

**Investigation of Inter-Area Available Transfer Capability (ATC) with Respect
to Network and Load Changes**

A Thesis

Submitted to the Faculty

of

Drexel University

by

Saffet Ayasun

in partial fulfillment of the

requirements for the degree

of

Master of Science

in Electrical Engineering

December 1997

To my parents and Elcin Kentel

ACKNOWLEDGMENTS

I would like thank my advisor, Dr. Robert Fischl, for his guidance, patience, encouragement and direction during the completion of this work. The many challenges and learning opportunities he has offered will always be appreciated. I would also like to thank the members of my thesis committee: Dr. R. Fischl, Dr. C. Nwankpa, Dr. D. Niebur.

I also would like to thank Dr. T. Wu for his cooperation, help and ideas during this work.

More personally, I wish to express my warmest appreciation to my mother and father without whose love, support and encouragement I would not have finished this work.

Most of all, I want to thank one of my best friends, Elcin Kentel for her advice, support and encouragement. This thesis is dedicated to my parents and Elcin.

TABLE OF CONTENTS

LIST OF TABLES	viii
LIST OF FIGURES	viii
ABSTRACT	xiii
CHAPTER 1 INTRODUCTION	1
1.1 BACKGROUND	1
1.2 PROBLEM DESCRIPTION	3
1.2.1 Open Access Scenario: The MW Net-Import and Transfer Spaces	3
1.2.2 Available Transfer Capability and Operating Constraints	6
1.2.3 Inter-Area Available Transfer Capability (ATC) Region Definitions	10
1.2.4 Sensitivity of the LFF and Security Regions to Load Variations	18
1.2.5 Assumptions on the Power System Model	19
1.3 PROBLEM FORMULATION	19
1.4 PROBLEM STATEMENT	21
1.5 APPROACH	23
1.6 ORGANIZATION OF THE THESIS	25
CHAPTER 2 THE STATE OF THE ART	26
2.1. INTRODUCTION	26
2.2 THE STEADY-STATE REGION-WISE SECURITY ASSESSMENT	27
2.3. THE IDENTIFICATION OF THE LOAD FLOW FEASIBILITY REGION	36

CHAPTER 3	ATC REGIONS REGIONS IN INTER-AREA MW NET-IMPORT SPACE	43
3.1	INTRODUCTION	43
3.2	BASE CASE ATC REGION IN THE MW NET-IMPORT SPACE.....	44
3.3	NEXT CONTINGENCY ATC REGIONS IN THE MW IMPORT SPACE..	44
3.4	SENSITIVITY OF THE REGIONS TO LOAD CHANGES.....	67
3.5	NOSE CURVES AND CONTINGENCY RANKING	69
3.6	SUMMARY OF THE RESULTS.....	72
CHAPTER 4	ATC REGIONS IN INTER-AREA MW TRANSFER SPACE.....	74
4.1	INTRODUCTION	74
4.2	BASE CASE ATC REGION IN THE MW TRANSFER SPACE.....	75
4.3	NEXT CONTINGENCY ATC REGIONS IN THE MW TRANSFER SPACE	81
4.4	SENSITIVITY OF THE REGIONS TO LOAD CHANGES.....	98
4.6	SUMMARY OF THE RESULTS.....	100
CHAPTER 5	CONCLUSIONS AND FUTURE WORK	102
5.1	CONCLUSIONS.....	102
5.2	FUTURE WORK.....	104
	LIST OF REFERENCE.....	105
APPENDIX A:	POWER FLOW EQUATIONS AND RADIAL SEARCH APPROACH..	109
A.1	THE SYSTEM MODEL.....	109
A.2	LOAD FLOW EQUATIONS CONSIDERING THE INTER-AREA IMPORT OF REAL POWER.....	111
A.3	LOAD ASSUMPTIONS AND GENERATION DISPATCH.....	114
A.4	FORMULATION OF THE LOAD FLOW EQUATIONS	115
A.5	RADIAL SERACH METHOD.....	117

APPENDIX B: SOFTWARE DOCUMENTATION	119
APPENDIX C: POWER SYSTEM TEST DATA.....	123
APPENDIX D: LIST OF SYMBOLS	126

LIST OF TABLES

<u>Table</u>	<u>Title</u>	<u>Page</u>
Table 1.2-1	The Functions of Areas	6
Table 1.2-2	Summary of the Region Definitions	10
Table 2.2-1	Region-Wise Steady-State Security Assessment Methods	34
Table 3.2-1	Summary of the Base Case Regions in the MW Net-Import space (P_I -space)	45
Table 3.3-1	Summary of the Next Contingency Regions in the MW Net- Import Space	52
Table 3.5-1	LFF Boundary Data and Contingency Ranking.....	71
Table 4.3-1	Summary of the Next Contingency Regions in the MW Transfer Space (P_T -space)	83
Table A.2-1	Summary of the Load Flow Unknown Voltage Variables.....	113
Table A.2-2	Load-Flow Equations.....	113
Table C-1	Initial Inter-Area Imports of Real Power	124
Table C-2	Generation Participation Factors.....	124
Table C-3	Bus data of the 31-bus system.....	124
Table C-4	Line data of the 31-bus system	125

LIST OF FIGURES

<u>Figure</u>	<u>Title</u>	<u>Page</u>
Figure 1.2-1	The 3-area power system and two different inter-area spaces.....	3
Figure 1.2-2	The Function of Areas.....	5
Figure 1.2-3	Illustration of base case security regions, R_{BCT} or R_{BCI} in the MW transfer space (P_T -space) or MW net-import space (P_I -space)	17
Figure 1.2-4	Illustration of next contingency security regions, $R_{NCT}^{(\lambda)}$ or $R_{NCI}^{(\lambda)}$ in the MW transfer space (P_T -space) or MW net-import space (P_I -space).....	17
Figure 2.3-1	Graphical representation of continuation method.....	39
Figure 2.3-2	Unimodal relationship between parameters r and k of the regularization method	40
Figure 3.2-1	Base case voltage security region, R_{VI} in the MW net-import space.....	46
Figure 3.2-2	Base case thermal security region, R_{TI} in the MW net-import space.....	47
Figure 3.2-3	Base case ATC region, R_{BCI} in the MW net-import space, $R_{BCI} = R_{FI} \cap R_{VI} \cap R_{TI}$	48
Figure 3.2-4	The fourth quadrant of the base case ATC region, R_{BCI} in the P_I -space	49
Figure 3.3-1	Next contingency LFF regions, $\bigcap_{(\lambda)} R_{FI}^{(\lambda)}$ in the MW net-import space.....	53
Figure 3.3-2	Line 8 outage voltage security region, $R_{VI}^{(8)}$ in the MW net-import space	56
Figure 3.3-3	Line 8 outage voltage drop limit region, $R_{\Delta VI}^{(8)}$ in the MW net-import space	56

Figure 3.3-4	Line 8 outage thermal security region, $\mathbf{R}_{\text{TI}}^{(8)}$ in the MW net-import space.....	57
Figure 3.3-5	Line 8 outage ATC region, $\mathbf{R}_{\text{NCI}}^{(8)}$ in the MW net-import space, $\mathbf{R}_{\text{NCI}}^{(8)} = \mathbf{R}_{\text{FI}}^{(8)} \cap \mathbf{R}_{\text{VI}}^{(8)} \cap \mathbf{R}_{\Delta\text{VI}}^{(8)} \cap \mathbf{R}_{\text{TI}}^{(8)}$	57
Figure 3.3-6	Line 11 outage voltage security region, $\mathbf{R}_{\text{VI}}^{(11)}$ in the MW net-import space.....	58
Figure 3.3-7	Line 11 outage voltage drop limit region, $\mathbf{R}_{\Delta\text{VI}}^{(11)}$ in the MW net-import space.....	58
Figure 3.3-8	Line 11 outage thermal security region, $\mathbf{R}_{\text{TI}}^{(11)}$ in the MW net-import space.....	59
Figure 3.3-9	Line 11 outage ATC region, $\mathbf{R}_{\text{NCI}}^{(11)}$ in the MW net-import space.....	59
Figure 3.3-10	Line 12 outage voltage security region, $\mathbf{R}_{\text{VI}}^{(12)}$ in the MW net-import space.....	60
Figure 3.3-11	Line 12 outage voltage drop limit region, $\mathbf{R}_{\Delta\text{VI}}^{(12)}$ in the MW net-import space.....	60
Figure 3.3-12	Line 12 outage thermal security region, $\mathbf{R}_{\text{TI}}^{(12)}$ in the MW net-import space.....	61
Figure 3.3-13	Line 12 outage ATC region, $\mathbf{R}_{\text{NCI}}^{(12)}$ in the MW net-import space, $\mathbf{R}_{\text{NCI}}^{(12)} = \mathbf{R}_{\text{FI}}^{(12)} \cap \mathbf{R}_{\text{VI}}^{(12)} \cap \mathbf{R}_{\Delta\text{VI}}^{(12)} \cap \mathbf{R}_{\text{TI}}^{(12)}$	61
Figure 3.3-14	Line 13 outage voltage security region, $\mathbf{R}_{\text{VI}}^{(13)}$ in the MW net-import space.....	62
Figure 3.3-15	Line 13 outage voltage drop limit region, $\mathbf{R}_{\Delta\text{VI}}^{(13)}$ in the MW net-import space.....	62
Figure 3.3-16	Line 13 outage thermal security region, $\mathbf{R}_{\text{TI}}^{(13)}$ in the MW net-import space.....	63
Figure 3.3-17	Line 13 outage ATC region, $\mathbf{R}_{\text{NCI}}^{(13)}$ in the MW net-import space, $\mathbf{R}_{\text{NCI}}^{(13)} = \mathbf{R}_{\text{FI}}^{(13)} \cap \mathbf{R}_{\text{VI}}^{(13)} \cap \mathbf{R}_{\Delta\text{VI}}^{(13)} \cap \mathbf{R}_{\text{TI}}^{(13)}$	63

Figure 3.3-18	Line 34 outage voltage security region, $\mathbf{R}_{\mathbf{VI}}^{(34)}$ in the MW net-import space.....	64
Figure 3.3-19	Line 34 outage voltage drop limit region, $\mathbf{R}_{\Delta\mathbf{VI}}^{(34)}$ in the MW net-import space.....	64
Figure 3.3-20	Line 34 outage thermal security region, $\mathbf{R}_{\mathbf{TI}}^{(34)}$ in the MW net-import space.....	65
Figure 3.3-21	Line 34 outage ATC region, $\mathbf{R}_{\mathbf{NCI}}^{(34)}$ in the MW net-import space, $\mathbf{R}_{\mathbf{NCI}}^{(34)} = \mathbf{R}_{\mathbf{FI}}^{(34)} \cap \mathbf{R}_{\mathbf{VI}}^{(34)} \cap \mathbf{R}_{\Delta\mathbf{VI}}^{(34)} \cap \mathbf{R}_{\mathbf{TI}}^{(34)}$	65
Figure 3.3-22	Next contingency voltage security region, $\bigcap_{(\lambda)} \mathbf{R}_{\mathbf{VI}}^{(\lambda)}$ in the $\mathbf{P}_I$ -space.....	66
Figure 3.3-23	Next contingency voltage drop limit region, $\bigcap_{(\lambda)} \mathbf{R}_{\Delta\mathbf{VI}}^{(\lambda)}$ in the $\mathbf{P}_I$ -space.....	66
Figure 3.3-24	Next contingency thermal security region, $\bigcap_{(\lambda)} \mathbf{R}_{\mathbf{TI}}^{(\lambda)}$ in the $\mathbf{P}_I$ -space.....	67
Figure 3.4-1	The effect of a change in load on the base case LFF region, $\mathbf{R}_{\mathbf{FI}}$ in the MW net-import space ($\mathbf{P}_I$ -space).....	68
Figure 3.4-2	The effect of a change in load on the line 11 outage LFF region, $\mathbf{R}_{\mathbf{FI}}^{(11)}$ in the MW net-import space ($\mathbf{P}_I$ -space).....	69
Figure 3.5-1	Plot of the nose curves, i.e. voltage magnitude versus area import level, r , in 40° direction for the 31-bus system.....	72
Figure 4.2-1	Base case voltage security region, $\mathbf{R}_{\mathbf{VT}}$ in the MW transfer space.....	76
Figure 4.2-2	Base case thermal security region, $\mathbf{R}_{\mathbf{TT}}$ in the MW transfer space.....	78
Figure 4.2.3	Base case ATC region, $\mathbf{R}_{\mathbf{BCT}}$ in the MW transfer space, $\mathbf{R}_{\mathbf{BCT}} = \mathbf{R}_{\mathbf{FT}} \cap \mathbf{R}_{\mathbf{VT}} \cap \mathbf{R}_{\mathbf{TT}}$	79
Figure 4.2-4	First quadrant of the base case ATC region, $\mathbf{R}_{\mathbf{BCT}}$ in the MW transfer space.....	80

Figure 4.3-1	Next contingency LFF regions, $\cap \mathbf{R}_{\mathbf{FT}}^{(\lambda)}$ in the MW transfer space.....	84
Figure 4.3-2	Line 8 outage voltage security region, $\mathbf{R}_{\mathbf{VT}}^{(8)}$ in the MW transfer space.....	87
Figure 4.3-3	Line 8 outage voltage drop limit region, $\mathbf{R}_{\Delta \mathbf{VT}}^{(8)}$ in the MW transfer space.....	87
Figure 4.3-4	Line 8 outage thermal security region, $\mathbf{R}_{\mathbf{TT}}^{(8)}$ in the MW transfer space.....	88
Figure 4.3-5	Line 8 outage ATC region, $\mathbf{R}_{\mathbf{NCT}}^{(8)}$ in the MW transfer space $\mathbf{R}_{\mathbf{NCT}}^{(8)} = \mathbf{R}_{\mathbf{FT}}^{(8)} \cap \mathbf{R}_{\mathbf{VT}}^{(8)} \cap \mathbf{R}_{\Delta \mathbf{VT}}^{(8)} \cap \mathbf{R}_{\mathbf{TT}}^{(8)}$	88
Figure 4.3-6	Line 11 outage voltage security region, $\mathbf{R}_{\mathbf{VT}}^{(11)}$ in the MW transfer space.....	89
Figure 4.3-7	Line 11 outage voltage drop limit region, $\mathbf{R}_{\Delta \mathbf{VT}}^{(11)}$ in the MW transfer space.....	89
Figure 4.3-8	Line 11 outage thermal security region, $\mathbf{R}_{\mathbf{TT}}^{(11)}$ in the MW transfer space.....	90
Figure 4.3-9	Line 11 outage ATC region, $\mathbf{R}_{\mathbf{NCT}}^{(11)}$ in the MW transfer space. $\mathbf{R}_{\mathbf{NCT}}^{(11)} = \mathbf{R}_{\mathbf{FT}}^{(11)} \cap \mathbf{R}_{\mathbf{VT}}^{(11)} \cap \mathbf{R}_{\Delta \mathbf{VT}}^{(11)} \cap \mathbf{R}_{\mathbf{TT}}^{(11)}$	90
Figure 4.3-10	Line 12 outage voltage security region, $\mathbf{R}_{\mathbf{VT}}^{(12)}$ in the MW transfer space.....	91
Figure 4.3-11	Line 12 outage voltage drop limit region, $\mathbf{R}_{\Delta \mathbf{VT}}^{(12)}$ in the MW transfer space.....	91
Figure 4.3-12	Line 12 outage thermal security region, $\mathbf{R}_{\mathbf{TT}}^{(12)}$ in the MW transfer space.....	92
Figure 4.3-13	Line 12 outage ATC region, $\mathbf{R}_{\mathbf{NCT}}^{(12)}$ in the MW transfer space $\mathbf{R}_{\mathbf{NCT}}^{(12)} = \mathbf{R}_{\mathbf{FT}}^{(12)} \cap \mathbf{R}_{\mathbf{VT}}^{(12)} \cap \mathbf{R}_{\Delta \mathbf{VT}}^{(12)} \cap \mathbf{R}_{\mathbf{TT}}^{(12)}$	92
Figure 4.3-14	Line 13 outage voltage security region, $\mathbf{R}_{\mathbf{VT}}^{(13)}$ in the MW transfer space.....	93

Figure 4.3-15	Line 13 outage voltage drop limit region, $R_{\Delta VT}^{(13)}$ in the MW transfer space.....	93
Figure 4.3-16	Line 13 outage thermal security region, $R_{TT}^{(13)}$ in the MW transfer space.....	94
Figure 4.3-17	Line 13 outage ATC region, $R_{NCT}^{(13)}$ in the MW transfer space $R_{NCT}^{(13)} = R_{FT}^{(13)} \cap R_{VT}^{(13)} \cap R_{\Delta VT}^{(13)} \cap R_{TT}^{(13)}$	94
Figure 4.3-18	Line 34 outage voltage security region, $R_{VT}^{(34)}$ in the MW transfer space.....	95
Figure 4.3-19	Line 34 outage voltage drop limit region, $R_{\Delta VT}^{(34)}$ in the MW transfer space.....	95
Figure 4.3-20	Line 34 outage thermal security region, $R_{TT}^{(34)}$ in the MW transfer space.....	96
Figure 4.3-21	Line 34 outage ATC region, $R_{NCT}^{(34)}$ in the MW transfer space $R_{NCT}^{(34)} = R_{FT}^{(34)} \cap R_{VT}^{(34)} \cap R_{\Delta VT}^{(34)} \cap R_{TT}^{(34)}$	96
Figure 4.3-22	Next contingency voltage security region, $\bigcap_{(\lambda)} R_{VT}^{(\lambda)}$ in the P_T -space.....	97
Figure 4.3-23	Next contingency voltage drop limit region, $\bigcap_{(\lambda)} R_{\Delta VT}^{(\lambda)}$ in the P_T -space	97
Figure 4.3-24	Next contingency thermal security region, $\bigcap_{(\lambda)} R_{TT}^{(\lambda)}$ in the P_T -space.....	98
Figure 4.4-1	The effect of a change in load on the base case LFF region, R_{FT} in the MW transfer (P_T -space)	99
Figure 4.4-2	The effect of a change in load on the line 11 outage LFF region, $R_{TI}^{(11)}$ in the MW transfer (P_T -space).....	100
Figure A-1	The 3-Area Power Network	109
Figure A-2	The illustration of radial-search method used to identify the LFF and security regions in the MW net-import space, P_I -space.....	118
Figure B-1	Illustration of data flow of the software.....	120
Figure B-2	File organization of the LFFAP package.....	121

Figure C-1	The 31-Bus System Diagram.....	123
------------	--------------------------------	-----

Abstract

Investigation of Inter-Area Available Transfer Capability with
Respect to Network and Load Changes

Saffet Ayasun
Dr. Robert Fischl

Under deregulation, there is a need to increase the utilization of transmission system and to relief its congestion. This results in a strong demand to evaluate the real power transfer capability of the transmission network. In this thesis, we use a region-wise security assessment method rather than the point-wise security assessment performed by the present one scenario at-a-time study approach to obtain all feasible and secure power transfer operating points, so called Available Transfer Capability (ATC). The reason for that is the large uncertainty one encounters in determining the real power flows in an open access operating scenario. We define ATC region as the intersection of the Load Flow Feasibility (LFF), voltage security, voltage drop limit and thermal security regions at two inter-area spaces (the MW net-import and transfer spaces) and give a clear picture of the interactions between the operating limits. We investigate a 2-dimensional ATC region which gives the inter-area transfer as a function net MW import into the *importing* area (Area B). Of interest is the sensitivity of boundaries of the ATC region with respect to network and load changes. A 3-area 31-bus system is used to perform the sensitivity studies and the results are presented graphically illustrating the changes in the base-case and next-contingency security region boundaries and the particular limiting constraints (i.e., bottlenecks) defining these boundaries.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The power utility industry is entering the age of deregulation, in which neighboring utilities and independent power producers may gain access to an electric company's transmission facilities for the purpose of serving remote customers. Deregulation of power industry inevitably points toward the need to operate power systems closer to their load carrying limits and there is a trend to increase the utilization of the existing transmission network to transfer larger amount of power from area to area. Therefore, calculation of feasible and secure transfer operating points, so called Available Transfer Capability (ATC) of the system, over a large set of operating scenarios is becoming more and more important. In the open transmission access, the number and variety of power transactions have been increasing. For example, one may be interested in calculating the maximum inter-area transfer and/or the maximum real power import into an area or a set of areas under both base case and next contingency conditions for a variety of transactions between areas.

In both planning and operating bulk power system, available transfer capability (ATC) is the primary measure of security of the network. Traditionally, a point-wise approach has been used to calculate the available transmission capability and it has generally been sufficient to consider only a predefined directions and contingencies when calculating ATC since most power transactions have occurred over short distances between a limited number of utilities [1]. However, as numerous extensive power transactions begin to take place currently, the problem of determining ATC becomes a increasingly complex. The current point-wise calculations of ATC provides only a scalar value of the transfer capability for a particular transaction and gives little information

on what happens to the system security under many different power transactions between areas. The key to evaluating of the ATC over a collection of operating scenarios is the identification of all feasible and secure operating points. A region-wise approach to the ATC calculations provides more information on system security and transfer capability [2, 3, 4]. The main idea behind this approach is to obtain a collection of all operating points, which may be generation level of each station, real power exchange among areas in the network or net bus injection, for which the power system satisfy the security constraints. The set of all feasible and secure operating points is called the security region. Once the region is obtained, one can identify the system security margin, the distance between the current operating point and security region boundary, and the most limiting system components (bottlenecks) such as transmission lines and buses.

The region-wise security assessment provides the operator/planner with a 2-dimensional graphical display of the available transmission capability of the system under different operating conditions. Rather than a scalar value of the ATC, it gives information on the size, shape and orientation of the ATC regions representing numerous types of real power transactions and allows utilities to develop transfer strategies.

The most difficult part of the identification of the inter-area available transfer capability is to determine the conditions which guarantee the existence of a voltage profile across the network, that is, the existence of a solution to the load flow equations. An efficient method and algorithm have been presented by Wu and Fischl to obtain Load Flow Feasibility (LFF) regions in the real power exchange space [3, 4, 5]. Another planning tool, called the Transmission and Voltage Limitation (TVLIM) program has been presented in [16]. TVLIM provides a graphical display of the set of all feasible and secure inter-area real power transfers. However, it was able to calculate only base case Load Flow Feasibility (LFF) region, thermal security region and next contingency thermal security region.

Based on the methods and algorithms in [2, 3, 4, 5], this thesis presents a two-dimensional picture of the inter-area available transfer capability, ATC regions, of a 3-area power system in the inter-area MW net-import space (P_I -space) and the MW transfer space (P_T -space) for both base case and next contingency cases. The following section gives the definitions of inter-area spaces, ATC, operating constraints and steady-state region definitions.

1.2 PROBLEM DESCRIPTION

1.2.1 Open Access Scenario: The MW Net-Import and Transfer Spaces

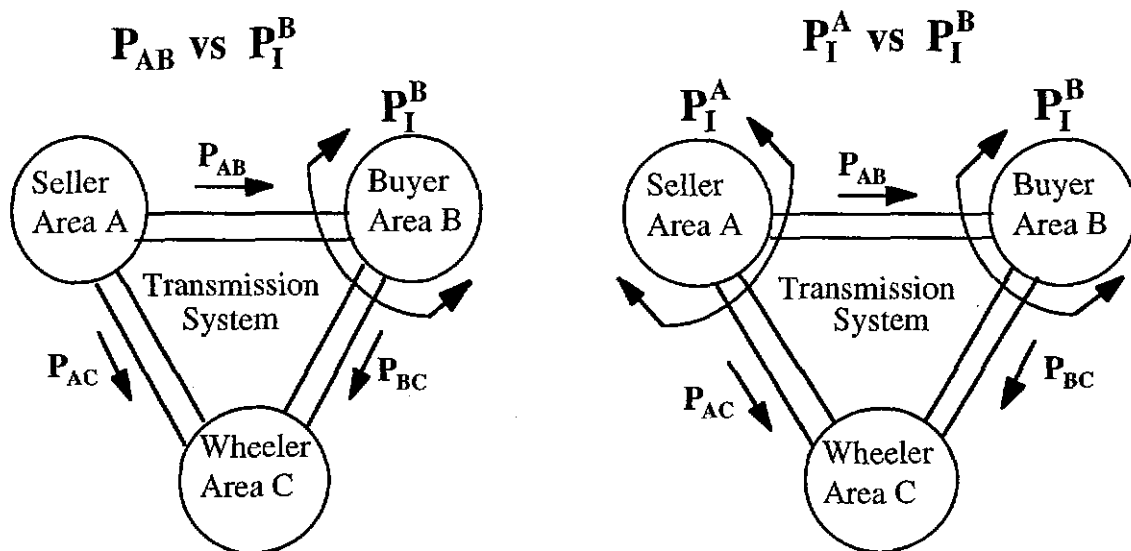


Figure 1.2-1 The 3-area power system and two different inter-area spaces

The simplest open access scenario can be defined by using a 3-area power system shown in Figure 1.2-1 where power exchange occurs between areas A and B. In other words, area B is a buyer (importing) area, area A is a seller (exporting) area while area C represents the rest of the "world" as a wheeler (swing) area. A bilateral trade is assumed between areas A and B, and real power transfer is simulated by raising generation in the seller area and lowering the corresponding amount of generation in the buyer area. The

MW net-import of real power into each area is denoted by P_I^A , P_I^B and P_I^C , respectively. P_{AB} , P_{AC} and P_{BC} represent the net real power transfers from area A to B, area A to C and area B to C. Note that, in general, the seller end real power (P_{AB}) is not equal to buyer end real power, ($-P_{BA}$) because of line losses. This is also the same for the MW transfers from area A to C (P_{AC}) and from area B to C (P_{BC}). Assuming that there are no line losses, the MW net-imports of real power into areas A, B and C can be-written as follows:

$$P_I^A = -P_{AB} - P_{AC} \quad (1.2.1)$$

$$P_I^B = P_{AB} - P_{BC} \quad (1.2.2)$$

$$P_I^C = P_{AC} + P_{BC} \quad (1.2.3)$$

The addition of Eqns. (1.2.1), (1.2.2) and (1.2.3) gives the fundamental relationship between inter-area imports, which stipulates that the sum of all net-imports of real power into areas must add up to zero, as in Eqn. (1.2.4).

$$P_I^A + P_I^B + P_I^C = 0 \quad (1.2.4)$$

As can be seen in Figure 1.2-1, we have six power flow unknowns (P_I^A , P_I^B , P_I^C , P_{AB} , P_{AC} and P_{BC}) and only three of them are independent. For our ATC analysis we select $\{P_{AB}, P_I^A$ and $P_I^B\}$ to be the independent ones. The remaining variables $\{P_I^C$, P_{AC} and $P_{BC}\}$ are related by:

$$\begin{bmatrix} P_I^C \\ P_{AC} \\ P_{BC} \end{bmatrix} = \begin{bmatrix} 0 & -1 & -1 \\ -1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} P_{AB} \\ P_I^A \\ P_I^B \end{bmatrix} \quad (1.2.5)$$

In this thesis, we study the transfer limits with respect to the three independent variables $\{P_{AB}, P_I^A$ and $P_I^B\}$ graphically taking 2 variables at-a-time. Specifically the following combinations are taken:

i) The MW transfer space (P_T -space):

$$P_T = [P_{AB} \ P_I^B]^T \quad (1.2.6)$$

ii) The MW net-import space (P_I -space):

$$P_I = [P_I^A \ P_I^B]^T \quad (1.2.7)$$

Any operating point ($P_{AB} - P_I^B$) or ($P_I^A - P_I^B$) is considered to be a secure operating point if thermal and voltage limit constraints are not violated. The regions in these two spaces enable us to visualize the available transfer capability (ATC) as a function of different transaction strategies. In the following, function of areas (i.e., buyer or seller) depending on the quadrant number of the ATC region are explained.

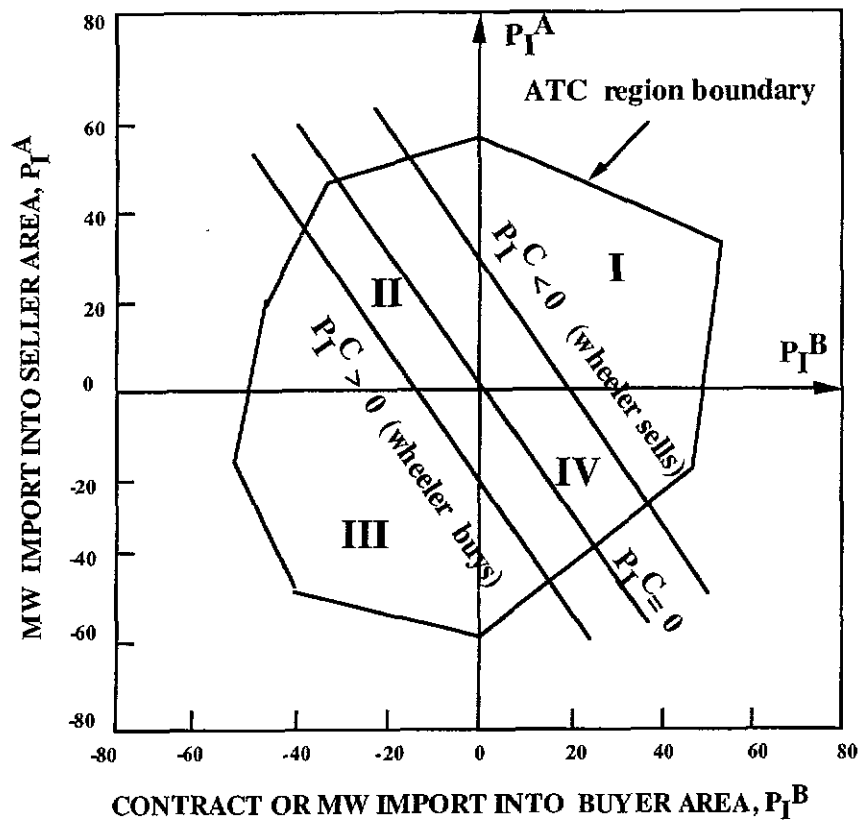


Figure 1.2-2 The Function of Areas

The ATC region in the MW net-import space (P_I -space) gives us information on the function of each area. Each quadrant in Figure 1.2-2 represents a different type of operating scenario depending on the sign of the MW net-import into each area. For example, quadrant I, where both MW net-import into area A, P_I^A and into area B, P_I^B are

greater than zero, represents the situation that area A and B act as buyer (consumer) areas while area C acts as a seller area. We are mostly interested in quadrant IV where area A acts as a seller area and area B acts as a buyer area, ($P_A^1 < 0$ and $P_B^1 > 0$). The MW net-import into the wheeler area, area C is zero when $P_A^1 = -P_B^1$ (along 135° and 315° search directions). Table 1.2-1 summarize the function of areas in each quadrant depending on the search direction.

Table 1.2-1 The Functions of areas

Quadrant Number (Search Direction)		Area Name		Area A		Area B	
I	(0° - 90°)	II	(90° - 180°)	III	(180° - 270°)	IV	(270° - 360°)
Buyer		Buyer		Seller		Seller	
($P_A^1 > 0$)		($P_A^1 > 0$)		($P_A^1 < 0$)		($P_B^1 < 0$)	
Buyer		Seller		Buyer		Seller	
($P_B^1 > 0$)		($P_B^1 < 0$)		($P_B^1 > 0$)		($P_B^1 < 0$)	

The following section gives the definition of Available Transfer Capability (ATC) and operating constraints.

1.2.2 Available Transfer Capability and Operating Constraints

The steady-state Available Transfer Capability (ATC) is the amount of real power that can be transferred from one area to another in a reliable manner subject to following operating constraints:

- Load Flow Feasibility (LFF), Eqn. (1.2.10)
- Thermal limits, Eqn. (1.2.11)
- Voltage magnitude limits, Eqn. (1.2.12)

- Voltage drop limits (under a line outage), Eqn. (1.2.13)

In other words,

ATC = minimum transfer capability of { maximum loading limit, thermal limit, voltage magnitude limit, voltage drop limit}.

The main purpose of the thesis is to investigate the sensitivity of Available Transfer Capability (ATC) of a 3-area power system shown Figure 1.2-1 with respect to:

- Buyer area (area B) MW net-import, P_1^B
- Network changes
- Load changes

Two different ATC measurements are used to evaluate the MW transfer capability of the network:

- MW transfer from seller to buyer area (P_{AB}) vs MW net-import into buyer area (P_1^B)
- MW net-import into buyer area (P_1^B) vs MW net-import into seller area (P_1^A)

In the steady-state operation of power system, load flow equations represent the balance between the generated power, load demand and system losses. The balance condition is given by set of non-linear equations:

$$P_i = V_i \sum_{k=1}^n V_k (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}), \text{ for } i=1, 2, 3, \dots, n_d+n_g \quad (1.2.8-a)$$

$$Q_i = V_i \sum_{k=1}^n V_k (G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}), \text{ for } i=1, 2, 3, \dots, n_d \quad (1.2.8-b)$$

where P_i and Q_i are the net real and reactive power injection at bus i . V_i is voltage magnitude and θ_i is the voltage phase angle at bus i . $G_{ik} + jB_{ik}$ is $(i, k)^{\text{th}}$ element of the

bus admittance matrix, $[Y_{BUS}]$ and n_d, n_g are the number of load (PQ) buses and the number of generator (PV) buses in the system, respectively.

In terms of the inter-area problem, Eqns. (1.2.8) can be written as:

$$f(x) = u \quad (1.2.9)$$

where

f = the set of $2n_d+n_g$ load flow equations in vector form, given by the right hand sides of Eqns. (1.2.8-a), (1.2.8-b) and, for the inter-area formulation Eqns. (1.3.3), (1.3.4)

$x = ((2n_d+n_g) \times 1)$ vector representing bus voltage magnitudes V_i , and angles θ_i

$u = ((2n_d+n_g) \times 1)$ vector of specified net real and reactive power injections P_i, Q_i and, for the inter-area formulation, the net imports of real power P_i^A, P_i^B into areas A and B

The solution to the power flow Eqns. (1.2.9) is necessary for all types of steady-state security assessment and thus, considered to be a hard constraint. On the other hand, the constraints dictated by thermal and voltage limits are soft ones and therefore can be relaxed if needed.

i) Load-flow feasibility constraint:

$$\exists x \text{ s.t } f(x) = u \quad (1.2.10)$$

Satisfaction of this constraint assures the existence of a voltage profile across the network, which is a necessary condition to obtain different kinds of security regions.

ii) Line flow (thermal) limit constraint:

$$|P_{ij}(C_\lambda)| \leq P_{ij}^M \quad (1.2.11)$$

iii) Voltage magnitude limit constraint:

$$V_i^L \leq V_i(C_\lambda) \leq V_i^U \quad (1.2.12)$$

iv) **Voltage drop limit constraint (under contingency operations):**

$$\Delta V_i (C_\lambda) \leq \Delta V_i^M \quad (1.2.13)$$

where the superscripts U and L represent the upper and lower limits, respectively, and M denotes the limiting value; and

C_λ = λ th contingency representing a facility outage

C_0 = Base case operation (no contingency)

$P_{ij} (C_\lambda)$ = post-contingency real power flow across the line ij due to C_λ

$\Delta V_i (C_\lambda) = V_i (C_\lambda) - V_i (C_0)$ = the voltage drop at bus i due to C_λ

$V_i (C_0)$ = pre-contingency (base case) voltage magnitude at bus i

Based on only the load flow feasibility criterion, an efficient method was proposed for identifying the steady-state LFF and security regions in [3]. The regions were illustrated in the inter-area MW net-import space ($\mathbf{P}_I$ -space). Based on the techniques and formulations developed by Wu and Fischl, we will obtain LFF and security regions in both the inter-area MW net-import and transfer spaces. The two dimensional graphical representation of the boundaries (i.e. binding constraints) of the following five (5) regions in the MW net-import and transfer spaces for base case and next contingency cases is the main goal of this thesis.

- i) LFF regions based on Load Flow Feasibility (LFF) constraint, Eqn. (1.2.10).
- ii) Voltage security regions based on LFF and voltage limit constraints, Eqns. (1.2.10 and 12).
- iii) Voltage drop limit regions based on LFF and voltage drop constraints, Eqns. (1.2.10 and 13).
- iv) Thermal security regions based on LFF and thermal limit constraints, Eqns. (1.2.10 and 11)

- v) ATC regions based on LFF and voltage limit, voltage drop limit and thermal limit constraints, Eqns. (1.2.10) - (1.2.13)

1.2.3 Inter-Area Available Transfer Capability (ATC) Region Definitions:

There are four different types of LFF, voltage, thermal and voltage drop limit security and ATC regions presented in this thesis. These regions are differentiated by inter-area space in which they are displayed and whether they are obtained for base case or next contingency operation. The section gives the definitions of the two dimensional graphical representation of the boundaries (i. e. binding constraints) of the regions in the MW net-import (P_i -space) and transfer (P_T -space) spaces for base case and next contingency cases. These regions are intended to provide operator/planner with information on ATC which is useful in system operation and planning, and explain numerous power transactions between areas. Table 1.2-2 summarizes the region definitions.

Table 1.2-2 Summary of the region definitions

Region Type	Operation Type			
	Base Case		Next Contingency	
	Import Space	Transfer Space	Import Space	Transfer Space
LFF	Eqn. (1.2.14)	Eqn. (1.2.21)	Eqn. (1.2.17)	Eqn. (1.2.24)
Voltage Security	Eqn. (1.2.15)	Eqn. (1.2.22)	Eqn. (1.2.18)	Eqn. (1.2.25)
Voltage Drop	-----	-----	Eqn. (1.2.19)	Eqn. (1.2.26)
Thermal Security	Eqn. (1.2.16)	Eqn.(1.2.23)	Eqn. (1.2.20)	Eqn. (1.2.27)

Load Flow Feasibility and Security Regions in the MW Net-Import Space

1) Base Case Load Flow Feasibility (LFF) Region:

$$\mathbf{R}_{FI} = \left\{ \mathbf{P}_I = \begin{bmatrix} P_I^A & P_I^B \end{bmatrix}^T : \exists \mathbf{x} \text{ such that } \mathbf{F}(\mathbf{x}, \mathbf{u}(\mathbf{P}_I)) = \mathbf{0} \right\} \quad (1.2.14)$$

where $\mathbf{F}$ is the set of load flow equations and $\mathbf{u}$ is the injection vector representing the specified net real and reactive power injections P_i , Q_i and, for the inter-area formulation, the MW net-imports of real power P_I^A , P_I^B into areas A and B.

2) Base Case Voltage Security Region:

$$\mathbf{R}_{VI} = \left\{ \mathbf{P}_I = \begin{bmatrix} P_I^A & P_I^B \end{bmatrix}^T : V_i^L \leq V_i(C_0) \leq V_i^U, \text{ for } \forall i, i = 1, \dots, n_d \right\} \quad (1.2.15)$$

where n_d is the number of load buses, $V_i(C_0)$ is the bus voltage magnitude at bus i under base case operation and V_i^L , V_i^U are the lower and upper voltage magnitude limits at bus i , respectively.

3) Base Case Thermal Security Region:

$$\mathbf{R}_{TI} = \left\{ \mathbf{P}_I = \begin{bmatrix} P_I^A & P_I^B \end{bmatrix}^T : |P_i(C_0)| \leq P_i^M, \text{ for } \forall i, i = 1, \dots, n_\ell \right\} \quad (1.2.16)$$

where n_ℓ is the number of lines in the network, $P_i(C_0)$ is base case real power flow across the line i (i.e., every line in areas A, B and C) and P_i^M is the maximum line loading limit for line i .

4) Next Contingency Load Flow Feasibility (LFF) Region:

$$\mathbf{R}_{FI}^{(\lambda)} = \left\{ \mathbf{P}_I = \begin{bmatrix} P_I^A & P_I^B \end{bmatrix}^T : \exists \mathbf{x}^\lambda \text{ such that } \mathbf{F}^\lambda(\mathbf{x}^\lambda, \mathbf{u}^\lambda(\mathbf{P}_I)) = \mathbf{0} \text{ for } \forall \lambda, \lambda = 1, \dots, n_C \right\} \quad (1.2.17)$$

where $\mathbf{F}^\lambda$ is the set of load flow equations under contingency C_λ , $\mathbf{u}^\lambda$ is the injection vector determined by $\mathbf{P}_I$ under contingency C_λ , and n_C is the number of contingencies. Note that there are no dimension changes under contingency operation (i.e., $\dim \mathbf{x}^\lambda = \dim \mathbf{x}$ and $\dim \mathbf{u}^\lambda = \dim \mathbf{u}$).

