ONLINE POWER SYSTEM SECURITY CLASSIFIER

AND ENHANCEMENT CONTROL

by

María Paloma de Arízón

Elec. Eng (Hons.), Universidad Simón Bolívar, Venezuela 1981
M. A. Sc., The University of British Columbia, 1984

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES

(Department of Electrical and Computer Engineering)

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

February, 2000

© María Paloma de Arízón, 2000
In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Electrical and Computer Engineering

The University of British Columbia
Vancouver, Canada

February 25, 2000
ABSTRACT

Today, the stable and reliable operation of power systems is becoming increasingly difficult. While, on the one hand, due to regulatory reforms, an increasing number of merchant plants and co-generators are being connected to the network, on the other, the expansion of transmission systems has been increasingly difficult due to environmental and land issues. As a result, thousands of power flow schedules are changed hourly, complicating the systems operation. This scenario has rendered the traditional system operation criteria, based on off-line studies, inadequate to cope with the constantly changing nature, and online assessment techniques are becoming increasingly important.

In this work, an approach based on “approximate reasoning techniques” is presented for the classification of dynamic security conditions in the power system and for the selection of dynamic security enhancement strategies (preventive control actions). The algorithm proposed combines energy functions and sensitivities to find the “membership” of the system to the subsets that determine its security status, as well as, the “membership” of the different generators to specific control related subsets. The algorithm proposed combines energy functions and sensitivities, together with physical equipment limitations, to select the generators voltage and power output such that the required security level is met.

The procedure uses optimisation methods for tuning the threshold values that describe the membership functions in order to obtain optimum preventive control strategies. The developed procedure was also designed to produce a simultaneous preventive control for a set of non-disjoint contingencies.

Finally to enhance the speed of the algorithm a new and time-saving technique for efficient \([Y_{bus}]\) matrix evaluations was developed in this work.

The results presented in the work show that the proposed method achieves the following objectives:
a) A fast and accurate classification of the system security conditions.

b) A classification that is flexible enough to allow the inclusion of other important parameters.

c) The development of a stability enhancement strategy that produces a system that is secure for a wide range of credible contingencies.

d) The development of a method that combines “firm” knowledge based on analytical solutions with “soft” expert system knowledge.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xv</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xx</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER I: INTRODUCTION</td>
<td>7</td>
</tr>
<tr>
<td>CHAPTER II: FRAMEWORK FOR ADAPTIVE FUZZY-LOGIC BASED ONLINE SECURITY ANALYSIS AND CONTROL (SAC)</td>
<td>12</td>
</tr>
<tr>
<td>2.1 Basic Definitions</td>
<td>12</td>
</tr>
<tr>
<td>2.2 Online Dynamic Security Analysis</td>
<td>14</td>
</tr>
<tr>
<td>2.3 Framework for Fuzzy Security Classifier and Preventive Control</td>
<td>15</td>
</tr>
<tr>
<td>CHAPTER III: EXPANDED TWO MACHINE EQUIVALENT SYSTEM</td>
<td>25</td>
</tr>
<tr>
<td>3.1 Two-Machine Equivalent for a Multimachine Power System</td>
<td>26</td>
</tr>
<tr>
<td>3.1.1 Two-Machine System</td>
<td>26</td>
</tr>
<tr>
<td>3.1.2 Definition of Energy Margin Using Lyapunov Solution Method</td>
<td>29</td>
</tr>
<tr>
<td>3.1.3 Two-Machine Equivalent for a Multimachine Network</td>
<td>31</td>
</tr>
<tr>
<td>3.1.4 Mode of Disturbance Evaluation</td>
<td>35</td>
</tr>
<tr>
<td>3.1.5 Analytical Sensitivity Development</td>
<td>35</td>
</tr>
<tr>
<td>3.2 Sensitivity Analysis and System Vulnerability Concepts</td>
<td>38</td>
</tr>
</tbody>
</table>
CHAPTER IV: SECURITY CLASSIFIER

4.1 Framework for Security and Vulnerability Assessment

4.1.1 Evaluation of the Threshold and Unacceptable Values

4.2 Definition of Performance Criterion

4.3 Defuzzification Procedure for the Security Classifier

4.3.1 Centre-of-Sums for Security Classifier Index

CHAPTER V: ADAPTIVE-FUZZY-LOGIC-BASED SECURITY ENHANCEMENT CONTROL

5.1 Output Adjustment by Approximate Reasoning

5.2 Membership Function Definition for Security Enhancement Evaluations

5.3 Security Enhancement Based on Approximate Reasoning

5.4 Adaptive Fuzzy Logic Controller

5.4.1 Adaptation Mechanism

5.5 Iterative Control Procedures

5.6 Adaptive Fuzzy Control Design for Security Evaluation

5.6.1 Optimization Procedure

5.6.2 Method of Steepest Descent

5.6.3 Conjugate Method

5.7 Step-by-Step Adaptation Procedure
CHAPTER VI: SIMULTANEOUS PREVENTIVE CONTROL............................ 78

6.1 Block Diagram of the Proposed Preventive Control Algorithm.............. 79

6.2 Mathematical Demonstration............................................. 83

6.3 Efficient $[Y_{bus}]$ Matrix Evaluation................................... 89

6.4 Pre-Processing of the $[Y_{bus}]$ Matrix............................... 90
   6.4.1 Evaluation of Pre-Fault, Fault and Post-Fault Matrices............... 90
   6.4.2 Algorithm for Security Analysis Using Pre-Processed Matrices...... 95
   6.4.3 Off-line Procedure.................................................. 95
   6.4.4 Online Process...................................................... 96

CHAPTER VII: RESULTS......................................................... 98

7.1 Three-Generator System.................................................. 101
   7.1.1 Calculation of the Critical Clearing Time Using the
         Two-Equivalent System.............................................. 102
   7.1.2 Three-Generator Security Classifier................................ 103
   7.1.3 Three-Generator Security Enhancement Control....................... 111
      7.1.3.1 Surf and contour diagrams...................................... 111
      7.1.3.2 Security enhancement control- without adaptive control........ 115
      7.1.3.3 Close-loop security enhancement control - without scaling..... 117
   7.1.4 Adaptive Security Enhancement Control - With Scaling............. 119
   7.1.5 Adaptive Voltage and Power Control................................ 122
   7.1.6 Adaptive Security Enhancement Control - With Scaling............. 123

7.2 Cigre Test Case.......................................................... 125
   7.2.1 Calculation of the Critical Clearing Time Using the
         Two-Equivalent System.............................................. 125
7.2.2 Cigre System Security Classifier .................................................. 126
7.2.3 Cigre System Security Enhancement Control Open
    Loop Output .................................................................................. 128
7.2.4 Cigre System Closed-Loop Security Enhancement Control - Without
    Adaptive Control ........................................................................... 131
7.2.5 Cigre System Security Enhancement Control - With
    Adaptive Control ........................................................................... 131
7.2.6 Cigre System Power-Voltage Control Loop ................................... 133
7.2.7 Cigre System - Simultaneous Preventive Control .......................... 134
7.3 Iowa - Test Case ........................................................................... 134
  7.3.1 Calculation of the Critical Clearing Time Using the
       Two-Equivalent System ............................................................... 135
7.3.2 Iowa System Security Classifier .................................................. 136
7.3.3 Iowa System Closed-Loop Security Enhancement Control-
       Without Adaptive Control ......................................................... 137
7.3.4 Iowa System Closed-Loop Security Enhancement Control-
       With Adaptive Control and Gradient Search Techniques .......... 139
7.3.5 Iowa System Security Enhancement Control-
       With Adaptive Control and Conjugate-Gradient Search Techniques 141
7.3.6 Iowa System - Power and Voltage Control ................................... 144
7.3.7 Iowa System - Simultaneous Preventive Control .......................... 145
7.4 Efficient $[Y_{bus}]$ Matrix Evaluation – Results ............................. 147

CHAPTER VIII: CONCLUSIONS AND RECOMMENDATIONS
FOR FURTHER WORK ........................................................................... 151

CHAPTER IX: REFERENCES .................................................................... 157
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 4.1</td>
<td>Security Classifier Matrix</td>
<td>50</td>
</tr>
<tr>
<td>Table 7.1</td>
<td>Three-Generator System Data</td>
<td>102</td>
</tr>
<tr>
<td>Table 7.2</td>
<td>Three-Generator System Critical Clearing Time</td>
<td>102</td>
</tr>
<tr>
<td>Table 7.3</td>
<td>Three-Generator System Energy Margin vs. Clearing Time</td>
<td>103</td>
</tr>
<tr>
<td>Table 7.4</td>
<td>Variation of Energy Margin Index with Equivalent Power</td>
<td>105</td>
</tr>
<tr>
<td>Table 7.5</td>
<td>Sensitivity to Equivalent Power - Faults 7-5, 9-6 and 4-5</td>
<td>108</td>
</tr>
<tr>
<td>Table 7.6</td>
<td>Threshold Values Evaluation Three-Generator Case</td>
<td>109</td>
</tr>
<tr>
<td>Table 7.7</td>
<td>Security Index and Security Vector for Different Contingencies Three-Generator Case tcl=0.2 s</td>
<td>110</td>
</tr>
<tr>
<td>Table 7.8</td>
<td>Security Index for Different Load Scenarios Three-Generator Case</td>
<td>110</td>
</tr>
<tr>
<td>Table 7.9</td>
<td>Open Loop Security Enhancement Control Three-Generator Case High Threshold Values</td>
<td>116</td>
</tr>
<tr>
<td>Table 7.10</td>
<td>Open Loop Security Enhancement Control Three-Generator Case Medium Threshold Values</td>
<td>116</td>
</tr>
<tr>
<td>Table 7.11</td>
<td>Open Loop Security Enhancement Control Three-Generator Case Small Threshold Values</td>
<td>117</td>
</tr>
<tr>
<td>Table 7.12</td>
<td>Closed-Loop Security Enhancement Control w/o Scaling Three-Generator Case</td>
<td>118</td>
</tr>
<tr>
<td>Table 7.13</td>
<td>Closed-Loop Security Enhancement Control with Scaling Three-Generator Case</td>
<td>119</td>
</tr>
<tr>
<td>Table 7.14</td>
<td>Closed-Loop Security Enhancement Control w/o Scaling Three-Generator Case</td>
<td>122</td>
</tr>
</tbody>
</table>
Table 7.15 Closed-Loop Security Enhancement Control with Scaling Three-Generator Case .................................................. 123

Table 7.16 Cigre's System Critical Clearing Time ................................................................. 126

Table 7.17 Threshold Values Evaluation $t_{cl}$ =0.39 s ......................................................... 126

Table 7.18 Security Index and Security Vector Cigre Case $t_{cl}$=0.39 s ................................. 127

Table 7.19 Security Index for Different Load Scenarios Cigre Case ...................................... 128

Table 7.20 Open Loop Security Enhancement Control Cigre Test Case High Threshold Values Fault 3-9 .................................................. 129

Table 7.21 Open Loop Security Enhancement Control Cigre Test Case Medium Threshold Values Fault 3-9 .................................................. 129

Table 7.22 Open Loop Security Enhancement Control Cigre Test Case Small Threshold Values Fault 3-9 .................................................. 130

Table 7.23 Closed-Loop Security Enhancement Control w/o Scaling Cigre Test Case .............................. 131

Table 7.24 Closed-Loop Security Enhancement Control with Scaling Cigre Test Case .............................. 132

Table 7.25 Closed-Loop Security Enhancement power and Voltage Control Cigre Test Case .............................. 133

Table 7.26 Simultaneous Preventive Control Power Control Cigre Test Case .............................. 134

Table 7.27 Iowa’s System Critical Clearing Time ................................................................. 135

Table 7.28 Data for Threshold Values Evaluation $t_{cl}$ =0.26 s .................................................. 137

Table 7.29 Iterative Procedure w/o Optimization High Threshold values .................................. 138

Table 7.30 Iterative Procedure w/o Optimization Small Threshold values .................................. 138

Table 7.31 Iterative Procedure with Optimization (Gradient) High Threshold Values .................. 139
Table 7.32 Iterative Procedure with Optimization (Gradient)
   Medium Threshold Values.................................................. 140

Table 7.33 Iterative Procedure with Optimization (Gradient)
   Small Threshold Values.................................................... 141

Table 7.34 Iterative Procedure with Optimization (Conjugate Method)
   High Threshold values..................................................... 142

Table 7.35 Iowa Case Power and Voltage Control.................................. 144

Table 7.36 Iowa Case Simultaneous Preventive Control.............................. 145

Table 7.37 Relation Between Times Involved on the Creation of the
   \([Y_{bus}]\) Matrix .................................................................. 149

Table 7.38 Simulation Results.......................................................... 149
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Major Components of Online Security Analysis</td>
<td>15</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Block Diagram of the SAC system</td>
<td>17</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Security Assessment Block</td>
<td>18</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Adaptive Security Enhancement Block</td>
<td>22</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Simultaneous Evaluation Block</td>
<td>23</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Two-Machine Electric System</td>
<td>27</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Membership Functions for the Security Classifier</td>
<td>46</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Thresholds Values Evaluation</td>
<td>47</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Security Index Membership Function</td>
<td>53</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Defuzzification Security Index</td>
<td>54</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Independent Centre-of-Sums Calculation</td>
<td>55</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Membership Functions for the Fuzzy Logic Control</td>
<td>64</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Adaptive Process Block Diagram</td>
<td>68</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Effect of Altering Scaling Factor</td>
<td>69</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Iterative Non-Adaptive Procedure</td>
<td>70</td>
</tr>
<tr>
<td>Figure 5.5</td>
<td>Sequential Power and Voltage Control</td>
<td>77</td>
</tr>
<tr>
<td>Figure 6.1</td>
<td>Simultaneous Preventive Control Block Diagram</td>
<td>82</td>
</tr>
<tr>
<td>Figure 6.2</td>
<td>Pointer Access for $[A_{ik}]$ Matrix Information</td>
<td>91</td>
</tr>
<tr>
<td>Figure 6.3</td>
<td>Pre-Order nxn Matrix</td>
<td>91</td>
</tr>
<tr>
<td>Figure 6.4</td>
<td>Pre-Process Store Tridimensional Matrices</td>
<td>94</td>
</tr>
<tr>
<td>Figure 6.5</td>
<td>Block Diagram of the Off-line Array Creation Process</td>
<td>96</td>
</tr>
</tbody>
</table>
Figure 6.6: Block Diagram for the Final Processing of the $[Y_{matrix}]$ ................................. 97

Figure 7.1: Three-Generator System................................................................................. 101

Figure 7.2: Energy Margin vs. Equivalent Power - Fault 7-5........................................ 106

Figure 7.3: Energy Margin vs. Equivalent Power - Fault 9-6........................................ 106

Figure 7.4: Energy Margin vs. Equivalent Power - Fault 4-5........................................ 107

Figure 7.5: Energy Margin vs. Equivalent Power - Faults 7-5, 9-6 and 4-5....................... 107

Figure 7.6: Surf Diagram - Fault line 7-5................................................................. 112

Figure 7.7: Surf Diagram - Fault 9-6................................................................. 112

Figure 7.8: Surf Diagram - Fault 4-5................................................................. 113

Figure 7.9: Contour Diagram - Fault 7-5................................................................. 113

Figure 7.10: Contour Diagram - Fault 9-6................................................................. 114

Figure 7.11: Contour Diagram - Fault 4-5................................................................. 114

Figure 7.12: Closed-Loop Energy Margin Levels per Iteration...................................... 120

Figure 7.13: Fault Line 7-5 Three-Generator Case Comparison
    of Security Enhancement Control Strategies................................................. 121

Figure 7.15: Fault Line 7-5 Three-Generator Case Comparison
    of Security Enhancement Control Strategies................................................. 124

Figure 7.16: Cigre Test Case......................................................................................... 125

Figure 7.17: Fault Line 3-9 Cigre-Generator Case Comparison
    of Security Enhancement Control Strategies................................................. 132

Figure 7.18: 17-Generator System – Fault cleared at 0.35 s....................................... 136

Figure 7.19: Fault Line 75-9 Iowa Case Comparison of Security Enhancement
    Control Strategies......................................................................................... 143

Figure 7.20: Contour Curve Fault 1............................................................................. 146

Figure 7.21: Contour Curve Fault 4............................................................................. 146

Figure A.1: Reduction to an $n$ Bus System.................................................................. 166
Figure A.2: Region of Attraction and Computation of $tcr$ .................................................. 170
Figure B.1: Classification of Fuzzy Reasoning [75]. .................................................. 181
Figure B.2: Reasoning Process of Mandani's Direct Method ........................................... 182
Figure B.3: Centre of Gravity Defuzzification Method ................................................. 184
Figure B.4: Centre-of-Sums Defuzzification Method .................................................. 185
Figure B.5: Centre-of-Height Defuzzification Method ................................................. 186
Figure B.6: First-of-Maxima Defuzzification Method .................................................. 187
Figure C.1: Steepest - Descent Gradient Method ......................................................... 194
LIST OF SYMBOLS

$COI$ : Centre-of-inertia power system reference

$\theta_i$ : $i^{th}$ machine's angular position with respect to the centre of inertia $COI$

$\omega_i$ : $i^{th}$ machine's angular angular speed deviation with respect to the centre of inertia $COI$

$\theta_{12}$ : Angular difference between machine's 1 and 2

$P_{coi}$ : Centre-of-inertia reference power

$M_i$ : $i^{th}$ machine inertia constant

$Pm_i$ : $i^{th}$ machine mechanical power

$E_i$ : $i^{th}$ machine constant voltage magnitude behind transient reactance

$G_{12}, B_{12}$ : Real and imaginary parts of $(i,j)$ elements of $Y_{bus}$ matrix, reduced to the internal nodes of the synchronous machines

$M_{eq}$ : Equivalent machine inertia

$\theta_{eq}$ : Equivalent machine angular position

$P_{eq}$ : Equivalent power

$V_{cr}$ : Kinetic energy acquired by the equivalent machine during the fault period

$V_{cl}$ : Potential energy of the equivalent (capacity to dissipate the acquired energy)

$\Delta V$ : Energy margin index

$\delta_o$ : System angular reference for $COI$

$G_A$ : Critical generators group

$G_B$ : Non-critical generators' group

$M_A$ : Total inertia of generators' group $A$

$M_B$ : Total inertia of generators' group $B$

$\theta_A$ : Equivalent angle with respect to $COI$ for group $A$
\( \theta_B \): Equivalent angle with respect to COI for group B

\( M_T \): Total inertia

\( P_{acA} \): Equivalent accelerating power for generators' of group A

\( P_{acB} \): Equivalent accelerating power for generators' of group B

\( M_{eq} \): Inertia of the two-machine equivalent model

\( \theta_{eq} \): Angle of the two-machine system equivalent

\( P_{aceq} \): Accelerating power of the two-machine system equivalent

\( \theta_{ij}^o \mid_{pf} \): Post-fault equilibrium point angle between generators \( i \) and \( j \)

\( \theta_{ij}^o \): Pre-fault equilibrium point angle between generators \( i \) and \( j \)

\( \Delta \theta_{AB} \): \( \theta_{AB} - \theta_{AB}^o \) variation of the equivalent angle with respect to the respective equilibrium points (fault or post-fault).

\( \frac{\partial \Delta V}{\partial p} \): Sensitivity of energy margin index with respect to parameter \( p \)

\( \frac{\partial \theta_{ij}^\text{cl}}{\partial p} \): Sensitivity with respect to parameter \( p \) of angle between machine \( i \) and \( j \) at clearance time.

\( \frac{\partial \omega_{ij}^\text{cl}}{\partial p} \): Sensitivity with respect to parameter \( p \) of angular speed between machine \( i \) and \( j \) at clearance time.

\( \frac{\partial \theta_{ij}^0}{\partial p} \): Sensitivity with respect to parameter \( p \) of initial angle between machine \( i \) and \( j \) at clearance time.

\( \Box \Box V \): Energy margin index variation

\( W(k_e,i) \): Kinetic Energy of the rotor of machine \( i \)

\( J_i \): Moment of inertia of machine \( i \)

\( Pd_i \): Damping Power of machine \( i \)

\( Pm_i \): Mechanical power input to the machine \( i \)

\( Pg_i \): Electrical power output of machine \( i \)
\[ Y_{bus} \]: Admittance \( n \times n \) matrix reduced to generator's internal nodes

\( n \): Number of generators

\[ I_A \]: Vector of generators' current injection \( I_i \)

\[ V_A \]: Vector of generators' internal voltages \( E_i \)

\( tcl \): Fault clearing time

\( ccl \): Critical clearing time

\( V(X) \): Lyapunov's function

\( Vcr \): Critical energy

\( HM \): High energy margin level

\( LM \): Low energy margin level

\( UM \): Unacceptable energy margin level

\( PHS \): Positive and high sensitivity

\( PLS \): Positive and low sensitivity

\( NHS \): Negative and high sensitivity

\( NLS \): Negative and low sensitivity

\( \mu_{HM} \): Membership value for high energy margin level

\( \mu_{LM} \): Membership value for low energy margin level

\( \mu_{UM} \): Membership value for unacceptable energy margin level

\( \mu_{PHS} \): Membership value for positive and high sensitivity

\( \mu_{PLS} \): Membership value for positive and low sensitivity

\( \mu_{NHS} \): Membership value for negative and high sensitivity

\( \mu_{NLS} \): Membership value for negative and low sensitivity

\( \Delta V_H \): Threshold value for the high energy margin level
\(\Delta V_{\text{min}}\): Threshold value for the minimum acceptable energy margin level

CS: Completely secure state

IS: Insecure state

AM: Alarm state: for which a preventive control action is required.

AT: Alert state

\(\mu_{\text{AM}}\): Membership value for alarm state

\(\mu_{\text{AT}}\): Membership value for alert state

\(\mu_{\text{CS}}\): Membership value for secure state

\(\mu_{\text{IS}}\): Membership value for insecure state

SI: Security Index

\[S_{\text{PI}} = \frac{\partial \Delta V}{\partial P_t}\]: Sensitivity of energy margin with respect to power output of generator \(i\)

\[S_{\text{EI}} = \frac{\partial \Delta V}{\partial E_i}\]: Sensitivity of energy margin with respect to internal voltage of generator \(i\)

\(P_t\): Power output of generator \(i\)

\(E_i\): Internal voltage of generator \(i\)

\(P_{i\text{-max}}\): Maximum power output of generator \(i\)

\(P_{i\text{-min}}\): Minimum power output of generator \(i\)

\(V_{i\text{-max}}\): Maximum voltage allowed in the external generator bus \(i\)

\(V_{i\text{-min}}\): Minimum voltage allowed in the external generator bus \(i\)

\(M_i\): Adjustable margin of output in “lower direction” generator \(i\)

\(\Delta V_D\): Desire energy margin level

\(\Delta V_o\): Operating point energy margin level

\(WR_i\): Raise weight factor for generator \(i\)

\(WL_i\): Lower weight factor for generator \(i\)
\[ \Delta \text{Error} = \frac{1}{2} \left( \Delta V - \Delta V_D \right)^2 \] : Energy margin error

\( \mu_{ig}(\Delta V) \) : Membership value for the energy margin function of generator \( g \) for rule \( i \)

\( \mu_{ig}(MR) \) : Membership value for the margin control membership function of generator \( g \) for rule \( i \).

\( \mu_{ig}(S_g) \) : Membership value for the sensitivity membership function of generator \( g \) for rule \( i \).

\( t \) : Iterative step (\( t \))

\( H_s \) : Hessian matrix of the error function

\( \lambda_s \) : Step size for the one-dimension quadratic interpolation procedure gradient optimization
ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to all those persons and institutions that helped me accomplish this work. I sincerely regret if I have missed any individuals, so just in case, to all of you thanks! You truly made my job easier.

In particular, I would like to express my deepest gratitude to:

Dr. José Martí, for his invaluable help direction and advice, during these last four years.

Dr. Tak Niimura, for introducing me to the beautiful area of approximate reasoning and its applications to the power area.

Dr. H.W. Dommel, that made my first stay at U.B.C. so memorable, that I was willing to come again thirteen years later to continue my Ph.D. studies.

The actual and old members of the power group, for their help and their ability to share their experience, and knowledge. The special bond we have created makes me feel that we will really keep in touch over the years.

Conicit (Consejo Nacional de Ciencias y Tecnologia) and The Universidad Simon Bolivar, Caracas – Venezuela, for their financial support.

Finally, on a very personal level, I would like to thank my mother, who I hold my deepest love and affection. Her encouragement helped me achieve all my goals, I cherish her love and continuous support, not to mention the three times she flew from Venezuela to Vancouver, just to help me get through.

To my husband, Nelson, for his help in so many aspects of this thesis project (technical discussions, proofreading, among others), I know that it does not sound very romantic, but all the time he gave to me, was a direct proof of his love. Most of all, thank you, for
all the great memories and moments we have shared along the years. At this time in my life, I cannot imagine being without him.

To my two wonderful daughters Alejandra and Patricia, for their understanding and believe it or not, their continuous support. Whenever I was tired or depressed, their encouraging words “Don’t worry Mom, you can do it!” lifted my spirit and kept me going. I hope you are proud of me, as I am of both of you. I love you!

And finally, I would like to remember my father, who truly loved his family and involuntary introduced me to the Electrical Engineering field. My deepest regret is that he is not with us anymore.
SUMMARY

In this work, a fuzzy logic approach is presented for the classification of dynamic security conditions and for the evaluation of dynamic security enhancement strategies. These strategies are based on preventive control actions derived from an adaptive fuzzy control algorithm.

The proposed framework for assessing and correcting system vulnerability involves two main steps:

• Determination of the security level that exists in the system at a given time.
• Determination of the control strategy to be applied, if needed, to enhance the system security level for a determined number of contingencies.

1- Determination of the Security Level at a given Time.

A discussion follows of the different evaluations involved in the determination of the security level, including the problems solved and the contributions made:

a) Energy Margin Evaluations

One of the key issues for the success of a fuzzy logic algorithm is the selection of the indexes to be “fuzzified”. In this work, Lyapunov techniques are applied in the context of an expanded two-machine equivalent system, similar to the one proposed in [15] [16]. The equivalent system allows the preservation of the generator identity and the network’s topology (Chapter III). This approach permits a fast and easy sensitivity analysis, which is then used to tune the control parameters.
b) Fuzzy Logic Classifier

The main objective of this step is to determine, using approximate reasoning, the security level of the system at a given operating point. The assessment of the degree of system vulnerability is done using fuzzy-logic relationships of the IF-THEN type, where the inputs are the energy margin index and its sensitivity to the equivalent power. After a pre-process defuzzification procedure a final security index is obtained. If the value of this index so warrants, the procedure enters the second loop described below. The pre-process defuzzification procedure is based on the centre-of-sum method [72], and has a speed advantage (particularly, when a pre-process evaluation is done in advance) and can be applied to fuzzy and singleton output set geometries. A detailed description of the classifier is performed in Chapter IV.

2- Output Adjustment by Approximate Reasoning

Three different control loops were modelled using fuzzy logic evaluation:

- Output power control
- Output voltage control
- Output power and voltage control

Even though voltage control is not a common practice for transient stability enhancement, it can be considered as a preventive step for increasing the level of the security margin. Power and voltage controls can be adjusted continuously, offering the best option for preventive control actions. The methods proposed are general and allow the consideration of other control actions such as reactor switching, series compensation, SVC, among others. In order to evaluate these control loops, the sensitivities of the energy margin with respect to the power and internal voltage output of each generator are obtained. Through this sensitivity evaluation, voltage and power control commands are
issued with the objective of taking the energy margin to the desired level. This is done by linearizing the energy margin function at the operating point. Even though it is not always the case, there is often a trade-off between security and cost. This work is concerned with simultaneous preventive control where the main objective is to achieve the desired energy margin level for several contingencies with a unique control strategy. Multi-objective optimisation (cost and security) is out of the scope of this work.

Several factors are taken into account in the decision making process using approximate reasoning:

a) Need for new control? (Membership function for energy margin index).

b) Sensitivities or influence of each generator in the process (Membership function for sensitivity evaluation).

c) Margin restriction for the output (generator’s physical limit) (Membership functions for the physically available margins).

These three constraints, which are physical and operative in nature, need to be evaluated because even in the presence of high sensitivities no control effect can be executed if the controllers have approached their limits. This indirectly reduces the incremental cost associated with rescheduling around the economical operating point, as generators already operating near their upper limits (high cost operating point) are not significantly moved.

Once the algorithm has verified the system security conditions with the use of the classifier, and with the knowledge of the impact of the evaluated controls, the algorithm seeks to improve the stability of the system.

Initially, constant threshold values were used, finding that:

- Power control was adequate. Due to the non-linearity of the problem the desired energy margin was improved but not enough to be taken to the desired specified level.
- Voltage control was not as effective if the system was highly unstable at the operating point, but nonetheless it helped to increase the energy margin level.

- A combination of both power and voltage control strategies proved to be effective. When these strategies are applied sequentially the system is driven using the power control to a specific energy level (smaller than the desired value) and from this point using voltage control the desired energy margin is reached.

The main drawback of the standard approach is that the threshold values of the membership functions are pre-set. Due to the non-linearity of the process there is no guarantee that the desired energy margin level will be obtained for all the varying system conditions. In order to compensate for this problem an adaptive-fuzzy or fuzzy-optimisation procedure was developed.

3- Adaptive Fuzzy-Logic Control

Since the conditions in the power system change continuously and a great number of different contingencies have to be evaluated, the approximate reasoning control algorithm proposed needs to be retuned for optimum performance at every given situation.

In this work, a self-tuning-performance-adaptive fuzzy control algorithm has been developed. Two iterative adaptive strategies were tested:

a) Simple iterative procedure: In this strategy, an iterative procedure is started through feedback of the generation power or voltage until the energy margin matches the desired levels. This method has the disadvantage in its dependence on the selected threshold values for the membership fuzzy logic sets.

As different combinations of power can produce the same energy margin, it is possible to obtain solutions which are far away from the economical
point, or to obtain operating points that have load-flow type convergency problems.

b) Fuzzy-optimisation procedure: This method uses a self-tuning algorithm where an iterative procedure is combined with scaling of the sensitivity membership functions. Through these optimisation techniques, the square of the error between the obtained energy margin and the desired one is reduced. The adjustment of the controls is then obtained using the simple steepest-descent gradient optimisation technique and the conjugate methods.

The details of both adaptive procedures are described in Chapter V.

4- Simultaneous Preventive Control

A great number of contingencies must be evaluated. In order to have a unique control strategy that increases the energy margin level to an adequate (sub-optimal) value and does so for all the contingencies, a simultaneous preventive control algorithm was developed. This algorithm reduces the possibility that control strategies developed for one condition might be prejudicial for others.

In all the energy margin evaluations, the reduced $[Y_{bus}]$ admittance matrix for pre-fault, fault and post fault conditions has to be obtained for each load condition. In order to speed-up the process in the security evaluation for different contingencies, computational savings can be obtained by using network tearing techniques and a pre-processing procedure, which requires recalculation of only those elements in the $[Y_{bus}]$ matrix that change value from one load condition to the next (Chapter VI).
5- Results

The algorithm was developed using an object-oriented compiler (ADA’95) and was tested for different benchmark cases. The results presented in this work show that the proposed method presents the following characteristics (Chapter VII):

a) Allows a fast and accurate classification of the system security condition. The classification is flexible enough to allow the inclusion of other important parameters, such as the power flow through a specific limiting line.

b) Using sensitivity evaluations and adaptive fuzzy logic procedures, new power and voltage output conditions are found which increase the security of the power system. These conditions satisfy physical and steady state limitations and represent a preventive dynamic control.

c) Provides through a special restricted optimisation procedure, preventive control commands that simultaneously increase the security for several contingencies under study.
CHAPTER I

INTRODUCTION

Today, due to the rapid changes that are taking place in the electric utility business, the stable and reliable operation of electric power systems is becoming increasingly difficult. Limited investments in new transmission facilities, the possibility of finding independent power producers connected to arbitrary points in the network and the existence of a deregulated competitive business environment, are forcing changes in the electric utility operation. The move is towards maximising the use of the existing transmission systems; as a consequence, the required increase in transmission capacity is performed mostly by operational means, thus increasing the dependency on control schemes and compensating devices (FACTS).

It has now become necessary for all the parties involved, that of power producer, transmission network controller and distribution company, to cooperate within a competitive framework to achieve the task of supplying power that is competitively priced and within the correct quality and security standards.

The situation above has rendered traditional systems operation criteria based on off-line studies inadequate to cope with the constantly changing nature of the problem, making online strategy techniques offering real-time preventive control strategies increasingly important. As a consequence, a great number of methods for online security analysis have been developed. These methods include more efficient time simulation [20], [21], utilising numerical step-by-step (SBS) time integration of the system differential equations. These methods, also called "indirect-type methods", have developed very strong power system modelling capabilities which are essential for the analysis of modern power systems equipped with complex control aids and special protection devices to reduce the effect of faults. However, in spite of their modelling capability and numerical speed-up evaluation, time domain methods have the shortcoming of producing a strictly
yes-or-no answer. Consequently, stability limits derivations are a trial-and-error task resulting in a large number of off-line stability evaluations. Therefore, these methods are not suitable by themselves for uncertain day-to-day power system operation. They also suffer from the disadvantage of not offering a security or performance index that can inform the power system operator of how far or close the system is to the instability borderline.

The capability of producing stability indices has been one of the major incentives for deriving the so-called direct methods [22-29]. The other advantage is the fast computational speed that these methods may offer. Originally, these methods used a simple model of the power system elements, but over the last two decades, significant progress has been made to improve their practicality, and to compensate for their limited modelling capability and accuracy issues. In doing so, however, they failed to achieve what they initially promised, that is, a fast evaluation of stability or security index. In order to have the best of both worlds, “hybrid type” methods have been proposed [29-31]. These methods compute the operational limit under actual operating conditions, but fall short in considering the trend in the security status of the system and do not incorporate the empirical knowledge of human experts who operate the particular power system. In addition, these methods do not offer preventive control actions aimed at increasing the security level under variable load conditions and for several contingencies. Other approaches also lack this consideration, among them, pattern-recognition/fuzzy [65-66] and expert system/artificial neural network [32] [33], whose main features consist of classifying the system between stable or unstable after a lengthy off-line learning approach.

