbody>
</table>

TABLE 6-8: POWER FLOW RESULTS AFTER UPFC CONTROL (CASE 2)

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 10-13</td>
<td>518.73 MVA</td>
<td>550 MVA</td>
<td>31.27 MVA</td>
</tr>
<tr>
<td>Line 13-14</td>
<td>528.56 MVA</td>
<td>550 MVA</td>
<td>21.44 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.96757 pu</td>
<td>$V_{min} = 0.95$ pu</td>
<td>0.01757 pu</td>
</tr>
</tbody>
</table>
From TABLE 6-6, it can be seen that $V_{se}$ is 0.350, which has exceeded its limit of 0.3, because the UPFC needs to control the line flow from -224.97 MW to -424.972 MW; and $MVA_{sh}$ is 235.6 MVA, which also has exceeded its limit of 200 MVA, because the UPFC needs to produce more reactive power to raise the voltage at bus 15 from 0.95836 to 1.01277.

This case indicates that the operational limits of UPFC have a significant effect on the control range of UPFC and it is very important to consider UPFC's operational limits when optimizing power flow with UPFC. Otherwise, we may get an infeasible operating point.

6.5.1.3 Case 3: The UPFC is Installed at Bus 4 to Control Power Flow on Line 4-14

The output results of the UPFC control program are as follows:

- Overloads and voltage violations have been relieved.
- The desired voltage at bus 4 is 0.95369 pu.
- The desired real power on line 4-14 is -350.355 MW.
- The desired reactive power on line 4-14 is 126.12 MVar.
- The average loadability on highly loaded lines is 0.6629.
- The iteration count of LP-based OPF is 2.
- The CPU time is 0.371 second.

The UPFC's state variables and control targets before and after UPFC control are shown in TABLE 6-9 and TABLE 6-10 respectively and the power flow results after corrective UPFC control are shown in TABLE 6-11.

| TABLE 6-9: Comparison of UPFC's Variables before and after Control (Case 3) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | $V_{sh}$        | $V_{se}$        | $\delta_{sh}$  | $\delta_{se}$  | $P_{sh}$        | $MVA_{sh}$      | $MVA_{se}$      |
| Before          | 0.885 pu        | 0.166 pu        | -19.9           | 65.7            | -2.82 MW        | 113.4 MVA       | 74.5 MVA        |
| After           | 0.991 pu        | 0.137 pu        | -21.2           | 131.8           | -31.4 MW        | 84.1 MVA        | 50.9 MVA        |
TABLE 6-10: CONTROL TARGETS OF UPFC BEFORE AND AFTER CONTROL (CASE 3)

<table>
<thead>
<tr>
<th></th>
<th>( V_i )</th>
<th>( P_j )</th>
<th>( Q_j )</th>
<th>Average loadability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>0.94878 pu</td>
<td>-425.54 MW</td>
<td>-73.88 MVar</td>
<td>0.6618</td>
</tr>
<tr>
<td>After</td>
<td>0.95369 pu</td>
<td>-350.36 MW</td>
<td>126.12 MVar</td>
<td>0.6629</td>
</tr>
</tbody>
</table>

TABLE 6-11: POWER FLOW RESULTS AFTER UPFC CONTROL (CASE 3)

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 10-13</td>
<td>532.28 MVA</td>
<td>550 MVA</td>
<td>17.72 MVA</td>
</tr>
<tr>
<td>Line 13-14</td>
<td>548.20 MVA</td>
<td>550 MVA</td>
<td>1.80 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.95369 pu</td>
<td>( V_{\text{min}} = 0.95 ) pu</td>
<td>0.00369 pu</td>
</tr>
</tbody>
</table>

When the LP-based OPF solution in first iteration is checked by an AC power flow, it is found that line 13-14 is still overloaded with an overload of 0.48 MVA (the apparent power on line 13-14 calculated by LP is 545.50 MVA, which is less than the line rating 550 MVA). That means the LP solution is not really feasible. When all the sensitivities are updated at the LP solution and the LP-based OPF is rerun, a feasible solution can be obtained as shown in TABLE 6-9~TABLE 6-11. This case shows that updating sensitivities for the LP-based OPF is essential to enlarge the solutions space.

In the cases shown, although corrective FACTS control is used to relieve only overloads and voltage violations by using existing FACTS devices in the power system, this algorithm could also provide suggestions for locating UPFC from a viewpoint of relieving overloads and voltage violations. By comparing the three cases shown, it can be observed that in Cases 1 and 2, UPFC control not only relieves overloads and voltage violations and achieves larger security margins (see TABLE 6-5 and TABLE 6-8), but also reduces the average loadabilities on highly loaded lines (see TABLE 6-4 and TABLE 6-7). However, in Case 3, although the UPFC control can relieve overloads and voltage violations, the security margins are very small, and the average loadability on highly loaded lines is
increased (see TABLE 6-9–TABLE 6-11). This indicates that line 4-14 is not a good location to install the UPFC from a viewpoint of relieving overloads and voltage violation.

6.5.2 The WECC 179-bus System

The one line diagram of the WECC 179-bus system is shown in Figure 6-7. The outage of line 170-171 is selected as a study case. The contingency analysis results are shown in TABLE 6-12 and the operational limits of the UPFC are shown in TABLE 6-13.
6.5.2.1 **Case 1: The UPFC is Installed at Bus 81 to Control Power Flow on Line 81-99**

The line 81-99 is a transmission corridor connecting the generation rich area in the East with the load center in the center portion of the grid. Therefore, it is assumed that the UPFC is installed at bus 81 to control power flow on line 81-99. The output results of the UPFC control program are as follows:

- Overloads and voltage violations have been relieved.
- The desired voltage at bus 81 is 1.02225 pu.
- The desired real power on line 81-99 is -364.37 MW.
- The desired reactive power on line 81-99 is -143.92 MVar.
- The average loadability on highly loaded lines is 0.6911.
- The iteration count of LP-based OPF is 1.
- The CPU time is 0.386 seconds

TABLE 6-14–TABLE 6-16 show that by the new LP-based OPF algorithm, a UPFC installed on line 81-99 is able to effectively relieve overloads and voltage violations cause by contingency of line 170-171 outage, and lower the average loadability on highly loaded lines at the same time.
TABLE 6-14: COMPARISON OF UPFC’S VARIABLES BEFORE AND AFTER CONTROL (CASE 1)

