



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING

Electrical powers and Machines Department

**Interaction of Synchronous Generators
Governors in Power Systems**

**التفاعل بين متحكمات القدرة للمولدات المتزامنة في نظم القوى
الكهربية**

Submitted By

Eng. Dalia Ahmed Abdel-Moamen Salem

م/ داليا أحمد عبد المؤمن سالم

Cairo – Egypt

2018



AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING

Electrical Powers and Machines Department

Examiners Committee

Name: Dalia Ahmed Abdel-Moamen
Thesis: Interaction Between Synchronous Generators Governors in Power Systems
Degree: Degree of Master of Science in Electrical Engineering
(Electrical Powers and Machines)

Approved by:

1- Prof. Dr. Mohammed Abdel-Latif Badr
Professor of Electrical powers and machines, Faculty of Engineering, Ain Shams University.
(Supervisor)

2- Prof. Dr. Mahmoud Abdel-Hamid Moustafa
Professor of Electrical powers and machines, Faculty of Engineering, Ain Shams University.
(Supervisor)

3- Dr. Rania Abdel-Wahed Swief
Doctor of Electrical powers and machines, Faculty of Engineering, Ain Shams University.
(Supervisor)

Date: / / 2018

STATEMENT

This dissertation is submitted to Ain Shams University for the degree of Master of Science in Electrical Engineering (Electrical powers and machines).

The work included in this thesis was carried out by the author at the Electrical powers and machines Department, Faculty of Engineering, Ain Shams University.

No part of this thesis has been submitted for a degree or qualification at other university or institution.

Name : Dalia Ahmed Abdel-Moamen

Signature :

Date : / / 2018

***To my beloved father, mother, brother
and sister for their help and support***

Dalia Ahmed Abdel-Moamen

Master Thesis, Ain Shams University

Power system stability is a fundamental concept which is involved in many studies. Nowadays, analysis of power systems is developed to include many other concepts and not to be limited to input mechanical power, output electrical power and load angle. It includes many sub definitions such as the natural frequency of the machine and the sub-synchronous resonance in addition to many other circumstances of the power system. This means that besides the associated electromagnetic behavior of the connected generators and their fluxes, electromechanical behavior will be mainly considered in this thesis. All the attention turns to the electromechanical behavior of the power system, the transient electromechanical behavior and all the relative concepts like inertia of all the connected rotating masses and the electrical forces connect the generator are considered the key point of its robustness against any sudden disturbance and the driving torques.

To get the full picture of these concepts, many models are created and studied through the vast literature sources on power systems. This thesis is divided into two main parts: the sub-transient period and the transient period of operation and the effect of governor response. During the sub- transient period, natural frequency of a machine, associated with the synchronizing power, slip power and inertia power are considered the dominant factors affect the machine behavior. While in transient period, governors are taking all the action.

Natural frequency is a unique and specific property of this machine and it is not considered a fixed parameter for it. It changes according to many factors, such as the machine connection, whether is it connected to an infinite bus network or forms a single stand alone generator supplying local loads or it is connected in parallel with other machines at a power network.

For transient stability analysis, the rotor dynamics of the induction motor have to be included. These dynamics affect the system stability

when severe disturbances hit it and cause frequency deviations. For large systems, frequency deviations are small. However, it may cause loss of synchronism and break the system into smaller areas. Motor loads are sensitive to system frequency deviations. Any change in the grid frequency, changes extremely the slip. This follows by changes of the motor torque and the motor speed. The demanded active and reactive powers change as well. Natural frequencies of induction motors is considered a unique property has a great effect on its behavior during different operation conditions. This work presents also the performance of the induction motors through different power systems. Based on time domain simulation models study the natural frequency of induction motors, their response in normal and abnormal operation is analyzed to illustrate the dynamics associated. The behavior of all types of machine when they are interconnected together in a power system, or singly connected is analyzed in this thesis.

ACKNOWLEDGMENT

First of all, my utmost thank should go to ALLAH for His mercy, help and guidance, without which this document would not be made possible.

