

**IDENTIFICATION OF COHERENT GROUPS OF
GENERATORS FOR OUT-OF-STEP PROTECTION:
A CASE STUDY OF SRI LANKAN POWER SYSTEM**

Viraj Viduranga Muthugala

(159371E)

Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

May 2019

**IDENTIFICATION OF COHERENT GROUPS OF
GENERATORS FOR OUT-OF-STEP PROTECTION:
A CASE STUDY OF SRI LANKAN POWER SYSTEM**

Viraj Viduranga Muthugala

(159371E)

Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree
Master of Science in Electrical Installation

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

May 2019

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature:

Date:

The above candidate has carried out research for the Master thesis under my supervision.

Signature of the supervisors:

Date:

Dr. W. D. Prasad

Signature of the supervisors:

Date:

Eng. W.D.A.S. Wijayapala

Signature of the supervisors:

Date:

Eng. D.G.R. Fernando

DEDICATION

I dedicate my M.Sc. research dissertation to my beloved parents and my wife for their guidance given throughout my life.

ACKNOWLEDGMENT

I would like to sincerely thank my internal supervisor, Dr. W.D. Prasad (Department of Electrical Engineering, University of Moratuwa), Eng. Rienzie Fernando (Managing Director, Amithi Power Consultants Pvt. Ltd) and Eng. W.D.A.S Wijayapala (Department of Electrical Engineering, University of Moratuwa) for their continuous support, encouragement and expertise in the field to make this Masters Research thesis a success.

I am really grateful to Eng. Jayasiri Karunanayake for being the originator of this research idea and for the guidance given to me to make this research a success.

I am also thankful to the thesis review panel comprised of Prof. H. Y. R Perera and Dr. N. de Silva for their time, effort put in to evaluate my research works and for the further discussions.

If not for the facilities provided by the Computer Laboratory of Dept. of Electrical Engineering, University of Moratuwa, it would not be possible to carry out the computer aided power system simulations. Therefore, my honest appreciations should go to the academic staff, Computer Laboratory Administrator and its technical staff.

As this study required plenty of data of Sri Lankan Power System, the assistance provided by my colleagues at Ceylon Electricity Board are greatly acknowledged.

My heartfelt gratitude shall go for my family and friends who had been caring, supporting and facilitating me throughout the time.

Abstract

Power systems are operated with tight stability margins, such that when a power system experiences a fault or disturbance, the generator rotors may be subject to severe oscillations. These oscillations in the generator rotor angle translate into severe power flow oscillations (or power swings) across the system. Power swings can be categorized as stable swings, for which, the system itself can recover and the unstable swings, where the system cannot recover itself, but needs some remedial action to gain stability. During power swings, magnitudes of voltages and currents can oscillate beyond their nominal values across the system. An unstable power swing condition can be identified as an Out-of-Step (OOS) event, which is a condition of angular instability or a state of Asynchronous Operation (AO) of generators. Out-of-Step event cannot be tolerable for a prolonged period of time due to its negative impact on power system equipment and its integrity. These oscillations might trigger distance relays and other backup relays removing key transmission elements leading to widespread outages and even blackouts. Controlled islanding of the system is one of the solutions to isolate the systems operating asynchronously during an OOS event. For this purpose, identification of generator coherency would come in handy in this process of control islanding, where the generators with similar rotor dynamic characteristics swing together forming separate clusters in the transmission network. Coherency analysis is fundamental for wide area measurement-based control in a power system. Also, it is important that the coherency identification becomes online based, as coherent groups may differ in response to various events and operating conditions. This thesis proposes a generalized methodology to identify coherent groups of generators as an online decision-making approach based on real-time data. This methodology will identify generators which tend to swing similarly at the initiation of OOS events based on real-time rotor angle trajectories and aid to identify possible clusters within the transmission network. Simulation results of OOS events on a 2-area 4-generator system, IEEE 16-generator 68-bus system and Sri Lankan power system were used for coherency identification using the proposed methodology. The case study considers the identification of the occurrence of OOS event in the Sri Lankan power system, as well as the formation of coherent groups of generators. Results indicate that the proposed methodology correctly identifies the number of groups and assigns each generator to its corresponding group. Further, it suggests the requirement of a Wide Area Measurement System (WAMS) to ensure wide area information availability in order to facilitate real-time decision making.