Another aspect in the area of the dynamic security enhancement deals with the constraints that exist in power system scheduling. These constraints can be generally classified into two categories: physical limits and operating limits. Schedules violating physical limits are not acceptable. Operating limits, however, are often imposed to enhance security without representing physical bounds. These constraints are “fuzzy” in nature and a crisp treatment may lead to an overly conservative solution. Currently, in
dynamic expert systems security applications, these soft constraints are modelled as crisp variables [22] [33]. Although operating limits can be successfully relaxed until a satisfactory schedule is obtained, such a trial and error method may not be efficient. Due to the nature of this problem, the use of fuzzy logic techniques seems a suitable approach to deal with the power systems operational and physical constraints.

Recent studies [56-61] demonstrate that the use of fuzzy logic theory in power system applications makes possible to assimilate a unified solution process consisting of human knowledge, operating margin restrictions and static security levels. In references [57-58] fuzzy methods were applied successfully to include these constraints in problems such as voltage limits, constraint power flow, generation dispatch, among others. Presently due to the lack of easy-to-obtain security indexes, fuzzy methods have not been successfully applied for online dynamic security enhancement and control.

There are a great deal of “uncertainties”, in the power system operations, not only due to the randomness in load fluctuations, but also because of the great number of constant changes in this “new economic environment” due to the company’s motivations, policies and strategies. Therefore, static-fuzzy evaluation techniques are not sufficient, making adaptive techniques, which have the ability to adjust to external changes in a wide number of applications, need to be implemented. In power systems security applications there is little or no experience with the use of adaptive-fuzzy methods, however, one could mention the work of Tomsovic in the adjustments of power system stabilisers [84].

It is clear that after an in depth analysis of the present situation and the bibliographical research there are a great number of unresolved aspects in the area of simultaneous preventive online dynamic security assessment and control. It is in this area that this dissertation makes significant contributions, which can be summarised as:

a) Moving the security evaluation closer to real time, causing a significant reduction in the number of conditions to be analysed.
b) A simplification of the computation of the security index by analytical means, while simultaneously maintaining a certain degree of information and detail capable of rendering specific control actions.

c) Emphasis on "trends" in security limits as system conditions change.

d) The development of algorithms and techniques that use information gathered in the security index evaluation to deal with different system constraints.

e) The production of preventive control actions aimed at increasing the power system dynamic security under variable load and system conditions, and for different contingencies under study.

In the work presented in this dissertation, a fuzzy logic approach is employed for the evaluation and classification of dynamic security conditions and for dynamic security enhancement through preventive control action.

The algorithm and program developed combine mathematical energy functions and sensitivities based on Lyapunov methods together with operator judgement to determine security levels, control sensitivity margin, physical equipment restrictions and eventually costs. This research and associated program is going to be used in the real-time simulator "OVNI" (Object Virtual Network Integrator), currently being developed at the University of British Columbia [50].

In this work, an "Adaptive Fuzzy-Logic based Online Security Analysis and Control Algorithm" was developed. Its main features include:

a) Given the actual state of the electric system at any given time, a computation is produced of the security margin index based on an expanded two-machine equivalent system with generator identity preservation.
b) Based on the energy margin and its sensitivity, the algorithm classifies the security level that exists in the system at a given time, using a pre-process defuzzification procedure.

c) An adaptive fuzzy control algorithm capable of dealing with uncertainties and constraints that exist in the system (physical and operational). Through optimisation procedures and fuzzy logic or approximate reasoning techniques, several types of simultaneous preventive control strategies are obtained.

d) The evaluation of a great number of contingencies under varying load conditions is a key factor in the speed of the simulation process. Important computational savings were obtained by developing pre-processing special network tearing techniques, and recalculating only those parts of the topology that change from one load evaluation to the next. The proposed matrix evaluation technique proves to be particularly efficient for large systems and multiple contingency evaluations.

e) The algorithm proposed is flexible enough to allow the incorporation of other types of control actions, as well as multi-objective optimisation procedures (cost, emissions, voltage security among others).

The proposed algorithm was tested for different system sizes and complexities while the proposed control actions were tested using a conventional step-by-step stability program, thus proving its effectiveness.
CHAPTER II

FRAMEWORK FOR ADAPTIVE FUZZY-LOGIC BASED ONLINE SECURITY ANALYSIS AND CONTROL (SAC)

2.1 Basic Definitions

The reliability of the bulk power system (generation plus high voltage transmission system), also called a Composite System is evaluated mainly through two indices, related to its principal attributes, ADEQUACY and SECURITY [1].

- **ADEQUACY**: the ability of the system to supply the aggregate electric power and energy requirements of the customers within component ratings and voltages limits, taking into account planned and unplanned component outages.

- **SECURITY**: the ability of the system to withstand sudden disturbances, such as unanticipated losses of systems components, without a loss in integrity.

Clearly, security assessment involves transient stability evaluation, while adequacy assessment concentrates on the steady state conditions after a disturbance or incident, such as a component failure. Although it is very convenient to deal with power systems under steady state conditions, such conditions do not exist in reality, as random fluctuations in the load are taking place continuously with subsequent adjustments of generation. At times, major disturbances occur, such as a fault followed by a loss of a generating unit or transmission line. In composite adequacy evaluations, the dynamics of the transition from one equilibrium state to another are neglected, therefore, successful operation requires only that the new operating state does not violate any limit such as active and reactive power generation, bus voltages magnitudes, line currents, among others.
However, due to the transients after a disturbance, the new desired operating state may never be reached due to fluctuations in the system frequency, bus voltages, etc. If these fluctuations exceed certain safe operating limits, loads may be disconnected in order to preserve a major portion of the system, producing cascading events that persist until the system completely separates or collapses. These effects are not accounted for in adequacy studies and must be captured in security evaluations.

A classification of the different states of the power system follows [1]:

a) ADEQUATE: All loads in the system are served with system components not stressed beyond their design ratings with bus voltages remaining within tolerance.

b) INADEQUATE: A state where some system elements are overstressed (exposed to overloads) and/or some bus voltages are out of limits.

c) PARTIALLY ADEQUATE: After a limited amount of load is removed by the control operator, the remaining loads are served with system components not stressed beyond their ratings with the bus voltages within tolerances.

d) STABLE: Power system stability may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [84].

e) UNSTABLE: The system will change its condition even if no further disturbances occur.

f) SECURE: A stable state where some credible disturbances may not result in system instability.

g) NON-SECURE: A stable state where some credible disturbances may result in system instability.
h) MARGINALLY ADEQUATE: Adequate states out of which some credible disturbances may transfer the system to an inadequate or unstable state.

i) SYSTEM COLLAPSE: A state where the majority of loads are left without supply.

2.2 Online Dynamic Security Analysis

There are five basic elements of online security analysis and control, namely: monitoring, assessment, security enhancement, emergency and restorative control [36]. These elements can be defined as follows:

a) Security Monitoring: During the online dynamic security analysis phase, it is identified whether the system is in the normal state or not, with the use of real-time system measurements. If the system is in an emergency state, emergency control takes place and if loads have been lost restorative action starts.

b) Security Assessment: If the system is in a normal state, continuously determine whether the system is secure or insecure according to a set of credible contingencies.

c) Security Enhancement: If the system is insecure, meaning, there is at least one contingency that can cause an emergency, determine what action should be taken to make the system secure.

d) Emergency Control (remedial action): Execute proper corrective actions to bring the system back to its normal state, following a contingency that causes the system to enter an emergency state.

e) Restorative Control: restore service to system loads.

The relationship between the major components of online security analysis are shown in Figure 2.1:
2.3 Framework for Fuzzy Security Classifier and Preventive Control

The work presented in this dissertation focuses on the areas of security assessment and security enhancement for online power system security evaluations.
The proposed framework for assessing and correcting system vulnerability includes two main blocks:

- Security Assessment: Determination and classification of the security level that exists in the system at a given instant of time.
- Security Enhancement: Determination of the control strategies to be applied if needed, to enhance the system security level.

This is accomplished using fuzzy logic techniques for both the evaluation and classification of dynamic security conditions, and to derive preventive control actions through an adaptive fuzzy control algorithm for the dynamic security enhancement.

The basic block diagram of the proposed security analysis and control program (SAC) is shown in Figure 2.2. This block is executed repeatedly, when doing real-time security assessment.

A brief explanation of the different steps of this process follows:

1. **Economic Dispatch**

   The assumption is made that at each instant of time, the power system is in its optimum economic operating point, even though this is not a limitation and other operating conditions can be used as initial operating points. Starting at this point, small changes in power generation and generator voltages can be performed in order to enhance the dynamic security.
Figure 2.2: Block Diagram of the SAC System
2. Security Assessment Block:

In this block the power system security is classified under one of the categories mentioned in 2.1, this is done with the use of fuzzy logic or approximate reasoning techniques, and includes the evaluation of (Figure 2.3):

- Energy Margin and Sensitivity Evaluation (a)
- Acquisition of Security Vector (b)
- Acquisition of Security Index (c)

Figure 2.3: Security Assessment Block

a) Calculation of energy margin index and sensitivities

One of the key aspects for the success of a fuzzy logic algorithm is the selection of the indices to be fuzzified. It is recognised that the proper framework for security analysis should incorporate information not only on the security level of the particular operating point, but also the trend in
this security level as changes in system operating conditions take place. Lyapunov's theorems applied to energy margin evaluations can provide efficient means to obtain an initial "good quality" estimate.

The trend in the security level as system conditions vary (changes in load, generation, for example) is given by the derivative of the energy margin with respect to a predefined sensitivity parameter "p". In this study the equivalent power $P_{\text{equiv}}$ is chosen as the sensitivity parameter in the evaluation of the security index. This parameter takes into account not only changes in load but also the power re-distribution among generators (a key factor in power system stability analysis). With these two parameters, the energy margin and sensitivity value, the proposed algorithm enters the next step.

It is to be noticed that the solution proposed in this work is intended to work in conjunction with an online real-time simulator, which will ultimately test the identified critical conditions on a detailed full network simulation.
b) Fuzzy logic classifier

The main objective of this step is to determine, using approximate reasoning, the security level of the system at a given operating point. Depending on the result of this classification, the program may or may not enter the "security enhancement loop". The assessment of the degree of system vulnerability is performed using fuzzy-logic relationships of the type IF-THEN. The inputs are the energy margin index and its sensitivity to the equivalent power and the outputs are the security vector (degree of membership of the security status to categories ranging from completely stable to unstable) and the security index (which summarises the information in the security vector).

If during the evaluation process the value of the security index is above a predefined level, any decision by the classifier is delayed until the next time step, when all the procedure is evaluated again for the new load conditions. If the security index is below the predefined decision level, the algorithm proceeds right away with the step of adaptive security enhancement control action.

3. Adaptive Security Enhancement Block:

As a final result of this block, the algorithm produces a group of preventive measures to be adopted in order to enhance power system security:

   a) Output adjustment by approximate reasoning

   Two types of control actions are considered in the algorithm: generator voltage control and generator power output control. Even though voltage control is not a common practice for transient stability enhancement, it can be considered as a preventive action for increasing the level of the security margin. Given that power and voltage controls can be adjusted continuously, they offer the best option for preventive control actions.
Nonetheless, the methods proposed are general and allow the consideration of other control actions such as reactor switching, series compensation, SVC, among others.

In order to obtain the desired control action at each generator, the sensitivities of the energy margin with respect to changes in its power and voltage are found. Then if the generator can effectively affect the energy margin, the new voltage and power settings are obtained with the objective of taking the energy margin to the desired level. Mathematically, this is achieved by linearising the energy margin function around the operating point for those generators that satisfy the following fuzzy relationship:

IF security enhancement is needed

AND a generator is controllable for effective security improvement

AND there is adequate margin of output adjustment to enhance the security level

THEN adjust the generator output

As in the case of the security classifier, fuzzy sets are defined for the energy margin, the sensitivity, and the availability of the control system.

b) Estimate control effect

The main drawback of the standard straightforward approach is that due to the non-linearity of the process, there is no guarantee that the desired energy margin level can be obtained directly for all the varying system conditions. In order to compensate for this problem the process enters the adaptive-fuzzy or fuzzy-optimisation loop.
c) Adaptive fuzzy-logic control

Since the conditions in the power system change continuously and several contingencies have to be evaluated, the approximate reasoning control algorithm needs to be "retuned" for optimum performance with every new situation. This can be achieved with an adaptive controller that automatically modifies itself to match the system conditions.

In this work, a self-tuning-performance-adaptive, fuzzy control algorithm is proposed. Through an optimisation procedure the square of the error between the actual energy margin level and the desired one is minimised.

![Figure 2.4: Adaptive Security Enhancement Block](image)

4. Simultaneous Preventive Control

A great number of contingencies must be evaluated simultaneously in order to have a control strategy that increases the energy margin level to an adequate value (sub-optimal) for all contingencies, and eliminates the possibility that control strategies developed for
one condition might be prejudicial for others. This is achieved by simultaneous consideration of all credible contingencies in the optimisation loop, with a method described in Chapter VI. The important element in this method is that after each contingency is evaluated, the changes in the generators output power are averaged, where this new condition is used for the new energy margin evaluation. This process is done for a fixed and small number of iterations. Afterwards, the critical generators’ output power for each contingency is used as the new condition. This method was found to produce a simultaneous adequate control strategy for a given set of contingencies (in those cases with a non-empty solution).

![Figure 2.5: Simultaneous Evaluation Block](image-url)
5. Final check and fine tuning

After the proposed changes in power and voltages have been calculated, the new steady state conditions are evaluated in order to check for overloads in limiting transmission lines. This is to be done in the power system simulator (OVNI), which will work in conjunction with this program. If the control actions cause line capacity limits to be exceeded, additional actions must be taken to alleviate the overload. The re-optimisation is entered with this additional limitation. Finally, before applying the controls to the real system, all credible contingencies for the dynamic security status are checked using OVNI, where a complete and detailed power system network is simulated.
CHAPTER III

EXPANDED TWO MACHINE EQUIVALENT SYSTEM

Lyapunov’s based direct energy method has played a major role in the calculation of the transient energy function for dynamic security assessment. This method evaluates the power system transient stability from an energy point of view. The advantages of transient energy methods are their fast computational speed and the qualitative measurement of the degree of the system stability, which provides the means to estimate the sensitivity of the system with respect to selected parameters. This last characteristic constitutes the basis of its use for security preventive control.

The early pioneers in using the energy functions methods were Magnusson (1947), Aylett (1958), Gless (1966), El-Abiad and Nagappan (1966). While Aylett proposed an energy integral approach, El-Abiad and Nagappan put the method in the context of Lyapunov’s stability theory. After 1966 there has been a significant effort in this area, documented in papers written by Foaud (1975), Ribbens-Pavella and Evans (1985).

Although computational improvements have been made, the transient energy methods (Appendix 1) become increasingly complex when detailed models of the power system are considered or when dealing with a differential-algebraic equation representation of power system components.

In the scope of the work in this dissertation, Lyapunov’s based energy method is oriented to be used as a means to classify the system condition. More critical, is the implementation of an online adaptive preventive control scheme that can be applied to a working power system. It is therefore necessary to obtain a speedy and efficient calculation of the energy margin indices, while simultaneously preserving in these calculations the system information, needed for a useful and flexible sensitivity evaluation.

The energy-based algorithm proposed is called the “expanded two-machine equivalent system”. The technique uses analytical formulas to determine the transient kinetic energy
acquired during the fault period and the potential energy of the post-contingency system when applied to a two-machine equivalent of a multimachine power system. In doing so, the classical model for the generator representation (constant voltage source behind an effective reactance) is used for the generators in the multimachine network. This model is very useful in stability studies, but is limited in the study of transients to only the first swing oscillation. However, this is sufficient for the domain and intent of this work, that is, security classification and preventive control.

The use of dynamic equivalents has been investigated by Xue et al. [15], and by Rahimi [16]. There is a significant difference between the approaches of these authors and the approach proposed here. In [16] only three phase faults at the generator buses are considered. In [15] the system is reduced to a one-machine infinite bus (OMIB) equivalent while the approach is based on the geometrical equal-area criteria for the calculation of the accelerating and decelerating energies. In doing so, the identity of the generators and network topology is lost. This eventually translates into a rather complicated and indirect sensitivity evaluation. In this approach, the generators' identity and network topology are preserved and load flow evaluations for the post-fault period are used. The energy margin is calculated directly, not through geometrical approximations, as is the case of the equal-area criteria, making the approach flexible and ideal for a fast and straightforward sensitivity evaluation.

3.1 Two-Machine Equivalent for a Multimachine Power System

3.1.1 Two-Machine System

Consider a simple two-machine system connected through a transmission line, as shown in Figure 3.1.
Figure 3.1: Two-Machine Electric System

The swing or oscillation equations for machines 1 and 2 using the centre-of-inertia formulation (Appendix 1) are given by:

\[
\begin{align*}
M_1 \dot{\theta}_1 &= P_1 - C_{12} \sin \theta_{12} - D_{12} \cos \theta_{12} - \frac{M_1}{M_1 + M_2} P_{\text{coi}} \\
M_2 \dot{\theta}_2 &= P_2 + C_{12} \sin \theta_{12} - D_{12} \cos \theta_{12} - \frac{M_2}{M_1 + M_2} P_{\text{coi}}
\end{align*}
\]

(3.1)

Where for \( i = 1 \) and 2

\( \delta_i, \ \omega_i = \) generator's rotor angle and rotor speed

\[
\delta_\alpha = \frac{1}{(M_1 + M_2)} \sum_{i=1}^{2} M_i \delta_i = \text{centre-of-angle reference COI co-ordinates}
\]

\[
\omega_\alpha = \frac{1}{(M_1 + M_2)} \sum_{i=1}^{2} M_i \omega_i = \text{centre-of-speed reference COI co-ordinates}
\]

\( \theta_i = \delta_i - \delta_\alpha = \) machine's angular position and angular speed deviation with respect to the centre of inertia COI

\( \omega_i = \omega_i - \omega_\alpha = \) machine's angular position and angular speed deviation with respect to the centre of inertia COI

\( \theta_{12} = \theta_1 - \theta_2 = \) angular difference between machines 1 and 2

\( M_i = i^{th} \text{ machine inertia constant} \)
Center-of-inertia equivalent power:

\[ P_{\text{col}} = \sum_{i=1}^{n} (P_i - P_{e, i}) \]

where \( P_i = P_{m, i} - E_i^2 G_{ii} \)

\[ P_{e, i} = \sum_{j \neq i}^{2} (C_{ij} \sin \theta_j + D_{ij} \cos \theta_j) \]

\( P_{m, i} \) = \( i \)th machine mechanical power

\( E_i = \) \( i \)th machine constant voltage magnitude behind transient reactance

\[ C_{12} = E_1 B_{12} E_2 \quad , \quad D_{12} = E_1 G_{12} E_2 \]

\( G_{ij}, B_{ij} \) = real and imaginary parts of \((ij)\) elements of post-disturbance \([Y_{bus}]\) matrix, reduced to the internal nodes of the synchronous machines

\( G_{ii}, B_{ii} \) = real and imaginary parts of \((ii)\) elements of post-disturbance \([Y_{bus}]\) matrix, reduced to the internal nodes of the synchronous machines

Combining both equations:

\[ \frac{M_1 M_2}{M_1 + M_2} \dot{\theta}_{12} = \frac{M_2 P_1 - M_1 P_2}{M_1 + M_2} - C_{12} \sin \theta_{12} - \frac{(M_2 - M_1)}{M_1 + M_2} D_{12} \cos \theta_{12} = P_{ac, \text{equiv}} \]

(3.2)

That can be re-written as:

\[ M_{eq} \dot{\theta}_{eq} = P_{eq} - C_{eq} \sin \theta_{eq} - D_{eq} \cos \theta_{eq} = P_{ac, \text{equiv}} \]

(3.3)

where

\[ M_{eq} = \frac{M_1 M_2}{M_1 + M_2} \]

\[ \dot{\theta}_{eq} = \dot{\theta}_{12} = \theta_1 - \theta_2 \]

\[ P_{eq} = \frac{M_2 P_1 - M_1 P_2}{M_1 + M_2} \]

\[ C_{eq} = C_{12} \]

\[ D_{eq} = \frac{M_2 - M_1}{M_1 + M_2} D_{12} \]

(3.4)
3.1.2 Definition of Energy Margin Using Lyapunov Solution Method

In its simple form, the transition of a power system undergoing a disturbance can be described by sets of differential equations similar to (3.2), where each set describes a particular state of the problem. If one considers both the fault and post-fault equations sets, (where the post-fault in some clearing fault switching operations can have different subsets) the following situation is produced:

a) Fault state:

If we integrate the accelerating power $P_{ac_{equiv}}$ in equation (3.3) between $t=0$ where the speed difference between generator's 1 and 2 $\omega_{12}$ is equal to zero (pre-fault equilibrium point), and $t=cl$, with $cl =$clearing time and $\omega_{12}|_{t=cl} = \omega_{cl}$ we have:

$$V_{cl} = \frac{1}{2} M_{eq} \omega_{cl}^2$$  

(3.5)

$V_{cl}$: Kinetic energy acquired by the equivalent machine during the fault period.

b) Post-fault state:

If we evaluate the accelerating power between $t=cl$, with initial condition $\theta_{12}|_{t=cl} = \theta_{cl}$ and final condition $\theta_{12}$, then we can define:

$$V_{p}(\theta_{12}^{pf}, \omega_{12}^{pf}) = -P_{12}(\theta_{12}^{pf} - \theta_{12}^{cl}) - C_{12}(\cos \theta_{12}^{pf} - \cos \theta_{12}^{cl}) + D_{eq}(\sin \theta_{12}^{pf} - \sin \theta_{12}^{cl})$$  

(3.6)

$V_{p}(\theta_{12}^{pf}, \omega_{12}^{pf})$: Potential Energy of the equivalent (capacity to dissipate the acquired energy).
If (3.6) is evaluated at the unstable equilibrium point \( \theta_{12}^{eq} = \theta_{12}^{ue} \), then the maximum decelerating energy is given by:

\[
V(\theta_{12}^{ue}, \omega_{12}^{ue}) = V_{cr} = -P_{12} (\theta_{12}^{ue} - \theta_{12}^{eq}) - C_{12} (\cos \theta_{12}^{ue} - \cos \theta_{12}^{eq}) + D_{eq} (\sin \theta_{12}^{ue} - \sin \theta_{12}^{eq}) \\
= \frac{1}{2} M_{eq} \left[ (\omega_{12}^{ue})^2 + \omega_{el}^2 \right]
\]  
(3.7)

If the system is stable, then \( \omega_{12} |^{ue} = 0 \) and \( V_{el} = V_{cr} \) meaning the system is able to "dissipate" in the post-fault event the same amount of energy absorbed during the fault period.

We can define the Energy Margin Index as:

\[
\Delta V = V_{cr} - V_{el}
\]  
(3.8)

Then if:

\( \Delta V \geq 0 \) the system is stable for the contingency evaluated (accelerating energy smaller than maximum decelerating energy)

\( \Delta V < 0 \) the system is unstable for the contingency evaluated (accelerating energy larger than maximum decelerating energy)

As it is possible to observe, no trajectory-path dependent integral appears when using the equivalent equation, which is not the case when traditional Lyapunov's methods are applied independently for each machine (Appendix 1).
3.1.3 Two-Machine Equivalent for a Multimachine Network

Consider a system with \( n \) generators, \( n > 2 \). When a disturbance occurs in the system, the generators split primarily into two groups, where one group is called the critical generators group \( G_a \), and the remainder or non-critical generators belong to group \( G_b \). The idea behind this two-machine equivalent is that each group can be represented by an equivalent generator, located at the centre of inertia of the respective group (Appendix 1). Then:

\[
\theta_A = \frac{1}{M_A} \sum_{i \in G_a} M_i \delta_i - \delta_0 = \delta_A - \delta_0
\]

\[
\theta_B = \frac{1}{M_B} \sum_{i \in G_b} M_i \delta_i - \delta_0 = \delta_B - \delta_0
\]

(3.9)

where

\( \delta_o = \) system angular reference

\[
M_A = \sum_{i \in G_a} M_i
\]

\[
M_B = \sum_{i \in G_b} M_i
\]

\[
\delta_A = \frac{1}{M_A} \sum_{i \in G_a} M_i \delta_i
\]

\[
\delta_B = \frac{1}{M_B} \sum_{i \in G_b} M_i \delta_i
\]

\[
M_T = \sum_{i \in G_a} M_i = \sum_{i \in G_b} M_i = M_A + M_B
\]

(3.10)

Without losing any generality, we can assume that the first \( n_a \) generators belong to \( G_a \) and the rest to \( G_b \), then the following equations for the accelerating power of each group are:
\[ M_A \dot{\theta}_A = \sum_{i=1}^{n_a} M_i \dot{\theta}_i = Pac_A \]

\[ M_B \dot{\theta}_B = \sum_{i=n_a+1}^{n} M_i \dot{\theta}_i = Pac_B \]

(3.11)

where

\[ Pac_A = \sum_{i=1}^{n_a} P_i - 2 \sum_{i=1}^{n_a-1} \sum_{j=i+1}^{n_a} D_{ij} \cos \theta_{ij} - \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_{ij} \sin \theta_{ij} - \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} D_{ij} \cos \theta_{ij} - \frac{M_A P_{coi}}{M_T} \]

\[ Pac_B = \sum_{i=n_a+1}^{n} P_i - 2 \sum_{i=n_a+1}^{n-1} \sum_{j=i+1}^{n} D_{ij} \cos \theta_{ij} + \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_{ij} \sin \theta_{ij} - \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} D_{ij} \cos \theta_{ij} - \frac{M_B P_{coi}}{M_T} \]

(3.12)

Combining equations (3.10) and (3.11):

\[ \frac{M_A M_B}{M_A + M_B} \dot{\theta}_{AB} = \frac{M_B Pac_A - M_A Pac_B}{M_T} = Pac_{equiv} \]

\[ M_{eq} \dot{\theta}_{eq} = Pac_{eq} \]

\[ M_{eq} = \frac{M_A M_B}{M_A + M_B} \]

\[ \theta_{eq} = \theta_{AB} = \theta_A - \theta_B \]

\[ Pac_{equiv} = \frac{1}{M_T} \left[ M_B \left( \sum_{i=1}^{n_a} P_i - 2 \sum_{i=1}^{n_a} \sum_{j=i+1}^{n_a} D_{ij} \cos \theta_{ij} \right) \right. \left. - M_A \left( \sum_{i=n_a+1}^{n} P_i - \sum_{i=n_a+1}^{n} \sum_{j=i+1}^{n} D_{ij} \cos \theta_{ij} \right) \right] \]

\[ - \sum_{i=1}^{n_a} \sum_{j=i+1}^{n_a} \left( C_{ij} \sin \theta_{ij} + \frac{M_B M_A}{M_T} D_{ij} \cos \theta_{ij} \right) \]

(3.13)

For the particular case where the angular differences among generators belonging to one group are small when compared with the differences among groups (coherency group oscillation), it is possible to establish the following relationships:
\[ \theta_{ij}^o \equiv \theta_i^o - \theta_j^o; \forall i, j \in G_a \text{ or } G_b \]

(3.14)

and

\[ \theta_{ij} \equiv \theta_{ij}^0 + \Delta \theta_A - \Delta \theta_B = \theta_{ij}^0 + \Delta \theta_{AB}; i \in G_a \text{ or } j \in G_b \]

(3.15)

where

\[ \theta_A = \theta_A^0 + \Delta \theta_A \]
\[ \theta_B = \theta_B^0 + \Delta \theta_B \]

(3.16)

Using (3.13), (3.15) and (3.16) the oscillation equation for each group is:

\[
M_A \ddot{\theta}_A = \sum_{i=1}^{n_a} P_i - 2 \sum_{i=1}^{n_a} \sum_{j=i+1}^{n_a} D_{ij} \cos \theta_{ij}^o - \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_{ij} \sin(\theta_{ij}^o + \Delta \theta_{AB}) \\
- \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} D_{ij} \cos(\theta_{ij}^o + \Delta \theta_{AB}) - \frac{M_A}{M_T} P_{col} 
\]

\[
M_B \ddot{\theta}_B = \sum_{i=n_a+1}^{n} P_i - 2 \sum_{i=n_a+1}^{n} \sum_{j=i+1}^{n} D_{ij} \cos \theta_{ij}^o - \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_{ij} \sin(\theta_{ij}^o + \Delta \theta_{AB}) \\
- \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} D_{ij} \cos(\theta_{ij}^o + \Delta \theta_{AB}) - \frac{M_B}{M_T} P_{col} 
\]

(3.17)

if we defined:

\[
P_A = \sum_{i=n_a+1}^{n_a} P_i - 2 \sum_{i=1}^{n_a} \sum_{j=i+1}^{n_a} D_{ij} \cos \theta_{ij}^o \\
P_B = \sum_{i=n_a+1}^{n} P_i - 2 \sum_{i=1}^{n_a} \sum_{j=i+1}^{n_a} D_{ij} \cos \theta_{ij}^o 
\]

(3.18)
After some mathematical manipulations the equation for the equivalent system is:

\[
\frac{M_A M_B}{M_A + M_B} \bar{\theta}_{AB} = \frac{M_B P_A - M_A P_B}{M_A + M_B} - \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_{ij} \sin(\theta_{AB} - \theta_{ij}^\circ + \theta_{ij}^o) \\
- \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} \frac{M_B - M_A}{M_B + M_A} D_{ij} \cos(\theta_{AB} - \theta_{AB}^\circ + \theta_{ij}^o)
\]

(3.19)

Evaluating (3.19) for the fault and post-fault conditions, the energy margin index for the two-machine equivalent is obtained as (Appendix 1):

\[
\Delta V = -\frac{1}{2} M_{eq} \bar{\omega}_{eq}^2 \bigg|_{cl} - P_{equiv}(\theta_{AB}^{ue} - \theta_{AB}^{cl}) - \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_{ij} \cos(\theta_{ij}^o + \Delta \theta_{AB}^{ue}) + \\
+ \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_{ij} \cos(\theta_{ij}^o + \Delta \theta_{AB}^{cl}) \\
+ \frac{M_B - M_A}{M_B + M_A} \left[ \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} D_{ij} \sin(\theta_{ij}^o) \bigg|_{pf} + \Delta \theta_{AB}^{ue} - D_{ij} \sin(\theta_{ij}^o + \Delta \theta_{AB}^{cl}) \right]
\]

(3.20)

\[
P_{equiv} = \frac{M_B P_A - M_A P_B}{M_A + M_B} = \text{equivalent power}
\]

\[
\theta_{ij}^o \big|_{pf} = \text{post-fault equilibrium point angle between generators } i \text{ and } j.
\]

\[
\theta_{ij}^o = \text{pre-fault equilibrium point.}
\]

\[
\Delta \theta_{AB} = \theta_{AB} - \theta_{AB}^o = \text{variation of the equivalent angle with respect to the respective equilibrium points (fault or post-fault).}
\]

In this evaluation, load-flow studies are required to obtain the post-fault value \( \theta_{ij}^o \big|_{pf} \) for all the generators, and \( \omega_e \) and \( \theta_{AB} \) are obtained by an integration of the oscillation equation (3.19) for the two-machine equivalent.
In the solution procedure, both the generators' identity and the network topology identities are maintained, allowing the sensitivity analysis with respect to network parameters or the internal voltage or power output of the generator to be calculated in a straightforward manner.

### 3.1.4 Mode of Disturbance Evaluation

The proposed evaluation procedure for the energy margin of the two-machine equivalent requires the identification of the group of severely disturbed generators or critical group that tends to swing away from the other non-critical group. A scheme for automatically generating the right mode of group separation is needed.

The issue of groups identification has been studied in detail by several researchers for its use in the traditional “energy margin type” evaluations of $P_{coi}$. In [45], for example, an automatic classification that depends on the kinetic energy at clearance time and the acceleration at clearance time is described; other schemes, as described in [53] use the rotor angles at the clearance time.

Based on the criteria adopted, a choice is made of which generators with higher energy and acceleration or angle deviation belong to the critical group. After a list of candidates for the “critical machines group” are obtained, the next step is to compute the critical clearance time $ccl$ for each alternative. The group with the smaller value is then selected, as the final critical generator cluster.

### 3.1.5 Analytical Sensitivity Development

The sensitivity of the energy margin to a given parameter $p$ is obtained by taking the partial derivative of $\Delta V$ with respect to $p$. In this work three different parameters $p$ were selected: the equivalent power $P_{equiv}$, the internal generator voltage $E_i$ and the generator output power $P_i$. Their selection is justified in the following chapters.