I would like to present my deepest gratitude to **Professor Dr. Mohammed Abdel-Latif Badr** for his humongous unconditional help, caring, valuable guidance and continuous support. He has generously devoted to me much of his knowledge and time and I deeply acknowledge him for that. I have learned so much from him rigorous research attitude, innovative thinking, and efficient work style. **Professor Dr. Mohammed** inspired me a sense of enthusiasm, optimism and motivation. I am very lucky to have Professor Dr. Mohammed as my supervisor. No words can express my appreciation to him. I will always be very grateful to him for my whole life.

I want to extend my greatest gratitude to my esteemed advisor, **Professor Dr. Mahmoud Abdel-Hamid Moustafa**, for his great support, professional advice, and profound understanding. He offered me so many advices and guided me all the way through my graduate study. His engaging arguments and strong feedback has contributed greatly to this thesis. I was very fortunate to have him as my advisor.

I would like also to express my deepest appreciation to **Dr. Rania Abdel-Wahed Swief** for her trust and unwavering support, professional advice, and profound understanding. She offered me so many advices and guided me all the way through my graduate study. Without her valuable thoughts, recommendation and patience, I would have never been able to complete this work. More importantly, I owe my research skills and style to her, stripping down a research problem to its essence: amenable to analysis yet general enough to yield insightful results to many facets of the problem. I am really grateful to her for her kind assistance towards the difficulties that I have faced in my personal life as well as her infinite passion in research work, which inspired me to work hard.

I would like also to express my deepest appreciation to my friends, who gave me help and support along the way. I am grateful to them for all the time and effort they took on my thesis.

Mother, father, brother and sisters thank you very much for your sincere love. Without your continuous support and prayers this work would not have been accomplished. Now it is time to dedicate this work to you.

TABLE OF CONTENTS

	<u>Page</u>
Abstract.....	i
Acknowledgement.....	iii
Tables of content	xii
List of Figures.....	viii
List of Tables.....	x
List of Abbreviations.....	xiii
 CHAPTER 1 : INTRODUCTION	
1.1 Thesis Background.....	1
1.2 Thesis Objective.....	1
1.3 Thesis Contributions.....	1
1.4 Thesis Outlines.....	2
1.5 Scientific publication.....	3
 CHAPTER 2 NATURAL FREQUENCY FOR SYNCHRONOUS GENERATOR	
2.1 Definition of PS Stability	4
2.2 PS Stability Classification	5
2.2.1 Rotor Angle Stability	5
2.2.1.1 Small disturbance rotor angle stability	6
2.2.1.2 Transient stability: Large disturbance rotor angle stability	7
2.3. Rotor Operation Basic Principles	7
2.3.1. Synchronizing power expression	9
2.3.2. Slip damping power in SG	12
2.3.3. Inertia power in SG	13
2.4. Natural Frequency Of A Synchronous Generator	14

2.4.1.	SG Natural frequency connected to infinite PS	17
2.4.2.	SG Natural frequency In Interconnected PS	17
2.4.3.	Oscillations between SGs and IMs	18
2.5.	Natural Frequency Effect On Transient Operation Phenomena	21
2.5.1.	"Hunting" phenomenon	22
2.5.2.	Switching impact on synchronous generators	24
2.5.3.	Faulty synchronization oscillations	24
2.5.3.1.	The SG synchronization with a phase error	25
2.5.3.2.	The SG synchronization with a frequency error	25
2.5.4.	Resynchronization after a short circuit fault	26
2.6.	Distribution of power impacts among SGs in PSs	29
2.6.1.	Impact effect on IGs	31
2.6.2.	System stability under power impact	32
2.7.	Conclusion	33
	REFERENCES	34

CHAPTER 3:PROPOSED METHODOLOGY TO DETERMINE THE NATURAL FREQUENCY

3.1.	Natural Frequency Laboratory Experiment Measurements	34
3.1.1.	Adding periodic disturbing torque to the driving torque of the prime mover	34
3.1.1.1.	Measuring the sharge motor output signal frequency	34
3.1.1.2.	Measuring the sharge motor mechanical speed	35
3.1.2.	Experimental setup	35
3.1.2.1.	For the shrage motor set	35
3.1.2.2.	For the driving 110 V DC motor	36
3.1.2.3.	For the main alternator under test	36