Keywords: Power Swing, Out-of-Step, Generator Coherency, Wide Area Measurement System, Sri Lankan Power System

Table of Contents

DECLARATION	i
DEDICATION	ii
ACKNOWLEDGMENT.....	iii
Abstract	iv
Table of Contents	v
List of Figures	viii
List of Tables.....	ix
List of Abbreviations.....	x
1 INTRODUCTION	1
1.1 Overview	1
1.1.1 Power Swings.....	2
1.1.2 Out of Step (OOS).....	3
1.1.3 Generator Coherency	5
1.1.4 Controlled islanding	6
1.1.5 Necessity of OOS protection for transmission network.....	6
1.2 Sri Lankan Power System	8
1.3 Importance of identifying generator coherency for OOS protection	9
1.4 Objectives of the study	10
1.5 Thesis outline	11
2 LITERATURE REVIEW.....	12
2.1 Out of Step (OOS) events leading to blackouts.....	12
2.2 OOS protection schemes adopted with Wide Area Measurement Systems (WAMSs).....	14
2.2.1 Basic structure of an OOS protection scheme.....	14
2.2.2 OOS Protection approaches	14
2.2.3 Classification based on detection of OOS.....	16
2.3 Generator Coherency Identification	17
2.3.1 Necessity of identifying generator coherency.....	17
2.3.2 Methods of identifying generator coherency	17
3 PROPOSED METHODOLOGY FOR IDENTIFICATION OF COHERENT GROUPS OF GENERATORS	23

3.1	Reasoning for the proposed methodology.....	23
3.2	Process of monitoring and fetching data	23
3.2.1	Derivation of rotor angles by PMUs	23
3.2.2	Data fetching	24
3.2.3	OOS detection criteria.....	26
3.3	Clustering operation	27
3.3.1	k-means clustering	27
3.3.2	Silhouette Criterion	29
3.4	Implementation of proposed methodology.....	29
3.4.1	Centre of Inertia based rotor angle (δ_{co}).....	30
3.4.2	Proposed methodology.....	31
4	VALIDATION OF THE PROPOSED METHODOLOGY	36
4.1	2 area 4 generator system	36
4.2	IEEE 16 generator 68 bus system.....	37
4.2.1	Contingency 1 (Loss of a transmission line).....	39
4.2.2	Contingency 2 (Loss of a transmission line)	40
4.2.3	Contingency 3 (Loss of a major load).....	41
4.2.4	Contingency 4 (Loss of a transmission line)	42
4.2.5	Contingency 5 (Loss of a generator).....	43
5	CASE STUDY ON SRI LANKAN POWER SYSTEM	45
5.1	Preparation of Sri Lankan Power System model.....	45
5.2	Validation of Sri Lankan Power System model	48
5.3	Case Study: Blackout in February 2016 in Sri Lankan power system	49
5.3.1	Background of the event	49
5.3.2	Application of the proposed methodology.....	51
6	CONCLUSIONS AND FUTURE DIRECTIONS.....	55
6.1	Conclusions	55
6.2	Future Directions	56
6.2.1	Practical Implementation	56
6.2.2	Studies on OOS in Sri Lankan Power System	58
7	REFERENCES.....	59

ANNEXURE A – Power Flow Data of 68 bus system.....	63
ANNEXURE B – Dynamics data of 68 bus system	66
ANNEXURE C – PSS®E Dynamic model assignment for SL Power System.....	69
ANNEXURE D – PSS®E Single Line Diagram of SL Power System	71