Applying the chain rule of differentiation to (3.18) the following general sensitivity formula is obtained:
\[
\frac{\partial \Delta V}{\partial p} = - \frac{M_A}{M_B} \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} \frac{\partial \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{eq}}} - \frac{\partial \theta_{ij}^{\text{eq}}}{\partial \theta_{ij}^{\text{cl}}} \left( \theta_{AB}^{\text{u}} - \theta_{AB}^{\text{cl}} \right) - \frac{\partial \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} \left( \theta_{AB}^{\text{u}} - \theta_{AB}^{\text{cl}} \right) - \frac{\partial \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} \left( \theta_{AB}^{\text{u}} - \theta_{AB}^{\text{cl}} \right)
\]

\[
\sum_{i=1}^{n_x} \sum_{j=1}^{n_y} \frac{\partial \Delta V}{\partial p} \left[ \cos(\theta_{ij}^{\text{cl}} + \Delta \theta_{ij}^{\text{cl}}) - \cos(\theta_{ij}^{\text{cl}}) \right]
\]

\[
+ \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} \left[ C_{ij} \sin(\theta_{ij}^{\text{cl}} + \Delta \theta_{ij}^{\text{cl}}) \left( \frac{\partial \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} + \frac{\partial \Delta \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} \right) \right]
\]

\[
\sum_{i=1}^{n_x} \sum_{j=1}^{n_y} D_{ij} \left[ \cos(\theta_{ij}^{\text{cl}} + \Delta \theta_{ij}^{\text{cl}}) \left( \frac{\partial \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} + \frac{\partial \Delta \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} \right) \right]
\]

\[
- \cos(\theta_{ij}^{\text{cl}}) \left( \frac{\partial \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} + \frac{\partial \Delta \theta_{ij}^{\text{cl}}}{\partial \theta_{ij}^{\text{cl}}} \right) \right] \}
\]

(3.21)

In determining the energy margin sensitivity, the sensitivity of a number of dependent variables to the parameter \( p \) also needs to be determined. These include:

\[
\frac{\partial \theta_{ij}^{\text{cl}}}{\partial p}, \quad \frac{\partial \omega_{ij}^{\text{cl}}}{\partial p}, \quad \frac{\partial \theta_{ij}^{\text{eq}}}{\partial p}, \quad \frac{\partial \theta_{ij}^{\text{cl}}}{\partial p}, \quad \text{for } i,j=1,2, \ldots, n \ i \neq j
\]

The sensitivity of the conditions at the end of the disturbance to the change in parameter \( p \) is obtained using dynamic sensitivity equations for the disturbed system and considering partial derivatives as follows (using the oscillation equation):
The above is a system of linear differential equations which can be integrated knowing the values of $\theta$ and $\omega$ at each time step. Thus

$$\frac{\partial \theta_{AB}}{\partial \phi} = \frac{\partial \omega_{AB}}{\partial \phi}$$

(3.22)

The sensitivity of the controlling $UE$ (Unstable Equilibrium Point) to the change in parameter $p$, $\frac{\partial \Delta \theta_{ue}}{\partial \phi}$, is determined from the sensitivity equations derived. Knowing that at the unstable equilibrium point, the time derivatives of $\theta$ and $\omega$ are zero. Therefore, using (3.21),

$$M_{eq} \frac{\partial}{\partial p} \left( \frac{d\theta_{AB}}{dt} \right) = M_{eq} \frac{\partial}{\partial p} \left( \frac{d\omega_{AB}}{dt} \right)$$

$$= \frac{1}{M_T} \left[ M_b \frac{\partial}{\partial p} \left( Pa - 2 \sum_{i=1}^{n_a} \sum_{j=1}^{n_a} D_{ij} \cos \theta_{ij} \right) - M_a \frac{\partial}{\partial p} \left( Pb - 2 \sum_{i=n_a+1}^{n} \sum_{j=1}^{n} D_{ij} \cos \theta_{ij} \right) \right]$$

$$- 2 \frac{\partial}{\partial p} \left( \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} (C_{ij} \sin \theta_{ij} + \frac{M_B - M_A}{M_B + M_A} D_{ij} \cos \theta_{ij}) \right)$$

$$\frac{\partial \theta_{AB}}{\partial \phi} = \frac{\partial \omega_{AB}}{\partial \phi}$$
\[
Meq \frac{\partial}{\partial p} \left( \omega_{AB} \right) = 0
\]
\[
0 = \frac{1}{M_T} \left[ M_b \frac{\partial}{\partial p} \left( Pa - 2 \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} D_{ij} \cos \theta_{ij} \right) - M_a \frac{\partial}{\partial p} \left( Pb - 2 \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} D_{ij} \cos \theta_{ij} \right) \right]
\]
\[
- \frac{\partial}{\partial p} \left( \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} \left( C_{ij} \sin \theta_{ij} + \frac{M_{B} - M_{A}}{M_{B} + M_{A}} D_{ij} \cos \theta_{ij} \right) \right)_{\theta=\theta_{se}}
\]
\[
\frac{\partial \omega_{AB}}{\partial p} \bigg|_{se} = 0
\]

(3.23)

Equations similar to (3.23) are also used to solve the pre-disturbance network to obtain changes in the initial operating point, due to a change in parameter \( \frac{\partial \omega_{AB}}{\partial p} \). Special consideration is allowed for the sensitivity of the slack bus with respect to parameter \( p \). That is \( \frac{\partial P_{\text{slack}}}{\partial p} \) when \( p \) alters the losses or power distribution of the power system.

### 3.2 Sensitivity Analysis and System Vulnerability Concepts

Sensitivity analysis is developed in this work to achieve two basic objectives:

a) Evaluation of the system vulnerability, by classifying the security level of the power system for a particular load and fault condition under study.

b) Develop control enhancement strategies.

Basically, the system security status can be measured only by some specified indices, such as the energy margin index. It is now recognised, however, that the proper framework for security assessment should include information about the security level as
well as the trend in the security status as the changes in system operating conditions take place [24].

Information on both the level of system security and its trend with respect to changes in the system parameters are included in the concept of system vulnerability. Within this concept, it is assumed that there is an acceptable level for the security indicator and for its trend (or sensitivity) to changes in system conditions. When the system security status is assessed, the level of security and its trend are determined. System vulnerability depends on whether these levels are below or above the threshold of acceptable levels. In Chapter IV, the selection of the index and parameters $p$ used to classify power system security is studied.

For control enhancement strategies, two types of “controls” are considered for the preventive loop: rescheduling of the generator power $P_i$ and control of the terminal voltage $E_i$.

There can be more than one parameter $p$ to be changed, and in this case the sensitivities to all the changing parameters are required. In obtaining the variation in energy margin level due to changes in more than one parameter the following expression is used:

$$\Delta(\Delta V) = \sum_{k=1}^{n} \frac{\partial(\Delta V)}{\partial p} \Delta p$$

(3.24)

It is assumed that only first derivatives of $\Delta V$ with respect to $p$ are considered, which neglects higher terms. However, for highly non-linear situations higher order derivatives could be included.
Numerics and knowledge are conceived as two relatively different forms of information. While numerics are usually derived from rigorous mathematical analysis, knowledge simulates human expertise.

In this dissertation, a fuzzy recognition approach to assess power system transient stability is presented, forms the first attempt to combine useful empirical knowledge human experts have gathered in long-time power system operation and analysis, with energy methods based on Lyapunov's functions for online security analysis. As described in Chapter III, energy methods are powerful tools that help the system operator determine at what distance from the stability/instability border the network is operating. Energy methods also have the flexibility of providing sensitivity information on how the energy margin is affected by varying system parameters. At the same time, operator knowledge and control equipment restrictions are easily taken into account in approximate reasoning (Fuzzy Logic) techniques, as their use in steady state evaluations has already been proven [57],[58]. Together, these two analytical tools provide an ideal combination for classifying and obtaining the degree of membership to a given non-analytical or linguistic classification.

In this chapter the security index classifier is presented. The main objective of this security classifier is to determine, using approximate reasoning, the security level of the system at a given operating point. Depending on the result of this classification, the program may or may not enter the security enhancement loop (Figure 1.1).

The security classifier inputs the energy margin index and the sensitivity value to the equivalent power producing two results in its output. First, a security vector informs the system operator of the degree of relevance of each security level, while finally a security index quantifies the degree of security/insecurity of the system. The assessment of the
degree of system vulnerability is done using fuzzy-logic relationships of the IF-THEN type.

The basic theory for fuzzy logic evaluations is given in appendix 2.

### 4.1 Framework for Security and Vulnerability Assessment

With the two-machine equivalent system formulated in Chapter III, the energy margin is a non-linear function of

$$
\Delta V = f (P_{\text{equiv}}, \omega_{\text{eq}}, \phi, E_i, \theta_i, D_{ij}, C_{ij}, \theta_{ij}, \theta_{\text{ud}})
$$

(4.1)

The trend in the security level as system conditions vary (changes in load, generation, for example) is given by the derivative of this energy margin function with respect to a predefined sensitivity parameter $p$.

In this study, the equivalent power $P_{\text{equiv}}$ is chosen as the sensitivity parameter in the evaluation of the security index. This parameter takes into account not only changes in load but also the power re-distribution among generators (a key factor in power system stability analysis).

The sensitivity to the power is given by:
\[
\frac{\partial \Delta V}{\partial P_{\text{equiv}}} = -M_{eq} \omega_{eq} \frac{\partial \omega}{\partial P_{\text{equiv}}} - (\theta_{\text{ue}}^{\text{eq}} - \theta_{\text{cl}}^{\text{eq}}) - P_{\text{equiv}} \left( \frac{\partial \theta_{\text{ue}}^{\text{eq}}}{\partial P_{\text{equiv}}} - \frac{\partial \theta_{\text{cl}}^{\text{eq}}}{\partial P_{\text{equiv}}} \right) + \\
\sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} C_j \left( \sin(\theta_y + \Delta \theta_{AB}) \left( \frac{\partial \theta_y}{\partial P_{\text{equiv}}} + \frac{\partial \Delta \theta_{AB}^{\text{cl}}}{\partial P_{\text{equiv}}} \right) \right) - \sin(\theta_y + \Delta \theta_{AB}) \left( \frac{\partial \theta_y}{\partial P_{\text{equiv}}} + \frac{\partial \Delta \theta_{AB}^{\text{cl}}}{\partial P_{\text{equiv}}} \right) \\
+ \frac{M_b - M_a}{M_b + M_a} \left( \sum_{i=1}^{n_a} \sum_{j=n_a+1}^{n} D_j \left( \cos(\theta_y + \Delta \theta_{MB}^{\text{ue}}) \left( \frac{\partial \theta_y}{\partial P_{\text{equiv}}} + \frac{\partial \Delta \theta_{AB}^{\text{cl}}}{\partial P_{\text{equiv}}} \right) \right) \\
- \cos(\theta_y + \Delta \theta_{AB}) \left( \frac{\partial \theta_y}{\partial P_{\text{equiv}}} + \frac{\partial \Delta \theta_{AB}^{\text{cl}}}{\partial P_{\text{equiv}}} \right) \right) \right)
\]

(4.2)

The methods to obtain
\[
\frac{\partial \theta_y}{\partial P_{\text{equiv}}}, \quad \frac{\partial \theta}{\partial P_{\text{equiv}}}, \quad \frac{\partial \theta_{AB}^{\text{cl}}}{\partial P_{\text{equiv}}}, \quad \frac{\partial \theta_{AB}^{\text{cl}}}{\partial P_{\text{equiv}}}
\]

are described in detail in Chapter III.

The assessment of the degree of system vulnerability is done using fuzzy-logic relationships where the inputs are the energy margin index and the sensitivity value to the equivalent power. The classification is performed according to the following linguistic levels:

\[
\Delta V =
\]

- High energy margin level (HM)
- Low energy margin level (LM)
- Unacceptable energy margin level (UM)

\[
\frac{\partial \Delta V}{\partial P_{\text{equiv}}} =
\]

- Positive and high sensitivity (PHS)
• Positive and low sensitivity (PLS)
• Negative and high sensitivity (NHS)
• Negative and low sensitivity (NLS)

As the border between classes is not “Crisp”, this becomes the first opportunity in this analysis to use the fuzzy set theory.

It is important to note that the classification is done for a particular contingency, without regards to its probability of occurrence.

The corresponding membership functions selected for both indexes \( \Delta V, \partial \Delta V / \partial P_{ppl} \) are shown in Figure 4.1.

The degrees of memberships are defined as follows:

a) The membership set \( \mu_{HM} \) of acceptable or high energy margin \( HM \) is defined as

\[
\mu_{HM} = \begin{cases} 
1 \text{ if } \Delta V \geq \Delta V_H \\
\frac{\Delta V - \Delta V_{\min}}{\Delta V_H - \Delta V_{\min}} \text{ if } \Delta V_{\min} \leq \Delta V \leq \Delta V_H \\
0 \text{ if } \Delta V \leq \Delta V_{\min}
\end{cases}
\]  

(4.4)

Where \( \Delta V_H \) is the threshold for the acceptable value of \( \Delta V \), and \( \Delta V_{\min} \) is the minimum secure level (Figure 4.1).
b) The membership set \( \mu_{LM} \) for low energy level margin \( LM \) is defined as

\[
\mu_{LM} = \begin{cases} 
0 & \text{if } \Delta V \leq 0 \\
\frac{\Delta V}{\Delta V_{\text{min}}} & \text{if } 0 \leq \Delta V \leq \Delta V_{\text{min}} \\
\frac{\Delta V - \Delta V_{\text{min}}}{\Delta V_{H} - \Delta V_{\text{min}}} & \text{if } \Delta V_{\text{min}} \leq \Delta V \leq \Delta V_{H} \\
0 & \text{if } \Delta V \geq \Delta V_{H}
\end{cases}
\]  

(4.5)

c) The membership set \( \mu_{UM} \) for the unacceptable energy margin level \( UM \) is defined as

\[
\mu_{UM} = \begin{cases} 
1 & \text{if } \Delta V \leq 0 \\
1 - \frac{\Delta V}{\Delta V_{\text{min}}} & \text{if } 0 \leq \Delta V \leq \Delta V_{\text{min}} \\
0 & \text{if } \Delta V \geq \Delta V_{m}
\end{cases}
\]  

(4.6)

The fuzzy sets membership functions for the high level and low level sensitivities \( \frac{\partial \Delta V}{\partial P_{\text{eqiv}}} \) (positive and negative) are obtained as follows.
a) Positive and high sensitivity \( PHS \)

\[
\mu_{PHS} = \begin{cases} 
1 & \text{for } \partial \Delta V / \partial P_{\text{equiv}} \geq S_H \\
\frac{\partial \Delta V}{\partial P} & \text{for } 0 \leq \partial \Delta V / \partial P_{\text{equiv}} \leq S_H \\
0 & \text{for } \partial \Delta V / \partial P \leq 0
\end{cases}
\]

(4.7)

b) Negative and high sensitivities \( NHS \)

\[
\mu_{NHS} = \begin{cases} 
1 & \text{for } \partial \Delta V / \partial P_{\text{equiv}} \leq -S_H \\
-\frac{\partial \Delta V}{\partial P} & \text{for } -S_H \leq \partial \Delta V / \partial P_{\text{equiv}} \leq 0 \\
0 & \text{for } \partial \Delta V / \partial P_{\text{equiv}} \geq 0
\end{cases}
\]

(4.8)

c) Positive and low sensitivities \( PLS \)

\[
\mu_{PLS} = \begin{cases} 
0 & \text{for } \partial \Delta V / \partial P_{\text{equiv}} \geq S_H \\
\frac{S_H - \partial \Delta V}{\partial P} & \text{for } 0 \leq \partial \Delta V / \partial P_{\text{equiv}} \leq S_H \\
\text{for } \partial \Delta V / \partial P_{\text{equiv}} < 0
\end{cases}
\]

(4.9)
d) Negative and low sensitivities NLS

\[
\mu_{NLS} = \begin{cases} 
0 \ldots \ldots \text{for} \ldots \ldots \frac{\partial \Delta V}{\partial P_{\text{equiv}}} \leq -S_H \\
S_H + \frac{\partial \Delta V}{\partial P} & \ldots \ldots \text{for} \ldots \ldots -S_H \leq \frac{\partial \Delta V}{\partial P_{\text{equiv}}} \leq 0 \\
0 \ldots \ldots \text{for} \ldots \ldots \frac{\partial \Delta V}{\partial P_{\text{equiv}}} > 0 
\end{cases}
\]

(4.10)

For the sensitivity definitions a dead band around zero is given, where if the sensitivity value falls inside this dead-band the security index is not evaluated during this evaluation cycle. If \( \frac{\partial \Delta V}{\partial P_{\text{equiv}}} < S_{db} \), the system conditions are similar to those in the previous system condition and therefore the security classifier is not activated.

![Figure 4.1: Membership Functions for the Security Classifier](image)

The shape of the membership functions will reflect the experience of the operators on what is unacceptable, low, high, rather high, for example. The threshold value for \( \Delta V \) and...
\( \partial \Delta V / \partial P_{\text{equiv}} \) reflects either the operator's experience or the utility's policy, as described below.

### 4.1.1 Evaluation of the Threshold and Unacceptable Values

In the absence of prior experience within the utility it is possible to obtain a "feeling" for the threshold values for \( \Delta V_H \) and \( \Delta V_{\text{min}} \). Consider (Figure 4.2), which shows the changes in the energy margin index with the control parameter \( P_{\text{equiv}} \) or some other key parameter \( p \).

This curve is in general very laborious to obtain, but it can be linearised at the operating point where an approximate maximum value for \( \Delta p \) \((\Delta p_{\text{max}})\) that makes \( \Delta V = 0 \) is given by:

\[
\Delta V^0 + \frac{\partial \Delta V}{\partial p} \bigg|_0 \Delta p_{\text{max}} = 0
\]

(4.11)
where

\[ p_{\text{max}} = p^0 + \Delta p_{\text{max}} \]  
(4.12)

With this equation a judgement call can be made on how heavily one may permit the system to be loaded, i.e., how close to \( p_{\text{max}} \). If we say that we allow between 80% or 90%, then we have that the \( p_{\text{lim}} (p_{\text{lim}}) \) is defined by choosing

\[ \Delta p_{\text{lim}} = \alpha p_{\text{max}} \quad 0.8 < \alpha < 0.9 \]  
(4.13)

and from equation (4.11),

\[ \Delta V_{\text{min}} = \Delta V^o + \frac{\partial \Delta V}{\partial p} \bigg|_o (p_{\text{lim}} - p_o) \]  
(4.14)

The value of \( \Delta V_H \) can be chosen arbitrarily, although it is ultimately a function of the company's policy on system security. In general, \( \Delta V_H \) should not be set too high, as this would imply an underloading of the system. A good choice for \( \Delta V_H \) is the value of \( \Delta V \) corresponding to the economic state of a predetermined load (i.e., if \( p_o \) is the economical steady state of the operating point, the corresponding value for \( \Delta V_o \) could be chosen as \( \Delta V_H \)). If several contingencies are simultaneously involved the threshold for \( \Delta V \) would be the maximum value among all of them. Once defined \( \Delta V_H \), the sensitivity threshold value is given by,

\[ \left. \frac{\partial \Delta V}{\partial p} \right|_H = - \frac{\Delta V_H}{(p_{\text{max}} - p_o)} \]  
(4.15)
Operator's experience plays an important role in the selection of the thresholds values. Also, the membership values can be defined directly by experts after the study of a large number of cases.

4.2 Definition of Performance Criterion

The problem to solve consists of the selection of a membership scale to provide fuzzy conclusions regarding system security conditions. In Chapter II a classification for the different security states given in [1] was described.

In these fuzzy evaluations, the security state is classified into four levels, but additional security levels can be included depending on a particular company's policy.

The linguistic indices that classify the system into four levels are:

a) Completely Secure (CS): where no preventive control action is required.

b) Insecure (IS): where a control action is mandatory.

c) Alarm (AM): for which a preventive control action is required.

d) Alert (AT): where it is necessary to continue monitoring the system, where a further action may be recommended.

Using the levels above and the membership functions for both inputs, ($\Delta V$ and $\partial\Delta V/\partial Pequiv$), we can define the following set of rules that classify the status of the system:

a) IF $\Delta V_i = HM$ and $\partial\Delta V/\partial Pequiv = PHS$, THEN CS

b) IF $\Delta V_i = HM$ and $\partial\Delta V/\partial Pequiv = PLS$, THEN CS

c) IF $\Delta V_i = HM$ and $\partial\Delta V/\partial Pequiv = NHS$, THEN AM

d) IF $\Delta V_i = HM$ and $\partial\Delta V/\partial Pequiv = NLS$, THEN AT

e) IF $\Delta V_i = LM$ and $\partial\Delta V/\partial Pequiv = PHS$, THEN CS

f) IF $\Delta V_i = LM$ and $\partial\Delta V/\partial Pequiv = PLS$, THEN CS
The conditions above are summarised in the security classifier matrix of Table 4.1 below:

Table 4.1

Security Classifier Matrix

<table>
<thead>
<tr>
<th>AV</th>
<th>PHS</th>
<th>PLS</th>
<th>NHS</th>
<th>NLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HM</td>
<td>CS</td>
<td>CS</td>
<td>AM</td>
<td>AT</td>
</tr>
<tr>
<td>LM</td>
<td>CS</td>
<td>CS</td>
<td>AM</td>
<td>AT</td>
</tr>
<tr>
<td>UM</td>
<td>IS</td>
<td>IS</td>
<td>IS</td>
<td>IS</td>
</tr>
</tbody>
</table>

The degree of membership to each element of the security classifier matrix is explained taking as an example the Alarm State (AM). In this case there are two rules in the security matrix that determine if the system is in an alarm state:

Rule 1:
IF $AV$ is a high energy margin level $HM$ and $\partial AV/\partial Pequiv$ is a negative high sensitivity $NHS$.
THEN the system is in Alarm State $AM$

Rule 2:
IF $AV$ is a low energy margin level $LM$ and $\partial AV/\partial Pequiv$ is a negative high sensitivity $NHS$.
THEN the system is in Alarm State $AM$
For a given $\Delta V$ and $\partial \Delta V / \partial \text{equiv}$ condition, which has known membership values to the fuzzy sets as defined in equations (4.4) to (4.10), an operation inference rule based on Mandami's direct method is very suitable when a small number of linguistic type of rules are used (Appendix 2). For each of the states under which the system is classified a membership value is obtained.

For rule 1, the membership value is given by:

$$\mu_{AM-1} = \min(\mu_{HM}(\Delta V), \mu_{NHS}(\partial \Delta V / \partial \text{equiv}))$$

For rule 2, the membership value is given by:

$$\mu_{AM-2} = \min(\mu_{LM}(\Delta V), \mu_{NHS}(\partial \Delta V / \partial \text{equiv}))$$

The final membership value for the alarm state will be given by:

$$\mu_{AM} = \max(\mu_{AM-1}, \mu_{AM-2})$$

Following this procedure, which is called the min-max compositional inference rule, the degree of belonging to the alarm state is obtained as:

$$\mu_{AM} = \max(\mu_{AM-1}) \quad i = 1..r_{AM}$$

$$r_{AM} = \text{number of rules that have as a result an Alarm State } AM$$

Similarly, we can calculate the membership function for the remainder of the three states.

Considering,

$$\mu_{IS} = \max(\mu_{IS-1}) \quad i = 1..r_{IS}$$

$$\mu_{AT} = \max(\mu_{AT-1}) \quad i = 1..r_{AT}$$
\[ \mu_{CS} = \max (\mu_{CS,i}) \quad i = 1..r_{CS} \]  

(4.19)

These states are summarised in the so-called security vector, given by

\[ \mu_{state} = (\mu_{CS}, \mu_{AT}, \mu_{AM}, \mu_{IS}) \]  

(4.20)

Where, \( \mu_{CS}, \mu_{AT}, \mu_{AM}, \mu_{IS} \) are the membership functions for the completely secure, alert, alarm and insecure states, respectively. This singleton component vector quantifies the system security between the several security levels. These values are then applied to the membership functions for the output index (Figure 4.4) and a final security fuzzy index (which will be used as the input for the security enhancement control loop) is obtained using the pre-process defuzzification procedure.

### 4.3 Defuzzification Procedure for the Security Classifier

In Appendix 2, the following defuzzification methods are described:

- Centre-of-area
- Centre-of-sums
- First-of-maxima defuzzification
- Middle-of-maxima
- Height method

The influence of the defuzzification method on the controller performance has been largely ignored, even though there is a general agreement that the use of the adequate defuzzification procedure is vital for fuzzy-logic evaluations [72]. There are several criteria, as pointed out in Appendix 2, which the ideal defuzzification method should satisfy. It is important to weigh these criteria in choosing the particular method to be used.
In the analysis for the security classifier, the centre-of-sum method was chosen as it satisfies the following characteristics, as described in Appendix 2:

- Continuity
- Disambiguity
- Plausibility
- Computational simplicity

If the trapezoidal membership functions shown in Figure 4.3 are used, the method allows for fast numerical pre-processing and it is therefore suitable for online applications.

![Security Index Membership Function](image)

**Figure 4.3: Security Index Membership Function**

4.3.1 Centre-of-Sums Method for Security Classifier Index

When the security vector obtained in the first step of the security classifier is applied to the membership function of Figure 4.3, the area to be defuzzified is graphically shown in Figure 4.4 for a particular set of $\mu_{CS}, \mu_{AT}, \mu_{AM}, \mu_{IS}$ (Appendix 2).
Figure 4.4: Defuzzification Security Index

Mathematically the centre of sums is given by:

\[ u^* = \frac{\sum_{i=1}^{f} \sum_{k=1}^{n} \mu_k(u_i)u_i}{\sum_{i=1}^{f} \sum_{k=1}^{n} \mu_k(u_i)u_i} \]

(4.21)

And for the continuous case:

\[ u^* = \frac{\int u_i \sum_{k=1}^{n} \mu_k(u)u_i}{\int \sum_{k=1}^{n} \mu_k(u)u_i} \]

(4.22)

What the pre-processing consists of is in obtaining the centre of gravity of each membership function independently as a function of the respective index of the security vector \( \mu_{state} = (\mu_{CS}, \mu_{AT}, \mu_{AM}, \mu_{IS}) \), as shown in Figure 4.5.
Figure 4.5: Independent Centre-of-Sums Calculation

Once this is performed, the final index is obtained by adding the independent results.

The final value for the security index is then given by:

\[
SI = \frac{\int u\mu_{CS}(u)du + \int u\mu_{AM}(u)du + \int u\mu_{AT}(u)du + \int u\mu_{IS}(u)du}{\int \mu_{CS}(u)du + \int \mu_{AM}(u)du + \int \mu_{AT}(u)du + \int \mu_{IS}(u)du}
\]  

(4.25)
Once the defuzzification procedure is carried out, a crisp security index is obtained when equations (4.23) and (4.24) are substitute in (4.25):

\[
SI = \frac{1}{6}\left( -\mu_{CS}^3 + 21\mu_{CS}^2 - 9\mu_{CS}^2 + 12\mu_{is}^2 - 3\mu_{is}^2 - 2\mu_{is}^2 + 24\mu_{AM} - 12\mu_{AM}^2 + 36\mu_{AT} - 18\mu_{AT}^2 \right)
\]

\[
= \frac{1}{4\mu_{CS}^2 - 2\mu_{CS}^2 + 8\mu_{is}^2 - 2\mu_{is}^2 + 8\mu_{AM}^2 - 4\mu_{AM}^2 + 8\mu_{AT}^2 - 4\mu_{AT}^2}
\]

\[(4.26)\]

Even though several forms of membership functions could be used, trapezoidal shapes were adopted for their simplicity and speed in the defuzzification process.

If during the evaluation process, the value of the security index is above a predefined level, any decision by the classifier as to whether or not to take a control action is delayed until the next time step when all the procedure is evaluated again for the new load condition. If the security index is below the predefined decision level, the algorithm directly proceeds to the stage of adaptive security enhancement control action.
CHAPTER V

ADAPTIVE-FUZZY-LOGIC-BASED SECURITY ENHANCEMENT CONTROL

The first step in the proposed method for assessing and improving system vulnerability, was the determination of the security level using the security classifier (Chapter IV), where as a final result the value of a security index is obtained. If during the evaluation process the value of the security index is found to exceed a predefined level, any corrective action in the system is delayed until the next time step when the whole procedure has been evaluated again for the new load condition. If the security index is below the predefined decision level, the algorithm proceeds immediately with the following block of security enhancement control action.

5.1 Output Adjustment by Approximate Reasoning

Two types of control actions are considered in the algorithm: generator voltage control and generator power output control. Even though voltage control is not a common practice for transient security enhancement, it can be considered as a preventive type of measure for increasing the level of security margin. As power and voltage controls can be adjusted continuously, they offer the best option for preventive control actions. Nonetheless, the method proposed here is general and allows for the consideration of other control actions such as reactor switching, series compensation, SVC, among others.

In order to develop the fuzzy security enhancement algorithm, the sensitivity of the energy margin with respect to each control parameter has to be obtained first:
\[
S_{P_i} = \left[ \frac{\partial \Delta V}{\partial P_i} \right] \\
S_{E_i} = \left[ \frac{\partial \Delta V}{\partial E_i} \right]
\]

(5.1)

where

\[ P_i = \text{power output of generator } i \]

\[ E_i = \text{internal voltage of generator } i \]

The above sensitivity factors can be obtained by either taking the partial derivatives of the energy margin, as shown in the general sensitivity equation (3.19), or by making a slight change in \( P_i \) or \( E_i \) and evaluated the changes of the energy margin. Due to the existence of an analytical expression for the energy margin as a function of the control parameters, the first method is used. This is one of the main advantages of the two-machine formulation proposed, as this method preserves the information about the generators and topologic parameters, and permits the analytical evaluation of the sensitivity expressions.

Using \( S_{E_i} \) and \( S_{P_i} \) and linearising the energy margin function at the operating point it is possible to estimate the energy margin increase \( \Delta(\Delta V) \) produced by a variation in either one or both of the control outputs \( E_u, P_i \):

\[
\Delta(\Delta V) = \sum_{i=1}^{\text{numgen}} \left( \left[ \frac{\partial \Delta V}{\partial P_i} \right]_{0} \right) \Delta P_i + \sum_{i=1}^{\text{numgen}} \left( \left[ \frac{\partial \Delta V}{\partial E_i} \right]_{0} \right) \Delta E_i
\]

(5.2)

The formulas above hold for systems that are linear or linearisable around the operating point. For highly non-linear situations, the second order sensitivity coefficients,
\[ S'_{P_i} = \frac{\partial S_{P_i}}{\partial P_i} = \frac{\partial^2 \Delta V}{\partial P_i^2} \]

\[ S'_{E_i} = \frac{\partial S_{E_i}}{\partial E_i} = \frac{\partial^2 \Delta V}{\partial E_i^2} \]

are necessary to preserve good accuracy. The use of \( S'_{P_i} \) or \( S'_{E_i} \) yields

\[
\Delta(\Delta V) = \sum_{i=1}^{\text{numgen}} S_{P_i} \Delta P_i + 0.5 S'_{P_i} (\Delta P_i)^2 + \sum_{i=1}^{\text{numgen}} S_{E_i} \Delta E_i + 0.5 S'_{E_i} (\Delta E_i)^2
\]

(5.4)

In this work, first order approximations are used and an iterative procedure is performed to achieve the desired final energy margin value for this non-linear evaluation.

Physical equipment limitations are taken into account with the use of fuzzy logic techniques, in order to incorporate these restrictions into the selection of the control settings.

The overall logic of the control can be described as follows:

IF security enhancement is needed, (index below a limit).
AND a generator is controllable for effective security improvement, (sensitivity values).
AND there is adequate margin of output adjustment to enhance the security level.
THEN adjust the output of the controller.

As in the case of the security classifier, fuzzy sets are defined by linear membership functions for the energy margin level, the sensitivity and the availability of the control system.
5.2 Membership Function Definition for Security Enhancement Evaluations

The IF-THEN rules are translated into the evaluation of the following membership functions (Figure 5.1):

a) Energy margin membership function: corresponds to the same function calculated for the security classifier: unacceptable margin ($UM$), low margin ($LM$), and high margin ($HM$).

b) Sensitivity membership function: represents the sensitivity of the energy margin index with respect to the power and with respect to the voltage for the specified generator. The sensitivity can be of two types: negative and high sensitivities ($NHS$) and positive and high sensitivities ($PHS$). In practical cases a dead-band interval $S_d$ is allowed in the membership function because practically no control effect is obtained when the sensitivity value is too small. Analytically this membership function are given by:

- Positive and High Sensitivity $PHS$

$$
\mu_{PHS} = \begin{cases} 
1 & \text{for } \frac{\partial \Delta V}{\partial \phi} \geq A, \\
\frac{\Delta V - S_d}{\phi} & \text{for } S_d \leq \frac{\partial \Delta V}{\partial \phi} \\
\frac{A_i - S_d}{\phi} & \text{for } \frac{\partial \Delta V}{\partial \phi} \leq S_d \\
0 & \text{for } \frac{\partial \Delta V}{\partial \phi} \leq S_d 
\end{cases}
$$

(5.5)
• Negative and High Sensitivities NHS

\[
\mu_{\text{NHS}} = \begin{cases} 
1 & \text{for } \frac{\partial \Delta V}{\partial p} \leq -A, \\
\frac{S_d + \frac{\partial \Delta V}{\partial p}}{S_d - A_i} & \text{for } -A \leq \frac{\partial \Delta V}{\partial p} \leq -S_d, \\
0 & \text{for } \frac{\partial \Delta V}{\partial p} \geq -S_d
\end{cases}
\]

(5.6)

These equations are valid for both controls by substituting parameter \( p \) with \( P_i \) (sensitivity membership functions with respect to power \( P_i \)) or with \( E_i \) (sensitivity membership with respect to voltage \( E_i \)).

c) Margin of Controller: even in the presence of high sensitivities no control effect can be executed if the controllers are already at or near their limits. There are operational and physical limits in power and voltage control given by:

\[
P_{i\text{-min}} < P_i < P_{i\text{-max}} \\
V_{i\text{-min}} < V_i < V_{i\text{-max}}
\]

where

- \( P_{i\text{-max}} \): maximum power output of generator \( i \)
- \( P_{i\text{-min}} \): minimum power output of generator \( i \)
- \( V_{i\text{-max}} \): maximum voltage allowed in the external generator bus
- \( V_{i\text{-min}} \): minimum voltage allowed in the external generator bus

The methodology assumes that the control is fully available if the adjustable margin \( M_i \) exceeds the desired change in the output (voltage or power). The least desirable generator to be controlled is the one whose margin is smaller than a control dead-band \( U_d \) (for voltage) or \( P_d \) (for power), which would be the case if the generators
are operating already near their physical limits. The conditions of control are shown by the following fuzzy sets applicable for both voltage and power control:

- Lower margin (ML) controllability

\[
\mu_{MLi} = \begin{cases} 
1 & \text{for} \quad M_{i} \leq R_{i} \\
\frac{U_{d} + M_{i}}{U_{d} - R_{i}} & \text{for} \quad -R_{i} \leq M_{i} \leq -U_{d} \\
0 & \text{for} \quad M_{i} \leq -U_{d}
\end{cases}
\]

(5.7)

where \( M_{i} \) is the adjustable margin of output in “lower direction” and given by:

\[
M_{i} = \begin{bmatrix} V_{i}^{\min} - V_{i} \\ P_{i}^{\min} - P_{i} \end{bmatrix}
\]

(5.8)

and \( R_{i} \) is the desired output adjustment such as:

\[
R_{i} = \frac{\Delta V_{D} - \Delta V_{o}}{\left( \frac{\partial V}{\partial p_{i}} \right)_{o}}
\]

(5.9)

where

\( \Delta V_{D} = \) Desire energy margin level.