<table>
<thead>
<tr>
<th></th>
<th>$V_{sh}$</th>
<th>$V_{se}$</th>
<th>$\delta_{sh}$</th>
<th>$\delta_{se}$</th>
<th>$P_{sh}$</th>
<th>$MVA_{sh}$</th>
<th>$MVA_{se}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>1.008 pu</td>
<td>0.053 pu</td>
<td>-23.3</td>
<td>-33.0</td>
<td>27.12 MW</td>
<td>30.60 MVA</td>
<td>28.47 MVA</td>
</tr>
<tr>
<td>After</td>
<td>1.006 pu</td>
<td>0.465 pu</td>
<td>-23.1</td>
<td>-85.7</td>
<td>29.98 MW</td>
<td>44.27 MVA</td>
<td>188.2 MVA</td>
</tr>
</tbody>
</table>

TABLE 6-15: CONTROL TARGETS OF UPFC BEFORE AND AFTER CONTROL (CASE 1)

<table>
<thead>
<tr>
<th></th>
<th>$V_i$</th>
<th>$P_j$</th>
<th>$Q_j$</th>
<th>Average Loadability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>1.0153 pu</td>
<td>-514.37 MW</td>
<td>-83.92 MVar</td>
<td>0.6971</td>
</tr>
<tr>
<td>After</td>
<td>1.02225 pu</td>
<td>-364.37 MW</td>
<td>-143.92 MVar</td>
<td>0.6911</td>
</tr>
</tbody>
</table>

TABLE 6-16: POWER FLOW RESULTS AFTER UPFC CONTROL (CASE 1)

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 170-171</td>
<td>1660.28 MVA</td>
<td>1700 MVA</td>
<td>39.72 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.95377 pu</td>
<td>$V_{\text{min}} = 0.95$ pu</td>
<td>0.00377 pu</td>
</tr>
</tbody>
</table>

6.5.2.2 Case 2: The UPFC is Installed at Bus 28 to Control Power Flow on Line 28-29

It is noted that line 28-29 is another transmission corridor connecting the rich generation area in the East with the load center in the South. Therefore, the UPFC can be installed at bus 28 to control power flow on line 28-29.

When the operational limits of the UPFC are still set as in TABLE 6-13, the results of the UPFC control program show that the UPFC control cannot relieve overloads and voltage violations. However, if the operational limits UPFC are reset as $-80 \leq P_{sh} \leq 80$ MW and $MVA_{se}, MVA_{sh} \leq 650$ MVA, then the output results of the UPFC control program are as follows:

- Overloads and voltage violations have been relieved.
- The desired voltage at bus 28 is 1.03662 pu.
- The desired real power on line 28-29 is 1148.47 MW.
- The desired reactive power on line 28-29 is 22.027 MVar.
- The average loadability on highly loaded lines is 0.6913.
- The iteration time of LP-based OPF is 1.
- The CPU time is 0.382 seconds.

The UPFC’s state variables and control targets before and after UPFC control are shown in TABLE 6-17 and TABLE 6-18 respectively and the power flow results after corrective UPFC control are shown in TABLE 6-19.

### TABLE 6-17: COMPARISON OF UPFC’S VARIABLES BEFORE AND AFTER CONTROL (CASE 2)

<table>
<thead>
<tr>
<th></th>
<th>$V_{sh}$</th>
<th>$V_{se}$</th>
<th>$\delta_{sh}$</th>
<th>$\delta_{se}$</th>
<th>$P_{sh}$</th>
<th>$MVA_{sh}$</th>
<th>$MVA_{se}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>1.189 pu</td>
<td>0.104 pu</td>
<td>-13.6</td>
<td>-164</td>
<td>66.20 MW</td>
<td>360.1 MVA</td>
<td>99.36 MVA</td>
</tr>
<tr>
<td>After</td>
<td>1.035 pu</td>
<td>0.565 pu</td>
<td>-31.5</td>
<td>-122</td>
<td>8.151 MW</td>
<td>8.561 MVA</td>
<td>622.1 MVA</td>
</tr>
</tbody>
</table>

### TABLE 6-18: CONTROL TARGETS OF UPFC BEFORE AND AFTER CONTROL (CASE 2)

<table>
<thead>
<tr>
<th></th>
<th>$V_i$</th>
<th>$P_i$</th>
<th>$Q_i$</th>
<th>Average Loadability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>1.0403 pu</td>
<td>999.96 MW</td>
<td>-37.97 MVar</td>
<td>0.6971</td>
</tr>
<tr>
<td>After</td>
<td>1.03662 pu</td>
<td>1148.47 MW</td>
<td>22.027 MVar</td>
<td>0.6913</td>
</tr>
</tbody>
</table>

### TABLE 6-19: POWER FLOW RESULTS AFTER UPFC CONTROL (CASE 2)

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 170-171</td>
<td>1658.42 MVA</td>
<td>1700 MVA</td>
<td>41.58 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 105</td>
<td>0.95279 pu</td>
<td>$V_{min} = 0.95$ pu</td>
<td>0.00279 pu</td>
</tr>
</tbody>
</table>

From TABLE 6-17, it can be found that before UPFC control, $P_{sh}$ is 66.20 MW, which has exceeded its limit of 50 MW; and $MVA_{sh}$ is 360.1 MVA and $MVA_{se}$ are 622.1 MVA.
after UPFC control, which also have exceeded their limits of 300 MVA. Only after the operational limits of the UPFC are enlarged, can a feasible solution be obtained as shown in TABLE 6-17~TABLE 6-19. However, the UPFC made by Westinghouse Electric Corporation only has the capacity of ±160 MVA for both shunt and series VSCs (a total rating of ±320 MVA) \[73],[90]-[91], and it is very difficult to build a UPFC with a capacity of ±1300 MVar (±650 MVA for each VSC) due to technology limitations and high cost. This case further reveals that it is essential to consider UPFC's operational limits when optimizing power flow with UPFC.

Through these 5 cases, it is observed that although a UPFC has 6 operational limits, only three of them, maximum voltage of series VSC, and MVA ratings of both series and shunt VSCs, are imposing decisive effects on UPFC's operation, and thereby, more attention should be focused on them.

