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

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DECLARATION

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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.

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Abstract

Power systems are operated with tight stability margins, such that when a power system experiences a fault or disturbance, the generator rotors may 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 system cannot recover itself, but need some remedial action to gain the 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 widespread outages and even blackouts. Controlled islanding of the system is one of the solutions to isolate the systems operating asynchronously during and 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 transmission network. Coherency analysis is fundamental for wide area measurement-based control in a power system. Also, it is important that the coherency identification to become online based, as coherent groups may differ in response to various event 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 transmission network. Simulation results of OOS events on 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 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 Wide Area Measurement System (WAMS) to ensure wide area information availability in order to facilitate the real time decision making.

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

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List of Abbreviations

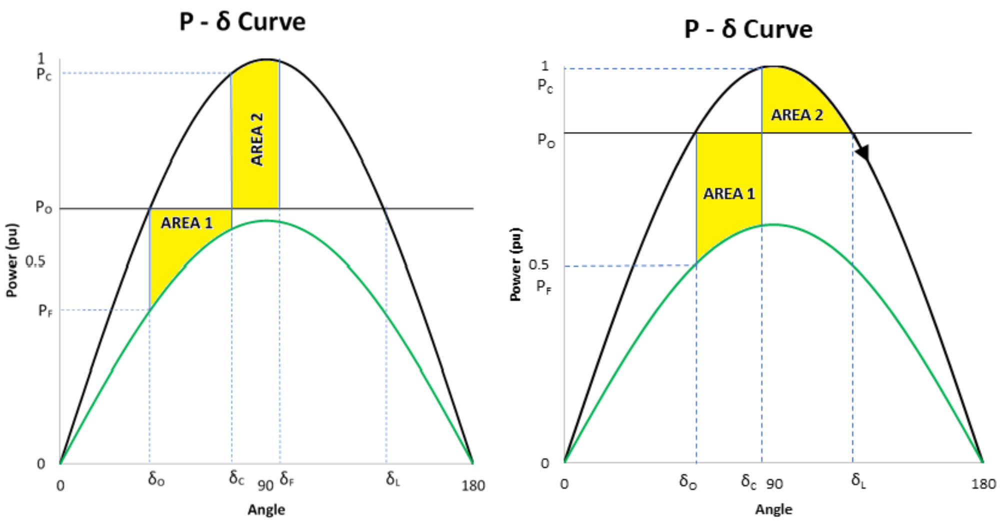
Abbreviation	Description
OOS	Out of Step
CEB	Ceylon Electricity Board
DFR	Digital Fault Recorder
PSB	Power Swing Blocking
OST	Out of Step Tripping
WAMS	Wide Area Measurement System
NCRE	Non-Conventional Renewable Energy
SCC	System Control Centre
WECC	Western Electricity Coordinating Council
PMU	Phasor 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

1 INTRODUCTION

1.1 Overview

In today's world, electricity plays a major role in making the human life effective, efficient and productive. With the increasing needs, demand for electricity increases rapidly. Necessity and awareness for a secure, reliable and quality power supply is escalating day by day as the interruption of power supply is adversely affecting the socio-economic aspects.

Utilities should monitor the growth of demand for electricity time to time and take necessary measures to expand the existing power system to cater the growing need. Expansion of the system should be done considering the demand to be met in years to come and required margin of stability to preserve the reliable operation of the system. Failure to do so timely will make troubles in meeting the demand and also the power system will become vulnerable to cascading failures throughout the system. This is because the power system will get heavily loaded with the growth of demand and stability margin will be endangered. Also, one cannot say that the availability of network components of a power system is 100% due to various reasons like maintenance activities and outages. This fact will also leave the power system defenceless to cascaded failures due to low stability margin and reduced network contingency as the way it is being operated.



(a) Adequately loaded (b) Highly loaded

Figure 1 – Effect of stability margin on a power system

Two cases in above figure show a power system with same capacity undergoing disturbance with same severity. In case (b), system is highly loaded and margin of stability is less compared to that of case (a). As per the equal area criterion of P-δ curves, accelerating and decelerating areas should be equal, in order to gain the stability by the system itself. In case (a), this condition is met but for case (b), operating point of power angle is pushed to its safe limit δ_L, while system is trying to gain the stability, yet failed at this point. Result will be a loss of synchronism which was created due to lower stability margin.

Therefore, after being subjected to disturbances, the power system may fail to recover itself, leading for a cascaded failure. In such cases, partial or total blackouts are imminent.

1.1.1 Power Swings

Power grid is a sophisticated dynamic system which delivers power from generation to load through series of transmission lines. A balance between generated and consumed active/reactive power is essential during steady-state operation. Any change in power generated, load demanded or the network topology will lead the power flow to change across the system until new equilibrium is reached. These changes are very common when operating a power system and automatically compensated with the aid of control systems. Normally, there are no adverse effects on the power system and its components.

Power swings originate in response to events in which sudden changes to electrical power occur. Power system faults, line switching, disconnection of generators and loss or addition of large loads are such kind of disturbances. During these disturbances, mechanical power supplied to the generators remains relatively constant due to slow governor action, while electrical power can be delivered changes depending on the disturbance [1]. This unbalance between the input power and the power delivered causes oscillations in machine rotor angles and can result in severe power swings across the network. This phenomenon becomes more significant when the power system is operated under tight stability margin.

For a stable power swing, system may remain stable and come to a new equilibrium over time, depending on the severity of the disturbance and post control actions being taken to overcome the instability. On the other hand, severe system disturbances can cause large separation of generator rotor angles leading to asynchronous operation of generators.

Large fluctuations of voltages and currents are possible even beyond their nominal values in these cases. Large power swings, whether being stable or unstable, can trigger protection functions of relays causing unwanted relay operations, which can worsen disturbance leading to partial or total blackouts.

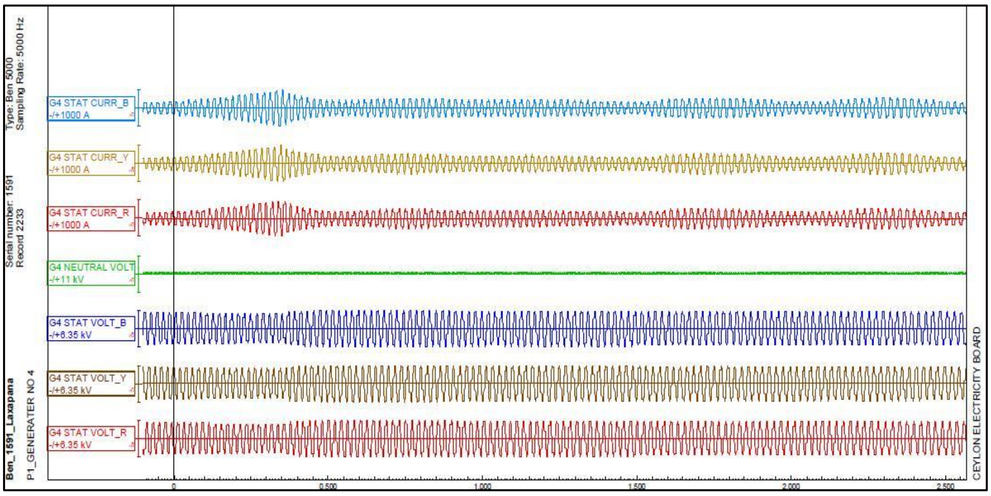


Figure 2 – DFR snapshot of Old Laxapana Power Station during blackout in February 2016

Above figure shows actual record of voltage and current recorded at Polpitiya Power Station during blackout event in February 2016. As per the records, it is quite evident that fluctuations are possible in voltages and currents after the initiation of power swings. Higher magnitudes in voltage and current can occur during these fluctuations leading to safety and security concerns in the power system.

1.1.2 Out of Step (OOS)

OOS event is ideally an unstable power swing condition, which cannot be tolerable for a prolonged period of time due to its negative impact on power system equipment and its integrity. Out of Step and Pole Slipping are similar designations for the condition where impedance trajectory lies across generator impedance characteristics. If the impedance trajectory goes through the characteristics of transmission line, then that is identified as an unstable power swing condition in the network [2].