5) Next Contingency Voltage Security Region:

$$\mathbf{R}_{VI}^{(\lambda)} = \left\{ \mathbf{P}_I = \begin{bmatrix} P_I^A & P_I^B \end{bmatrix}^T : V_i^L \leq V_i(C_\lambda) \leq V_i^U \text{ for } \forall i, \lambda; \right. \\ \left. i = 1, \dots, n_d \text{ and } \lambda = 1, \dots, n_C \right\} \quad (1.2.18)$$

where $V_i(C_\lambda)$ is the bus voltage magnitude at bus i under contingency C_λ , V_i^L and V_i^U are the lower and upper voltage magnitude limits at bus i , and n_d , n_C are the number of the load buses and contingencies, respectively.

6) Next Contingency Voltage Drop (ΔV) Limit Region:

$$\mathbf{R}_{\Delta VI}^{(\lambda)} = \left\{ \mathbf{P}_I = \begin{bmatrix} P_I^A & P_I^B \end{bmatrix}^T : \max_{\lambda} \left\{ \max_i (\Delta V_i(C_\lambda) = |V_i(C_\lambda) - V_i(C_0)|) \right\} \leq \Delta V_i^M \right\} \\ \text{for } \forall i, \lambda; \quad i = 1, \dots, n_d \text{ and } \lambda = 1, \dots, n_C \quad (1.2.19)$$

where $V_i(C_0)$ is the pre-contingency voltage magnitude at bus i , $V_i(C_\lambda)$ is the voltage magnitude at bus i under contingency C_λ , $\Delta V_i(C_\lambda)$ is the voltage drop at bus i due to C_λ , ΔV_i^M is the maximum allowable bus voltage drop due to an outage, and n_d , n_C are the number of buses and contingencies, respectively.

7) Next Contingency Thermal Security Region:

$$\mathbf{R}_{TI}^{(\lambda)} = \left\{ \mathbf{P}_I = \begin{bmatrix} P_I^A & P_I^B \end{bmatrix}^T : |P_i(C_\lambda)| \leq P_i^M \text{ for } \forall i, \lambda; \quad i = 1, \dots, n_\ell \text{ and } \lambda = 1, \dots, n_C \right\} \quad (1.2.20)$$

where $P_i(C_\lambda)$ is real power flow across the line i (i.e., every line in areas A, B and C), P_i^M is the maximum line loading limit for line i and n_ℓ , n_C are the number of lines and contingencies, respectively.

Load Flow Feasibility and Security Regions in the MW Transfer Space

The LFF and security regions in the MW transfer space ($\mathbf{P}_T$ -space) could be defined in the same way as those in the MW net-import space. Instead of using net-import real power into area A, P_I^A , as one of the control variables, real power transfer from area A to B, P_{AB} has been used to display the LFF, security and ATC regions in the MW transfer space. The boundaries of these regions indicate the maximum power transfer capability of the network from area A to B, P_{AB} under the constraints given by Eqns. (1.2.10) - (1.2.13). The real power transfer from area A to B, P_{AB} is defined as the summation of real power flows, taken into account the direction of power flows, through the tie lines connecting areas A and B. The LFF and security regions in the MW transfer space ($\mathbf{P}_T$ -space) for base case and next contingency cases could be defined mathematically as follows:

1) Base Case Load Flow Feasibility (LFF) Region:

$$\mathbf{R}_{FT} = \left\{ \mathbf{P}_T = [P_{AB} \ P_I^B]^T : \exists \mathbf{x} \text{ such that } \mathbf{F}(\mathbf{x}, \mathbf{u}(\mathbf{P}_T)) = \mathbf{0} \right\} \quad (1.2.21)$$

where $\mathbf{F}$ is the set of load flow equations and $\mathbf{u}$ is the injection vector representing the specified net real and reactive power injections P_i , Q_i and, for the inter-area formulation, the MW net-import into area B, P_I^B and MW transfer from area A to B, P_{AB}

2) Base Case Voltage Security Region:

$$\mathbf{R}_{VT} = \left\{ \mathbf{P}_T = [P_{AB} \ P_I^B]^T : V_i^L \leq V_i(C_0) \leq V_i^U, \text{ for } \forall i, i = 1, \dots, n_d \right\} \quad (1.2.22)$$

where n_d is the number of load buses, $V_i(C_0)$ is the bus voltage magnitude at bus i under base case operation and V_i^L , V_i^U are the lower and upper voltage magnitude limits at bus i , respectively.

3) Base Case Thermal Security Region:

$$\mathbf{R}_{\text{TT}} = \left\{ \mathbf{P}_{\text{T}} = \begin{bmatrix} P_{\text{AB}} & P_{\text{I}}^{\text{B}} \end{bmatrix}^{\text{T}} : |P_{\text{i}}(\text{C}_0)| \leq P_{\text{i}}^{\text{M}}, \text{ for } \forall i, i = 1, \dots, n_{\ell} \right\} \quad (1.2.23)$$

where n_{ℓ} is the number of lines in the network, $P_{\text{i}}(\text{C}_0)$ is base case real power flow across the line i (i.e., every line in areas A, B and C), and P_{i}^{M} is the maximum line loading limit for line i .

4) Next Contingency Load Flow Feasibility (LFF) Region:

$$\mathbf{R}_{\text{FT}}^{(\lambda)} = \left\{ \mathbf{P}_{\text{T}} = \begin{bmatrix} P_{\text{AB}} & P_{\text{I}}^{\text{B}} \end{bmatrix}^{\text{T}} : \exists \mathbf{x}^{\lambda} \text{ such that } \mathbf{F}^{\lambda}(\mathbf{x}^{\lambda}, \mathbf{u}^{\lambda}(\mathbf{P}_{\text{T}})) = 0 \text{ for } \forall \lambda, \lambda = 1, \dots, n_{\text{C}} \right\} \quad (1.2.24)$$

where $\mathbf{F}^{\lambda}$ is the set of load flow equations under contingency C_{λ} , $\mathbf{u}^{\lambda}$ is the injection vector determined by $\mathbf{P}_{\text{T}}$ under contingency C_{λ} , and n_{C} is the number of contingency.

5) Next Contingency Voltage Security Region:

$$\mathbf{R}_{\text{VT}}^{(\lambda)} = \left\{ \mathbf{P}_{\text{T}} = \begin{bmatrix} P_{\text{AB}} & P_{\text{I}}^{\text{B}} \end{bmatrix}^{\text{T}} : V_{\text{i}}^{\text{L}} \leq V_{\text{i}}(\text{C}_{\lambda}) \leq V_{\text{i}}^{\text{U}} \text{ for } \forall i, \lambda; \right. \\ \left. i = 1, \dots, n_{\text{d}} \text{ and } \lambda = 1, \dots, n_{\text{C}} \right\} \quad (1.2.25)$$

where $V_{\text{i}}(\text{C}_{\lambda})$ is the bus voltage magnitude at bus i under contingency C_{λ} , V_{i}^{L} and V_{i}^{U} are the lower and upper voltage magnitude limits at bus i , and n_{d} , n_{C} are the number of the load buses and contingencies, respectively.

6) Next Contingency Voltage Drop (ΔV) Limit Region:

$$\mathbf{R}_{\Delta\text{VT}}^{(\lambda)} = \left\{ \mathbf{P}_{\text{T}} = \begin{bmatrix} P_{\text{AB}} & P_{\text{I}}^{\text{B}} \end{bmatrix}^{\text{T}} : \max_{\lambda} \left\{ \max_i (\Delta V_{\text{i}}(\text{C}_{\lambda}) = |V_{\text{i}}(\text{C}_{\lambda}) - V_{\text{i}}(\text{C}_0)|) \right\} \leq \Delta V_{\text{i}}^{\text{M}} \right. \\ \left. \text{for } \forall i, \lambda; i = 1, \dots, n_{\text{d}} \text{ and } \lambda = 1, \dots, n_{\text{C}} \right\} \quad (1.2.26)$$

where $V_{\text{i}}(\text{C}_0)$ is the pre-contingency (base case) voltage magnitude at bus i , $V_{\text{i}}(\text{C}_{\lambda})$ is the voltage magnitude at bus i under contingency C_{λ} , $\Delta V_{\text{i}}(\text{C}_{\lambda})$ is the voltage drop at bus i due

to C_λ , ΔV_i^M is the maximum allowable bus voltage drop due to an outage, and n_d , n_c are the number of buses and contingencies, respectively.

7) Next Contingency Thermal Security Region:

$$\mathbf{R}_{TT}^{(\lambda)} = \left\{ \mathbf{P}_T = [P_{AB} \ P_I^B]^T : |P_i(C_\lambda)| \leq P_i^M \text{ for } \forall i, \lambda; i = 1, \dots, n_\ell \text{ and } \lambda = 1, \dots, n_C \right\} \quad (1.2.27)$$

where $P_i(C_\lambda)$ is real power flow across the line i , P_i^M is the maximum line loading limit for line i and n_ℓ , n_C are the number of lines and contingencies, respectively.

The Available Transfer Capability (ATC) regions in the MW net-import space ($\mathbf{P}_I$ -space) and transfer space ($\mathbf{P}_T$ -space) have been illustrated hypothetically in Figure 1.2-3 and 1.2-4. Figure 1.2-3 shows the base case ATC regions in two spaces. It is the intersection of the regions of Eqns. (1.2.14-16) in the MW net-import space and is the intersection of the regions Eqns. (1.2.21-23) in the MW transfer space:

$$\mathbf{R}_{BCI} = \mathbf{R}_{FI} \cap \mathbf{R}_{VI} \cap \mathbf{R}_{TI} \quad \text{and} \quad \mathbf{R}_{BCT} = \mathbf{R}_{FT} \cap \mathbf{R}_{VT} \cap \mathbf{R}_{TT} \quad (1.2.28)$$

The boundary of this region represents the feasible and secure transfer capability of the network under its base case topology. The region contains the set of feasible and secure MW import vectors, $\mathbf{P}_I = [P_I^A \ P_I^B]^T$, or MW transfer vector, $\mathbf{P}_T = [P_{AB} \ P_I^B]^T$, for which there is a secure voltage profile with no overloads. It can be seen from Figure 1.2-3 that the boundary of the base case ATC region may be determined by all the operating constraints in different search directions. The thick black lines represent the boundary of LFF region. These constraints are displayed everywhere, because they are hard constraints and they indicate the absolute limit of system operation; i.e., there is no solution to the load flow equations beyond this boundary. The heavy and lighter dashed lines represent the MW area import or transfer limits imposed by the thermal and voltage magnitude limits, respectively. Figure 1.2-4 shows the ATC regions in the MW net-import space ($\mathbf{P}_I$ -space) and transfer space ($\mathbf{P}_T$ -space) under contingency operation. It is

the intersection of the regions of Eqns. (1.2.17-20) in the MW net-import space and is the intersection of the regions Eqns. (1.2.24-27) in the MW transfer space:

$$\mathbf{R}_{\text{NCI}}^{(\lambda)} = \mathbf{R}_{\text{FI}}^{(\lambda)} \cap \mathbf{R}_{\text{VI}}^{(\lambda)} \cap \mathbf{R}_{\Delta\text{VI}}^{(\lambda)} \cap \mathbf{R}_{\text{TI}}^{(\lambda)} \quad \text{and} \quad \mathbf{R}_{\text{NCT}}^{(\lambda)} = \mathbf{R}_{\text{FT}}^{(\lambda)} \cap \mathbf{R}_{\text{VT}}^{(\lambda)} \cap \mathbf{R}_{\Delta\text{VT}}^{(\lambda)} \cap \mathbf{R}_{\text{TT}}^{(\lambda)} \quad (1.2.29)$$

If any given operation point $\mathbf{P}_I$ or $\mathbf{P}_T$ lies within the next contingency security region, the system can withstand any line outage from the contingency list without violating any security constraints. Unlike the base case situation, there is one more type of constraint, voltage drop limit, represented by the cross-hatched line. In addition to information about type and which component limits the inter-area import level shown in Figure 1.2-3, the next contingency region identifies the most binding contingencies as well. In other words, it illustrates how a specified line outage can limit the real power transfers from area A and B. As it is seen from Figure 1.2-4, voltage drop limit constraint may also decrease the transfer capability of the network in some search directions. It is expected that next case ATC region would be a subset of the base case ATC region in both MW net-import space and transfer space. The graphical display of the security regions in the MW transfer space gives the utilities much more information than these in the MW net-import space. For instance, utility B can plan how much power can be imported from utility A without violating any operating constraints under either base case or next contingency operations.

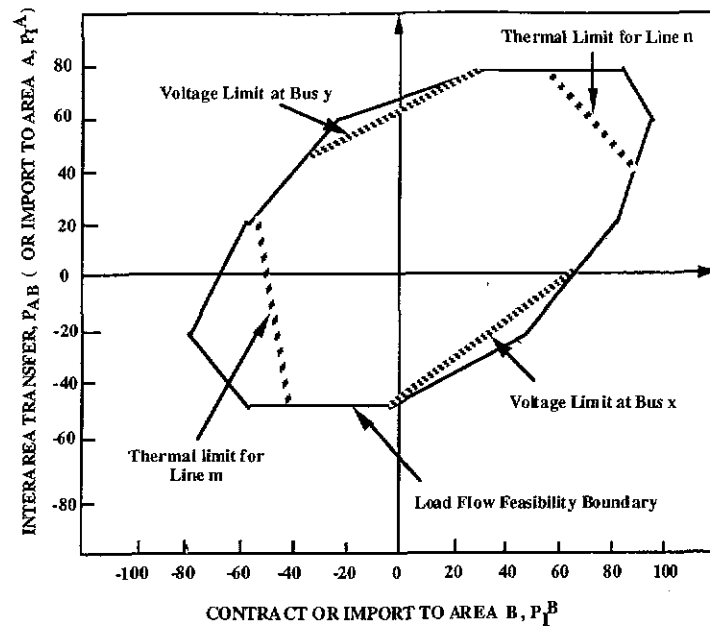


Figure 1.2-3 Illustration of base case security regions R_{BCT} or R_{BCI} in the MW transfer space (P_T -space) or MW net-import space (P_I -space)

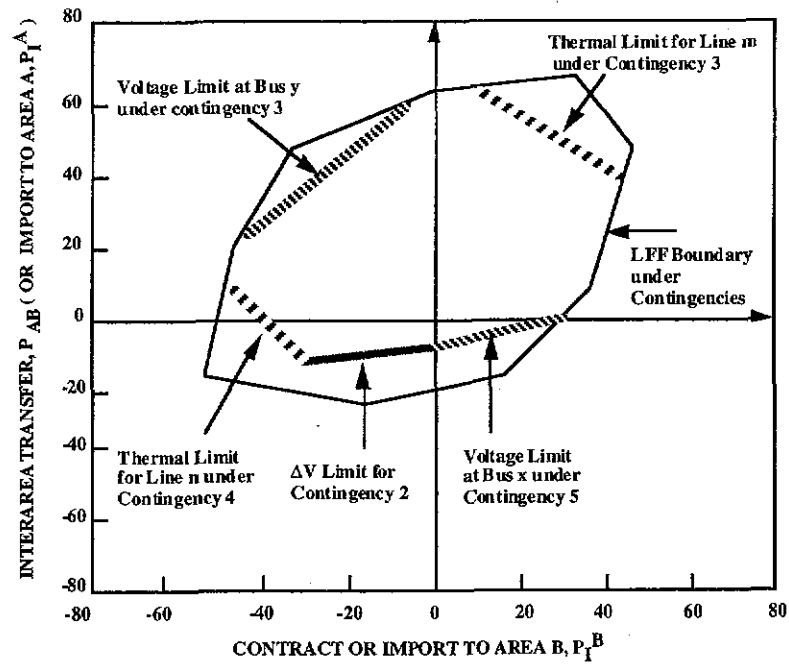


Figure 1.2-4 Illustration of next contingency security regions, $R_{NCT}^{(\lambda)}$ or $R_{NCI}^{(\lambda)}$ in the MW transfer space (P_T -space) or MW net-import space (P_I -space)

1.2.4 Sensitivity of the LFF and Security Regions to Load Variations

The uncertainty in the load profile in an existing power network has been increasing significantly. It may be given many different reasons for load uncertainty, such as deregulation, load forecast inaccuracies, measurement error, or unscheduled outage. Especially under the deregulation of the electric utility industry, power utilities may face to lose customers, since customers may have the freedom to choose the most economic power supplier utility. This fact makes the load level more probabilistic in nature. Therefore increasing uncertainty in load demand and the trend to increase the utilization of transmission system make it necessary to investigate the sensitivity of the Load Flow Feasibility (LFF) and steady-state security regions and ATC regions to different load change scenarios. An efficient method for steady-state security assessment in the presence of uncertainty in the load levels has been presented in [7]. In that method, a set-theoretic formulation of the security assessment problem was developed and it was based on the computation of the security region described in the operating space of either generation levels of individual units, or net power interchange, or both. In this thesis, using the formulation and software presented in [5], sensitivity of LFF and security regions to load changes at PQ buses shall also be examined. The following situations will be taken into consideration:

- i) Equal load active and reactive power demand increase at every load buses in the three-area power network, keeping power factor constant.
- ii) Real and reactive load increase at the load buses of either only importing area, area B, or exporting area, area A; keeping power factor constant.
- iii) Power factor changes.

Before giving the problem formulation and statement, let us first state the assumptions used by this thesis regarding to the power system model:

1.2.5 Assumptions on the Power System Model

- (1) The power system used in this thesis has three areas connected to each other by tie lines.
- (2) Each area has its own slack bus, either system slack bus or area (local) slack bus. Slack bus in area C (wheeler area) is defined as the system slack bus.
- (3) Area A is the exporting area, area B is the importing area and area C the swing area representing the rest of the network.
- (4) A bilateral trade is assumed between areas A and B.
- (5) Real power transfer is simulated by raising generation in the seller area (area A) and lowering the corresponding amount of generation in the buyer area
- (6) Generation buses are represented by PV buses. PV buses always have enough reactive power supply to maintain their voltage magnitude at constant.
- (7) Load buses are represented by PQ buses whose P and Q are held constant.
- (8) Real power generations are dispatched according to prescribed Generation Participation Factors (GPF).
- (10) Transmission line losses are neglected.
- (11) TCUL settings are fixed.
- (12) Contingency cases are limited to single line first contingencies outage.
- (13) There exists a base-case point, $\mathbf{P}_I^0$, of inter-area imports of real power.

1.3 PROBLEM FORMULATION

The load flow equations which have been used to characterize the LFF and security regions in the MW net-import space ($\mathbf{P}_I$ -space) and transfer space ($\mathbf{P}_T$ -space) consists of the traditional load flow equations plus two additional equations that describe the inter-area real power imports [5, 7]. These equations are given in polar form as follows:

$$P_i = V_i \sum_{k=1}^n V_k (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}), \text{ for } i=1, 2, 3, \dots, n_d+n_g \quad (1.3.1)$$

$$Q_i = V_i \sum_{k=1}^n V_k (G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}), \text{ for } i=1, 2, 3, \dots, n_d \quad (1.3.2)$$

where;

P_i = net real power injection at bus i

Q_i = net reactive power injection at bus i

V_i = voltage magnitude at bus i

θ_i = voltage phase angle at bus i

$G_{ik} + jB_{ik}$ = (i, k) th element of the bus admittance matrix, $[Y_{BUS}]$

n_d and n_g = total number of load (PQ) buses and generator (PV) buses

Note that each area has its own slack bus and slack bus in area C is selected as the system slack bus and thus, its voltage magnitude and phase angle are known. On the other hand, there are two local slack buses where only voltage magnitude are specified and their phase angles have to be calculated. The total number of unknown variables is $2n_d+n_g+2$. Therefore, we need two more load flow equations in addition to Eqns (1.3.1-2). Inter-area net real power imports can be related to bus voltages by the following equations:

$$\begin{aligned} P_I^A = & \sum_{i \in I_B, k \in I_A} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] \\ & + \sum_{i \in I_C, k \in I_A} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] \end{aligned} \quad (1.3.3)$$

$$\begin{aligned}
P_l^B = & \sum_{i \in I_A, k \in I_B} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] \\
& + \sum_{i \in I_C, k \in I_B} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right]
\end{aligned} \quad (1.3.4)$$

where

I_A, I_B, I_C = set of all the buses in area A, B or C respectively.

$g_{ik} + j b_{ik}$ = series admittance of the line connecting buses i and k

The above load flow equations can be expressed in general vector form:

$$\mathbf{f}(\mathbf{x}) = \mathbf{u}(\mathbf{P}_l) \quad (1.3.5)$$

where $\mathbf{f}(\mathbf{x})$ represents the right hand side of Eqns. (1.3.1) - (1.3.4); $\mathbf{x}$ is the state variables containing voltage magnitudes and phase angles, and $\mathbf{u}(\mathbf{P}_l)$ represents the left hand side of Eqns. (1.3.1) - (1.3.4). The derivation of $\mathbf{u}$ as a function of inter-area real power import vector, $\mathbf{P}_l$, is presented in Appendix A. The load flow equations depending on the parameter of inter-area import level, r , which has been used in radial search approach for a particular direction ϕ_i and a fixed contingency, could be given in the following form (see Appendix A for more details):

$$\mathbf{F}^\lambda(\mathbf{x}, r) = \mathbf{f}^\lambda(\mathbf{x}) - [\mathbf{u}^0 + r \mathbf{w}(\phi_i)] = \mathbf{0} \quad (1.3.6)$$

1.4 PROBLEM STATEMENT

Over all the purpose of this thesis is that given a power system model satisfying assumptions stated in Section 1.2.5, base case operation point ($\mathbf{P}_l^0$) and a list of line outage contingencies, C_λ , for $\lambda = 0, 1, 2, \dots, n_c$ is to obtain the LFF security and ATC regions defined in Section 1.2.2 in the MW net-import and transfer space as well as the voltage profile, $\mathbf{x}^\lambda$, inside the regions. The problem of the identification of LFF region

has been stated very neatly by Wu [5]. Therefore, only the problem statement of security regions identification has been described in this section.

Based on the problem formulation presented in Section 1.3 and Appendix A, solution of the overall problem mentioned above can be reduced the identification of parameter indicating the level of inter-area imports of real power, r , in specified radial directions of search. As stated earlier, there are two types of space ($\mathbf{P}_I$ or $\mathbf{P}_T$) in which the regions are displayed, thus, we have two problem statements:

Problem 1.4.1: The identification of security region boundary point in a given direction in the MW net-import space, $\mathbf{P}_I$ -space

Given:

- (1) Load Flow Equation in Eqn. (1.3.6), i. e. $\mathbf{F}^\lambda(\mathbf{x}, r) = \mathbf{f}^\lambda(\mathbf{x}) - [\mathbf{u}^0 + r \mathbf{w}(\phi_i)] = \mathbf{0}$
where ϕ_i representing a prescribed angular direction of search, is constant.
- (2) A list of line outage contingencies, C_λ , for $\lambda=0,1,2,\dots,n_C$.

Find:

- (1) The maximum value of inter-area import level (r), whose corresponding voltage profile, $\mathbf{x}$, must satisfy voltage limit constraint for base case; voltage limit and voltage drop limit constraints for contingency cases to determine the voltage security and voltage drop limit region boundary point.
- (2) The maximum value of inter-area import level, (r), whose corresponding power flows across the transmission lines in the network must satisfy the thermal limit constraint for both base case and contingency cases to determine the boundary point of thermal security region.

Once the maximum value of inter-area import level, at which no operating constraint is violated, is known in any search of direction; $\mathbf{P}_I = [\mathbf{P}_I^A \ \mathbf{P}_I^B]^T$ can be found easily using the

following equation (Remember that the existence a base-case point, P_I^0 , of inter-area imports of real power is assumed):

$$P_I - P_I^0 = r \begin{bmatrix} \sin\phi \\ \cos\phi \end{bmatrix} \quad (1.3.7)$$

Problem 1.4.2: The identification of security region boundary point in a given direction in the MW transfer space, P_T -space.

Given:

- (1) Load Flow Equation in Eqn. (1.3.6), i. e. $F^\lambda(x, r) = f^\lambda(x) - [u^0 + r w(\phi_i)] = 0$ where ϕ_i representing a prescribed angular direction of search, is constant.
- (2) A list of line outage contingencies, C_λ , for $\lambda=0, 1, 2, \dots, n_c$.

Find:

- (1) The maximum transfer of real power from area A to B, P_{AB} and net-import into area B, P_I^B , in the given search direction whose corresponding voltage profile, x , has to satisfy voltage limit constraint for base case; voltage limit and voltage drop limit constraints for contingency cases to determine the voltage security and voltage drop limit region boundary point.
- (2) The maximum transfer of real power from area A to B, P_{AB} and net-import into area B, P_I^B , in the given search direction whose corresponding power flows across the transmission lines in the network must satisfy the thermal limit constraint for both base case and contingency cases to determine the boundary point of thermal security region.

1.5 APPROACH

We use the radial search approach in the P_I -plane [3, 5] to identify the boundary point of security regions and to check the existence or nonexistence of a solution to Eqn. (1.3.5). Remember that the existence of a solution to the power flow Eqn. (1.3.5) is the necessary condition for the all types of steady-state security assessment for a particular

operating condition, i.e., for a given network configuration, (or contingency), load level and power injection. If there is a solution, it should be checked whether voltage profile and power flows across the transmission lines satisfy the operating constraints defined by Eqns. (1.2.10-13) for the security assessment.

The search procedure to obtain voltage security, voltage drop limit and thermal security regions in the MW net-import space, P_I -space, could be stated as follows:

- 1) Select an initial direction of search (say at angle $\phi = 0^\circ$).
- 2) Increase inter-area import level, r , along the search direction until voltage magnitude limit constraint, Eqn. (1.2.12), is violated to get voltage security region boundary point, or until thermal limit constraint, Eqn. (1.2.11) is violated to obtain thermal security region boundary point for base case and next contingency cases. Once the boundary point is found, record the coordinates of that point in the $P_I^A - P_I^B$ plane.
- 3) Increase inter-area import level, r , along the search direction until voltage drop limit constraint, Eqn. (1.2.13), is violated to determine the boundary point of voltage drop limit region for contingency cases.
- 4) Change the direction of search incrementally (by $\Delta\phi$) in the counter clockwise direction and repeat Step 2) and Step 3) until the final direction of search is reached.
- 5) Join the boundary points by straight-line segments to obtain the approximate regions.

The boundary point of security regions in the MW transfer space could be determined in the same way as in the MW net-import space. However, instead of net-import into area, P_I^A , real power transfer from area A to area B, P_{AB} , has to be calculated to display the security regions in the P_T -space. To do so, first the boundary points of the security regions in P_I -space, dictated by all the operating constraints, have been determined by following the step 1), 2), 3) and 4) mentioned above. Then, real power transfer, P_{AB} , corresponding to these boundary points in P_I -space have been calculated. Remember that real power transfer from area A to B is defined as the summation of the

real power, taken into consideration the direction of power flows, on the tie lines connecting the two areas. Once the boundary points of each security region are found, the security region is plotted by connecting these points in the $\mathbf{P}_T$ -space.

1.6 ORGANIZATION OF THE THESIS

The organization of the following chapters of this thesis is as follows: Chapter 2 describes the state of art in identification of LFF region in import space and state of art in region-wise steady-state security assessment. Chapter 3 presents the simulation results of LFF, security and ATC regions in the MW net-import space ($\mathbf{P}_I$ -space) for base case and next contingency cases using a 3-area 31-bus system. Chapter 4 shows the LFF, security and ATC regions in the MW transfer space ($\mathbf{P}_T$ -space). The conclusions and some recommendations for further research have been presented in Chapter 5.

Appendix A gives the details of both load flow equations considering the inter-area imports of real power and radial search approach used to identify the boundary points of the regions. Appendix B provides information about software. Appendix C documents the 31-bus system data and thermal limit of the transmission lines. Appendix D gives a list of symbols used in this thesis.

CHAPTER 2

THE STATE OF THE ART

2.1. INTRODUCTION

This chapter presents a literature review of the current available approaches in the steady-state security assessment problem and the identification of Load Flow Feasibility (LFF) regions. Power system steady-state security assessment can be classified into two major approaches: "Point-wise" and "region-wise" security assessment. Point-wise security assessment is to perform a repetitive load flow calculations to evaluate the security for each operating point following a set of postulated contingencies. The region-wise security assessment approach for determining the system security is conceptually different from the point-wise evaluation of the system security. The whole idea behind this approach is to obtain a collection of all operating points, which may be generation level of each station, real power exchange among areas in the network, or net bus injection, for which the power system satisfy the security constraints given by Eqns.(1.2.10) - (1.2.13) in Chapter 1, Section 1.2.2. The collection of the feasible and secure operating points is called the steady-state security region. Once the region is obtained, one needs only to check if a given operation point lies within the security region and how far this operating state is from the boundary of the security region, so-called security margin.

The purpose of the Load-Flow Feasibility (LFF) analysis is to investigate the existence of load flow solutions. The Load Flow Feasibility region is the set of the injection space, within which any injection point guarantees the existence of a voltage profile across the system. The injection space can be active/reactive power bus injection and/or inter-area injection. Since the LFF region identification methods and algorithms proposed in [3, 4, 5] were used to obtain the steady-state security regions in this thesis, a brief literature review

in LFF region identification and region-wise security assessment will be presented in this chapter.

2.2 THE STEADY-STATE REGION-WISE SECURITY ASSESSMENT

The concept of the steady-state security region was first introduced in 1975 by Hnyilicza, Lee and Schweppe [8]. Based on DC load flow model, they defined the thermal security regions in the operating space of either generation levels of individual generating stations, net power interchange, or bus load levels. The DC load flow model allowed them to express the thermal limit constraints on post-contingency line flows in terms of the pre-contingency operating variables. The thermal limit criteria for steady-state security was derived in the form of a set of linear inequality constraints under the transmission line and generator contingencies. They introduced three types of security regions: i) The normal operating region ii) The line contingency security region iii) The generator contingency security region. Each region was bounded by a set of hyperplanes with the property that any given power injection pattern that fell inside the region was said to be steady-state secure. When generation level was used as the operating space, a load (PQ) bus was chosen as the system slack bus. The Bounding Hyperbox Algorithm was proposed to find the minimal description of the region, i.e., to eliminate redundant constraints in the description of the security region.

In 1976, a similar approach to that given in [8] to identify the thermal security region was proposed by DeMaio and Fischl [9]. Their method was a faster and more efficient way for obtaining the most economical and minimal description of the steady-state security region. They used several set of constraints to define the thermal limits of the network under normal and contingency outage operation and the generation limits. The security region was defined in the operating space of generation levels as the intersection of the following two security region: i) Transmission security region ii) Generation security region. The first region represents the set of all operating points for which the transmission

network is secure (i.e., no element is overloaded), while the second region represents the set of all operating points within the generating unit limits and the available reserve. By choosing the appropriate sets of constraints, the defined “normal secure” and “normal insecure” operating regions in the space of generator real power injection. The normal secure region was based on the normal (nominal) power flow ratings of the transmission lines, while the normal insecure region was based on the emergency line ratings. Any operating point inside the both regions were able to survive any of the pre-determined set of next contingencies such that the post contingency power flows remained within the nominal or emergency line ratings. A generator bus rather than a load bus, as in [8], was chosen as the system slack bus, which matches more closely to the standard AC load flow calculations. They introduced the use of the polytope identification of Mattheiss [10] to obtain the most binding constraints of the security regions. In the hyperbox algorithm used to screen out irrelevant constraints in [8], at least the solution of $2n$ linear programming (LP) problems were required to eliminate the irrelevant constraints and the algorithm was unable to identify “most secure” points inside the region, which are essential in developing control strategies for steady-state security enhancement. On the other hand, the method in [9] required the solution of only one LP problem to identify a specific security region and was able to obtain the “most secure” operation point inside the region without any additional computations.

Fischl, Ejebe and DeMaio [7] extended the method presented in [9] to include the load uncertainty in the steady-state security assessment problem. The variations in load profile were assumed to be uniformly distributed on a known interval; specifically, they replaced the base case real power load vector $\mathbf{P}_d^0$ by the vector quantity $\mathbf{P}_d^0 + \delta\mathbf{P}_d$ where $\delta\mathbf{P}_d$ represents the uncertainty in the load profile. This allowed the authors to make security assessment of power system recognizing the uncertainties without recourse to stochastic or probabilistic load flow. The Mattheiss Algorithm was used again to identify the thermal security region. Furthermore, a security margin, $y(x)$, was defined to monitor the system

security in terms of the location of the operating state inside the region, where x is the operation variables. Based on the margins an efficient algorithm was presented to identify the binding constraints (i.e., to eliminate the irrelevant constraints) and the "most secure" operating points inside the region and identify the "bottlenecks" in the case of the nonexistence of thermal security region. Based on the knowledge of the maximum security margin, a relative security index were defined as follows:

$$SI(\mathbf{P}_g) = \frac{y(\mathbf{P}_g)}{y^*} \quad (2.1.1)$$

where $y(\mathbf{P}_g)$ is the security margin for an operating point $\mathbf{P}_g$ (i.e., the Euclidean distance from $\mathbf{P}_g$ to the closest boundary point of the thermal security region) and y^* is the maximum security margin. This security index can be used to measure the security of the any economic dispatch

In 1980, Mescua and Fischl [11] presented a method to address the problem of determining the most secure voltage profile for an electric power system. They tried to obtain a set of voltage magnitudes which would maintain the voltage profile and generation of reactive power within an acceptable limits in electric power system. A linear reactive power-voltage magnitude relationship was developed to relate load bus voltages and reactive power generations in terms of generator bus voltages and reactive load demands. The voltage security region was defined by the constraints on the reactive power generations and bus voltages in the space of generator bus voltage magnitudes.

The idea of security region was extended by Banakar and Galiana in [12], where a method so called "security corridors" was proposed for steady-state security assessment. They used the rectangular coordinates of power flow equations to derive linear and quadratic approximation formulas for the characterizations of the security region and restricted the range of system operating points to an area around its predicted, slowly varying trajectory. Based on the assumption that the normal range of system operating points can be restricted to the neighborhood of the system's predicted trajectory, they

characterized only a small part of the operating space by using a relatively small number of operating and security constraints. The security corridor was formed by the secure operating points among the operating points surrounding a trajectory. The security corridors existed in the combined space of generator control vectors $\mathbf{P}_g$ and $\mathbf{V}_g$ and the real and reactive load vectors $\mathbf{P}_d$ and $\mathbf{Q}_d$. Three types of constraints were used to define the boundary of the security corridor. i) Voltage magnitude limit constraints, as in Eqn. (1.2.12), ii) the minimum and maximum limits on generator reactive power injection vector, $\mathbf{Q}_g$, given by:

$$\mathbf{Q}_g^m \leq \mathbf{Q}_g \leq \mathbf{Q}_g^M \quad (2.1.2)$$

and iii) limits on the current flowing in the lines of the network. The two major motivations behind the security corridor concept can be explained as follows: First, there is a need for a greater level of confidence in the security of a particular operating point than can be provided by the regions based on the DC load flow model. Remember that the transformation of constraints into the operating space as suggested in [8] was based on DC load flow model. Although the model in [8] was accurate enough in estimating the real power flows and thus, was suitable for treating planning problems, it could not establish the security of a given operating point completely and accurately. Secondly, since the number of constraints defining a security set in the operating space described by Hnyilicza et al. are normally very large, the authors deemed the use of such security sets for security control impractical. Furthermore, they thought that because of the non-sparsity of these constraints, security monitoring procedures based on the explicit representation of security sets were not competitive with the conventional numerical schemes. However, the further research has not been done about the security corridor concept, due to the time-varying nature of corridors, the difficulty of their visualization, and their conservative range. The security corridors are, in fact, regions found within predefined boundaries that change with time.

In 1982, Dersin and Levis [13] again addressed the region-wise thermal security problem. Using the mathematical programming duality, explicit conditions were found which characterized the feasible sets of load demands that can be served with the available generation resources without overloading the transmission line and transformers. Although they started with the DC load flow model to derive linear constraints, the authors chose to fix the generation levels and work in the space of load bus real power demands, rather than use of formulations in [7], [8] and [9]. The key contribution of their work was an explicit description of the feasibility set for a general power system consisting of generation, transmission and subtransmission. Instead of the thermal security region definitions in Eqns. (1.2.16) and (1.2.20), the authors derived a complex distance function for the boundary of the thermal security region based on concepts in mathematical programming duality. However, the practical advantage of this approach was not clear. Furthermore, the complex derivation did not give indications of how large a system can be used on, or the efficiency of the computations necessary to obtain it.

F.F. Wu and Kumagai [6] formulated the security region problem as one of determining the sufficient conditions for the existence of solutions to AC power flow equations in the set defined by the security constraint. In their approach, the decoupled power equations were used merely as a stepping stone and the resulting steady-state security regions, hyperboxes in the space of real and reactive power injections at the load buses, and real power injections at the generator buses, were exact without approximations. Voltage magnitude limits and transmission line current limits were considered as the set of security constraints to obtain the security regions. The modeling assumptions imposed on the system are not restrictive, but the theoretical conditions used by the authors to identify the secure operating points restrict their location to the hyperboxes in the operating space. Since the actual shape of the security regions are quite irregular in general, the hyperboxes are overly conservative. Nevertheless, the analytic

approaches for deriving the steady-state security regions and results established by the authors serve as a theoretical basis for further research.

In 1986, Liu [14] presented a method to construct the maximal steady-state security region based on the DC load flow model. Using the same DC load flow formulation of the thermal constraints as was used by DeMaio and Fischl in [9], the author used a novel procedure to expand the hyperboxes (security region) given a selected base point and growth pattern. The proposed approach has three steps. First an initial secure region (hyperbox) was obtained analytically. Next a developed algorithm was used to expand the upper and lower bounds of the initial region in certain chosen dimensions of the control space. The final step of the method was to solve a set of optimization problems to obtain a maximal security region, which still remains in the form of hyperbox. Although the algorithm is fast, its accuracy is poor, since the security regions are always defined in the conservative hyperboxes. The hyperboxes do not show which line constraints are binding on the region and where. To get a more accurate security region, one could take the union of the hyperboxes expanded in several different directions. Nevertheless, this approach might help to more accurately characterize the nonlinear regions formulated by Wu and Kumagai [6].

In 1993, T. Wu and Fischl [3] developed an efficient technique to identify the boundary of the steady-state security region based on the load flow feasibility constraint given by Eqn. (1.2.10). No other security constraints such as voltage limit, thermal limit or voltage drop limit constraint were taken into consideration while determining the regions. The purpose was to generate a graphical display of a set of inter-area MW transfers which guaranteed the existence of a voltage profile across the network. The set of operating points defines the Load Flow Feasibility (LFF) region which exists in the inter-area MW net import space (cf. Sec. 1.2.1). A radial search method was used to determine the boundary points of the region. Along each direction of search in the MW net-import space, $P_1^A - P_1^B$

space, several regularized load flows were run until the system Jacobian matrix became singular. The point where the Jacobian matrix is singular is also called as maximum loading point, saddle-node bifurcation point, turning point or critical loading point. The radial searches were performed at discrete angles and boundary point were found, then were connected via interpolation to obtain an approximate region. The method had ability to control the accuracy of the approximation by judicious choice of search directions. A regularization method proposed by Kataoka [15] was used in their approach because it has a larger region of convergence around each boundary point.

In 1994, Wunderlich, T. Wu, Fischl and O'Connell [16] developed a new planning tool, called the Transmission and Voltage Limitation (TVLIM) program to provide a graphical display of the set of all feasible and secure inter-area transfers. The authors actually combined the efficient algorithm in [3] for generating the LFF region boundary and the region-wise security approach proposed in [9] to get the security regions in the MW net-import space. The following region definitions were given for base case and next contingency cases in the $P_1^A - P_1^B$ space: i) LFF regions, Eqns.(1.2.14) and (1.2.17) . ii) Thermal security regions, Eqns.(1.2.16) and (1.2.20). iii) Voltage security regions, Eqns.(1.2.15) and (1.2.18). iv) Next contingency voltage drop limit region, Eqn. (1.2.19). However, TVLIM program was able to calculate only base case LFF region, thermal security region and next contingency thermal security region. The approach taken for constructing the thermal security region was based on the formulation of analytical constraints for the line loading limits. DC load flow model was modified for specification of inter-area imports and the thermal limits constraints formulations were derived for the inter-area real power space.

The region-wise security analysis works discussed above are summarized for comparisons in Table 2.2-1 below.