3.1.2.4.	For the mechanical counter	36
3.1.2.5.	The procedures of the work	37
3.2.	SG Natural Frequency Mathematical Calculation	39
3.3.	SG Natural Frequency By MATLAB	41
3.4.	Natural Frequency Of Oscillations For IMs	41
3.4.1.	IM in power grid	41
3.4.2.	IM Natural Frequency	42
3.4.3.	Factors affecting natural frequency of IM	43
3.4.4.	IM under sudden changes	45
3.4.5.	Estimation of the IM natural frequency	46
3.5.	Conclusion	46
	REFERENCES	15

Chapter 4 : Case Studies and MATLAB Simulation Verification

4.1.	Overview Of The Case Studies	48
4.1.1.	Case Study 1: 7 areas PS analysis	48
4.1.1.1	Simulation Initialization And Results	51
4.1.1.2.	Changing the inertia effect	53
4.1.2.	Case Study 2: 2 areas PS analysis	54
4.1.3.	Case Study 3: Mixed system with different types of SGs	57
4.1.4.	. Case Study 4: 2 SGs to infinite bus	60
4.1.5.	Case Study 5: Disconnection of a SG and Re-connection again	64
4.1.6.	Case Study 6: A three phase short circuit fault	65
4.1.7.	Case Study 7: Another PS analysis with Three phase short circuit fault	67
4.1.8.	Case Study 8: Adding Loads/ Removing them again	70
4.1.9.	Case Study 9: Verification for [4] graphical representation of (2)	73

4.1.10.	Case Study 10: 5 areas PS analysis during short circuit fault	74
4.1.11.	Case Study 11: IG to infinite grid	75
4.2.	Analysis of [1] applications	76
4.2.1.	Case Study 12: Classification of SGs depending on their performance	76
4.2.2.	Case Study 13: Inertia effect on SG oscillations	77
4.2.3.	Case study 14: 3 areas PS	78
4.2.4.	Case Study 15: Autonmous 3 areas PS	82
4.3.	Analysis of [4] applications	83
4.3.1.	Case Study 16: 3 areas mixed PS with short circuit fault	83
4.4.	Analysis of [3] applications	86
4.4.1.	Case Study: PS during load shedding analysis	86
4.5.	Conclusion	88

REFERENCES

Chapter 5 Sub-Synchronous Resonance

5.1.	Sub-Synchronous resonance In Power Networks	89
5.2.	Types Of Sub-Synchronous Resonance In PSs	90
5.2.1.	Sub-Synchronous due to induction generators (IGE) - The Asynchronous Effect	90
5.2.2.	Sub-Synchronous due to torsional interactions	91
5.2.3.	Sub-Synchronous due to transient torque - Transient Shaft Stress	91
5.3.	Case Study	92
5.4.	The reason of SSR in wind farms	93
5.5.	Detecting Sub-Synchronous Resonance In Power Systems	94
5.5.1.	Frequency Scanning Technique	94
5.5.2.	Electromagnetic Transient Simulation	95

5.6.	The Reason Of Sub-Synchronous Resonance In Synchronous Generators	95
5.7.	Some Events: Texas Event - October 2009	95
5.8.	Conclusion	96

REFERENCES

Chapter 6: Response of synchronous machines operating in parallel to a power impact

6.1.	Power Perturbation Distribution at "Governor-Action" period	97
6.2.	A new classification of synchronous generators	98
6.2.1.	Unregulated Synchronous Generators	98
6.2.1.1.	Armature Reaction Demagnetizing Effect	98
6.2.1.2.	Speed Small Changes Effect	99
6.2.2.	Regulated Synchronous Generators	100
6.3.	Load Frequency Control	100
6.3.1.	Primary Control, Governors	101
6.3.1.1.	System dynamics and load damping	102
6.3.1.2.	Modeling of governors	105
6.3.1.2.1.	Hydraulic Governor Modeling	106
6.3.1.2.2.	Thermal governor Modeling	107
6.3.1.2.3.	Speed Governing System	110
6.3.1.2.4.	Hydraulic Valve Actuator	112
6.3.1.2.5.	Turbine-Generator Response	113
6.3.1.2.6.	Speed Governor Static Performance	113
6.3.1.3.	Single area system with ALFC	115
6.3.1.3.1.	ALFC Closed Loop	115
6.3.1.3.2.	Control Area Concept	117
6.3.1.3.3.	Primary ALFC Loop Static Response	117