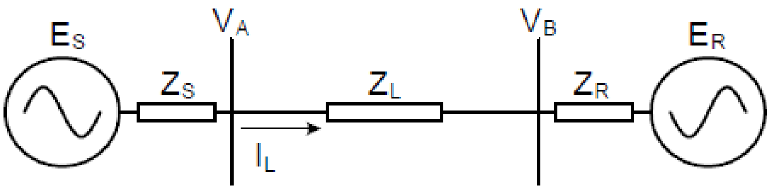
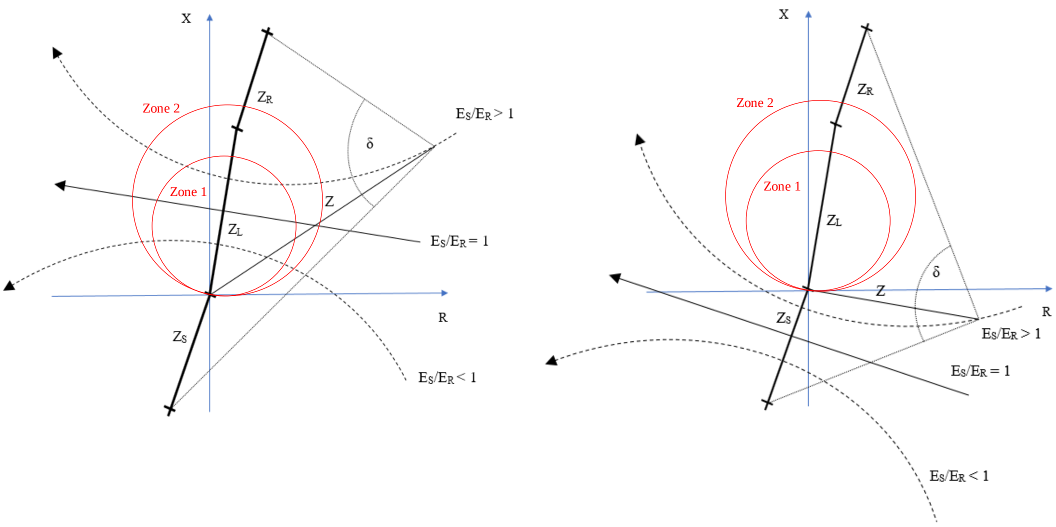


Figure 3 – Two machine system



(a) Power swing on transmission line (b) Pole slipping

Figure 4 – Impedance loci during power swing and pole slipping

Figure 3 shows two machine system in which sending and receiving end source impedances are represented by Z_S and Z_R respectively. Z_L represents the transmission line impedance. Figure 4 shows the impedance trajectories related with two possible power swing cases of above two machine system. Being subjected to a power swing condition, operating point of impedance follows a path as indicated in above graphs. Shape of loci differs as per the ratio of E_S/E_R. When the trajectory of impedance crosses the transmission line or source impedance characteristics power angle is 180^0 apart and it will appear as a balance three phase fault.

In case (a), impedance trajectory crosses the transmission line impedance characteristics Z_L. Distance relays are prone to operate as it appears as a three phase fault, unless Power Swing Blocking (PSB) is provided. This phenonminon happens when the transmission system is relatively weak and sources of generation are equally dominant [1].

Case (b) represents a situation where locus of impedance travels across generator impedance characteristics during a swing condition. Rotor flux slips with respect to that of stator. Pole slipping protection is provided in generating stations in order to detecct this phenomenon and isolate for equipment safety. Pole slipping is likely to occur on a weak generator which is connected to strong transmission network [3].

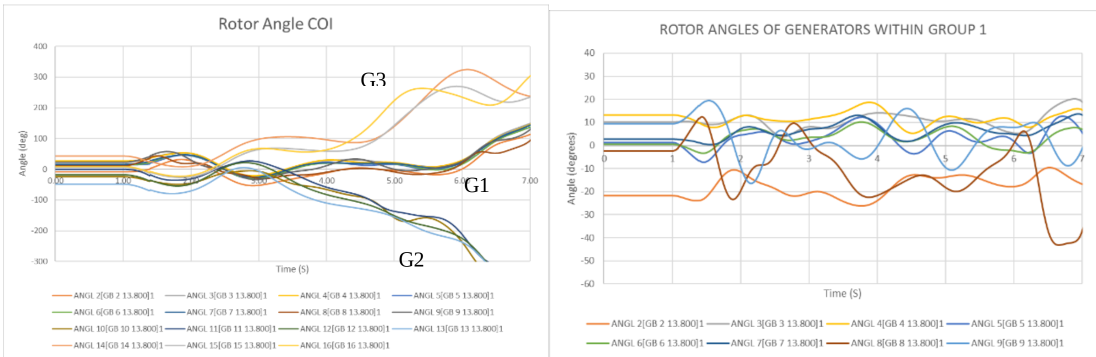
However, both of these cases refer to the same; Out of Step or loss of synchronism. If two or multiple areas lose synchronism, those should be separated in order to avoid equipment damage and cascading failures.

1.1.3 Generator Coherency

Coherency of generators in power system can be identified as the tendency of group of generators to swing together after a disturbance. Generators under same coherent group should oscillate at same angular speed maintaining same rotor angle deviation. That means generators with similar rotor dynamics come under same coherent groups. Two generators are said to be coherent, if their rotor angle deviation does not exceed a given threshold value [4].

$$\max \left|\delta_i(t) - \delta_j(t)\right| \leq \text{€} \tag{1}$$

where $t \in [0, T]$, $\delta_i(t)$ and $\delta_j(t)$ are rotor angles of i and j at time t, € is the given threshold for angle deviation [5].



(a) Formation of coherent groups as per rotor angle deviation

(b) Rotor angle deviation of generators within group 1

Figure 5 – Rotor angle trajectories of IEEE 68 bus system after loss of generator 1

Figure 5 shows the behaviour of the rotor angles of generators related to an example case on IEEE 68 bus system. As per figure 5(a), formation of 3 coherent groups of generators can be observed as the deviation of rotor angles is significant among the groups and it grows over the time. If intra-group rotor angles were considered in coherent group, the deviation is less and approximately stay intact over the time. In figure 5(b), rotor angles of generators within group 1 is shown and deviation is less than 70^0 for same time span considered for figure 5(a). Small scale intra-group rotor angle oscillations are possible among the generators in the same coherent group as far as they do not deviate largely.

Identification of generator coherency of a power system will come in handy when system separation is imminent due to OOS condition. In such cases, controlled islanding is a necessity to avoid further propagation of the failure.

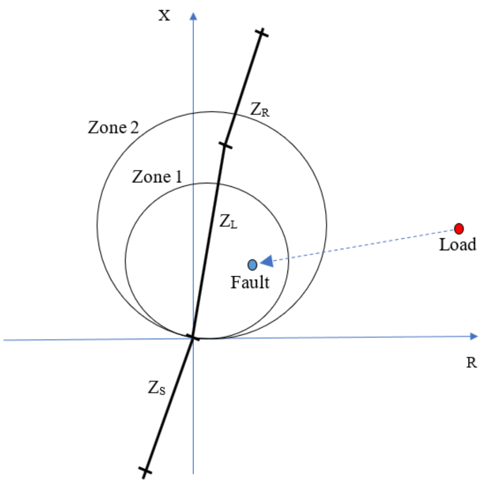
1.1.4 Controlled islanding

Controlled islanding is one of the control actions that has been proposed to deal with power system instabilities to avoid system-wide failures. This scheme is a last resort application, in case of imminent system separation and the preparation of the power system for such situations is a necessity [6].

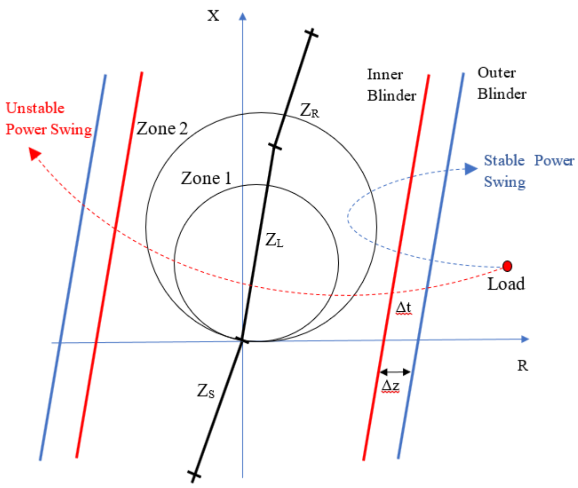
This scheme splits the power system into several subsystems depending on the similarities observed on network parameters during the period of instability. Purpose of this scheme is to form stable islands by opening transmission lines at optimum points of the network. While doing so, it should account the load generation balance, voltage stability, generator coherency and decay of out of step condition within each sub system [7].

1.1.5 Necessity of OOS protection for transmission network

Operation of distance relay: Distance relay operates to line faults as per behaviour of positive sequence impedance by observing from one end of the line. During normal load condition, impedance vector stays far away from line protection zones in R-X plane and it jumps into protection zones during a fault instantly. Number of protection zones are defined to be operated on faults to provide the discrimination related to severity of the fault, in which zone 1 trips the line almost instantly while other zones do the same with a time delay. Figure 6(a) briefs this operation of distance relay in case of faults.