Table 2.2-1 Region-Wise Steady-State Security Assessment Methods

Author, Year & Reference	Control Space ($\mathbf{u}$)	Load Flow Model	Region Type
Hnylicza, Lee, Schweppe (1975) [8]	$\mathbf{P}_g$ or $\mathbf{P}_l$	DC Load Flow	$\{ \mathbf{u} : \mathbf{P}_l(\mathbf{u}, \mathbf{P}_d^0) \leq \mathbf{R}_l, \mathbf{u}^m \leq \mathbf{u} \leq \mathbf{u}^M \}$
DeMaio, Fischl (1976) [9]	$\mathbf{P}_g$	DC Load Flow	$\{ \mathbf{u} : \mathbf{P}_l(\mathbf{u}, \mathbf{P}_d^0) \leq \mathbf{R}_l, \mathbf{u}^m \leq \mathbf{u} \leq \mathbf{u}^M \}$
Fischl, Ejebe, DeMaio (1976) [7]	$\mathbf{P}_g$	DC Load Flow	$\{ \mathbf{u} : \mathbf{P}_l(\mathbf{u}, \mathbf{P}_d^0 + \delta \mathbf{P}_d) \leq \mathbf{R}_l, \mathbf{u}^m \leq \mathbf{u} \leq \mathbf{u}^M \}$
Mescua, Fischl (1980) [11]	$\mathbf{V}_g$	Linear	$\{ \mathbf{u} : \mathbf{u}^m \leq \mathbf{u} \leq \mathbf{u}^M, \mathbf{Q}_g^m \leq \mathbf{Q}(\mathbf{u}, \mathbf{Q}_d^0) \leq \mathbf{Q}_g^M \}$
Banakar, Galiana (1981) [12]	$\mathbf{P}_g, \mathbf{Q}_g, \mathbf{V}_g, \mathbf{Q}_d$	Quadratic	$\left\{ \mathbf{u} : \mathbf{V}_d^m \leq \mathbf{V}_d \leq \mathbf{V}_d^M, \mathbf{I}_l(\mathbf{u}) \leq \mathbf{I}_l^M, \mathbf{Q}_g^m \leq \mathbf{Q}(\mathbf{u}) \leq \mathbf{Q}_g^M \right\}$
Dersin, Levis (1982) [13]	$\mathbf{P}_d$	DC Load Flow	$\{ \mathbf{u} : \mathbf{P}_l(\mathbf{u}, \mathbf{P}_g) \leq \mathbf{R}_l, \mathbf{0} \leq \mathbf{P}_g \leq \mathbf{P}_g^M \}$
Wu, F.F., Kumagai, (1982) [6]	$\mathbf{P}_g, \mathbf{P}_d, \mathbf{Q}_d$	AC Load Flow	$\{ \mathbf{u} : \mathbf{I}_l(\mathbf{P}_g, \mathbf{P}_d, \mathbf{V}) \leq \mathbf{I}_l^M, \mathbf{V}^m \leq \mathbf{V}(\mathbf{Q}_d) \leq \mathbf{V}^M \}$
Liu (1986) [14]	$\mathbf{P}_g$	DC Load Flow	$\{ \mathbf{u} : \mathbf{P}_l(\mathbf{u}, \mathbf{P}_d^0) \leq \mathbf{R}_l, \mathbf{u}^m \leq \mathbf{u} \leq \mathbf{u}^M \}$
Wu, T., Fischl (1993) [3]	$\mathbf{P}_l$	AC Load Flow	$\{ \mathbf{u} : \exists \mathbf{x} \text{ s.t. } \mathbf{f}(\mathbf{x}) = \mathbf{u}(\mathbf{P}_l) \}$

Table 2.2-1 (Cont'd)

Wunderlich, Wu, T., Fischl, O'Connell (1994) [16]	$\mathbf{P}_l$	DC Load Flow	LFF: $\{\mathbf{u} = \mathbf{P}_l : \exists \mathbf{x} \text{ s.t. } \mathbf{F}(\mathbf{x}, \mathbf{u}(\mathbf{P}_l)) = \mathbf{0}\}$ Thermal: $\{\mathbf{u} = \mathbf{P}_l : -\mathbf{P}_l^M \leq \mathbf{P}_l^A(\mathbf{P}_l) \leq \mathbf{P}_l^M, \forall \lambda\}$ where $\lambda=0, 1, \dots, n_c$
---	----------------	-----------------	--

Notation in Table 2.2-1:

$\mathbf{P}_l$: The vector of line real power flow

$\mathbf{P}_d^o$: The vector of nominal real power load demands

$\mathbf{R}_l$: The power flow rating

$\mathbf{P}_d$: The real power load demand vector

$\mathbf{Q}_d$: The reactive power load demand vector

$\delta \mathbf{P}_d$: The load deviation vector from the nominal value of load demands

$\mathbf{P}_g$: The real power generation vector

$\mathbf{Q}_g$: The reactive power generation vector

$\mathbf{I}_l$: The line currents vector

$\mathbf{V}_d$: The load buses voltage vector

$\mathbf{V}_g$: The generator buses voltage vector

λ : The contingency identification number

n_c : The number of contingencies

m and M represent the minimum and maximum limits on any vector quantity.

Based on the literature review in region-wise security assessment methods, LFF region identification algorithm in [3, 4, 5] seems to be the most suitable and realistic method to obtain several different security regions in the MW net-import space, $\mathbf{P}_l$ -space, and the MW transfer space, $\mathbf{P}_T$ -space (cf. Section 1.2.2). Even though, the formulations of

thermal constraints in the inter-area net import space in [16] were based on the DC load flow model, the idea of getting security regions such as thermal, voltage security for base and next contingency cases and voltage drop limit region for next contingency cases is very helpful indeed. Because the overall security region, defined intersection of security regions, provides information about such items as which system components are most limiting and which transmission lines or buses are the weak links. In the next section, a brief literature review on the techniques for identifying the boundary points of LFF regions shall be presented.

2.3 THE IDENTIFICATION OF THE LOAD FLOW FEASIBILITY (LFF) REGION

The first attempt to propose the concept of Load Flow Feasibility (LFF) region in an injection space was done by Galiana and Jarsis, [17]. Their primary effort was to show that the LFF region can be computed analytically. After the result of their study, a scalar criterion, called the steady-state stability margin (SM) for a given injection vector inside the region was defined. This margin a quantitative measure of feasibility such that it indicates the closest distance between the operating point and the feasible boundary in all directions. Although their work provides researchers with substantial information about the Load Flow Feasibility problem, it is not an efficient method numerically and is based on a wrong assumption that the LFF region is convex. Araposthatis *et. al.* [18] and Kwantny *et. al.* [19] studied the existence of equilibria of power system via bifurcation theory. The two approaches are related in that the boundary of the LFF region is generically a set of turning points of the set of load flow equations. This researches lead to study of load flow feasibility problem using bifurcation theory.

However, instead of using a region-wise approach to obtain LFF region, most of the researchers concentrated on computing a boundary of the LFF region. The boundary point is often referred as the critical loading point [20], maximum loading point [21], and point of voltage collapse [22]. No matter what name is given to the boundary point, the

main characteristic of this point is that the Jacobian matrix of the load flow equations is singular (i.e., its determinant is zero) at this point. Since the Jacobian matrix is singular at the point of boundary and ill-conditioned around the point, it is very difficult to find the boundary point by using traditional Newton Raphson (NR) method. Therefore, most of the researchers have been trying to eliminate the singularity of the Jacobian and to enlarge the region of convergency around the near-singular point. Now, the method related to the identification of the LFF boundary point will be explained briefly.

The methods of obtaining the boundary point (maximum loading point, saddle node bifurcation point, turning point, critical point) can be classified into two major categories:

- i) Direct Methods [17, 21-25]
- ii) Indirect Methods [15, 20, 26, 27]

Direct methods use the fact that the Jacobian matrix of the load flow equations is singular, which is the characteristic of the boundary point, to compute the LFF boundary. Among the direct methods, the point of voltage collapse types [21-23, 25] are used very often to obtain the boundary of the LFF regions. These types of methods uses the singularity of the Jacobian and the fact that any singular matrix has an eigenvalue at origin. The following set of nonlinear equations are usually solved via the Newton Raphson method [28].

$$\mathbf{F}(\mathbf{x}, r) = \mathbf{0} \quad (2.3.1)$$

$$(\mathbf{D}_{\mathbf{x}} \mathbf{F}) \mathbf{v} = \mathbf{0} \quad (2.3.2)$$

$$\mathbf{v}^T \mathbf{v} - 1 = 0 \quad (2.3.3)$$

Where $\mathbf{F}$ is the load flow equations, $(\mathbf{D}_{\mathbf{x}} \mathbf{F})$ is the Jacobian matrix, $\mathbf{v}$ is the right eigenvector associated with the eigenvalue at origin and r is a parameter indicating the loading (and/or generation and/or area imports) levels. Equation (2.3.1) is the set of load flow equations. Equation (2.3.3) ensures that the vector $\mathbf{v}$ is nontrivial. Equation (2.3.2) together with (2.3.3) establish the singularity of the Jacobian matrix, $(\mathbf{D}_{\mathbf{x}} \mathbf{F})$. To obtain the boundary point (saddle node bifurcation point) only the set of nonlinear algebraic equations given above need to be solved. However, this means solving a set of nonlinear equations

twice as big as the original, and a good initial estimate of the turning point as well as the voltage profile and right eigenvector is needed to start the iteration process. Continuation method, indirect one, is usually used to provide such an initial point for the direct methods.

Indirect method develop computational techniques to overcome the singularity problem of the Jacobian matrix, usually by modifying the Jacobian in a certain way such that the modified Jacobian becomes nonsingular at the boundary of the LFF region where the original one was. There are two types of indirect methods:

- i) Continuation methods [20, 26, 27]
- ii) Regularization method [15]

Continuation methods, sometimes called curve tracing or path following, are useful tools to generate solution curves (nose curves in power engineering) for general nonlinear algebraic equations with a varying parameter, such as load flow equations with import level parameter, r in Eqn. (2.3.1). The continuation method is to start from a given base case operating point, $(\mathbf{x}_0, r_0)$ and produce a series of solution points, $(\mathbf{x}_i, r_i)$ in a prescribed direction, determined by participating load and generation variations, until the nose point (boundary point), $(\mathbf{x}^*, r^*)$ is reached. Continuation methods usually have the following four basic components: i) Parameterization ii) Predictor iii) Corrector iv) Step-size control as is shown in Figure 2.3-1. Parameterization is a mathematical way of identifying each solution on the solution curve so that next solution or previous solution can be quantified. The purpose of the predictor is to find an approximation point of the next solution by solving a set simultaneous linear equations. After the predictor has produced an approximation for the next solution, the error must be corrected before it accumulates. Any effective numerical procedure such as Newton Raphson, for solving a set of nonlinear algebraic equations can be used for a corrector. The step-length control is one of the key elements affecting computational efficiency of a continuation method. The step length control must correspond to the predictor, the corrector and the underlying parameter.

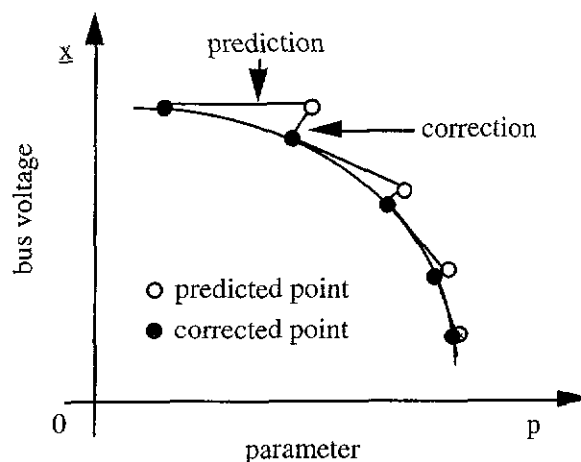


Figure 2.3-1 Graphical representation of continuation method

The Homotopy Continuation Method [20] overcomes the singularity of the Jacobian matrix by adding the equation of a hyperplane perpendicular to a vector tangent to the solution surface in the state variable space, thereby augmenting the Jacobian by a single additional row and column. Parameterization Continuation Methods [26, 27] trade the load level parameter with the state variables to eliminate the singularity of the Jacobian matrix. The common problem of the continuation methods [20, 26, 27] is the selection of the step-length. It is safe to choose a constant and small step-length in any continuation methods. However, this constant step-length may often lead to inefficient computation. Similarly, an inadequately large step-length can cause divergence around the boundary point. In the prediction step of the Homotopy Continuation Method, the Jacobian matrix must be inverted, which causes a numerical problem around the boundary point. In the correction step of the Parameterization Continuation Methods, once a state variable is parameterized, a fixed value must be selected for it. Inappropriate selection of this value may result in divergence problems. Continuation methods are slower than the direct methods for finding the boundary points of the LFF regions, but they provide direct methods with good initial

guess. The main advantage of the continuation methods is that they provide information on the voltage profile along the way as the operating point moves.

Regularization Method [15] was proposed to overcome the singularity problem around the maximum loading point by defining the load level parameter, r as a function of bus voltage and a new parameter, k :

$$r = g(k, \mathbf{x}) \quad (2.3.4)$$

The selection of regularization function, $g(k, \mathbf{x})$ is not unique. However, Kataoka recommended the following function in [15]:

$$r = g(k, \mathbf{x}) = k [(\mathbf{e}_{2p})^T \mathbf{x}]^2 = k V_p^2 \quad (2.3.5)$$

Where V_p is the voltage magnitude at a pre-selected load bus. The degree of drop in the voltage of the bus in response to the increase in k determines the load level (import level) of the whole system, so that this load bus is called as the pilot bus. The salient feature of the regularization method is the existence of a unimodal relationship between r and k around the boundary point, $r^*(k^*)$ as is shown in Figure 2.3-2 (a).

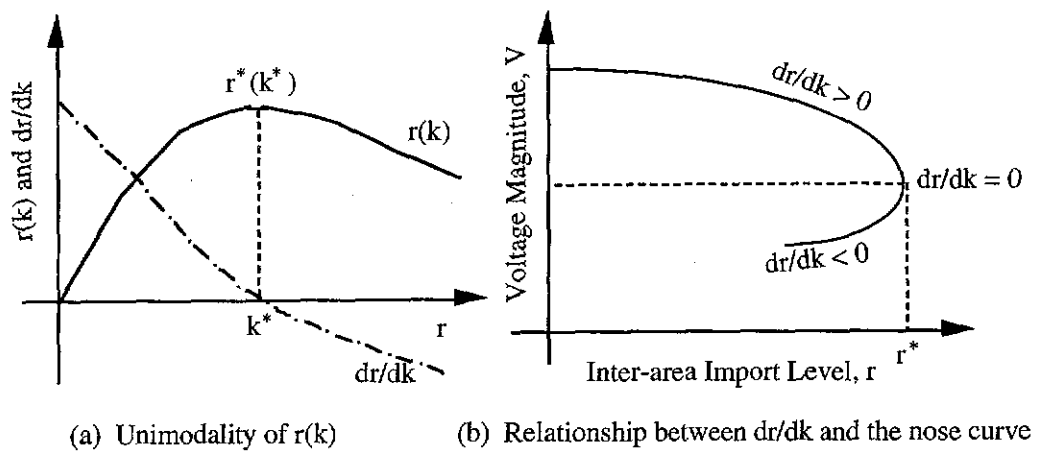


Figure 2.3-2 Unimodal relationship between parameters r and k of the regularization method

The unimodal relationship also implies that dr/dk , as a function of k , is monotonically decreasing around the critical point. Moreover, the sign of dr/dk indicates the location of the operating point, as shown in Figure 2.3-2 (b), relative to the turning point where $dr/dk=0$. Therefore, the sign of the derivative can be used as a direction-indicator in any search process for the boundary point. The regularization method enables one use single-variable search techniques to compute the boundary point because the regularization method can obtain the voltage profile on not only the upper but also lower part of the nose curve while the sign of dr/dk can indicate if the operating point is on the upper or on the lower part. However, the theoretical foundation of the regularization method and the selection of an appropriate pilot bus was not treated sufficiently in [15]. In [29], a theoretical framework was presented for checking the validity of a given regularization function.

The regularization method was applied very well to the identification of the LFF region in the MW net-import space in [3, 4, 5, 30]. In these research work the regularization method was treated as a special parameterization technique of a continuation method. The principles of both continuation methods and the regularization method were used in [3, 4, 5, 30] by T. Wu and R. Fischl to develop simple, reliable and efficient algorithms for finding the LFF boundary points. They formulated the load flow equations by using the regularization function, $g(k, \mathbf{x})$.

$$\mathbf{H}(\mathbf{x}, k) = \mathbf{f}(\mathbf{x}) - [\mathbf{u}^0 + g(k, \mathbf{x})\mathbf{w}(\phi_i)] = \mathbf{0} \quad (2.3.6)$$

Using the radial search method they identified the LFF region boundary. Moreover, the theoretical analysis of regularization method and selection regularization function (i.e., selection of pilot bus) were presented in [5]. T. Wu and R. Fischl [4] proposed efficient methods for estimating post-contingency LFF boundary points, based on the knowledge of the pre-contingency LFF boundary points. The predicted post-contingency LFF boundary points were used to rank the line outage contingencies and to determine the contingencies which limit inter-area power transfer.

However, they did not consider any operating constraints such as, thermal limits in the lines, voltage magnitude and voltage drop limits in the load buses, while obtaining the LFF regions. Based on their researches, this thesis is applying all the security constraints to obtain the steady-state security regions for base case and next contingency cases. The security regions will be illustrated in the different space, namely the MW net-import space (P_I -space) and the MW transfer space (P_T -space)

CHAPTER 3

ATC REGIONS IN INTER-AREA MW NET-IMPORT SPACE

3.1 INTRODUCTION

This chapter presents Available Transfer Capability (ATC) regions in the MW net-import space ($\mathbf{P}_I$ -space). Specifically, the boundaries of the 2-dimensional $\mathbf{R}_I$'s defined in Section 1.2.2. ATC regions for two different operating conditions, base case and next contingency cases, are investigated using a 3-area 31-bus system (whose line diagram and data are given in Appendix C). As shown in Figure 1.2-1, the power system under study has three areas, called areas A, B and C where area A is the exporting area (seller), area B is the importing area (buyer) and area C is the wheeling area (wheeler). The MW net-import into areas are denoted by P_I^A , P_I^B and P_I^C , respectively. The inter-area MW net-import space ($\mathbf{P}_I$ -space) is a 2 dimensional space of MW net-import into area A, P_I^A and MW net-import into area B, P_I^B , which is defined as follows:

$$\mathbf{P}_I = [P_I^A, P_I^B]^T \quad (3.1.1)$$

Any operating point (P_I^A, P_I^B) is considered to be a secure operating point if thermal, voltage magnitude and voltage drop limit constraints defined in Section 1.2.2 are not violated. The ATC region is defined as the collection of all secure operating points in the MW net-import space ($\mathbf{P}_I$ -space). The ATC region is bounded by the intersection of 4 security regions:

- $\mathbf{R}_{FI}$ -region, Load Flow Feasibility (LFF) region defined by Eqns. (1.2.14 or 17)
- $\mathbf{R}_{VI}$ -region, voltage security region defined by Eqns. (1.2.15 or 18)
- $\mathbf{R}_{\Delta VI}$ -region, voltage drop limit region defined by Eqn. (1.2.19)

- R_{TI} -region, thermal security region defined by Eqns. (1.2.16 or 20)

Recall that LFF R_{FI} -region represents a hard constraint of the maximum real power import of the network while the other 3 regions (i.e., R_{VI} , $R_{\Delta VI}$ and R_{TI}) represents soft constraints and their boundaries depend on the value of the limits in Eqns. (1.2.11-13) selected by the operator. Therefore, the hard limiting boundary of R_{FI} -region is always shown when any of the other region boundaries are shown. Note that while displaying the regions, markers are used in the following sections to indicate different security regions. The next section illustrates the base case ATC region in the MW net-import space (P_I -space).

3.2 BASE CASE ATC REGION IN THE MW NET-IMPORT SPACE

This section investigates the base case ATC region, R_{BCI} defined by Eqn. (1.2.28) as $R_{BCI} = R_{FI} \cap R_{VI} \cap R_{TI}$ in the MW net-import space (P_I -space) for the 31-bus system in Appendix C when there is no line outages. Four kinds of regions are investigated:

- Base case Load Flow Feasibility region, R_{FI} -region
- Base case voltage security region, R_{VI} -region
- Base case thermal security region, R_{TI} -region
- Base case ATC region, R_{BCI} -region

The R_{VI} -region boundary is based on voltage limit constraints of Eqn. (1.2.12) ($0.95 \leq |V_i| \leq 1.05$). Base case R_{TI} -region boundary is based on the values of thermal limits of each transmission line in the network given in Table C-4 of Appendix C. The LFF R_{FI} -region boundary is generated by performing radial searches spaced 5° starting from the zero import point to determine the boundary points and then joining set of

boundary points by straight lines (see Section A.5 of Appendix A for details). The boundaries of the regions R_{VI} and R_{TI} are generated similarly except that their boundary points are computed only at 15° intervals using the radial search. The specific study performed is summarized in Table 3.2-1 which gives the figure numbers of base case security regions and ATC region.

Table 3.2-1 Summary of the base case regions in the MW net-import space (P_I -space)

The 3- area 31-bus system data is in Appendix C			Voltage limits: $0.95 \leq V_i \leq 1.05$ Thermal limits is in Table C-4	
Case	LFF Region R_{FI}	Voltage Security Region $R_{FI} \cap R_{VI}$	Thermal Security Region $R_{FI} \cap R_{TI}$	ATC Region R_{BCI}
Base case	Fig. 3.2-1, 2 and 3	Fig. 3.2-1	Fig. 3.2-2	Fig. 3.2-3
Comments	It is symmetric around the origin	The most limiting buses are bus 11, 15, 27 and 29, many of which belong to area C	The most binding lines are 12, 13, and 34 which are tie lines between areas	Base case ATC region is totally determined by thermal limit constraints

Examples of the regions, R_{FI} , R_{VI} , R_{TI} and R_{BCI} are shown in Figures 3.2-1, 2 and 3. Figure 3.2-1 shows base case LFF region, R_{FI} -region and voltage security region, R_{VI} -region together in the MW net-import space. The base case LFF and voltage security region are plotted together to illustrate how voltage limit constraints bound the MW net-import into areas A and B. The various segments of the voltage security region boundary are shown. Different buses are limiting the import level in different directions. It is observed that many of the limiting buses belong to area C (wheeler) such as buses 15, 27 and 29. Only bus 11 which is a limiting one around directions 300° - 330° is in area A. It is worth to mention that when area C buys real power, i.e. $P_I^C > 0$, bus 27 limits

the import to area A and B. On the other hand, if area C exports power, $P_i^C < 0$, bus 29 is the limiting one. The voltage security region gives all operating points, $\mathbf{P}_i = [P_i^A, P_i^B]^T$ which satisfy voltage limit constraints (i.e., $0.95 \leq |V_i| \leq 1.05$ for all buses, $i = 1, \dots, 31$).

Both $\mathbf{R}_{FI}$ and $\mathbf{R}_{VI}$ regions are symmetric around the origin. Note that under the voltage magnitude limit constraints, the maximum real power that area B can import (P_i^B) is decreasing from 25 pu to 15 pu, while MW net-import into area A (P_i^A) is decreasing from 20 pu to 16 pu.

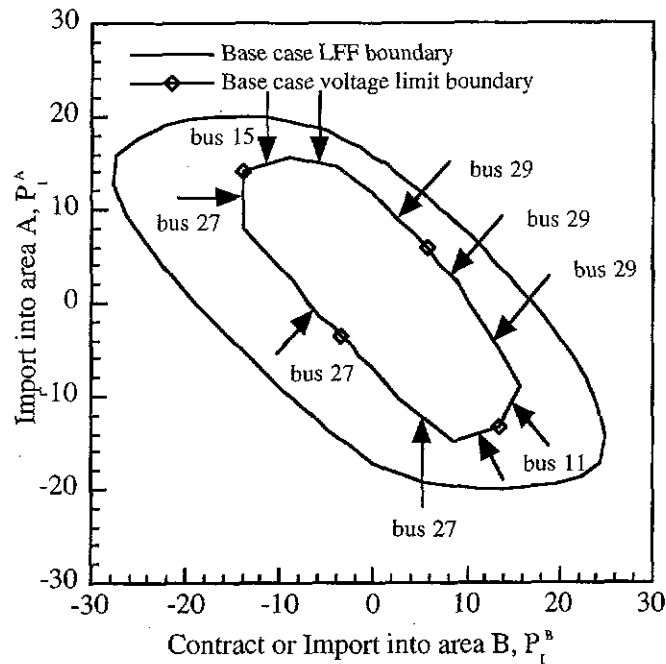


Figure 3.2-1 Base case voltage security region, $\mathbf{R}_{VI}$ in the MW net-import space

Figure 3.2-2 displays base case thermal security region, $\mathbf{R}_{TI}$ -region with respect to LFF region, $\mathbf{R}_{FI}$ -region in the MW net-import space ($\mathbf{P}_i$ -space). The boundary of this thermal security region indicates the maximum MW import level in the MW net-import space dictated by thermal limits. The following lines are the limiting ones: Lines 12, 13, 27 and 34. The various segments of the thermal security region boundary represent

different real power flows scenarios in the 3-area power system. The net-import into area C is exactly zero along the line with a (-1) slope in the P_1^B - P_1^A plane (See Figure 1.2-2). When area C buys real power, $P_1^C > 0$ i.e., between 135° and 315° search directions under the line mentioned above, line 13 and 27 become overloaded. As seen from Figure C-1 of Appendix C, line 13 is tie line between area B and C. If this line hits its thermal limit, that means most of the power imported by area C is coming from area B through this line. When area C sells real power, $P_1^C < 0$, again lines 13 and 27 are overloaded. That implies the large amount of power area C sells goes to area B. When the absolute value of net-import into area C is small, line 34 connected between area A and C, bounds the real power import into areas A and B.

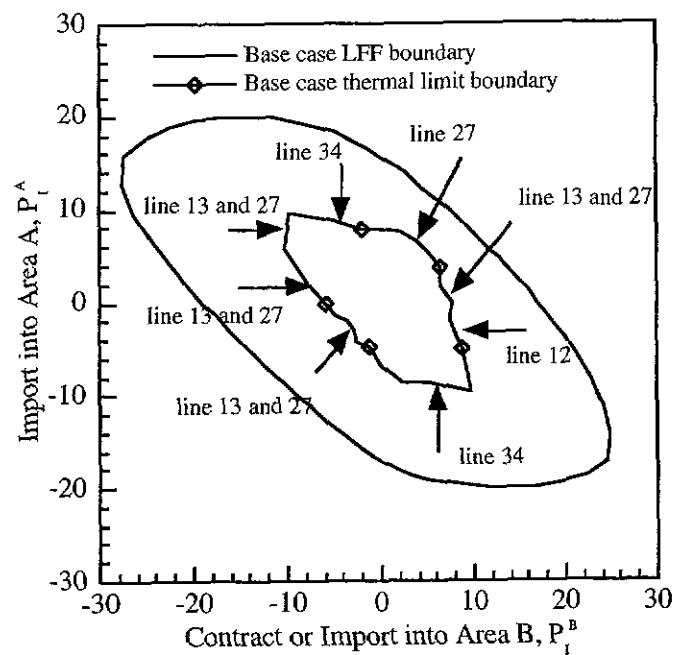


Figure 3.2-2 Base case thermal security region, R_{TI} in the MW net-import space

Figure 3.2-3 shows the base case ATC region, R_{BCI} as the intersection of LFF region, R_{FI} -region, voltage security region, R_{VI} -region and thermal security region,

R_{TI} -region ($R_{BCI} = R_{FI} \cap R_{VI} \cap R_{TI}$). The shadowed area is the set of operating points (P_1^A, P_1^B) for which all line flows in the system guaranteed to be within their rated limits and there is a secure voltage profile for each load bus. Three different regions are plotted together in Figure 3.2-3 to show how voltage limit and thermal limit constraints affect the real power import capability of the network. Although voltage limit constraints are not limiting the MW net-import into areas A and B as much as the thermal limits do, there are operating points where they are coincident. Note that since these constraints represent soft limits, Fig. 3.2-3 shows that it is possible to have a voltage limiting operation and not a thermal limiting operation.

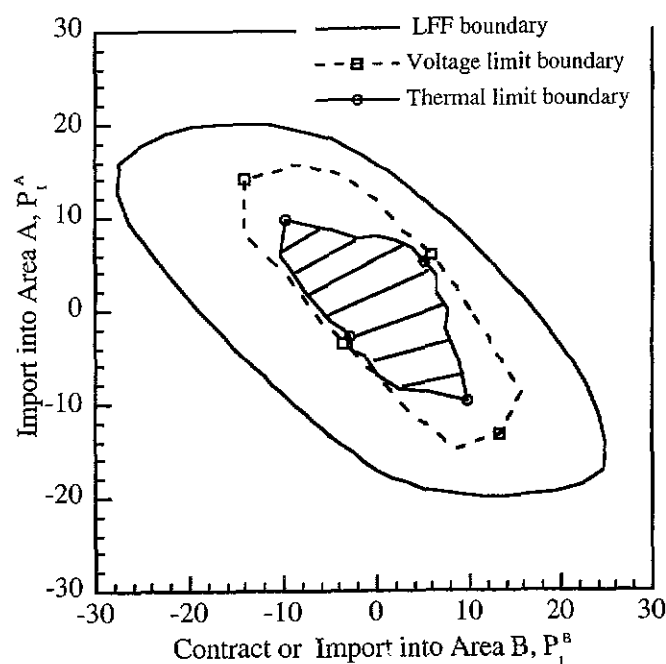


Figure 3.2-3 Base case ATC region, R_{BCI} in the MW net-import space

$$R_{BCI} = R_{FI} \cap R_{VI} \cap R_{TI}$$

The ATC region in Figure 3.2-3 also provides information on the functions of areas i.e., seller or buyer area (See also Figure 1.2-2). Since we are mostly interested in

the operation scenario for which area A is the seller area and area B is the buyer area, we look at the quadrant IV of the base case ATC region, R_{BCI} in the MW net-import space. Figure 3.2-4 represents the operating scenario such that area B is the buyer ($P_I^B > 0$) and area A is the seller ($P_I^A < 0$). Although this is a 2-D picture of the ATC in the P_I -space, it also provides information on the role of the wheeler area, area C. Along the line where $P_I^C = 0$, ($P_I^B = -P_I^A$), wheeler area (area C) does not consume any real power. Above this line the wheeler area acts as a buyer area and for a fixed value of P_I^C we have a range of MW net-import into area A and B. For example, $-10 \text{ pu} \leq P_I^A \leq -20 \text{ pu}$ and $0 \text{ pu} \leq P_I^B \leq 10 \text{ pu}$ for $P_I^C = 10 \text{ pu}$. On the other hand, below the line where $P_I^C = 0 \text{ pu}$, area C act as a seller area. For $P_I^C = -10 \text{ pu}$, the ranges of MW net-import into areas A and B are $0 \text{ pu} \leq P_I^A \leq -15 \text{ pu}$ and $10 \text{ pu} \leq P_I^B \leq 25 \text{ pu}$, respectively.

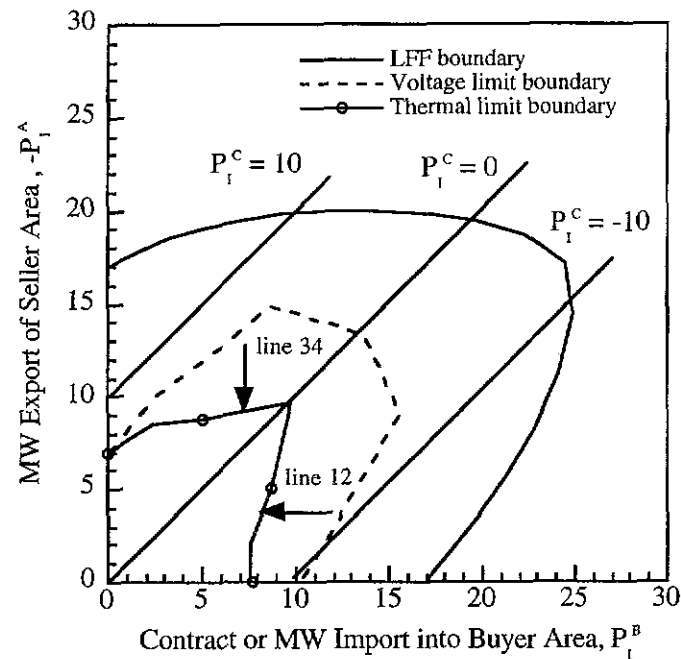


Figure 3.2-4 The fourth quadrant of the base case ATC region, R_{BCI} in the P_I -space

3.3 NEXT CONTINGENCY ATC REGIONS IN THE MW IMPORT SPACE

In this section, ATC regions in the MW net-import space (P_I -space) under different line outages are investigated for the 31-bus system whose one line diagram and data are given in Appendix C. The ATC regions are obtained using the algorithm discussed in Section 1.5 of Chapter 1. The LFF $R_{FI}^{(\lambda)}$ -region is generated by performing radial searches spaced 5° starting from the zero import point, $[P_I^A = 0, P_I^B = 0]^T$ to determine the boundary points and then joining set of boundary points by straight lines (see Section A.5 of Appendix A for details). The boundary of voltage security region, $R_{VI}^{(\lambda)}$ -region; voltage drop limit region, $R_{\Delta VI}^{(\lambda)}$ -region and thermal security region, $R_{TI}^{(\lambda)}$ -region are generated similarly except that their boundary points are computed only at 15° intervals using the radial search. The tie lines which connect the areas have been chosen as the contingency list to define the next contingency ATC regions. The contingencies are outage of lines {8, 11, 12, 13, 34}. These lines have been studied, because they are inter-area tie lines and outage of any of these lines directly affect the MW net-import into areas A and B more than any other lines in the system. Unlike the base case situation, one additional operating constraint, voltage drop limit constraint, is considered to determine the severity of bus voltage drops due to a line outage. The voltage drop limit is selected to be 5% drop in voltage magnitude under a line outage. The other two sets of constraints (i.e., bus voltage magnitude and thermal limits) are taken to be the same as those used in the base case study of Section 3.2. Specifically, the lower and upper bus voltage limits are 0.95 and 1.05 pu, respectively and transmission line flow limits are those given in Table C-4 of Appendix C.

Before showing the ATC regions under different line outages, we show the changes in the security regions as different lines are out. The specific study performed is summarized in Table 3.3-1 which gives all different types of security regions given in this section. The first column illustrates the contingency cases (i.e., line numbers)

considered in this study. The second column gives figure numbers of LFF regions, $\mathbf{R}_{\mathbf{FI}}^{(\lambda)}$ for each line outage and next contingency LFF region, $\bigcap_{(\lambda)} \mathbf{R}_{\mathbf{FI}}^{(\lambda)}$. The figure numbers of voltage security regions, $\mathbf{R}_{\mathbf{FI}}^{(\lambda)} \cap \mathbf{R}_{\mathbf{VI}}^{(\lambda)}$ are given in the third column. The fourth and fifth columns show the figure numbers of voltage drop regions, $\mathbf{R}_{\mathbf{FI}}^{(\lambda)} \cap \mathbf{R}_{\Delta\mathbf{VI}}^{(\lambda)}$ and thermal security regions, $\mathbf{R}_{\mathbf{FI}}^{(\lambda)} \cap \mathbf{R}_{\mathbf{TI}}^{(\lambda)}$, respectively. Finally the last column gives the figure numbers of ATC regions for each line outage, $\mathbf{R}_{\mathbf{NCI}}^{(\lambda)}$. In the last row, some general comments on the regions are provided.

Basically, the following six types of regions are illustrated for each line outage ($\lambda = 8, 11, 12, 13, 34$):

- Load Flow Feasibility (LFF) regions, $\bigcap_{(\lambda)} \mathbf{R}_{\mathbf{FI}}^{(\lambda)}$
- Voltage security regions, $\mathbf{R}_{\mathbf{FI}}^{(\lambda)} \cap \mathbf{R}_{\mathbf{VI}}^{(\lambda)}$
- Voltage drop (ΔV) limit regions, $\mathbf{R}_{\mathbf{FI}}^{(\lambda)} \cap \mathbf{R}_{\Delta\mathbf{VI}}^{(\lambda)}$
- Thermal security regions, $\mathbf{R}_{\mathbf{FI}}^{(\lambda)} \cap \mathbf{R}_{\mathbf{TI}}^{(\lambda)}$
- ATC regions, $\mathbf{R}_{\mathbf{NCI}}^{(\lambda)} = \mathbf{R}_{\mathbf{FI}}^{(\lambda)} \cap \mathbf{R}_{\mathbf{VI}}^{(\lambda)} \cap \mathbf{R}_{\Delta\mathbf{VI}}^{(\lambda)} \cap \mathbf{R}_{\mathbf{TI}}^{(\lambda)}$
- Next contingency voltage security, voltage drop limit and thermal security regions, $\bigcap_{(\lambda)} \mathbf{R}_{\mathbf{VI}}^{(\lambda)}$, $\bigcap_{(\lambda)} \mathbf{R}_{\Delta\mathbf{VI}}^{(\lambda)}$ and $\bigcap_{(\lambda)} \mathbf{R}_{\mathbf{TI}}^{(\lambda)}$

Table 3.3-1 Summary of the next contingency regions in the MW net-import space ($\mathbf{P}_I$ -space)

The 3-area 31-bus system data is in Appendix C			Voltage limits: $0.95 \leq V_i \leq 1.05$ Voltage drop limits: $\Delta V_i \leq 0.05$ Thermal limits is in Table C-4		
Contingency Cases (λ)	LFF Regions Under line Outages $R_{FI}^{(\lambda)}$	Voltage Security Regions $R_{FI}^{(\lambda)} \cap R_{VI}^{(\lambda)}$	Voltage Drop Limit Regions $R_{FI}^{(\lambda)} \cap R_{\Delta VI}^{(\lambda)}$	Thermal Security Regions $R_{FI}^{(\lambda)} \cap R_{TI}^{(\lambda)}$	ATC Regions for Each Contingency $R_{NCI}^{(\lambda)}$
Base Case (0)	Fig. 3.3-1	-----	-----	-----	-----
Line 8 (8)	Fig. 3.3-1	Fig. 3.3-2	Fig. 3.3-3	Fig. 3.3-4	Fig. 3.3-5
Line 11 (11)	Fig. 3.3-1	Fig. 3.3-6	Fig. 3.3-7	Fig. 3.3-8	Fig. 3.3-9
Line 12 (12)	Fig. 3.3-1	Fig. 3.3-10	Fig. 3.3-11	Fig. 3.3-12	Fig. 3.3-13
Line 13 (13)	Fig. 3.3-1	Fig. 3.3-14	Fig. 3.3-15	Fig. 3.3-16	Fig. 3.3-17
Line 34 (34)	Fig. 3.3-1	Fig. 3.3-18	Fig. 3.3-19	Fig. 3.3-20	Fig. 3.3-21
Next Contingency Regions $\cap R_I^{(\lambda)}$	Fig. 3.3-1	Fig. 3.3-22	Fig. 3.3-23	Fig. 3.3-24	-----
Comments	The most binding outages are lines 12 and 34 outages	The most limiting buses are 11, 15, 27 and 29, many of which are in area C	Voltage drop limit constraints do not have much effect on the MW import capacity of the system	Thermal limits have the most significant effect on the MW net-import into areas	Their boundaries are dictated by thermal limits

Figure 3.3-1 shows the comparison of LFF, $\mathbf{R}_{\text{FI}}^{(\lambda)}$ -regions under different line outages with base case LFF, $\mathbf{R}_{\text{FI}}$ -region to indicate how LFF regions change under different contingency cases. The next contingency LFF region boundaries are determined by LFF regions of line 12 and 34 outages. The LFF regions are symmetric around the origin. The shadowed area is the intersection of the LFF regions and gives a set of feasible operating points, $\mathbf{P}_I = [P_I^A, P_I^B]^T$. The LFF, $\mathbf{R}_{\text{FI}}^{(34)}$ -region boundary has a different property than the other ones. It shows a large of P_I^B over which the maximum MW net-import into area A, P_I^A is constant. Specifically, maximum, $P_I^A \cong 10$ pu for $-24 \text{ pu} \leq P_I^B \leq 8 \text{ pu}$ and $P_I^A \cong -8 \text{ pu}$ for $-8 \text{ pu} \leq P_I^B \leq 24 \text{ pu}$.