6.3.1.3.4.	ALFC Loop Dynamic Response	118
6.4.	Secondary control : Automatic Generation Control AGC	120
6.4.1.	AGC Operation In Isolated Single Area Mode	121
6.4.2.	AGC operation in a two area PS	122
6.4.3.	AGC Operation In A Multi Area PS	125
6.5.	Tertiary Control	126
6.6.	Conclusion	126
	REFERENCES	

Chapter 7: Conclusion and Future Work

7.1.	Conclusion	127
7.2.	Future Work	129
7.2.1.	Nuclear Energy Technology	129
7.2.2.	Future Competence Power Systems	130

List Of Figures:

CHAPTER 2

Natural Frequency For Synchronous Generator

Figure (2.1): A single SG connected to a very huge PS	9
Figure (2.2): Analog representation of a PS	10
Figure (2.3): Magnetic fluxes and their corresponding voltages	10
Figure (2.4): Power-angle relationship	10
Figure (2.5): Different powers during connecting to grid	13
Figure (2.6): Power-Angle Curve for SG	14
Figure (2.7) Oscillatory behavior of SG due to an impact	17
Figure (2.8): 2 SG connected to infinite bus	18
Figure (2.9): Graphical representation of all machines natural frequencies	18
Figure (2.10): Power system equivalent diagram	19
Figure (2.11): Two SG connected to two IM	19
Figure (2.12): Oscillations of the rotors for system machines	20
Figure (2.13): Different response of SG and IM	20
Figure (2.15): Rotors speeds of all machines in the system	21
Figure (2.16): Retardation behavior of interconnected generators	23
Figure (2.17): PS with two natural frequencies	23
Figure (2.18): The angular positions of the two pole wheels due to fault.	27
Figure (2.19): Single diagram of two areas PS	28
Figure (2.20): Rotors speeds of two areas PS including fault period	28
Figure (2.21): Rotor angles changes due to 3 phase short circuit	29
Figure (2.22): Retardation of interconnected SGs after disturbance	31
Figure (2.23.1): Power network	32
Figure (2.23.2): Retardation of the system voltage after impact	32

CHAPTER 3

Proposed Methodology To Determine The Natural Frequency

Figure (3.1) The mechanical counter	36
Figure (3.2): The experimental set to measure SG natural frequency	38
Figure(3.3): Armature current versus SG natural frequency	39
Figure (3.4): 2 SGs connected to infinite bus	39
Figure (3.5): SG rotor speed versus time to indicate its natural frequency	41
Figure (3.6): Induction motor connected to grid	41
Figure (3.7): Oscillations of IM connected to grid	43
Figure (3.8): Two IMs connected to infinite bus	43
Figure (3.9): Rotors speeds of two IMs connected to grid.	44
Figure (3.10): Rotors speeds during fault	45
Figure (3.11): Voltage dip across IM2	45
Figure (3.12): Voltage dip across IM1.	45
Figure (3.13): Parameters measurement system for IM	46

CHAPTER 4

Case Studies and MATLAB Simulation Verification

Figure (4.1): 7 areas power system	50
Figure (4.2): Rotors speeds-Time relationship for a system consists of seven generators connected together, the whole simulation period	52
Figure (4.3) Rotors speeds of all machines at start	52
Figure (4.4): Powers-Time relationship for a system consists of seven generators connected together	52
Figure (4.5): Rotors speeds-Time relationship for a system consists of seven generators connected together after H changing	53
Figure (4.6): Powers against time when changing inertia constants for generators	53
Figure(4.7): Two area power system	54