(a) Distance relay characteristics



(b) Double blinder scheme

Figure 6 – Protection for power swing and out of step on distance relays

Expected operation distance relay under stable/unstable power swings: Similarly, as faults, power swings can cause the load impedance to enter into relay's operating characteristics, which is normally outside of that under steady state conditions. False detection and operation of these relays can cause undesired tripping of transmission lines and key elements of the system leading to a cascaded failure. Since the phenomenon of power swing is an electromechanical process, rate of change of apparent impedance during a power swing is slow compared to that of a fault. This fact is used in distance relays to detect power swings and OOS events. Figure 6(b) illustrates the double blinder scheme used for above purpose, which is most popular scheme yet, uses conventional rate of change of apparent impedance approach. There are many other schemes which use the rate of change of apparent impedance similar to double blinder scheme and the principle of operation is almost the same [1].

- **Power swing detection and Power Swing Blocking (PSB):** Distance relays should not operate unintentionally during stable or unstable power swing conditions and should allow the system to return to stability in case of stable power swings. This random operation of relays can cause undesired separation of the power system [1] [8]. Therefore, it is important for distance relays to distinguish between faults and power swings and prevent unwanted relay operations during dynamic conditions of the system.

  Double blinder scheme shown in figure 6(b) uses two pair of blinders Δz apart and a timer t_{PSB}. As the impedance vector enters the outer blinder, timer t_{PSB} starts and stops when it crosses the inner blinder. If the timer t_{PSB} expires before the impedance vector crosses the inner blinder, then it is declared as a power swing and the PSB is applied as per the necessity to avoid unnecessary tripping due to power swings [1] [9]. Otherwise, a fault is declared and the distance relay is allowed to do its normal operation.

- **Out of Step (OOS) detection and Out of Step Tripping (OST):** On the other hand, severe system disturbances can cause large separation of generator rotor angles leading to loss of synchronism within the system. In such cases, entire system might separate into two or multiple sub systems. When two or multiple areas of a power system lose synchronism, those should be separated immediately in a controlled manner. Uncontrolled tripping of circuit breakers during an OOS condition could cause damages to equipment and personnel and help cascading failures to occur [1] [8]. In order to make this happen, it is important to differentiate between stable and unstable power swing conditions, whatever the OOS protection philosophy being applied.

  Another timer setting t_{OST} is used in double blinder scheme is used with the same blinder setting with a Δz gap. Timer t_{OST} is less than the timer t_{PSB} as unstable swings move faster than the stable ones. Both the timers start at the same time when the impedance vector enters the outer blinder. If only the timer t_{OST} expires and not the timer t_{PSB}, before crossing the inner blinder, an unstable swing is detected. Decision for tripping can be initiated with the detection of OOS [1] [9].

Drawbacks related with conventional schemes: Finding the optimum settings for the timers for OST and PSB is not always an easy task and requires sophisticated grid analysis. Also, these settings are required to be reviewed time to time as the power system evolves, which is a tiresome exercise. Further, it should be noted that the decision to choose the precise locations for OST for separation of network is a tricky exercise, because of the dynamic behaviour of the power system. OOS protection scheme should be able to cope with this dynamic behaviour, if it is to deliver fast, reliable and promising control action.

Further, it is not recommended to apply only the blocking feature for unstable power swings without controlled network separation. This is because in case of unstable power swings, system separation is definite, which is a natural phenomenon. If the system is kept connected, damages to the equipment and personnel are possible due to high voltages and currents generated as a result of power swing [8].

Also, these local measurement-based approaches lack the capability of overseeing the entire system thus, may fail providing the optimum decision. This is where, Wide Area Measurement System (WAMS) based protection approaches can be used as per their greater observability over the entire power system [10]. Online protection scheme based on real time data with a fast and reliable communication network is the ideal solution.

1.2 Sri Lankan Power System

History of electricity in Sri Lanka runs towards early 1880s. Initial encounter of electricity in Sri Lanka was in 1882 and ever since power system had evolved going through various phases. In 1969, Ceylon Electricity Board was formed under the Parliament Act No. 17 of 1969, which was a vital turning point of the electricity industry of the country. In the present case, Sri Lankan power system comprises of 4086.9 MW of installed capacity serving a 2.5 GW night peak in daily demand. Generation of electricity is diversified among Hydro (34%), Thermal Oil (CEB – 14.8%, IPP – 15.4%), Thermal Coal (22%), NCRE (13.8%) [11]–[13].

Transmission network is operated at 220 kV and 132 kV voltages with transmission lines spanning around 600 km and 2310 km respectively. Approximately, 60 grid substations are fed through the network. Distribution system is operated at 33 kV and 11 kV voltages spanning about 32,863 km and electricity is served to the end user at 400 V (line-to-line) fulfilling the needs of 6,193,131 customers around the country. Electrification ratio is 99.7 % and 100 % electricity accessibility has been achieved [11]–[13].

Ceylon Electricity Board (CEB) has generation, transmission and distribution licensees. When it comes to Transmission Licensee, the CEB will be sole owner and the system functions as Single Buyer Model. The System Control Centre (SCC) plans and carries out the operation of generation and transmission system in order to achieve reliability, quality and operational economy. SCC is equipped with supervisory control, which was established in the recent past.

Within last 4 years, power system of Sri Lanka had to face three massive blows leading to total blackouts of the system. In September 2015, 5 hours blackout was encountered leaving country's one and only coal power plant with 3 x 300 MW out of order for another few days. In 2016, two total system collapses occurred in February and March persisting for 3 hours and 7 hours respectively[14], [15]. Longest blackout of the country was in May 1996 which lasted for 4 days.

The blackout in February 2016 took special attention of the committee appointed by Ministry of Power & Energy for the investigation of the incident. As per the investigation committee, power system had encountered severe power oscillations leading to an OOS scenario, where the network had undergone unintentional separation and islanding during final stages of the system collapse. The situation had been totally unexpected and protection schemes used had not been prepared for such situations by the time. The committee had suggested strongly to do further studies to figure out the adoptability of OOS protection to the Sri Lankan power system as a recommendation [15].

Phenomena of Out of Step has been faced by many countries around the world and the end result has been disastrous leading to partial or total blackouts as remedial actions were not taken timely and wisely. These phenomena get more frequent and dominant over the time as complexity and scale of the power networks increase. As a result, the necessity of investigations and analysis for OOS conditions have become much important today than yesterday.

1.3 Importance of identifying generator coherency for OOS protection

During a disturbed condition in the power system, electric path is also disturbed for the electrical power to flow steadily. Electrical power delivered out of the generators get reduced due to changes happen in the electrical path of the power system but, mechanical power delivered to the rotors remains nearly unchanged since the governor actions are too slow comparatively. Thus, imbalance is built up in generator rotors making them to accelerate and rotor angles advance relative to some generators of the power system based on rotor dynamics of each generator.

This relative advancement of generator rotors is the point of initiation of the power swings across the entire system. As discussed previously, generators showing similar rotor angle responses during a disturbed condition maintain the synchronism among each other. Those generators try to dominated over a certain part of the power system, which is a probable island under OOS condition. This means that a cluster of generators swings together resembles a possible island in the network and observing the behaviour of rotor angles gives a fine direction in identify possible clusters of generators showing coherency. Finding the coherency among the generators facilitates the process of identifying possible islands for network separation if required under an OOS condition. Therefore, identifying generator coherency is in utmost importance for OOS scenarios.

1.4 Objectives of the study

The main goal of this study is to introduce an online measurement-based approach to determine generator coherency using online measurements subsequent to contingencies in the power system. The contingency might lead to an OOS situation under which controlled separation of the network is required for satisfactory operation in at least part of the network. Following objectives are set in order to achieve this target.

1. Study the techniques used for controlled islanding and the importance of identification of generator coherency during OOS conditions
2. Study the occurrence of past blackout events in Sri Lankan power system to identify possible OOS condition using PSS/E simulation environment
3. Development of online decision-making algorithm to determine generator coherency using real time data
4. Validation of proposed methodology in IEEE benchmark power systems and application of the same on Sri Lankan power system for further validation and for identification possible islanding of network
5. Figure out the possibility of practical implementation of the proposed methodology in Sri Lankan Power system

1.5 Thesis outline

Rest of the thesis is ordered as follows covering the achievement of the objective highlighted in section 1.3.

Chapter 2 provides a comprehensive review on literature related to occurrences of OOS events led to cascading failures over the world. Also, the WAMS based techniques used for generator coherency identification for possible network islanding are discussed. Further, preparation of the current power system of Sri Lanka to face OOS events are also emphasised here.

Chapter 3 presents the methodology proposed to identify coherent groups of generators in a network subjected to an OOS condition.

Chapter 4 brings out the validation of the proposed methodology of identifying coherent groups of generators with the results of contingencies done one selected benchmark power systems. Simulations results are compared with that of the proposed methodology to figure out its robustness in this chapter.

Chapter 5 includes the case study done on Sri Lankan power system, together with model validation and results showing formation of coherent groups of generators during a past contingency. Further, results of the proposed methodology are obtained showing the same coherency of the generators and the possible dangers of current Sri Lankan power system that can be avoided by following this methodology are emphasized.

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Chapter 6 presents the conclusions and future directions of the study.