\( \Delta V_{o} = \) Operating point energy margin level.
• Raise margin (ML) controllability.

\[
\mu_{MRLi} = \begin{cases} 
1 & \text{for } M_i \geq R_i \\
\frac{M_i - U_d}{R_i - U_d} & \text{for } U_d \leq M_i \leq R_i \\
0 & \text{for } M_i \leq U_d 
\end{cases}
\]

(5.10)

where \( M_i \) is the adjustable margin of output in “rising direction” and given by:

\[
M_i = \begin{cases} 
V_{i}^{\max} - V_i \\
P_{i}^{\max} - P_i 
\end{cases}
\]

(5.11)

Even though the aim of this research is to produce a controller that restores the desired energy margin level, and no multi-objective simultaneous security and cost optimisation is developed, an indirectly low-cost control strategy is obtained. As the original starting point is the economical operating point the strategy favours changes in generators whose outputs (power or voltage) are farther away from its limits. It can be inferred that the control will preferably move those generators that are around their nominal operating point and are most sensitive. Minimising the moves upward for those generators highly loaded and downward for those generators lightly loaded. In general, a small variation in the total cost should be expected. Cost factor considerations will be considered in future research, so that the controller output is also a minimum cost.
Figure 5.1: Membership Functions for the Fuzzy Logic Control
5.3 Security Enhancement Based on Approximate Reasoning

For the security enhancement control, we can establish, the following rules for raising and lowering power or voltage commands, as was done for the case of the security classifier. In this case, Takagi and Sugeno adaptability formulas (Appendix 2) are used, as there is a linear relation between the input \((\Delta V, \partial \Delta V / \partial t)\) and output \((P_i, E_i)\) elements, thus

Control Rules:

\[ R_1: \quad \text{IF } \Delta V \text{ belongs to } LM \text{ with a degree of } \mu_{LM} \]
and \(\partial \Delta V / \partial t\) belongs to \(PHS\) with a degree of \(\mu_{PHS}\)
and \(M_i\) belongs to \(MR\) with a degree of \(\mu_{MR}\)
Then: \(WR = \mu_{LM} \mu_{PHS} \mu_{MR}\)

\[ R_2: \quad \text{IF } \Delta V \text{ belongs to } UM \text{ with a degree of } \mu_{UM} \]
and \(\partial \Delta V / \partial t\) belongs to \(PHS\) with a degree of \(\mu_{PHS}\)
and \(M_i\) belongs to \(MR\) with a degree of \(\mu_{MR}\)
Then: \(WR = \mu_{UM} \mu_{PHS} \mu_{MR}\)

\[ R_3: \quad \text{IF } \Delta V \text{ belongs to } LM \text{ with a degree of } \mu_{LM} \]
and \(\partial \Delta V / \partial t\) belongs to \(NHS\) with a degree of \(\mu_{NHS}\)
and \(M_i\) belongs to \(ML\) with a degree of \(\mu_{ML}\)
Then: \(WL = \mu_{LM} \mu_{NHS} \mu_{ML}\)

\[ R_4: \quad \text{IF } \Delta V \text{ belongs to } UM \text{ with a degree of } \mu_{UM} \]
and \(\partial \Delta V / \partial t\) belongs to \(NHS\) with a degree of \(\mu_{NHS}\)
and \(M_i\) belongs to \(ML\) with a degree of \(\mu_{ML}\)
Then: \(WL = \mu_{UM} \mu_{NHS} \mu_{ML}\)
$WR_i$ and $WL_i$ are proportional to the raise and lower output adjustment for the controller at generator $i$ respectively, and $p_i$ is power or voltage signal (depending on the type of control evaluated) with $i = 2,3,...n$ ($n =$ total number of control generators).

One form of adjusting the control signal for generator $i$ would be:

$$\Delta p_i = \left( \frac{WR_{tot,i} + WL_{tot,i}}{\sum_{j=2}^{numgen} WR_{tot,j} + \sum_{j=2}^{numgen} WL_{tot,j}} \right) \frac{(\Delta V_D - \Delta V_o)}{\frac{\partial \Delta V}{\partial p_i}}$$

With:

$$WR_{tot,i} = WR_i|_{Rule1} + WR_i|_{Rule2}$$
$$WL_{tot,i} = WL_i|_{Rule3} + WL_i|_{Rule4}$$

$numgen =$ number of control generator

$j = 1$ is the slack bus

The term in brackets represents the sharing of the control action between generators to reduce the error $(\Delta V_D - \Delta V_o)$.

In the case of a linear system, this evaluation would be sufficient to take the energy margin to the required level. The present case is a non-linear system. The steady state load-flow conditions also have to be revised as variations in one or more of the output parameters affect the losses and power distribution, even in the event of only one contingency and load condition analysis. Therefore, this action will not in all likelihood take the system to the desired effective security level. Independent of this condition of non-linearity, another drawback of the standard straightforward approach is that the threshold values for the membership functions are preset and therefore do not guarantee an effective control for all loads and all contingencies. The solution to this drawback is the
development of an adaptive fuzzy logic controller that has the flexibility to accommodate to these constantly changing situations.

5.4 Adaptive Fuzzy Logic Controller

Since the conditions in the power system change continuously and different contingencies are evaluated, the approximate reasoning control algorithm proposed needs to be "retuned" for optimum performance at any given situation. This can be achieved with an adaptive controller that automatically modifies itself to match the system condition. There are a number of parameters that can be varied in the algorithm to modify the controller's performance. A brief explanation is given below.

The emphasis is on evaluating and adapting parameters of the fuzzy inference controller. It is worth indicating that there are two very distinct aspects to the controller. One refers to its fuzzy logic decisions and the other denotes traditional control capabilities. In general:

a) The fuzzy controller must exhibit knowledge type of rules that have to be organised and accessed in a logical manner.

b) At the same time, the fuzzy controller must be a feedback controller to allow for a close-loop adaptive procedure.

In the present study, both aspects are included. The feedback mechanism consists of a consecutive evaluation of the energy margin level and comparison with the desired value, as can be shown in the functional block diagram of the process in Figure 5.2.
Adaptive inference generally contains two extra components on top of the standard mechanism itself. The first is a “process monitor” that detects changes in the process characteristics. This usually takes the form of a performance measure that assesses how well the controller is working. The second component is the adaptation mechanism itself, which uses information passed by the process monitor to update the controller parameters and to adapt the controller to the changing characteristic of the power system.

5.4.1 Adaptation Mechanism

A fuzzy knowledge based controller FKBC contains a number of parameters that can be altered to modify the controller performance. The adaptation mechanisms are responsible for this task. Specifically, the adaptation mechanism can modify:

- The scaling factors for each variable
- The fuzzy set representing the meaning of linguistic values
- The if-then rules
A brief description of the effect of these changes follows:

a) The scaling factor: altering the scaling factor changes the classification of an input value. This varies the sensitivity of the controller to the input and is equivalent to changes in the controller gain for classical controls. In the fuzzy rules presented for the security enhancement algorithm, this translates in a change in $WR$ or $WL$. This procedure is shown for a membership to the set “small” in Figure 5.3.

![Figure 5.3: Effect of Altering Scaling Factor](image)

Clearly, a value such as 3 that would not be classified as small in adjustment A would be classified as such in adjustments B and C.

b) Altering shape: another gain tuning mechanism is to alter the shape of the fuzzy sets. They can be achieved by increasing the sensitivity of the controller to smaller values. Whereas altering the scaling factors alters the gain uniformly across the entire input universe, changing the shape of specific fuzzy sets allows the gain to be modified within specific regions of that universe.

c) Modifying the fuzzy set definition: the performance monitor assesses the controller’s performance on the basis of the error and the change-of-error...
of the process output variables based on what is desirable from a regulatory control perspective. The fuzzy set definitions are changed accordingly.

5.5 Iterative Control Procedures

In this work two iterative adaptive strategies were tested. In the first strategy, the required correction in the process output was sought only by changes in the process input variables. This can be done by an iterative procedure through feedback of the selected adjusted generator power or voltage $P_i$ or $E_i$, until the energy margin matches the desired level.

![Figure 5.4: Iterative Non-Adaptive Procedure](image)

Making an analogy with steady state evaluations, the algorithm is similar to solving the load flow equations through an iterative solution method.

For the power and voltage control parameters:

$$E_i(t + 1) = K(\mu) \left( \frac{\Delta V_i - \Delta V_D}{\partial \Delta V/\partial E_i} \right) + E_i(t)$$

(5.13)
Where $K(\mu)$ is a function of the membership values at the operating point (no scaling of the membership functions).

The other method is a self-tuning oriented method. This iterative procedure is combined with variation of the function $K(\mu)$, through a scaling of the sensitivity threshold values, as described below.

5.6 Adaptive Fuzzy Control Design for Security Evaluation

In this case we have the following:

- Single output: Energy margin index ($\Delta V$).
- Multiple input: $P_i$, $E_i$ (power and voltage output from generator $i$).
- Non-linear system.
- Discrete time modelling.

Where in the case of the power controller:

$$
\Delta V(t + 1) = \Delta V(t) + \sum_{i=1}^{\text{nugen}} \left( \frac{\partial \Delta V}{\partial P_i} \right) (P_i(t + 1) - P_i(t))
$$

and

$$
\Delta P_i = P_i(t + 1) - P_i(t)
$$

(5.14)

$t$: iteration counter which is increased until the calculation stops when the error is less than a specified tolerance.

As a first approach to the adaptive procedure, a scaling algorithm is proposed. In this fuzzy logic approach, the threshold values for the sensitivity membership functions are altered using optimisation procedures, so that the desired energy margin level is reached.
5.6.1 Optimisation Procedure

Two optimisation procedures were evaluated to minimise the square of the error function between the desired energy margin level and the actual value.

\[
Error = \frac{1}{2} (\Delta V - \Delta V_D)^2
\]

(5.15)

In this study, the objective function parameters to be altered are the threshold values \(A_i\) of the membership functions for the sensitivity of each control generator.

In order to write the function to be minimised as a function of the parameter \(A\), it is necessary to re-write equation (5.14) as a function of \(\mu_{\Delta V_{AP}}\), and evaluate for the power control exclusively, as follows:

\[
\Delta (\Delta V) = \sum_{s=2}^{numgen} \left( \frac{\partial \Delta V}{\partial P_g} \right)_o \Delta P_g + \left( \frac{\partial \Delta V}{\partial P_1} \right)_o \Delta P_1 = \Delta V(t+1) - \Delta V(t)
\]

(5.16)

Note that the slack bus contribution is separated because it is not considered to be a control generator, as it is needed to compensate for the losses.

Since,

\[
\Delta (\Delta V) = \Delta V(t+1) - \Delta V_D = Error
\]

(5.17)

then

\[
Error = \frac{1}{2} \left( \sum_{s=2}^{numgen} \left( \frac{\partial \Delta V}{\partial P_g} \right)_o \Delta P_g + \left( \frac{\partial \Delta V}{\partial P_1} \right)_o \Delta P_1 \right)^2
\]

(5.18)
using (5.12)

\[
\Delta P_g = \frac{\sum_{i=1}^{\text{rules}} \left( \frac{\Delta V_D - \Delta V}{\frac{\partial \Delta V}{\partial P_g}} \right) \mu_{ig}}{\sum_{g=2}^{\text{numgen rules}} \sum_{i=1}^{\text{rules}} \mu_{ig}}
\]

where

\[
\mu_{ig} = K_{ig}(t) \mu_{sig}(t)
\]

(5.19)

\[
K_{ig}(t) = \mu_{ig}(\Delta V) \mu_{ig}(M_i)
\]

(5.20)

\[
\mu_{ig}(\Delta V) = \text{membership value for the energy margin function of generator } g \text{ for rule } i.
\]

\[
\mu_{ig}(MR) = \text{membership value for the margin control membership function of generator } g \text{ for rule } i.
\]

\[
\mu_{sig}(MR) = \text{membership value for the sensitivity membership function of generator } g \text{ for rule } i.
\]

\[
t = \text{iterative step (t)}
\]

The membership function for the sensitivity of generator \( g \) is obtained using Figure 5.1, excluding the dead band.

\[
\mu_{sg} = \begin{cases} 
\left| \frac{\partial \Delta V}{\partial P_i} \right| S_g < A_g \\
A_g \\
1 \end{cases}
\]

(5.22)
Substituting into the error equation formula:

\[
E = \frac{1}{2} \left( \sum_{i=2}^{\text{numgen}} \left( \frac{\partial \Delta V}{\partial P_i} \right)_o \left( \sum_{g=1}^{\text{rules}} \frac{\partial \Delta V}{\partial P_i} K_{gi} \frac{|S_{i_o}|}{A_i} + \frac{\partial \Delta V}{\partial P_1} \Delta P_1 \right) \right)^2
\]

(5.23)

produces the function to be minimised. The two optimisation methods use to find \( A_i \) are explained theoretically in Appendix 3, and they are:

- The steepest descent method
- The conjugate method

5.6.2 Method of Steepest Descent

One of the simplest methods for solving the optimisation problem is the steepest descent algorithm which is an iterative algorithm that seeks to decrease the value of the objective function with each iteration. At any point the objective function decreases most rapidly in the direction of the negative gradient vector of its parameters at that point. If the error function to minimise is \( E(A_i) \) \( i = 2 \ldots \text{numgen} \) the gradient descent method gives the new value \( A_i(t+1) \) as function of \( A_i(t) \) by the following equation:

\[
A_i(t+1) = A_i(t) - \lambda \frac{\partial \text{Error}}{\partial A_i}
\]

(5.24)

where : \( \frac{\partial \text{Error}}{\partial A_i} \) is the gradient of the error
and $\lambda_d$ is a value that controls how much the parameters are altered at each iteration, and is obtained through a quadratic interpolation for the specified direction (Appendix 3). As the iteration proceeds, the objective function converges to a local minimum.

The gradient evaluation was obtained analytically and programmed using Ada 95, and the optimisation subroutines were translated from a C++ version and adapted for the problem under evaluation using Ada 95.

### 5.6.3 Conjugate Method

In conjugate and variable metric methods, the goal is the same as in the steepest descent gradient method. The difference is that the direction of the search is not done in the direction of the gradient but in that of a "deflected gradient".

\[
A_i = A_i + \lambda_i r_s \\
r_s = -H_s \nabla f(A_s)
\]

(5.25)

$H_s$ = Hessian matrix of the error function

The basic idea is to build, iteratively, a good approximation of the inverse of the Hessian, as shown in Appendix 3.

The practical application of the optimisation procedures is described as follows.

### 5.7 Step-by-Step Adaptation Procedure

Once an adaptation mechanism has been selected, the optimisation procedure proceeds as follows:
• The controller rules are evaluated with the input data (steady-state operating conditions) to obtain the antecedent value $\mu_i$ for each rule and the suggested control output power $P_i$ (5.19).

• The energy margin level corresponding to these $P_i s'$ is evaluated. If this level differs from the desired value, the gradient of the error (5.15) with respect to the threshold values $A_i$ is obtained.

• A one-parameter optimisation procedure is performed to evaluate $\lambda$.

• Parameters $A_i s'$ are updated (5.24) and new $P_i s'$ are calculated.

• The new energy margin level is obtained and the new inference error (5.15) is evaluated. If this error is not within the specified tolerance, the procedure continues until convergence is achieved.

At each iteration, the power output at the slack bus is calculated. As the iteration proceeds, the objective function converges to a local minimum. For the final solution, the steady state conditions are checked.

A similar process is followed independently by the voltage control. The advantage of the voltage control is that by changing the $EMF$ values of the generators output, the system is taken to the desired level without significantly changing the power distribution of the system (only for the slack bus). Therefore, it does not produce significant deviations from the original operating point (economic solution). Unfortunately, as was indicated previously, voltage control is not sufficient to take an insecure, or alarm condition to a secure or alert condition level. In these cases, power control is needed to bring the system to a secure state.

Maximum advantage can be obtained from both controls by connecting them sequentially, where first the adaptive power loop takes the system to a secure energy margin level, but smaller than the desired one, and afterwards with the use of voltage control, the final energy margin is obtained, as shown in the block diagram of Figure 5.5.
Energy Margin Evaluation

\[ \Delta V \]

ADAPTIVE POWER OUTPUT CONTROL

\[ \Delta V < \Delta V_p \]

no

VOLTAGE OUTPUT CONTROL

Next load evaluation

Figure 5.5: Sequential Power and Voltage Control
CHAPTER VI

SIMULTANEOUS PREVENTIVE CONTROL

In Chapter V, an adaptive security enhancement algorithm was presented. This algorithm gives a preventive control action for only one specific contingency. If this corrective action is applied directly, it might in some circumstances have an adverse effect for other of the contingencies under study. Therefore, the next step in the block diagram of Figure 2.2 is to develop a control strategy which will prove to be effective but non-optimal for a set of previously chosen contingencies.

In the simultaneous evaluations, several aspects have to be considered:

a) Stability should be assured for a defined number of contingencies, based on several criteria, among them: the probability of the fault occurrence, severity importance, among others.

b) For the contingencies selected, a sub-optimal control strategy is obtained and accepted for the given operating point. This strategy should assure the security status for all credible contingencies under study.

The scheme to be applied should maximise the number of contingencies for which the system is classified into a secure state, independently of the final specific value of the energy margin level. This implies that a neighbourhood around the desired level in which the security margin level lies about is allowed. In doing so, the fact that there are going to be contingencies with completely unrelated security domains, for which there is no common control strategy that can possibly be applied, is accepted. A decision that takes into account other criteria, such as, cost, steady-state conditions, for example has to be made by the system operator.

In this work, a preventive simultaneous control strategy is developed for a number of previously selected contingencies. These contingencies have almost the same probability of occurrence. The effectiveness of the method was verified for up to four contingencies for
the Iowa system (see Chapter VII). In this chapter, it is demonstrated that the proposed procedure increases simultaneously the energy margin level for two contingencies, taking the system to a secure state for both cases.

As a final aspect in this chapter, fast techniques are given in order to create the three different \([Y_{bus}]\) matrices involved (pre-fault, fault and post-fault) for all the contingencies and for each new load condition (external loop of the block diagram for security enhancement and control of Figure 2.2).

6.1 Block Diagram of the Proposed Preventive Control Algorithm

Figure 6.1 shows the block diagram for the proposed simultaneous control algorithm. An explanation of the steps involved follows:

a) A screening process for the contingencies has previously been done, as a result, a set of contingencies with similar degree of occurrence have been selected.

b) For each contingency \(z\), the power control strategy that takes the energy margin value to the desired level is obtained using the method described in Chapter V:

\[
P_{ij} = \text{selected final power output of generator } i, \text{ for contingency } z\]

\[
i = 2..\text{numgen}
\]

c) An average of the output power obtained in b) for each generator when evaluating all the contingencies is calculated:

\[
P_i = \frac{1}{numcon} \sum_{z=1}^{numcon} P_{ij}^z
\]

\(numcon = \text{number of contingencies evaluated}\)
These powers constitute the new set of initial conditions in step b.

d) The feedback or iterative process eventually converges after several iterations. In order to speed-up the process, the following consideration is introduced. After a selected number of iterations \( l \) are executed (between 2 or 3), the power output for the generators is calculated by a weighted average of the power of each generator for each contingency, where:

\[
P_{ij+1} = \frac{\sum_{j=1}^{numcon} w_{ij} P_{ij}'}{\sum_{j=1}^{numcon} w_{ij}}
\]

with,

\[
w_{ij} = \text{abs} \left[ \frac{S_{ij}'}{\max_{j=1..numcon} (S_{ij}')} \right]
\]

(6.2)

with,

\( P_{ij}' \) : output power of generator \( i \) for contingency \( j \) in iteration number \( l \)

\( S_{ij}' \) : sensitivity of generator \( i \) for contingency \( j \) in iteration number \( l \)

\( w_{ij} \) : weighting factor
If a generator is classified as non-critical for all the contingencies, the power given by (6.2) is similar to the simple average of (6.1). These final power outputs are applied to the system and if it classifies the system for all contingencies as secure the process ends, otherwise, the adaptive security enhancement process continues.
Input contingency data to be evaluated simultaneously

Obtain Adaptive Power Strategy $P_{i|z}$

Obtain weighted average for Generator Power Output

Obtain with this power distribution the New Security Level

Figure 6.1: Simultaneous Preventive Control Block Diagram
6.2 Mathematical Demonstration

In this section, a mathematical demonstration of the how and why the simultaneous control process described in the previous section is outlined. For simplicity, only two contingencies $A$ and $B$ are considered. Criteria to determine when two contingencies have a disjoint security space are given.

From equation (3.23), we know that for contingency $A$ the new energy margin level for a power variation of $\Delta P_i$ is given by (assuming a linear process):

$$ \Delta V|_A = \Delta V_o|_A + \sum_{i=1}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i}|_A \Delta P_i|_A $$

(6.3)

If generator 1 is the slack bus, and losses are neglected, then:

$$ \Delta V|_A = \Delta V_o|_A + \sum_{i=2}^{\text{numgen}} \left( \frac{\partial \Delta V}{\partial P_i}|_A - \frac{\partial \Delta V}{\partial P_1}|_A \right) \Delta P_i|_A = \Delta V_o|_A + \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i}|_A^{*} \Delta P_i|_A $$

with

$$ \frac{\partial \Delta V}{\partial P_i}|_A^{*} = \left( \frac{\partial \Delta V}{\partial P_i}|_A - \frac{\partial \Delta V}{\partial P_1}|_A \right) $$

Similarly, for contingency $B$,

$$ \Delta V|_B = \Delta V_o|_B + \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i}|_B \Delta P_i|_B $$

(6.4)
If:

\[ \Delta P_{A}^{D} = \text{Power variation needed in order to take the energy margin level to the desired value } \Delta V_{D} \text{ for contingency } A. \]

\[ \Delta P_{B}^{D} = \text{Power change in order to take the energy margin level to the desired value } \Delta V_{D} \text{ for contingency } B. \]

and a common \( \Delta P_{i} \) is used for the power control deviation,

\[ \Delta P_{i} = \frac{1}{2} \left( \Delta P_{A}^{D} + \Delta P_{B}^{D} \right) \]  
(6.5)

Substituting (6.5) into (6.3) and (6.4),

\[ \Delta V_{A} = \Delta V_{A}^{*} + \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V_{A}^{*}}{\partial P_{i}} \left|_{A} \frac{1}{2} \left( \Delta P_{A}^{D} + \Delta P_{B}^{D} \right) \right. \]  
(6.6)

\[ \Delta V_{B} = \Delta V_{B}^{*} + \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V_{B}^{*}}{\partial P_{i}} \left|_{B} \frac{1}{2} \left( \Delta P_{A}^{D} + \Delta P_{B}^{D} \right) \right. \]  
(6.7)

Separating (6.6) and (6.7) into their independent terms, we have

\[ \Delta V_{A} = \frac{1}{2} \left( \Delta V_{A}^{*} + \Delta V_{A}^{*} \right) + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V_{A}^{*}}{\partial P_{i}} \left|_{A} \Delta P_{i}^{D} \right. \]  
(6.8a)

\[ \Delta V_{B} = \frac{1}{2} \left( \Delta V_{B}^{*} + \Delta V_{B}^{*} \right) + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V_{B}^{*}}{\partial P_{i}} \left|_{B} \Delta P_{i}^{D} \right. \]  
(6.8b)
Since,

\[
\frac{\Delta V_D}{2} = \frac{1}{2} \Delta V_o \bigg|_A + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i} \bigg|_A \Delta P_i^D |_A
\]

\[
\frac{\Delta V_D}{2} = \frac{1}{2} \Delta V_o \bigg|_B + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i} \bigg|_B \Delta P_i^D |_B
\]

then

\[
\Delta V = \frac{1}{2} \Delta V_D + \frac{1}{2} \Delta V_o \bigg|_A + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i} \bigg|_A \Delta P_i^D |_B
\]

\[
\Delta V = \frac{1}{2} \Delta V_D + \frac{1}{2} \Delta V_o \bigg|_B + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i} \bigg|_B \Delta P_i^D |_A
\]

(6.9)

(6.10)

In order to understand the process, it is necessary to evaluate the behaviour of the last term in the equalities 6.10 for different conditions of the generator. It is important to remember that the sensitivity of the critical generators has an opposite sign to that of non-critical generators, as a consequence the power variation also has opposite signs.

The following cases are considered:

a) If contingencies \( A \) and \( B \) classify the generators in the power system in exactly the same manner, between non-critical and critical, then:

\[
\frac{1}{2} \Delta V_o \bigg|_A + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i} \bigg|_A \Delta P_i^D |_B > 0
\]

\[
\frac{1}{2} \Delta V_o \bigg|_B + \frac{1}{2} \sum_{i=2}^{\text{numgen}} \frac{\partial \Delta V}{\partial P_i} \bigg|_B \Delta P_i^D |_A > 0
\]
The energy margin for both contingencies is increased in each iteration and at the end both values will be around the desired energy margin level.

b) If \( A \) and \( B \) are totally disjoint contingencies, that is, the critical generators of \( A \) are the non-critical generators of \( B \), and viceversa (very rare situation). Then:

\[
\frac{1}{2} \sum_{i=1}^{numgen} \left. \frac{\partial \Delta V}{\partial P_i} \right| \Delta P_i^{[A]} < 0
\]

\[
\frac{1}{2} \sum_{i=1}^{numgen} \left. \frac{\partial \Delta V}{\partial P_i} \right| \Delta P_i^{[B]} < 0
\]

That is, there is no simultaneous solution that achieves the desired energy margin level for all contingencies.

c) Mixed critical and non-critical generators between contingencies \( A \) and \( B \), meaning that \( A \) and \( B \) have in common several generators in the non-critical group or in the critical one.

In this case, several conditions are evaluated separately:

- If \( i \) is a critical generator for contingency \( A \) and a non-critical generator for contingency \( B \), or viceversa, then:

\[
\frac{1}{2} \sum_{i=2}^{numgen} \left. \frac{\partial \Delta V}{\partial P_i} \right| \Delta P_i^{[A]} < 0
\]

\[
\frac{1}{2} \sum_{i=1}^{numgen} \left. \frac{\partial \Delta V}{\partial P_i} \right| \Delta P_i^{[B]} < 0
\]
- If \( i \) is a critical generator for contingency \( A \) and a critical generator for contingency \( B \), then:

\[
\frac{1}{2} \sum_{i=2}^{n_{\text{gen}}} \frac{\partial \Delta V}{\partial P_i} \left|_{A} \right. \Delta P_i \left|_{B}^{D} > 0 \right.
\]

\[
\frac{1}{2} \sum_{i=2}^{n_{\text{gen}}} \frac{\partial \Delta V}{\partial P_i} \left|_{B} \right. \Delta P_i \left|_{A}^{D} > 0 \right.
\]

- If \( i \) is a non-critical generator for contingency \( A \) and a non-critical generator for contingency \( B \), then:

\[
\frac{1}{2} \sum_{i=2}^{n_{\text{gen}}} \frac{\partial \Delta V}{\partial P_i} \left|_{A} \right. \Delta P_i \left|_{B}^{D} > 0 \right.
\]

\[
\frac{1}{2} \sum_{i=2}^{n_{\text{gen}}} \frac{\partial \Delta V}{\partial P_i} \left|_{B} \right. \Delta P_i \left|_{A}^{D} > 0 \right.
\]

In general, if the number of common non-critical generators is high, the procedure will increase the energy margin level for all the conditions simultaneously. These criteria can be used for the formation of groups of contingencies for which simultaneous control can be sought, and produce schemes accordingly. However, unless the faults evaluated are electrically close, the condition above is rare, and the contribution of some elements is going to be negative. Hence, in order to obtain a final result higher than the minimum acceptable energy margin level, it is important that in the individual adaptive loop the specified energy margin level \( \Delta V_D \) be high (higher than the minimum acceptable) so that when these negative values are added in (6.10), the energy margin values for contingencies \( A \) and \( B \) are still adequate.

In order to speed-up the procedure and as mentioned in the description of the block diagram of Figure 6.1, after two or three iterations, the generator power output is substituted by the weighted value given by (6.12). In this case formula (6.10) can be decomposed as:
\[
\Delta V^i_{A} = \Delta V^0_A + \sum_{i=1}^{\text{numgen}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_A \frac{(w_{iA} \Delta P_i^i_A + w_{iB} \Delta P_i^i_B)}{w_{iA} + w_{iB}} \\
\sum_{i=\text{critA}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_A \frac{(w_{iA} \Delta P_i^i_A + w_{iB} \Delta P_i^i_B)}{w_{iA} + w_{iB}} - \sum_{i=\text{critB}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_A \frac{(w_{iA} \Delta P_i^i_A + w_{iB} \Delta P_i^i_B)}{w_{iA} + w_{iB}}
\]

\[ (6.11) \]

\[
\Delta V^i_{B} = \Delta V^0_B + \sum_{i=1}^{\text{numgen}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_B \frac{(w_{iA} \Delta P_i^i_A + w_{iB} \Delta P_i^i_B)}{w_{iA} + w_{iB}} \\
\sum_{i=\text{critA}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_B \frac{(w_{iA} \Delta P_i^i_A + w_{iB} \Delta P_i^i_B)}{w_{iA} + w_{iB}} - \sum_{i=\text{critB}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_B \frac{(w_{iA} \Delta P_i^i_A + w_{iB} \Delta P_i^i_B)}{w_{iA} + w_{iB}}
\]

\[ (6.12) \]

In contingency \( A \), the term,
\[
\sum_{i=\text{critA}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_A \frac{w_{iA}}{w_{iA} + w_{iB}} \Delta P_i^i_A
\]
is positive and has a high value, while the term
\[
\sum_{i=\text{critB}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_A \frac{w_{iB}}{w_{iA} + w_{iB}} \Delta P_i^i_B
\]
is normally negative and small. Similarly,
\[
\sum_{i=\text{critA}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_A \frac{w_{iA}}{w_{iA} + w_{iB}} \Delta P_i^i_A
\]
is positive but small and
\[
\sum_{i=\text{critB}} \left. \frac{\partial \Delta V^i}{\partial P_i} \right|_A \frac{w_{iB}}{w_{iA} + w_{iB}} \Delta P_i^i_B
\]
is negative and small, so the net effect is an increase in the energy margin level for \( A \).

A similar analysis can be done for contingency \( B \). Normally it is reasonable to think that if this is done from the beginning instead of taking the average of the power outputs' as in (6.5), the faster the security state is reached. However, in the first iterations there is a
great risk that numerous negative terms can have a high value producing instead a negative effect, ultimately preventing convergency from being achieved.

It is to be noted that this procedure was successfully tested for several contingencies and conditions, but it cannot be guaranteed, that for all the cases a simultaneous control strategy will be obtained. The method presents a strategy to reach such simultaneous control only if it exists. Note that even in the case that simultaneous control cannot be achieved, this is flagged and then other actions can be taken as, for example, load reductions.

6.3 Efficient \( [Y_{bus}] \) Matrix Evaluation

In an energy management system (EMS), multiple contingencies need to be evaluated every few minutes to provide continuous online dynamic security assessment. Therefore, important computational savings can be achieved in these evaluations by using network tearing techniques and recalculating only those parts of the topology that change from one load condition to the next. In these security evaluations the time involved in the construction of the three \( [Y_{bus}] \) matrices for pre-fault, fault and post-fault, for all the contingencies when a new load condition is evaluated is high. This has been demonstrated to be problematic in security evaluations [15], [32]. Therefore techniques to speed-up this process are necessary to improve the efficiency of the overall online security assessment.

This section describes a new pre-processing technique developed for the \( [Y_{bus}] \) matrix evaluation, which is suitable to be used with parallel processing. The basic idea of the proposed procedure is to pre-store as much as possible pre-process “no-load-related” admittance values in different tri-dimensional arrays, similar to the one shown in Figure 6.2. These arrays are created only once, from off-line data, and allows for a-posteriori fast and efficient “construction” of the system \( [Y_{bus}] \) matrix, after adding the actual loads, during the online security margin evaluation.
6.4 Pre-Processing of the $[Y_{bus}]$ Matrix

A description of the pre-process methodology employed for the construction of the pre-fault, fault, and post-fault $[Y_{bus}]$ matrices is given below.

6.4.1 Evaluation of Pre-Fault, Fault and Post-Fault Matrices

Changes in the $[Y_{bus}]$ matrix configuration are due mainly to:

- Contingencies: each contingency represents a change in the system topology and alters considerably the fault and post-fault $[Y_{bus}]$ matrices.
- Load variation: as normal load fluctuations take place, they affect the value of the diagonal (shunt elements) of the $[Y_{bus}]$ for pre-fault, fault and post-fault conditions.

The idea behind the proposed procedure is to store in four tri-dimensional arrays $[A_{ik}]$ with the following dimension:

$$\text{Dim} \ [A_{ik}] = m \times n \times p, \ p = 0..\text{numcon}$$

Where $\text{numcon}$ is equal to the number of contingencies under analysis and $p$ is a pointer to a matrix of dimension $m \times n$, where admittance values for a specific contingency are stored. The value $p = 0$ corresponds to the pre-fault information and the value $p = 1..\text{numcon}$ corresponds to the particular contingency under study. In these matrices, constant pre-processed, no-load related admittance information is stored. These matrices are then used in the final $[Y_{bus}]$ matrix evaluation, when the varying load conditions are included.
In conventional stability studies, when there is a change in the system (load variation or fault) the \([Y_{bus}]\) matrix is first built and then reduced down to the size of the internal generator nodes. In the method presented, the starting point consists in the creation of the complete no-load admittance matrix. For simplicity, the matrix sub-indices are ordered as follows (Figure 6.3): first the generator internal nodes, second the generator external nodes, followed by the non-generator load nodes, and finally the rest of the nodes. It is then possible to arrive to the \(n \times n\) matrix shown in Figure 6.3 for a pre-defined pre-fault \((p=0)\) or post-contingency state \((p=1..\text{numcon})\).