6.6 Summary

Under emergency situation, FACTS devices can be employed for corrective control to relieve overloads and voltage violations caused by system contingencies since FACTS control is economical and fast, and only causes small disturbance to the system. Focusing on UPFC, this chapter presents a new LP-based OPF algorithm for corrective FACTS control. The objective function is to minimize average loadability on highly loaded transmission lines. This algorithm makes it very easy to take into account the operational constraints for FACTS devices during optimization by using a set of newly derived sensitivities for FACTS devices. It is also convenient to incorporate this algorithm with the existing LP-based OPF programs since the decoupled equivalent bus model for FACTS devices is adopted. Simulation results on the New England 39-bus system and the WECC 179-bus system indicate that this algorithm is effective, fast, and accurate in finding the optimal parameter settings for FACTS devices for corrective control.
CHAPTER 7 : BINARY INTEGER PROGRAMMING BASED OPF FOR LINE AND BUS-BAR SWITCHING

7.1 Introduction

Chapter 3 presented a line and bus-bar switching algorithm based on the fast decoupled power flow with limited iteration count. This algorithm is effective and fast enough for small and medium sized systems. However, it may not be suitable for large scale systems.

In this chapter, a binary integer programming (BIP) based OPF algorithm is developed to find the best line and bus-bar switching action for relieving overloads and voltage violations. In the new algorithm, based on the sparse inverse technique and Newton-Raphson sensitivities, an equivalent power compensation model (PCM) for line and bus-bar switching is proposed to simulate complicated and multiple bus-bar switching actions and line switching actions. For the new algorithm, the system size will not impose a significant effect on computational time and the multiple line and bus-bar switching actions can be easily handled. The new algorithm is tested on the 39-bus New England system and the WECC 179-bus system.

7.2 A New Model for Line Switching

In [7]-[10],[20], switching a line out was modeled by adding two power injections [8],[20], or two constant current injections [7],[9]-[10], to the system, one at each end of the line to be switched out. The line was actually left in the system and the effects of its being dropped were modeled by injections, as shown in Figure 7-1.

In these models, the DC distribution factor was employed to calculate the injections such that only real power could be considered and the reactive power and voltage problem were thereby ignored, and the computation results were not accurate enough in many situations.
Moreover, it was very difficult to model a line to be switched in by these models. Therefore, a new line switching model is proposed such that all the problems mentioned above can be easily handled.

![Diagram of Line Outage Model Using Injections](image)

**Figure 7-1: Line Outage Model Using Injections**

### 7.2.1. Switching out a Transmission Line

A line $k$ with a power flow $P_y + jQ_y$ at the sending end and a power flow $P_y + jQ_y$ at the receiving end can be equivalent to two power injections at each end of the line without the line, i.e., the two systems in Figure 7-2 (a) and (b) are equivalent.

![Diagram of Switching out a Transmission Line](image)

**Figure 7-2: Diagrams of Switching out a Transmission Line**
In Figure 7-2, the system (a) becomes the system (c) by switching out the line \( k \), and the system (b) becomes the system (d) by adding two power injections, which are opposite to the original line flow. Thus the system (c) and the system (d) are equivalent, and they are both equivalent to the system (e), where the line \( k \) is still left in the system and the effects of its being switched out are modeled by two power injections.

Let matrix \( A \) be the Newton-Raphson sensitivity matrix of bus power injections with respect to system state variables, bus voltage angles \( \delta \) and bus voltage magnitude \( V \), in the original system (a), i.e.,

\[
A = \begin{bmatrix}
\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\
\frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}
\end{bmatrix} = \begin{bmatrix}
\text{Re}\left(\frac{\partial S}{\partial \delta}\right) & \text{Re}\left(\frac{\partial S}{\partial V}\right) \\
\text{Im}\left(\frac{\partial S}{\partial \delta}\right) & \text{Im}\left(\frac{\partial S}{\partial V}\right)
\end{bmatrix}
\] (7-1)

where \( P \) and \( Q \) are the bus real and reactive power injection vectors, \( \delta \) and \( V \) are the bus voltage angle and magnitude vectors, \( S \) is the bus complex power injection vector.

Let \( B \) be the sensitivity matrix of bus power injections at bus \( i \) and bus \( j \) with respect to bus generations, i.e.,

\[
B = \begin{bmatrix}
\frac{\partial P}{\partial P_g} & \frac{\partial P}{\partial Q_g} \\
\frac{\partial Q}{\partial P_g} & \frac{\partial Q}{\partial Q_g}
\end{bmatrix} = \begin{bmatrix}
1 & i \\
\text{1} & j \\
\text{1} & \text{nb} + i \\
\text{1} & \text{nb} + j
\end{bmatrix}
\] (7-2)

where \( P_g \) and \( Q_g \) are bus real and reactive generation vectors at bus \( i \) and bus \( j \), \( nb \) is the number of buses.

For the original system (a), the Newton-Raphson sensitivities can be obtained as follows,
\[
\frac{\partial \mathbf{S}}{\partial \delta} = j \cdot \text{diag} \mathbf{V} \cdot (\text{diag} \mathbf{I} - \mathbf{Y} \cdot \text{diag} \mathbf{V})^* \\
\frac{\partial \mathbf{S}}{\partial \mathbf{V}} = (\text{diag} \mathbf{I})^* \cdot \text{diag} \mathbf{V}_\delta + \text{diag} \mathbf{V} \cdot (\mathbf{Y} \cdot \text{diag} \mathbf{V}_\delta)^*
\]

where \( \text{diag} \mathbf{V} \) is the diagonal matrix with system voltage vector \( \mathbf{V} \) as the diagonal, \( \text{diag} \mathbf{I} \) is the diagonal matrix with system bus current injection \( \mathbf{I} = \mathbf{Y} \cdot \mathbf{V} \) as the diagonal, \( \mathbf{Y} \) is the system admittance matrix, \( \text{diag} \mathbf{V}_\delta \) is the diagonal matrix with normalized system voltage vector \( \cos \delta + j \sin \delta \) as the diagonal.

For the original system (a) and the modified system (b), the state variables, bus voltage magnitudes and angles, are the same, and the only difference between them is the system admittance matrix. By node-oriented modification method [80], the system admittance modification matrix can be expressed as follows:

\[
\Delta \mathbf{Y} = \mathbf{M} \cdot \delta \mathbf{y} \cdot \mathbf{M}^T = \begin{bmatrix}
1 & 1 \\
1 & 1 \\
\end{bmatrix} \begin{bmatrix}
\frac{\Delta y_{\text{series}}}{2} + \frac{\Delta y_{\text{shunt}}}{2} & -\Delta y_{\text{series}} \\
-\Delta y_{\text{series}} & \frac{\Delta y_{\text{series}}}{2} + \frac{\Delta y_{\text{shunt}}}{2}
\end{bmatrix} \begin{bmatrix}
1 & 1 \\
1 & 1 \\
\end{bmatrix}
\]

(7-5)