Chapter Summary

Chapter 1 discussed about the phenomenon of power swings and OOS and possible disastrous outcomes that may arise of remedial actions are not taken timely and wisely. Also, protection approaches adopted to deal with such disturbances are highlighted in this chapter. Further, a summary of Sri Lankan power system is given in this chapter providing examples of cascading failures occurred during last few decades.

Next chapter will focus on the history of OOS events, methodologies adopted for network splitting and preparation of Sri Lankan power system for such cases.

2 LITERATURE REVIEW

This chapter provides a comprehensive review on the literature related to Out of Step (OOS) events and Generator Coherency Identification.

2.1 Out of Step (OOS) events leading to blackouts

OOS event is one of the most disastrous situations in a power system which leads the power system towards partial or total power outages. Initiation of such events is due to tripping of key elements of the network, making inter-area load-generation imbalances. As a result, severe power oscillations generate in between those crippled regions making the system vulnerable for loss of synchronism within the network. Unless an optimum control action is taken timely, blackout is inevitable [16]. Following are some of the similar blackout cases recorded in history, which were associated with OOS events.

Table 1 – OOS events leading to power outages over the world

Year	Region	Reason	OOS condition
September 1965 [2]	North-east US	Maloperation of protection relay and subsequent tripping of a healthy transmission line	Formation of 5 islands and 2 of them in blackouts
January 1994 [2]	Northridge area of Los Angeles	Maloperation of breakers due to earthquake	Formation of unstable islands within WECC
August 1994 [17]	Italy	Line tripping due to fire	High oscillations between the north and south of Italy leading to a blackout
December 1994 [2], [18]	WECC interconnection, US	SLG fault and tripping of 345 kV lines	Power oscillations in 500 kV system between Canada, US Pacific Northwest, California
July 1996 [2], [18]	WECC interconnection, US	Maloperation of breaker and tripping of a healthy 345 kV transmission line	Severe power swings from Oregon to Western Idaho. Five islands formed with a blackout in southern Idaho.
August 1996 [2]	North-west US	Tripping of 500 kV transmission line and lack of N-1 security	Inter-area oscillations and total system broke-up into 4 islands
January 2002 [18]	Brazil	440 kV line tripping due to protection error	Oscillatory process of 440 kV transmission network leading to partial blackout in southern region

Year	Region	Reason	OOS condition
August 2003 [18]	North America/ Canada	Tripping of several transmission lines due to overloading, overgrown vegetation	Large power oscillations through New York and Ontario into Michigan
January 2003 [17]	Croatia	Short circuit on 400 kV line, protection did not break one pole	Breakage of the island 110 kV links and northern 220 kV link. PS separation and blackout
September 2003 [18]	Sweden & Denmark	Loss of nuclear generator 1200 MW	Heavy power oscillations in the system, very low voltages separation of grid into 2 islands
September 2003 [19]	Italy	Tripping of major tie line between Italy and Switzerland due to overloading	Loss of synchronism of Italian grid with UCTE
January 2005 [17]	Malaysia	Opening of a 275 kV bus section circuit breaker caused the adjacent 275 kV bus section circuit breaker to trip on overcurrent.	Power swung on to the parallel 132 kV network. After this event, the North East and the Central–South sub systems began to pull apart.
November 2006 [20]	Continental European transmission grid	Switching off of line with lack of N-1 security	Separation of UCTE grid into three separate areas (West, North-East and South-East)
April 2007 [21]	Colombia	Human error while doing a bus transfer in Torca substation	Partition of system into two islands (Boyaca and Santander regions)
September 2011 [22]	Arizona and Baja California	Loss of a single 500 kV transmission line and lack of N-1 security	Formation of several unstable islands
July 2012 [23]	Northern India	Transmission line tripping due to overloading	Many transmission lines tripping on distance protection due to power swings

There may be number of possible reasons for initial tripping of key elements of a power system. Natural phenomenon, human intervention, mal-operation of equipment, lack of maintenance/inspection are some possible reasons for initiation of such disastrous situations. What may be possible to come to next is transiently unstable and weakly connected subsystems which a susceptible for cascaded outages.

2.2 OOS protection schemes adopted with Wide Area Measurement Systems (WAMSs)

2.2.1 Basic structure of an OOS protection scheme

Generally, an OOS protection scheme can be understood as per the following.

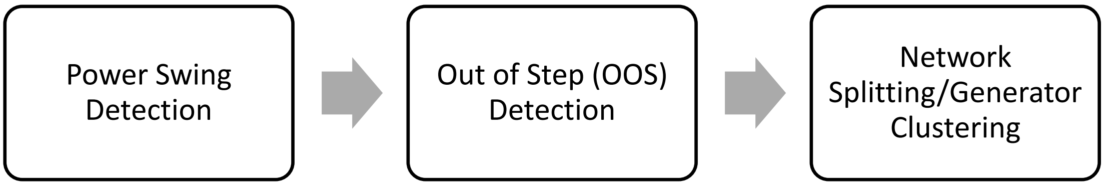


Figure 7 – Typical flow of an OOS protection scheme

First task is to discriminate a power swing from a fault. Slow and steady behaviour of system parameters are used for the discrimination. For an example, if the trajectory of apparent impedance were monitored, a sudden change can be observed from one point to another in the case of a fault, which happens almost instantly. For a power swing condition, whether being stable or unstable, it will be a slowly moving continuous trajectory [1], [8]. This phenomenon was discussed earlier in chapter with being related to the figure 6(b). Purpose of this discrimination is to avoid unnecessary tripping of network elements and allow the system to recover itself.

In the second phase, the power swing is identified to be stable or unstable. At this point, the decision is taken to initiate controlled islanding or generator coherency identification.

Generator coherency identification or network splitting is done based on the algorithms being used and system parameters being monitored.

2.2.2 OOS Protection approaches

OOS protection schemes mainly come under two categories [10].

- Local protection schemes

Local OOS protection schemes are widely used in utility networks. Modern protection relays normally come with the feature of OOS protection and variation of apparent impedance is monitored normally for the power swing and OOS detection. Several settings needed to be uploaded to the protection device in order to detect a power swing and discriminate an OOS condition. Decision of these protection settings is a tricky exercise since those are highly network specific and number of off-line simulations are needed to carried out covering all possible network contingencies. Further, location to apply OOS protection devices should be done considering location of OOS detection and opening of transmission lines for network separation. This means that the location of protection application is fixed and opening points are predefined, for which the decision have to be made after doing extensive simulation studies identifying probable islands within the power system under various contingencies.

- Wide Area Measurement System (WAMS) based protection

Occurrence of system wide disturbances in a power system is a challenging situation to deal with, because of the complexity and hugeness of modern power systems. Fast developing, evolving nature and randomness make chaotic situation and give a real hard time for the predefined protection schemes to keep the system alive at the end. In order to achieve most reliable protection scheme, it is essential to consider the dynamic nature of a power system facilitated by the real time data monitoring. Local protection schemes fail most of the time providing optimal decision for system wide disturbances because of dynamic behaviour and lack of observability of overall network. On the other hand, WAMS based protection schemes provide excellent observability and optimality in decision making for the same purpose [10].

WAMS based protection schemes use voltage and current measurements from widely disbursed locations in the power system in real time. Phasor Measurement Units (PMUs) are the basis of WAMS based protection schemes, which calculate fundamental phasors by measured voltages and currents. Most fascinating feature is all the measurements are synchronized with Global Positioning System (GPS) and time stamped, by which all the measurements are synchronized to a common time reference [24]. This is a very important application since it accounts the time variation when the measurements are done at different physical locations. Bringing the measured data to common time frame makes them directly comparable and facilitate the understanding and analysis certain phenomenon of power system [25].

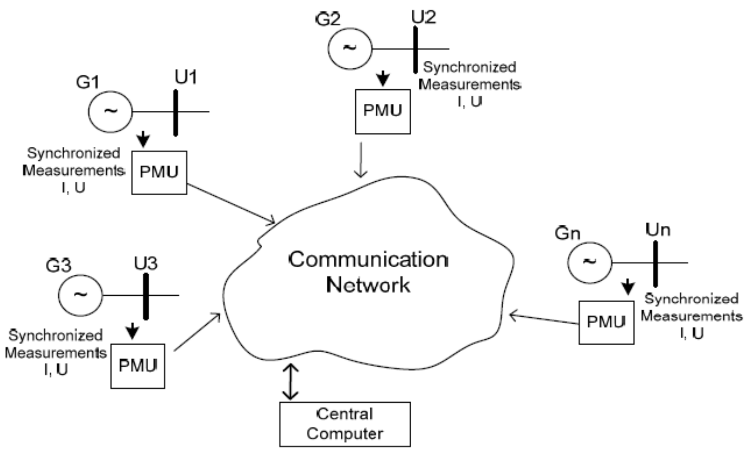


Figure 8 – Basic structure of WAMS [10]

WAMS needs to have sufficient number of PMUs installed at critical locations of the network in order to gather rightful information with time synchronization applied [10]. Measured data should be sent via fast and reliable communication network. Finally, a fast, reliable and well proven algorithm running on a real time operating and decision-making computer is required to process measured data and decide on what control actions to take. In case of OOS condition, the central computer will send instructions back to the relevant relay through the same path if isolation of network component is required [5], [25].