In the matrix of Figure 6.3,

- **numgen**: total number of generators nodes.
- **num_nodes**: total number of nodes including generator internal nodes.
- **num_load**: total number of load nodes excluding loads at generator buses.
Analysing this initial matrix, it is possible to observe that for a given condition the elements of the matrices $[B]$, $[C]$ and $[D]$ are constant and the load values will only affect the diagonal elements of matrix $[A]$. Therefore, after a first Kron reduction to nodes $r = 2^{\text{numgen}} + \text{num_loads}$, the second step in the total reduction process towards the final formation of the $[Y_{inj}]$ matrix is performed. Mathematically, we first perform a Kron reduction on the matrix shown in Figure 6.3, that is re-written as:

$$\begin{bmatrix} I_r \\ 0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{1r} \\ V_{2r} \end{bmatrix}$$

(6.13)

with

$$[I_r] = \begin{bmatrix} I_{\text{gen}} & 0 & 0 \end{bmatrix}^T \quad [V_{1r}] = \begin{bmatrix} V_{\text{gen}} \\ V_{\text{load}} \end{bmatrix}^T \quad \text{and} \quad [V_{2r}] = \begin{bmatrix} V_{\text{no-load}} \end{bmatrix}^T$$

where $r = 2^{\text{numgen}} + \text{num_load}$

After some algebraic manipulation $I_r$ can be found to be given by:

$$[I_r] = \left( [A] - [B][D]^{-1}[C] \right) [V_{1r}]$$

(6.14)

where

$$[K] = [B][D]^{-1}[C] = \begin{bmatrix} K_a & K_b \\ K_c & K_d \end{bmatrix}$$

(6.15)

is a constant matrix, with dimensions:

$[K_a] : a \times a$ matrix

$[K_b] : a \times b$ matrix

$[K_c] : b \times a$ matrix
$[K_d]: b \times b$ matrix

and

$a = \text{numgen}$ and $b = \text{numgen} + \text{num_load}$

Equation (6.14) can be re-written as:

$$
\begin{bmatrix}
I_g \\
0
\end{bmatrix} = \begin{bmatrix}
A_a - K_a & A_b - K_b \\
A_c - K_c & A_d - K_d
\end{bmatrix}
\begin{bmatrix}
V_{\text{numgen}} \\
V_{\text{numgen-r}}
\end{bmatrix}
$$

(6.16)

This last pre-reduced matrix is the complete no-load $[Y_{bus}]$ matrix, reduced to the generators and non-generator load-nodes. For each topological condition, matrices $[A_{ck}] = [A_c - K_c]$ and $[A_{bk}] = [A_b - K_b]$ are constant and independent of load variations. Only the diagonal elements of matrices $[A_{ak}] = [A_a - K_a]$ or $[A_{ak}] = [A_a - K_a]$ are altered when the load is included in each time step evaluation of the EMS. The load admittance values are simple to include because in the reduced matrix the load nodes are preserved. Incorporating the load into a node $i$ consists in directly adding the value of the load admittance to the corresponding diagonal element on submatrix $[A_{ak}]$ if the load is connected to a generator station, or to $[A_{dk}]$ in the case of a non-generator bus. Finally, the matrix reduced down to the internal generator nodes is:

$$
\begin{bmatrix}
I_g \\
0
\end{bmatrix} = ([A_{ak}] - [A_{bk} I A_{dk}]^{-1} [A_{ck}] [V_{\text{numgen}}])
$$

(6.17)

In the full solution process, only the last matrix reduction (6.17) is executed online. The off-line process consists in the creation of the pre-processed matrices $[A_{ak}]$, $[A_{bk}]$ $[A_{ck}]$ and $[A_{ak}]$ see (Figure 6.4). Including the load into these sub-matrices at each time step is both simple and fast.
The method described can be used in the evaluation of the pre-fault, fault and post-fault admittance matrices. In the special case of the fault matrix, the matrix is formed from the pre-fault matrices by simply connecting an "equivalent load" of high conductance to the faulted node. For faults applied at no-load nodes, an "equivalent load" of high conductance is connected to the corresponding diagonal value of $[D]$ in equation (6.13). Mathematically, manipulation and matrix inversion reduction has to be performed as fast as possible. It is convenient to separate the corresponding complex $[Y_{bus}]$ matrices into two real matrices, corresponding to the real and imaginary parts, and to obtain the inverse of the complex matrix through manipulations on the real matrices.

One important aspect of the solution process is that all pre-processing is performed off-line, and only in each real-time loop the part of including the load changes and the evaluation of the final matrix on (6.17) is done. This obviously accelerates the procedure when compared to traditional ways of solving this problem.

Figure 6.4: Pre-Process Storage Tri-dimensional Matrices
6.4.2 Algorithm for Security Analysis Using Pre-Processed Matrices

The implementation of the concepts outlined above for online security analysis is described below. As indicated, there are two processes: one off-line and one online, where the off-line calculations are done only once in the whole EMS process, while the online one is activated each time a new load condition is evaluated.

6.4.3 Off-Line Procedure

In the off-line procedure, the pre-processed tri-dimensional arrays for $[A_{ak}]$, $[A_{bk}]$ $[A_{ck}]$ and $[A_{dk}]$ are calculated from the line parameters and do not include the load impedance.

These arrays are simultaneously created for pre-fault and post-fault conditions. A block diagram of the procedure is shown in Figure 6.5.
6.4.4 Online Process

The different arrays created with the off-line procedure are stored in memory and depending on the contingency under study, a value to a pointer is selected to access the corresponding no-load matrices. The arrays are then processed to include the load admittance in each time loop of the security evaluation and control algorithm. This procedure is described in Figure 6.6.
Modifying diagonal elements $[A_{oo}] [A_{oo}]$

Obtention of final $Y_{bus}$ for pre-fault, fault and post-fault conditions (6.13)

Entering Security Process

Figure 6.6: Block Diagram for the Final Processing of the $[Y_{matrix}]$
CHAPTER VII

RESULTS

The method proposed for the security classifier and enhancement control was applied and tested on three different systems:

a) Anderson & Fouad three-generator system [52]: consists of a nine-bus system, and was selected because it allows for a detailed and graphical description of the results.

b) CIGRE test case: A typical benchmark study used in power system transient stability evaluation using energy margin techniques [53], [15].

c) Iowa 17-generator, 162-bus equivalent: A real system, with benchmark results given by sophisticated transient stability programs [82]. In this system the electrical proximity of the generation plants results in a very complex dynamic behaviour.

For all the evaluations:

- Only three phase faults were considered.
- The synchronous machine was modelled with the classical representation of a constant source behind an impedance.

In this chapter, the following results are shown for the three systems under evaluation:

a) Critical clearing times obtained with the proposed equivalent method.

b) Security index using the security classifier.
c) Control enhancement strategies using adaptive and non-adaptive procedures.

d) Preventive control strategies.

e) Time ratios involved in the evaluation of the \([Y_{bus}]\) matrices.

For some of the results, a comparison with step-by-step (SBS) stability evaluations, including graphical descriptions of the problem under study, are given.

All the simulations were done using a set of programs developed using an Object Ada'95 compiler. A brief description of the program structure follows:

a) Off-line evaluation programs

In the first set of programs, the no-load related sub-matrices \([A_{au}], [A_{bk}], [A_{ck}]\) and \([A_{dk}]\) are obtained.

b) Online security classifier and control loop

The main program consists of a set of related packages which are sequentially accessed, giving as a final output the security classifier and the security enhancement strategies for the contingencies under evaluation. These packages perform the following tasks:

- Final \([Y_{bus}]\) matrix evaluation. The program receives from the off-line procedure the no-load related admittance matrix and the load-flow results, and gives back the pre-fault, fault and post-fault matrices for all the contingencies and for the load under evaluation.

- Security classifier and enhancement control subprograms. In this package, first the security classifier and the security index are obtained. This involves different types of evaluations for the energy margin and the sensitivity with respect to the
equivalent power. These evaluations include the solution of the load flow equations for the calculation of post-fault equilibrium points, and also involve the integration of the fault oscillation equations in order to obtain the angles and their sensitivities values with respect to the generator output power and voltage at clearing time.

The different parts of this program include the following independent packages:

a) Evaluation of the security classifier. The energy margin and its sensitivity to the equivalent power allows this package to output the security vector, and the security index (Chapter IV). If the security index falls below a specific value, the security enhancement process is started and the new control strategies are calculated. In the presence of an adaptive algorithm the program will enter the optimisation procedure.

b) Optimisation procedure. Using the optimisation techniques described in this thesis, suggested threshold values for the sensitivities are obtained in order to take the energy margin error to zero. This optimisation package is formed by different sub-packages that first calculate the vector direction (gradient or conjugate gradient), then find the interval into which the minimum lies (bracketing procedure), and finally calculate, using a single parameter optimisation procedure, the new set of threshold values for which the error function is at a minimum (Appendix 3).

c) With the group of threshold values obtained in b), the control security enhancement package evaluates the new control outputs.

d) Simultaneous preventive control steps are executed for all the contingencies and then an external loop in the main program takes the average of the power generators, according to the procedure specified in Chapter VI, and the simultaneous preventive loop is executed. Finally, the new security indices and energy margin levels are obtained for the group of contingencies.
7.1 Three-Generator System

The one-line diagram of the system is shown in Figure 7.1 and the component's data are given in Table 7.1.

Figure 7.1: Three-Generator System
7.1.1 Calculation of the Critical Clearing Time Using the Two-Equivalent System

In order to verify the accuracy of the proposed energy margin index, the critical clearing time, \(ccl\), is obtained using the proposed method and compared with the values obtained with a step-by-step (SBS) stability program, where the generators’ differential equations are solved every time step. Table 7.2 shows the results for the different contingencies under study.

Table 7.2
Three-Generator System Critical Clearing Time

<table>
<thead>
<tr>
<th>Fault at Bus - Opening Line</th>
<th>(ccl) - SBS (s)</th>
<th>(ccl) - (AV) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7  7-5</td>
<td>0.169</td>
<td>0.167</td>
</tr>
<tr>
<td>9  9-6</td>
<td>0.223</td>
<td>0.235</td>
</tr>
<tr>
<td>6  6-9</td>
<td>0.397</td>
<td>0.384</td>
</tr>
<tr>
<td>5  5-4</td>
<td>0.389</td>
<td>0.385</td>
</tr>
<tr>
<td>4  4-5</td>
<td>0.309</td>
<td>0.303</td>
</tr>
<tr>
<td>9  9-8</td>
<td>0.245</td>
<td>0.242</td>
</tr>
<tr>
<td>4  4-6</td>
<td>0.310</td>
<td>0.30</td>
</tr>
<tr>
<td>7  7-8</td>
<td>0.185</td>
<td>0.185</td>
</tr>
</tbody>
</table>
For this three-generator system, the energy margin index using the proposed method is calculated for different clearance times and for different faults, as shown in Table 7.3.

Table 7.3
Three-Generator System Energy Margin vs. Clearing Time

<table>
<thead>
<tr>
<th>Clearing Time (s)</th>
<th>$\Delta V$ (p.u.)</th>
<th>$\Delta V$ (p.u.)</th>
<th>$\Delta V$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7-5</td>
<td>9-6</td>
<td>4-5</td>
</tr>
<tr>
<td>0.12</td>
<td>0.5243</td>
<td>1.6662</td>
<td>1.9774</td>
</tr>
<tr>
<td>0.14</td>
<td>0.3574</td>
<td>1.5336</td>
<td>1.8850</td>
</tr>
<tr>
<td>0.16</td>
<td>0.0998</td>
<td>1.3171</td>
<td>1.7480</td>
</tr>
<tr>
<td>0.18</td>
<td>-0.1363</td>
<td>1.1114</td>
<td>1.6260</td>
</tr>
<tr>
<td>0.20</td>
<td>-0.5489</td>
<td>0.7383</td>
<td>1.4140</td>
</tr>
<tr>
<td>0.22</td>
<td>-0.9684</td>
<td>0.3469</td>
<td>1.1956</td>
</tr>
<tr>
<td>0.24</td>
<td>-1.3264</td>
<td>0.5518</td>
<td>1.0033</td>
</tr>
<tr>
<td>0.26</td>
<td>-1.9519</td>
<td>-0.6033</td>
<td>0.6451</td>
</tr>
<tr>
<td>0.28</td>
<td>-2.3281</td>
<td>-0.9758</td>
<td>0.4078</td>
</tr>
<tr>
<td>0.30</td>
<td>-2.8163</td>
<td>-1.4654</td>
<td>0.5728</td>
</tr>
<tr>
<td>0.32</td>
<td>-3.3589</td>
<td>-2.0125</td>
<td>-0.4494</td>
</tr>
</tbody>
</table>

Table 7.2 compares the values obtained for the critical clearing time using the energy margin method and those obtained with the SBS simulation. The deviations between both results are very small (less than 3%), and except for the value at bus 9, the energy margin method gives conservative answers, that is, smaller critical clearing times than those given by the SBS program.

7.1.2 Three-Generator Security Classifier

In order to apply the procedure explained in Chapter IV, the variation of the energy margin index with the equivalent power is obtained.

Under normal operating conditions, changes in the equivalent power are due mainly to generation re-scheduling or to normal load fluctuations. Table 7.4 shows the variation of the energy margin when small changes around the operating point are carried out on generator 3’s output power, while keeping constant the power of generator 2. These results are also graphically shown on Figures 7.2 to 7.4.
In this case, generator 1 is the selected slack bus, so its output power is given by the load flow system equations.
<table>
<thead>
<tr>
<th>Fault 4-5</th>
<th>Power Distribution</th>
<th>Pequiv (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.87496</td>
<td>190.00000</td>
<td>1.02980</td>
</tr>
<tr>
<td>8.9026</td>
<td>191.00000</td>
<td>0.97580</td>
</tr>
<tr>
<td>7.6864</td>
<td>192.00000</td>
<td>0.92180</td>
</tr>
<tr>
<td>6.5703</td>
<td>193.00000</td>
<td>0.86780</td>
</tr>
<tr>
<td>5.4697</td>
<td>194.00000</td>
<td>0.81380</td>
</tr>
<tr>
<td>4.3690</td>
<td>195.00000</td>
<td>0.75980</td>
</tr>
<tr>
<td>3.2684</td>
<td>196.00000</td>
<td>0.70580</td>
</tr>
<tr>
<td>2.1678</td>
<td>197.00000</td>
<td>0.65180</td>
</tr>
<tr>
<td>1.0672</td>
<td>198.00000</td>
<td>0.59780</td>
</tr>
<tr>
<td>0.0000</td>
<td>199.00000</td>
<td>0.54380</td>
</tr>
</tbody>
</table>

Variation of Energy Margin With Equivalent Power

Table 7.4
Figure 7.2: Energy Margin vs. Equivalent Power - Fault 7-5

Figure 7.3: Energy Margin vs. Equivalent Power - Fault 9-6
Energy Margin (p.u.)

Figure 7.4: Energy Margin vs. Equivalent Power - Fault 4-5

Energy Margin (p.u.)

Figure 7.5: Energy Margin vs. Equivalent Power - Faults 7-5, 9-6 and 4-5
Table 7.5 shows the variation of the sensitivity of the energy margin with respect to the equivalent power for the three faults under consideration.

Table 7.5

Sensitivity to Equivalent Power - Faults 7-5, 9-6 and 4-5

<table>
<thead>
<tr>
<th>Fault 7-5</th>
<th>Fault 9-6</th>
<th>Fault 4-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{equiv}}$ (p.u.)</td>
<td>$\partial AV/\partial P_{\text{equiv}}$ (p.u.)</td>
<td>$P_{\text{equiv}}$ (p.u.)</td>
</tr>
<tr>
<td>1.05381</td>
<td>-4.71943</td>
<td>0.482453</td>
</tr>
<tr>
<td>1.05359</td>
<td>-4.75866</td>
<td>0.49235</td>
</tr>
<tr>
<td>1.05337</td>
<td>-4.79987</td>
<td>0.50224</td>
</tr>
<tr>
<td>1.05315</td>
<td>-4.84321</td>
<td>0.51214</td>
</tr>
<tr>
<td>1.05292</td>
<td>-4.88885</td>
<td>0.52204</td>
</tr>
<tr>
<td>1.05270</td>
<td>-4.93695</td>
<td>0.53193</td>
</tr>
<tr>
<td>1.05247</td>
<td>-4.98772</td>
<td>0.54183</td>
</tr>
<tr>
<td>1.18416</td>
<td>-3.91997</td>
<td>0.55173</td>
</tr>
<tr>
<td>1.19404</td>
<td>-3.92024</td>
<td>0.56162</td>
</tr>
<tr>
<td>1.20392</td>
<td>-3.92074</td>
<td>0.57153</td>
</tr>
<tr>
<td>1.21382</td>
<td>-3.92149</td>
<td>0.58142</td>
</tr>
<tr>
<td>1.22371</td>
<td>-3.92251</td>
<td>0.59132</td>
</tr>
<tr>
<td>1.23362</td>
<td>-3.92381</td>
<td>0.60121</td>
</tr>
<tr>
<td>1.24353</td>
<td>-3.92541</td>
<td>0.61111</td>
</tr>
<tr>
<td>1.25345</td>
<td>-3.92734</td>
<td>0.62101</td>
</tr>
<tr>
<td>1.26338</td>
<td>-3.92961</td>
<td>0.63091</td>
</tr>
<tr>
<td>1.27332</td>
<td>-3.93225</td>
<td>0.64081</td>
</tr>
<tr>
<td>1.28326</td>
<td>-3.93528</td>
<td>0.65070</td>
</tr>
<tr>
<td>1.29321</td>
<td>-3.93873</td>
<td>0.66060</td>
</tr>
</tbody>
</table>

Figures 7.2 to 7.4 show the energy margin curves as functions of the equivalent power $P_{\text{equiv}}$, for three different faults. A comparison among them as shown in Figure 7.5 leads to the interesting observation that for the same power generator distribution there are two different levels of $P_{\text{equiv}}$. This can also be observed in Table 7.4, where for faults at line 9-6 and 4-5, $P_{\text{equiv}}$ lies in the interval [0.4 0.65] p.u., and except for a fault at line 7-5, the equivalent power lies between [1.05 and 1.3]. This serves to reaffirm the importance of using $P_{\text{equiv}}$ as a parameter for the sensitivity evaluation instead of the total power load or generation.

With the knowledge of the energy margin levels and their sensitivity with respect to the equivalent power at the operating point, the different threshold values for the membership
functions of the security classifier can be obtained using the procedure explained in Chapter IV (equations (4.11) to (4.15)). With a value of $\alpha$ equal to 0.95, the results showed in Table 7.6 are obtained.

**Table 7.6**

<table>
<thead>
<tr>
<th>Fault</th>
<th>$\Delta V_o$ (p.u.)</th>
<th>$\Delta V_{min}$ (p.u.)</th>
<th>$P_{equiv}/P_o$ (p.u.)</th>
<th>$\partial \Delta V/\partial P_{equiv}$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5</td>
<td>-0.548878</td>
<td>0.2271</td>
<td>1.04545</td>
<td>-4.86901</td>
</tr>
<tr>
<td>9-6</td>
<td>0.738278</td>
<td>0.2441</td>
<td>0.52863</td>
<td>-7.83770</td>
</tr>
<tr>
<td>4-5</td>
<td>1.41398</td>
<td>0.1646</td>
<td>0.52584</td>
<td>-3.57223</td>
</tr>
<tr>
<td>6-9</td>
<td>0.86481</td>
<td>0.1852</td>
<td>1.11808</td>
<td>-2.53964</td>
</tr>
<tr>
<td>5-4</td>
<td>1.64497</td>
<td>0.1707</td>
<td>0.52584</td>
<td>-3.36553</td>
</tr>
<tr>
<td>9-8</td>
<td>0.80094</td>
<td>0.1952</td>
<td>0.51029</td>
<td>-6.0802</td>
</tr>
<tr>
<td>4-6</td>
<td>1.41620</td>
<td>0.1810</td>
<td>0.62532</td>
<td>-3.52486</td>
</tr>
<tr>
<td>7-8</td>
<td>-0.30908</td>
<td>0.1931</td>
<td>1.1213</td>
<td>-3.7207</td>
</tr>
</tbody>
</table>

$\Delta V_o$ = Energy margin at the operating point
$\Delta V_{min}$ = Minimum energy margin for the specific fault

The threshold values for the energy margin index and sensitivity with respect to the equivalent power are:

$$\Delta V_{min} = \max [\Delta V_{min}] = 0.2442 \text{ p.u.}$$  and

$$\partial \Delta V/\partial P_{equiv} = \min [\abs{\partial \Delta V/\partial P_{equiv}}] = 2.5396 \text{ p.u.}$$

Once these values are specified, either by calculation or defined by the company’s policy, they are held constant for the security classifier evaluation shown in Table 7.7.
Table 7.7
Security Index and Security Vector for Different Contingencies
Three-Generator Case $tcl=0.2$ s

<table>
<thead>
<tr>
<th>Fault</th>
<th>Security Vector</th>
<th>Security Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-5</td>
<td>(0,0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>9-6</td>
<td>(0,0.6538,0.346,0)</td>
<td>0.6515</td>
</tr>
<tr>
<td>6-9</td>
<td>(0.08211,0.1788,0)</td>
<td>0.6871</td>
</tr>
<tr>
<td>5-4</td>
<td>(0,1,0,0)</td>
<td>0.7500</td>
</tr>
<tr>
<td>4-5</td>
<td>(0.073665,0.26334,0)</td>
<td>0.6676</td>
</tr>
<tr>
<td>9-8</td>
<td>(0,1,0,0)</td>
<td>0.7500</td>
</tr>
<tr>
<td>4-6</td>
<td>(0,0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>7-8</td>
<td>(0,0,0,1)</td>
<td>0.1944</td>
</tr>
</tbody>
</table>

Different load scenarios (as a percentage of the base case) were studied to evaluate their effect on the security vector and on the security index. The results are shown in Table 7.8.

Table 7.8
Security Index for Different Load Scenarios Three-Generator Case

<table>
<thead>
<tr>
<th>Load % Fault</th>
<th>$\Delta V$ (p.u.)</th>
<th>$\frac{\Delta V}{\Delta P_{equiv}}$ (p.u.)</th>
<th>$P_{equiv}$ (p.u.)</th>
<th>Security Vector</th>
<th>Security Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% 7-5</td>
<td>-0.6829</td>
<td>-5.1526</td>
<td>1.0716</td>
<td>(0,0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>98% 7-5</td>
<td>-0.6003</td>
<td>-4.9697</td>
<td>1.0561</td>
<td>(0,0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>102% 7-5</td>
<td>-0.4941</td>
<td>-4.7803</td>
<td>1.0349</td>
<td>(0,0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>104% 7-5</td>
<td>-0.4408</td>
<td>-4.6991</td>
<td>1.0242</td>
<td>(0,0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>95% 9-6</td>
<td>0.64789</td>
<td>-7.8012</td>
<td>0.5414</td>
<td>(0.054,0.46,0)</td>
<td>0.638</td>
</tr>
<tr>
<td>98% 9-6</td>
<td>0.6992</td>
<td>-7.8195</td>
<td>0.5338</td>
<td>(0.061,0.39,0)</td>
<td>0.6423</td>
</tr>
<tr>
<td>102% 9-6</td>
<td>0.7734</td>
<td>-7.8597</td>
<td>0.5234</td>
<td>(0.07,0.3,0)</td>
<td>0.6602</td>
</tr>
<tr>
<td>104% 9-6</td>
<td>-0.8102</td>
<td>-7.8789</td>
<td>0.5181</td>
<td>(0.075,0.25,0)</td>
<td>0.6702</td>
</tr>
<tr>
<td>95% 4-5</td>
<td>1.1602</td>
<td>-3.5442</td>
<td>0.6050</td>
<td>(0,1,0,0)</td>
<td>0.75</td>
</tr>
<tr>
<td>98% 4-5</td>
<td>1.3115</td>
<td>-3.5614</td>
<td>0.5579</td>
<td>(0,1,0,0)</td>
<td>0.75</td>
</tr>
<tr>
<td>102% 4-5</td>
<td>1.5161</td>
<td>-3.5839</td>
<td>0.4939</td>
<td>(0,1,0,0)</td>
<td>0.75</td>
</tr>
<tr>
<td>104% 4-5</td>
<td>1.6179</td>
<td>-3.5939</td>
<td>0.4623</td>
<td>(0,1,0,0)</td>
<td>0.75</td>
</tr>
</tbody>
</table>

(1) Security Vector: ($\mu_{CS}$, $\mu_{AT}$, $\mu_{HAM}$, $\mu_{MS}$)

In the calculation of the sensitivity index, the minimum energy margin level $\Delta V_{min}$ is set to a value different from zero. This eliminates potential problems in case of unforeseen contingencies or drastic changing conditions. This value can be considered conservative,
so it must also be a company's policy to determine its value, including the setting for the final desired energy margin level.

In Table 7.7 the security index is obtained and the last column shows how the security index changes with load conditions. It is possible to observe that in the cases were the security vector has more than one component different from zero, such as in the fault at line 9-6, there is a variation of the security index with the load. This is equivalent to variations in $ccI$ when a SBS evaluation is used. In the other cases, due to the inference rules and the threshold values selected for the energy margin levels, the security vector has a non-zero element, equal to one, giving a constant value for the security index. Again, operator experience plays an important role in determining the acceptable values for the threshold values depending on the needs of a particular company. Table 7.8 shows how a decrease in load does not translate into an increment on the energy margin level. For fault at 7-5, an increment in load reflects a decrease in $P_{equiv}$, and an increase in the energy margin level. The opposite situation will take place for the fault at line 9-6. This is due to the fact that for transient stability purposes the key factor is the distribution of the generators power among non-critical and critical machines, being $P_{equiv}$ the parameter that effectively reflects this process.

7.1.3 Three-Generator Security Enhancement Control

After the system security level is classified, and depending on the values of the security index, the process enters the following block of simultaneous security enhancement control.

7.1.3.1 Surface and contour diagrams

In Figures 7.6 to 7.8, the surface tri-dimensional diagrams of $\Delta V$ with respect of the output power for generators 2 and 3 are shown for faults at lines 7-5, 9-6 and 4-5. The contour curves for the same functions are given in Figures 7.9 to 7.11. These diagrams graphically depict the zones where the system is secure and insecure.
Figure 7.6: Surf Diagram - Fault line 7-5

Figure 7.7: Surf Diagram - Fault 9-6
Figure 7.8: Surf Diagram - Fault 4-5

Figure 7.9: Contour Diagram - Fault 7-5
Figure 7.10: Contour Diagram - Fault 9-6

Figure 7.11: Contour Diagram - Fault 4-5
The surface and constant energy-margin contour curves, of Figures 7.6 to 7.11 demonstrate the existence of multiple control actions that can result in a desired energy margin level. The control enhancement procedure eliminates several of these possible actions, such as those that cannot be obtained if the voltage and power margins of the generators are out of their physical limits. In addition, the enhancement procedure takes into account which generator can be more successful in achieving the desired energy margin level. If the contour curves obtained for the different contingencies are superimposed, it is possible to observe how an increment/decrement of the power of the generator can affect the energy level for the different faults. The power variation can enhance both of the fault conditions, as in the three-generator case. In the last example, however, an adverse effect for different contingencies is going to be observed.

7.1.3.2 Security enhancement control - without adaptive control

To test the security enhancement function without adaptive control, the desired energy margin was set to 1.0 (p.u) (a high value in order to covered for drastic changing system conditions). Tables 7.9, 7.10 and 7.11 show the results obtained for two faults, that take place on line 7-5 and on line 9-6 for the open loop non-adaptive algorithm based on three different levels for the sensitivity threshold values: high, medium and small. The purpose of choosing these three different levels is to evaluate and understand the effect of the membership functions in the final results for the individual generators' output power. The information in these tables gives for the power controller the membership function for the sensitivities: positive and high \( \mu_{PHS} \) and negative and high \( \mu_{NHS} \), including the higher and lower output margin \( \mu_{MR} \) and \( \mu_{ML} \) (Figure 5.1). Additionally, they show for each generator \( i \) the open-loop power output \( P_i \) as in equation (5.12). Finally, in the last two rows of the table, the new energy margin level and security vectors using the indicated output powers are given.
### Table 7.9
**Open Loop Security Enhancement Control Three-Generator Case**

#### High Threshold Values

| Generator | Fault 7-5 | | Fault 9-6 | | |
|-----------|-----------| |-----------| | |
|           | 2 | 3 | 2 | 3 | |
| $\Delta V_a$ (p.u.) | -0.54887 | | $\Delta V_a$ (p.u.) | 0.73827 | |
| Security Vector | (0,0,0,1) | | Security Vector | (0,0.6538,0.3462,0) | |
| Security Index | 0.194 | | Security Index | 0.65146 | |
| $P_{i_{old}}$ | 1.63 | 0.85 | $P_{i_{old}}$ | 1.63 | 0.85 |
| $\mu_{PDS}$ | 0 | 0.08794 | $\mu_{PDS}$ | 0.04939 | 0 |
| $\mu_{HRS}$ | 0.3878 | 0 | $\mu_{HRS}$ | 0 | 0.5098 |
| $\mu_{MR}$ | 0 | 0.03298 | $\mu_{MR}$ | 0.56047 | 0 |
| $\mu_{AG}$ | 1 | 0 | $\mu_{AG}$ | 0 | 1 |
| $P_{i_{new}}$ | 1.261 | 0.94219 | $P_{i_{new}}$ | 1.65662 | 0.80237 |
| $\Delta V_{new}$ (p.u.) | 0.5911 | | $\Delta V_{new}$ (p.u.) | 1.02282 | |
| Security Vector | (0,0.4589,0.5411,0) | | Security Vector | (0,0.976,0.245,0) | |
| Security Index | 0.6182 | | Security Index | 0.7384 | |

### Table 7.10
**Open Loop Security Enhancement Control Three-Generator Case**

#### Medium Threshold Values

| Generator | Fault 7-5 | | Fault 9-6 | | |
|-----------|-----------| |-----------| | |
|           | 2 | 3 | 2 | 3 | |
| $\Delta V_a$ (p.u.) | -0.54887 | | $\Delta V_a$ (p.u.) | 0.73827 | |
| Security Vector | (0,0,0,1) | | Security Vector | (0,0.6538,0.3462,0) | |
| Security Index | 0.194 | | Security Index | 0.6515 | |
| $P_{i_{old}}$ | 1.63 | 0.85 | $P_{i_{old}}$ | 1.63 | 0.85 |
| $\mu_{PDS}$ | 0 | 0.40484 | $\mu_{PDS}$ | 0.2256 | 0 |
| $\mu_{HRS}$ | 1 | 0 | $\mu_{HRS}$ | 0 | 1 |
| $\mu_{MR}$ | 0 | 0.249 | $\mu_{MR}$ | 0.56047 | 0 |
| $\mu_{AG}$ | 1 | 0 | $\mu_{AG}$ | 0 | 1 |
| $P_{i_{new}}$ | 1.2859 | 1.0079 | $P_{i_{new}}$ | 1.68805 | 0.80543 |
| $\Delta V_{new}$ (p.u.) | 0.3414 | | $\Delta V_{new}$ (p.u.) | 0.98146 | |
| Security Vector | (0,0.1288,0.9712,0) | | Security Vector | (0.9755,0.2453,0) | |
| Security Index | 0.5492 | | Security Index | 0.7384 | |
### Table 7.11
Open Loop Security Enhancement Control Three-Generator Case
Small Threshold Values

<table>
<thead>
<tr>
<th>Generator</th>
<th>Fault 7-5</th>
<th>Fault 9-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>Generator</td>
</tr>
<tr>
<td>$\Delta V_s$ (p.u.)</td>
<td>-0.54887</td>
<td>$\Delta V_s$ (p.u.)</td>
</tr>
<tr>
<td>Security Vector</td>
<td>(0,0.1,0)</td>
<td>Security Vector</td>
</tr>
<tr>
<td>Security Index</td>
<td>0.194</td>
<td>Security Index</td>
</tr>
<tr>
<td>$P_{i , old}$</td>
<td>1.63</td>
<td>0.85</td>
</tr>
<tr>
<td>$\mu_{\text{PHS}}$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$\mu_{\text{MHS}}$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\mu_{\text{MMR}}$</td>
<td>0</td>
<td>0.2494</td>
</tr>
<tr>
<td>$\mu_{\text{MML}}$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$P_{i , new}$</td>
<td>1.3179</td>
<td>1.19389</td>
</tr>
<tr>
<td>$\Delta V_{new}$ (p.u.)</td>
<td>-0.34098</td>
<td>$\Delta V_{new}$ (p.u.)</td>
</tr>
<tr>
<td>Security Vector</td>
<td>(0,0,0,1)</td>
<td>Security Vector</td>
</tr>
<tr>
<td>Security Index</td>
<td>0.1944</td>
<td>Security Index</td>
</tr>
</tbody>
</table>

#### 7.1.3.3 Closed-loop security enhancement control - without scaling

Two different closed-loop procedures were considered. In the first one, the membership functions are maintained constant and an iterative procedure is started by feedback of the last power output obtained for the generators $P_i$. Table 7.12 shows the final power output of each generator required to obtain the desired energy margin value for different sensitivity threshold levels.
Table 7.12
Closed-Loop Security Enhancement Control w/o Scaling Three-Generator Case

<table>
<thead>
<tr>
<th>Generator</th>
<th>2</th>
<th>3</th>
<th>$\Delta V_{mew}$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial generator's output</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.6300</td>
<td>0.8500</td>
<td>-0.54887</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.6300</td>
<td>0.8500</td>
<td>0.73827</td>
</tr>
<tr>
<td>High threshold values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.1993</td>
<td>0.8803</td>
<td>0.9991</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.6525</td>
<td>0.8064</td>
<td>1.0000</td>
</tr>
<tr>
<td>Medium threshold values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.1794</td>
<td>0.9027</td>
<td>1.0005</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.6971</td>
<td>0.8015</td>
<td>0.9999</td>
</tr>
<tr>
<td>Small threshold values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.13911</td>
<td>1.11548</td>
<td>0.97528</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>0.96169</td>
<td>1.61906</td>
<td>0.62854</td>
</tr>
</tbody>
</table>

These different levels are chosen so that the initial or departure membership values for the sensitivities are around $\mu_{\Delta V/\Delta P_i} \approx 1$ for small threshold values, $\mu_{\Delta V/\Delta P_i} \leq 0.2$ for high threshold values, and in-between for medium threshold values. The number of iterations needed to achieve the final desired energy margin varies between faults and threshold values. The following energy margin vectors have as the $j$th component the energy margin obtained at iteration number $j$.