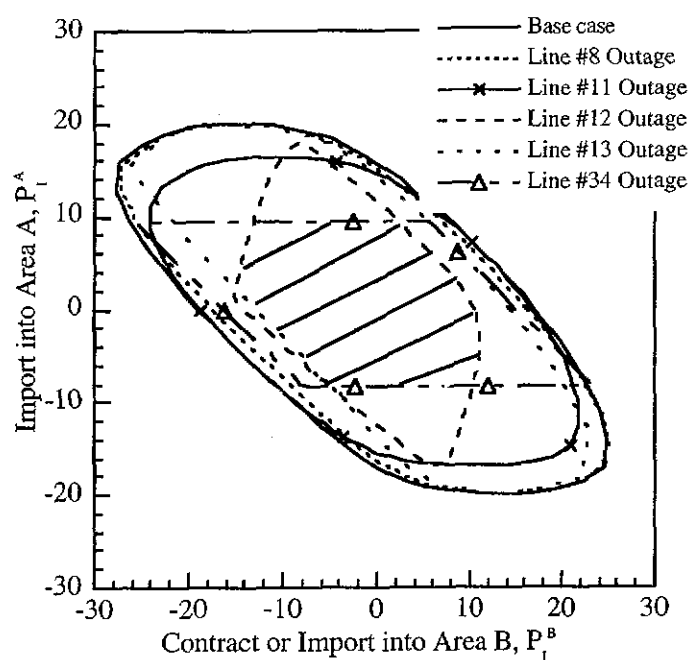


Figure 3.3-1 Next contingency LFF regions, $\bigcap_{(\lambda)} \mathbf{R}_{\text{FI}}^{(\lambda)}$ in the MW net-import space

Figures 3.3-2, 3.3-6, 3.3-10, 3.3-14 and 3.3-18 illustrate the voltage security regions, $\mathbf{R}_{FI}^{(\lambda)} \cap \mathbf{R}_{VI}^{(\lambda)}$ under contingency operations for $\lambda = 8, 11, 12, 13$ and 34 , respectively. In these figures, each voltage security region is compared with its corresponding LFF region to show the effect of voltage magnitude limit constraints on the MW import capability of the system under contingencies and there is secure voltage profile inside the voltage security regions. That is, all the operating points inside the voltage security region, $\mathbf{P}_i = [\mathbf{P}_i^A \ \mathbf{P}_i^B]^T$ satisfy the voltage magnitude limit constraint $0.95 \leq |V_i| \leq 1.05$ for all buses, $i = 1, \dots, 31$. Different line segments of each security regions are shown to identify the weak buses in the system. Many of the limiting buses (buses 15, 27 and 29) belong to wheeler area (area C) showing the importance of the parallel flow. The largest voltage security region is obtained when line 8 is out.

Figures 3.3-3, 3.3-7, 3.3-11, 3.3-15 and 3.3-19 show voltage drop (ΔV) limit regions, $\mathbf{R}_{FI}^{(\lambda)} \cap \mathbf{R}_{\Delta VI}^{(\lambda)}$ under different line outage cases for $\lambda = 8, 11, 12, 13$ and 34 , respectively. As it can be seen from these figures, voltage drop limit constraints do not bound MW net-import into areas A to B as much as voltage magnitude limits do when lines 8 and 11 are out. However, when lines 12, 13 and 34 are out, voltage drop constraints limit the MW import capability of the system.

Figure 3.3-4, 3.3-8, 3.3-12, 3.3-16 and 3.3-20 display thermal security regions, $\mathbf{R}_{FI}^{(\lambda)} \cap \mathbf{R}_{TI}^{(\lambda)}$, under contingency operations for $\lambda = 8, 11, 12, 13$ and 34 , respectively. The binding transmission lines are shown in different search directions. Not only the tie lines such as lines 8, 12, 13 and 34 but also other lines such as lines 15, 20, 26, 27 and 28 hit their rated limits under line outages as MW net-import into areas increases. Note that lines 20, 26, 27 and 28 are in area C. That implies that power exchange between areas A and B causes thermal problems in the transmission lines of area C which does not involve in real power transactions.

Figure 3.3-5 shows the ATC region for line 8 outage, $R_{NCI}^{(8)}$. In this figure, LFF, voltage security, voltage drop limit and thermal security regions are plotted together to show how each operating constraint affects the transfer capability of the system. The ATC region is the intersection of the LFF and security regions, $R_{NCI}^{(8)} = R_{FI}^{(8)} \cap R_{VI}^{(8)} \cap R_{\Delta VI}^{(8)} \cap R_{TI}^{(8)}$. It is clear from Figure 3.3-5 that the most binding constraint is thermal limit and the least one is voltage drop limit constraint. Note, however, that this statement is based on the example system used and may not be true in general for other network or other selection of limits (since these limits are soft limits).

Figures 3.3-9, 3.3-13, 3.3-17, and 3.3-21 illustrate the ATC regions, $R_{NCI}^{(\lambda)}$ ($R_{NCI}^{(\lambda)} = R_{FI}^{(\lambda)} \cap R_{VI}^{(\lambda)} \cap R_{\Delta VI}^{(\lambda)} \cap R_{TI}^{(\lambda)}$) for line 11, 12, 13 and 34 outages, respectively in the MW net-import space. It is observed from these figures that operating constraints make LFF regions smaller, especially line loading limits are the most significant constraints which prevent areas from importing and exporting real power among themselves. Figure 4.3-17 shows that ATC region boundary may be dictated not only thermal limits but also voltage magnitude limits under a particular contingency. The shadowed region in each figure is called the ATC region for the corresponding outage in which no operation point violates any security constraints. Each ATC region gives a set of MW net-import points such that voltage magnitude of each bus in the system is between 0.95 pu and 1.05 pu, voltage drop due to a line outage is less than 0.05 pu and transmission lines do not hit their rated limits.

Figures 3.3-22, 23 and 24 display the next contingency voltage security, voltage drop limit and thermal security regions ($\cap_{(\lambda)} R_{VI}^{(\lambda)}$, $\cap_{(\lambda)} R_{\Delta VI}^{(\lambda)}$ and $\cap_{(\lambda)} R_{TI}^{(\lambda)}$) for $\lambda = 8, 11, 12,$

13 and 34, respectively. Again, line 12 outage is the most significant one in terms of the real power transfer capability. It has the smallest security regions preventing areas from exchanging real power.

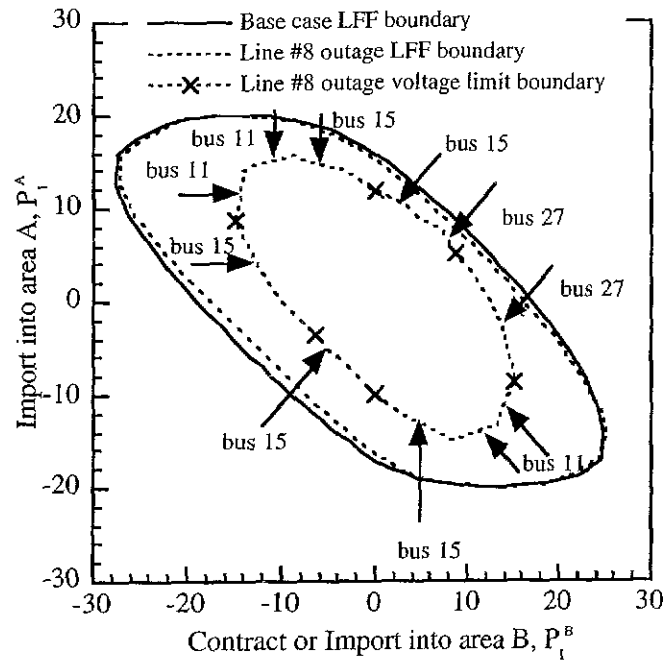


Figure 3.3-2 Line 8 outage voltage security region, $R_{VI}^{(8)}$ in the MW net-import space

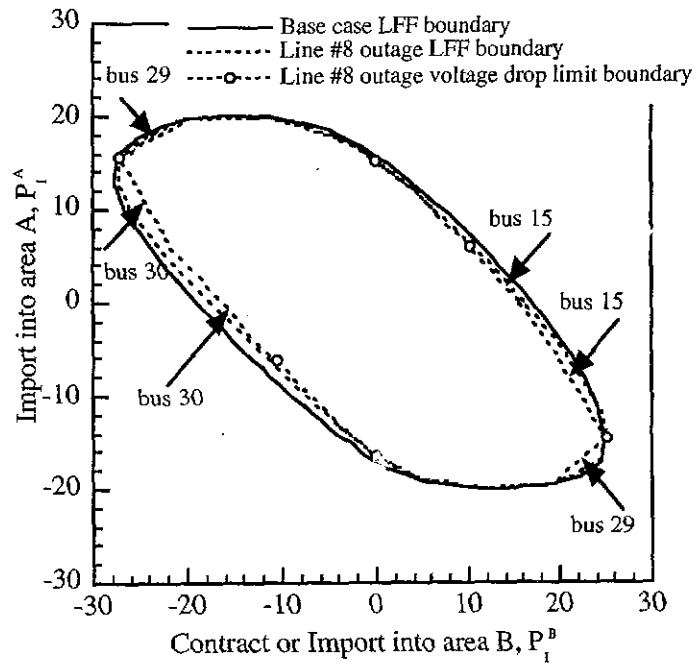


Figure 3.3-3 Line 8 outage voltage drop limit region, $R_{\Delta VI}^{(8)}$ in the MW net-import space

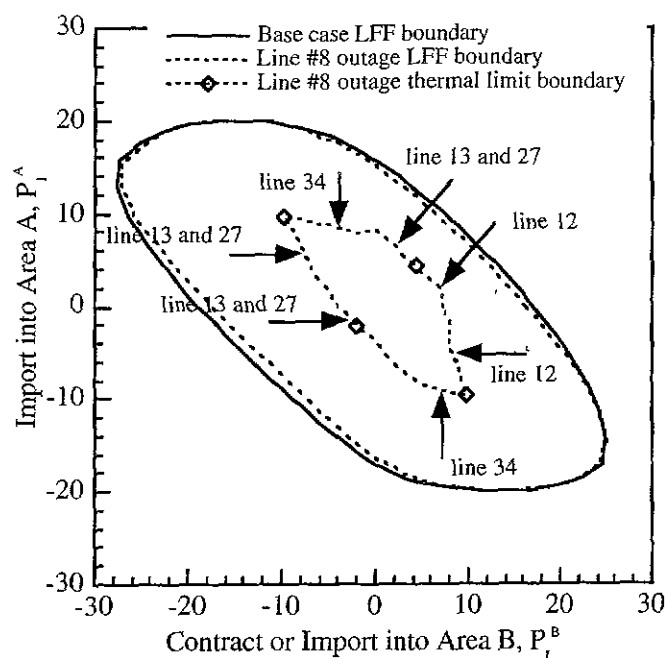


Figure 3.3-4 Line 8 outage thermal security region, $R_{TI}^{(8)}$ in the MW net-import space

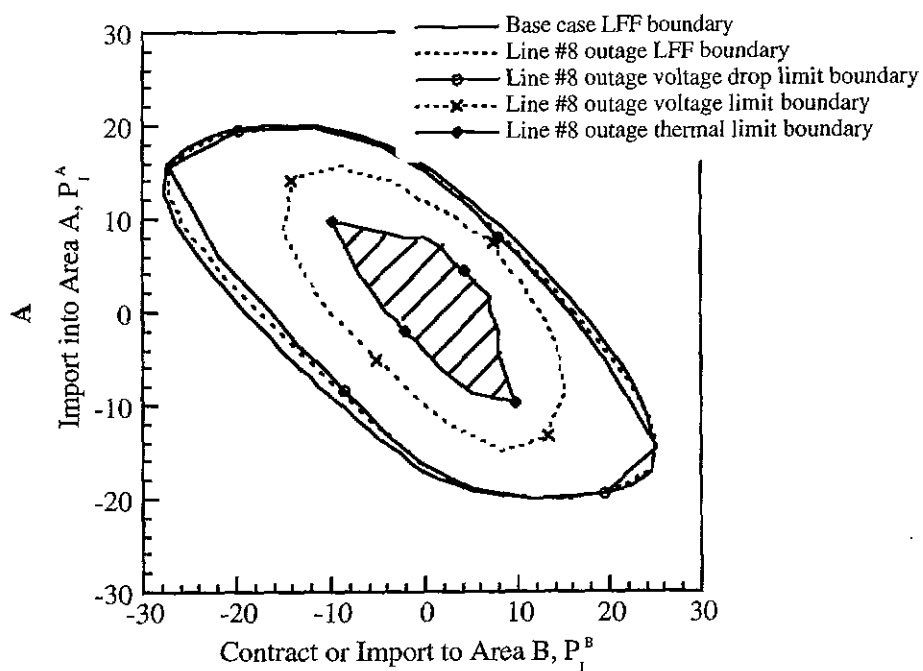


Figure 3.3-5 Line 8 outage ATC region, $R_{NCI}^{(8)}$ in the MW net-import space

$$R_{NCI}^{(8)} = R_{FI}^{(8)} \cap R_{VI}^{(8)} \cap R_{\Delta VI}^{(8)} \cap R_{TI}^{(8)}$$

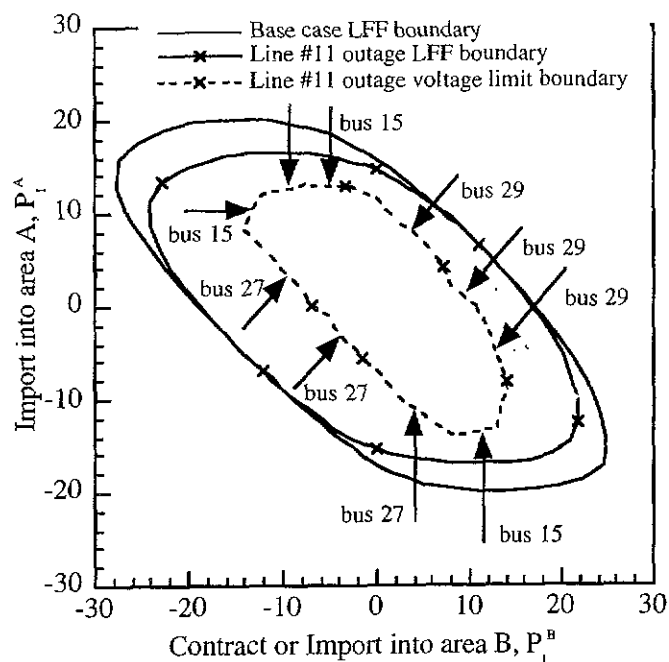


Figure 3.3-6 Line 11 outage voltage security region, $R_{VI}^{(11)}$ in the MW net-import space

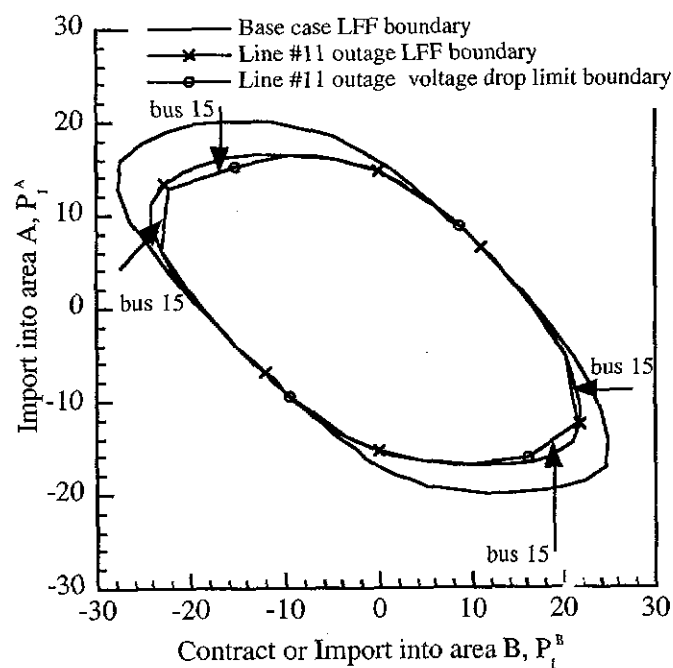


Figure 3.3-7 Line 11 outage voltage drop limit region, $R_{\Delta VI}^{(11)}$ in the MW net-import space

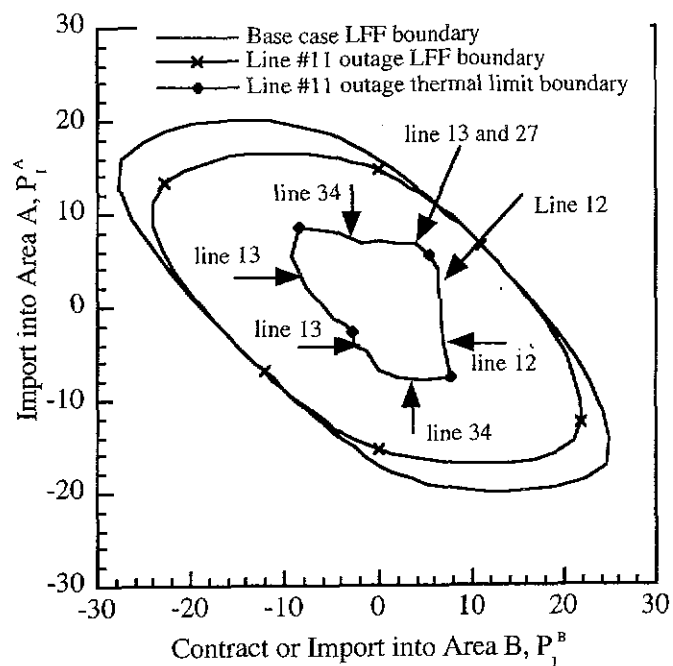


Figure 3.3-8 Line 11 outage thermal security region, $R_{TI}^{(11)}$ in the MW net-import space

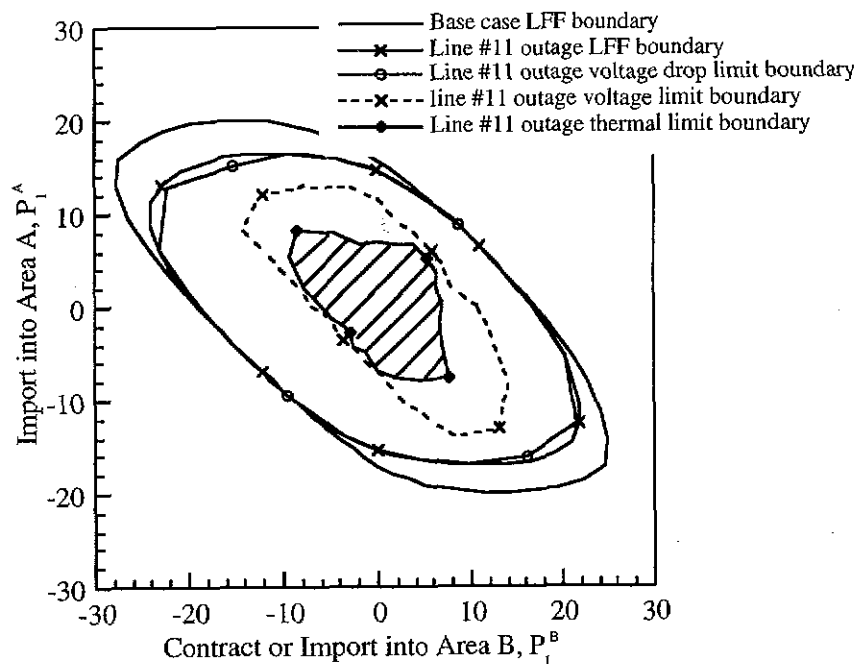


Figure 3.3-9 Line 11 outage ATC region, $R_{NCI}^{(11)}$ in the MW net-import space

$$R_{NCI}^{(11)} = R_{FI}^{(11)} \cap R_{VI}^{(11)} \cap R_{\Delta VI}^{(11)} \cap R_{TI}^{(11)}$$

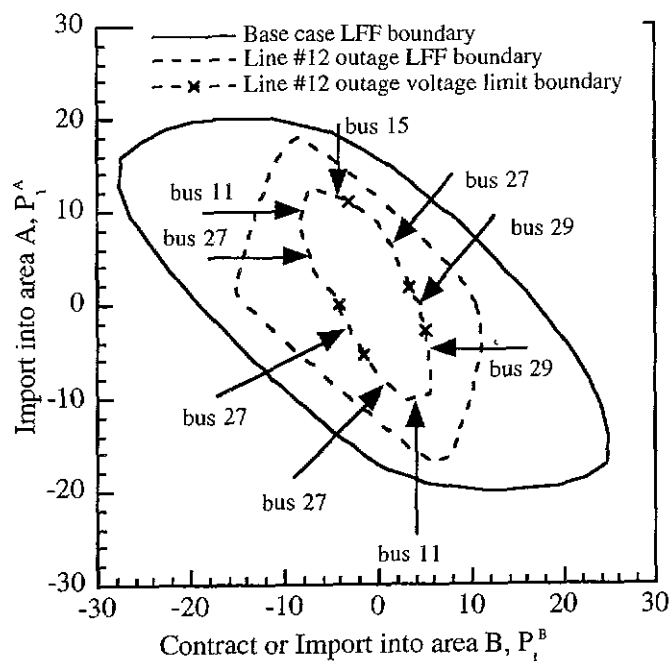


Figure 3.3-10 Line 12 outage voltage security region, $R_{VI}^{(12)}$ in the MW net-import space

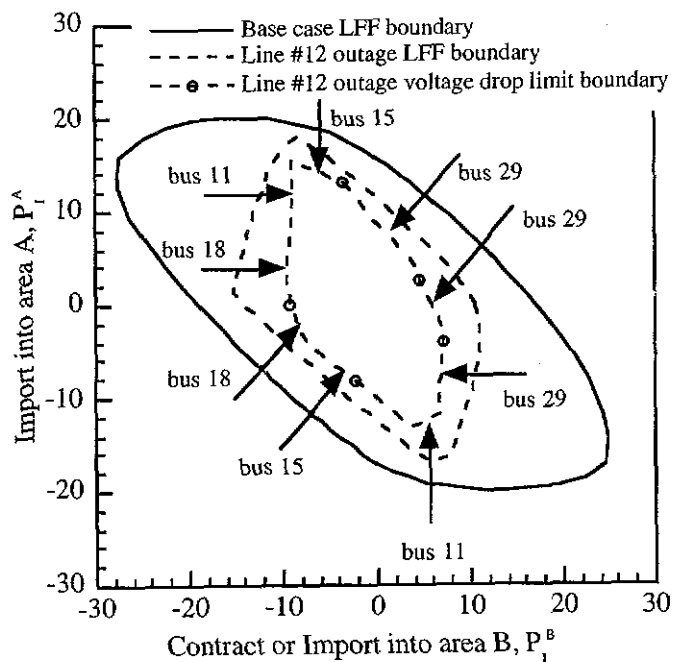


Figure 3.3-11 Line 12 outage voltage drop limit region, $R_{\Delta VI}^{(12)}$ in the MW net-import space

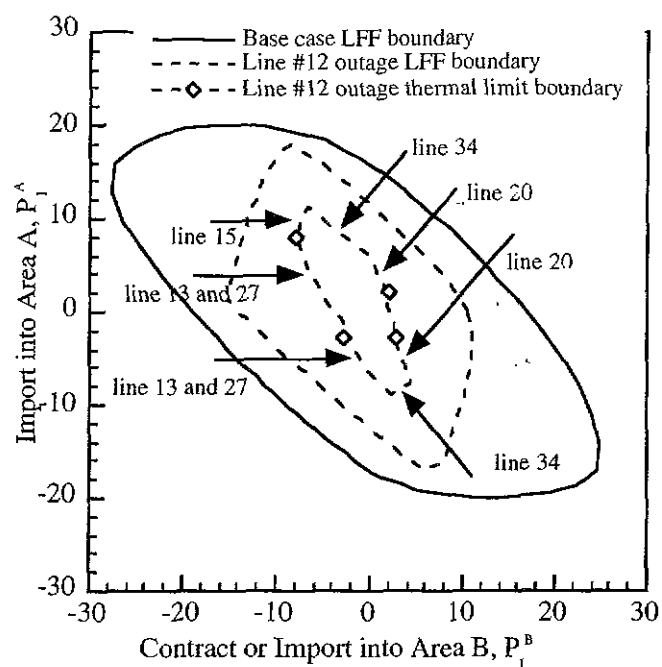


Figure 3.3-12 Line 12 outage thermal security region, $R_{TI}^{(12)}$ in the MW net-import space

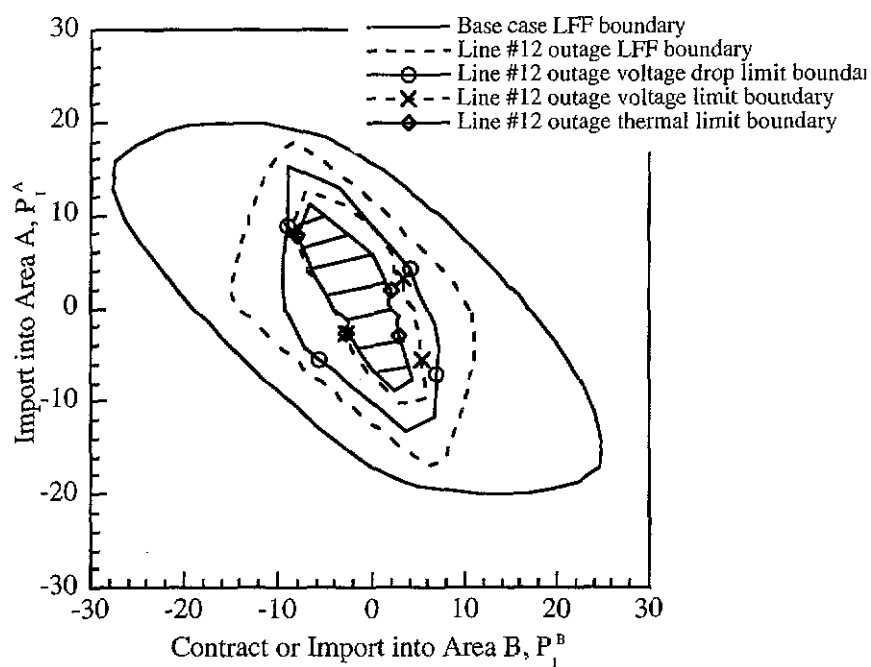


Figure 3.3-13 Line 12 outage ATC region, $R_{NCI}^{(12)}$ in the MW net-import space

$$R_{NCI}^{(12)} = R_{FI}^{(12)} \cap R_{VI}^{(12)} \cap R_{\Delta VI}^{(12)} \cap R_{TI}^{(12)}$$

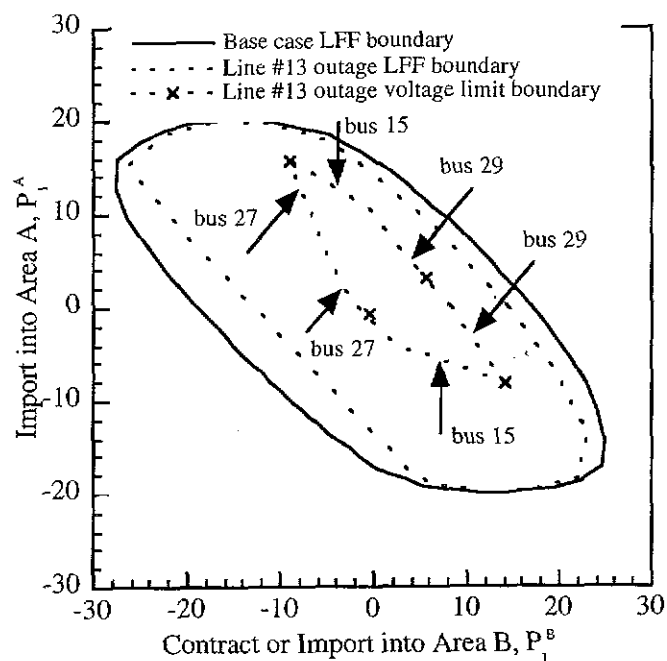


Figure 3.3-14 Line 13 outage voltage security region, $R_{VI}^{(13)}$ in the MW net-import space

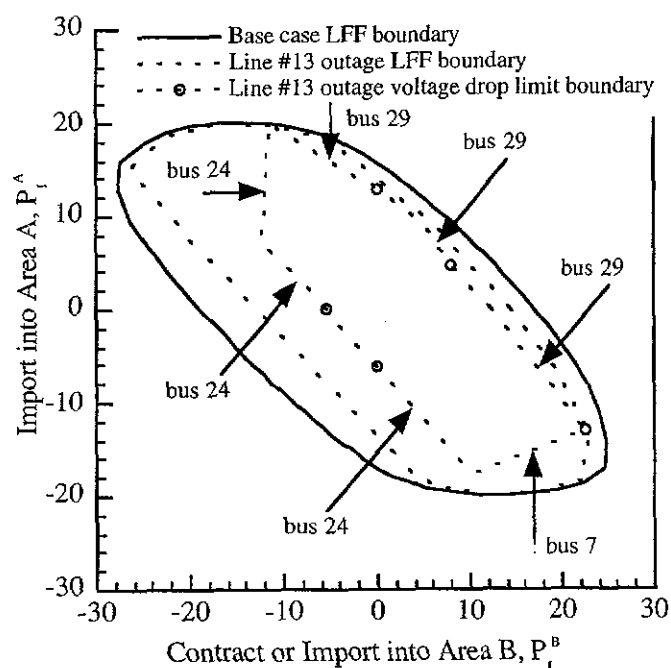


Figure 3.3-15 Line 13 outage voltage drop limit region, $R_{\Delta VI}^{(13)}$ in the MW net-import space

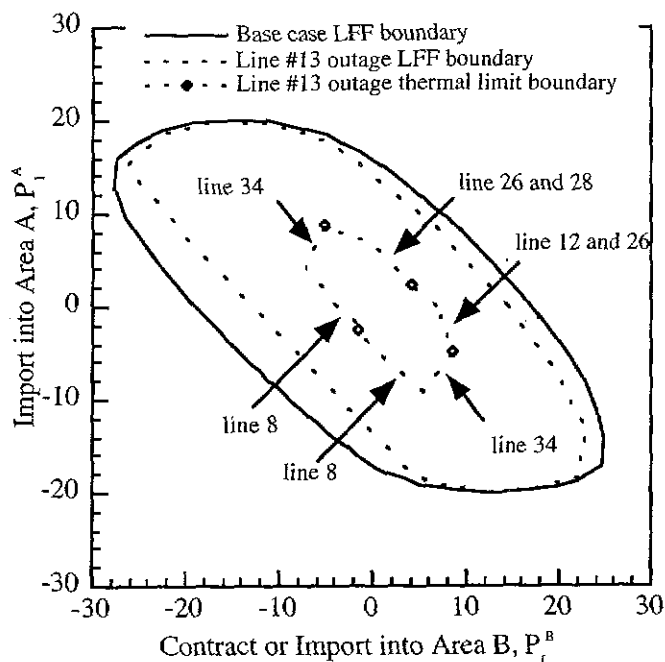


Figure 3.3-16 Line 13 outage thermal security region, $R_{TI}^{(13)}$ in the MW net-import space

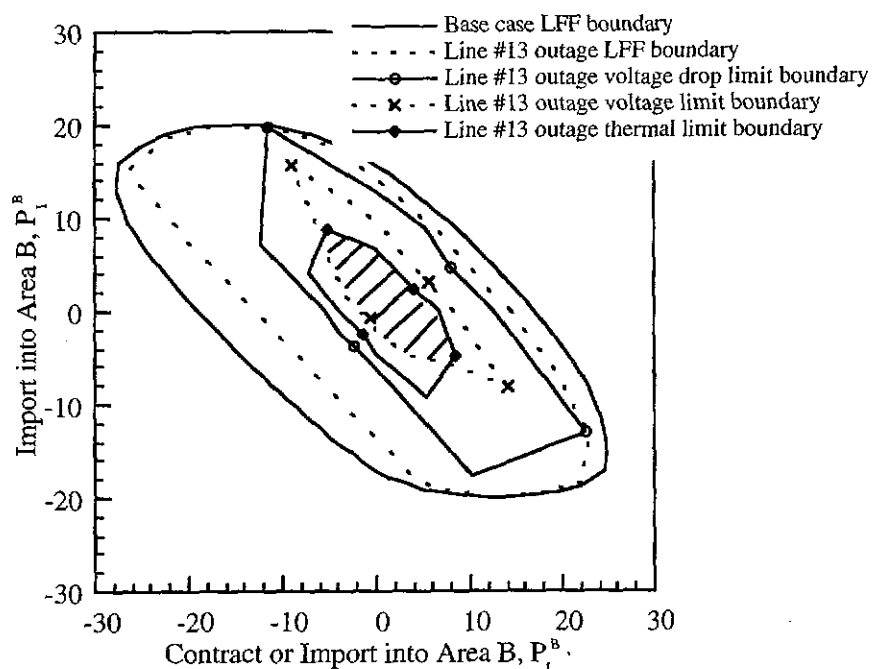


Figure 3.3-17 Line 13 outage ATC region, $R_{NCI}^{(13)}$ in the MW net-import space

$$R_{NCI}^{(13)} = R_{FI}^{(13)} \cap R_{VI}^{(13)} \cap R_{AVI}^{(13)} \cap R_{TI}^{(13)}$$

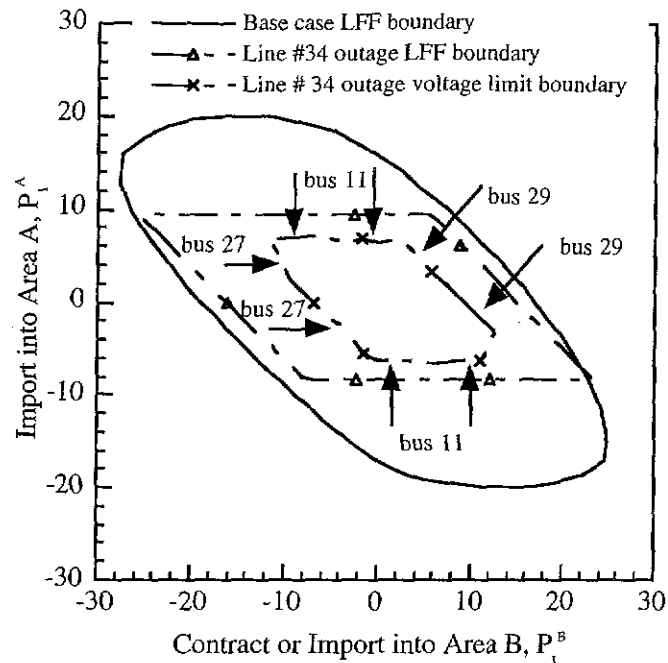


Figure 3.3-18 Line 34 outage voltage security region, $R_{VI}^{(34)}$ in the MW net-import space

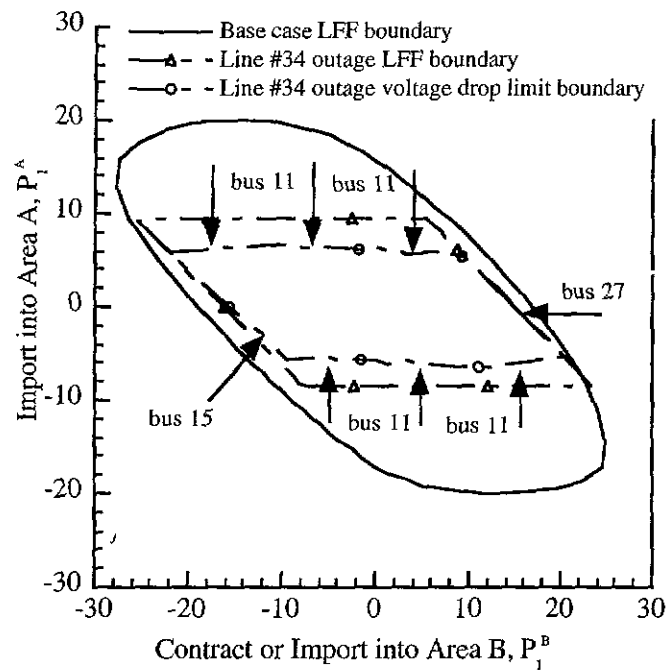


Figure 3.3-19 Line 34 outage voltage drop limit region, $R_{\Delta VI}^{(34)}$ in the MW net-import space

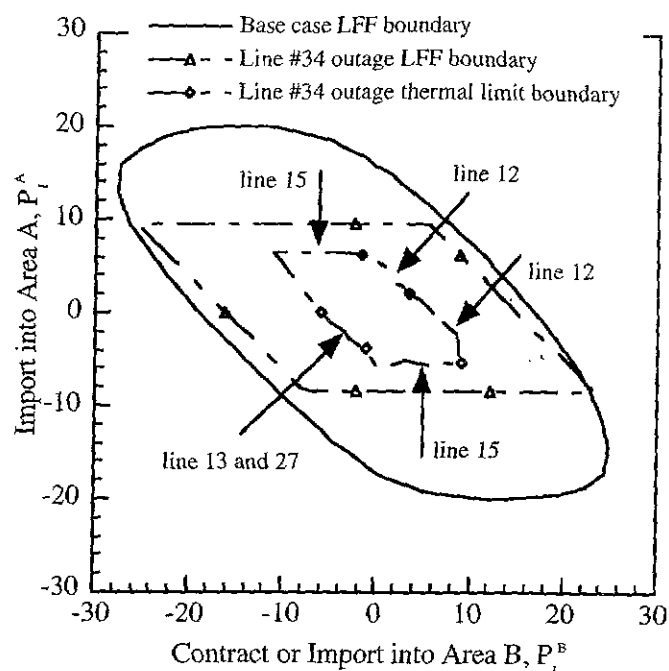


Figure 3.3-20 Line 34 outage thermal security region, $R_{TI}^{(34)}$ in the MW net-import space

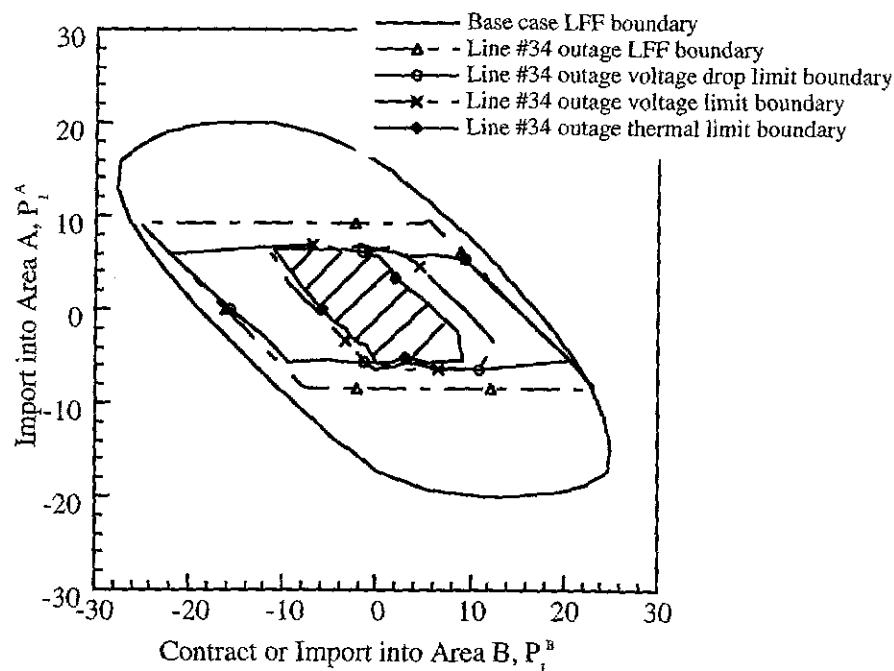


Figure 3.3-21 Line 34 outage ATC region, $R_{NCI}^{(34)}$ in the MW net-import space

$$R_{NCI}^{(34)} = R_{FI}^{(34)} \cap R_{VI}^{(34)} \cap R_{AVI}^{(34)} \cap R_{TI}^{(34)}$$

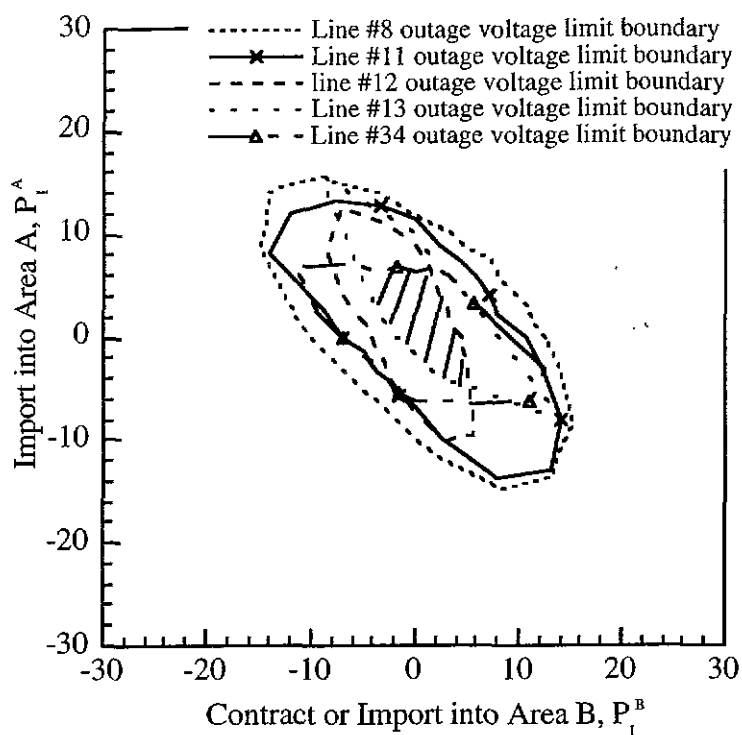


Figure 3.3-22 Next contingency voltage security region, $\bigcap_{(\lambda)} R_{VI}^{(\lambda)}$ in the P_I -space

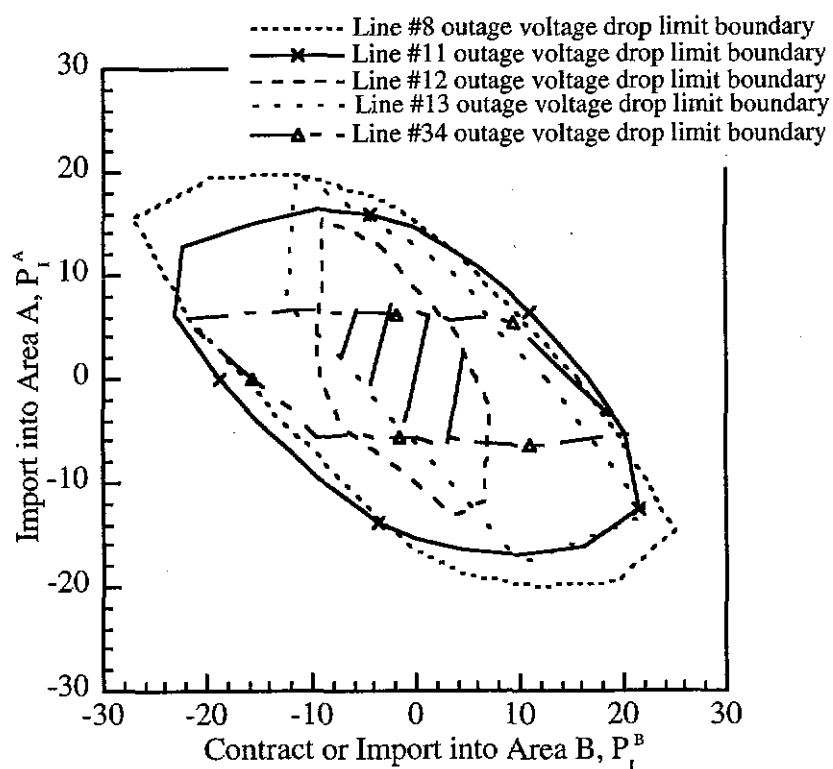


Figure 3.3-23 Next contingency voltage drop limit region, $\bigcap_{(\lambda)} R_{\Delta VI}^{(\lambda)}$ in the P_I -space

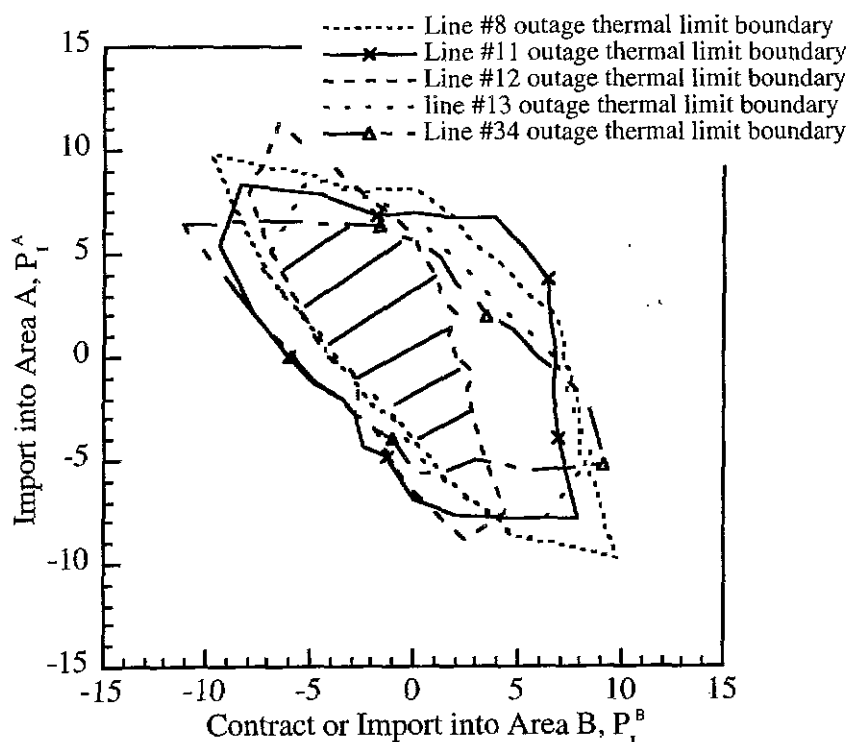


Figure 3.3-24 Next contingency thermal security region, $\bigcap_{(\lambda)} \mathbf{R}_{\text{TI}}^{(\lambda)}$ in the $\mathbf{P}_I$ -space

3.4 SENSITIVITY OF THE REGIONS TO LOAD CHANGES

This section investigates sensitivity of the regions to load changes. Figure 3.4-1 compares base case LFF regions, $\mathbf{R}_{\text{FI}}$ under two different load scenarios: i) Base load given in Table C-3 of Appendix C ii) 300% increase of base load. As can be seen from this figure, the boundary of base case LFF region is sensitive to a change in the load. Figure 3.4-2 shows the effect of 300% increase of base case load on the boundary of the line 11 outage LFF region, $\mathbf{R}_{\text{FI}}^{(11)}$. The LFF regions shrink when the load is increased. The reason for selecting 300% load increase is that LFF regions do not change significantly when base load is increased by 100% or 200%. On the other hand, it is observed that both voltage and thermal security regions under base case and contingency cases disappear even if the load is increased by 100%. Recall that the boundaries of the

regions depend on the values of soft operating limits. Thus, the security regions can be obtained if the soft limits (i.e., voltage and thermal limits) are relaxed.