2.2.3 Classification based on detection of OOS

As discussed in previous section, WAMSs bring out great observability over the system parameters in real time. A variety of methods have been adopted based on the parameters being monitored and algorithms being used, when it comes to online approach. Following are some of the methodologies being adopted for online OOS protection schemes [10], [26].

- Rotor/voltage angle control based
  Angle control-based schemes rely on the behaviour of angle of voltage phasors measured at critical locations of the network or rotor angles measured/estimated at generator rotating masses. Activation of protection will be based on the exceedance of the given threshold for angle difference [2].

- Distance algorithm based
  Distance algorithm-based protection simply works on the behaviour of apparent impedance. This is incorporated in distance relays and monitors the way of the movement of impedance trajectory towards protection zones [1], [27].

- Swing Centre Voltage (SCV)
  In a two-machine equivalent system, the electrical centre can be identified as the electrical mid-point of total system impedance including the line and its two sources. If the angle difference of the two machines becomes 180 degrees during a power swing condition, then the voltage at electrical centre goes to zero and this is referred to as Swing Centre Voltage. When the two-machine system loses stability, the angle difference of two machines increases over the time. Therefore, SCV also varies with the propagation of OOS condition [1], [28].

- Energy function based
  During a fault in the system, maximum amount of energy is absorbed by a generator. After the clearance of the fault, that stored energy must be released.

Net absorbed energy for a selected period of time after the fault is compared with absorbed energy during the fault for the assessment of OOS [2].

Angle control based and distance algorithm-based methods are most popular in utility industry due to their feasibility when it comes to practice.

2.3 Generator Coherency Identification

2.3.1 Necessity of identifying generator coherency

Identification of coherent groups of generators is one of the key elements in the process of controlled islanding to avoid cascading failures of a power system. Coherency of generators during an OOS condition gives a much-needed direction towards the formation of stable subsystems. It is important for the generators to be coherent in each island in order to maintain the stability.

Further, generator coherency is not certain and varies time to time depending on the network topology and the operating conditions. This fact will merely put those off-line studies away, because predefined network separation may worsen the situation furthermore. Therefore, when it comes to the real problem, online coherency identification scheme based on real time data will be an ideal solution. With improvement of PMUs and fast, reliable communication networks online coherency identification of generators has become practical.

2.3.2 Methods of identifying generator coherency

Number of methods have been adopted to identify coherent groups of generators and primarily can be categorized into two types; model based and measurement based. In model-based techniques, linearized models together with system parameters are used to analyse oscillations and identify coherency. With the availability of PMUs, measurement-based techniques have become more dominant and popular. This is because of the lack of dependency on accurate linearized models and system parameters [29]. Also, relying on real time measured data gives a greater outcome irrespective of the contingency that the power system faces. Few algorithms available in the literature are summarized below [30].

- **Hilbert-Haung transform (HHT)**
  This technique is a way of extracting Intrinsic Mode Functions (IMFs) [31] by applying Empirical Mode Decomposition (EMD) [31] to a complicated signal. Huang's EMD technique is used for this initial purpose of HHT. In the next phase, instantaneous phase, amplitude and frequency is computed for each IMF, by applying Hilbert transform on them. Following equation shows the application of Hilbert transform on real valued signal *x(t)*.

$$H\{x(t)\} = \frac{1}{\pi} \, PV \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (2)$$

PV indicates the principle value of the singular integral. The analytic signal is defined as

$$z(t) = x(t) + i[y(t)] = a(t)e^{i\theta(t)} \tag{3}$$

Where *y(t)* is the complex conjugate of real valued signal *x(t)*.

$$a(t) = \sqrt{x^2 + y^2} \tag{4}$$

$$\theta(t) = \arctan \frac{y}{x} \tag{5}$$

$$\omega = {}^{d\theta}/_{dt} \tag{6}$$

Here, *a(t)* is the amplitude function, *θ(t)* is the phase function and *ω* is instantaneous frequency [31], [32].

In [33], coherency is examined by studying the instantaneous phase differences of oscillations in generator angles. Swing curves are decomposed and the most dominant vector is extracted. Application of Hilbert transform provides the instantaneous phase of above dominant vectors. Evaluation of phase angle difference can be used reveal the coherency information.

- **Fourier Analysis (FA)**

  FA is a way of approximating a general function by a summation of trigonometric functions. The process of decomposing a general function simpler trigonometric functions is called Fourier Transform (FT). Continuous Fourier Transform (CFT) [34] is denoted by the following, which produces a continuous function of frequency known as frequency distribution.

$$S(f) = \int_{-\infty}^{\infty} s(t)\, e^{-i2\pi ft} dt \tag{7}$$

Where, *t* is time and *f* is frequency in complex form. Similarly, Discrete Fourier Transform (DFT) [34], [35] is an equivalent of CFT when signals are known only at *N* instants with a period of *T*.

$$S(f) = \sum_{k=0}^{N-1} s(k)\, e^{-i2\pi fkT} \tag{8}$$

In [36], authors have adopted DFT on generator rotor speeds for coherency identification. Based on post disturbance data of generator parameter, frequency spectrum is analysed for each generator and most dominant vector is identified by phase angle and its magnitude. After comparing the phase angle of the dominant vector of all the generators, the coherency is determined.

- **Correlation Characteristics**

  The strength of linear association between two variables is assessed by the correlation characteristics. Flowing equation evaluates the correlation coefficient, which ranges from -1 to 1. Larger coefficient is a sign of better correlation between two variables [37], [38].

$$CR_{ij} = \frac{n\sum\left(\delta_i\delta_j\right) - (\sum\delta_i)(\sum\delta_j)}{\sqrt{[n\sum{\delta_i}^2 - (\sum\delta_i)^2][n\sum{\delta_j}^2 - (\sum\delta_j)^2]}} \tag{9}$$

  Correlation coefficients are used as an online tool for generator coherency identification in [37]. The approach is based on correlation characteristics of generator rotor angle oscillation. Correlation coefficients are calculated for each pair of generators. Correlation coefficient being close to 1 indicates a better relationship between two generators. Therefore, coherent groups of generators are identified when correlation coefficient is higher than the given threshold.

- **Independent Component Analysis (ICA)**

  ICA is a data driven computation methodology which separates multivariate signal into additive, independent subcomponents. Subcomponents are assumed to be non-gaussian and statistically independent from each other. ICA assumes that the outputs are influenced by a set of hidden sources, which are statistically independent of each other contributing to each output.

  The data are represented by following random vector *x* and hidden components by h. A linear static transformation *W* is used on *x* to achieve h [39].

$$x = (x_1, x_2, \dots\dots\dots\dots\dots x_m)^T \tag{10}$$

$$h = (h_1, h_2, \dots\dots\dots\dots\dots h_n)^T \tag{11}$$

$$h = Wx \tag{12}$$

  ICA based coherency identification techniques is adopted in [29], in which generator speed and bus angle data are used as the inputs. Authors have used spectral ICA technique which identifies single peak Independent Components (ICs). By means of this spectral ICA, a spectrum can be extracted into a combination of single peak ICs. A mixing ratio is defined for ICs and is extracted for clustering generators and buses considering common features of measured signals.

- **Artificial Neural Network (ANN)**

  Application of ANNs allows actions similar to human reasoning as ANNs gather experience during the process of training. This fact will make ANN based techniques being capable of pattern recognition, faster computation and robust. ANN is a group of connected nodes. These nodes behave as Artificial Neurons (ANs) and can transmit signals from one to another. Output of an ANN is computed typically by a non-linear function from the summation of its inputs. Ans and their connections have a factor of weighing, which is normally adjusted during the process of learning [40].

  Radial Basis Function (RBF) network [41], [42] is a feed forward neural network consisting single non-linear hidden layer. Input nodes pass the inputs to the hidden layer without any weighing and the transfer function of the hidden layer is as follows.

  $$\varphi_j(x) = e^{\frac{\left\|x-\mu_j\right\|^2}{2\sigma_j{}^2}} \tag{13}$$

  Where, μ_j is the vector determining the center of RBF φ_j and σ_j is the width of the vector. The connection between hidden and the output nodes is a linear summation of units and given by,

  $$y_k(x) = \sum_{j=1}^{h} w_{kj}\,\varphi_j(x) + w_{ko} \tag{14}$$

  Where, w_{kj} is the weight of the connection between k^{th} output node and the j^{th} hidden node and w_{ko} is the bias.

  In [42], authors have adopted RBF based ANN technique for coherency identification of the generators. Authors have used 2 RBF networks; in which, one network determines the status of synchronism while the other figures out the coherent group number. Active and reactive power flows of generator and load buses are considered as inputs for the determination of coherency.