Hence, the difference between sensitivities of the original system (a) and the modified system (b) is,

\[
\Delta \frac{\partial \mathbf{S}}{\partial \delta} = j \cdot \text{diag} \mathbf{V} \cdot (\Delta \text{diag} \mathbf{I} - \Delta \mathbf{Y} \cdot \text{diag} \mathbf{V})^* \\
\Delta \frac{\partial \mathbf{S}}{\partial \mathbf{V}} = (\Delta \text{diag} \mathbf{I})^* \cdot \text{diag} \mathbf{V}_\delta + \text{diag} \mathbf{V} \cdot (\Delta \mathbf{Y} \cdot \text{diag} \mathbf{V}_\delta)^*
\]

where \( \Delta \text{diag} \mathbf{I} \) is the diagonal matrix with system bus current injection modification \( \Delta \mathbf{I} = \Delta \mathbf{Y} \cdot \mathbf{V} \) as the diagonal.
It can be noted that the matrices $\Delta \frac{\partial S}{\partial \delta}$ and $\Delta \frac{\partial S}{\partial V}$ are sparse matrices with only 4 elements at corresponding locations. Therefore, the incremental Newton-Raphson sensitivity matrix $\Delta A$ has only 16 elements at corresponding locations. Let $\Delta a$ be the matrix consisting of these non-zero elements in $\Delta A$, which can be obtained from (7-6)-(7-7), then

\[
\Delta A = \begin{bmatrix}
\operatorname{Re}(\Delta \frac{\partial S}{\partial \delta}) & \operatorname{Re}(\Delta \frac{\partial S}{\partial V}) \\
\operatorname{Im}(\Delta \frac{\partial S}{\partial \delta}) & \operatorname{Im}(\Delta \frac{\partial S}{\partial V})
\end{bmatrix}
\begin{bmatrix}
i \\
j
\end{bmatrix}
= \begin{bmatrix}
i \\
j
\end{bmatrix} \cdot \Delta a \cdot 
\begin{bmatrix}
1 & 1 \\
1 & 1
\end{bmatrix}
= B \cdot \Delta a \cdot B^T
\]

(7-8)

Let $\Delta X = \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix}$ be the incremental system state variable vector and $\Delta G = [P_y, P_{ji}, Q_y, Q_{ji}]^T$ be the power injection vector in the system (d), then the system power balance equation describing changes from the system (b) to the system (d) is,

\[
(A + \Delta A) \cdot \Delta X = (A + B \cdot \Delta a \cdot B^T) \cdot \Delta X = B \cdot \Delta G
\]

(7-9)

By the inverse matrix modification lemma [80],

\[
\Delta X = (A^{-1} - A^{-1} \cdot B \cdot C \cdot B^T \cdot A^{-1}) \cdot B \cdot \Delta G
\]

(7-10)

Where $C = (\Delta a^{-1} + Z)^{-1}$ and $Z = B^T \cdot A^{-1} \cdot B$

Let $\Delta G_c = [P_{g,i}, P_{g,j}, Q_{g,i}, Q_{g,j}]^T$ be the power compensation vector in the system (e), then the system power balance equation describing changes from the system (a) to the system (e) is as follows,
\[
A \cdot \Delta X = B \cdot \Delta G_c \tag{7-11}
\]

Hence,

\[
\Delta G_c = (B^T \cdot B)^{-1} B^T \cdot A \cdot \Delta X = B^T \cdot A \cdot \Delta X \tag{7-12}
\]

Since the systems (a) and (b) are equivalent and the systems (d) and (e) are equivalent, the incremental state variables \(\Delta X\) in (7-10) and (7-12) should also be the same, then

\[
\Delta G_c = B^T \cdot A \cdot (A^{-1} - A^{-1} \cdot B \cdot C \cdot B^T \cdot A^{-1}) \cdot B \cdot \Delta G
\]

\[
= B^T \cdot (I - B \cdot C \cdot B^T \cdot A^{-1}) \cdot B \cdot \Delta G
\]

\[
= (B^T - C \cdot B^T \cdot A^{-1}) \cdot B \cdot \Delta G
\tag{7-13}
\]

where I is the identity matrix.

The power compensations for switching out multiple lines can be also calculated by (7-13).

**7.2.2 Switching in a Transmission Line**

The diagrams for switching in a transmission line are shown in Figure 7-3.

![Diagram of switching in a transmission line](image-url)
In Figure 7-3, the system (a) is equivalent to the system (b), and the power injections are equal to the power flow on the line $k$ by the compensation criteria [20]. Since the bus voltage magnitudes and angles of both bus $i$ and bus $j$ can be obtained from the original system (a), the power flows on line $k$ are as follows:

$$P_i + jQ_i = \bar{V}_i \cdot (\bar{V}_i - \bar{V}_j) \cdot y_{ij} - V_i^2 \cdot b_{ij} / 2$$  \hspace{1cm} (7-14)

$$P_j + jQ_j = \bar{V}_j \cdot (\bar{V}_j - \bar{V}_i) \cdot y_{ij} - V_j^2 \cdot b_{ij} / 2$$  \hspace{1cm} (7-15)

where $y_{ij}$ is the series admittance of line $k$, and $b_{ij}$ is the shunt susceptance of line $k$.

Let $\Delta G = [P_g, P_j, Q_g, Q_j]^T$ be the power injection vector in the system (d), then the power compensation vector in the system (e), $\Delta G_c = [P_{g,i}, P_{g,j}, Q_{g,i}, Q_{g,j}]^T$, can be obtained as described in Section 7.2.1,

$$\Delta G_c = B^T \cdot A \cdot (A^{-1} - A^{-1} \cdot B \cdot C \cdot B^T \cdot A^{-1}) \cdot B \cdot \Delta G$$

$$= B^T \cdot (I - B \cdot C \cdot B^T \cdot A^{-1}) \cdot B \cdot \Delta G$$  \hspace{1cm} (7-16)

where $I$ is the identity matrix.

The power compensations for switching out multiple lines can be also calculated by (7-16).

Equations (7-13) and (7-16) have the same expressions except that the power injection vectors are different. Thus, the proposed power compensation model (PCM) can simulate both switching out a line and switching in a line. In the model, the system configuration is not changed and the effects of switching lines can be modeled as two power injections which can be calculated by (7-13) or (7-16).