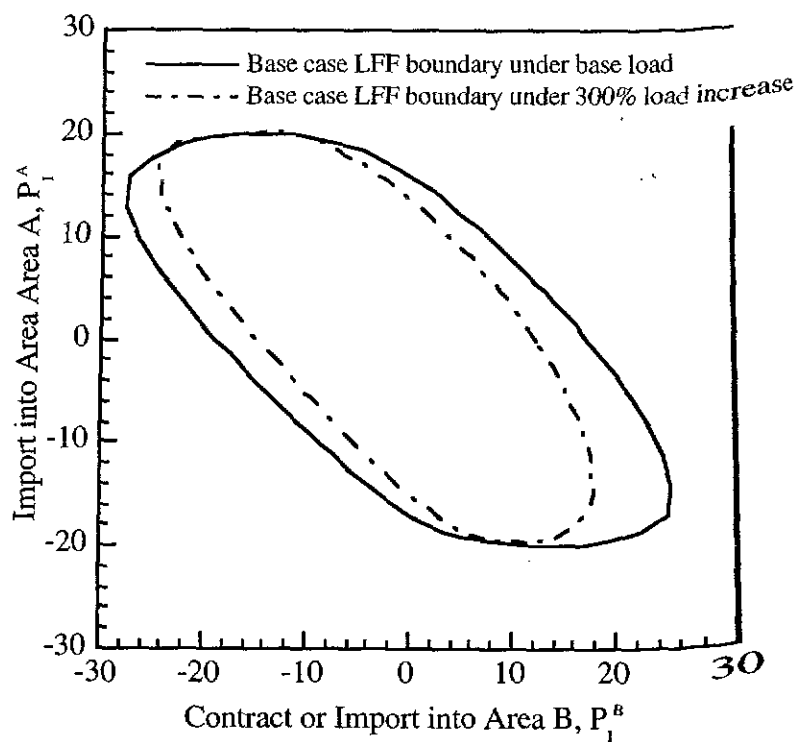


Figure 3.4-1 The effect of a change in load on the base case LFF region, R_{FI} in the MW net-import space (P_I -space)

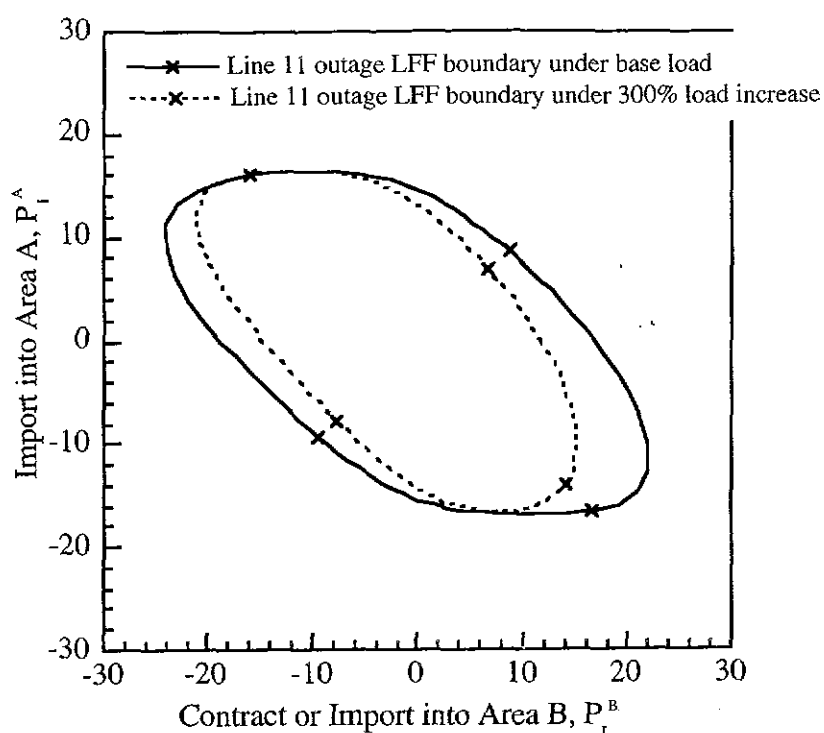


Figure 3.4-2 The effect of a change in load on the line 11 outage LFF region, $\mathbf{R}_{FI}^{(11)}$ in the MW net-import space ($\mathbf{P}_t$ -space)

3.5 NOSE CURVES AND CONTINGENCY RANKING

As it is mentioned earlier, the identification of the LFF-region is the key point of the security and ATC region identification, i.e., determining the complete nose curves in all directions under pre and post contingency operations. This section shows some examples of nose curves, i.e. the plot of voltage magnitude versus inter area import level, r . In Figure 3.5-1, voltage magnitudes at some pilot buses are plotted versus area import level, r , in the 40° direction of search for base case and some critical contingency cases. The selection of the pilot bus is the key issue in the regularization method. The pilot bus and step-length should be selected properly to obtain complete nose curve. Note that different pilot buses have been used to get LFF and security region boundary points for different cases. In Figure 3.5-1 (a), (c) and (d), bus 31 is the pilot bus. In Figure 3.5-1

(b), bus 15 is the pilot bus. In Figure 3.5-1 (e), bus 29 and in Figure 3.5-1 (f), bus 27 are the pilot buses. It is obvious from Figure 3.5-1 that nose curves are not smooth curves because of insufficient number of points on the continuation path since the step-length is selected to minimize the number of steps necessary to obtain the boundary points. Since the lower portion of the nose curves are not necessary for identification of boundary points they are not obtained completely, and only enough lower portion of the nose curves are obtained to illustrate the completeness of the nose curves.

In section 3.3, intersection of the LFF regions under different contingencies is given (see Figure 3.3-1). Different types contingencies are binding the inter area real power transfer in different search directions. The most limiting contingencies are line 12, 13 and 34. This fact can also be observed from Table 3.5-1. In Table 3.5-1, boundary points data for all contingencies in the directions spaced 20° are given. In the last column of this table, the contingencies are ranked from the most limiting to the least limiting contingencies, where C0 represents base case and C# denotes contingency of line number # outage. The boundary data associated with the most limiting contingencies are in **bold** characters. It is clear from Table 3.5-1 that bold characters never appears in column 2, 3, and 4. Therefore, base case, lines 8 and 11 outages are not binding in all direction that have been searched. For 40° search direction, the accuracy of the boundary points in Table 3.5-1 can be proved by checking the area import level of the nose points in Figure 3.5-1. For example, the maximum area import level, r , is around 8.2 or 8.3, which is the same value as in Table 3.5-1 for 40° under line 12 outage, Figure 3.5-1 (d).

Table 3.5-1 LFF boundary data and contingency ranking

ϕ (deg)	r^* (C0)	r^* (C8)	r^* (C11)	r^* (C12)	r^* (C13)	r^* (C34)	Contingency Ranking
0	16.96	16.14	16.73	10.50	14.28	14.99	C12, C13, C34, C8, C11, C0
20	13.59	12.85	13.58	8.95	11.52	11.70	C12, C13, C34, C8, C11, C0
40	12.34	11.67	12.31	8.29	10.59	10.64	C12, C13, C34, C8, C11, C0
60	12.51	11.86	12.32	8.56	10.89	10.98	C12, C13, C34, C8, C11, C0
80	14.13	13.48	13.50	9.99	12.59	9.52	C34, C12, C13, C8, C11, C0
100	17.77	17.25	15.75	13.75	16.60	9.52	C34, C12, C11, C13, C8, C0
120	22.97	22.91	19.02	19.63	22.87	10.82	C34, C11, C12, C13, C8, C0
140	29.44	29.29	24.10	16.58	29.27	14.58	C34, C12, C11, C13, C8, C0
160	28.05	27.32	25.57	15.16	21.00	27.08	C12, C13, C11, C34, C8, C0
180	18.90	17.40	18.77	14.07	12.88	16.18	C13, C12, C34, C8, C11, C0
200	14.88	13.60	14.88	10.80	10.18	12.63	C13, C12, C34, C8, C11, C0
220	13.45	12.36	13.39	9.61	9.36	11.49	C13, C12, C34, C8, C11, C0
240	13.64	12.65	13.41	9.69	9.76	9.79	C12, C13, C34, C8, C11, C0
260	15.46	14.57	14.56	11.07	11.68	8.61	C34, C12, C13, C11, C8, C0
280	18.84	18.45	16.47	14.79	17.13	8.61	C34, C12, C11, C13, C8, C0
300	23.02	23.00	19.58	16.85	22.99	9.79	C34, C12, C11, C13, C8, C0
320	29.14	28.88	24.84	13.34	28.81	13.18	C34, C12, C11, C13, C8, C0
340	24.24	23.97	22.49	11.78	20.93	24.78	C12, C13, C11, C8, C0, C34
360	16.96	16.14	16.73	10.50	14.28	14.99	C12, C13, C34, C8, C11, C0

Table 3.5-1 LFF boundary data and contingency ranking

ϕ (deg)	r^* (C0)	r^* (C8)	r^* (C11)	r^* (C12)	r^* (C13)	r^* (C34)	Contingency Ranking
0	16.96	16.14	16.73	10.50	14.28	14.99	C12, C13, C34, C8, C11, C0
20	13.59	12.85	13.58	8.95	11.52	11.70	C12, C13, C34, C8, C11, C0
40	12.34	11.67	12.31	8.29	10.59	10.64	C12, C13, C34, C8, C11, C0
60	12.51	11.86	12.32	8.56	10.89	10.98	C12, C13, C34, C8, C11, C0
80	14.13	13.48	13.50	9.99	12.59	9.52	C34, C12, C13, C8, C11, C0
100	17.77	17.25	15.75	13.75	16.60	9.52	C34, C12, C11, C13, C8, C0
120	22.97	22.91	19.02	19.63	22.87	10.82	C34, C11, C12, C13, C8, C0
140	29.44	29.29	24.10	16.58	29.27	14.58	C34, C12, C11, C13, C8, C0
160	28.05	27.32	25.57	15.16	21.00	27.08	C12, C13, C11, C34, C8, C0
180	18.90	17.40	18.77	14.07	12.88	16.18	C13, C12, C34, C8, C11, C0
200	14.88	13.60	14.88	10.80	10.18	12.63	C13, C12, C34, C8, C11, C0
220	13.45	12.36	13.39	9.61	9.36	11.49	C13, C12, C34, C8, C11, C0
240	13.64	12.65	13.41	9.69	9.76	9.79	C12, C13, C34, C8, C11, C0
260	15.46	14.57	14.56	11.07	11.68	8.61	C34, C12, C13, C11, C8, C0
280	18.84	18.45	16.47	14.79	17.13	8.61	C34, C12, C11, C13, C8, C0
300	23.02	23.00	19.58	16.85	22.99	9.79	C34, C12, C11, C13, C8, C0
320	29.14	28.88	24.84	13.34	28.81	13.18	C34, C12, C11, C13, C8, C0
340	24.24	23.97	22.49	11.78	20.93	24.78	C12, C13, C11, C8, C0, C34
360	16.96	16.14	16.73	10.50	14.28	14.99	C12, C13, C34, C8, C11, C0

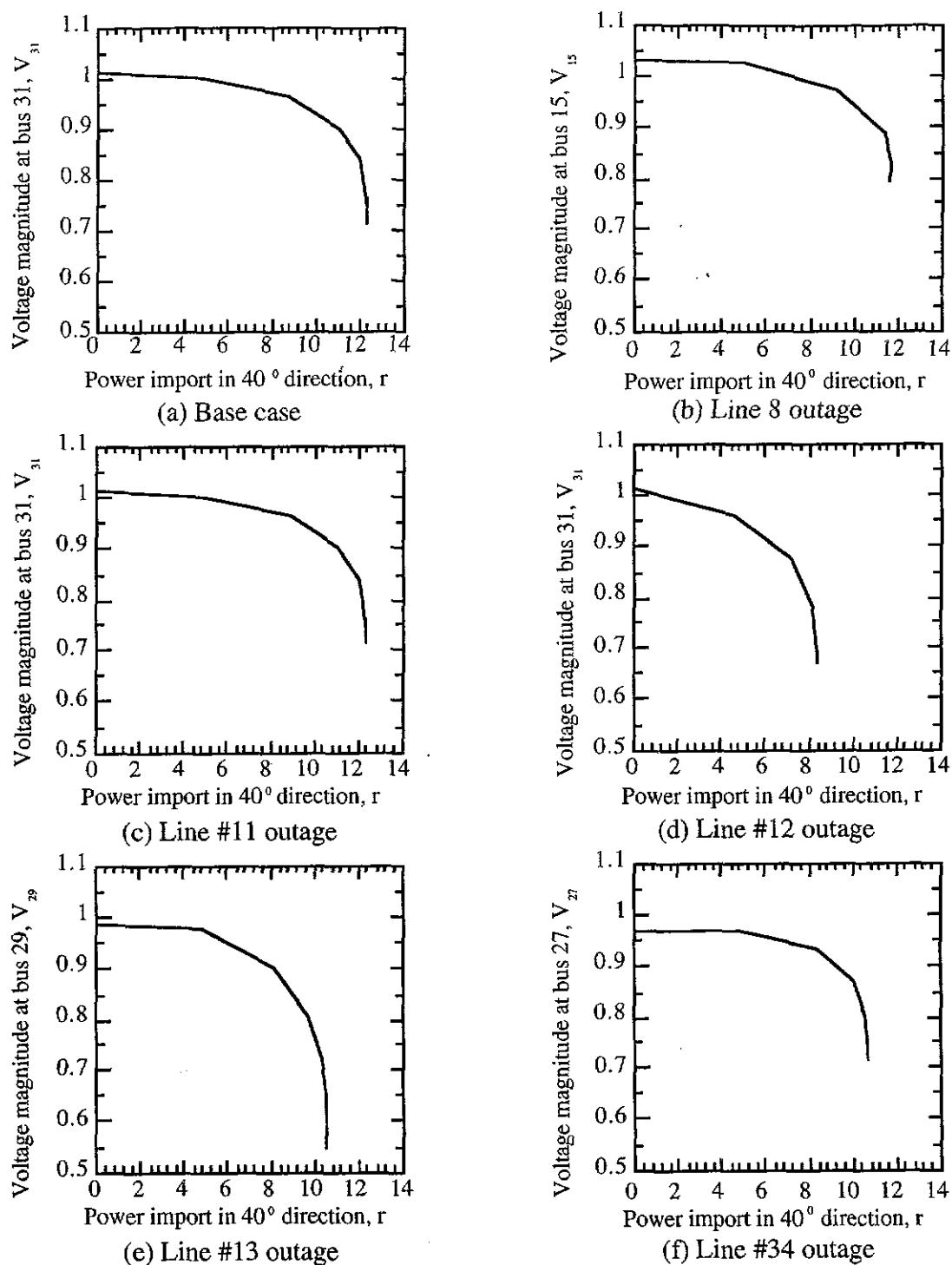


Figure 3.5-1 Plot of the nose curves, i.e. voltage magnitude versus area import level, r , in 40° search direction for the 3-area 31-bus system

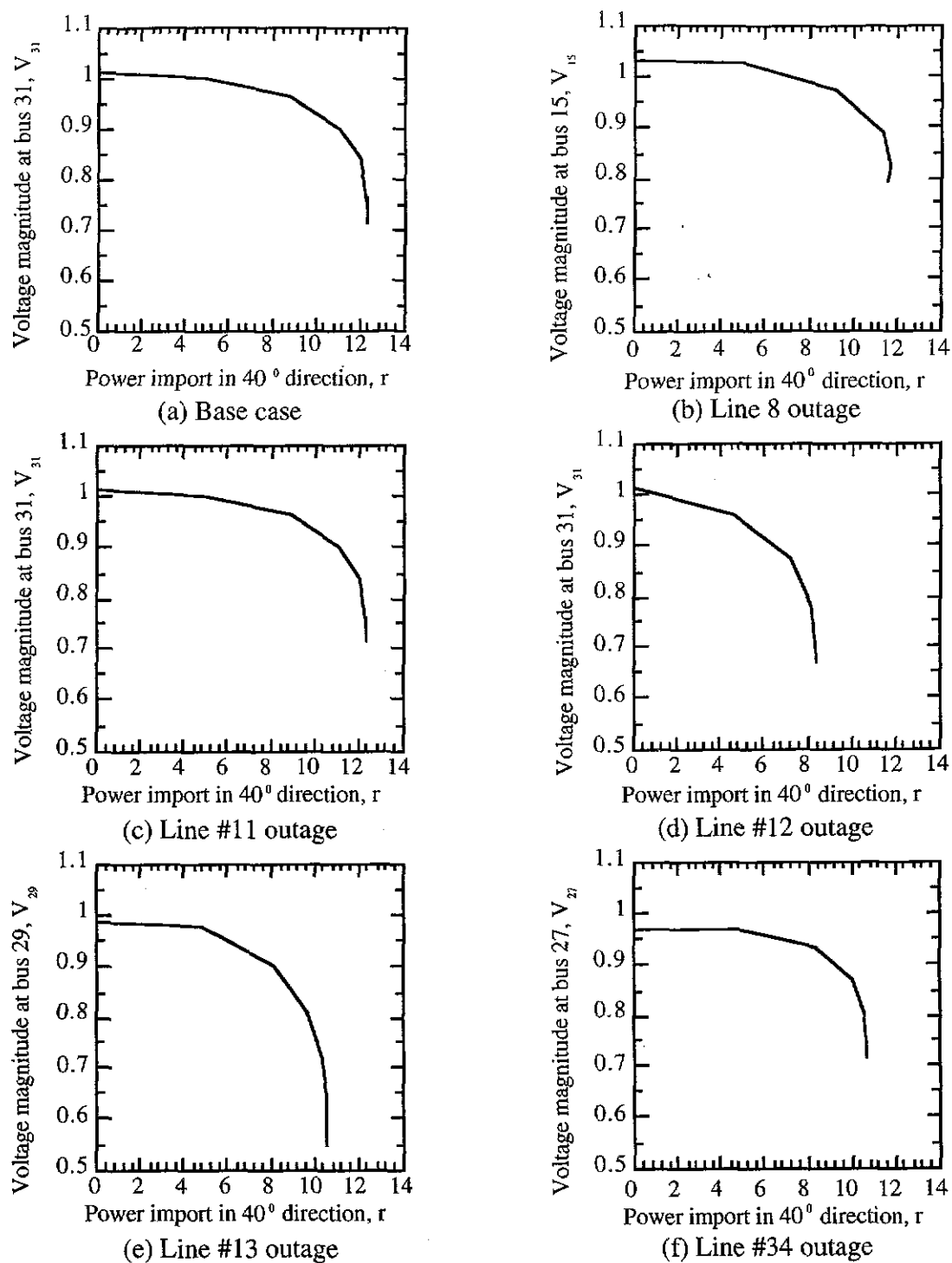


Figure 3.5-1 Plot of the nose curves, i.e. voltage magnitude versus area import level, r , in 40° search direction for the 3-area 31-bus system

3.6 SUMMARY OF THE RESULTS

Using a region-wise approach, Available Transfer Capability (ATC) regions of a 3-area 31-bus system in the MW net-import space (P_i -space) are investigated under base case and contingency cases. The tie lines between areas have been considered as the contingency list to investigate the sensitivity of the regions with respect to network changes. The following results and conclusions are obtained:

- LFF, voltage security, voltage drop limit and thermal security regions for base case and lines 8, 11, 12, 13 and 34 have been presented. It has been observed that the boundaries of the regions are very much sensitive to network changes.
- 2-Dimensional representation of Available Transfer Capability of the system, so called ATC regions, have been presented as the intersection of the security regions. The size, shape and orientation of ATC regions are the functions of network changes. The smallest ATC region is obtained under line 12 outage operation.
- With the help of ATC regions, the function of each area for different operating scenarios (i.e., buyer, seller or wheeler) is identified.
- The security margins and weak components of the system such as buses and transmission lines are identified. It is observed that real power exchange between two areas (areas A and B) cause voltage problems in the third area, wheeler area, due to the parallel flows.
- The sensitivity of the regions to load changes are also investigated. The security regions disappear when load level at each load bus in the system is increased.
- ATC regions represents numerous types of real power transactions and allows utilities to develop transfer strategies.

CHAPTER 4

ATC REGIONS IN INTER-AREA MW TRANSFER SPACE

4.1 INTRODUCTION

This chapter presents graphical display of Available Transfer Capability (ATC) regions in the MW transfer space ($\mathbf{P}_T$ -space). Specifically, the boundaries of the 2-dimensional $\mathbf{R}_T$'s defined in Section 1.2.2. ATC regions for two different operating conditions, namely base case and next contingency cases, are investigated using a 3-area 31-bus system (whose line diagram and data are given in Appendix C). As shown in Figure 1.2-1, the power system under investigation has three areas, called areas A, B and C, where area A is the exporting area (seller), area B is the importing area (buyer) and area C is the wheeling area (wheeler). The MW transfer space ($\mathbf{P}_T$ -space) is a 2 dimensional space of inter-area real power transfer between areas A and B, P_{AB} and MW net-import into area B, P_I^B which is defined as follows:

$$\mathbf{P}_T = [P_{AB} \ P_I^B]^T \quad (4.1.1)$$

Any operating point (P_{AB}, P_I^B) is considered to be secure operating point if it does not violate any of the operating constraints given in Section 1.2.2. The ATC region is defined as the collection of all secure operating points in the MW transfer space ($\mathbf{P}_T$ -space). The ATC region is bounded by the intersection of 4 security regions:

- $\mathbf{R}_{FT}$ -region, the LFF region defined by Eqns. (1.2.21 or 24)
- $\mathbf{R}_{VT}$ -region, the voltage security region defined by Eqns. (1.2.22 or 25)
- $\mathbf{R}_{\Delta VT}$ -region, voltage drop limit region defined by Eqn. (1.2.26)
- $\mathbf{R}_{TT}$ -region, thermal security region defined by Eqn. (1.2.23 or 27).

Recall that the LFF $\mathbf{R}_{FT}$ -region represents a hard constraint of the maximum power transfer of the network while the other 3 regions (i.e., $\mathbf{R}_{VT}$, $\mathbf{R}_{\Delta VT}$ and $\mathbf{R}_{TT}$) represent soft constraints and their boundaries depend on the value of the limits in Eqns. (1.2.11-13) selected by the operator. Thus, the hard limiting boundary of $\mathbf{R}_{FT}$ is always shown when any of the other region boundaries are shown. Note that while illustrating the regions, markers are used in the following sections to indicate different regions. The next section illustrates the ATC region under base case operating condition in the $\mathbf{P}_T$ -space.

4.2 BASE CASE ATC REGION IN THE MW TRANSFER SPACE

This section investigates the base case ATC region, $\mathbf{R}_{BCT}$ defined by Eqn. (1.2.28) as $\mathbf{R}_{BCT} = \mathbf{R}_{FT} \cap \mathbf{R}_{VT} \cap \mathbf{R}_{TT}$ in the MW transfer space ($\mathbf{P}_T$ -space) for the 31-bus system in Appendix C when there is no contingencies. Four kinds of regions are investigated:

- Base case Load Flow Feasibility (LFF) region, $\mathbf{R}_{FT}$ -region
- Base case voltage security region, $\mathbf{R}_{VT}$ -region
- Base case thermal security region, $\mathbf{R}_{TT}$ -region
- Base case ATC region, $\mathbf{R}_{BCT}$ -region

The $\mathbf{R}_{VT}$ -region boundary is based on voltage limit constraints of Eqn. (1.2.12), $0.95 \leq |V_i| \leq 1.05$. The base case $\mathbf{R}_{TT}$ -region boundary is based on the values of thermal limits of each transmission line in the network given in Table C-4 of Appendix C. The LFF $\mathbf{R}_{FT}$ -region boundary is generated by performing radial searches spaced 5° starting from the zero transfer point to determine the boundary points and then joining set of boundary points by straight lines (see Section A.5 of Appendix A for details). The

boundaries of the regions R_{VT} and R_{TT} are generated similarly except that their boundary points are computed only at 15° intervals using the radial search.

Examples of the regions R_{VT} , R_{TT} and R_{BCT} for a 31-bus system are shown in Figures. 4.2-1, 4.2-2 and 4.2-3. Fig. 4.2-1 shows the base case LFF region, R_{FT} -region with respect to the voltage security region, R_{VT} -region. The shadowed area gives all operating points, $P_T = [P_{AB} \ P_I^B]^T$ which satisfy the voltage limit constraints (i.e., $0.95 \leq |V_i| \leq 1.05$ for all buses, $i=1, \dots, 31$). Note that as the MW net-import into area B, P_I^B increases the range of secure P_{AB} transfers diminishes showing the decrease in system robustness. For example,

For $P_I^B = 5$ pu, -2 pu $\leq P_{AB} \leq 5$ pu

For $P_I^B = 10$ pu, 1 pu $\leq P_{AB} \leq 6$ pu

For $P_I^B = 14$ pu, 4 pu $\leq P_{AB} \leq 6$ pu

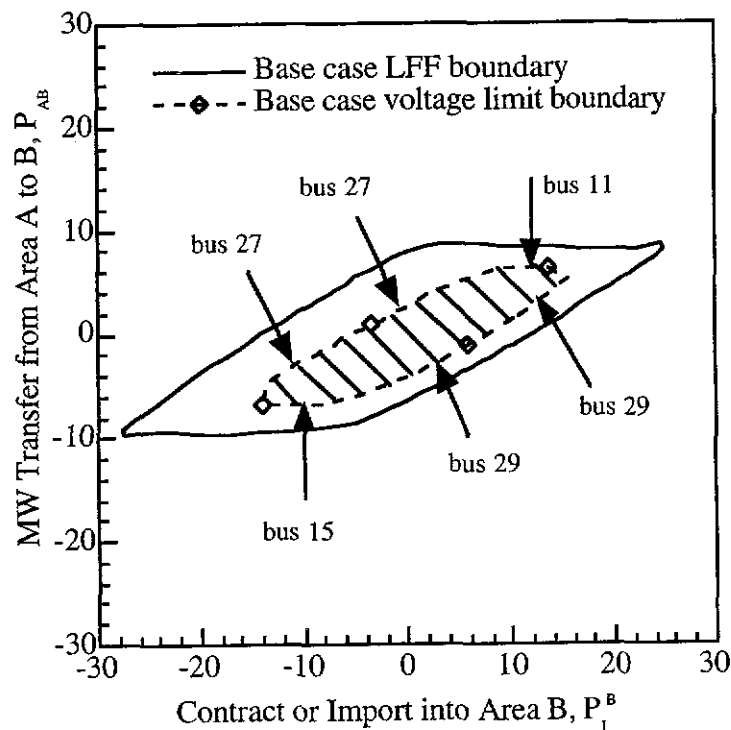


Figure 4.2-1 Base case voltage security region, R_{VT} in the MW transfer space

In addition to that, $\mathbf{R}_{VT}$ -region does not possess any type of symmetry. The LFF $\mathbf{R}_{FT}$ -region has similar properties and shows a large of P_I^B over which the maximum MW transfer, P_{AB} is constant. Specifically, maximum $P_{AB} \cong 10$ pu for $2 \text{ pu} \leq P_I^B \leq 20$ pu and $P_{AB} \cong -10$ pu for $-28 \text{ pu} \leq P_I^B \leq -4$ pu. Note that negative values of P_I^B imply that area B exports and negative values of P_{AB} imply the MW transfers from area B to A. As seen in Figure 4.2-1, different buses are limiting the MW transfer capability of the system. These are buses 15, 27, 29 (in the wheeler area, area C) and bus 11 (in the seller area, area A). The fact that many of the limiting buses belong to area C indicates that the MW real power exchange between area A and B causes voltage problems in area C due to the parallel flow phenomenon.

Figure 4.2-2 displays base case LFF region, $\mathbf{R}_{FT}$ -region with respect to the thermal security region, $\mathbf{R}_{TT}$ -region in the MW transfer space ($\mathbf{P}_T$ -space). The shadowed area is the base case thermal security region and it gives all operating points, $\mathbf{P}_T = [P_{AB} \ P_I^B]^T$ which satisfy the thermal limit constraints given in Table C-4 of Appendix C. The existence of load flow solution is the necessary condition to get thermal security region boundaries. Therefore, base case LFF $\mathbf{R}_{FT}$ -region is also shown in Figure 4.2-2. The boundaries of LFF region indicate the absolute limit of system operation, i.e., there is no solution to the load flow equations beyond these boundaries. Thermal security region, $\mathbf{R}_{TT}$ -region is smaller in size than the voltage security region, $\mathbf{R}_{VT}$ -region in Figure 4.2-1. As the MW real power demand of area B, P_I^B changes from -10 pu to 10 pu, the secure MW real power transfer from area A to B, P_{AB} changes between -5 pu to 4 pu, showing the decrease in system MW transfer capability. The MW real power transfer capability of the system is bounded by not only tie lines (line 12, 13 and 34) but also another line (line 27) in area C. Note that in Figure C-1 of Appendix A, lines 12 and 13 are the tie lines between areas B and C, while line 34 is the tie line from

Area A to C. Thus, MW power flow path, i.e., real power transfer from area A to B through the wheeler area, area C.

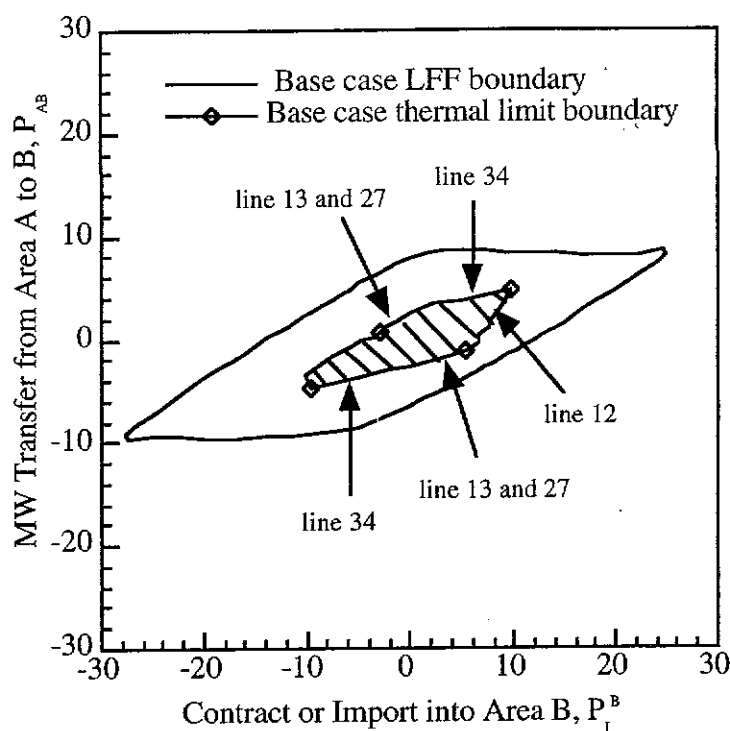


Figure 4.2-2 Base case thermal security region, R_{TT} in the MW transfer space

Figure 4.2-3 shows the base case ATC region, R_{BCT} -region in the P_T -space as the intersection of the LFF region, R_{FT} -region; voltage security region, R_{VT} -region and thermal security region, R_{TT} -region ($R_{BCT} = R_{IT} \cap R_{VT} \cap R_{TT}$). The boundary of the shadowed region gives the maximum MW transfer capability of the network under its base case topology. Instead of a scalar value for Available Transfer Capability (ATC), this region gives a set of megawatt transfer operation points $P_T = [P_{AB} \ P_I^B]^T$, representing numerous power transactions between areas A and B for which there is a secure voltage profile with no overloads in the transmission lines. Three different regions are plotted together in Figure 4.2-3 to show how voltage limit and thermal limit constraints affect the real power transfer capability of the network. Although voltage

limit constraints are not limiting the real power transfer from area A to B as much as the thermal limits do, there are operating points where they are coincident. Note that since these constraints represent soft limits, Fig. 4.2-3 shows that it is possible to have a voltage limiting operation and not a thermal limiting operation.

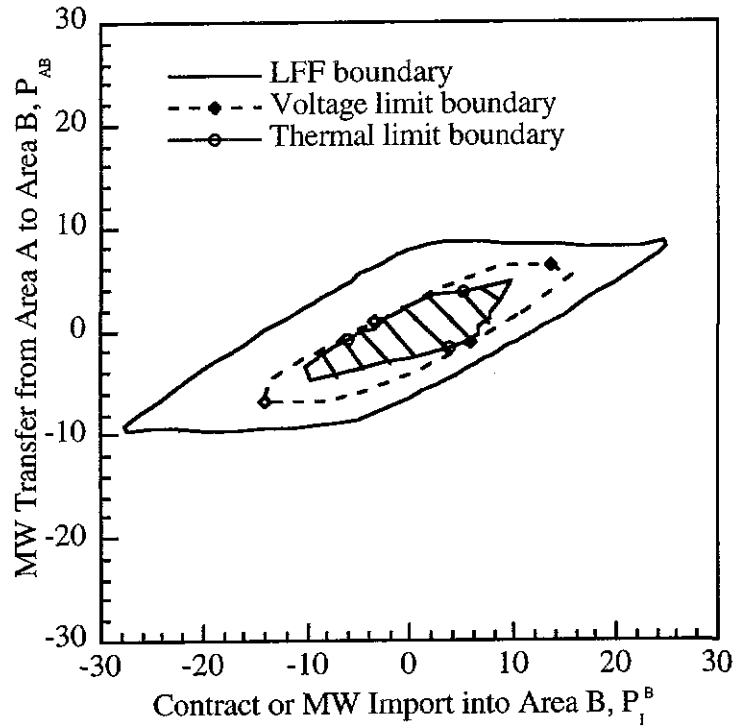


Figure 4.2-3 Base case ATC region, R_{BCT} in the MW transfer space

$$R_{BCT} = R_{FT} \cap R_{VT} \cap R_{TT}$$

The ATC region in Figure 4.2-3 also provides information on different types of transactions between areas. Each quadrant represents a different type of operating scenario. The most important quadrant is the first one where $P_{AB} > 0$ and $P_I^B > 0$, since it is considered that real power exchange occurs between area A and B. Figure 4.2-4 illustrates the first quadrant of base case ATC region. It gives the maximum amount of power that can be transferred from area A to B, $P_{AB} > 0$, when area B acts as a buyer area, $P_I^B > 0$. The LFF R_{FT} -region in Figure 4.2-4 shows large of P_I^B over which the maximum MW transfer, P_{AB} is constant. Specifically, maximum $P_{AB} \cong 8$ pu for

$2 \text{ pu} \leq P_I^B \leq 18 \text{ pu}$. Since area A can not export real power to area B more than 8 pu, the rest of area B demands will be supplied by the wheeler area, area C. Note that this graph shows not only interaction between MW transfer from area A to B, P_{AB} and MW net-import into area B, P_I^B but also gives information about the real power flows between areas B and C, P_{CB} . Three fixed values of P_{CB} are illustrated to indicate the power flow direction between area B and C depending on the location inside the region. Along the line where $P_{CB} = 0$, MW power imported by area B comes from only area A (recall from Figure 1.2-1 that $P_I^B = P_{AB} + P_{CB}$). When $P_{CB} > 0$, both area A and C sells power to area B. On the other hand, when $P_{CB} < 0$, area B exports power to area C and imports from area A at the same time.