- **Graph Theory**

  Graph theory is a study of graphs, in which quantifiable objects are linked together based on the relations in between. A graph *G* comprises of vertices *V*, which denotes objects and edges *E* showing the connection between vertices[43].

  $$G = (V, E) \tag{15}$$

  In [44], authors suggest that the mutual influence of network topology and dynamic behaviour related to coherency phenomenon can be easily understood by converting generating system into an equivalent graph with vertices and edges. Further, coherency is determined by evaluating the synchronizing power between generators.

$$H_{ik} = E_i V_k B_{ik} Cos(\delta_{ik}) \quad (16)$$

Where, E_i is transient emf of generator *i*, V_k is the voltage at generator *k*, B_{ik} is the imaginary part of the element *ik* in the transfer admittance matrix and δ_{ik} is the angular difference between generators *i* and *k*. Being subjected to a disturbance at node *k*, rotor of generator *i* with inertia coefficient M_i accelerates as per the following.

$$\gamma_i = \frac{H_{ik}}{M_i} \Delta_k \quad (17)$$

For generators *i* and *j* to be coherent their rotor accelerations should be equal.

$$\frac{H_{jk}}{M_j} = \frac{H_{ik}}{M_i} \quad (18)$$

Thus, this definition of a generator being affected while other generator suffers a disturbance is used to create a complete graph for the entire power system. Generators of the system make the nodes of the graph and edges are by,

$$min(\frac{H_{ik}}{M_i}, \frac{H_{ki}}{M_k}) \quad (19)$$

Finally, a complete graph is achieved, in which every pair of distinct nodes is adjacent.

Once the graph is created as described above, coherency is determined such that coherent generators have stronger edges between the generators within their own group, while having weak edges among generators in other groups. For a group of generators to be coherent, coherency between each pair of the generators in that group is to be determined. Generally, a process of partitioning a given graph of generator system is done by finding the edges that will split the initial graph into desired number of sub groups, when removed.

For graph partitioning, authors of [44] have proposed following algorithms; *Recursive Spectral Bisection, Maximum Spanning Tree Clustering and Minimum Cut Tree Clustering*.

Chapter Summary

In this chapter, most disastrous power outages around the world in last few decades were discussed in which the phenomenon of OOS was observed. Further, the basics OOS protection scheme and its relevancy in modern power systems were highlighted. Also, the importance of identifying the coherent group of generators during an OOS condition was emphasized together with some of the techniques used for this coherency identification. Next chapter will introduce a generalized methodology to identify generator coherency for OOS conditions, which can be applied using real time measured data.

3 PROPOSED METHODOLOGY FOR IDENTIFICATION OF COHERENT GROUPS OF GENERATORS

This chapter explains the proposed methodology for online identification of generator coherency. The proposed methodology can be implemented using real time data measurements.

Application of WAMSs in power systems is highly encouraged in this study in order to make use of online generator coherency identifications schemes which facilitate OOS protections schemes using real time data measurements.

3.1 Reasoning for the proposed methodology

As previously discussed, when a power system is subjected to a disturbance, generator rotors undergo severe oscillations. This is because the impedance seen by the generator is altered by the fault, yet power delivered from the prime mover remains approximately unchanged due to relatively slow governor action [1]. These oscillations in generator rotors translate severe power swings across the power system. In that sense, rotor angles of generators provide a fine direction in the process of coherency identification of generators.

A measurement-based technique is much preferable as per the availability of wide area measurements. Further, it provides greater independency, observability and situational awareness of the power system. To identify the coherency, the data should be clustered based on their similarities and deficiencies. Data clustering algorithms like k-means Clustering is ideal for this particular purpose. k-means Clustering is a popular scheme of data clustering due to its simplicity and its guaranteed convergence of the solution [45].

Proposed methodology can be studied in two steps, where the first step is the process of fetching data / monitoring and second step is the clustering operation of fetched data. All the aspects of proposed methodology will be discussed in details under next sub topics.

3.2 Process of monitoring and fetching data

Behaviour of generator rotor angles are observed for the OOS detection and coherency identification of generators.

3.2.1 Derivation of rotor angles by PMUs

Rotor angle of a generator is not directly measurable by PMU due to the mechanical nature of it. Thus, rotor angle should be derived from the electrical measurements obtained by PMU. Generator terminal voltage $V\angle\theta$ and output current $I\angle\varphi$ phasors are used for the calculation of generator rotor angle, which can be measured by PMU in real time. Following figure and the equations explains the process of calculating generator rotor angle from the measured data by PMU [46].

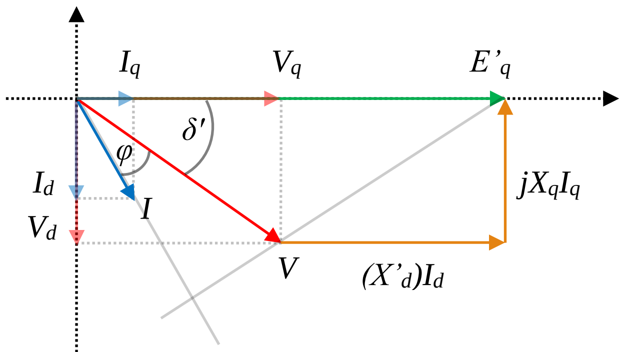


Figure 9 – Generator voltage-current phasor diagram

$$V_t \sin(\delta') = X_q I_a \cos(\delta' + \varphi) \tag{20}$$

$$V_t \sin(\delta') = X_q I_a [\cos(\delta') \cos(\varphi) - \sin(\delta') \sin(\varphi)] \tag{21}$$

$$[V_t + X_q I_a \sin(\varphi)] \sin(\delta') = [X_q I_a \cos(\varphi)] \cos(\delta') \tag{22}$$

$$\tan(\delta') = \frac{X_q I_a \cos(\varphi)}{V_t + X_q I_a \sin(\varphi)} \tag{23}$$

Where,
δ' is rotor angle of the generator with respect to its local terminal voltage
V_t is magnitude of generator terminal voltage measured by PMU
I_a is magnitude of generator output current measured by PMU
φ is phase angle of generator output current with respect to its terminal voltage measured by PMU
X_d, X_q are transient reactances of the generator's direct and quadrature axes, respectively

Therefore, PMU data can be used to derive rotor angle of the generator as per the above. Calculated rotor angles are to be processed further for generator coherency identification.

3.2.2 Data fetching

Generator rotor angles should be derived at each generator station with the aid of PMUs as stated above and transmitted through the fibre optics network to the central controller. Sample time for the measurements is 10 ms for this case. It is assumed that the generator rotor angles of all the generators are readily available at the central controller for further processing.

Sampling rate: Typically, sampling rate for commercially available PMUs ranges from 0.5 – 2 samples per one cycle. For the simulation purposes, sampling rate of 2 samples per cycle is considered. Therefore, sampling time is 10 ms for 50 H_z power system [47].

Process of fetching rotor angle data can be identified as shown in Fig. 9 below.

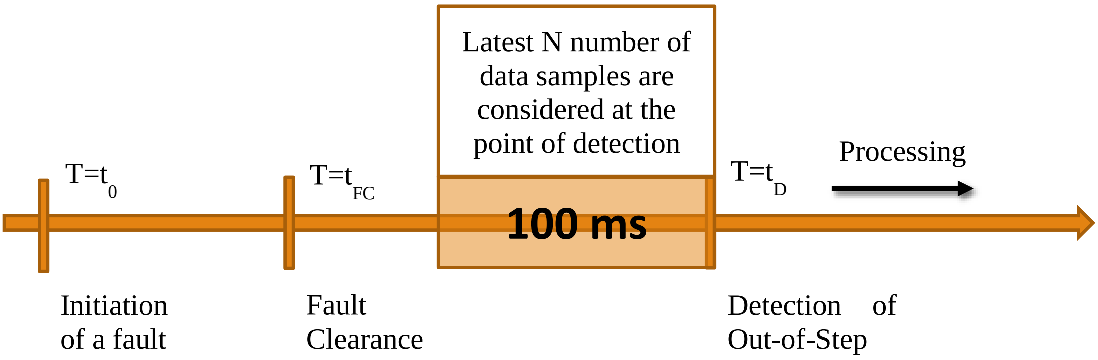


Figure 10 – Process of data fetching of proposed methodology

STEP (1) A disturbance is initiated at random time in the power system. Let's say that this time T = t_o.

STEP (2) At T = t_{FC}, the fault is cleared as per the protection applied. Monitoring of generator rotor angle data is triggered after the clearance of fault. Exceedance of the difference of rotor angles of any two generators from the given threshold *D* is checked at every time step. As the time proceeds, predefined set of latest past data is kept in a buffer for processing.

