



شبكة المعلومات الجامعية
التوثيق الإلكتروني والميكرو فيلم

بسم الله الرحمن الرحيم



MONA MAGHRABY



شبكة المعلومات الجامعية
التوثيق الإلكتروني والميكرو فيلم



شبكة المعلومات الجامعية التوثيق الإلكتروني والميكرو فيلم



MONA MAGHRABY



شبكة المعلومات الجامعية
التوثيق الإلكتروني والميكروفيلم

جامعة عين شمس

التوثيق الإلكتروني والميكروفيلم

قسم

نقسم بالله العظيم أن المادة التي تم توثيقها وتسجيلها
علي هذه الأقراص المدمجة قد أعدت دون أية تغيرات



يجب أن

تحفظ هذه الأقراص المدمجة بعيدا عن الغبار



MONA MAGHRABY



AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Electrical Power and Machines Department

Wide-Area Control for Dynamic Stability Enhancement of Large Electric Power Systems

By

Eng.: Mousa Mohamed Helmy Mousa Elroby

M.Sc. in Electrical Engineering, Cairo University, 2013

A Thesis Submitted in Partial Fulfillment of the Requirements of the Degree
of **Doctor of Philosophy**

In

Electrical Engineering (Electrical Power and Machines Engineering)

Supervised by

Prof. : Hossam Eldin Abdallah Talaat

Prof. : Mohamed Ahmed Moustafa Hassan

Prof. : Said Fouad Mohamed Mekhamer

Cairo - (2020)



AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Electrical Power and Machines Department

Wide-Area Control for Dynamic Stability Enhancement of Large Electric Power Systems

By

Eng.: Mousa Mohamed Helmy Mousa Elroby

A Thesis Submitted in Partial Fulfillment of the Requirements of
the Degree of Doctor of Philosophy in Electrical Engineering
(Electrical Power and Machines Engineering)

Supervision Committee

Name and Affiliation

Signature

Prof./ Hossam Eldin Abdallah Talaat

Electrical Power and Machines Department,
Faculty of Engineering, Ain Shams University

.....

Prof./ Mohamed Ahmed Moustafa Hassan

Electrical Power Department,
Faculty of Engineering, Cairo University

.....

Prof. / Said Fouad Mohamed Mekhamer

Electrical Power and Machines Department,
Faculty of Engineering, Ain Shams University

.....

Date: 16/9/2020



AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Electrical Power and Machines Department

Wide-Area Control for Dynamic Stability Enhancement of Large Electric Power Systems

By

Eng.: Mousa Mohamed Helmy Mousa Elroby

A Thesis Submitted in Partial Fulfillment of the Requirements of
the Degree of Doctor of Philosophy in Electrical Engineering
(Electrical Power and Machines Engineering)

Examiners' Committee

Name and Affiliation

Signature

Dr/ Adel Aly Emamy Salem

Head of Control Sector, National Energy Control
Center, Egyptian Electricity Transmission Company

.....

Prof./ Abdel-aal Hassan Ismail Mantawy

Electrical Power and Machines Department,
Faculty of Engineering, Ain Shams University

.....

Prof./ Hossam Eldin Abdallah Talaat

Electrical Power and Machines Department,
Faculty of Engineering, Ain Shams University

.....

Prof. / Mohamed Ahmed Moustafa Hassan

Electrical Power Department,
Faculty of Engineering, Cairo University

.....

Date: 16/9/2020

Table of Contents

List of Figures	VII
List of Tables	XII
List of Appendices	XIV
List of Abbreviations	XV
Abstract	XX
Statement	XXII
Acknowledgment.....	XXIII
Chapter 1 : Introduction	- 1 -
1.1 Power System Stability	- 1 -
1.1.1 Power system stability classification	- 3 -
1.1.2 Electromechanical oscillation mechanisms.....	- 8 -
1.2 Power System Electromechanical Oscillations Damping	- 10 -
1.2.1 Practical issues of wide-area damping control design.....	- 14 -
1.2.1.1 Analysis methods of the power system model.....	- 15 -
1.2.1.2 Power system actuators	- 18 -
1.2.1.3 Measuring instruments	- 18 -
1.2.1.4 Controller design method.....	- 22 -
1.2.1.4.1 Offline design	- 23 -
1.2.1.4.2 Adaptive design.....	- 24 -
1.3 Research Motivations	- 27 -
1.4 Trajectory-Based Supplementary Control	- 32 -
1.5 The Principle of the Proposed Controller.....	- 33 -
1.5.1 Description of the reinforcement learning control system....	- 34 -
1.5.2 Implementation strategy.....	- 35 -