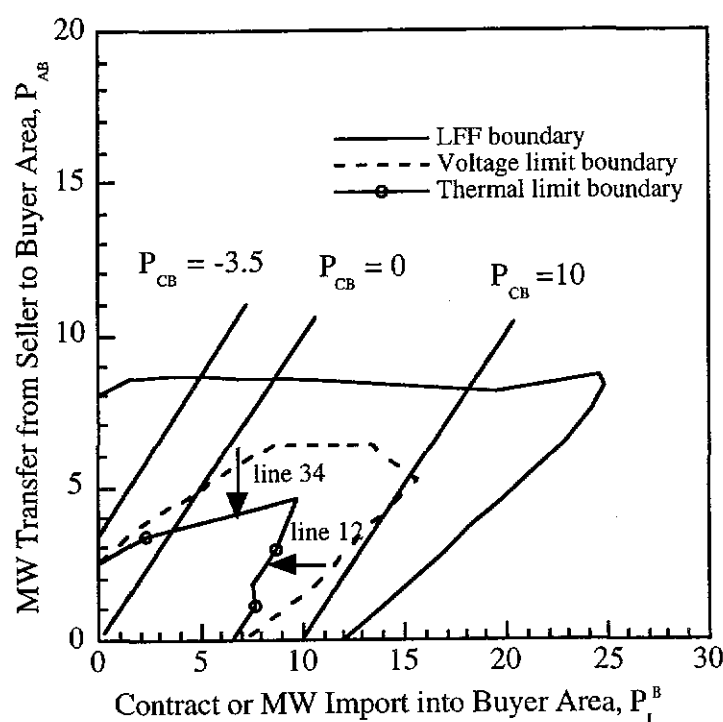


Figure 4.2-4 First quadrant of the base case ATC region, R_{BCT} in the MW transfer space

4.3 NEXT CONTINGENCY ATC REGIONS IN THE MW TRANSFER SPACE

In this section, ATC regions under different line outages are investigated for the 31-bus system whose one line diagram and data are given in Appendix C. The ATC regions are obtained using the algorithm discussed in Section 1.5 of Chapter 1. The LFF $R_{FT}^{(\lambda)}$ -region boundary is generated by performing radial searches spaced 5° starting from the zero transfer point to determine the boundary points and then joining set of boundary points by straight lines (see Section A.5 of Appendix A for details). The boundaries of voltage security region, $R_{VT}^{(\lambda)}$ -region; voltage drop limit region, $R_{\Delta VT}^{(\lambda)}$ -region and thermal security region, $R_{TT}^{(\lambda)}$ -region are generated similarly except that their boundary points are computed only at 15° intervals using the radial search. The contingencies considered to define next contingency ATC region are outage of lines {8, 11, 12, 13, 34} and those are the only ones used to characterize next contingency ATC region. These lines have been studied, because they are part of the inter-area tie lines which directly affect the MW transfer capability of the system. For the next contingency ATC region, another constraint is considered, it is the voltage drop limit constraint which represents the maximum allowable voltage drop in bus voltage magnitude due to a contingency. In this study, the voltage drop limit is selected to be 5% drop in voltage magnitude under a contingency. The other two sets of constraints (i. e., bus voltage magnitude and thermal limits) are taken to be the same as those used in the base case study of Section 4.2. Specifically, the lower and upper bus voltage limits are 0.95 and 1.05 pu, respectively and transmission line flow limits are those given in Table C-4 of Appendix C.

Before showing the next contingency regions, we show the change in the security regions as different lines are outages. The specific study performed is summarized in Table 4.3-1 which gives all the different type of security regions given in this section. The first column illustrates the contingency cases (i.e., line numbers) considered in this

study. The second column gives figure numbers of LFF regions, $R_{FT}^{(\lambda)}$ for each line outage and next contingency LFF region, $\cap R_{FT}^{(\lambda)}$. The figure numbers of voltage security regions, $R_{FT}^{(\lambda)} \cap R_{VT}^{(\lambda)}$ are given in the third column. The fourth and fifth columns show the figure numbers of voltage drop regions, $R_{FT}^{(\lambda)} \cap R_{\Delta VT}^{(\lambda)}$ and thermal security regions, $R_{FT}^{(\lambda)} \cap R_{TT}^{(\lambda)}$, respectively. Finally the last column gives the figure numbers of ATC regions for each line outage, $R_{NCT}^{(\lambda)}$. In the last row, some general comments on the regions are given.

Basically, the following six types of regions are illustrated for each line outage ($\lambda = 8, 11, 12, 13, 34$):

- Load Flow Feasibility (LFF) regions, $\cap R_{FT}^{(\lambda)}$
- Voltage security regions, $R_{FT}^{(\lambda)} \cap R_{VT}^{(\lambda)}$
- Voltage drop (ΔV) limit regions, $R_{FT}^{(\lambda)} \cap R_{\Delta VT}^{(\lambda)}$
- Thermal security regions, $R_{FT}^{(\lambda)} \cap R_{TT}^{(\lambda)}$
- ATC regions, $R_{NCT}^{(\lambda)} = R_{FT}^{(\lambda)} \cap R_{VT}^{(\lambda)} \cap R_{\Delta VT}^{(\lambda)} \cap R_{TT}^{(\lambda)}$
- Next contingency voltage limit, voltage drop and thermal security regions,

$$\cap R_{VT}^{(\lambda)}, \cap R_{\Delta VT}^{(\lambda)} \text{ and } \cap R_{TT}^{(\lambda)}$$

Table 4.3-1 Summary of the next contingency regions in the MW transfer space (P_T -space)

The 3-area 31-bus system data is in Appendix C			Voltage limits: $0.95 \leq V_i \leq 1.05$ Voltage drop limits: $\Delta V_i \leq 0.05$ Thermal limits is in Table C-4		
Contingency Cases (λ)	LFF Regions Under Line Outages $R_{FT}^{(\lambda)}$	Voltage Security Regions $R_{FT}^{(\lambda)} \cap R_{VT}^{(\lambda)}$	Voltage Drop Limit Regions $R_{FT}^{(\lambda)} \cap R_{\Delta VT}^{(\lambda)}$	Thermal Security Regions $R_{FT}^{(\lambda)} \cap R_{TT}^{(\lambda)}$	ATC Regions for each contingency $R_{NCT}^{(\lambda)}$
Base Case (0)	Fig. 4.3-1	-----	-----	-----	-----
Line 8 (8)	Fig. 4.3-1	Fig. 4.3-2	Fig. 4.3-3	Fig. 4.3-4	Fig. 4.3-5
Line 11 (11)	Fig. 4.3-1	Fig. 4.3-6	Fig. 4.3-7	Fig. 4.3-8	Fig. 4.3-9
Line 12 (12)	Fig. 4.3-1	Fig. 4.3-10	Fig. 4.3-11	Fig. 4.3-12	Fig. 4.3-13
Line 13 (13)	Fig. 4.3-1	Fig. 4.3-14	Fig. 4.3-15	Fig. 4.3-16	Fig. 4.3-17
Line 34 (34)	Fig. 4.3-1	Fig. 4.3-18	Fig. 4.3-19	Fig. 4.3-20	Fig. 4.3-21
Next Contingency Regions $\cap R_T^{(\lambda)}$ (λ)	Fig. 4.3-1	Fig. 4.3-22	Fig. 4.3-23	Fig. 4.3-24	-----
Comments	The most binding outage is line 12	Voltage magnitude constraint limits real power transfer a lot	Voltage drop limits do not bound MW transfer too much	Line loading limits prevent areas from exchanging MW power among them	It is dictated mostly by thermal limits under line outages

Figure 4.3-1 illustrates the comparison of LFF regions under different line outages with the base case LFF region. The shadowed area is the intersection of the regions, $\bigcap R_{FT}^{(\lambda)}$. As seen from Figure 4.3-1, different contingencies are limiting the real power transfer capability of the system in different search directions and the boundary of the intersection is mostly determined by the line 12 outage. Moreover, LFF regions under contingencies can i) shrink, ii) increase in size, iii) shift and iv) be bigger than the base case region in some directions. It is worth to mention that when line 34 is out, the amount of real power which can be imported by area B is increasing in some particular directions. The reason for this increase, is that line 34 is the only tie line between area A and C. Therefore, the swing area, area C, can not import any power from area A when line 34 is out and all the real power exported by area A is going to be imported by area B.

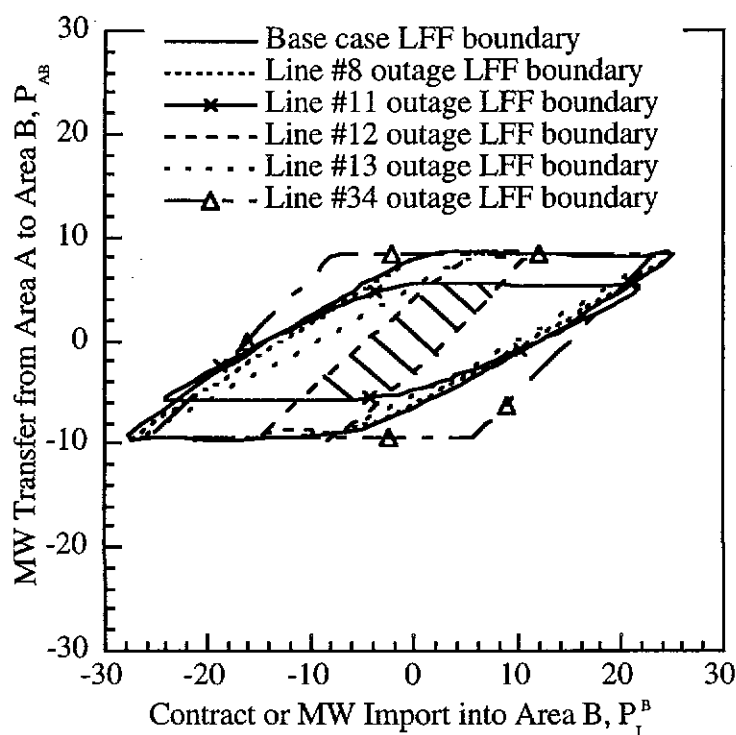


Figure 4.3-1 Next contingency LFF regions, $\bigcap R_{FT}^{(\lambda)}$ in the MW transfer space

Figures 4.3-2, 4.3-6, 4.3-10, 4.3-14 and 4.3-18 show the voltage security regions, $\mathbf{R}_{\text{FT}}^{(\lambda)} \cap \mathbf{R}_{\text{VT}}^{(\lambda)}$, under contingency operations for $\lambda = 8, 11, 12, 13$ and 34 , respectively. In these figures, each voltage security region is compared with its corresponding LFF region to show the effect of voltage magnitude limit constraints on the MW transfer capability of the system under contingencies and there is secure voltage profile inside the shadowed regions. That is, all the operating points inside the shadowed region, $\mathbf{P}_T = [P_{AB} \ P_i^B]^T$ satisfy the voltage magnitude limit constraints (i.e., $0.95 \leq |V_i| \leq 1.05$ for all buses, $i = 1, \dots, 31$). Different line segments of each security region are shown to identify the weak buses in the system. Many of the critical buses (buses 15, 27 and 29) belong to wheeler area (area C) showing the importance of the parallel flow. The largest two voltage security regions are obtained when lines 8 and 34 are out.

Figures 4.3-3, 4.3-7, 4.3-11, 4.3-15, and 4.3-19 illustrate voltage drop (ΔV) limit regions, $\mathbf{R}_{\text{FT}}^{(\lambda)} \cap \mathbf{R}_{\Delta\text{VT}}^{(\lambda)}$, under different line outage cases for $\lambda = 8, 11, 12, 13$ and 34 , respectively. As it can be seen from these figures, voltage drop limit constraint does not bound MW transfer from area A to B too much. For example, under line 8 or line 11 outages, LFF and voltage drop limit region are identical. However, when line 12, 13 and 34 are out, voltage drop constraints limit the MW transfer capability of the system.

Figures 4.3-4, 4.3-8, 4.3-12, 4.3-16 and 4.3-20 display the thermal security regions, $\mathbf{R}_{\text{FT}}^{(\lambda)} \cap \mathbf{R}_{\text{TT}}^{(\lambda)}$, under contingency operations for $\lambda = 8, 11, 12, 13$ and 34 , respectively. The binding transmission lines are shown in different search directions. Not only the tie lines such as lines 8, 12, 13 and 34 but also other lines such as lines 15, 20, 26, 27 and 28 become overloaded as MW transfer between areas A and B increases. Thermal limit constraints are the most limiting for all line outage cases considered.

Figure 4.3-5 shows the ATC region for line 8 outage, $\mathbf{R}_{\text{NCT}}^{(8)}$. In this figure, LFF, voltage security, voltage drop limit and thermal security regions are plotted together to show how each operating constraint affects the transfer capability of the system. The ATC region is the intersection of the LFF and security regions, $\mathbf{R}_{\text{NCT}}^{(8)} = \mathbf{R}_{\text{FT}}^{(8)} \cap \mathbf{R}_{\text{VT}}^{(8)} \cap \mathbf{R}_{\Delta\text{VT}}^{(8)} \cap \mathbf{R}_{\text{TT}}^{(8)}$. It is clear from Figure 4.3-5 that the most binding constraint is thermal limit and the least one is voltage drop limit constraint. Note, however, that this statement based on the example system used and may not be true in general for other network or other selection of limits (since these limits are soft limits).

Figures 4.3-9, 4.3-13, 4.3-17, and 4.3-21 illustrate the ATC regions, $\mathbf{R}_{\text{NCT}}^{(\lambda)}$ ($\mathbf{R}_{\text{NCT}}^{(\lambda)} = \mathbf{R}_{\text{FT}}^{(\lambda)} \cap \mathbf{R}_{\text{VT}}^{(\lambda)} \cap \mathbf{R}_{\Delta\text{VT}}^{(\lambda)} \cap \mathbf{R}_{\text{TT}}^{(\lambda)}$) for line 11, 12, 13 and 34 outages, respectively in the MW transfer space ($\mathbf{P}_T$ -space). It is observed from these figures that operating constraints make feasible transfer regions smaller, especially line loading limits are the most significant constraints which prevent areas from importing and exporting real power among themselves. Figure 4.3-17 shows that ATC region boundary may be dictated not only thermal limits but also voltage magnitude limits under a particular contingency. Even though many of the contingency operations can cause a smaller ATC region, line 34 is an exception. Because the largest transfer region is obtained under line 34 outage. The shadowed region in each figure is called the ATC region for the corresponding outage in which no operation point violates any security constraints. Moreover, the size, shape and orientation of the ATC regions are functions of network changes.

Figures 4.3-22, 23 and 24 display the next contingency voltage, voltage drop limit and thermal security regions ($\bigcap_{(\lambda)} \mathbf{R}_{\text{VT}}^{(\lambda)}$, $\bigcap_{(\lambda)} \mathbf{R}_{\Delta\text{VT}}^{(\lambda)}$ and $\bigcap_{(\lambda)} \mathbf{R}_{\text{TT}}^{(\lambda)}$) for $\lambda = 8, 11, 12, 13$

and 34, respectively. Again, line 12 outage is the most significant one in terms of the real power transfer capability. It has the smallest security regions preventing areas from exchanging real power.

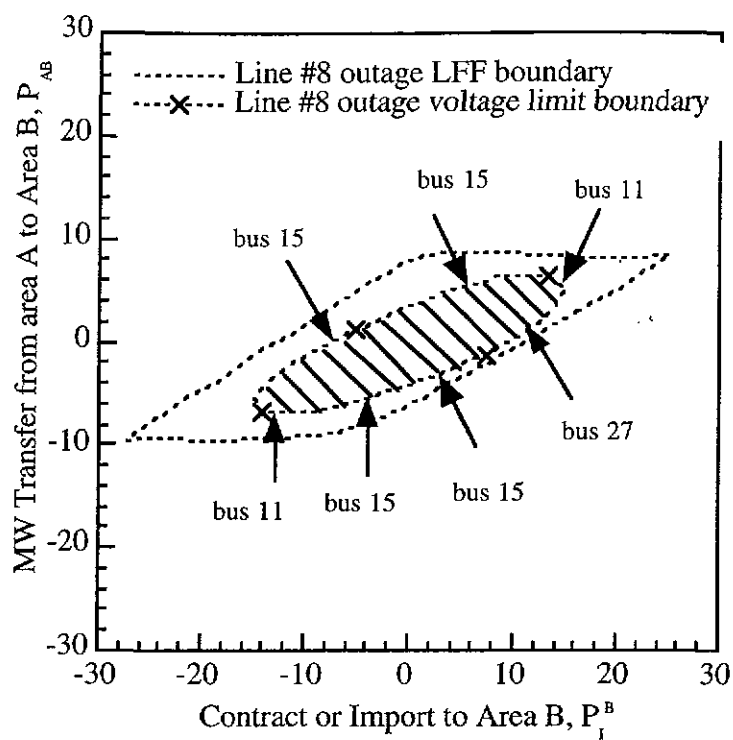


Figure 4.3-2 Line 8 outage voltage security region, $R_{VT}^{(8)}$ in the MW transfer space

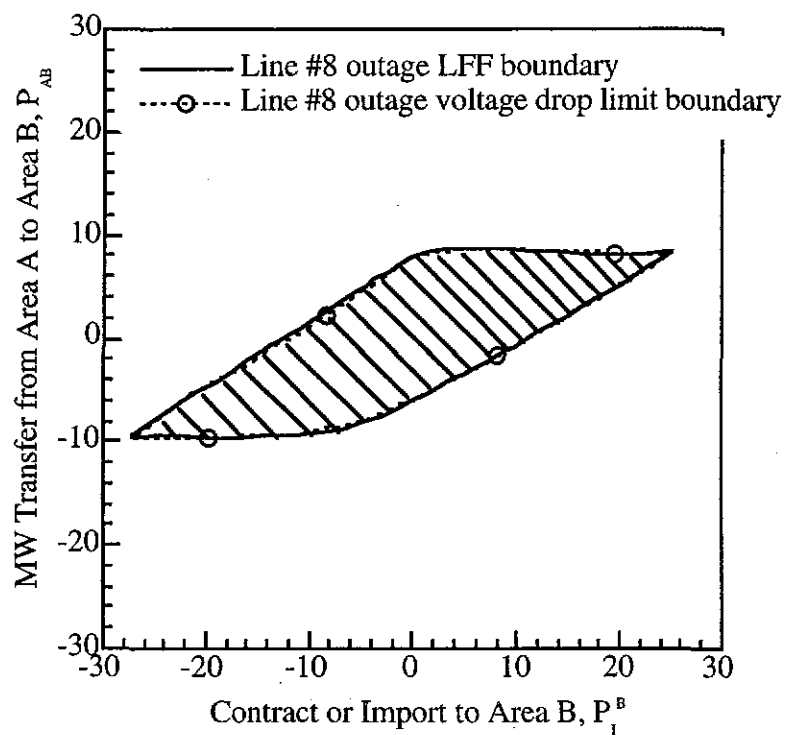


Figure 4.3-3 Line 8 outage voltage drop limit region, $R_{\Delta VT}^{(8)}$ in the MW transfer space

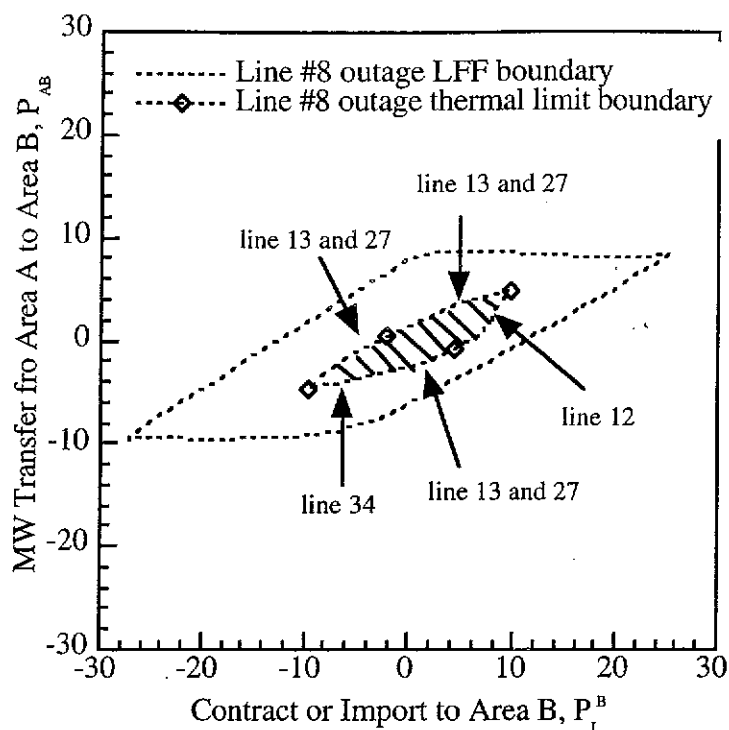


Figure 4.3-4 Line 8 outage thermal security region, $R_{TT}^{(8)}$ in the MW transfer space

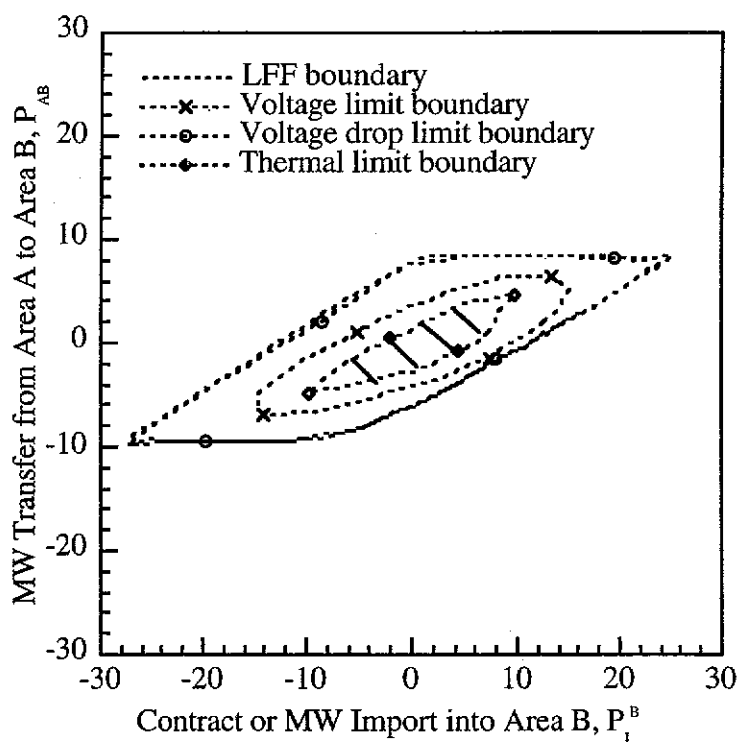


Figure 4.3-5 Line 8 outage ATC region, $R_{NCT}^{(8)}$ in the MW transfer space

$$R_{NCT}^{(8)} = R_{FT}^{(8)} \cap R_{VT}^{(8)} \cap R_{\Delta VT}^{(8)} \cap R_{TT}^{(8)}$$

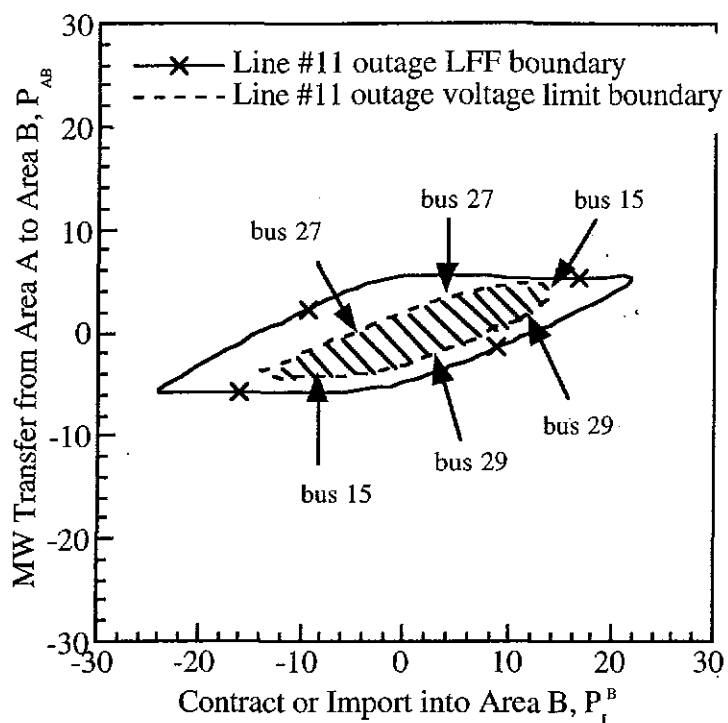


Figure 4.3-6 Line 11 outage voltage security region, $R_{VT}^{(11)}$ in the MW transfer space

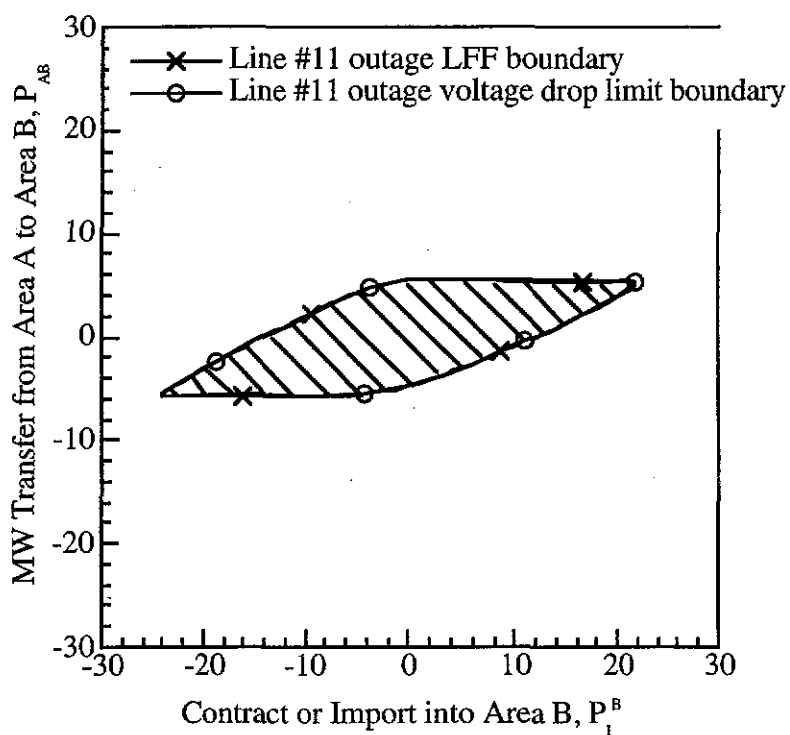


Figure 4.3-7 Line 11 outage voltage drop limit region, $R_{\Delta VT}^{(11)}$ in the MW transfer space

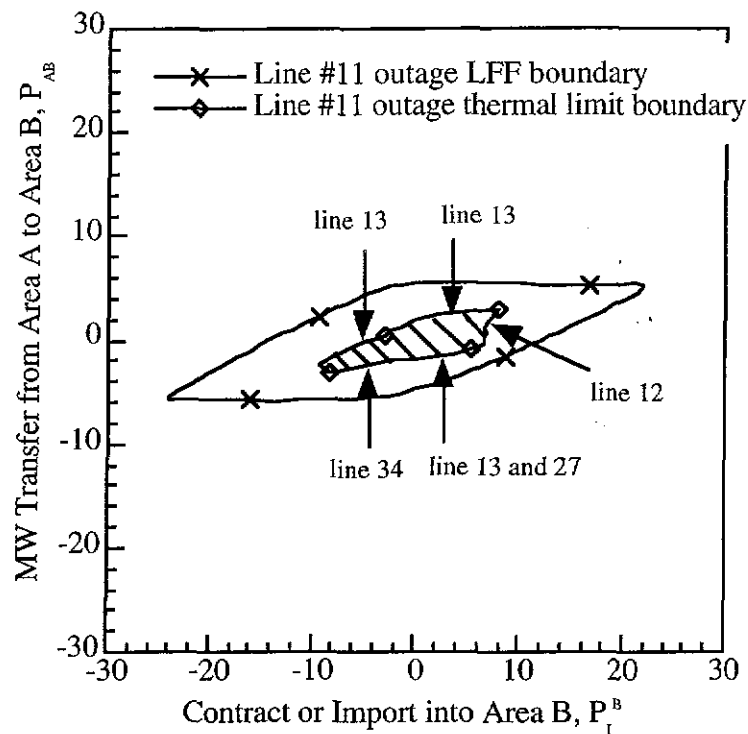


Figure 4.3-8 Line 11 outage thermal security region, $R_{TT}^{(11)}$ in the MW transfer space

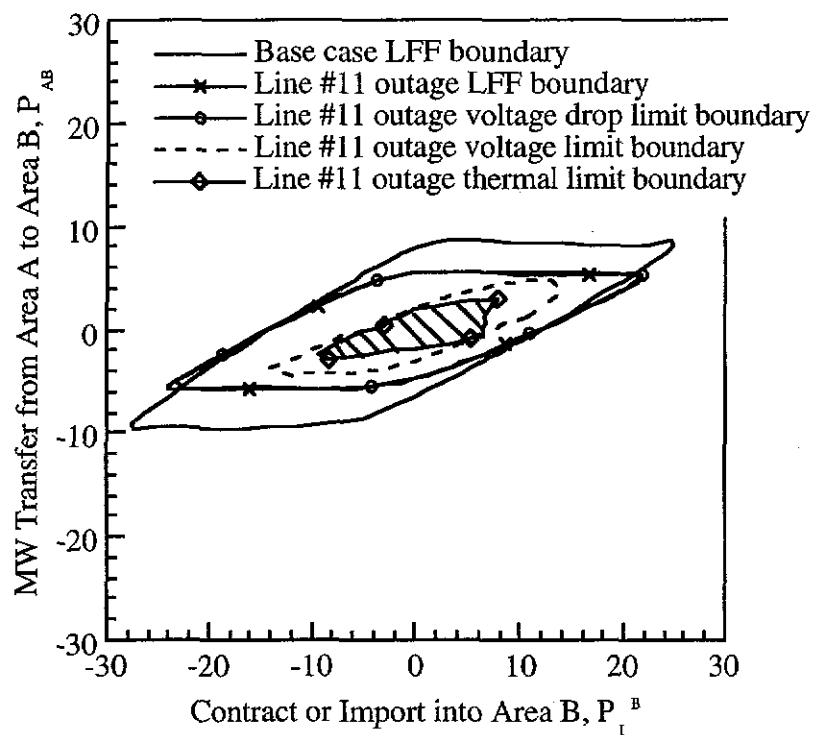


Figure 4.3-9 Line 11 outage ATC region, $R_{NCT}^{(11)}$ in the MW transfer space.

$$R_{NCT}^{(11)} = R_{FT}^{(11)} \cap R_{VT}^{(11)} \cap R_{\Delta VT}^{(11)} \cap R_{TT}^{(11)}$$

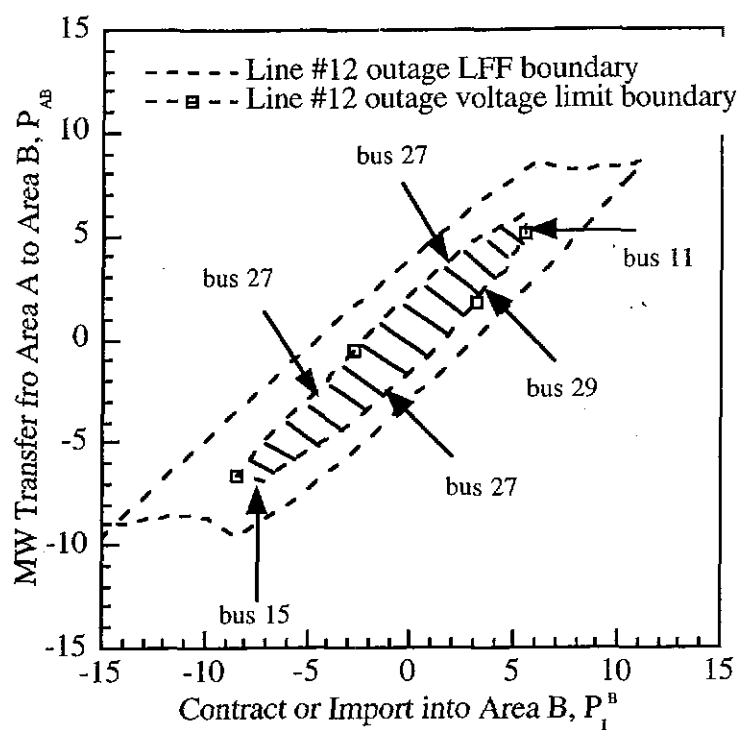


Figure 4.3-10 Line 12 outage voltage security region, $R_{VT}^{(12)}$ in the MW transfer space

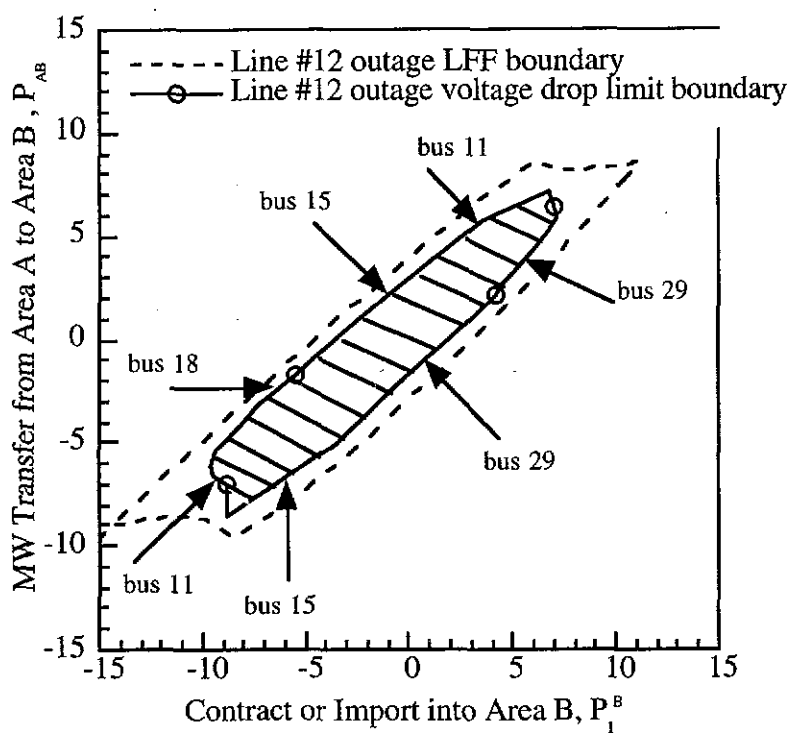


Figure 4.3-11 Line 12 outage voltage drop limit region, $R_{\Delta VT}^{(12)}$ in the MW transfer space

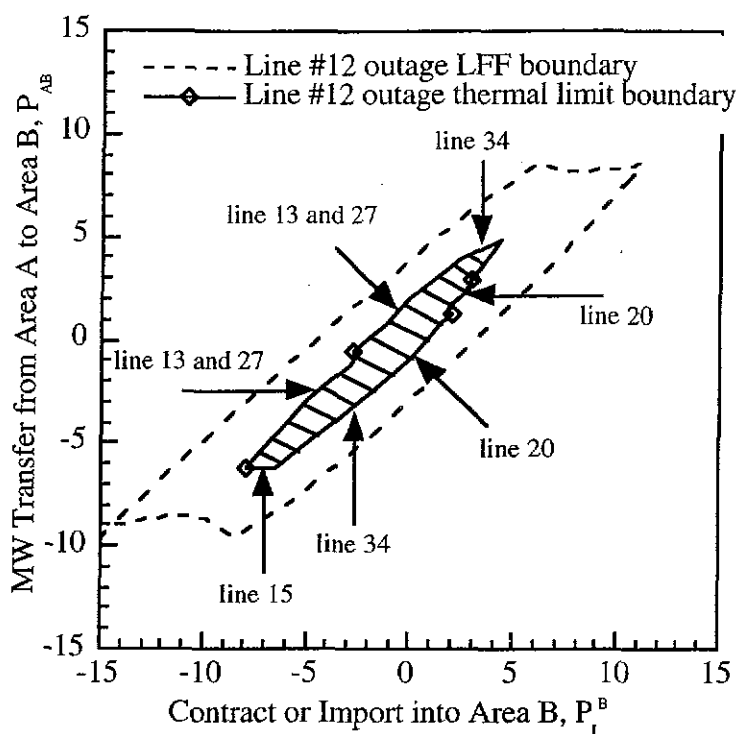


Figure 4.3-12 Line 12 outage thermal security region, $R_{TT}^{(12)}$ in the MW transfer space

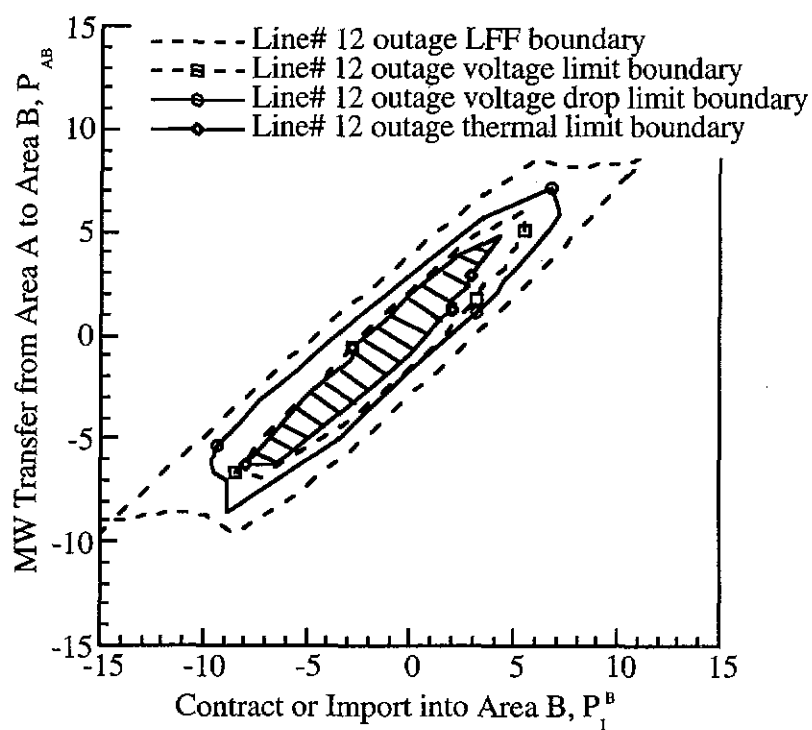


Figure 4.3-13 Line 12 outage ATC region, $R_{NCT}^{(12)}$ in the MW transfer space

$$R_{NCT}^{(12)} = R_{FT}^{(12)} \cap R_{VT}^{(12)} \cap R_{\Delta VT}^{(12)} \cap R_{TT}^{(12)}$$

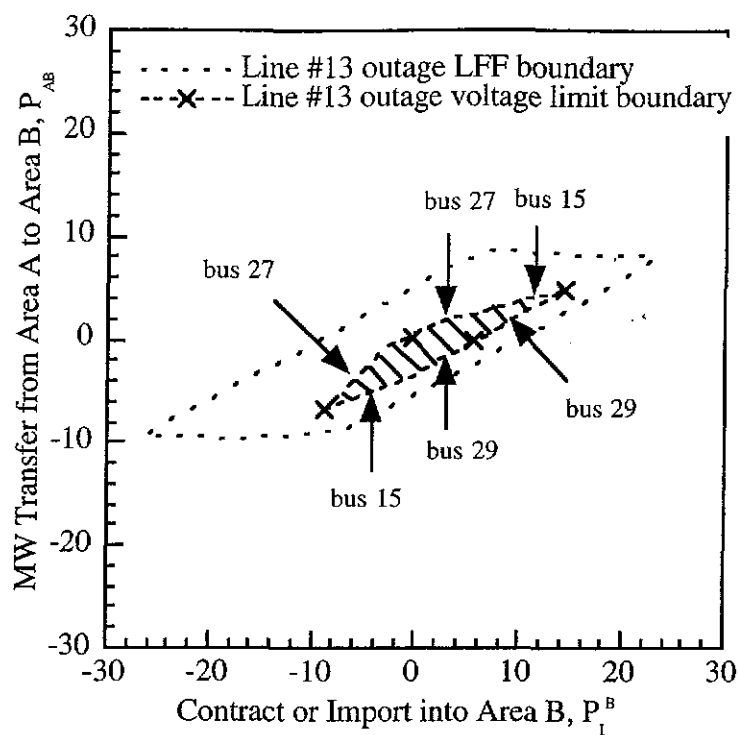


Figure 4.3-14 Line 13 outage voltage security region, $R_{VT}^{(13)}$ in the MW transfer space