STEP (3) Detection of OOS occurs at T = T_D. At the point of detection, latest N number of data samples are considered for the clustering of generators. In this study, samples within 5 cycles of the fundamental frequency (100 ms) are considered. This feature of considering past data for the clustering operation makes the process more efficient and less time consuming.

Time window T: Latest rotor angle data at the point of OOS detection carry the finest coherency information of the generators since the deviation of the rotor angle are furthest from each other during this period. Making this time window unnecessarily lengthy adds additional past rotor angle data which occupy less deviation from each other and this may introduce difficulties in differentiating rotor angle data into separate groups. This fact can be further understood by observing figure 10. At the same time, time window T should include sufficient amount of data and should not be unnecessarily short, in order to make sure that trajectory of the rotor angle is considered and the solidity of the rotor angle data maintained per each generator. Considering above facts, time window of 100 ms or 5 cycles is selected which occupies 10 rotor angle data samples with 10 ms interval.

3.2.3 OOS detection criteria

After occurrence of a disturbance, generators will contribute to the fault depending on the electrical distance to the location of fault and inertia of the prime mover. Response of the generators will be visible in their position of the rotor angle. After the clearance of the disturbance, the rotor angles will try to regain a new equilibrium point following an oscillatory behaviour because of the inertia characteristics of the prime mover. Because of this post disturbance oscillatory behaviour of rotor angles, it is possible for some generators to be pulled away largely from each other, which endangers the synchronism of the generators. If so, the detection of OOS is necessary in order to proceed with the clustering operation of generators.

Figure 10 elaborates an example plot of generator rotor angles. It shows the detection of OOS followed by a data set within the time window T.

- After the clearance of the disturbance, OOS detection criteria is observed at each data sample, in real time.

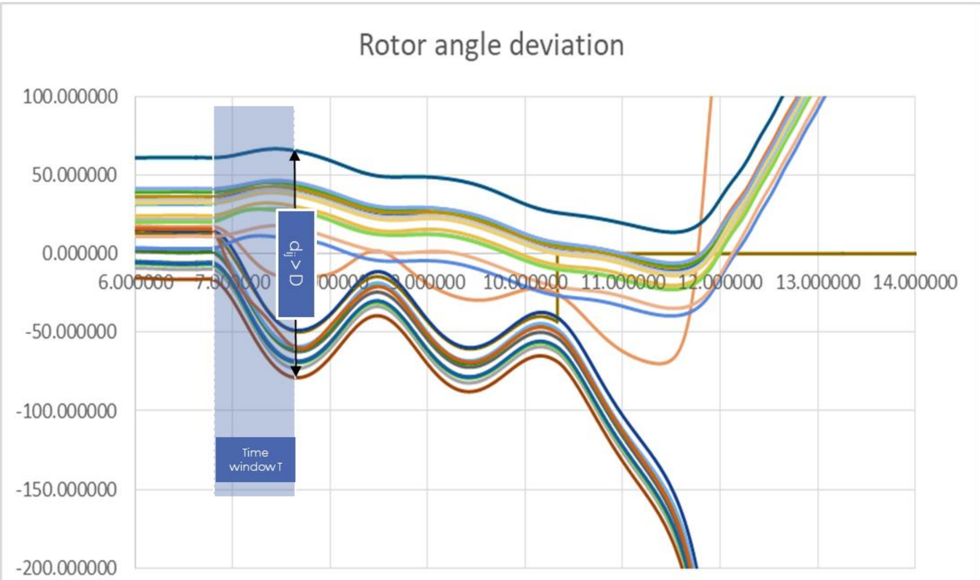


Figure 11 – OOS detection and Time window for data fetching of proposed methodology

- As shown in figure 10, whenever the deviation of the rotor angle of any two generators exceeds the given threshold (D), clustering operation starts.

$$\delta_{ij}(t) = \delta_i(t) - \delta_j(t) \tag{24}$$

$$\delta_{ij}(t) > D \tag{25}$$

- At the point of OOS detection, latest data sample within the predefined time window T is only considered for generator clustering.

3.3 Clustering operation

The rotor angle data stored within a predefined time window is clustered using k-means clustering algorithm [48], in order to identify generator coherent groups.

3.3.1 k-means clustering

k-means clustering is a simple, unsupervised learning algorithm, which follows a simple procedure to classify a given data set into defined number of groups. Most importantly, this algorithm imposes less computational burden, which makes it more appropriate to be used than other types of data clustering approaches. Algorithm aims to partition *n* number of data points into *k* number of clusters. Ultimate goal of the algorithm is to find the groups in the entire data set. This algorithm is simple, efficient and guaranteed to converge to a realistic solution [30].

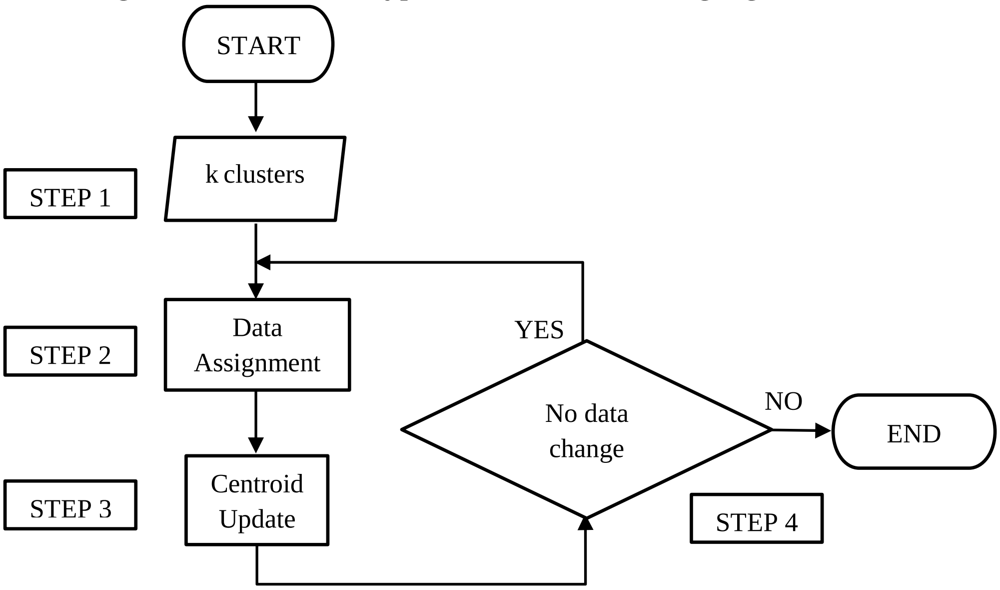
Algorithm uses an iterative process, where each data point is correctly assigned to relevant group iteratively. It tries to keep inter cluster data points as close as possible while making clusters as distant as possible from each other. Algorithm runs based on the criterion of, minimizing Squared Euclidean Distances between the data points and the corresponding cluster centroid [45].

Inputs to the algorithm are,

- Number of clusters (k) – This is the number of coherent groups of generators
- Set of data – Rotor angle data measurements of the generator

This algorithm is an iterative process as previously discussed and it can be understood as per the following flow chart [45].

Figure 12 – Flow of a typical k-means clustering algorithm



STEP (1) Number of clusters k

Number of cluster k is a user input and centroids are created per each cluster, randomly.

STEP (2) Assignment of Data

Each cluster is represented by a single centroid. Based on Squared Euclidean Distance, each data point is assigned to the nearest centroid/cluster.

$$Squared\ Euclidean\ Distance\ (dist(x, c_i)) = (x - c_k)^2 \quad (26)$$

Where, x is each data point in the data set and c_k is a centroid of a cluster.

STEP (3) Update Centroid

After the assignment of a data point, centroids are calculated again. This is achieved by taking the mean value of all the data points in the corresponding cluster.

$$c_k = \frac{1}{N} \sum_{i=1}^{N} (x_i) \quad (27)$$

Where, N is number of data assignments in corresponding cluster with centroid c_k.

STEP (4) Algorithm iterates between Step 2 & 3 until convergence is met. For the stopping criteria of algorithm, one of the following conditions should be met.

a. No data point change clusters and sum of the distances from the data points to the corresponding centroid is minimized
b. Maximum number of iterations are reached.

Each centroid defines a particular cluster and represents all the data points in that cluster. Following figure shows an example case of a data distribution being clustered into 4 groups. Cluster centroids are represented by asterisk marks.

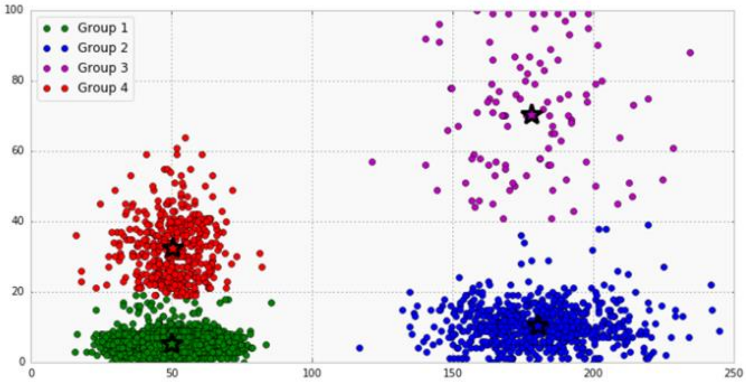


Figure 13 – Example data plot of a k-means clustering application [49]

3.3.2 Silhouette Criterion

As discussed in previous sub topic, number of clusters k will be a user input. This is not the expected outcome, since the optimum number of generator clusters should be decided based on the rotor angle data distribution. In order to overcome this gap, Silhouette Criterion is applied.