1.6	Thesis Structure.....	36 -
1.7	Summary of the Chapter	38 -
Chapter 2 : Literature Review		39 -
2.1	Phasor Measurement Uint Literature Review.....	39 -
2.1.1	Historical background of PMU	39 -
2.1.2	PMUs' number optimization	42 -
2.1.2.1	Numerical approach.....	42 -
2.1.2.2	Topological approach.....	44 -
2.1.2.2.1	Finding the minimum set of PMUs	45 -
2.1.2.2.2	Finding network topology based on minimum set of PMUs.....	49 -
2.1.2.2.3	Finding PMUs and their CI simultaneously	51 -
2.1.3	PMUs application.....	52 -
2.1.3.1	PMUs in system protection.....	52 -
2.1.3.2	PMUs in voltage and inter-area monitoring	57 -
2.2	FACTS Literature Review.....	66 -
2.2.1	Historical background of FACTS	66 -
2.2.2	Optimization methods for FACTS allocation problem	68 -
2.2.2.1	Analytic approaches	69 -
2.2.2.2	Arithmetic programming approaches.....	70 -
2.2.2.3	Hybrid approaches	71 -
2.2.2.4	Metaheuristic optimization techniques	73 -
2.2.2.4.1	Single metaheuristic optimization techniques	74 -
2.2.2.4.2	Hybrid metaheuristic optimization techniques	82 -
2.2.3	Application of the FACTs devices	83 -

2.2.3.1	Enhancing static performance.....	84 -
2.2.3.2	Enhancing dynamic performance.....	95 -
2.3	Wide Area Control Literature Review	106 -
2.3.1	Summary of past research in wide area control.....	106 -
2.3.2	Applications of PMUs and WAMS	113 -
2.4	Summary of the Chapter	115 -
Chapter 3 : Optimal Placement of Phasor Measurement Units		116 -
3.1	PMUs Placement Problem Motivation.....	116 -
3.2	Objectives of the PMU Study	124 -
3.3	Basic Concepts of the Problem Formulation	125 -
3.3.1	Meta-heuristic optimization techniques.....	125 -
3.3.1.1	Binary optimization using hybrid PSO and GSA	125 -
3.3.1.2	Binary Teaching-learning based optimization	129 -
3.3.2	Minimum spanning tree	131 -
3.3.3	Power system islanding	134 -
3.3.4	Power system observability	136 -
3.3.4.1	Complete observability.....	139 -
3.3.4.2	Depth-of-one unobservability	143 -
3.3.4.3	Depth-of-two unobservability	144 -
3.3.4.4	The general observability constraint	145 -
3.3.5	Quality of service	147 -
3.3.5.1	Latency time of the WAMS	147 -
3.3.5.2	WAMS reliability.....	149 -
3.3.6	WAMS cost calculation	152 -

3.4	PMU Problem Formulation and Implementation	155 -
3.4.1	Using BPSOGSA as the main algorithm	156 -
3.4.1.1	Using BPSOGSA combined with MST	156 -
3.4.1.2	Using BPSOGSA	158 -
3.4.1.3	Implementation considerations to reduce the run time.....	160 -
3.4.1.4	Results and discussion	161 -
3.4.1.4.1	Using BPSOGSA combined with MST	161 -
3.4.1.4.2	Using BPSOGSA	167 -
3.4.2	Using BTLBOA as the main algorithm	172 -
3.4.2.1	Using BTLBOA combined with MST	173 -
3.4.2.2	Using BTLBOA	174 -
3.4.2.3	Results and discussion	176 -
3.4.2.3.1	Using BTLBOA combined with MST	176 -
3.4.2.3.2	Using BTLBOA	179 -
3.5	Summary of the Chapter	182 -
Chapter 4 : Solution of FACTS Allocation Problem		184 -
4.1	FACTS Allocation Problem Motivation	184 -
4.2	Objectives of the FACTS Study	187 -
4.3	Basic Concept of the Problem Formulation.....	187 -
4.3.1	The slow coherency indices	187 -
4.3.2	Probabilistic optimal power flow	189 -
4.3.3	FACTS model.....	192 -
4.3.3.1	Thyristor controlled series capacitor	192 -
4.3.3.2	Static synchronous compensator	193 -

4.3.3.3	FACTS cost	- 193 -
4.3.4	Optimal power flow	- 194 -
4.3.5	Teaching-learning based optimization	- 196 -
4.4	Problem Statement	- 197 -
4.5	FACTS Allocation Case Study	- 198 -
4.6	Summary of the Chapter	- 204 -
Chapter 5 : Wide Area Controller.....		- 205 -
5.1	Inter-Area Oscillation.....	- 205 -
5.2	Objectives and Contribution of the Wide Area Control Study	- 206 -
5.3	Basic concept of the Problem Formulation.....	- 207 -
5.3.1	Wide area control structure	- 208 -
5.3.2	Latency time of the wide area control.....	- 209 -
5.3.3	Wide area controller design.....	- 211 -
5.3.3.1	PSS dynamic model.....	- 212 -
5.3.3.2	TCSC dynamic model	- 213 -
5.3.3.3	Discussion on fuzzy logic	- 214 -
5.3.3.4	Reinforcement learning control.....	- 216 -
5.4	Control Problem Formulation.....	- 219 -
5.4.1	Training of the actor-critic networks.....	- 224 -
5.4.2	Controller parameters and used power system model	- 225 -
5.5	Wide Area Damping Control Case Study	- 225 -
5.6	Summary of the Chapter	- 228 -
Chapter 6 : Conclusion and Recommendations for Future Work		- 230 -