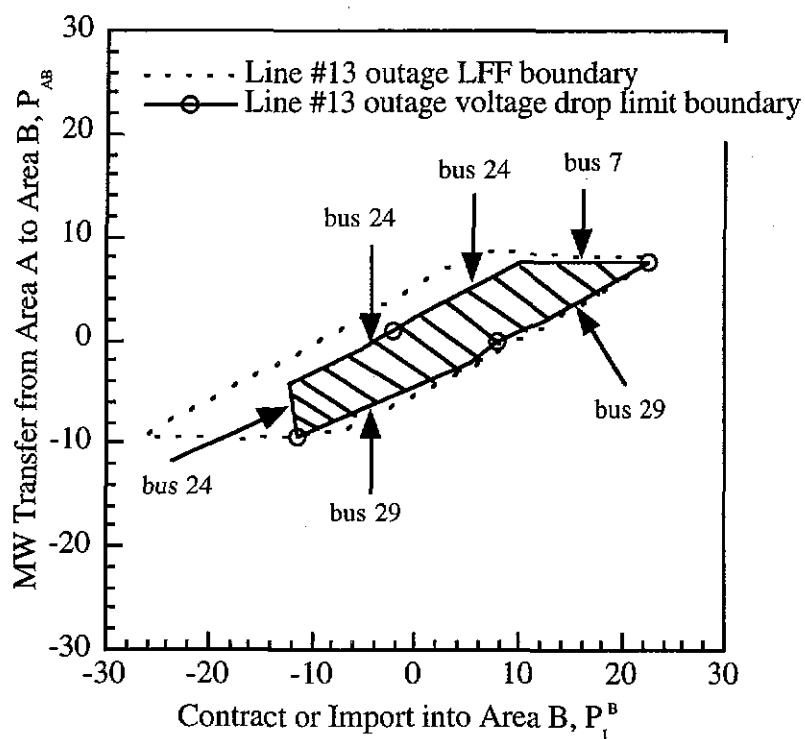


Figure 4.3-15 Line 13 outage voltage drop limit region, $R_{\Delta VT}^{(13)}$ in the MW transfer space

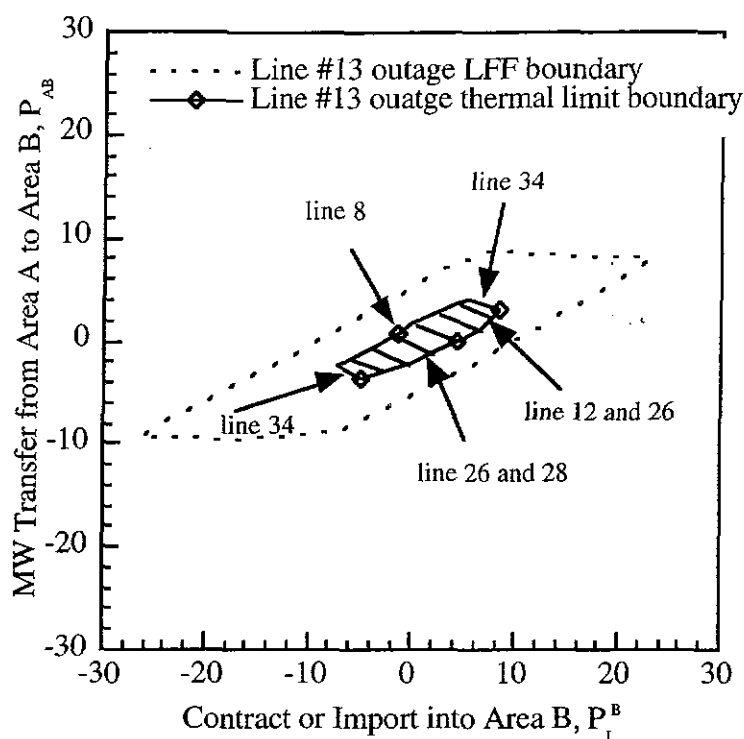


Figure 4.3-16 Line 13 outage thermal security region, $R_{TT}^{(13)}$ in the MW transfer space

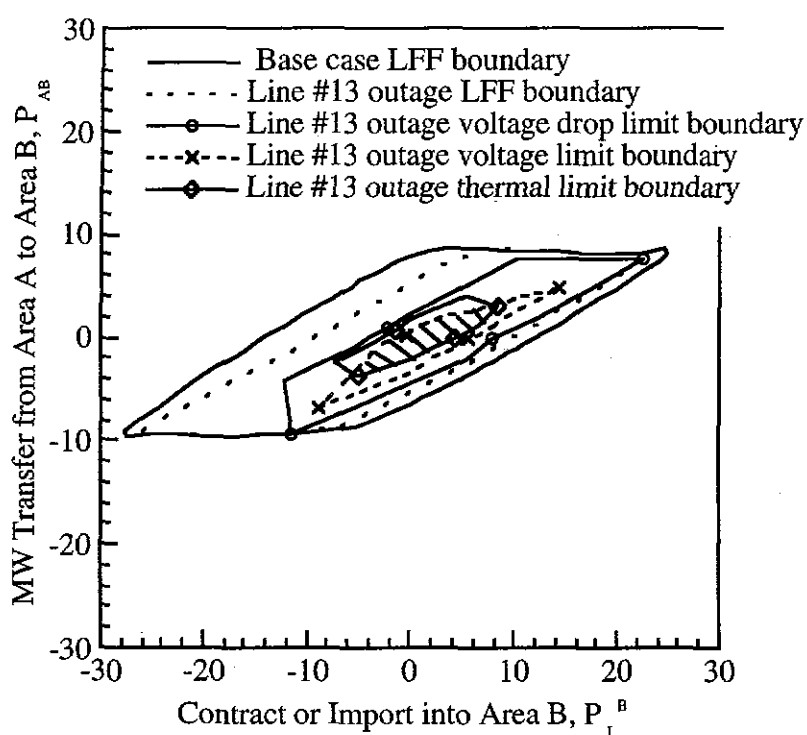


Figure 4.3-17 Line 13 outage ATC region, $R_{NCT}^{(13)}$ in the MW transfer space

$$R_{NCT}^{(13)} = R_{FT}^{(13)} \cap R_{VT}^{(13)} \cap R_{\Delta VT}^{(13)} \cap R_{TT}^{(13)}$$

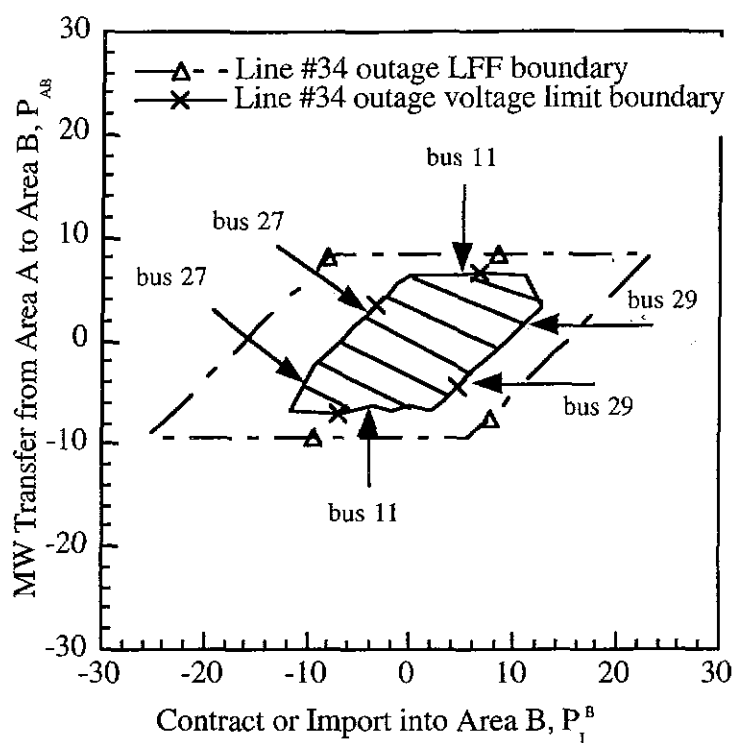


Figure 4.3-18 Line 34 outage voltage security region, $R_{VT}^{(34)}$ in the MW transfer space

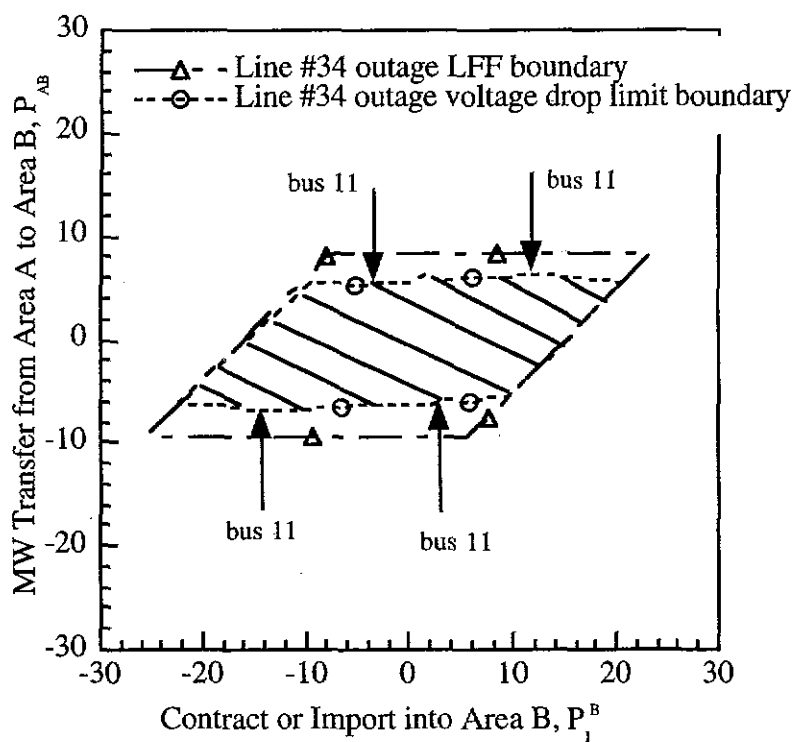


Figure 4.3-19 Line 34 outage voltage drop limit region, $R_{\Delta VT}^{(34)}$ in the MW transfer space

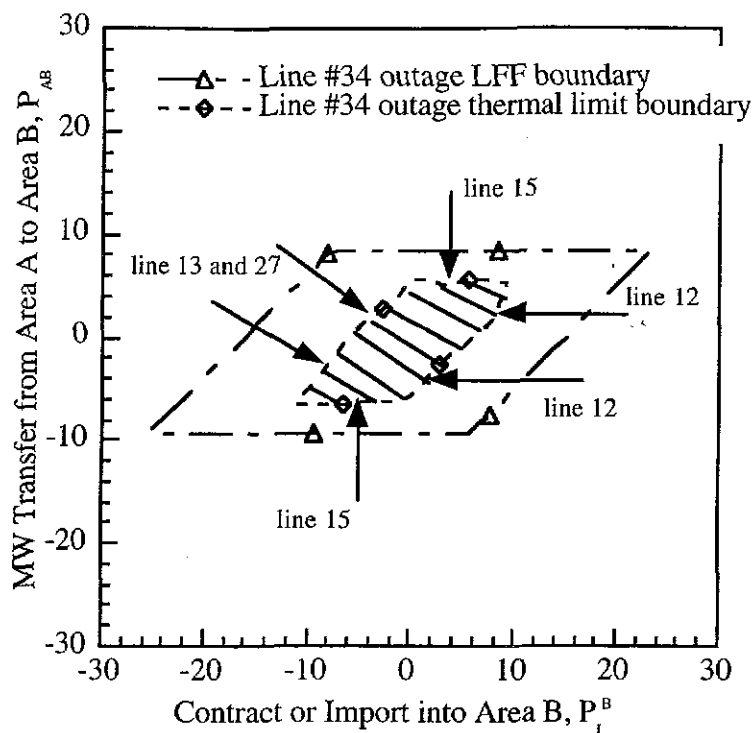


Figure 4.3-20 Line 34 outage thermal security region, $R_{TT}^{(34)}$ in the MW transfer space

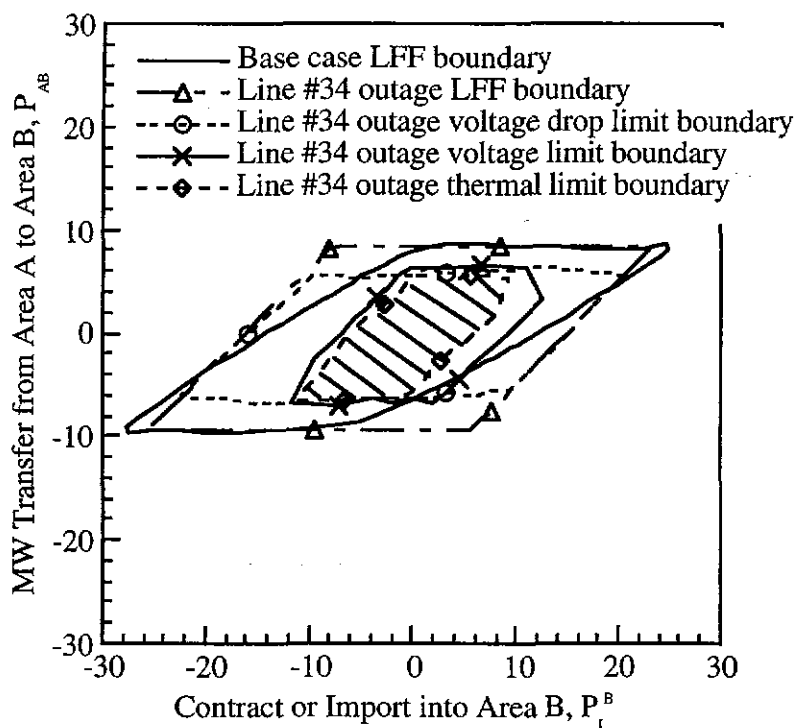


Figure 4.3-21 Line 34 outage ATC region, $R_{NCT}^{(34)}$, in the MW transfer space

$$R_{NCT}^{(34)} = R_{FT}^{(34)} \cap R_{VT}^{(34)} \cap R_{\Delta VT}^{(34)} \cap R_{TT}^{(34)}$$

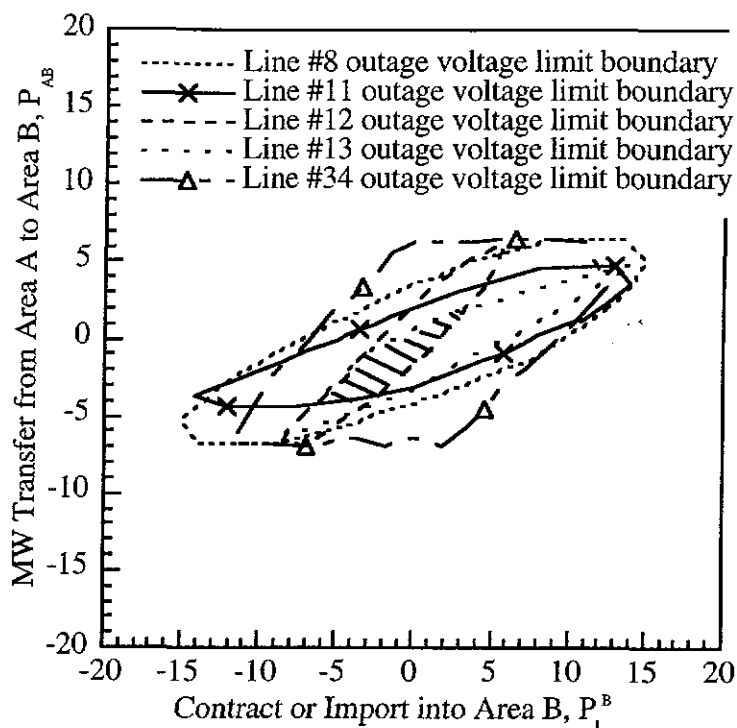


Figure 4.3-22 Next contingency voltage security region, $\cap R_{VT}^{(\lambda)}$ in the P_T -space

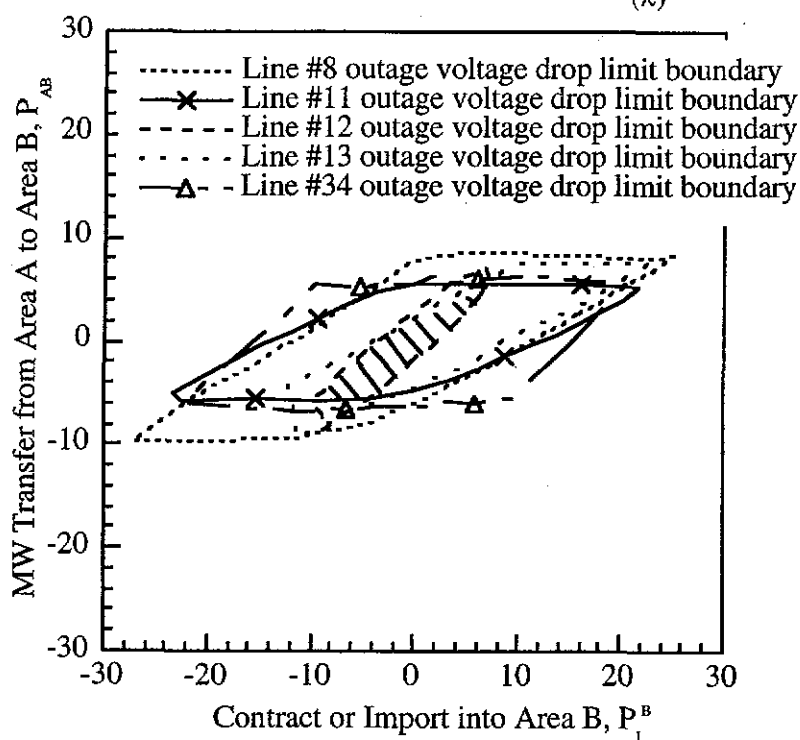


Figure 4.3-23 Next contingency voltage drop limit region, $\cap R_{\Delta VT}^{(\lambda)}$ in the P_T -space

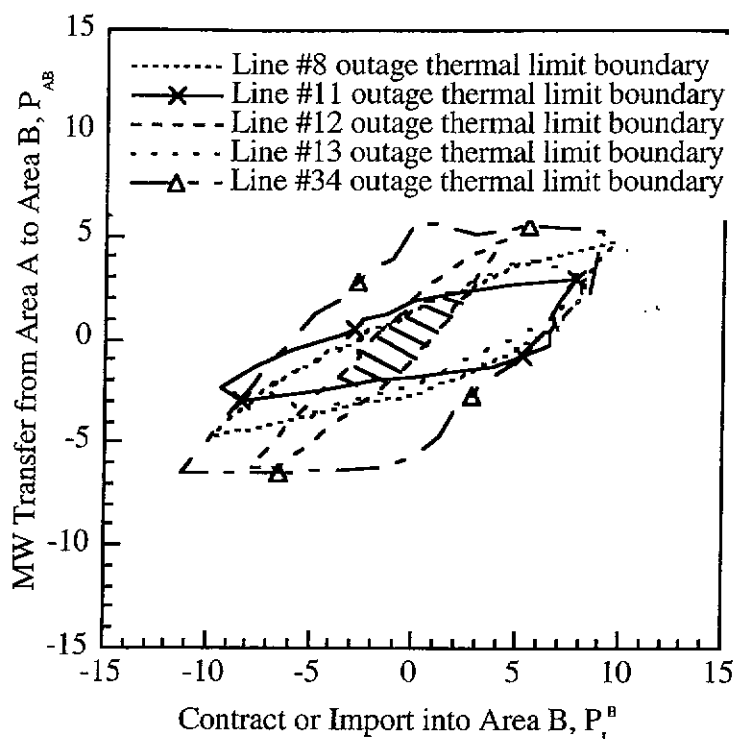


Figure 4.3-24 Next contingency thermal security region, $\bigcap R_{TT}^{(\lambda)}$ in the P_T -space

4.4 SENSITIVITY OF THE REGIONS TO LOAD CHANGES

This section investigates sensitivity of the regions to load changes. The base load given in Table C-3 of Appendix C is increased by 300 % to see how any load changes may affect the MW transfer capability of the system. Figure 4.4-1 shows that the boundary of base case LFF R_{FT} -region is sensitive to a change in the load in some search directions. Figure 4.4-2 shows the effect of 300% increase of base load on the boundary of the line 11 outage LFF region, $R_{FT}^{(11)}$. The transfer capability of the system decreases when the load level increases. The reason for selecting 300% load increase is that LFF regions do not change significantly when base load is increased by 100% or 200%. On the other hand, it is worth to mention that both voltage and thermal security regions under base case and contingency cases disappear even if the load is increased by 100%. Since the boundaries of the security regions are imposed by the soft limits (i.e.,

voltage and thermal limits), they can be relaxed depending on the system in order to obtain ATC regions under different load scenarios.

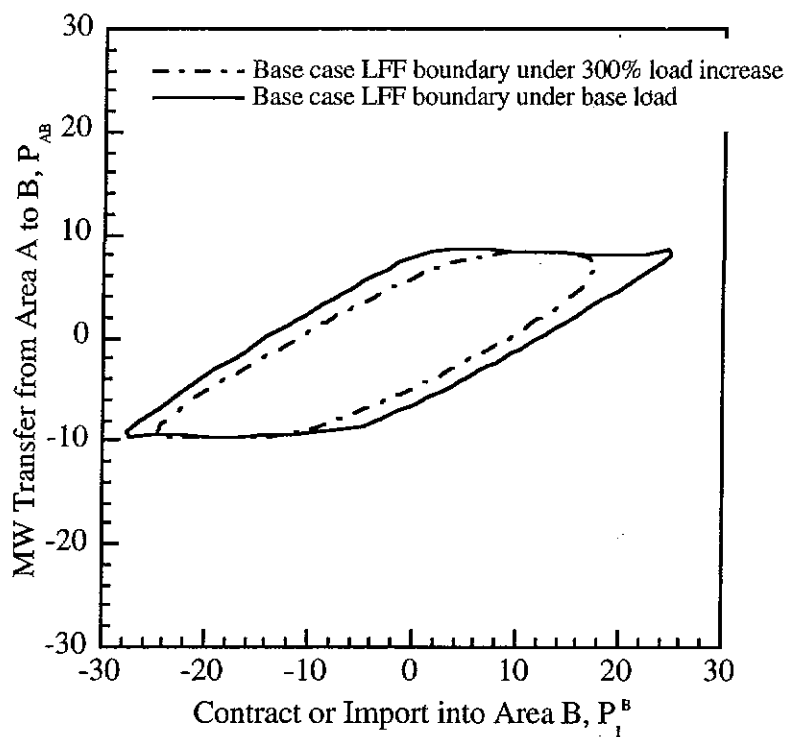


Figure 4.4-1 The effect of a change in load on the base case LFF region, R_{FT} in the MW transfer (P_T -space)

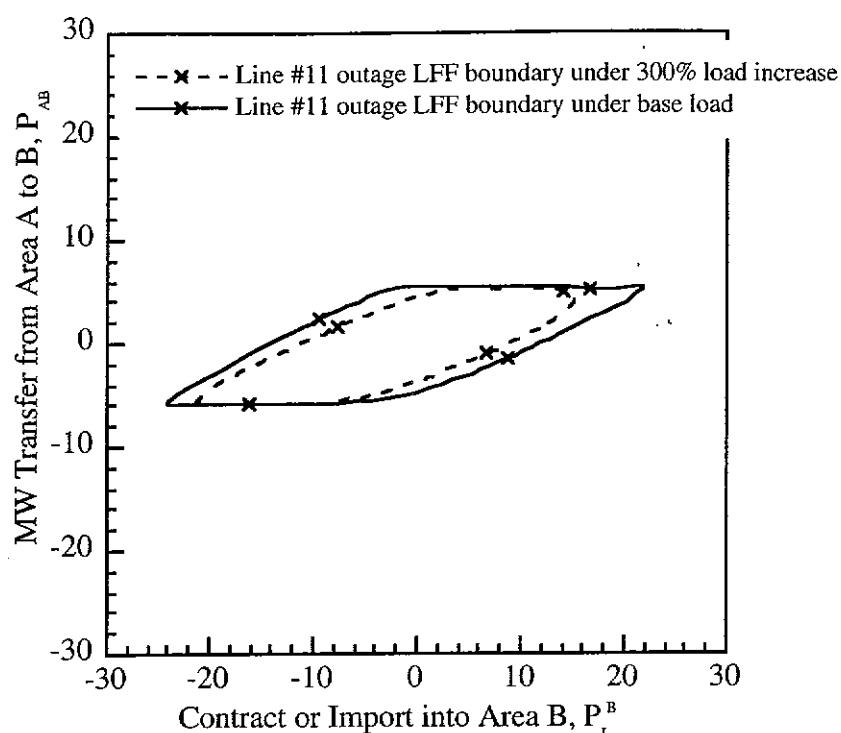


Figure 4.4-2 The effect of a change in load on the line 11 outage LFF region, $R_{TI}^{(11)}$ in the MW transfer (P_T -space)

4.5 SUMMARY OF THE RESULTS

A region-wise security approach is used to identify the transfer capability of the system. The available transfer capability (ATC) regions of a 3-area 31-bus system under base case and contingency operations have been investigated. The contingencies considered to define ATC regions are outage of tie lines between areas { lines 8, 11, 12, 13, 34}. The following results and conclusions are obtained:

- LFF, voltage, thermal security and ATC regions of a 3-area power system under base case and contingency operations are presented. It has been found out that the size, shape and orientation of the regions are functions of network changes.

- The limiting parts of the network such as buses and transmission lines are identified. It is observed that voltage problems occur in the buses of wheeler area due to power exchanges between buyer and seller areas.

- For the system under study, the boundary of ATC regions are dictated by thermal limit constraints. This observation may not be true for other systems depending on the values of soft constraints.

- The security regions disappear when load level in all areas are increased, which means the boundary of the regions are very much sensitive to load changes.

- With the help of ATC region, real power flows between areas are identified under variety of operating scenarios

- The MW transfer from area A to B, P_{AB} is the function of MW net-import into buyer area (area B), P_I^B and as the MW net-import into area B, P_I^B increases the range of secure P_{AB} transfers diminishes showing the decrease in system robustness.

- The MW real power transfer capability of the system can be increased if the soft constraints (voltage and thermal limits) are relaxed.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this thesis, Available Transfer Capability (ATC) of a 3-area 31-bus power system has been investigated. To represent the simplest open access scenario, different roles are assigned to each area of the system, namely buyer area, seller area and wheeler area. Two different ATC measurements are used to evaluate the MW transfer capability of the system:

- MW transfer from seller to buyer area vs MW net-import into buyer area
- MW net-import into buyer area vs MW net-import into seller area

While evaluating the system maximum transfer capability, not only Load Flow Feasibility (LFF) constraint but also voltage limit, voltage drop limit and thermal limit constraints have been taken into account to analyze the effects of the operating constraints. The ATC region is defined as the intersection of the following steady-state security regions under different operating conditions:

- Load Flow Feasibility (LFF) region
- Voltage security region
- Voltage drop limit region
- Thermal security region.

A MW transfer space (MW transfer from seller to buyer area vs MW import into buyer area) is defined to examine the dependency of the regions on space in which they are displayed and to investigate possible real power exchange scenarios between buyer and seller areas. The security and ATC regions are illustrated as two-dimensional graphics in

both MW net-import and transfer spaces, Chapter 3 and Chapter 4, respectively. In those Chapters each security region is compared with LFF region to visualize how operating constraints may decrease the system real power transfer/import capability. With the help of the region-wise approach, security margins and weak component of the system, so called bottlenecks, are identified.

The ATC regions show that system transfer capability is determined by the thermal limits of transmission lines for the network under investigation. However, this observation is based on the example system used and may not be true in general for other networks or other selection of limits.

It is observed that the most critical buses belong to the wheeler area, which shows that parallel power flow is becoming an important issue in the open access environment. It is also worth to mention that not only tie lines are limiting MW transfer capability of the system, as expected, but also some other lines which belong to the wheeler area may limit ATC of the system in some search directions.

It has been found that LFF and security regions are much sensitive to network changes. The post contingency region can either (i) shrink, or (ii) increase in size, or (iii) shift, or (iv) be bigger than the base case region in some search directions. The ATC regions in the MW transfer space, Chapter 3, indicate that MW transfer from seller to buyer area is the function of MW net-import into buyer area and as MW net-import into buyer area increases, the range of secure transfers diminish showing the decrease in system robustness.

The graphical representation of the all possible feasible and secure operation points may help planners visualize the Available Transfer Capability (ATC) of the system over set of line outages and allow utilities to develop transfer strategies.. It has been observed that the size, shape and orientation of regions are functions of the space in which they are illustrated and of the network changes.

5.2 RECOMMENDATIONS

In order to apply this algorithm to more practical power systems, the assumptions given in Chapter 1, Section 1.2.4 have to be re-visited. For example, the Generation Participation Factors (GPF) should be updated according to economic dispatch rather than using constant GPF's, limits of real and reactive power generations should be taken into consideration and load flow equations should be remodeled to include the control actions of TCUL and phase-shifting transformers.

The sensitivity of the ATC regions with respect to different load change scenarios should be investigated in details.

Different values of voltage and thermal limits should be tried to get a better picture of interaction between operating limits.

The algorithm and software should be modified to address the Available Transfer Capability (ATC) of a multi-area power system, particularly the case when one of the areas is the distribution system across which power is transferred.

The number of areas should be increased and multilateral trades between areas should be considered to represent more practical power networks.

LIST OF REFERENCES

LIST OF REFERENCES

- [1] R. P. Klump and T. J. Overbye, "A Transmission-based Voltage Stability Measure for Available Transfer Capability (ATC) Calculations," Proceedings of the 28th North American Power Symposium, pp.351-357, M.I.T, November 1996.
- [2] S. Wunderlich, Identification of Steady-State Thermal Security Regions for power Systems, MS Thesis, Drexel University, Philadelphia, PA, August, 1994.
- [3] T. Wu and R. Fischl, "Load Flow Feasibility Region Identification in Inter-Area Real Power Import Space," The 11th Power System Computation Conference, Avignon, France, August, 1993.
- [4] T. Wu and R. Fischl, "An Algorithm for Detecting the Contingencies Which Limit the Inter-Area Megawatt Transfer," Proceedings of the 25th Annual North American Power Symposium, Washington D.C., October, 1993.
- [5] T. Wu, Identification of Maximum Inter-Area Power Transfer Regions of Power Networks: The Three-Area Problem, Ph.D. Dissertation, Drexel University, Philadelphia, PA, December, 1995.
- [6] F. F. Wu and S. Kumagai, "Steady-State Security Regions of Power Systems," IEEE Transactions on Circuit and Systems, Vol. CAS-29, pp. 702-711, September, 1982.
- [7] R. Fischl, F. C. Ejebe and J. A. DeMaio, "Identification of Power System Steady-State Security Regions Under Load Uncertainty," Paper No. A76 495-2, IEEE Summer Power Meeting, July, 1976.
- [8] E. Hnyilicza, S. T. Lee and F. C. Schweppe, "Steady-State Security Regions: Set Theoretic Approach," Proceedings of 1975 PICA Conference, pp. 347-355.
- [9] J. A. DeMaio and R. Fischl, "Fast Identification of the Steady-State Security Regions for Power System Security Enhancement," Paper No. A76-076-0, IEEE Winter Power Meeting, January, 1976.

- [10] T. H. Matthiss, "An Algorithm for Determining Irrelevant Constraints and All Vertices in Systems of Linear Inequalities," Operations Research, Vol. 21, pp. 247-260, 1973.
- [11] J. Mescua and R. Fischl, "On the Determination of a Secure Voltage Profile for an Electric Power System," Proceedings of the IEEE 1980 International Symposium on Circuit and Systems, 80CH1564-4, Vol. 3 of 3, April, 1980.
- [12] M. H. Banakar and F. D. Galiana, "Power System Security Corridors Concept and Computation," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, pp. 4524-4532, November, 1981.
- [13] P. Dersin and A. H. Levis, "Feasibility Sets of Steady-State Loads in Electric Power Networks," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, pp. 60-70, January, 1982.
- [14] C. C. Liu, "A New Method for the Construction of Maximal Steady-State Security Regions of Power Systems," IEEE Transactions on Power Systems, Vol. PWRS-1, No. 4, pp. 19-27, November, 1986.
- [15] Y. Kataoka, "An Approach for the Regularization of a Power Flow Solution Around the Maximum Loading Point," 91 WM 099-2, IEEE/PES 1991 Winter Meeting, New York, New York, February, 1991.
- [16] S. Wunderlich, T. Wu, R. Fischl and R. O'Connel, "An Inter-Area Transmission and Voltage Limitation (TVLIM) Program," Paper No. 94, SM 554-6 PWRS, IEEE/PES Summer Meeting, July, 1994.
- [17] J. Jarsis, F. D. Galiana, "Quantitive Analysis of Steady-State Stability in Power Networks," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 1 January, 1981.
- [18] A. Araposthatis, S. Sastry and P. Varaiya, "Analysis of Power-Flow Equation," Electrical Power and Energy Systems, Vol. 3, No. 3, pp.115-126. July, 1981.
- [19] H. G. Kwany, A. K. Pasrija and L. Y. Bahar, "Static Bifurcations in Electric Power Networks: Loss of Steady-State Stability and Voltage Collapse," IEEE Transactions on Circuit and Systems, Vol CAS-33, No. 10, pp. 981-991, October, 1986.
- [20] K. Iba, H. Suzuki, M. Egawa, T. Watanabe, "Calculation of Critical Loading Condition with Nose Curve Using Homotopy Continuation Method," IEEE Transactions on Power Systems, Vol. 6, No. 2, May, 1991.

- [21] R. John Evans, Jr., Maximum Power System Loadability, MS Thesis, University of Illinois at Urbana-Champaign, 1990.
- [22] Claudio A. Canizares and Fernando L. Alvarado, "Point of Collapse and Continuation Methods for Large AC/DC System," 92 WM 103-2 PWRs, IEEE/PES 1992 Winter Meeting, New York, New York, January, 1992.
- [23] F. Alvarado and T. H. Jung, "Direct Detection of Voltage Collapse Conditions," Proceedings: Bulk Power System Voltage Phenomena-Voltage Stability and Security, EPRI Report EL-6183, pp. 5-23~ 5-38, 1989.
- [24] F. D. Galiana and Z. C. Zeng, "Analysis of the Load Flow behavior Near a Jacobian Singularity," Proceedings of the IEEE Power Industry Computer Applications Conference, pp. 149-155, May, 1991.
- [25] Z. C. Zeng, F. D. Galiana, B. T. Ooi and N. Yorina, "A Simplified Approach to Estimate Maximum Loading Conditions in the Load Flow Problem," 92 WM 307-9 PWRs, IEEE/PES 1992 Winter Meeting, New York, New York, January, 1992.
- [26] Hsiao-Dong Chiang, W. Ma, J. Thomas and J. S. Thorp, "A Tool for Analyzing Voltage Collapse in Electric Power Systems," Proceedings of the 10th Power System Computation Conference, Graz, Austria, August, 1990.
- [27] V. Ajjarapu and C. Christy, "The Continuation Power Flow: A Tool for Steady-State Voltage Stability Analysis," Proceedings of the IEEE Power Industry Computer Applications Conference, pp. 304-311, May, 1991.
- [28] R. Seydel, From Equilibrium to Chaos: Practical Bifurcation and Stability Analysis, Elsevier Science Publishing Co., Inc., New York, 1988.
- [29] R. J. Jumeau and H. D. Chiang, "Parameterizations of the Load-Flow Equations for Eliminating Ill-Conditioning Load Flow Solutions," 92 SM 586-8 PWR, IEEE/PES 1992 Summer Meeting, Seattle, WA, July, 1992.
- [30] T. Wu, Load-Flow Feasibility Evaluation of Inter-Area Imports of Real Power, MS Thesis, Drexel University, Philadelphia, PA, 1992.
- [31] M. Kubicek, "Algorithm 502: Dependence of Solution of Nonlinear Systems on a Parameter," ACM Transactions on Mathematical Software, Vol. 2, No. 1, March, 1976.
- [32] W. C. Rheinboldt, "A Local Parameterized Continuation Process," ACM Transactions on Mathematical Software, Vol. 9, No. 2, pp. 215-235, June, 1983.

- [33] N. Balu, T. Bertram, A. Bose, V. Brandwajn, G. Cauley, D. Curtice, A. Fouad, L. Fink, M. G. Lauby, B. F. Wollenberg, J. N. Wrubel, "On-Line Power System Security Analysis," Proceedings of the IEEE, Vol. 80, No. 2, pp.262-280, February, 1992.
- [34] G. C. Ejebe, Assessment of Power System Security Under Load Uncertainty, Ph.D. Thesis, Drexel University, Philadelphia, PA, May, 1976.
- [35] T. F. Halpin, Contingency Selection Theory for Steady-State Security Assessment of Power Systems, Ph.D. Thesis, Drexel University, Philadelphia, PA, June, 1982.
- [36] H. D. Chiang, A. J. Flueck, K. S. Shah, N. Balu, "Cpflow: A Practical Tool for Tracing Power System Steady-State Stationary Behavior due to Load and Generation Variations," 94 WM 244-4 PWRD, IEEE/pes 1994 Winter Meeting, New York, New York, February, 1994.

APPENDICES

APPENDIX A

POWER FLOW EQUATIONS AND RADIAL SEARCH APPROACH

APPENDIX A

POWER FLOW EQUATIONS AND RADIAL SEARCH APPROACH

A.1 THE SYSTEM MODEL

In this appendix, the inter-area import of real power has been considered as the control variables to formulate the load-flow equations. As shown in Figure A-1, the power network has three areas connected through the tie lines, namely A, B and C. The MW net-import of real power into each area is denoted by P_I^A , P_I^B and P_I^C , respectively. P_{AB} , P_{AC} and P_{BC} represent the net real power transfers from area A to B, area A to C and area B to C. The power system has n buses among which there are n_g generator (PV) buses, n_d load (PQ) buses and three slack buses. Each area has its own slack bus. The slack bus in area C is defined as the system slack as bus while the other two are local slack buses.

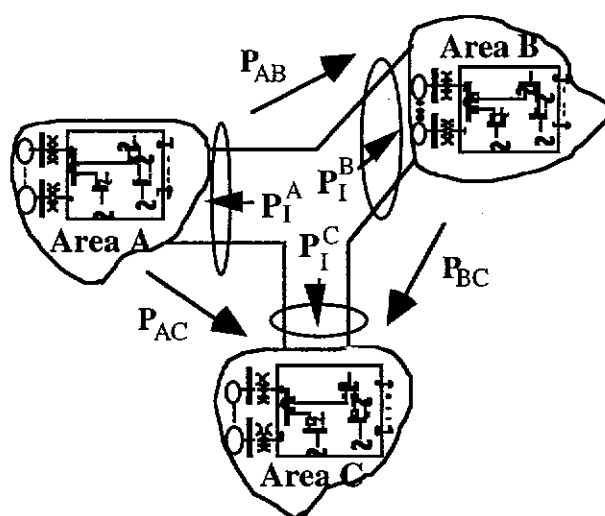


Figure A-1 The 3-Area Power Network

The variables specified at a bus characterize the bus type. In the following, definitions of bus types are given to classify the buses.

Definition A.1: System Slack (generation) Bus - the bus where voltage magnitude V and the phase angle θ are specified, usually $V_{\text{slack}} = 1 \angle 0^\circ$.

Definition A.2: Local Slack (generation) Buses - the bus where only voltage magnitude V is specified. (They are generator, PV, buses whose V is specified but P is not)

Definition A.3: PV (generation) Buses - the bus where voltage magnitude V and real power generation P are specified.

Definition A.4: PQ (load) Buses - the bus where the real and reactive load demand $P+jQ$ are specified.

As shown in Figure A-1, the net imports of real power into area A, B and C are:

$$P_I^A = -P_{AB} - P_{AC} \quad (\text{A.1.1})$$

$$P_I^B = P_{AB} - P_{BC} \quad (\text{A.1.2})$$

$$P_I^C = P_{AC} + P_{BC} \quad (\text{A.1.3})$$

The addition of equations (A.1.1), (A.1.2) and (A.1.3) gives the fundamental relationship between inter-area imports, which stipulates that the sum of all net-imports of real power into areas must add up to zero, as in Equation (A.1.4).

$$P_I^A + P_I^B + P_I^C = 0 \quad (\text{A.1.4})$$

In this thesis, two types of space have been used to obtain Load Flow Feasibility (LFF) regions and security regions: The inter-area MW net-import space and MW transfer space. The inter-area MW net-import space is defined by using only two net-import variables, namely P_I^A and P_I^B . Because it is clear from (A.1.4) that it is sufficient to specify two of the three import variables. Once P_I^A and P_I^B are specified, P_I^C can be easily

found by using (A.1.4). The inter-area MW net import space, $\mathbf{P}_I$ -space is defined as the following vector:

$$\mathbf{P}_I = [P_I^A \ P_I^B]^T \quad (\text{A.1.5})$$

Since it is assumed that area A is the exporting area and area B is the importing area, it is necessary to define a new real power space including net-import to area B, P_I^B and real power transfer from area A to B, P_{AB} . This new space has been called as the MW transfer space, $\mathbf{P}_T$ -space and defined as follows:

$$\mathbf{P}_T = [P_{AB} \ P_I^B]^T \quad (\text{A.1.6})$$

The objective of this research is to obtain LFF and different types of security regions in the $\mathbf{P}_I$ and $\mathbf{P}_T$ -space. Since, in general, the inter-area transfer P_{AB} is controlled by raising and lowering the generation in areas A and B, namely the net imports P_I^A and P_I^B , the system security is assessed by assessing the security of the $(P_I^A - P_I^B)$ point [7, 8].