- Energy margin vectors - high threshold values
  Fault 7-5 : [-0.5489 0.59103 1.14767 0.9478 1.0185 0.9934 1.0024 0.9991]
  Fault 9-6 : [ 0.73822 1.0228 1.000]

- Energy margin vectors - medium threshold values
  Fault 7-5 : [-0.5489 0.34141 2.14056 0.91544 1.0302 0.9893 0.9986 1.0005]
  Fault 9-6 : [ 0.73822 0.98914 0.9951 0.9987 0.9999]
Energy margin vectors - small threshold values
Fault 7-5 : [-0.5489 -0.3409 1.5057 0.8226 1.0648 0.9766 1.0084 0.9969 1.0011 0.9995]
Fault 9-6 : [ 0.7382 -0.13837 1.4264 0.8578 1.049 0.9831 1.0058 0.9979 1.0007]

7.1.4 Adaptive Security Enhancement Control - With Scaling

This second closed-loop procedure corresponds to the adjustment of the sensitivity threshold values through an optimisation procedure. Two different optimisation methods were used in the evaluation: the gradient technique and the conjugate gradient Polak-Riviere algorithm. In this case, due to the small size of the system, and the fast convergence of the gradient method, the conjugate gradient method was not needed. The results obtained using the gradient technique are shown in Table 7.13.

Table 7.13
Closed-Loop Security Enhancement Control with Scaling Three-Generator Case

<table>
<thead>
<tr>
<th>Generator</th>
<th>2</th>
<th>3</th>
<th>$\Delta V_{new}$ (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial generator's output</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.63</td>
<td>0.85</td>
<td>-0.54887</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.63</td>
<td>0.85</td>
<td>0.73827</td>
</tr>
<tr>
<td>High threshold values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.3221</td>
<td>0.8792</td>
<td>1.00123</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.6347</td>
<td>0.8144</td>
<td>1.0004</td>
</tr>
<tr>
<td>Medium threshold values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.20861</td>
<td>0.93095</td>
<td>0.9928</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.7027</td>
<td>0.8105</td>
<td>0.9999</td>
</tr>
<tr>
<td>Small threshold values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>No convergence achieved</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.778</td>
<td>0.4671</td>
<td>1.0064</td>
</tr>
</tbody>
</table>

Energy margin vectors - high threshold values
Fault 7-5 : [-0.54887 0.59103 0.9594 0.9961 1.00123]
Fault 9-6 : [ 0.73822 1.0004]
- Energy margin vectors - medium threshold values
  Fault 7-5: [-0.54887 0.5526 0.9423 0.9928]
  Fault 9-6: [0.73822 0.981013 0.9999]

- Energy margin vectors - small threshold values
  Fault 9-6: [0.7382 -0.1379 0.8573 0.982 1.0064]

Figure 7.12 shows graphs of the energy margin value for each iteration, for the non-adaptive and adaptive procedures.

![Energy Margin - Fault 7-5 high threshold values](image1)

![Energy Margin - Fault 7-5 high threshold values](image2)

*Figure 7.12: Closed-Loop Energy Margin Levels per Iteration*
In Figure 7.13 the effect of applying the control strategy using the high threshold values obtained for the open-loop adaptive and non-adaptive control algorithms are shown.

![Figure 7.13: Fault Line 7-5 Three-Generator Case Comparison of Security Enhancement Control Strategies](image)

The results given in Tables 7.9 to 7.11 show that the open-loop security enhancement control strategy is not able to take the system to the desired energy margin level due to the non-linearity of the process. This justifies going to a closed-loop procedure. Two different closed-loop procedures, both adaptive and non-adaptive, were evaluated. As can be observed, the number of iterations needed with an adaptive procedure is higher. In this case only gradient techniques were employed due to the small system size and its easy and fast convergence. In the case of the non-adaptive iterative loop, the use of small threshold values produced higher power variation for all the generators due to the fact that the membership values for the sensitivity are close to one, affecting the steady-state convergence of the load flow system equations.
In Figure 7.13 the two adaptive strategies effectively stabilise the system for a fault at line 7-5 in comparison to the open-loop strategy.

7.1.5 *Adaptive Voltage and Power Control*

Voltage control offers as a main advantage the possibility of increasing the security margin without significantly changing the power distribution at the operating point, while its main limitation is that the maximum variation allowed for the generator's voltage is normally not sufficient to take the energy margin to the desired value. A combination of both controls is suitable for most of the cases. First, the power control takes the system energy margin to a level smaller than the desired value, but greater than the minimum acceptable, and from this point the voltage control loop is in charge to achieve the final desired value.

In the following results the energy margin level is taken to a value above 0.33 p.u. by power control, while voltage control then allows the target of 1.0 p.u. to be reached.

| Generator          | $E_1$ (p.u.) | $E_2$ (p.u.) | $E_3$ (p.u.) | $\Delta V_{new}$ (p.u.) | # of iterations |
|--------------------|-------------|-------------|-------------|--------------------------|-----------------
| **Generator's output power - Only power loop** |             |             |             |                          |                 |
| Fault 7-5          | 1.0605      | 1.3446      | 0.82048     | 0.66394                  | 2               |
| Fault 9-6          | 0.7203      | 1.6552      | 0.82057     | 0.9091                   | 2               |
| **Initial generators Internal Voltage** | $E_1 = 1.0566$ p.u. | $E_2 = 1.0502$ p.u. | $E_3 = 1.0170$ p.u. |             |                 |
| **Final generators internal voltage - High threshold values** |             |             |             |                          |                 |
| Fault 7-5          | 1.0602      | 1.06642     | 1.06707     | 1.00518                  | 6               |
| Fault 9-6          | 1.0534      | 1.0551      | 1.0335      | 1.00017                  | 4               |
| **Final generators internal voltage - Medium threshold values** |             |             |             |                          |                 |
| Fault 7-5          | 1.0608      | 1.06581     | 1.0655      | 1.00836                  | 8               |
| Fault 9-6          | 1.0508      | 1.0508      | 1.0328      | 0.9988                   | 4               |
| **Final generators internal voltage - Small threshold values** |             |             |             |                          |                 |
| Fault 7-5          | 1.06124     | 1.06564     | 1.06645     | 0.99082                  | 11              |
| Fault 9-6          | 0.98        | 1.0695      | 1.06005     | 0.99318                  | 6               |
7.1.6 Adaptive Security Enhancement Control - With Scaling

Table 7.15 shows the results of the second adaptive procedure, which adjusts the threshold values using the gradient optimisation procedure.

### Table 7.15

Closed-Loop Security Enhancement Control with Scaling Three-Generator Case

<table>
<thead>
<tr>
<th>Generator’s output power – Only power loop</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>( \Delta V_{\text{new}} ) (p.u.)</th>
<th># of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault 7-5</td>
<td>1.0605</td>
<td>1.3446</td>
<td>0.82048</td>
<td>0.66394</td>
<td>2</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>0.7203</td>
<td>1.6552</td>
<td>0.82057</td>
<td>0.9091</td>
<td>2</td>
</tr>
<tr>
<td>Initial generators internal Voltage ( E_1 = 1.0566 ) p.u. ( E_2 = 1.0502 ) p.u. ( E_3 = 1.0170 ) p.u.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 7-5</td>
<td>1.0565</td>
<td>1.0575</td>
<td>1.02866</td>
<td>1.00955</td>
<td>4</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.0533</td>
<td>1.05508</td>
<td>1.03359</td>
<td>0.99997</td>
<td>2</td>
</tr>
</tbody>
</table>

### Final generators internal voltage - High threshold values

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>( \Delta V_{\text{new}} ) (p.u.)</th>
<th># of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault 7-5</td>
<td>1.0616</td>
<td>1.06657</td>
<td>1.06752</td>
<td>0.99137</td>
<td>4</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>1.0514</td>
<td>1.05798</td>
<td>1.0326</td>
<td>0.99993</td>
<td>2</td>
</tr>
</tbody>
</table>

### Final generators internal voltage - Medium threshold values

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>( \Delta V_{\text{new}} ) (p.u.)</th>
<th># of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault 7-5</td>
<td>1.0619</td>
<td>1.0665</td>
<td>1.06792</td>
<td>1.00859</td>
<td>4</td>
</tr>
<tr>
<td>Fault 9-6</td>
<td>0.99336</td>
<td>1.0695</td>
<td>1.0526</td>
<td>0.99758</td>
<td>2</td>
</tr>
</tbody>
</table>

The results obtained for the power and voltage control loops using the high threshold values and adaptive control were applied to the system under study. The angle variation of generator 2 for a fault at bus 7-5 was evaluated for the case of both loops working together and when only the power control loop is activated.
Figure 7.15: Fault line 7-5 Three-Generator Case Comparison of Security Enhancement Control Strategies

For the two-loop strategy, adaptive and non-adaptive procedures were employed. Faster convergence was found to occur in the case that the adaptive loop is used. It is interesting to also note that for the generator at bus 1 the control action for contingency 7-5 implies an increase in the generator voltage, while for fault at 9-6 it is the opposite. In the end, due to the application of a unique final control action, one of the faults will be negatively affected. This justifies the search for a higher desired energy margin level so that when all the strategies are combined, even for those negatively affected, the energy margin will remain stable.

Figure 7.15 compares the results using only power control, or both. It is possible to observe the higher damping when both loops are used, mainly due to the smaller deviation on the output power of the generators.
7.2 CIGRE Test Case

As a second example, the CIGRE test case was employed. This is one of the smallest benchmark cases documented for traditional energy margin evaluations. The system is shown in Figure 7.5 and the data is given in [53].

Figure 7.16: CIGRE Test Case

7.2.1 Calculation of the Critical Clearing Time Using the Two-Equivalent System

In order to further verify the accuracy of the proposed energy margin index, the critical clearing time (ccl) is obtained using the proposed method, and compared with the output from a conventional (SBS) stability program. The type of fault applied is a three phase fault, with clearance at $t = 0.39\ s$ and no reclosing. Table 7.16 shows a comparison between the critical clearance time (ccl) calculated using both a conventional step by step (SBS) stability program and by the proposed method.
Table 7.16
CIGRE's System Critical Clearing Time

<table>
<thead>
<tr>
<th>Fault at Bus - Opening Line</th>
<th>ccl - SBS (s)</th>
<th>ccl - ΔV (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 3</td>
<td>0.345</td>
<td>0.340</td>
</tr>
<tr>
<td>3 - 9</td>
<td>0.396</td>
<td>0.381</td>
</tr>
<tr>
<td>2 - 2 - 3</td>
<td>0.380</td>
<td>0.393</td>
</tr>
<tr>
<td>2 - 2 - 10</td>
<td>0.392</td>
<td>0.399</td>
</tr>
<tr>
<td>8 - 8 - 6</td>
<td>0.445</td>
<td>0.425</td>
</tr>
<tr>
<td>4 - 4 - 3</td>
<td>0.492</td>
<td>0.484</td>
</tr>
</tbody>
</table>

A comparison between the respective ccl's shows that the method gives accurate results, when compared to those obtained with the SBS program, the differences between both values are less than three percent. Except for the fault 2-3, the results are somewhat conservative.

7.2.2 CIGRE System Security Classifier

Table 7.17 gives the parameters necessary to obtain the threshold values for the security classifier, using the same procedure as that implemented for the three-generator case.

Table 7.17
Threshold Values Evaluation tcl = 0.39 s

<table>
<thead>
<tr>
<th>Fault</th>
<th>ΔV_o (p.u.)</th>
<th>ΔV_min (p.u.)</th>
<th>P_{equiv/o} (p.u.)</th>
<th>\frac{∂ΔV}{∂P_{equiv/o}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>-3.682</td>
<td>0.3564</td>
<td>1.1654</td>
<td>-9.2886</td>
</tr>
<tr>
<td>3-9</td>
<td>-0.240</td>
<td>0.9699</td>
<td>1.2778</td>
<td>-15.369</td>
</tr>
<tr>
<td>2-3</td>
<td>0.431</td>
<td>-3.4631</td>
<td>-0.2805</td>
<td>-12.424</td>
</tr>
<tr>
<td>8-6</td>
<td>0.795</td>
<td>0.2063</td>
<td>0.2081</td>
<td>-16.017</td>
</tr>
<tr>
<td>4-3</td>
<td>14.21</td>
<td>1.15</td>
<td>0.5342</td>
<td>-16.612</td>
</tr>
</tbody>
</table>

The selected threshold values for the energy margin index and sensitivity with respect to the equivalent power are:

\[ ΔV_{min} = 1.15 \text{ (p.u.)} \quad \frac{∂ΔV}{∂P_{equiv/o}} = 9.288 \text{ (p.u.)} \]
With this information, the security index and the security vector (eq. 4.20) are obtained for all the selected faults and the results are shown in Table 7.18.

**Table 7.18**

Security Index and Security Vector

**CIGRE Case $t_{cl}=0.39$ s**

<table>
<thead>
<tr>
<th>Fault</th>
<th>Security Vector</th>
<th>Security Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>$(0,0,0,1)$</td>
<td>0.1944</td>
</tr>
<tr>
<td>3-9</td>
<td>$(0,0,0,1)$</td>
<td>0.1944</td>
</tr>
<tr>
<td>2-3</td>
<td>$(0.4308,0.569,0)$</td>
<td>0.3429</td>
</tr>
<tr>
<td>2-10</td>
<td>$(0.00909,0.091,0)$</td>
<td>0.4618</td>
</tr>
<tr>
<td>8-6</td>
<td>$(0.00795,0.205)$</td>
<td>0.4272</td>
</tr>
<tr>
<td>4-3</td>
<td>$(0,1,0,0)$</td>
<td>0.7500</td>
</tr>
</tbody>
</table>

Security Vector = $(CS, AT, AM, IS)$

A comparison with the respective $ccl's$ demonstrates that the proposed method using energy margin level $\Delta V$ and the sensitivity value $\partial \Delta V/\partial P_{equiv}$ classify the system correctly.

Various load scenarios were studied to evaluate their effect on the security vector and security index under variable load conditions. Table 7.19 shows the results obtained for different load values, as a percentage of the base case load for faults at particular lines.
<table>
<thead>
<tr>
<th>Load % Fault</th>
<th>ΔV (p.u.)</th>
<th>∂ΔV/∂P_{equiv} (p.u.)</th>
<th>P_{equiv} (p.u.)</th>
<th>Security Vector</th>
<th>Security Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% 1-3</td>
<td>6.5516</td>
<td>-14.5913</td>
<td>0.4414</td>
<td>(0,1,0,0)</td>
<td>0.750</td>
</tr>
<tr>
<td>98% 1-3</td>
<td>-0.0932</td>
<td>-12.6209</td>
<td>0.8746</td>
<td>(0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>101% 1-3</td>
<td>-4.904</td>
<td>-7.1071</td>
<td>1.3118</td>
<td>(0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>95% 3-9</td>
<td>-1.428</td>
<td>-14.4054</td>
<td>1.3407</td>
<td>(0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>98% 3-9</td>
<td>-0.766</td>
<td>-14.8826</td>
<td>1.3109</td>
<td>(0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>101% 3-9</td>
<td>-0.062</td>
<td>-15.3691</td>
<td>1.2809</td>
<td>(0,0,1)</td>
<td>0.1944</td>
</tr>
<tr>
<td>95% 8-6</td>
<td>0.2216</td>
<td>-15.3416</td>
<td>0.3079</td>
<td>(0,0,0.22,0.78)</td>
<td>0.2859</td>
</tr>
<tr>
<td>98% 8-6</td>
<td>0.3816</td>
<td>-15.4521</td>
<td>0.27226</td>
<td>(0,0,0.38,0.62)</td>
<td>0.3309</td>
</tr>
<tr>
<td>101% 8-6</td>
<td>0.5385</td>
<td>-15.5569</td>
<td>0.23622</td>
<td>(0,0,0.54,0.46)</td>
<td>0.3676</td>
</tr>
</tbody>
</table>

This table also shows the relevance of using ΔV and ∂ΔV/∂P_{equiv} as input parameters to the classifier. Analysing, for example, the contingency in the line 3-9 as the system load increases the equivalent power decreases and the system becomes more stable, as reflected in the values of the energy margin. The opposite takes place in the case of line 1-3, where an increase in the load translates into an increment in the equivalent power, and the system exhibits smaller energy margin levels. These results and evaluations were verified with a full-size stability program. In addition, the table reveals the steep decrease in the energy margin level when a 1% of load variation occurs for the fault on line 1-3. If only the energy margin criteria were used for the classifier, this condition due to its high-energy margin level would be classified as completely secure, if one ignores the effect of its high sensitivity. When the sensitivity of the energy margin is included, the classification of its particular state is no longer considered a secure state but an alert state.

7.2.3 CIGRE System Security Enhancement Control – Open Loop Output

To evaluate the security enhancement without adaptive control, the desired energy margin was set to 1.25 (p.u.). Tables 7.20, 7.21 and 7.22 show the results obtained for a fault on line 3-9 for the open loop (non-adaptive) algorithm and for three sensitivity threshold levels.
Table 7.20
Open Loop Security Enhancement Control CIGRE Test Case
High Threshold Values Fault 3-9

<table>
<thead>
<tr>
<th>Generator</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V_o$ (p.u)</td>
<td>-0.24925</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Vector</td>
<td>(0, 0, 0, 1)</td>
<td>Sec. Index</td>
<td>0.1944</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu_{PHS}$</td>
<td>0.201</td>
<td>0</td>
<td>0.2144</td>
<td>0.2137</td>
<td>0.1698</td>
<td>0.2694</td>
</tr>
<tr>
<td>$\mu_{NHS}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu_{MR}$</td>
<td>0.3869</td>
<td>0</td>
<td>0.9653</td>
<td>0.7452</td>
<td>0.5107</td>
<td>0.5534</td>
</tr>
<tr>
<td>$\mu_{ML}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$P_i$ new</td>
<td>1.2287</td>
<td>2.4864</td>
<td>3.0766</td>
<td>2.3585</td>
<td>1.6324</td>
<td>1.75696</td>
</tr>
<tr>
<td>$\Delta V_{new}$ (p.u)</td>
<td>0.88853</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Vector</td>
<td>(0, 0, 0.8885, 0.1115)</td>
<td>Sec. Index</td>
<td>0.454914</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.21
Open Loop Security Enhancement Control CIGRE Test Case
Medium Threshold Values Fault 3-9

<table>
<thead>
<tr>
<th>Generator</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V_o$ (p.u)</td>
<td>-0.24925</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Vector</td>
<td>(0, 0, 0, 1)</td>
<td>Sec. Index</td>
<td>0.1944</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu_{PHS}$</td>
<td>0.4033</td>
<td>0</td>
<td>0.4628</td>
<td>0.4556</td>
<td>0.3966</td>
<td>0.4939</td>
</tr>
<tr>
<td>$\mu_{NHS}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu_{MR}$</td>
<td>0.3869</td>
<td>0</td>
<td>0.9653</td>
<td>0.7452</td>
<td>0.5107</td>
<td>0.5534</td>
</tr>
<tr>
<td>$\mu_{ML}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$P_i$ new</td>
<td>1.2399</td>
<td>2.5088</td>
<td>3.1148</td>
<td>2.3866</td>
<td>1.6524</td>
<td>1.811</td>
</tr>
<tr>
<td>$\Delta V_{new}$ (p.u)</td>
<td>0.52646</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Vector</td>
<td>(0, 0, 0.52646, 0.47354)</td>
<td>Sec. Index</td>
<td>0.364912</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 7.22
Open Loop Security Enhancement Control CIGRE Test Case
Small Threshold Values Fault 3-9

<table>
<thead>
<tr>
<th>Generator</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta V_o$ (p.u)</td>
<td></td>
<td></td>
<td></td>
<td>0.24925</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Vector</td>
<td>(0, 0, 0, 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Index</td>
<td>0.1944</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu_{PHS}$</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\mu_{NHS}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\mu_{MR}$</td>
<td>0.3869</td>
<td>0</td>
<td>0.9652</td>
<td>0.7452</td>
<td>0.5106</td>
<td>0.5534</td>
</tr>
<tr>
<td>$\mu_{ML}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$P_i$ new</td>
<td>1.2576</td>
<td>2.5303</td>
<td>3.1442</td>
<td>2.4105</td>
<td>1.6768</td>
<td>1.8238</td>
</tr>
<tr>
<td>$\Delta V_{new}$ (p.u)</td>
<td>0.1858</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Vector</td>
<td>(0, 0, 0.1858, 0.8142)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sec. Index</td>
<td>0.2741</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tables 7.20 to 7.22 also show, for the power controller, the membership function for the sensitivities: positive and high $\mu_{PHS}$ and negative and high $\mu_{NHS}$, including the higher and lower output margins $\mu_{MR}$ and $\mu_{ML}$. They also give the final open loop control power output signal $P_i$ required to obtain the desired energy margin for each one of the generators. Finally, in their last two rows, the new energy margin level obtained using the indicated power outputs and the new security vectors are shown.

The results (without the adaptive procedure) demonstrate the need for a closed-loop algorithm. The final power outputs for the threshold levels studied do not take the energy margin to the desired value, due to the non-linearity of the process and the non-adequacy of the membership functions among other reasons. For example, comparing the results obtained for the contingency in line 3-9 for the different threshold values, it can be observed in Table 7.22 that all the sensitivity membership values are equal to one, leaving all the generators with the same opportunity to contribute, limited only by their physical margin. In this case, a solution in which the generators have a higher deviation from the optimum dispatch point is reached, which does not necessarily mean a higher energy margin level, while causing steady state convergence problems in a number of cases. Evaluating the maximum threshold scenario, the high threshold values (Table 7.20), will...
ignore most of the generators, except those with the highest sensitivities. This is more desirable than the previous case, but it still fails to reach the desired $\Delta V$.

7.2.4 CIGRE System Closed-Loop Security Enhancement Control - Without Adaptive Control

Two different closed-loop procedures were considered. Table 7.23 shows for different threshold values the final power output for each generator needed in order to obtain the desired energy margin when a non-scaling iterative feedback procedure is implemented.

Table 7.23
Closed-Loop Security Enhancement Control w/o Scaling CIGRE Test Case

<table>
<thead>
<tr>
<th>Generator</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>$\Delta V$ (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial generator’s output power (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.2</td>
<td>2.56</td>
<td>3.0</td>
<td>2.3</td>
<td>1.6</td>
<td>1.74</td>
<td>-0.240</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2</td>
<td>2.56</td>
<td>3.0</td>
<td>2.3</td>
<td>1.6</td>
<td>1.74</td>
<td>0.795</td>
</tr>
<tr>
<td>Generator’s output power – High Threshold Values (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.25</td>
<td>2.463</td>
<td>3.1027</td>
<td>2.384</td>
<td>1.6532</td>
<td>1.829</td>
<td>1.2496</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.22</td>
<td>2.604</td>
<td>3.046</td>
<td>2.3418</td>
<td>1.6242</td>
<td>1.6814</td>
<td>1.2499</td>
</tr>
<tr>
<td>Generator’s output power – Medium Threshold Values (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.3292</td>
<td>2.4605</td>
<td>3.2322</td>
<td>2.5014</td>
<td>1.7502</td>
<td>1.9347</td>
<td>1.2494</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2383</td>
<td>2.6254</td>
<td>3.0719</td>
<td>2.3655</td>
<td>1.6439</td>
<td>1.6812</td>
<td>1.2498</td>
</tr>
<tr>
<td>Generator’s output power – Small Threshold Values (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.4393</td>
<td>2.4527</td>
<td>3.5333</td>
<td>2.7579</td>
<td>1.9197</td>
<td>2.0876</td>
<td>1.2493</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.4138</td>
<td>2.8932</td>
<td>3.3487</td>
<td>2.6357</td>
<td>1.8256</td>
<td>1.6785</td>
<td>1.2494</td>
</tr>
</tbody>
</table>

7.2.5 CIGRE System Closed-Loop Security Enhancement Control - With Adaptive Control

This second closed-loop method corresponds to the adjustment of the sensitivity parameters using the gradient method technique. Conjugate methods are not needed due to the small system size. The results are shown in Table 7.24.
Table 7.24
Closed-Loop Security Enhancement Control with Scaling CIGRE Test Case

<table>
<thead>
<tr>
<th>Generator</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>ΔV (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial generator's output power (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.2</td>
<td>2.56</td>
<td>3.0</td>
<td>2.3</td>
<td>1.6</td>
<td>1.74</td>
<td>-0.240</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2</td>
<td>2.56</td>
<td>3.0</td>
<td>2.3</td>
<td>1.6</td>
<td>1.74</td>
<td>0.795</td>
</tr>
<tr>
<td>Generator's output power – High Threshold Values (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.2381</td>
<td>2.4637</td>
<td>3.0798</td>
<td>2.3698</td>
<td>1.6368</td>
<td>1.7975</td>
<td>1.25</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2214</td>
<td>2.6036</td>
<td>3.0426</td>
<td>2.3388</td>
<td>1.6217</td>
<td>1.6821</td>
<td>1.2445</td>
</tr>
<tr>
<td>Generator's output power – Medium Threshold Values (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.2564</td>
<td>2.4633</td>
<td>3.1213</td>
<td>2.4150</td>
<td>1.6598</td>
<td>1.8150</td>
<td>1.2498</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2368</td>
<td>2.6333</td>
<td>3.0651</td>
<td>2.3603</td>
<td>1.6381</td>
<td>1.6817</td>
<td>1.2474</td>
</tr>
<tr>
<td>Generator's output power – Small Threshold Values (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.2750</td>
<td>2.4627</td>
<td>3.1553</td>
<td>2.4559</td>
<td>1.6858</td>
<td>1.8366</td>
<td>1.2468</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2449</td>
<td>2.9229</td>
<td>3.1005</td>
<td>2.3902</td>
<td>1.6485</td>
<td>1.6829</td>
<td>1.2482</td>
</tr>
</tbody>
</table>

Figure 7.6 shows the angle variation of generator 3 when a fault is applied on line 3-9 for the different strategies developed.

Figure 7.17: Fault Line 3-9 CIGRE-Generator Case Comparison of Security Enhancement Control Strategies
Comparing the open-loop results in Tables 7.20 to 7.22 with the closed-loop values in Tables 7.23 and 7.24, it is possible to observe that the desired energy margin level can be achieved at the expense of a more time-intensive algorithm. The adaptation procedure tends to eliminate one of the main problems of the open-loop algorithm, which is the large dependency of the generator outputs with the selection of the threshold values.

Figure 7.17 shows the angle variation of generator 3 when a fault is applied on line 3-9, with and without security enhancement techniques. In the presence of the power output control the system is stabilised. For stable cases, where the adaptive procedure was used, smaller oscillations are present, directly associated with higher energy margin levels (the desired value). In the case where there is an absence of an adaptive procedure, the energy margin obtained is smaller than the specified value and the system is more oscillatory.

### 7.2.6 CIGRE System Power-Voltage Control Loop

In the following results, the energy margin level is taken to a value above 1.18 p.u. using power control schemes, while the target of 1.25 p.u. is later reached using voltage control exclusively.

| Table 7.25 |
|---|---|---|---|---|---|---|---|
| Generator’s output power (p.u.) | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Fault 3-9 | 1.9794 | 1.2366 | 2.4675 | 3.0793 | 2.3679 | 1.6360 | 1.7972 |
| Fault 8-6 | 2.0639 | 1.2177 | 2.5979 | 3.0397 | 2.3355 | 1.6191 | 1.6896 |
| Generator’s initial internal voltage | | | | | | | |
| Internal EMF (p.u.) | 1.1060 | 1.1635 | 1.1058 | 1.0965 | 1.1059 | 1.0441 | 1.0761 |
| Generator’s final output Voltage – High Threshold Values (p.u.) | | | | | | | |
| Fault 3-9 | 1.1091 | 1.1655 | 1.1071 | 1.0975 | 1.1074 | 1.0455 | 1.0774 |
| Fault 8-6 | 1.1134 | 1.1677 | 1.1084 | 1.0988 | 1.1090 | 1.0466 | 1.0788 |
| Generator’s final output power – Small Threshold Values (p.u.) | | | | | | | |
| Fault 3-9 | 1.1091 | 1.1653 | 1.1071 | 1.0975 | 1.1075 | 1.0454 | 1.0776 |
| Fault 8-6 | 1.1176 | 1.1712 | 1.1160 | 1.1019 | 1.1156 | 1.0541 | 1.0777 |
7.2.7 CIGRE System Simultaneous Preventive Control

If the power strategy suggested in Table 7.24 for fault 3-9 and the higher threshold values is applied directly as the output power of the system, the system condition for fault 8-6 deteriorates and the energy margin level for this fault decreases from 1.2445 p.u. to 0.326899 p.u. It is necessary, therefore, to implement the simultaneous power control as described in Chapter VI.

In Table 7.26 the simultaneous unique control strategy is shown. When these values are used, the energy value for fault 3-9 increases with respect to the target of 1.25 p.u., while there is a slight decrease for fault 8-6.

Table 7.26
Simultaneous Preventive Power Control CIGRE Test Case

<table>
<thead>
<tr>
<th>Fault</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>ΔV(p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power Output Individual Preventive Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.23814</td>
<td>2.46373</td>
<td>3.07981</td>
<td>2.36982</td>
<td>1.63681</td>
<td>1.79747</td>
<td>1.25</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2214</td>
<td>2.6031</td>
<td>3.04264</td>
<td>2.3388</td>
<td>1.62168</td>
<td>1.6821</td>
<td>1.244</td>
</tr>
<tr>
<td></td>
<td>Power Output Simultaneous Preventive Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault 3-9</td>
<td>1.2464</td>
<td>2.46322</td>
<td>3.09336</td>
<td>2.38778</td>
<td>1.64906</td>
<td>1.6814</td>
<td>1.275</td>
</tr>
<tr>
<td>Fault 8-6</td>
<td>1.2464</td>
<td>2.46322</td>
<td>3.09336</td>
<td>2.38778</td>
<td>1.64906</td>
<td>1.6814</td>
<td>1.2389</td>
</tr>
</tbody>
</table>

7.3 Iowa - Test Case

The one-line diagram for the Iowa test case is shown in reference [82]. The system has several generating plants along the banks of the Missouri River. The electrical proximity of these plants results in a very complex dynamic behaviour of the system. For a three phase fault close to the plants a large number of plants are severely disturbed, resulting in a complex mode of disturbance. In this system, four different faults were evaluated:

a) Fault 1: Consists of a three-phase fault at bus 75, cleared by opening the line between bus 75 and bus 9. The effect of the fault is a complex mode of disturbance, seven generators close to the fault are severely disturbed. In
the critical case, however, only one generator loses synchronism with respect to the rest. This fault is the only result documented by [82].

b) Fault 2: Fault applied at generator’s bus 15 with opening of the line between bus 8 and bus 15.

c) Fault 3: Fault at bus 70 with opening of the line between bus 70 and bus 153.

d) Fault 4: Fault at generator’s bus 27 with opening of the line between buses 27 and 31.

The numbering corresponds to the Iowa case given in [82]. The same type of analysis executed for previous cases is repeated for the Iowa 17-generator system.

7.3.1 Calculation of the Critical Clearing Time Using the Two-Equivalent System

The critical clearing time is obtained for the four selected contingencies using the proposed method and compared with the values obtained using a conventional SBS stability program.

Table 7.27

<table>
<thead>
<tr>
<th>Iowa’s System Critical Clearing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault at Bus - Opening Line</td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>75-9</td>
</tr>
<tr>
<td>8-15</td>
</tr>
<tr>
<td>70-153</td>
</tr>
<tr>
<td>27-31</td>
</tr>
</tbody>
</table>
Figure 7.18 shows for a fault at bus 75 with opening of line 75-9 at $tcl = 0.345$ s the interesting dynamic behaviour observed for this system where seven generators close to the fault are disturbed, but only one loses synchronism.

In order to continue testing the proposed model, the critical clearing time was obtained for the four faults, and the results were shown in Table 7.27. As in the previous cases, the results, when compared with the ones obtain using a $SBS$ methods, are smaller than the corresponding values using the $SBS$ program.

### 7.3.2 Iowa System Security Classifier

The parameters necessary for the calculation of the threshold values are given in Table 7.28.
Table 7.28
Data for Threshold Values Evaluation $tcl = 0.26 \text{ s}$

<table>
<thead>
<tr>
<th>Fault</th>
<th>$\Delta V_0$ (p.u.)</th>
<th>$P_{\text{equiv/o}}$ (p.u.)</th>
<th>$\partial \Delta V/\partial P_{\text{equiv/o}}$</th>
<th>Security Vector</th>
<th>Security Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>75-9</td>
<td>4.1956</td>
<td>3.97456</td>
<td>-11.1922</td>
<td>(0, 1, 0, 0)</td>
<td>0.75</td>
</tr>
<tr>
<td>8-15</td>
<td>-0.3182</td>
<td>2.9334</td>
<td>-1.5090</td>
<td>(0, 0, 0, 1)</td>
<td>0.194</td>
</tr>
<tr>
<td>70-153</td>
<td>-5.6806</td>
<td>3.94538</td>
<td>-2.4714</td>
<td>(0, 0, 0, 1)</td>
<td>0.194</td>
</tr>
<tr>
<td>27-31</td>
<td>-13.3134</td>
<td>11.6938</td>
<td>-1.4818</td>
<td>(0, 0, 0, 1)</td>
<td>0.194</td>
</tr>
</tbody>
</table>

The threshold values for the energy margin index and sensitivity with respect to the equivalent power are:

$$\Delta V_{\text{min}} = 0.5 \text{ p.u.}, \quad \partial \Delta V/\partial P_{\text{equiv}} = 1.50 \text{ p.u.}$$

In this benchmark case, no open-loop evaluation was performed because it is clear that it is not possible to take the system to the desired value in one single iteration.