### 7.3 A New Model for Bus-bar Switching

The general bus-bar switching model proposed in chapter 3 is still employed here. Thus, a bus-bar switching scenario is equivalent to multiple line switching actions. For a bus-bar with $m$ lines connected to it (including load and shunt elements), every new node generated
is involved in every bus-bar switching scenario, and thereby, the power injection vector
\( \Delta G = [P_1, ..., P_m, Q_1, ..., Q_m]^T \) and the power compensation vector,
\( \Delta G_C = [P_{g,1}, ..., P_{g,m}, Q_{g,1}, ..., Q_{g,m}]^T \) both have the dimension of \( 2m \times 1 \). For the \( n^{th} \) new node, the corresponding elements in \( \Delta G \), \( P_n \) and \( Q_n \), are equal to the summation of power flows on all breaker lines which are connected to it and will be switched out.

For the bus-bar switching action shown in Figure 7-4,
\[
\Delta G = [P_1, P_2, P_3, P_4, Q_1, Q_2, Q_3, Q_4]^T,
\]
where \( P_1 = P_{13} + P_{14} \), \( P_2 = P_{23} + P_{24} \), \( P_3 = P_{31} + P_{32} \), \( P_4 = P_{41} + P_{42} \) and \( Q_1 = Q_{13} + Q_{14} \), \( Q_2 = Q_{23} + Q_{24} \), \( Q_3 = Q_{31} + Q_{32} \), \( Q_4 = Q_{41} + Q_{42} \). Thus, the power compensations at all new nodes can be calculated by (7-13).

![Diagram of a bus-bar with four branches](image)

(a) The Model of the Bus-bar with Four Lines  (b) Switching Action with the Lines L1 and L2 on One Bus-bar and Lines L3 and L4 on the Other Bus-bar

**Figure 7-4: The Model Diagrams of a Bus-bar with Four Branches**

### 7.4 Binary Integer Programming Based OPF for Line and Bus-bar Switching

#### 7.4.1 System State Variables

It is presumed that the objective of line and bus-bar switching is to only relieve
overloads and voltage violations without changing the real power and reactive power outputs of generators. Therefore, the system state variables are the voltage magnitudes at all PQ buses and voltage angles at all buses except the reference bus and the total number of state variables is \( nb + npq - 1 \), where \( nb \) is the number of buses and \( npq \) is the number of PQ buses.

### 7.4.2 Control Variables

The control variables are the binary integer variables representing line switching and bus-bar switching actions, as defined as follows,

\[
u_i = \begin{cases} 
1, & \text{if line } i \text{ is switched out/in, or bus-bar switching scenario } i \text{ is chosen} \\
0, & \text{otherwise}
\end{cases}
\]  

(7-17)

### 7.4.3 Objective Function

Since the line and bus-bar switching mainly affect the power flows on transmission lines, the objective function of line and bus-bar switching can be chosen as minimizing average loadability on highly loaded lines, as shown in (7-18),

\[
\text{Min } \Delta z = \frac{1}{2nh} \left\{ \sum_{i=1}^{nh} \left( \frac{\partial MVA_y}{\partial x} + \frac{\partial MVA_x}{\partial x} \right) \Delta x \right\} MVA_{i,\text{max}}
\]

(7-18)

where \( nh \) is the number of highly loaded lines whose loadabilities are larger than the loadability index. Usually, the loadability index can be set as 0.5.

### 7.4.4 Equality Constraints

The equality constraints include bus real power balance (for all PV buses and PQ buses), bus reactive power balance (for all PQ buses), and the constraints for the number of switching actions. The linearized power constraint is as follows:

\[
A \cdot \Delta X = D \cdot u
\]

(7-19)
where \( A \) is the system Newton-Raphson sensitivity matrix, and \( D = [D_1 \ D_2] \) is the power compensation matrix for switching actions and \( D_1 \) is the compensation submatrix for line switching power actions and \( D_2 \) is the power compensation submatrix for bus-bar switching actions.

For the submatrices \( D_1 \) or \( D_2 \), the \( k^{th} \) column is the power compensation vector for the \( k^{th} \) line switching or bus-bar switching scenario, i.e.,

\[
D_k = B_k \cdot \Delta G_{c,k}
\]  

(7-20)

where \( B_k \) and \( G_{c,k} \) can be obtained as described in Sections 7.2 and 7.3.

The constraint for the number of switching actions has different expressions depending on different requirements.

If only one line switching or one bus-bar switching is allowed at one time, then we have

\[
\sum_{i=1}^{n_l+n_{bb}} u_i \leq 1
\]  

(7-21)

If one line switching and one bus-bar switching are allowed at one time, then we have

\[
\sum_{i=1}^{n_l+n_{bb}} u_i \leq 2
\]  

(7-22)

\[
\sum_{i=1}^{n_l} u_i \leq 1
\]  

(7-23)

\[
\sum_{i=1+n_l}^{n_l+n_{bb}} u_i \leq 1
\]  

(7-24)

where \( n_l \) is the number of line switching candidates and \( n_{bb} \) is the number of total bus-bar switching scenarios.

7.4.5 Inequality Constraints

The inequality constraints are system security constraints, such as line flow constraints (including receiving end flow and sending end flow) and bus voltage magnitude constraints.
The linearized system security constraints are as follows:

\[ MVA_{ij}(x^0) + \frac{\partial MVA_{ij}(x^0)}{\partial x} \Delta x \leq MVA_{i,\text{max}} \]  
(7-25)

\[ MVA_{ij}(x^0) + \frac{\partial MVA_{ij}(x^0)}{\partial x} \Delta x \leq MVA_{i,\text{max}} \]  
(7-26)

\[ V_{j,\text{min}} \leq V_j(x^0) + \Delta V_j \leq V_{j,\text{max}} \]  
(7-27)

where \( i = 1, 2, \ldots, nl \) and \( j = 1, 2, \ldots, npq \).

7.4.6 Algorithm

Bus-bar switching is always preferred to line switching since bus-bar switching only causes small disturbances in power systems. Therefore, in the proposed algorithm, BIP-based OPF is first employed to find the best bus-bar switching action. If there is no feasible bus-bar switching action, BIP-based OPF is then employed to find the best line switching action. If there is still no feasible line switching action, BIP-based OPF is finally employed to find the best combined line and bus-bar switching actions. More than one line switching and more than one bus-bar switching are not allowed in order to maintain the system security above an accepted level.

The new BIP based OPF line and bus-bar switching algorithm is outlined as follows:

(1) Data input.
(2) Contingency analysis.
(3) If there is overload or voltage violation, go to step (4), otherwise, go to step (13).
(4) Establish models for all bus-bar switching.
(5) Calculate Newton-Raphson sensitivities for base case.
(6) Calculate power compensations for all line switching and bus-bar switching candidates.
(7) Run BIP-based OPF for bus-bar switching.
(8) If find a solution, check it with AC power flow. If this solution is feasible, record the results. Otherwise, go to step (13)

(9) Run BIP-based OPF for line switching.