6.1	Conclusion of the Thesis.....	- 230 -
6.1.1	Contribution in PMU optimal placement	- 232 -
6.1.2	Contribution in FACTS allocation.....	- 233 -
6.1.3	Contribution in the WADC	- 233 -
6.2	Recommendations for Future Work.....	- 234 -
Appendix A		- 236 -
A.1	The systems data used in PMUs optimal placement	- 236 -
A.2	Results of the IEEE 39-bus system (Free selection of the CC)	- 241 -
A.2.1	Using BPSOGSA combined with MST	- 241 -
A.2.2	Using BPSOGSA.....	- 243 -
Appendix B		- 245 -
References.....		- 247 -
List of publications.....		- 279 -

List of Figures

Figure 1.1 Power system stability classification	- 3 -
Figure 1.2 Structure of WADC system	- 13 -
Figure 1.3 Design flowchart of WADC	- 14 -
Figure 1.4 GPS synchronization	- 19 -
Figure 1.5 Structure of WAMS	- 20 -
Figure 1.6 Latency time distribution in China Southern network	- 22 -
Figure 1.7 Inter-area oscillations in the European power system	- 28 -
Figure 1.8 Trajectory damping control	- 34 -
Figure 1.9 Supplementary damping control	- 36 -
Figure 2.1 Description of objective functions for FACTS allocation problem	- 85 -
Figure 3.1 An illustration of the WAMS	- 118 -
Figure 3.2 PMU hardware block diagram	- 120 -
Figure 3.3 Pseudocode of BPSOGSA	- 129 -
Figure 3.4 Pseudocode of Dijkstra's algorithm	- 132 -
Figure 3.5 MST Pseudocode	- 132 -
Figure 3.6 An example of MST for specific nodes in the network	- 133 -
Figure 3.7 An example of MMST for specific nodes in the network	- 134 -
Figure 3.8 The IEEE 118-bus test system representing the weak connections ..	- 136 -
Figure 3.9 An example of complete observability scenario	- 137 -
Figure 3.10 An example of depth-of-one unobservability scenario	- 138 -
Figure 3.11 An example of depth-of-two unobservability scenario	- 139 -
Figure 3.12 The power system without conventional measurements	- 140 -
Figure 3.13 The power system with conventional measurements Rule 1	- 141 -
Figure 3.14 The power system with conventional measurements Rule 2	- 141 -
Figure 3.15 The power system with conventional measurements Rule 3	- 141 -
Figure 3.16 The latency time of the communication network	- 148 -
Figure 3.17 The path components in the completeobservability without redundancy case	- 150 -
Figure 3.18 The path components in the redundancy case with PMU at Rnode and Nnode	- 151 -

Figure 3.19 The path components in the redundancy case with PMUs only at Nnodes	152 -
Figure 3.20 Flowchart of BPSOGSA with MST	157 -
Figure 3.21 The pseudocode of connectivity algorithm.....	159 -
Figure 3.22 Flowchart of BPSOGSA.....	160 -
Figure 3.23 The network topology using the BPSOGSA-MST for the IEEE 14-bus test system (CC free selection case).....	162 -
Figure 3.24 The total cost convergence curve using the BPSOGSA-MST for the IEEE 14-bus test system (CC free selection case).....	162 -
Figure 3.25 The latency time convergence curve using the BPSOGSA-MST for the IEEE 14-bus test system (CC free selection case)	163 -
Figure 3.26 The network topology using the BPSOGSA-MST for the IEEE 14-bus test system (CC predefined selection case).....	164 -
Figure 3.27 The total cost convergence curve using the BPSOGSA-MST for the IEEE 14-bus test system (CC predefined selection case).....	164 -
Figure 3.28 The latency time convergence curve using the BPSOGSA-MST for the IEEE 14-bus test system (CC predefined selection case)	165 -
Figure 3.29 The network topology using the BPSOGSA-MST for the IEEE 118-bus test system (CC free selection case).....	165 -
Figure 3.30 The total cost convergence curve using the BPSOGSA-MST for the IEEE 118-bus test system (CC free selection case)	166 -
Figure 3.31 The latency time convergence curve using the BPSOGSA-MST for the IEEE 118-bus test system (CC free selection case)	166 -
Figure 3.32 The Network topology using the BPSOGSA for the IEEE 14-bus test system (CC free selection case)	167 -
Figure 3.33 The total cost convergence curve using the BPSOGSA for the IEEE 14-bus test system (CC free selection case)	168 -
Figure 3.34 The latency time convergence curve using the BPSOGSA for the IEEE 14-bus test system (CC free selection case).....	168 -
Figure 3.35 The network topology using the BPSOGSA for the IEEE 14-bus test system (CC predefined selection case)	169 -