A.2 THE LOAD-FLOW EQUATIONS CONSIDERING THE INTER-AREA IMPORTS OF REAL POWER

In the steady-state operation of a power system, load flow equations represent the balance between the generated power, load demand and the system losses. The balance condition is given by a set of non-linear equations. The load-flow equations give the relations among power injection at each bus, voltage magnitudes and phases as well as power flows over transmission lines. The bus voltages and power injections must satisfy the following equations:

$$P_i = V_i \sum_{k=1}^n V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}), \text{ for } i=1, 2, 3, \dots, n \quad (\text{A.2.1})$$

$$Q_i = V_i \sum_{k=1}^n V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}), \text{ for } i=1, 2, 3, \dots, n \quad (\text{A.2.2})$$

where

P_i = net real power injection at bus i

Q_i = net reactive power injection at bus i

V_i = voltage magnitude at bus i

θ_i = voltage phase angle at bus i

$G_{ik} + jB_{ik}$ = $(i, k)^{th}$ element of the bus admittance matrix, $[Y_{BUS}]$

$n = (n_g + n_d + 3)$ = total number of buses in the power system

Inter-area net real power imports are related to bus voltages by the following equations:

$$P_I^A = \sum_{i \in I_B, k \in I_A} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] + \sum_{i \in I_C, k \in I_A} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] \quad (A.2.3)$$

$$P_I^B = \sum_{i \in I_A, k \in I_B} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] + \sum_{i \in I_C, k \in I_B} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] \quad (A.2.4)$$

$$P_I^C = \sum_{i \in I_A, k \in I_C} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] + \sum_{i \in I_B, k \in I_C} \left[\frac{1}{2} (V_i^2 - V_k^2) g_{ik} - V_i V_k b_{ik} \sin \theta_{ik} \right] \quad (A.2.5)$$

where

I_A, I_B, I_C = set of all the buses in area A, B or C respectively.

$g_{ik} + j b_{ik}$ = series admittance of the line connecting buses i and k

The bus voltage magnitudes and phases are the unknown load-flow variables in (A.2.1)-(A.2.5) and total number of unknown voltage variables is $(2n_d + n_g + 2)$. Table A.2-1 summarizes the unknown variables. Note that total number of equations in (A.2.1)-

(A.2.5) is $(2n+3)$. Only $(2n_d+n_g+2)$ equations of $(2n+3)$ equations are needed to be solved for voltage variables. Table A.2-2 shows the necessary equations.

Table A.2-1 Summary of the load-flow unknown voltage variables

Load-flow unknown variables	Number of variables
θ_i at PQ and PV buses for $i=1, \dots, n_d, n_d+1, \dots, n_d+n_g, n_d+n_g+1, \dots, n_d+n_g+1$	$n-1 (=n_d+n_g+2)$
V_i at PQ buses for $i=1, \dots, n_d$	n_d
Note: Total number of load-flow equations = $2n_d+n_g+2$	

Table A.2-2 Load-flow Equations

Specified Variables	Load-flow Equations
P_i at PQ and PV buses for $i=1, \dots, n_d, n_d+1, \dots, n_d+n_g$	(A.2.1) for $i=1, \dots, n_d, n_d+1, \dots, n_d+n_g$
Q_i at PQ buses for $i=1, \dots, n_d$	(A.2.2) for $i=1, \dots, n_d$
P_I^A , inter-area real power import into area A	(A.2.3)
P_I^B , inter-area real power import into area B	(A.2.4)
Note: Total number of load-flow equations = $2n_d+n_g+2$	

The load-flow equations can be expressed in general vector form:

$$f(\mathbf{x}) = \mathbf{u} \quad (\text{A.2.6})$$

where $\mathbf{x}$ is a vector defining the unknown voltage variables, (V, θ) ; $\mathbf{u}$ is the injection vector representing the specified $(P_i, Q_i, P_I^A$ and $P_I^B)$ variables. When (A.2.6) is compared to (A.2.1)-(A.2.5), it is seen that the injection vector $\mathbf{u}$ represents the left hand side of (A.2.1)-(A.2.5) while $f(\mathbf{x})$ defines the corresponding right hand side of (A.2.1)-(A.2.5). The detailed information about the vector $\mathbf{x}$ and $\mathbf{u}$ can be found in [Wu, MS thesis].

In order to find out the effects of the line-outages on the voltage variables, load-flow equations should be redefined considering the line admittance as a variable. The right

hand side of (A.2.1)-(A.2.5) can be defined to be $f(\mathbf{x}, y_\lambda)$. Then load-flow equations that consider the outage-line admittance as a variable is:

$$\mathbf{f}(\mathbf{x}, y_\lambda) = \mathbf{u} \quad (\text{A.2.7})$$

where y_λ is the line admittance of the line number λ

Up to this point, the load-flow equations are formulated by considering the inter-area imports of real power as part of injection variables. In the next section, formulation are presented how to get a new set of equations whose specified variables are the only vector $\mathbf{P}_I$, the inter-area imports of real power.

A.3 LOAD ASSUMPTIONS AND GENERATION DISPATCH

In order to obtain feasible and secure the MW import capability in the $\mathbf{P}_I$ -space, and MW transfer capability $\mathbf{P}_T$ -space, it is necessary to specify how the generation in each area depends on the inter-area imports. In other words, we want to represent the injection vector $\mathbf{u}$ as a function of $\mathbf{P}_I$. The injection vector $\mathbf{u}$ is defined as a linear function of $\mathbf{P}_I$, namely:

$$\begin{aligned} \mathbf{u}(\mathbf{P}_I) &= \mathbf{u}^0 + \Delta\mathbf{u}(\Delta\mathbf{P}_I) = \mathbf{u}^0 + \Delta\mathbf{u}(\mathbf{P}_I - \mathbf{P}_I^0) \\ &= \mathbf{u}^0 + \mathbf{W} \Delta\mathbf{P}_I = \mathbf{u}^0 + \mathbf{W}(\mathbf{P}_I - \mathbf{P}_I^0) \end{aligned} \quad (\text{A.3.1})$$

where

$\mathbf{u}^0$ = base-case injection vector

$\mathbf{P}_I^0$ = base-case inter-area imports of real power

$\Delta\mathbf{u}(\Delta\mathbf{P}_I)$ = change of injection due to the change of inter-area imports of real power.

and $\mathbf{W}$ represents the various participation factors. In this thesis we assume that the load (i.e., PQ buses) are held constant so the $\mathbf{W}$ represents the generator participation factors as follows:

Definition A.5: Generation Participation Factor in Area A (α_{gi}) is the fraction of generation change at the i^{th} generator in area A relative to the total generation change in area A, i.e.

$$\alpha_{gi} = \frac{\Delta P_{gi}^A}{\sum_{i \in I_g^A} \Delta P_{gi}^A} \quad i \in I_g^A \quad (\text{A.3.2})$$

The generation participation factors represent how much change of real power generation each generator must provide. The generation participation factors for area B and C and $\mathbf{W}$ generation participation factor matrix are given in details in [Wu, MS thesis].

A.4 FORMULATION OF LOAD-FLOW EQUATIONS

A method for identification of security regions in the MW transfer space, PI-space has been presented in [Wu&Fischl 93]. The most difficult part of the security region identification problem is the identification of the LFF region boundary. A brief summary of load-flow formulations developed in [Wu, Ph.D. thesis] to get the LFF regions rigorously is given in this section. The load-flow equations containing net import vector $\mathbf{P}_I$ are obtained by substituting (A.3.1) into (A.2.7):

$$\mathbf{F}(\mathbf{x}, \mathbf{P}_I, \mathbf{y}_\lambda) = \mathbf{f}(\mathbf{x}, \mathbf{y}_\lambda) - \mathbf{u}(\mathbf{P}_I) = \mathbf{0} \quad (\text{A.4.1})$$

where

$$\mathbf{u}(\mathbf{P}_I) = \mathbf{u}^0 + \mathbf{W}(\mathbf{P}_I - \mathbf{P}_I^0) \quad (\text{A.4.2})$$

where $\mathbf{u}^0 \in \mathbb{R}^n$, and $\mathbf{P}_I^0 \in \mathbb{R}^2$, are the original injection and area import of real power; $\mathbf{W} \in \mathbb{R}^{n \times 2}$ is the constant Generation Participation Factors matrix. Since radial search approach is used, it is convenient to represent $(\mathbf{P}_I - \mathbf{P}_I^0)$ in its polar coordinates with r and ϕ being the radius and angle, which means:

$$\mathbf{P}_I - \mathbf{P}_I^0 = r \begin{bmatrix} \sin \phi \\ \cos \phi \end{bmatrix} \quad (\text{A.4.3})$$

When we substitute (A.4.3) to (a.4.2) we get:

$$\mathbf{u}(\mathbf{P}_I) = \mathbf{u}^0 + r \mathbf{w}(\phi) \quad (\text{A.4.4})$$

where

$$\mathbf{w}(\phi) = \mathbf{W} \begin{bmatrix} \sin\phi \\ \cos\phi \end{bmatrix} \quad (\text{A.4.5})$$

When we replace $\mathbf{u}(\mathbf{P}_I)$ of (A.4.1) by $\mathbf{u}$ of (A.4.4) we obtain:

$$\mathbf{F}(\mathbf{x}, r, \phi, y_\lambda) = \mathbf{f}(\mathbf{x}, y_\lambda) - [\mathbf{u}^0 + r \mathbf{w}(\phi)] = \mathbf{0} \quad (\text{A.4.6})$$

Equation (A.4.6) defines the same power balance relationship as (A.4.1). The only difference between these two equations is that net-import vector $\mathbf{P}_I$ is represented by its polar form in (A.4.6). During the outage of the line, y_λ varies from its base case value to zero. The value of y_λ is zero after contingency. Therefore, the contingency parameter y_λ is considered to be constant, for example, when a fixed contingency is considered, one can neglect y_λ from (A.4.6) to get:

$$\mathbf{F}(\mathbf{x}, r, \phi) = \mathbf{f}(\mathbf{x}) - [\mathbf{u}^0 + r \mathbf{w}(\phi)] = \mathbf{0} \quad (\text{A.4.7})$$

It is clear from (A.4.7) that this set of equations represent the problem of studying the dependence of the solutions of a nonlinear system on two parameters, i.e., r and ϕ . When the radial search approach is used to obtain the LFF and security regions, (A.4.7) reduces to an one parameter dependent set of equations at each angular direction $\phi = \phi_i$, for $i = 1, 2, \dots, m$.

$$\mathbf{F}(\mathbf{x}, r) = \mathbf{f}(\mathbf{x}) - [\mathbf{u}^0 + r \mathbf{w}(\phi_i)] = \mathbf{0} \quad (\text{A.4.8})$$

Equation (A.4.8) is a non-linear equation depending on one parameter, r ,

In the next section, radial search method used to compute LFF and security region boundary is explained.

A.5 RADIAL SEARCH METHOD

The radial search approach has been presented to compute the boundary of the LFF region R_f in [Wu&Fischl 93]. The regularization method [Kataoka 91] is the main tool in the radial search method. This search method performs outward radial search starting from base case import point, $\mathbf{P}_I^O$, in a set of directions defined by the angles $\{\phi_i\}$ to obtain the boundary point of the LFF region (denoted by r^*). The scalar parameter r^* represent the maximum values of r which satisfies equation (A.4.4). The set of operation points $\{\mathbf{P}_I^{(i)} \mid i = 1, 2, \dots, m\}$ indicates the boundary points of LFF region in Figure A-2, where m represents the total number of search directions. Since the method is based on radial search any operation point $\mathbf{P}_I$ in the MW net-import space can be represented by its polar coordinates (r, ϕ) around base case operation point $\mathbf{P}_I^O$:

$$\mathbf{P}_I^{(i)} = [\mathbf{P}_I^A \ \mathbf{P}_I^B]^T = \mathbf{P}_I^O + r_i [\sin\phi_i \ \cos\phi_i]^T \quad (\text{A.5.1})$$

where $\mathbf{P}_I^O = [\mathbf{P}_I^{A0} \ \mathbf{P}_I^{B0}]^T$ is the base imports vector. The radius r is increased along the each search direction until the maximum value of it is obtained to compute the LFF boundary point. In order to get the security region boundaries, r is increased until any of the operations constraints defined in Chapter I, Section 1.2 are reached at each direction. The boundary points $\mathbf{P}_I^{(i)}$ are then joined to construct an approximation of the regions in the MW net-import space as shown in Figure A-2.

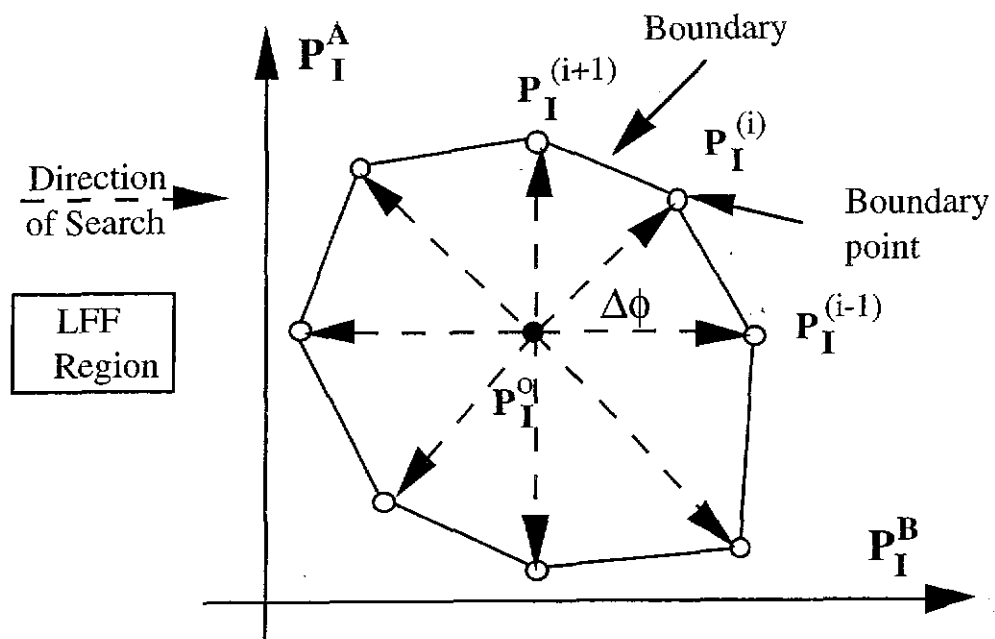


Figure A-2 The illustration of radial-search method used to identify the LFF and security regions in the MW net-import space, P_I -space

APPENDIX B
SOFTWARE DOCUMENTATION

APPENDIX B

SOFTWARE DOCUMENTATION

The software consists of three major components: Database Application Programs (DBApps) and the LFF Analysis Programs (LFFAP) and the Security Region Boundary (SRB) computation Program. The data flow is shown in Figure B-1 and it should be noted that the present version uses 2 computers: The IBM RISC 6000 performs all the computation while the Macintosh contains the input and output data and performs the boundary computation (using Foxpro and Excel) and plotting the region (using KaleidaGraph). The DBApps and LFF simulator which were developed by Wu [5] are implemented using Microsoft FoxPro 2.5 on the Macintosh and ANSI C programming language on the IBM RISC 6000, respectively. The DBApps consist of two functional modules: the project manager and the data processor. The project manager keeps track of the simulation projects. The data processor processes the output data generated by the LFF simulator to produce reports and plots. The LFFAP is designed so that the coupling between the DBApps and the LFF simulator is kept at minimum. The reason for doing so is that the LFF simulator often has to be executed on a machine where FoxPro is not available, for example, a UNIX station, for its heavy computational requirement. In this case, the output files are transferred to the Macintosh or PC where FoxPro is available via ftp (File Transfer Protocol). Although the DBApps and the LFF simulator can be executed independently, they work together to provide users with an efficient and convenient tool for performing LFF analysis.

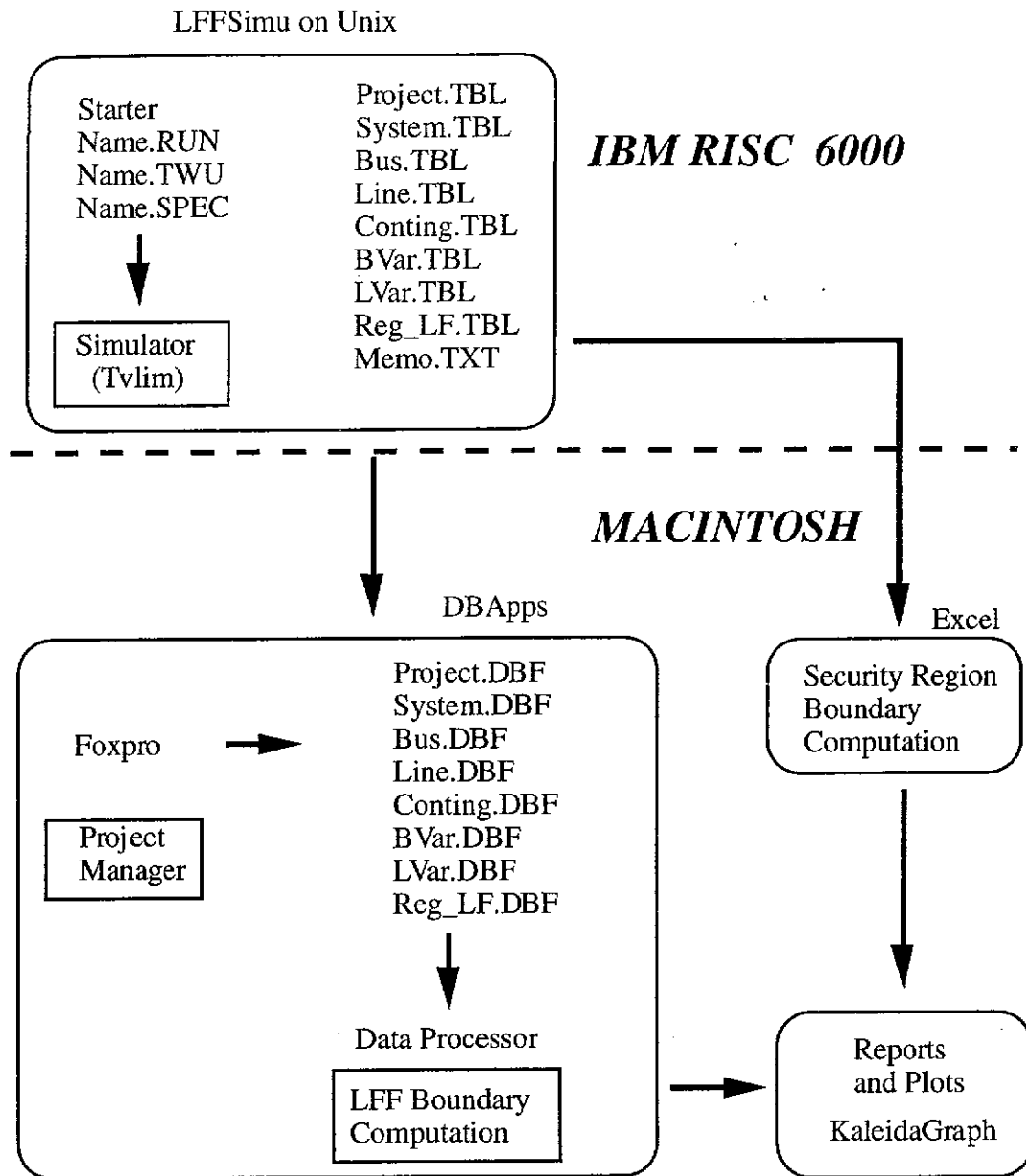


Figure B-1 Illustration of data flow of the software

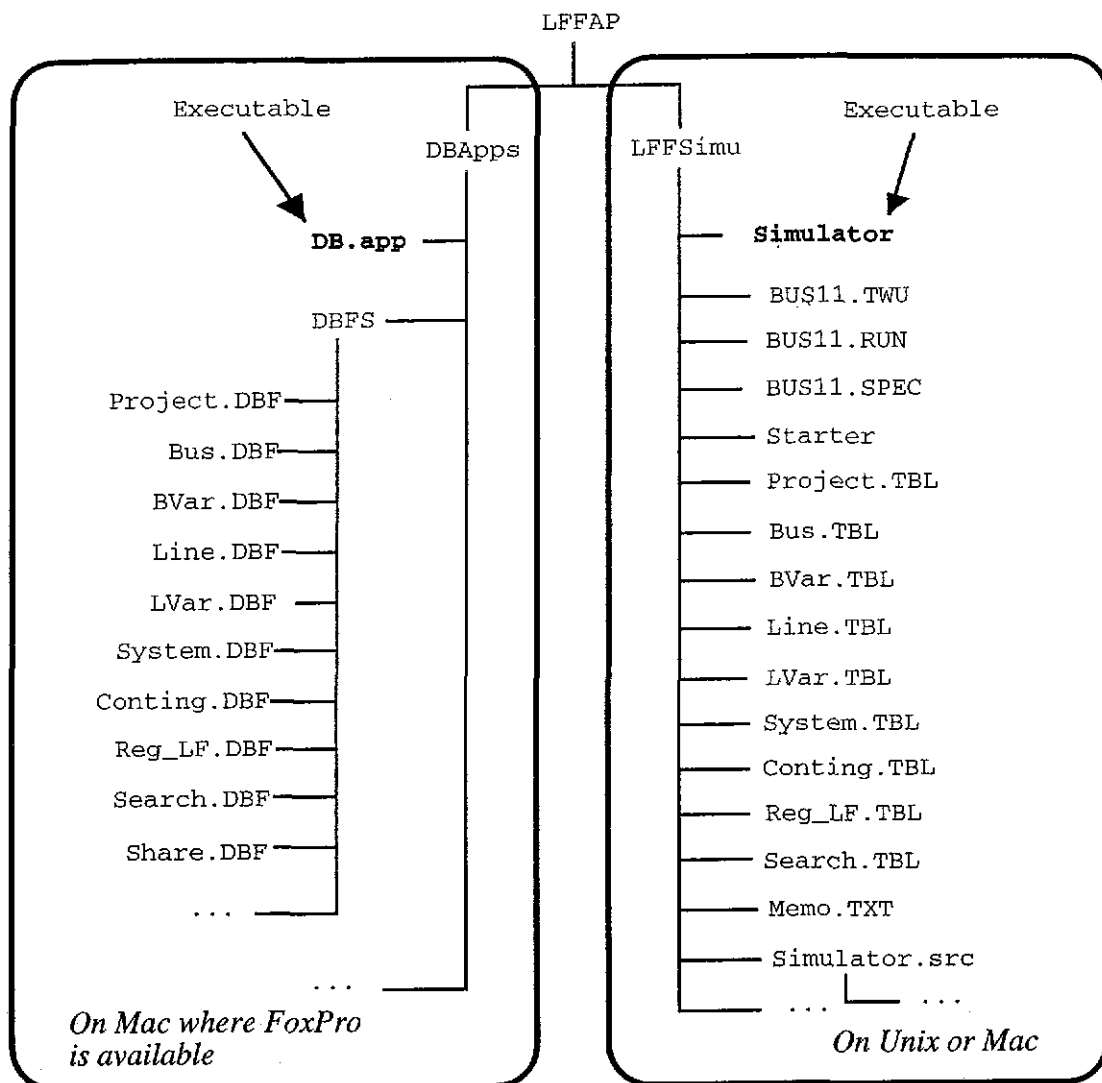


Figure B-2 File organization of the LFFAP package

As illustrated in Figure B-2, the LFFAP package is stored in a folder named "LFFAP" which is the root of the tree in Figure B-2. In "LFFAP" folder, the DBApps and the LFF simulator are stored in the two folders named "DBApps" and "LFFSimu", respectively. Under "DBApps", the file named "DB.app" is the executable FoxPro application file. Under "DBFS" stored are the DBF files used by the project manager and the data processor. The other folders under "DBApps", which are not shown explicitly in Figure B-2, contain the FoxPro programs and other objects that are necessary for building

"DB.app". Under "LFFSimu", the file named "Simulator" is the executable file that performs the LFF computation. "Simulator.src" is the folder where the C source codes are saved. The other files in Figure B-2 under "LFFSimu" are the input and output files used by the LFF simulator. Information about the files under DBApps and LFFSimu and user guides in greater detail were provided in Appendix D of [5].

As mentioned in [5], the LFF simulator reads input data from four input files: Starter, "*.RUN", "*.TWU" and "*.SPEC". Then it generates ten output files: "Project.TBL", "System.TBL", "Bus.TBL", "Line.TBL", "Conting.TBL", "BVar.TBL", "LVar.TBL", "Reg_LF", "Search.TBL" and "Memo.TXT". For our Security Region Boundary calculations, we use these "TBL" files. All the "TBL" files are transferred to Macintosh where Excel is available via ftp (File Transfer Protocol). Among those output files, three of them, "BVar.TBL", "Reg_LF" and "LVar.TBL", are the ones used to obtain security region boundary points. "BVar.TBL" contains output data of voltage magnitude (VM), voltage phase angle (VP), real power injection (P) and reactive power injection (Q) of each bus in the system while "LVar.TBL" contains output data of real power flow (PIJ), reactive power flow (QIJ) of each transmission line in the system after load flow computations. Using sort and filter commands in Excel, voltage magnitude and real power flow data have been searched to obtain the boundary points which satisfy the voltage and thermal constraints. Once the boundary points are obtained in all search directions, Kaleidagraph graphic program is used to plot the regions.

APPENDIX C

THE 3-AREA 31-BUS POWER SYSTEM DIAGRAM AND DATA

APPENDIX C

THE 3-AREA 31-BUS POWER SYSTEM DIAGRAM AND DATA

THE 31-BUS POWER SYSTEM DIAGRAM AND DATA

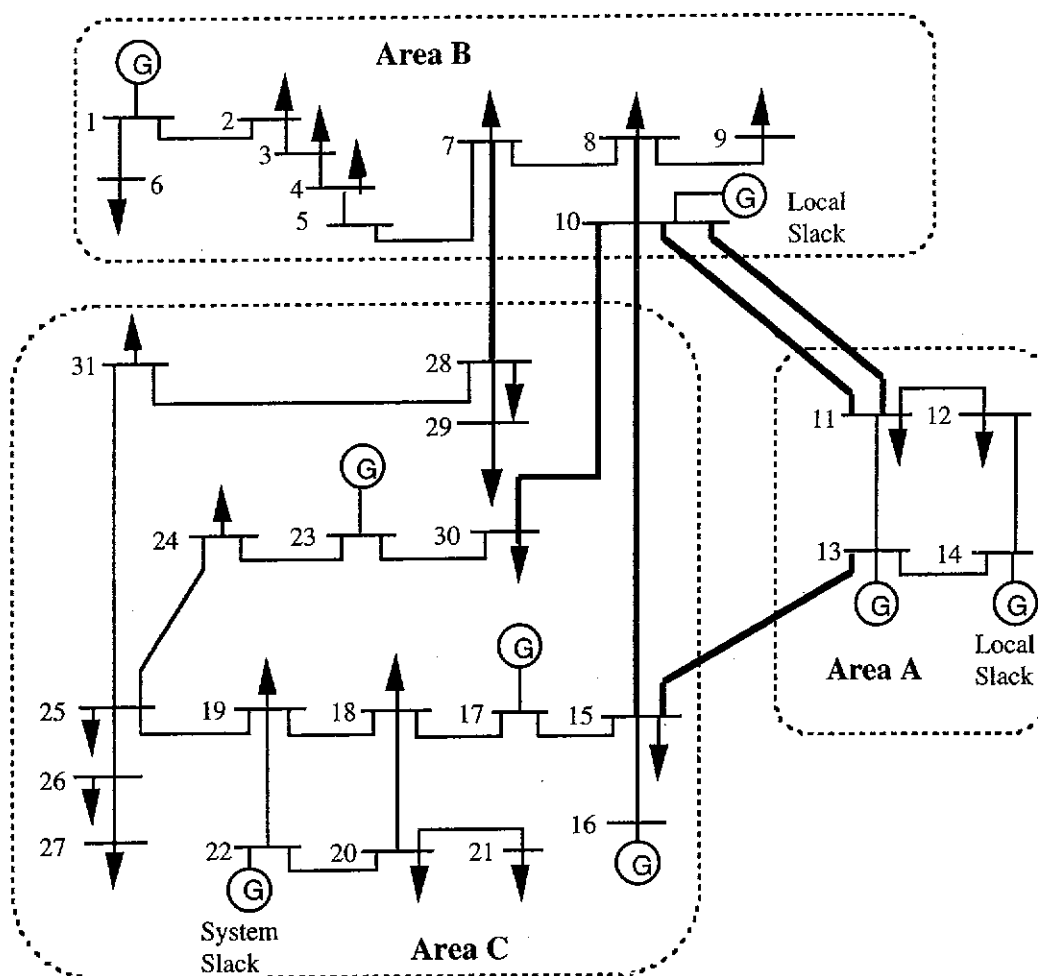


Figure C-1 The 31-Bus System Diagram

Table C-1 Initial Inter-area Imports of Real Power

Area	Imports (p.u.)
A	$P_I^A = 0.0$
B	$P_I^B = 0.0$
C	$P_I^C = 0.0$

Table C-2 Generation Participation Factors

Bus Number	Area	GF
1	B	0.00
13	A	1.00
16	C	0.32
17	C	0.52
23	C	0.16

Table C-3 Bus data of the 31-bus system

Bus	Area	Bus Type [†]	V (p.u.)	P (p.u.)	Q(p.u.)
1	B	2	1.0000	0.5400	
2	B	1		-0.1900	-0.1000
3	B	1		0.0000	0.0000
4	B	1		-0.2800	-0.0200
5	B	1		0.0000	0.0000
6	B	1		0.0000	0.0000
7	B	1		-0.0300	-0.0200
8	B	1		0.0000	0.0000
9	B	1		-0.0300	-0.0200
10	B	4	1.0300		
11	A	1		-0.1900	0.0000
12	A	1		-0.3100	-0.1300
13	A	2	1.0000	0.5000	
14	A	4	1.0000		
15	C	1	1.0300	0.0000	0.0000
16	C	2	1.0300	0.6500	
17	C	2	1.0300	1.0500	
18	C	1		0.0000	0.0000
19	C	1		0.0000	0.0000
20	C	1		-0.0900	-0.0300
21	C	1		0.0000	-0.0700
22	C	3	1.0000		
23	C	2	1.0300	0.0000	
24	C	1		0.0000	0.0000
25	C	1		0.0000	0.0000
26	C	1		0.0000	0.0000

[†] 1-PQ, 2-PV, 3-Slack, 4-Local Slack

27	C	1		-0.4300	-0.1100
28	C	1		0.0000	0.0000
29	C	1		-0.0700	-0.0700
30	C	1		0.0000	0.0000
31	C	1		0.0000	0.0000

Table C - 4 Line data of the 31-bus system

Line	From	To	R (p.u.)	X (p.u.)	Charge (p.u.)	Thermal Limits (p.u.)
1	1	2	0.000	0.017	0.000	1.000
2	1	6	0.016	0.047	0.020	0.500
3	2	3	0.000	0.023	0.000	0.500
4	3	4	0.051	0.096	0.000	0.500
5	4	5	0.019	0.037	0.000	0.500
6	5	7	0.020	0.038	0.006	0.500
7	7	8	0.004	0.014	0.000	1.000
8	7	28	0.089	0.169	0.000	1.000
9	8	9	0.000	0.535	0.000	0.500
10	8	10	0.003	0.103	0.000	1.000
11	10	11	0.022	0.138	0.005	5.000
12	10	15	0.013	0.039	0.116	5.000
13	10	30	0.021	0.041	0.000	1.000
14	11	12	0.008	0.196	0.000	1.000
15	11	13	0.009	0.054	0.008	5.000
16	13	14	0.007	0.193	0.000	5.000
17	15	16	0.004	0.120	0.000	5.000
18	15	17	0.003	0.081	0.000	5.000
19	18	17	0.012	0.120	0.000	5.000
20	18	19	0.052	0.084	0.000	1.000
21	18	20	0.115	0.186	0.000	1.000
22	19	22	0.121	0.199	0.000	2.000
23	19	25	0.043	0.083	0.000	2.000
24	20	21	0.000	0.235	0.000	0.000
25	20	22	0.100	0.174	0.000	1.000
26	23	24	0.000	0.132	0.000	1.000
27	23	30	0.032	0.316	0.000	1.000
28	24	25	0.012	0.021	0.002	1.000
29	25	26	0.006	0.011	0.000	0.500
30	25	31	0.035	0.034	0.000	1.000
31	26	27	0.048	0.092	0.000	0.050
32	28	29	0.001	0.170	0.000	0.100
33	28	31	0.031	0.058	0.000	1.000
34	13	15	0.011	0.069	0.010	5.000
35	12	16	0.009	0.054	0.008	5.000
36	10	11	0.022	0.138	0.005	5.000

APPENDIX D
LIST OF SYMBOLS

APPENDIX D

LIST OF SYMBOLS

General Conventions

1. Subscripts

A	Variable associated with area A
AB	Variable associated with area A and B
AC	Variable associated with area A and C
B	Variable associated with area B
BC	Variable associated with area B and C
C	Variable associated with area C
d	Variable associated with a load (PQ) bus
g	Variable associated with a generator (PV) bus
I	Variable associated with inter-area imports
p	Variable associated with a pilot bus
T	Variable associated with inter-area transfers
ℓ	Variable associated with a transmission line

2. Superscripts

A	Variable associated with area A
B	Variable associated with area B
C	Variable associated with area C
L	denotes the lower limit on a variable
M	denotes the limiting value on a variable
0	denotes the base case value of a variable
U	denotes the upper limit on a variable
λ	variable associated with contingency λ

3. All variables in **bold** area matrices, vectors or regions

<u>Symbol</u>	<u>Description</u>	<u>Section First Introduced</u>
α_{gi}	Generation participation factor for the i -th generator in area A	Section A.1
b_{ik}	Imaginary part of the series admittance of the line connecting buses i and k	Section 1.3
B_{ik}	Imaginary part of the (i, k) -th element of the bus admittance matrix, $[Y_{BUS}]$	Section 1.2.2
C_λ	λ -th contingency of a facility outage	Section 1.2.2
$(D_x F)$	Derivative of the vector function F with respect to vector x , Jacobian matrix	Section 2.3.1
e_{2p}	A column vector, $(e_{2p})^T = [0 \ 0 \ \dots \ 0 \ 1 \ 0 \ \dots \ 0]$, where only the $2p$ -th element is nonzero.	Section 2.3.1
f	Bus injection as a function of voltage profiles	Section 1.2.2
f^λ	Bus injection as a function of voltage profiles and the magnitude of admittance of line λ	Section 1.3
F	Conventional load flow equation with one parameter, r	Section 1.2.3
F^λ	Conventional load flow equation with two parameters, r and y_λ	Section 1.2.3
ϕ	The angular direction of search.	Section 1.3
g_{ik}	Real part of the series admittance of the line connecting buses i and k	Section 1.2.2
g	Regularization function used in the regularization method.	Section 2.3.1
G_{ik}	Real part of the (i, k) -th element of the bus admittance matrix, $[Y_{BUS}]$	Section 1.3
I_A	The set of all indices of buses in area A	Section 1.3
I_B	The set of all indices of buses in area B	Section 1.3
I_C	The set of all indices of buses in area C	Section 1.3
k	An alternative parameter used in continuation methods and regularization method.	Section 2.3.1

k^*	The boundary value of k which yields the maximum value of r .	Section 2.3.1
λ	Line outage contingency identification number	Section 1.2.2
m	The total number of LFF or security region boundary points found by the radial search	Section A.3
n	The total number of buses in a power system	Section 1.3
n_c	The total number of prescribed contingencies	Section 1.2.3
n_d	The total number of load buses in a power system	Section 1.2.3
n_g	The total number of generator buses in a power system	Section 1.2.3
n_l	The total number of lines in a power system	Section 1.2.3
P_{AB}	The inter-area transfer of real power from area A to B	Section 1.2.1
P_{AC}	The inter-area transfer of real power from area A to C	Section 1.2.1
P_I^A	The net import of real power into area A	Section 1.2.1
ΔP_{gi}^A	The generation change at the i -th generator in area A	Section A.3
P_{BC}	The inter-area transfer of real power from area B to C	Section 1.2.1
P_I^B	The net import of real power into area B	Section 1.2.1
P_I^C	The net import of real power into area C	Section 1.2.1
P_i	The net real power injection at bus i	Section 1.2.2
$\mathbf{P}_I$	The inter-area MW net-import space defined by $\mathbf{P}_I = [P_I^A \ P_I^B]^T$	Section 1.2.1
$P_{ij}(C_\lambda)$	Post contingency real power flow across the line ij due to C_λ	Section 1.2.2
$\mathbf{P}_I^\circ$	The base import point in the $\mathbf{P}_I^\circ$ space, where the radial search starts	Section 1.4
$\mathbf{P}_I^{(i)}$	The i -th LFF boundary point found by radial search	Section A.3

$\mathbf{P}_T$	The inter-area MW transfer space defined by $\mathbf{P}_T = [\mathbf{P}_{AB} \ \mathbf{P}_I^B]^T$	Section 1.2.1
Q_i	The net reactive power injection at bus i	Section 1.2.2
r	Radial distance from the base import point, $\mathbf{P}_I^\circ$, to any point in the $\mathbf{P}_I$ space along a given direction.	Section 1.3
r^*	Radial distance from the base import point, $\mathbf{P}_I^\circ$, to a LFF boundary point along a given direction.	Section 2.3.1
r_0	Initial value of r for starting the continuation process; usually $r_0 = 0$.	Section 2.3.1
$\mathbf{R}_{FI}$	Base case Load Flow Feasibility (LFF) region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{FI}^{(\lambda)}$	Next contingency LFF region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{TI}$	Base case thermal security region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{TI}^{(\lambda)}$	Next contingency thermal security region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{VI}$	Base case voltage security region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{VI}^{(\lambda)}$	Next contingency voltage security region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{\Delta VI}^{(\lambda)}$	Next contingency voltage drop (ΔV) limit region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{BCI}$	Base case ATC region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{NCI}^{(\lambda)}$	Next contingency ATC region in the MW net-import space, $\mathbf{P}_I$ -space	Section 1.2.3
$\mathbf{R}_{FT}$	Base case LFF region in the MW transfer space, $\mathbf{P}_T$ -space	Section 1.2.3
$\mathbf{R}_{FT}^{(\lambda)}$	Next contingency LFF region in the MW transfer space, $\mathbf{P}_T$ -space	Section 1.2.3

R_{TT}	Base case thermal security region in the MW transfer space, P_T -space	Section 1.2.3
$R_{TT}^{(\lambda)}$	Next contingency thermal security region in the MW transfer space, P_T -space	Section 1.2.3
R_{VT}	Base case voltage security region in the MW transfer space, P_T -space	Section 1.2.3
$R_{VT}^{(\lambda)}$	Next Contingency voltage security region in the MW transfer space, P_T -space	Section 1.2.3
$R_{\Delta VT}^{(\lambda)}$	Next contingency voltage drop limit (ΔV) region in the MW transfer space, P_T -space	Section 1.2.3
R_{BCT}	Base case ATC region in the MW transfer space, P_T -space	Section 1.2.3
$R_{NCT}^{(\lambda)}$	Next contingency ATC region in the MW transfer space, P_T -space	Section 1.2.3
θ_i	Voltage phase angle at bus i	Section 1.2.2
u	The bus injection vector that contains real and reactive power bus injections and the prescribed inter area real power imports	Section 1.2.2
u^o	The bus injection vector when $P_I = P_I^o$.	Section 1.3
v	The right eigenvector associated with the eigenvalue at origin	Section 2.3.1
V_i	Voltage magnitude at bus i	Section 1.2.2
V_p	Voltage magnitude at the pilot bus	Section 2.3.1
$w(\phi)$	A column vector dictated by the Generation Participation factors and the direction of search	Section 1.3
W	A constant matrix, $W \in R^{n \times 2}$, comprised of Generation Participation Factors	Section A.3
x	A column vector whose components are magnitudes and phase angles of bus voltage	Section 1.2.2
x^*	Bus voltage vector, x , evaluated at the LFF boundary point	Section 2.3.1

$\mathbf{x}_0$	Bus voltage vector, $\mathbf{x}$, evaluated at the base-import point, the starting point on the continuation path	Section 2.3.1
y_λ	Magnitude of the line admittance related to contingency λ .	Section 1.3

$\mathbf{x}_0$	Bus voltage vector, $\mathbf{x}$, evaluated at the base-import point, the starting point on the continuation path	Section 2.3.1
y_λ	Magnitude of the line admittance related to contingency λ .	Section 1.3