(10) If find a solution, check it with AC power flow. If this solution is feasible, record the results. Otherwise, go to step (13)

(11) Run BIP-based OPF for line and bus-bar switching.

(12) If find a solution, check it with AC power flow. If this solution is feasible, record the results. Otherwise, BIP-based OPF cannot find a feasible corrective switching solution, go to step (13).

(13) Stop and print all results.

7.5 Case Studies

The BIP-based OPF algorithm is implemented with MATLAB and tested on the New England 39-bus system and the WECC 179-bus system on a PC (2.8MHz CPU).

7.5.1 The New England 39-bus System

7.5.1.1 Line Switching Solution

The outage of line 7 (from bus 4 to bus 5) is selected to test the proposed line and bus-bar switching algorithm, and the contingency analysis results are shown in TABLE 7-1.

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 17</td>
<td>10</td>
<td>13</td>
<td>568.26 MVA</td>
<td>550 MVA</td>
<td>18.26 MVA</td>
</tr>
<tr>
<td>LINE 18</td>
<td>13</td>
<td>14</td>
<td>574.69 MVA</td>
<td>550 MVA</td>
<td>24.69 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.94937 pu</td>
<td>( V_{\text{min}} = 0.95 \text{ pu} )</td>
<td>- 0.00063 pu</td>
</tr>
</tbody>
</table>
30 lines are selected as line switching candidates and the output results of the line and bus-bar switching program are as follows:

- Bus-bar switching actions cannot relieve all the overloads and voltage violations.
- Overloads and voltage violations have been relieved by line switching action.
- The best switching action is to switch out line 1 (from bus 1 to bus 2).
- The average loadability on highly loaded lines is 0.6518.
- The CPU time is 0.118 seconds.

The power flow results after switching out line 1 are shown in TABLE 7-2, and the system diagram for the switching action is shown in Figure 7-5.

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 17</td>
<td>10</td>
<td>13</td>
<td>531.15 MVA</td>
<td>550 MVA</td>
<td>18.85 MVA</td>
</tr>
<tr>
<td>Line 18</td>
<td>13</td>
<td>14</td>
<td>534.02 MVA</td>
<td>550 MVA</td>
<td>15.98 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 4</td>
<td>0.95021 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>$V_{\text{max}} = 1.05 \text{ pu}$</td>
</tr>
</tbody>
</table>

TABLE 7-2 shows that switching out line 1 can effectively relieve overloads and voltage violation and reduce the average loadability on highly loaded lines from 0.6617 to 0.6518 at the same time.

7.5.1.2 Bus-bar Switching Solution

The system operation conditions are modified in order to test the bus-bar switching algorithm. The outage of line 7 (from bus 4 to bus 5) is still selected for analysis. The contingency analysis results are shown in TABLE 7-3.
Line 1 is recommended to be switched off.

Voltage violation at bus 4 is relieved.

Overloads on lines 17 and 18 are relieved.

Contingency: Outage of Line 7

**FIGURE 7-5: LINE 1 IS RECOMMENDED TO BE SWITCHED OUT**

**TABLE 7-3: CONTINGENCY ANALYSIS RESULTS FOR OUTAGE OF LINE 7**

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 17</td>
<td>10</td>
<td>13</td>
<td>561.27 MVA</td>
<td>550 MVA</td>
<td>11.27 MVA</td>
</tr>
<tr>
<td>Line 18</td>
<td>13</td>
<td>14</td>
<td>569.61 MVA</td>
<td>550 MVA</td>
<td>19.61 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>1.0523 pu</td>
<td>$V_{min} = 0.95$ pu, $V_{max} = 1.05$ pu</td>
<td>+0.0023 pu</td>
</tr>
</tbody>
</table>

The buses 2, 8, 16, and 26 are selected as bus-bar switching candidates. The output
results of the line and bus-bar switching program are as follows:

- Overloads and voltage violation have been relieved by bus-bar switching.
- The best switching action is to split off bus-bar 2 with line 1-2 and line 2-3 being switched on one split bus-bar (bus 2'), and line 2-25 and line 2-30 being switched on the other split bus-bar (bus 2")
- The average loadability on highly loaded lines is 0.6947.
- The CPU time is 0.159 seconds.

The power flow results after splitting bus-bar 2 are shown in TABLE 7-4 and the system diagram for splitting bus-bar 2 is shown in Figure 7-6.

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>From Bus</th>
<th>To Bus</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 17</td>
<td>10</td>
<td>13</td>
<td>537.21 MVA</td>
<td>550 MVA</td>
<td>12.79 MVA</td>
</tr>
<tr>
<td>Line 18</td>
<td>13</td>
<td>14</td>
<td>538.34 MVA</td>
<td>550 MVA</td>
<td>11.66 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>1.03983 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$</td>
<td>0.01017 pu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{\text{max}} = 1.05 \text{ pu}$</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 7-4 shows that the bus-bar switching can effectively relieve overloads and voltage violation. However, it is seen that the average loadability on highly loaded lines after bus-bar switching is increased from 0.6763 to 0.6947.

Furthermore, if line switching and bus-bar switching are calculated at the same time, it is found that switching out line 1-2 not only could relieve overloads and voltage violation but also could decrease the average loadability on highly loaded lines from 0.6763 to 0.6683, and therefore, is selected as the best switching action. In this algorithm, bus-bar switching, however, is still chosen as the best switching action because it will cause small disturbances in the system.
7.5.2 The WECC 179-bus System

The one-line diagram of the WECC 179-bus system is shown in Figure 7-7.

7.5.2.1 Bus-bar Switching Solution

The outage of line 170-171 is selected to test the proposed line and bus-bar switching algorithm, and the contingency analysis results are shown in TABLE 7-5.
FIGURE 7-7: ONE-LINE DIAGRAM OF THE WECC 179-BUS SYSTEM

TABLE 7-5: CONTINGENCY ANALYSIS RESULTS FOR OUTAGE OF LINE 170-171

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 83-168</td>
<td>1729.25 MVA</td>
<td>1700 MVA</td>
<td>29.25 MVA</td>
</tr>
<tr>
<td>Line 168-169</td>
<td>1744.10 MVA</td>
<td>1700 MVA</td>
<td>44.10 MVA</td>
</tr>
<tr>
<td>Line 169-114</td>
<td>1724.10 MVA</td>
<td>1700 MVA</td>
<td>24.10 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 84</td>
<td>1.06028 pu</td>
<td>$V_{\min} = 0.95$ pu, $V_{\max} = 1.06$ pu</td>
<td>+0.00028 pu</td>
</tr>
</tbody>
</table>
The output results of the line and bus-bar switching program are as follows:

- Overloads and voltage violations have been relieved by bus-bar switching.
- The best switching action is to split off bus-bar 83 with lines 83-94, 83-98, 83-168, and load 83 being switched on one split bus (bus 831) and lines 83-89 and 83-172 being switched on the other split bus-bar (bus 832).
- The average loadability on highly loaded lines is 0.6912.
- The CPU time for the analysis is 1.859 seconds.