List of Figures

	Page
Figure 1 – Effect of stability margin on a power system	1
Figure 2 – DFR snapshot of Old Laxapana Power Station during blackout in February 2016.....	3
Figure 3 – Two machine system	3
Figure 4 – Impedance loci during power swing and pole slipping	4
Figure 5 – Rotor angle trajectories of IEEE 68 bus system after loss of generator 1 ..	5
Figure 6 – Protection for power swing and out of step on distance relays	6
Figure 7 – Typical flow of an OOS protection scheme	14
Figure 8 – Basic structure of WAMS [10].....	15
Figure 9 – Generator voltage-current phasor diagram	24
Figure 10 – Process of data fetching of proposed methodology.....	25
Figure 11 – OOS detection and Time window for data fetching of proposed methodology.....	26
Figure 12 – Flow of a typical k-means clustering algorithm	27
Figure 13 – Example data plot of a k-means clustering application [49]	28
Figure 14 – Flow of proposed methodology	31
Figure 15 – Step 4 of proposed methodology explained	33
Figure 16 – Steps 5 & 6 of proposed methodology explained.....	34
Figure 17 – Steps 7, 8, 9 & 10 of proposed methodology explained.....	35
Figure 18 – 2 area 4 generator system [55].....	36
Figure 19 – (a) MATLAB output, (b) PSS®E rotor angle plot of 2 area 4 generator system.....	37
Figure 20 – 16 generator 68 bus system [56].....	38
Figure 21 – PSS®E rotor angle plot of contingency 1 of 68 bus system.....	39
Figure 22 –MATLAB output of contingency 1 of 68 bus system	40
Figure 23 – PSS®E rotor angle plot of contingency 2 of 68 bus system.....	40
Figure 24 –MATLAB output of contingency 2 of 68 bus system	41
Figure 25 – PSS®E rotor angle plot of contingency 3 of 68 bus system.....	41
Figure 26 –MATLAB output of contingency 3 of 68 bus system	42
Figure 27 – PSS®E rotor angle plot of contingency 4 of 68 bus system.....	42
Figure 28 –MATLAB output of contingency 4 of 68 bus system	43
Figure 29 – PSS®E rotor angle plot of contingency 5 of 68 bus system.....	43
Figure 30 –MATLAB output of contingency 5 of 68 bus system	44
Figure 31 –Process of preparation of the PSS®E simulation model of Sri Lankan Power System.....	47
Figure 32 – Frequency response of PSS®E at LVPP unit 3	48
Figure 33 – Comparison of actual frequency vs PSS®E response at LVPP unit 3 ...	48
Figure 34 –Frequency response of PSS®E at Colombo Substation C 132 kV.....	50

Figure 35 – Comparison of actual frequency vs PSS®E response at Colombo Substation C 132 kV	51
Figure 36 – PSS®E rotor angle plot of Sri Lankan Power System on February 2016 blackout.....	51
Figure 37 –MATLAB output of Sri Lankan power system on February 2016 blackout	52
Figure 38 – Geographic locations of coherent generator groups in Sri Lankan power system [57].....	54
Figure 39 –Typical WAMS architecture [2]	57

List of Tables

	Page
Table 1 – OOS events leading to power outages over the world	12
Table 2 – PSS®E simulation results of contingency 1 of 68 bus system	40
Table 3 – PSS®E simulation results of contingency 2 of 68 bus system	41
Table 4 – PSS®E simulation results of contingency 3 of 68 bus system	42
Table 5 – PSS®E simulation results of contingency 4 of 68 bus system	43
Table 6 – PSS®E simulation results of contingency 5 of 68 bus system	44
Table 7 – Sequence of events during 25 th February 2016 blackout [15]	50
Table 8 – PSS®E simulation results of Sri Lankan power system on February 2016 blackout.....	52
Table 9 – MATLAB IDs of generators in Sri Lankan Power System	53

List of Abbreviations

Abbreviation	Description
OOS	Out of Step
CEB	Ceylon Electricity Board
DFR	Digital Fault Recorder
PSB	Power Swing Blocking
OST	Out of Step Tripping
WAMS	Wide Area Measurement System
NCRE	Non-Conventional Renewable Energy
SCC	System Control Centre
WECC	Western Electricity Coordinating Council
PMU	Phasor Measurement Unit
GPS	Global Positioning System
SCV	Swing Centre Voltage
HHT	Hilbert Haung Transform
CFT	Continuous Fourier Transform
DFT	Discrete Fourier Transform
ICA	Independent Component Analysis
ANN	Artificial Neural Network
RBF	Radial Basis Function
COI	Centre of Inertia
NETS	New England Test System
NYPS	New York Power System
OEM	Original Equipment Manufacturer
GSS	Grid Sub Station
FCB	Fast Cut Back
LVPP	Lak Vijaya Power Plant
LPC	Local Protection Centre
SPC	System Protection Centre
OPGW	Optical Ground Wire
SCADA	Supervisory Control and Data Acquisition
SL	Sri Lankan