7.3.3 Iowa System Closed-Loop Security Enhancement Control Without Adaptive Control

In this case, three different closed-loop procedures were considered: the non-scaling feedback procedure (constant threshold values), the second methodology consists in the optimisation using gradient search techniques, and the third is the optimisation procedure which uses the conjugate gradient technique. Tables 7.29 and 7.30 show, for different threshold values, the final mechanical power output of each generator required to obtain for all the different faults a desired energy margin of 0.75 p.u. within the given error tolerance of $10^{-4}$ p.u. and a clearance time of 0.33 seconds. The energy margin target of 1.0 p.u. is going to be reached afterwards with the combination of power and voltage control.
### Table 7.29
Iterative Procedure w/o Optimisation High Threshold Values

<table>
<thead>
<tr>
<th>$\Delta V_x$ (p.u.)</th>
<th>Fault 1</th>
<th>Fault 2</th>
<th>Fault 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.1791</td>
<td>-17.59</td>
<td>-22.75</td>
</tr>
<tr>
<td># of iterations</td>
<td>6</td>
<td>13</td>
<td>7</td>
</tr>
<tr>
<td>Generator Power (p.u)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generator Final Power Output (p.u.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20.0</td>
<td>20.0454</td>
<td>27.3592</td>
</tr>
<tr>
<td>2</td>
<td>7.94</td>
<td>7.9413</td>
<td>7.3872</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
<td>15.030</td>
<td>12.5826</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>15.0451</td>
<td>14.5296</td>
</tr>
<tr>
<td>5</td>
<td>4.47</td>
<td>4.4719</td>
<td>4.0985</td>
</tr>
<tr>
<td>6</td>
<td>10.55</td>
<td>10.5755</td>
<td>10.1081</td>
</tr>
<tr>
<td>7</td>
<td>1.309</td>
<td>1.3152</td>
<td>1.2882</td>
</tr>
<tr>
<td>8</td>
<td>0.82</td>
<td>0.8152</td>
<td>0.7722</td>
</tr>
<tr>
<td>9</td>
<td>5.502</td>
<td>5.5038</td>
<td>5.0705</td>
</tr>
<tr>
<td>10</td>
<td>1.31</td>
<td>1.3017</td>
<td>1.1828</td>
</tr>
<tr>
<td>11</td>
<td>1.73</td>
<td>1.7237</td>
<td>1.5674</td>
</tr>
<tr>
<td>12</td>
<td>6.20</td>
<td>6.2248</td>
<td>5.8027</td>
</tr>
<tr>
<td>13</td>
<td>25.1</td>
<td>25.755</td>
<td>25.3123</td>
</tr>
<tr>
<td>14</td>
<td>23.88</td>
<td>23.909</td>
<td>23.5344</td>
</tr>
<tr>
<td>15</td>
<td>24.67</td>
<td>24.688</td>
<td>24.2964</td>
</tr>
<tr>
<td>16</td>
<td>4.55</td>
<td>4.2802</td>
<td>4.2056</td>
</tr>
<tr>
<td>17</td>
<td>5.75</td>
<td>5.7569</td>
<td>5.3356</td>
</tr>
</tbody>
</table>

### Table 7.30
Iterative Procedure w/o Optimisation Small Threshold Values

<table>
<thead>
<tr>
<th>$\Delta V_x$ (p.u.)</th>
<th>Fault 1</th>
<th>Fault 2</th>
<th>Fault 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.1791</td>
<td>-17.59</td>
<td>-22.75</td>
</tr>
<tr>
<td># of iterations</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generator Power (p.u)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generator Final Power Output (p.u.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20.0</td>
<td>Oscillatory</td>
<td>Load Flow</td>
</tr>
<tr>
<td>2</td>
<td>7.94</td>
<td>Convergence problems</td>
<td>11.7006</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
<td></td>
<td>14.0506</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td></td>
<td>1.3069</td>
</tr>
<tr>
<td>5</td>
<td>4.47</td>
<td></td>
<td>1.2882</td>
</tr>
<tr>
<td>6</td>
<td>10.55</td>
<td></td>
<td>1.35173</td>
</tr>
<tr>
<td>7</td>
<td>1.309</td>
<td></td>
<td>1.37147</td>
</tr>
<tr>
<td>8</td>
<td>0.82</td>
<td></td>
<td>0.7796</td>
</tr>
<tr>
<td>9</td>
<td>5.502</td>
<td></td>
<td>4.0926</td>
</tr>
<tr>
<td>10</td>
<td>1.31</td>
<td></td>
<td>1.3006</td>
</tr>
<tr>
<td>11</td>
<td>1.73</td>
<td></td>
<td>1.4506</td>
</tr>
<tr>
<td>12</td>
<td>6.20</td>
<td></td>
<td>6.6484</td>
</tr>
<tr>
<td>13</td>
<td>25.1</td>
<td></td>
<td>20.7572</td>
</tr>
<tr>
<td>14</td>
<td>23.88</td>
<td></td>
<td>18.8591</td>
</tr>
<tr>
<td>15</td>
<td>24.67</td>
<td></td>
<td>19.4847</td>
</tr>
<tr>
<td>16</td>
<td>4.55</td>
<td></td>
<td>5.2359</td>
</tr>
<tr>
<td>17</td>
<td>5.75</td>
<td></td>
<td>5.8742</td>
</tr>
</tbody>
</table>
Tables 7.29 and 7.30 show, for the closed-loop non-adaptive procedure, the resulting final generators output power for the different threshold levels. In Table 7.29 the system achieves a solution for all the contingencies under study. This is not the case when using the small threshold values, where there are faults for which no solution can be achieved.

For all the faults under study, when no optimisation methods are used, the number of iterations is high, between 6 and 8 depending on the fault location.

### 7.3.4 Iowa System Closed-Loop Security Enhancement Control- With Adaptive Control and Gradient Search Techniques

Tables 7.31, 7.32 and 7.33 show the different results obtained using this method, with respective high, medium and small threshold values.

#### Table 7.31

**Iterative Procedure with Optimisation (Gradient) High Threshold Values**

<table>
<thead>
<tr>
<th>Generator Power (p.u.)</th>
<th>Fault 1</th>
<th>Fault 2</th>
<th>Fault 3</th>
<th>Fault 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>#of iterations</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Generator Final Power Output (p.u.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20.0</td>
<td>19.9051</td>
<td>22.8015</td>
<td>20.2134</td>
</tr>
<tr>
<td>2</td>
<td>7.94</td>
<td>7.9513</td>
<td>7.8195</td>
<td>7.8794</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
<td>15.0399</td>
<td>12.5749</td>
<td>14.9372</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>15.0551</td>
<td>14.979</td>
<td>14.8948</td>
</tr>
<tr>
<td>5</td>
<td>4.47</td>
<td>4.48922</td>
<td>4.4281</td>
<td>2.8612</td>
</tr>
<tr>
<td>6</td>
<td>10.55</td>
<td>10.5845</td>
<td>10.5095</td>
<td>10.4969</td>
</tr>
<tr>
<td>7</td>
<td>1.309</td>
<td>1.32116</td>
<td>1.3436</td>
<td>1.3078</td>
</tr>
<tr>
<td>8</td>
<td>0.82</td>
<td>0.8214</td>
<td>0.8228</td>
<td>0.8182</td>
</tr>
<tr>
<td>9</td>
<td>5.502</td>
<td>5.5136</td>
<td>5.4286</td>
<td>5.4616</td>
</tr>
<tr>
<td>10</td>
<td>1.31</td>
<td>1.31168</td>
<td>1.3071</td>
<td>1.3044</td>
</tr>
<tr>
<td>11</td>
<td>1.73</td>
<td>1.7338</td>
<td>1.7257</td>
<td>1.7221</td>
</tr>
<tr>
<td>12</td>
<td>6.20</td>
<td>6.2349</td>
<td>6.1873</td>
<td>6.1563</td>
</tr>
<tr>
<td>13</td>
<td>25.1</td>
<td>25.764</td>
<td>25.715</td>
<td>25.6554</td>
</tr>
<tr>
<td>14</td>
<td>23.88</td>
<td>23.917</td>
<td>23.870</td>
<td>23.8302</td>
</tr>
<tr>
<td>16</td>
<td>4.55</td>
<td>4.27987</td>
<td>4.5382</td>
<td>4.51998</td>
</tr>
<tr>
<td>17</td>
<td>5.75</td>
<td>5.7668</td>
<td>5.6998</td>
<td>5.7096</td>
</tr>
</tbody>
</table>
Table 7.32
Iterative Procedure with Optimisation (Gradient) Medium Threshold Values

<table>
<thead>
<tr>
<th>Generator</th>
<th>Power (p.u.)</th>
<th>Fault 1 (p.u.)</th>
<th>Fault 2 (p.u.)</th>
<th>Fault 3 (p.u.)</th>
<th>Fault 4 (p.u.)</th>
<th># of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>18.9283</td>
<td>26.9185</td>
<td>23.2479</td>
<td>28.2571</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>7.94</td>
<td>8.0357</td>
<td>7.6795</td>
<td>7.9801</td>
<td>7.3979</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
<td>15.1160</td>
<td>12.5610</td>
<td>15.0875</td>
<td>14.4290</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>15.1496</td>
<td>15.3160</td>
<td>10.046</td>
<td>14.7667</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>4.47</td>
<td>4.5188</td>
<td>4.1967</td>
<td>4.5118</td>
<td>2.8801</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10.55</td>
<td>10.6659</td>
<td>10.6950</td>
<td>10.6026</td>
<td>9.7349</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.309</td>
<td>1.3695</td>
<td>1.2083</td>
<td>1.4381</td>
<td>1.2265</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.82</td>
<td>0.8447</td>
<td>0.6568</td>
<td>0.8753</td>
<td>0.7424</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>5.502</td>
<td>5.5489</td>
<td>4.9670</td>
<td>5.5621</td>
<td>4.9556</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.31</td>
<td>1.3318</td>
<td>1.0436</td>
<td>1.3499</td>
<td>1.1544</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.73</td>
<td>1.7607</td>
<td>1.2857</td>
<td>1.8153</td>
<td>1.5256</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>6.20</td>
<td>6.3097</td>
<td>6.2589</td>
<td>6.2567</td>
<td>5.7550</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>23.88</td>
<td>24.0435</td>
<td>22.841</td>
<td>24.2793</td>
<td>23.1739</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>4.55</td>
<td>4.2793</td>
<td>4.5187</td>
<td>4.5970</td>
<td>4.1070</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>5.75</td>
<td>5.8264</td>
<td>5.6219</td>
<td>5.7924</td>
<td>5.2970</td>
<td></td>
</tr>
</tbody>
</table>
### Table 7.33

Iterative Procedure with Optimisation (Gradient) Small Threshold Values

<table>
<thead>
<tr>
<th>Fault</th>
<th>$AV_v$ (p.u.)</th>
<th># of iterations</th>
<th>Generator Power (p.u.)</th>
<th>Generator Final Power Output (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault 1</td>
<td>-1.1791</td>
<td>3</td>
<td>20.0</td>
<td>15.3059</td>
</tr>
<tr>
<td>Fault 2</td>
<td>-17.59</td>
<td>8</td>
<td>7.94</td>
<td>8.4682</td>
</tr>
<tr>
<td>Fault 3</td>
<td>-12.3132</td>
<td>16</td>
<td>15.0</td>
<td>15.453</td>
</tr>
<tr>
<td>Fault 4</td>
<td>-22.75</td>
<td>2</td>
<td>15.0</td>
<td>15.595</td>
</tr>
</tbody>
</table>

7.3.5 Iowa System Security Enhancement Control- With Adaptive Control and Conjugate-Gradient Search Techniques

The application of the conjugate gradient technique was justified due to the system size. Table 7.34 shows the results obtained for faults 2 and 3 (higher iteration number) and the medium threshold values case.
Table 7.34
Iterative Procedure with Optimisation (Conjugate Method) Medium Threshold Values

<table>
<thead>
<tr>
<th>Generator</th>
<th>Power (p.u.)</th>
<th>Generator Final Power Output (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>22.7833</td>
</tr>
<tr>
<td>2</td>
<td>7.94</td>
<td>7.90152</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
<td>12.5658</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>15.321</td>
</tr>
<tr>
<td>5</td>
<td>4.47</td>
<td>4.442</td>
</tr>
<tr>
<td>6</td>
<td>10.55</td>
<td>10.732</td>
</tr>
<tr>
<td>7</td>
<td>1.309</td>
<td>1.3733</td>
</tr>
<tr>
<td>8</td>
<td>0.82</td>
<td>0.6776</td>
</tr>
<tr>
<td>9</td>
<td>5.502</td>
<td>5.4882</td>
</tr>
<tr>
<td>10</td>
<td>1.31</td>
<td>1.2892</td>
</tr>
<tr>
<td>11</td>
<td>1.73</td>
<td>1.3951</td>
</tr>
<tr>
<td>12</td>
<td>6.20</td>
<td>6.3316</td>
</tr>
<tr>
<td>13</td>
<td>25.1</td>
<td>25.629</td>
</tr>
<tr>
<td>14</td>
<td>23.88</td>
<td>23.432</td>
</tr>
<tr>
<td>15</td>
<td>24.67</td>
<td>24.654</td>
</tr>
<tr>
<td>16</td>
<td>4.55</td>
<td>4.628</td>
</tr>
<tr>
<td>17</td>
<td>5.75</td>
<td>5.7643</td>
</tr>
</tbody>
</table>
Figure 7.19: Fault line 75-9 Iowa Case Comparison of Security Enhancement Control Strategies

When the scaling procedure is used as in Tables 7.31, 7.32 and 7.33, we now have convergence for all the faults and for the three threshold levels. In the case of fault 2, where the non-adaptive procedure fails due to load flow problems, the gradient optimisation succeeds as the first iteration modifies the threshold values and subsequently the generators output powers are adjusted achieving load-flow convergence. Therefore, this optimisation procedure has a greater chance of succeeding.

Even using the gradient optimisation technique, the number of iterations needed in some cases is relatively high, and the use of a conjugate gradient method seems justified. In this case the use of a more efficient method decreases the total number of iterations to five. The problem with this method is that each iteration of the conjugate gradient technique takes a great number of function evaluations in order to obtain the Hessian matrix, as explained in Appendix 3.
Figure 7.19 shows the results obtained for the generator behaviour when fault 1 is applied with a clearance time $ccl = 0.26$ s, for the different control strategies obtained in which the critical generator is stabilised.

7.3.6 Iowa System - Power and Voltage Control

In the following results, the energy margin level is taken to a value above 0.95 p.u. by power control. The target of 1.0 p.u. is then reached using voltage control. The gradient optimisation technique was used for the power loop while no scaling was used for the voltage loop. The values of the final power for the power control loop as well as the final voltage obtained with the voltage control loop are given for each fault.

Table 7.35
Iowa Case Power and Voltage Control

<table>
<thead>
<tr>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Power (p.u.)</td>
</tr>
<tr>
<td>Fault 1</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Fault 1</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>13</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
<td>17</td>
</tr>
</tbody>
</table>
7.3.7 Iowa System - Simultaneous Preventive Control

Using high threshold values, the simultaneous preventive control strategy was implemented for the four contingencies under study. The results are shown in Table 7.36.

### Table 7.36

**Iowa Case Simultaneous Preventive Control**

<table>
<thead>
<tr>
<th>Generator</th>
<th>Original Power (p.u.)</th>
<th>Final Power Fault 1 (p.u.)</th>
<th>Final Power Fault 2 (p.u.)</th>
<th>Final Power Fault 3 (p.u.)</th>
<th>Final Power Fault 4 (p.u.)</th>
<th>Simultaneous output power (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>19.9051</td>
<td>22.8015</td>
<td>20.2134</td>
<td>24.0413</td>
<td>29.0238</td>
</tr>
<tr>
<td>2</td>
<td>7.94</td>
<td>7.9513</td>
<td>7.8195</td>
<td>7.8794</td>
<td>7.9864</td>
<td>7.8302</td>
</tr>
<tr>
<td>3</td>
<td>15.0</td>
<td>15.0399</td>
<td>12.5749</td>
<td>14.9372</td>
<td>15.1134</td>
<td>12.5845</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>15.0551</td>
<td>14.979</td>
<td>14.8948</td>
<td>10.0437</td>
<td>10.007</td>
</tr>
<tr>
<td>5</td>
<td>4.47</td>
<td>4.48922</td>
<td>4.4281</td>
<td>2.8612</td>
<td>4.5126</td>
<td>2.8692</td>
</tr>
<tr>
<td>6</td>
<td>10.55</td>
<td>1.05845</td>
<td>10.5095</td>
<td>10.4969</td>
<td>10.4969</td>
<td>10.5682</td>
</tr>
<tr>
<td>7</td>
<td>1.309</td>
<td>1.32116</td>
<td>1.3436</td>
<td>1.3078</td>
<td>1.3482</td>
<td>1.4112</td>
</tr>
<tr>
<td>8</td>
<td>0.82</td>
<td>0.8214</td>
<td>0.8228</td>
<td>0.8182</td>
<td>0.8295</td>
<td>0.8353</td>
</tr>
<tr>
<td>9</td>
<td>5.502</td>
<td>5.5136</td>
<td>5.4286</td>
<td>5.4616</td>
<td>5.5413</td>
<td>5.4691</td>
</tr>
<tr>
<td>10</td>
<td>1.31</td>
<td>1.31168</td>
<td>1.3071</td>
<td>1.3044</td>
<td>1.3251</td>
<td>1.3215</td>
</tr>
<tr>
<td>11</td>
<td>1.73</td>
<td>1.7338</td>
<td>1.7257</td>
<td>1.7221</td>
<td>1.7502</td>
<td>1.7481</td>
</tr>
<tr>
<td>13</td>
<td>25.1</td>
<td>25.764</td>
<td>2.5715</td>
<td>25.6554</td>
<td>25.862</td>
<td>25.9823</td>
</tr>
<tr>
<td>14</td>
<td>23.88</td>
<td>23.917</td>
<td>23.870</td>
<td>23.8302</td>
<td>23.995</td>
<td>24.0688</td>
</tr>
<tr>
<td>16</td>
<td>4.55</td>
<td>4.27987</td>
<td>4.5382</td>
<td>4.51998</td>
<td>4.6262</td>
<td>4.2614</td>
</tr>
<tr>
<td>17</td>
<td>5.75</td>
<td>5.7668</td>
<td>5.6998</td>
<td>5.7096</td>
<td>5.8121</td>
<td>5.7221</td>
</tr>
</tbody>
</table>

Final energy margin using the previous simultaneous control strategy

Fault 1- Bus 75: \( \Delta V = 0.3991 \) p.u.

Fault 2 - Bus 15: \( \Delta V = 0.6214 \) p.u.

Fault 3 - Bus 70: \( \Delta V = 0.7545 \) p.u.

Fault 4 – Bus 27: \( \Delta V = 0.567 \) p.u.

Table 7.36 shows the generator output for each individual fault while the last column displays the final common power output. With these generator outputs, the energy margin target of 0.75 p.u. for the energy margin level is not reached for all the contingencies, but the system is taken inside the stable region. One needs to target a very high-energy
margin for all contingencies, so that when the natural drop occurs the system is still stable.

For faults 1 and 4, the contour curves shown in Figures 7.20 and 7.21 are obtained.

![Contour Curve Fault 1](image1)

**Figure 7.20: Contour Curve Fault 1**

![Contour Curve Fault 4](image2)

**Figure 7.21: Contour Curve Fault 4**
Figures 7.20 and 7.21 represent the energy margin contour curves for faults 1 and 4, as a function of generators 16 (bus 130) and 4 (bus 27) output power. The remainder of the generators' power outputs are kept constant and equal to the values given in Table 7.33.

Generators 4 and 16 were selected because they are, respectively, the critical generators for Fault 1 (generator 16) and for Fault 4 (generator 4). In Figure 7.21, the energy margin for fault 4 is minimally affected by the power output of generator 16, influenced by the output power of generator 4. If this power increases the energy margin decreases. In Figure 7.20 we observe that there is no independence of fault 1 from the output of generator 4, although its effect is not as important as that of generator 16. An increase in the output power of generator 4 will translate into an increase in the energy margin level. The variations in generator 4 output power has opposite effect on Faults 1 and 4. A unique output power strategy for generator 4 would increase the energy margin level for one fault and decrease the value for the other. Thus, it is significant that the system will be stable for both contingencies when a combined strategy with a high targeted energy margin is employed.

7.4 Efficient $[Y_{bus}]$ Matrix Evaluation - Results

The algorithm developed in Chapter VI for the efficient calculation of the $[Y_{bus}]$ matrix each time a new load condition is evaluated is compared with conventional procedures for four benchmark systems. The results demonstrate the increased efficiency of the proposed method as the dimensions of the system and the number of contingencies to be evaluated increase.

The conventional procedure consists of the complete creation of the $[Y_{bus}]$ matrix whenever there is a change in the load or in the topological configuration of the system due to a fault.

The time to compute the $[Y_{bus}]$ matrices for a set of contingencies ($numcon$) with the proposed method and for each load evaluation is given by:
\[ T_{tot} = numcon \times (X_1 + X_2) \]

(7.1)

\[ T_{tot} = \text{total time employed by the proposed pre-process method} \]

\[ X_1 = \text{time required for the formation of the no-load matrix (off-line procedure) for a given contingency} \]

\[ X_2 = \text{time per load actualisation} \]

But if a comparison on the same basis is done, \( X_1 \) should not be included in the process because, the no-load matrix is created only once and inside the off-line procedure. Then the total time for the suggested process is:

\[ T_{tot} = numcon \times X_2 \]

(7.2)

In each time interval in the more conventional procedure, the pre-fault, fault and post fault matrices are created. The pre-fault matrix is created only once, while the post-fault and fault matrix are derived from the pre-fault matrix, but obtained for each contingency. Using the conventional method the total time is given by:

\[ T_{conv} = X_3 + numcon \times (X_4 + X_5) \]

(7.3)

where,

\[ T_{conv} = \text{total time employed by the conventional method} \]

\[ X_3 = \text{time require to form the pre-fault matrix} \]

\[ X_4 = \text{time require to form the fault matrix for each contingency} \]

\[ X_5 = \text{time require to form the post-fault matrix for each contingency} \]
The times involved were compared for different systems sizes:

a) IEEE-RTS system: comprises 24 buses, 11 generators and 9 non-generator load buses.

b) CIGRE system: comprises 10 buses, 7 generators and 3 non-generator load buses.

c) Three-generator system: 9 buses, 3 generators, and 3 non-generator load buses.

d) Reduced Iowa system: comprises 162 buses, 17 generators, and 107 load buses.

Table 7.37 shows the ratio between the times involved in a conventional procedure versus the proposed methodology in which ten contingencies are evaluated. In Table 7.38, the specific times for a Pentium II 266 MHz are given. The compiler used for the complete security evaluation is Object Ada 95 designed by Aonix.

Table 7.37
Relation Between Times Involved on the Creation of the $[Y_{bus}]$ Matrix

<table>
<thead>
<tr>
<th>System</th>
<th>Time ratio conventional / proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson</td>
<td>1.00</td>
</tr>
<tr>
<td>CIGRE</td>
<td>2.00</td>
</tr>
<tr>
<td>Iowa</td>
<td>1.32</td>
</tr>
<tr>
<td>RTS</td>
<td>3.37</td>
</tr>
</tbody>
</table>

Table 7.38
Simulation Results

<table>
<thead>
<tr>
<th>System</th>
<th>$X_1$ (s)</th>
<th>$X_2$ (s)</th>
<th>$X_3$ (s)</th>
<th>$X_4$  (s)</th>
<th>$X_5$  (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-gen</td>
<td>0.058</td>
<td>0.009</td>
<td>0.009</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CIGRE</td>
<td>0.0149</td>
<td>0.01</td>
<td>0.01</td>
<td>0.0095</td>
<td>0.05</td>
</tr>
<tr>
<td>Iowa</td>
<td>10.46</td>
<td>2.6240</td>
<td>3.6149</td>
<td>3.4650</td>
<td>3.375</td>
</tr>
<tr>
<td>RTS</td>
<td>0.177</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.09</td>
</tr>
</tbody>
</table>
As can be seen, the proposed method cannot match the classical method for the small case of the three generators system. Nevertheless, even for a small system as the CIGRE 7 generators - 10 bus case, it is twice as fast. In the case of the Iowa system the number of load buses is high. Around 80% of the buses are either generator or load type buses. Given, a system of the same dimension, for example 162 buses but with only 30% of the total number of buses are of generator or load type, the ratio shown in Table 7.37 for the Iowa case would increase to twelve.

It is clear from the previous discussions that the number of non-generator load buses increases the advantage of the method proposed decreases, because less pre-processing is allowed.
CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

This dissertation presents a fast method for the determination of a power system’s security level and the selection of simultaneous preventive control strategies based on fuzzy logic techniques. The importance of such methodology was established after an extensive bibliographical research, which revealed that there is a need for the development of fast techniques that can combine transient stability evaluations, with the determination of adequate preventive control strategies, suitable for a constantly changing and unpredictable environment.

The power system transient stability problem is modelled in this work using energy margin methods, due to their speed and their availability to provide an index. For the classification of the system’s state and selection of preventive control actions, approximate reasoning or fuzzy logic techniques were chosen for the security classifier and control enhancement because of their flexibility and capability. Fuzzy logic techniques are able to represent, under the same conceptual framework, numerical and linguistic-numerical considerations that offer the advantage of adaptability to varying system conditions (adaptive-optimisation procedure).

The main conclusions and observations of this work are:

1) Transient Stability Evaluation

One of the key issues for the success of a fuzzy logic algorithm is the appropriate selection of indices to be “fuzzified”. Energy margin methods are fast and provide one index (the energy margin) that summarises the state of the system. The traditional shortcomings of the energy methods were overcome in this work with the development of a generalised two-machine equivalent. The generalised method proposed possessed advantages, over traditional energy margin methods in that:
• it is a path independent method
• allows one-step computation of the energy margin index
• allows the preservation of the generator identity and network topology
• permits fast and straightforward sensitivity analysis to evaluate the desired power and voltage outputs in the security enhancement block
• in the proposed method, the post-fault angle conditions are obtained using load-flow evaluations, and no geometrical simplifications are made as in previous work [15] and [16]
• the algorithm is flexible with respect to the type, sequence and location of faults

The focus of this research is "preventive security control evaluation", and the proposed method provides a fast and efficient tool for on-line dynamic security evaluation to be used in the selection of preventive controls. However, the proposed approach should not be used for conventional transient stability evaluation, where an exact analysis of the consequences of a specific fault condition and its corrective measures (e.g., high-speed fault clearing, dynamic braking, reactor switching or power stabilisers for example) are to be evaluated.

Due to the preventive nature of the proposed method, the approximations made are not critical since the main objective is to provide information to be used in the selection of control measures to avoid the risk of instability. Once the suggested control strategy has been determined it can be fully and accurately checked using a detailed power system simulator, which in this case will be UBC's real-time simulator.

The effectiveness of the proposed method was demonstrated in Chapter VII, where the critical clearing times obtained were compared with very good agreement with the results of conventional step-by-step methods for different system dimensions.
2) Security Classifier

Using approximate reasoning, the security level of the system is evaluated according to a standard classification, as given in [1] and [2]. In this evaluation, approximate reasoning proved to be successful in combining a linguistic classification with numerical data. The Operator’s experience is taken into account throughout the evaluation, as for example in the definition of the security matrix and the selection of the threshold values.

It is a fundamental aspect of this work the recognition that security assessment should include information about the security level as well as the trend in the security status as the system changes. The energy margin and its sensitivity with respect to the equivalent power measure these aspects, and they prove to be good indices for the determination of the security level.

The fuzzy-logic techniques employed can take into account the different interpretations that individuals can give to the same phenomena. In addition, the classification algorithm is sufficiently flexible to allow the inclusion of other important parameters, as for example power flow through a specific line.

As a final output of the classifier, a “crisp” security index is produced using a pre-process deffuzification procedure. Depending on the value of this security index the algorithm enters or does not enter the enhancement control loop.

3) Security Enhancement Control

The control enhancement process consists of two control loops (generator voltage and power) which are used sequentially. The algorithm developed selects from all the possible combinations that can restore the system to the desired energy margin level, those combinations that satisfy other requirements such as physical equipment limitation. By taking into account the different sensitivities levels, it minimises the deviation from the original point (deemed to be optimum) by preferentially assigning the control action to the most sensitive generators.

During the implementation it was found that, due to the high degree of non-linearity of the system, first order approximations did not offer sufficient information to take the
energy margin level to the desired value. Therefore, a feedback iterative procedure was implemented. In addition, given the nature of the problem where different contingencies are to be evaluated for varying load conditions the online enhancement control algorithm demands the use of an adaptive mechanism. The selected adaptive mechanism is based on modifying the threshold values (scaling) in the membership functions that describe the power and voltages sensitivities. This adaptive method, combined with the feedback loop, produced a strategy that, as shown, takes the error or difference between the actual energy margin and the desired value to zero in a small number of iterations, even for large systems.

In the selection of the threshold values above, two optimisation methods were implemented, demonstrating their effectiveness in the reduction of the number of iterations.

The conjugate gradient method requires a smaller number of iterations to converge to a solution, but the steepest descent technique requires less number of calculations per iteration. Therefore, selecting the optimum method needs to be evaluated independently for each system by off-line simulations.

In addition, in this work an algorithm that produces a simultaneous preventive control strategy for a set of contingencies was presented. The use of high-energy margin targets for each individual contingency was justified by the need to ensure that when the weighted average control strategy is enacted the effective energy margin value obtained for all the configurations remaining inside acceptable values. The proposed method proved to be effective in allowing the determination of a unique control criterion for a selected set of non-disjoint contingencies. Criteria to determine the contingency sets to which to apply the simultaneous preventive control algorithm are also given in this work. It is important to determine that when one is in the presence of disjoint contingencies, the simultaneous solution might be non-existent.

Finally, given that speed is fundamental to obtain the maximum benefits of the proposed methodology, a new technique for the computation of admittance matrix was introduced. This technique based on only computing online those elements of the matrix that change
each time a new load evaluation is needed, resulted in significant time-savings with respect to traditional methods. The technique permits the incorporation of the changing load at each time step under evaluation without the need of recalculating and reducing the complete \([Y_{bus}]\) matrix. The proposed algorithm produces an improvement in computer time of up to 12 times with respect to more conventional procedures.

Summarising, the method proposed in this dissertation allows for:

a) A fast and accurate classification of the system security condition, taking into account the operator's experience and the physical equipment limitation. In addition, the classification is flexible enough to allow the inclusion of other important parameters, as for example, power flow limits.

b) The selection of new power and voltage output conditions for the generators in the system, which increase the security for variable load conditions and multiple contingencies.

The following studies are suggested for future research:

a) A multi-objective optimisation method based on Pareto's optimal techniques (where two or more operational goals are given by non-linear functions and can be transformed into a single objective maximisation). This analysis can be executed in order to obtain, if feasible, for a particular set of contingencies the least-cost alternative for the preventive control.

b) Different control elements and steady-state limits can be incorporated into the classifier. As an example, the maximum permitted power flow of a particular transmission line can be taken into account for the security enhancement control using network sensitivity factors. These factors show the approximate change in line flows for changes in generation on the network configuration and are easily derived from DC load flow evaluations. Steady state sensitivity factors can then
be combined with dynamic sensitivities in the selection of the control enhancement dynamic strategy.

c) The interface between the security classifier and enhancement control with the real-time network simulator has to be implemented. Important time saving evaluations could be obtained in the security algorithm if several intermediate values as angles and bus voltages were obtained by direct measure on the real-time system simulator. This interface is also required for the evaluation of the final suggested control strategy.

d) In order to move towards the creation of a complete energy management system, (EMS), the application of the proposed techniques to other types of problems, as voltage stability and transactions in open access systems, can be developed in the near future.

e) Parallel processing could be incorporated in order to evaluate several sets of contingencies simultaneously.
CHAPTER IX

REFERENCES


[57] Niimura T. and Yokoyama R., “Post-Processing of Economic Dispatch Solutions for Security Enhancement Based on Approximate Reasoning”, accepted for publication on IEEE Transactions on Power Systems, 95SM571-0 PWRD.


APPENDIX A

ENERGY MARGIN FUNCTIONS FOR POWER SYSTEM STABILITY

The question of stability is whether for a given disturbance, large or small, the trajectories of the pre-disturbance operating quantities of the system during the disturbance remain in the domain of attraction of the post-disturbance equilibrium point when the disturbance is removed. This concept is one of transient stability, which is a function of the power network, its steady state operating condition, and the disturbance itself. This appendix presents a brief review of the basic theoretical aspects of energy methods based on Lyapunov's theorems, when applied to a multimachine system for transient stability studies.

A.1 Basic Equations and Definitions for Stability Studies using Direct Methods

A.1.1 Mathematical Models of Multimachine Power Systems.