The power flow results after the splitting bus-bar 83 are shown in TABLE 7-6 and the system diagram for the switching action is shown in Figure 7-8 (The arrows represent the directions of power flow.).

TABLE 7-6 shows that splitting bus-bar 83 can effectively relieve overloads and voltage violation and reduce the average loadability on highly loaded lines from 0.6968 to 0.6912 at the same time.

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 83-168</td>
<td>1530.56 MVA</td>
<td>1700 MVA</td>
<td>169.44 MVA</td>
</tr>
<tr>
<td>Line 168-169</td>
<td>1531.06 MVA</td>
<td>1700 MVA</td>
<td>168.94 MVA</td>
</tr>
<tr>
<td>Line 169-114</td>
<td>1533.85 MVA</td>
<td>1700 MVA</td>
<td>166.15 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 84</td>
<td>1.05763 pu</td>
<td>$V_{\text{min}} = 0.95 \text{ pu}$  $V_{\text{max}} = 1.06 \text{ pu}$</td>
<td>0.00247 pu</td>
</tr>
</tbody>
</table>
7.5.2.2  Line and Bus-bar Switching Solution

For the same contingency of line 170-171 outage, if more power is transferred from the North part of system to the South part, more overloads are caused on line 83-168, 168-169, and 169-114, as shown in TABLE 7-7. Thus, no single bus-bar switching action or single line switching action can relieve all overloads and voltage violations. However, a combination solution of line and bus-bar switching actions could be found, as shown in Figure 7-9 and TABLE 7-8.

TABLE 7-7: CONTINGENCY ANALYSIS RESULTS FOR OUTAGE OF LINE 170-171

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Amount of Overload</th>
</tr>
</thead>
<tbody>
<tr>
<td>1772.99 MVA</td>
<td>1700 MVA</td>
<td>72.99 MVA</td>
<td>1772.99 MVA</td>
</tr>
<tr>
<td>1793.82 MVA</td>
<td>1700 MVA</td>
<td>93.82 MVA</td>
<td>1793.82 MVA</td>
</tr>
<tr>
<td>1761.43 MVA</td>
<td>1700 MVA</td>
<td>61.43 MVA</td>
<td>1761.43 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Amount of Voltage Violation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 81</td>
<td>1.06049 pu</td>
<td>$V_{min} = 0.95$ pu $V_{max} = 1.06$ pu</td>
<td>+0.00049 pu</td>
</tr>
</tbody>
</table>

FIGURE 7-8: THE RELEVANT PORTION OF THE WECC 179-BUS SYSTEM
The output results of the line and bus-bar switching program are as follows:

- Overloads and voltage violations have been relieved by line switching action and bus-bar switching action.
- The best switching actions are to switching out line 81-99 and split off bus-bar 83 with lines 83-94, 83-98, 83-172, and load 83 being switched on one split bus (bus 831) and lines 83-89 and 83-168 being switched on the other split bus-bar (bus 832).
- The average loadability on highly loaded lines is 0.5463.
- The CPU time for the analysis is 3.359 seconds.

The power flow results after the switching actions are shown in TABLE 7-8 and the system diagram for the switching actions is shown in Figure 7-9 (The arrows represent the directions of power flow.).

From TABLE 7-8, it can be seen that not only all overloads and voltage violation are relieved by switching out line 81-99 and splitting bus-bar 83, but also the average loadability on highly loaded lines is greatly reduced, from 0.7002 to 0.5463.

By comparing these two cases, it can be observed that the bus-bar 83 is split in different scenarios (see Figure 7-8 and Figure 7-9), which shows that the general bus-bar switching model proposed in chapter 3 is very effective to simulate any kind of bus-bar switching scenario.

### TABLE 7-8: POWER FLOW RESULTS AFTER SPLITTING OFF BUS-BAR 83

<table>
<thead>
<tr>
<th>Overloaded Line</th>
<th>Line Flow</th>
<th>Line Flow Rating</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 83-168</td>
<td>1506.72 MVA</td>
<td>1700 MVA</td>
<td>193.28 MVA</td>
</tr>
<tr>
<td>Line 168-169</td>
<td>1523.45 MVA</td>
<td>1700 MVA</td>
<td>176.55 MVA</td>
</tr>
<tr>
<td>Line 169-114</td>
<td>1486.80 MVA</td>
<td>1700 MVA</td>
<td>213.20 MVA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Violation</th>
<th>Bus Voltage</th>
<th>Voltage Limits</th>
<th>Security Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 81</td>
<td>1.04824 pu</td>
<td>$V_{max} = 1.06$ pu</td>
<td>0.01176 pu</td>
</tr>
</tbody>
</table>
7.6 Summary

Under the environment of restructuring the power industry, line and bus-bar switching has a great advantage of economy compared with other corrective control methods, such as generation rescheduling, load shedding, and system islanding. In order to improve computational speed such that the line and bus-bar switching could be applied for large-scale power systems, the following work dealing with line and bus-bar switching has been done in this chapter:

- A new model for line switching and bus-bar switching is proposed based on the Newton-Raphson method and sparse inverse technique. This model can take into account both real power and voltage issues and simplifies the handling of both switching in lines as well as switching out lines.
- A BIP based OPF algorithm for line and bus-bar switching is developed to relieve overloads and voltage violations caused by system contingencies. With this algorithm, the size of systems will not significantly affect the computational time and multiple switching actions can be easily handled.
Simulation studies on the 39-bus New England system and the WECC 179-bus system show that the proposed BIP based OPF algorithm for line and bus-bar switching is able to effectively solve the problems of overloads and voltage violations and significantly reduce the computing time.

Since the new algorithm is based on the Newton-Raphson sensitivities, it is very easy to incorporate this algorithm with the existing LP-based OPF programs to enlarge the solution space under emergency situation by adding line and bus-bar switching as a control strategy.
CHAPTER 8 : CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

In this research, the application of transmission system reconfiguration (TSR) for corrective control has been investigated. This research has been motivated mainly by the great economical advantage of TSR under the environment of deregulation and its ability for fast control. This research has focused on using TSR actions, including transmission line switching, bus-bar switching, shunt element switching, and FACTS control, to relieve overloads and voltage violations caused by system contingencies. The main contributions of this research are the development of the general models for line switching and bus-bar switching, the derivation of multiple iteration based voltage distribution factor for shunt element switching, and the development of TSR algorithms for line and bus-bar switching, shunt element switching, and corrective FACTS control. All the proposed new algorithms have been implemented with MATLAB and tested on the New England 39-bus system and the WECC 179-bus system. The simulation results indicate that they could effectively solve the problems of overloads and voltage violations and significantly reduce computing time.

8.2 Specific Contributions

The specific contributions of this research can be summarized as follows:

1. Development of a general bus-bar switching model. All the previous studies could only deal with simple bus-bar switching, which limited the research for bus-bar switching in some sense. This model, however, considers all kinds of bus-bar layouts, including breaker-and-a-half, double-bus-single-breaker, double-bus-double-breaker, and main-and-transfer-bus, etc, such that any complicated bus-bar switching scenario can be simulated.
2. **Development of power compensation model (PCM) for line switching and bus-bar switching.** In the past studies for power injection model or current compensation model for line switching, the DC distribution factor was employed to calculate the injections and only real power could be considered. Although the computational speed was fast, the computation results were not accurate enough in many situations. Moreover, it was very difficult to model a line to be switched in by these models. This PCM, however, is based on the Newton-Raphson sensitivities and the sparse inverse technique such that both real power and reactive power could be taken into account. It is also very easy to deal with switching in and switching out a transmission line as well as multiple line switching and bus-bar switching. This model builds the foundation for using LP method to treat line and bus-bar switching.

3. **Development of multiple iteration based voltage distribution factor (VDF) for shunt element switching.** All the past studies on reactive power/voltage distribution factor only considered the first iteration in the power flow calculation [53]-[56]. However, in some situation this could cause big errors. This research, however, has derived a new voltage distribution factor based on multiple iterations in the fast decoupled power flow, and the simulation results show that the new VDF could significantly reduce the computation error due to linearization.

4. **Development of the line and bus-bar switching algorithm based on the fast decoupled power flow with limited iteration count.** In this algorithm, the fast decoupled power flow is employed to obtain both real power and voltage solutions and in order to get a trade off between convergence accuracy and computational speed, the iteration tolerance is enlarged and the iteration count is limited. A performance index of security margin (PISM) is defined to evaluate the line and bus-bar switching actions, which can take into account line flow margin and bus
voltage margin at the same time. Simulation results indicate that this algorithm is effective and fast enough to find line and bus-bar switching solution for small and medium sized systems.

5. **Development of the shunt switching algorithm for corrective voltage control based on voltage change matrix.** Based on the newly derived VDF, the concept of voltage change matrix (VCM) is proposed in this research. The VCM is built with the voltage change vectors per bank (bank capacity times corresponding voltage distribution factor vector) as columns such that any linear combination of the columns represents the voltage change vector corresponding to multiple shunt switching actions. Then the system voltage security margin (SVSM) is defined to evaluate shunt switching actions. This shunt switching algorithm is very fast since no power flow calculation is involved.

6. **Integration of line switching, bus-bar switching, and shunt switching algorithms.** Line and bus-bar switching is mainly used to solve the overload problem and shunt element switching is mainly employed to deal with the voltage problem. In some severe situations, the overloads and voltage violations may not be relieved by only line and bus-bar switching or only by shunt switching. Therefore, this research integrates the line switching, bus-bar switching, and shunt switching algorithms into one corrective switching algorithm in order to enlarge the solution space for corrective control. Simulation results show that the integrated corrective switching algorithm can effectively solve the problems of overloads and voltage violations.

7. **Development of LP-based OPF for corrective FACTS control.** The robustness and high computational speed of the LP method makes it attractive for FACTS control. In this research, the sensitivities of FACTS devices are derived such that
the operational constraints of FACTS devices could be taken into account during optimization. Then an LP-based OPF algorithm for corrective FACTS control is developed to minimize the average loadability on highly loaded lines as an objective function. Simulation results show that this algorithm is fast for on-line corrective control and overcomes the shortcoming of not taking into account the operational constraints of FACTS devices.

8. Development of BIP-based OPF for line and bus-bar switching. The fast decoupled power flow based line and bus-bar switching algorithm proposed in chapter 3 is accurate and fast enough for small and medium sized systems. However, it may not be suitable for large scale systems and it is hard to handle multiple switching actions. Therefore, this research develops a BIP-based OPF algorithm for line and bus-bar switching based on the newly proposed power compensation model. Simulation results indicate that this algorithm is not only very effective in considering multiple switching actions, but can also significantly reduce computational time. This algorithm establishes the foundation for incorporating line and bus-bar switching with the commonly used LP-based OPF algorithms.

8.3 Future Work

The requirements for on-line corrective control are high speed and effectiveness. Under emergency situations, finding a feasible solution is more important than finding an optimal solution. This research has proposed a general framework for transmission system reconfiguration. Future work should focus on the following aspects.

1. Network reduction or local adaptation. For a large-scale interconnected transmission system, if the whole system is modeled for calculation, it will take a long time to get the solution. However, it is widely known that a contingency only
has a limited geographical effect [20]. Therefore, the corrective actions which could relieve overloads and voltage violations are limited in the local region around the overloaded lines and buses with voltage problem. If the system could be reduced to a relative small size, the TSR algorithms proposed in this research would solve the problems of overloads and voltage violations more effectively. Therefore, further studies are needed for network reduction or local adaptation.

2. **Incorporation of the proposed TSR algorithms with the existing LP-based programs.** This research has proposed an LP-based OPF algorithm for corrective FACTS control and a binary integer programming based OPF algorithm for line and bus-bar switching. This has established the foundation to incorporate the TSR algorithms with the existing LP-based OPF programs to enlarge the solution space for corrective control. Further studies in this area will improve the practical value of this research. This is also the final research target for this project.

3. **Consideration of dynamic performance of the TSR actions.** This research has only focused on the steady-state performance of TSR actions. However, the dynamic effects of the TSR actions are not negligible. The system may be vulnerable if the dynamical effects of TSR actions are always ignored, as shown in Section 5.5. However, dynamical analysis is computationally burdensome and is a bottleneck for on-line corrective control. Further research on dynamic performance of the TSR actions is challenging but important.
REFERENCES


http://www.eecs.wsu.edu/~mani/yonghong.PDF.