The dynamic behaviour of any given synchronous machine $i$ can be described by its swing equation as:

$$\frac{dW(ke,i)}{dt} + Pd_i = Pm_i - Pg_i$$

$$W(ke,i) = \frac{1}{2}J\omega_i^2$$

(A.1)

where

$W(ke,i) =$ Kinetic energy of the rotor of machine $i$

$J =$ moment of inertia of machine $i$

$Pd_i =$ Damping Power of machine $i$

$Pm_i =$ Mechanical power input to the machine $i$
\( P_{gi} = \text{Electrical power output of machine } i \)

Equation A.1, although exact, is highly non-linear, and for direct solution methods it is assumed that for a stable system the machine's speed can not differ appreciably from the steady state speed \( \omega_0 \). With this assumption, A.1 is simplified by assuming \( \omega = \omega_0 \) and the traditional swing equation of machine \( i \) is obtained,

\[
M_i \frac{d^2 \delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = Pm_i - Pe_i
\]

(A.2)

\( \delta_i = \text{Rotor angle with respect to a synchronous rotating reference frame (electrical radians)} \)

\( M_i = J \omega_0 = \text{constant of inertia of machine } i \)

Equation A.2 above also makes the following assumption regarding the damping power \( (Pd_i) \), which generally has two components:

\[
Pd_i = D_i \omega_i + \sum_{j=1}^{n} D_j \left( \frac{d\delta_i}{dt} - \frac{d\delta_j}{dt} \right)
\]

(A.3)

The first term is proportional to the frequency, while the second term relates to the asynchronous torque between the machines. This last term can normally be neglected, and A.3 is transformed into

\[
Pd_i = D_i \omega_i = D_i \frac{d\delta_i}{dt}
\]

(A.4)

Traditionally at this stage, the following additional simplifying assumptions are made for direct solution methods:
a) The network is assumed to be in the sinusoidal state where the time constants of the transmission network are negligible small compared to the electromechanical frequency of oscillation.

b) The synchronous machines are represented by a voltage source of constant magnitude determined from the steady state conditions existing prior to the fault (pre-fault load flow).

c) The phase angle of the voltages behind the transient reactances coincide with the rotor angle $\delta$, (approximate model of the synchronous machine).

d) Loads are represented as constant impedances based on the pre-fault voltage conditions obtained from a load flow.

e) The mechanical input power $P_m$ is assumed to be constant and equal to the pre-fault value during the time interval of interest.

With the assumptions above, a Kron reduction to the internal nodes of the machines for the $[Y_{bus}]$ matrix can be done as shown in Figure A.1:

![Figure A.1: Reduction to an n Bus System](image)
\[ [I_A] = [\tilde{Y}_{bus}] [V_A] \]  

(A.5)

where

\[ [\tilde{Y}_{bus}] = \text{admittance } n \times n \text{ matrix reduced to generator's internal nodes} \]

\( n = \text{number of generators} \)

\[ [I_A] = \text{vector of machine current injection } I_i \]

\[ [V_A] = \text{vector of machine internal voltages } E_i \]

The expression for the generated real power is:

\[ P_{g_i} = \text{Re} \{ E_i I_i^* \} \]  

(A.6)

with

\[ E_i = |E_i| \angle \delta_i \]

\[ Y_{ij} = G_{ij} + jB_{ij} = |Y_{ij}| \angle \phi_{ij} \]

\[ G_{ij} = |Y_{ij}| \cos \phi_{ij} \]

\[ B_{ij} = |Y_{ij}| \sin \phi_{ij} \]

(A.7)

and

\[ I_i = \sum_{j=1}^{n} Y_{ij} E_j \]  

(A.8)

Defining

\[ D_{ij} = |E_i| * |E_j| * |Y_{ij}| * \cos \phi_{ij} \]

\[ C_{ij} = |E_i| * |E_j| * |Y_{ij}| * \sin \phi_{ij} \]  

(A.9)
It is possible to re-write equation (A.6) as:

\[ P_{g_i} = G_n |E_i|^2 + \sum_{j \neq i}^n \left( C_y \sin \delta_j + D_y \cos \delta_j \right) \]  

(A.10)

where \( \delta_j \) is the angle between the internal voltage (rotors) of generator \( i \) and \( j \).

Substituting this expression into the machine differential swing equation (A.2),

\[ M_i \frac{d^2 \delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i - P_{e_i} \]  

(A.11)

with \( P_{e_i} \) the angle dependent component of the torque.

\[ P_{e_i} = \sum_{j \neq i}^n \left( C_y \sin \delta_j + D_y \cos \delta_j \right) \]  

(A.12)

and \( P_i \),

\[ P_i = P_{m_i} - G_n |E_i|^2 \]  

(A.13)

A.1.2 Definition of the Stability Problem for Direct Solution Methods

In its simplest form, the transition of a power system undergoing a disturbance is described by a set of differential equations, in which each equation corresponds to a particular state of the problem:
a) Faulted state (fa):

\[ M_i \frac{d^2 \delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i^{fa} - Pe_i^{fa} \]

(A.14)

for: \( 0 < t < t_{cl} \) \( t_{cl} = \) fault clearing time

and initial conditions: \( \delta_i(0) \) given by the steady state conditions,

\[ \frac{d\delta_i}{dt}(0) = 0 \quad \text{for} \ i=1,\ldots,n \]

b) Post-fault state (pf):

\[ M_i \frac{d^2 \delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i^{pf} - Pe_i^{pf} \]

(A.15)

for: \( t > t_{cl} \) \( t_{cl} = \) fault clearing time

and initial conditions: \( \delta_i(t_{cl}) \), and

\[ \frac{d\delta_i}{dt}(t_{cl}) \quad \text{for} \ i=1,\ldots,n \]

given from the previous fault condition.

One may discern the mathematical ramifications of the above problem stated. There are basically two sets of differential equations, which exhibit a discontinuity at \( t_{cl}=cl \). The boundedness of the trajectory rather than stability of the origin or the equilibrium point is desired. Lyapunov's method addresses itself to the question of avoiding this repetitive simulation and having just one simulation to find \( ccl \) (critical clearing time), directly. When adapted to a scalar function Lyapunov's method states:
"If for a given system, one is able to find a function $V(X)$ such that it is always positive except at $X=0$ where it is zero and its derivative is negative except at $X=0$, where is zero, we say that the system returns to the origin if it is disturbed".

We define then: \[ V(X) = \text{Lyapunov's Function}, \]

where the initial conditions for the post fault system at $t=cl$ corresponds to the terminal values of $\delta$ and $d\delta/dt$ obtained from the integration of the faulted system equations at $t=cl$. For the construction of $V(x)$, the region of attraction is built around the post fault equilibrium point $\delta_s$. For stability we will examine if the terminal state of the faulted system lies within the region of attraction of the post fault system, or what is equivalent, if the trajectory of $\delta_s$ defined by the post fault equations and with initial conditions $\delta(cI)$ will converge to $\delta_s$ as $t \to \infty$. The largest value of $cl$ showing this to be true is called the critical clearing time $ccl$.

From the above discussion, it is clear that if we have an accurate estimate of the region of attraction of $\delta_s$, then $ccl$ is obtained when the trajectory of the post fault machine angles' exit in the region of attraction, as graphically shown in Figure A.2 [53].

![Figure A.2: Region of Attraction and Computation of tcr](image-url)
Lyapunov's Theorem provides a basis for estimating the region of attraction of a particular system.

The function generally used transfers the post-fault stable equilibrium point to the origin, where \( V(x) = 0 \). The faulted equations are then integrated until \( V(x) = C \) and the instant of time when this equality is satisfied is an estimate of \( ccl \) (critical clearance time).

### A.2 Formulation of Lyapunov's Methods for Power Systems

The formulation known as “State Space Model in Centre of Angle Reference Frame” is particularly suited for the energy function approach analysis of power systems, and was initially proposed by Tavora and Smith [53].

Adding the \( n \) swing equation (A.2):

\[
\sum_{i=1}^{n} M_i \ddot{\delta}_i + \sum_{i=1}^{n} D_i \dot{\delta}_i = \sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_{ei} \quad i = 1 \ldots n
\]

(A.16)

and defining the centre of angle \( \delta_o \) as:

\[
\delta_o = \frac{1}{M_T} \sum_{i=1}^{n} M_i \delta_i
\]

\[
M_T = \sum_{i=1}^{n} M_i
\]

(A.17)

and

\[
\theta_i = \delta_i - \delta_o
\]

(A.18)
which implies that:

\[ \dot{\theta}_i = \omega_i - \omega_o \]  

(A.19)

All \( \theta_i \) and \( \omega_i \) are linearly independent, since from the definition of \( \theta_i \) it follows that:

\[ \sum_{i=1}^{n} M_i \theta_i = 0 \quad \text{and} \quad \sum_{i=1}^{n} M_i \dot{\theta}_i = \sum_{i=1}^{n} M_i \ddot{\omega}_i = 0 \quad \text{where} \quad \ddot{\omega}_i = \omega_i - \omega_o \]

(A.20)

Using (A.20), plus equation (A.12) for \( P_e \), and neglecting the damping \( D_s \), and defining:

\[ P_{coi} = \sum_{i=1}^{n} P_i - 2 \sum_{i=1}^{n} \sum_{j=i+1}^{n} D_{ij} \cos \delta_{ij} \]

(A.21)

Equation (A.2) in the new co-ordinates become after a rather lengthy manipulation for the individual machine \( i \):

\[ M_i \ddot{\theta}_i = P_i - P_e - \frac{M_i}{M_T} P_{coi} \]

(A.22)

\[ i = 1, 2, \ldots n \]

A.2.1 Lyapunov's Function for Power Systems

With the change of reference to the centre of the inertia frame, it is possible to obtain the Lyapunov function \( V(X) \) by integrating the swing equations for each of the machines in the system. First the integrals of motion of the system are constructed and they become the energy functions required for Lyapunov's stability evaluations [53]. Integrating
equation A.21 between the post-fault stable equilibrium point \( \theta = \theta_s \) with \( \omega_s = 0 \) or \( (\theta_s,0) \) and a point \((\theta,\omega)\), the following energy function is obtained:

\[
V(\theta,\omega) = \frac{1}{2} \sum_{i=1}^{n} M_i \dot{\theta}_i^2 - \sum_{i=1}^{n} P_i (\theta_i - \theta_i^s) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} C_{ij} (\cos \theta_{ij} - \cos \theta_{ij}^s) - \int D_y \cos \theta_y d(\theta_i + \theta_j)
\]

(A.23)

The first term in the equation represents the kinetic energy and the remaining terms represent rotor positional energy, stored magnetic energy, and the dissipation energy of the system. The dissipation term (transfer conductance between internal buses \( i \) and \( j \)) is path dependent, and it is a generally held view that this term prevents the construction of an analytical Lyapunov function. The dissipation term will be incorporated by approximating the actual system trajectory between \( \theta_s \) and \( \theta \) by a linear trajectory (trapezoidal rule). Then the modified equation A.23 can be written as:

\[
V(\theta,\omega) = \frac{1}{2} \sum_{i=1}^{n} M_i \dot{\theta}_i^2 - \sum_{i=1}^{n} P_i (\theta_i - \theta_i^s) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} C_{ij} (\cos \theta_{ij} - \cos \theta_{ij}^s) - I_y
\]

\[
I_y = D_y \frac{\theta_i + \theta_j - \theta_i^s - \theta_j^s}{\theta_y - \theta_y^s} (\sin \theta_y - \sin \theta_y^s)
\]

(A.24)

The region of attraction of \((\theta_s,0)\) is defined by the inequality

\[
V(\theta,\omega) < V_{cr}
\]

(A.25)
Where \( Vcr = \text{critical energy} \)

A multimachine system is limited by the value of the energy at the unstable equilibrium point \( V(\theta^{ue}, \theta) \)

\[
Vcr = V|_{\theta^{ue}} = - \sum_{i=1}^{n} P_i (\theta_i^{ue} - \theta_i^s) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left[ C_{ij} (\cos \theta_i^{ue} - \cos \theta_j^s) - I_{ij}^{ue} \right]
\]

(A.26)

The limitation of the transient energy function \( V(\theta, \omega) \) described above (A.25-26) arises from the need to compute a constant value \( C \) which defines the region of attraction of the post-fault system. \( Vcr \) (Critical Energy) is then the value of \( C \).

A.2.2 Energy Margin Index

The energy margin index is defined as the difference between the critical energy \( Vcr \) and the transient energy (A.24) evaluated at \( t=cl \) or \( Vcl \), is defined as:

\[
\Delta V = Vcr - Vcl
\]

(A.27)

or

\[
\Delta V = -\frac{1}{2} \sum_{i=1}^{n} M_i \dot{\theta}_i^2 - \sum_{i=1}^{n} P_i (\theta_i^{ue} - \theta_i^{cl}) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left[ C_{ij} (\cos \theta_i^{ue} - \cos \theta_j^{cl}) - I_{ij}^{ue} \right]
\]
With this index it is possible to determine if the system is inside the region of stability because if \( \Delta V > 0 \) the system is stable because the critical energy is higher than the transient energy function and it is unstable if \( \Delta V < 0 \).

### A.2.3 The Kinetic Energy Correction of the Transient Energy Margin

If \( cr \) is the index of the set of critical generators and \( sys \) denotes the set of non-critical machines, then the position and speed of the inertial centre of the group of critical machines is given by:

\[
\theta_{cr} = \frac{1}{M_{cr}} \sum_{i \in cr} M_i \theta_i
\]

\[
\bar{\omega}_{cr} = \frac{1}{M_{cr}} \sum_{i \in cr} M_i \bar{\omega}_i
\]

\[
M_{cr} = \sum_{i \in cr} M_i
\]  
(A.28)

The component of the kinetic energy, which tends to separate the two groups of machines is called the corrected kinetic energy and is given by:

\[
V_{ke \text{ corr}} = \frac{1}{2} M_{eq} \bar{\omega}_{eq}^2
\]

\[
M_{eq} = \frac{M_{cr} M_{sys}}{M_{cr} + M_{sys}}
\]

\[
\bar{\omega}_{eq} = \bar{\omega}_{cr} - \bar{\omega}_{sys}
\]

\[
M_{sys} = \sum_{i \in sys} M_i
\]

\[
\bar{\omega}_{sys} = (\sum_{i \in sys} M_i \bar{\omega}_i / M_{sys})
\]  
(A.29)
Then the original kinetic energy term $V_{cr}$ in equation A.28 should be replaced with the corrected $V_{cl}$ in order to eliminate the effect to the machine oscillations that do not contribute to the separation of the system, then,

\[
\Delta V = \frac{1}{2} M_{eq} \omega_{eq}^2 - \sum_{i=1}^{n} P_i (\theta_i^{\text{se}} - \theta_i^{\text{cl}}) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} C_y (\cos \theta_y^{\text{se}} - \cos \theta_y^{\text{cl}}) - I_y \mid_{\sigma^e}
\]

(A.30)

The transient energy function method can be used to accurately assess the transient stability of the system via the energy margin index $\Delta V$. Such an assessment could result in the energy margin being either positive or negative depending on whether the system is stable or unstable.
APPENDIX B

FUZZY LOGIC TECHNIQUES

B.1 Basics of Fuzzy Set Theory

B.1.1 Classical Sets and Fuzzy Sets

Let \( X \) be the universe of objects with elements \( x \), where \( A \) is a sub-set of \( X \). Membership of \( x \) to the classical crisp set \( A \) can be viewed as a characteristic function \( \mu_A(x) \), such that:

\[
\mu_A(x) = \begin{cases} 
1 & \text{if } x \in A \\
0 & \text{if } x \not\in A 
\end{cases}
\]

(B.1)

For a "fuzzy set \( A \)" of the universe \( X \), the grade of membership of \( x \) in \( A \) is defined as:

\[
\mu_A(x) \in [0,1]
\]

(B.2)

Where \( \mu_A(x) \) is called the membership function. The value of \( \mu_A(x) \) can be anywhere from 0 to 1 being this the main difference between fuzzy and crisp sets, where only a 0 or 1 answer is given. The closer the value of \( \mu_A(x) \) is to 1 the more \( x \) belongs to \( A \). Therefore, the fuzzy set \( A \) has no sharp boundary.

Fuzzy set elements are ordered pairs indicating the value of a set of elements and their degree of membership.

\[
A = \{(x, \mu_A(x)) \mid x \in X\}
\]

(B.3)
B.1.2 Basic Fuzzy Set Operations

For two fuzzy sets $A$ and $B$, the following fuzzy operations are defined:

- **Union operation**
  \[
  \mu_{A \cup B}(x) = \max\{\mu_A(x), \mu_B(x)\}
  \]  
  \[\text{(B.4)}\]

- **Intersection operation**
  \[
  \mu_{A \cap B}(x) = \min\{\mu_A(x), \mu_B(x)\}
  \]  
  \[\text{(B.5)}\]

- **Complement operation**
  \[
  \overline{\mu}_A(x) = 1 - \mu_A(x)
  \]  
  \[\text{(B.6)}\]

B.1.3 Fuzzy Relations

The cause and effect relationship between the antecedent and the conclusion for expert knowledge $A \rightarrow B$ is called a fuzzy relation and is denoted by $R$:

\[
R = A \rightarrow B
\]
\[\text{(B.7)}\]

$R$ can be though as a fuzzy set on the cartesian product $X \times Y$ of the total space for the conclusion $Y$. Also, the process for obtaining a (fuzzy) inference result $B'$ from observed data $A'$ using $A \rightarrow B$ is expressed in the shorthand notation form as:

\[
B' = A' \circ R = A' \circ (A \rightarrow B)
\]
\[\text{(B.8)}\]
where $\circ$ is a compositional rule of fuzzy inference, and $A \rightarrow B$, is called a fuzzy relation.

There exist several methods for converting this relation to fuzzy relations, but basically they can be reduced to Zadeh’s Method and Mandami’s Method.

- Fuzzy relations using Zadeh’s method, states that the membership to the relationship of a pair of input $x$ and output $y$ is given by:

$$
\mu_R(x, y) = 1 \land \left( 1 - \mu_A(x) + \mu_B(y) \right)
$$

(B.9)

- Conversion to fuzzy relations using Mandami’s method:

$$
R = A \rightarrow B = A \times B
$$

$$
\mu_R(x, y) = \mu_A(x) \land \mu_B(y)
$$

(B.10)

For the composition rule of inference of the result $B'$ from a fuzzy input set $A'$:

$$
B' = A' \circ R
$$

$$
\mu_{B'}(x, y) = \max \{ \mu_A(x) \land \mu_R(x, y) \}
$$

(B.11)
B.2 Application of Fuzzy Set Theory

When fuzzy set theory is used to solve real problems, the following steps are generally followed:

a) The problem to be solved should first be stated mathematically/linguistically.

b) Definition of thresholds values for the variables: for a variable, there is a specific value with the greatest degree of satisfaction evaluated from empirical knowledge and a certain deviation is acceptable with decreasing degree of satisfaction until a value is completely unacceptable. The two values corresponding to the greatest and least degree of satisfaction are termed thresholds.

c) Fuzzy quantification: based on the threshold values proper forms of membership functions are available, such as linear, piece-wise linear, trapezoidal, parabolic and several others. The membership functions should reflect the change in variables evaluated by experts.

d) Selection of the fuzzy operations: in terms of the practical decision making process by human experts, a proper fuzzy operation is selected so that the results obtained are similar to those obtained by experts. The interpretation of results using fuzzy systems are based on domain experts reasoning. Therefore, at this level, a hybrid fuzzy set expert system scheme could be in some cases the best option. The most commonly used operations between fuzzy sets are given by Mamdami’s and Zadeh’s.

B.3 Approximate Reasoning

Fuzzy inference or fuzzy reasoning, often called approximate reasoning, is the most important technique for practical applications of fuzzy logic, as all reasoning or inference
for crisp Artificial Intelligence (AI) can be viewed as a special case of fuzzy expert systems.

There are many varieties of approximate reasoning methods. Fuzzy reasoning methods are roughly classified as indicated in Figure B.1 [75] and the most important characteristics of some of the direct method are explained. An indirect method conducts reasoning by truth-value space and are not use in this research.

![Figure B.1: Classification of Fuzzy Reasoning [75]](image)

**B.3.1 Mandani's Direct Method and Defuzzification procedures**

Mandani’s direct method is based on min-max operations. In order to understand the reasoning mechanism the example given in [75] for two rules is shown:

Rule 1: If \( x \) is \( A_1 \) and \( y \) is \( B_1 \) then \( z \) is \( C_1 \)

Rule 2: If \( x \) is \( A_2 \) and \( y \) is \( B_2 \) then \( z \) is \( C_2 \)

(B.12)
where $A_1, A_2, B_1, B_2, C_1, C_2$ are fuzzy sets. Figure B.2 shows the reasoning process.

Figure B.2: Reasoning Process of Mandani’s Direct Method

Now assume that $x_0$ and $y_0$ to be the input for the premise part variables $x$ and $y$, the reasoning process for the adaptability of each rule for the input $(x_0, y_0)$ is:

Adaptability rule 1:  $W_1 = \mu_{A_1} \cap \mu_{B_1} = \min(\mu_{A_1}, \mu_{B_1})$

Adaptability rule 2:  $W_2 = \mu_{A_2} \cap \mu_{B_2} = \min(\mu_{A_2}, \mu_{B_2})$
The second step applies the adaptability given by (B.13) to the fuzzy set in the consequence part and obtain the conclusion of each rule, where:

Conclusion rule 1: \( \mu_{C'1} = W_1 \cap \mu_{C1} \)

Conclusion rule 2: \( \mu_{C'2} = W_2 \cap \mu_{C2} \)

Then the final conclusion is obtained by aggregating both conclusions,

Final conclusion: \( \mu_C = \mu_{C'1} \cup \mu_{C'2} \)

The final conclusion is given by a fuzzy set, then a defuzzification procedure follows in order to obtain a value as the output of the reasoning process.

Defuzzification is the final phase of the fuzzy reasoning procedure, the evaluation of the model propositions is handled through an aggregation process that produces the final fuzzy regions for each solution variable. This region is then decomposed using one of the defuzzification methods.

There are several defuzzification procedures and it is possible to create a different one depending on the particular characteristics of the problem. The most commonly used defuzzification methods are, the centre-of-area, the centre-of-sums, centre-of-largest area, first-of-maxima, middle-of-height and height method. A brief explanation of each one follows:

a) Centre-of-area: this is the best well-known defuzzification method which determines the center of area below the combine membership function.

Figure B.3 shows the operation graphically, and is mathematically given by:

\[
CG = \frac{\int u \mu_u(u) du}{\int \mu_u(u) du}
\]

(B.14)
This operation is computationally rather complex and therefore results in quite slow inference cycles.

b) Centre-of-sums: it is a similar but faster defuzzification procedure, where the contribution of the area of each membership functions is considered individually. Thus overlapping are reflected more than once and are mathematically defined as:

\[
CS = \frac{\int u \sum_{k=1}^{n} \mu_{CLU}(k)du}{\int \sum_{k=1}^{n} \mu_{CLU}(k)du}
\]

\[n = \text{number of membership functions}\]

(B.15)
c) Height: This method takes the peak value of each function and builds the weighted sum of these peaks. The height method is both a very simple and very quick method, but neither the shape nor the support play a role in the computation of the index.

\[
CH = \frac{\sum_{k=1}^{m} C(k)\mu_{jk}}{\sum_{k=1}^{n} \mu_{jk}}
\]

(B.16)
d) First-of-maxima: Takes the smallest value of the domain U with maximal membership degree in U. Cf graphically is shown in Figure B.6. The alternative version is called last-of-maxima Cl.

\[
\text{hgt}(U) = \sup_{u \in U} \mu(u)
\]

\[
\{ u \in U | \mu_U(u) = \text{hgt}(U) \}
\]

(B.17)
e) Middle-of-maxima: is the average of the last of maxima and the first of maxima.

Some criteria for the evaluation of defuzzification methods are:

- Continuity: a small change in the input, should not result in a large change in the output.

- Disambiguity: when the defuzzification method cannot choose between the areas covered by the membership functions ambiguity results.

- Plausibility: Every defuzzified control output has a horizontal component $u^* \in U$ and a vertical component $\mu_{u^*} \in [0,1]$. We defined $u^*$ to be plausible if it lies approximately in the middle of the support of $U$ and has a high degree of membership in $U$.

- Computational complexity: This criterion is particular important for online applications. The height method together with the middle and first-of-
maxima is a faster method, whereas the center-of-area method is slower. The computational complexity of center-of-sum depends on the shape of the output membership functions.

B.3.2 Fuzzy Reasoning Using Linear Functions

As more variables are taken into account in the premises, the method described presents the problem that the number of rules increases exponentially, making them very difficult to construct. This problem can be avoided using the linear function method, which can be stated, for a given relationship rule \( i \) of a total of \( r \) rules:

Rule \( i \):

\[
\text{IF } x_j \text{ is } A_{ik} \ldots \text{ and } x_n \text{ is } A_{in} \\
\text{THEN } y_i = c_{io} + c_{il} x_1 + \ldots + c_{in} x_n
\]

(B.18)

Where \( i \) is the suffix of the rule, \( A_{ik} \) for \( (k = 1, 2, 3, \ldots n) \) are fuzzy sets, \( x_k \) is an input variable, \( y_i \) is the output from the \( i \)-th rule, and \( c_{ik} \) for \( k = 0, 1, \ldots n \) are the parameter of the consequence.

The fuzzy reasoning value is then given by the weight average of the results of the \( r \) rules means, as follows:

\[
y = \frac{\sum_{i=1}^{r} w_i y_i}{\sum_{i=1}^{r} w_i}
\]

(B.19)
where \( w_i \) is the adaptability of the premises of the \( i \)-th rule and is given by:

\[
w_i = \prod_{k=1}^{n} \mu_{A_{ik}}(x_k)
\]

(B.20)

and \( \mu_{A_{ik}}(x_k) \) is the membership value of fuzzy set \( A_{ik} \).

\[\text{B.3.3 Simplified Fuzzy Reasoning}\]

This method can be seen as a special case of the linear function method, where the consequence \( i \), instead of a linear function, is a real value, also called “singleton”. For example, a two-input, one-output fuzzy reasoning rule is expressed as:

Rule \( i \):

\[
\begin{align*}
\text{IF } & x_i \text{ is } A_i \text{ and } y \text{ is } B_i \\
\text{THEN } & z = c_i = c_i \\
\end{align*}
\]

for \( i = 1,2,3,\ldots r \)

(B.21)

where \( c_i \) is a constant real value.

The conclusion of the reasoning is:

\[
z = \frac{\sum_{i=1}^{r} w_i z_i}{\sum_{i=1}^{r} w_i} = \frac{\sum_{i=1}^{r} w_i c_i}{\sum_{i=1}^{r} w_i}
\]

(B.22)
where

$$w_i = \mu_{a_i}(x) \land \mu_{b_i}(y)$$

(B.23)

The simplified method has the following advantages, in that the reasoning mechanism is simple, the computation is fast and the results vary little from those of the direct method.
APPENDIX C

OPTIMISATION PROCEDURE

Optimisation techniques must be stated in terms of mathematical relations before being applied to a specific problem. Assuming that the problem can be formulated in terms of minimising an error function \( E(X) \):

\[
\min E(\bar{X}) \quad \bar{X} = (x_1, x_2, \ldots, x_n)
\]  

(C.1)

There are different optimisation techniques that can be used to minimise the error function \( E(X) \). Its selection depends on the specific problem under study. In general, more sophisticated optimisation techniques evaluate the first or higher order derivatives, while other methods do not require them. Hence, it is possible to divide the optimisation techniques into the following categories:

a) Simple search methods (non-derivative): perhaps one of the simplest ways to minimise the error function is to vary each available parameter \( x_i \) one at the time. After this is done for all the parameters, the process would start again with the first parameter \( x_1 \) since each step in this minimisation procedure is a single parameter search, the quadratic interpolation method may be used to find the minimum [76] [77].

b) Slope-following methods: slope-following methods evaluate the first derivatives of the error function \( (\partial E(X)/\partial x_i) \) and uses this information to indicate how the parameters should be changed in order to minimise the error. The first derivatives determine the gradient of the error function. The gradient values gives the direction of the greatest change in error, thus to minimise the error the method proceeds in opposite direction. This is the
basis of the steepest-descent method, which uses the gradient to predict parameter changes for error optimisation.

c) Second order methods: the slope-following methods tend to reduce the error rapidly in the initial stages of an optimisation procedure, however their convergence is rather slow as the minimum is approached. To improve the rate of convergence, one can use not only first derivative but also second derivatives (Hessian evaluation). The various second-order methods differ mainly in the way they try to approximate the second order derivatives, without having to perform a direct calculation.

d) Simulate annealing methods: this is a rather new technique suitable for optimisation problems of large scale especially, those where a desired global extremum is hidden among many poorer local extrema. This method has been applied to problems with discrete variables, being its application much more complicated for the case where there are continuous control parameters.

A review of the gradient-techniques and the second-order type conjugate methods are presented in this appendix. These techniques are used in unconstrained optimisation problem.

When dealing with real optimisation problems certain additional constraints and restrictions, usually in the form of equations, are placed on the variables. There are several methods to deal with these constraints. The most common and effective of these methods is the Lagrange multipliers, which transforms a bounded problem to an unbounded one, to which any of the previously discussed optimisation techniques can be applied.

In general, in any constrained optimisation problem, the first task will be to select an initial set of parameters that are located in the feasible region. Once a feasible set of initial parameters has been determined, the optimisation procedure can start by applying an optimisation program and monitoring the way the parameters are varied. However, if the optimisation procedure attempts to force the parameters into the forbidden region, then they are limited in each iteration of the optimisation procedure. In the problem discussed
in this work membership functions are used to deal with the physical constraint imposed by the generators' limitations. Therefore, in each step of the optimisation procedure, the membership evaluation incorporates the restrictions inside the error formulation, and the two previously mentioned unconstrained techniques could be applied. In the remainder of this appendix a description of these optimisation methods used is presented.

C.1 The Steepest-Descent Optimisation Technique

Given a function \( f(X) \), whose partial derivatives exist, it is known that the gradient \( \nabla f(x) \) is a vector pointing in the direction of the greatest rate of increase of \( f(X) \). Therefore the negative of the gradient points in the direction of the greatest rate of decrease of \( f(X) \). The steps involved in the procedure are:

1. Select an initial starting point (best estimate) for vector \( x=x_0 \).
2. The general iteration steps begins. Designating the \( s-th \) iteration \( (s=0,1,2,3,\ldots) \), calculate \( \nabla f(X_s) \).
3. Moving in the direction of \( -\nabla f(X_s) \), calculate a step size \( \lambda_s \) that minimises:

\[
\lambda^* = \min_{\lambda} \left[ f(X_s - \lambda \nabla f(X_s)) \right]
\]

this is a one-dimensional minimisation on \( \lambda_s \), and can be solved using a quadratic interpolation procedure.

4. Calculate the new \( X_{s+1} \):

\[
X_{s+1} = X_s - \lambda_s \nabla f(X_s)
\]

5. Terminate the calculation if:
Where \( \varepsilon \) is some pre-assigned tolerance. It is possible to use other criteria as stop rule, the smaller the \( \varepsilon \) more precisely will the location of the minimum be found, however greater number of iterations steps will be required. The main problem with this gradient method is that the successive steps are orthogonal or perpendicular to each other, as shown in Figure C.1. This is produced by the fact that the new gradient at the minimum point of any line minimisation is perpendicular to the direction just traversed. Therefore, depending on the function configuration, a zigzag approach to the optimum is obtained, and it could even not take it to the minimum. An improvement to this method contemplates moving, not down the new gradient, but rather in the direction that is somehow constructed to be conjugate to the old gradient, and insofar as possible, to all previous directions transverse, thus reaching the minimum in a smaller number of iterations. There are two methods that accomplish this construction: conjugate gradient methods and variable metric methods. Both methods are similar and they only differ in the dimension of the variables stored.

**Figure C.1: Steepest - Descent Gradient Method**

### C.2 Conjugate Gradient Methods

Hestieres and Strefel, first proposed the method of conjugate gradients for solving a set of simultaneous linear equations having a symmetric positive definite matrix of coefficients, in 1952. Fletcher Powell used these approach and Davidon’s ideas to develop
a successful method, which is an enormous improvement over simple steepest descent procedures.

The Fletcher-Powell method is constructed in such a way, that if the function to be optimised is quadratic in n-variables then the Fletcher-Powell iteration scheme converges to the optimal solution in \( n \) iterations. It also gives reasonably good results for functions which are not quadratic. The Fletcher-Powell method is a gradient method, or more properly a modified gradient method. Essentially what is involved is the use of certain information which is generated at each iteration to construct the Hessian matrix of the function.

The use of the Hessian, or an approximation to the Hessian, indicates that it attempts to use second-order information or an approximation to second-order information, this Hessian is approximated by the gradient or first order information at two points.

The following is a step-by-step description of the Fletcher-Powell algorithm.

\section*{C.2.1 The Fletcher-Powell Method}

1. As a first step a positive definite matrix \( H_0 \) and some initial point, \( x_0 \) are selected. For convenience \( H_0 \) can be chosen to be the identity matrix \( I \).

2. The general iteration steps begins. For the \( s \)-th iteration \( (s=0,1,2,3...) \).
   Calculate the gradient vector \( \nabla f(X_s) \)

3. Calculate a direction in which to move. This is given by:

\[
\bar{r}_s = -H_s \nabla f(X_s)
\]  

(C.5)

4. In order to move in the direction \( r_n \), calculate using a quadratic interpolation procedure the step size \( \lambda_s \). In this particular case the function to minimise is an error function:
\[
f(X_s - \lambda_s \nabla f(\bar{X}_s)) = \min_{\lambda_s} f(\bar{X}_s - \lambda_s \nabla f(\bar{X}_s))
\]

5. Calculate

\[
\bar{\beta}_s = \bar{\lambda}_s \bar{r}_s
\]

(C.6)

6. Calculate

\[
\begin{align*}
\bar{X}_{s+1} &= \bar{X}_s + \bar{\beta}_s \\
\bar{Y}_s &= \nabla f(\bar{X}_{s+1}) - \nabla f(\bar{X}_s)
\end{align*}
\]

(C.7)

7. Calculate the two matrices \(A_s\) and \(B_s\)

\[
A_s = \frac{\bar{\beta}_s \bar{\beta}_s}{\bar{\beta}_s \bar{Y}_s} \\
\bar{\beta}_s = \frac{-H_s \bar{Y}_s \bar{Y}_s'}{\bar{Y}_s' H_s \bar{Y}_s}
\]

8. Calculate the next approximation in the sequence of \(H\) matrices

\[
H_{s+1} = H_s + A_s + B_s
\]

(C.8)

9. Terminate the calculation if,

\[
f(\bar{X}_s) - f(\bar{X}_{s+1}) \leq \varepsilon
\]

(C.9)
The algorithm converges with no difficulty. It is assumed that the function has a minimum or a maximum on the interior of the region under construction.