Main objective of this algorithm is to define optimum number of clusters for the given data set. Silhouette value is a measure of similarity of a datum to its own cluster compared to foreign clusters.

Assume the set of data has already been clustered into k groups using k-means clustering. Silhouette value can be calculated as per the following [50], [51].

$$S(i) = \frac{b(i) - a(i)}{\max\{b(i), a(i)\}} \tag{28}$$

Where,

a(i) is the average distance between *i* and all other data within its own cluster, for each datum *i*,

b(i) is the smallest average distance of *i* to all points in any other cluster, in which *i* is not a member,

As per the above equation, Silhouette value ranges from -1 to 1.

$$-1 \leq S(i) \leq 1 \tag{29}$$

For $S(i)$ to be closed to 1, *a(i)* should be a smaller value compared to *b(i)*. This indicates that *i* is well matched to its own cluster and poorly matched to its neighbouring cluster. Similarly, if $S(i)$ to be closed to -1, then *i* is preferred to be clustered in its neighbouring cluster than its own. A value close to 0 indicates that the datum is at the boundary of two clusters.

Average of $S(i)$ over all the points in a particular cluster indicates how well those points are matched within the cluster. Similarly, if average $S(i)$ of entire data set is considered, that shows how appropriately all the data have been clustered.

Therefore, optimum number of clusters are selected, when Average Silhouette Value $S_{avg}(i)$ is close to 1[50].

3.4 Implementation of proposed methodology

k-mean clustering algorithm is the basement of the proposed methodology and Silhouette Criterion is applied on top of k-means clustering to determine the optimum number of clusters.

Input data set is $n \times z$ matrix consisting *z* number of rotor angle data samples per each generator measured at *n* number of generators within time window T.

3.4.1 Centre of Inertia based rotor angle (δ_{COI})

Synchronism of a power system is a relative phenomenon of rotor angle positions and actually is determined by the relative motions among the machines. Power system synchronism related studies considering the absolute rotor angles is immaterial , since there is no true meaning of it. Therefore, rotor angles should be addressed relative to a common reference frame.

Centre of Inertia (COI) based rotor angle is a better reference for rotor angle studies, since it represents the mean motion of the power system and it has the advantage of being symmetrical. Therefore, a better understanding and a clear observation can be achieved regarding how the inter-generator rotor angle movements happen.

Thus, COI based rotor angle is used as the reference for all plots and for data to be processed [52], [53].

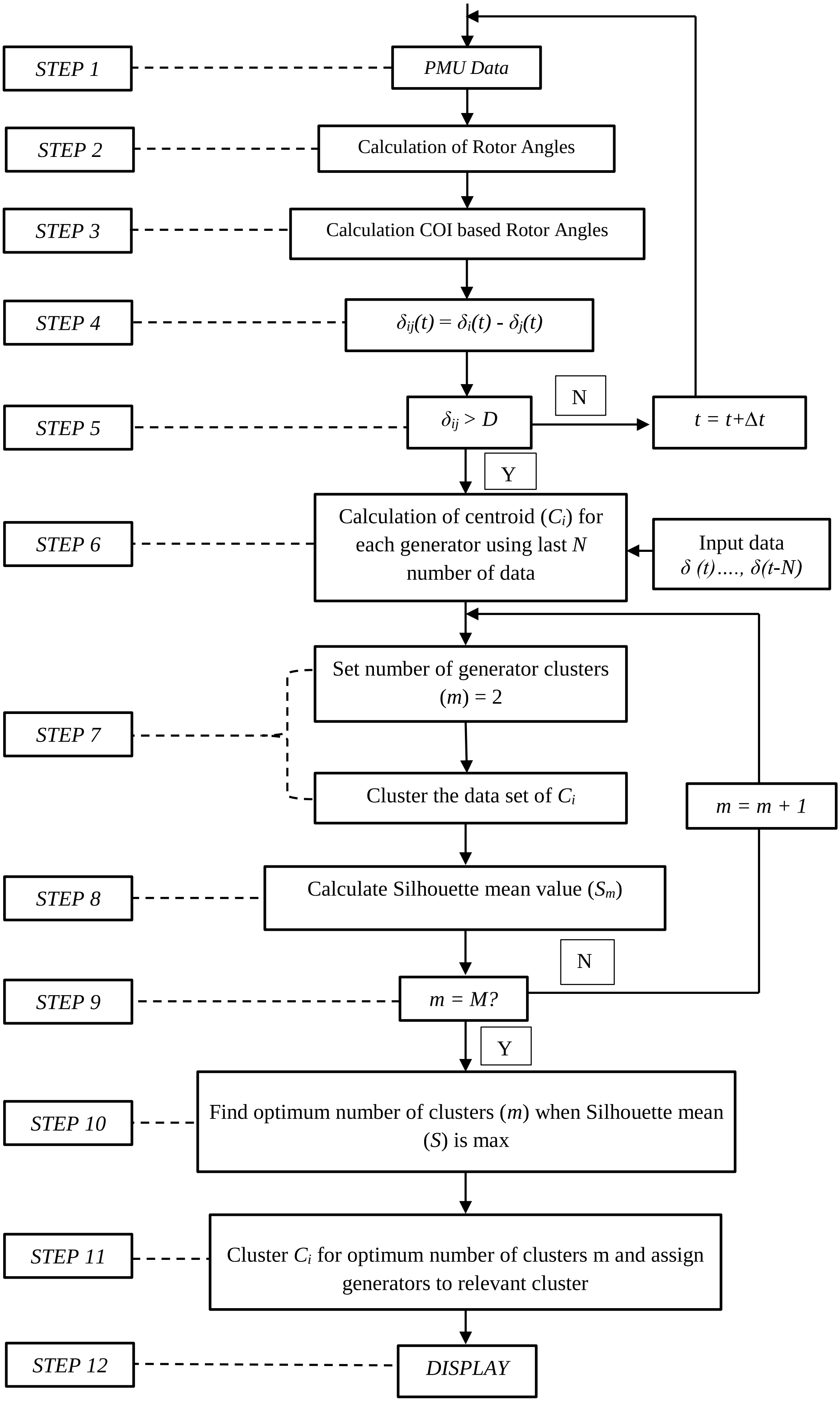
$$\delta_{COI} = \frac{\sum_{k=1}^{n} H_k \delta_k}{\sum_{k=1}^{n} H_k} \qquad (30)$$

where H_k is the inertia constant and δ_k is the rotor angle of kth machine of the system. Therefore, rotor angle of kth machine relative to COI will be

$$\delta_{relative} = \delta_k - \delta_{COI} \qquad (31)$$

3.4.2 Proposed methodology

Figure 14 – Flow of proposed methodology



Proposed methodology can be understood as per the above flow chart. Each step of the aforementioned methodology is explained in detail below:

STEP (1) PMU data

Voltage and current phasors are measured at the generator terminals.

STEP (2) Calculation of Rotor Angles

Rotor angles of each generators are calculated using voltage and current phasors measured by PMU. Calculation of rotor angles is as per the equation 23 in section 3.2.1.

STEP (3) Calculation of COI based Rotor Angles

After achieving rotor angle data of all the generators, those data are reoriented based on Centre of Inertia (COI) of the system. COI based rotor angle is calculated as per the equation 30 and COI based relative rotor angle is derived for each generator according to equation 31 in section 3.4.1.

STEP (4) Deviation of Rotor Angles

Deviation of rotor angles are calculated among all the generators.

STEP (5) OOS Detection

Rotor angle deviations from previous step is compared with the threshold value D for any violation of the condition to determine an OOS condition. If the condition is not violated, next set of data sample is assessed.

STEP (6) Centroid Calculation (C_i)

Calculation of centroids (C_i) of rotor angle data for each generator is initiated after the determination of the condition to be OOS. Latest rotor angle data at the point of OOS detection is used and the time window T is 100 ms or 5 cycles.

Purpose of finding a centroid (C_i) for each generator is to identify that centroid as a representor for corresponding generator during time window T. Centroid (C_i) calculated for each generator will carry the properties of all the rotor angle data measured within time window T.

Calculation of the centroid (C_i) is done by applying k-means clustering algorithm to each generator separately with input k (number of groups) =1. Therefore, algorithm clusters all the rotor angle data of a generator into a single group; thus, one centroid (C_i) per generator will be the output.

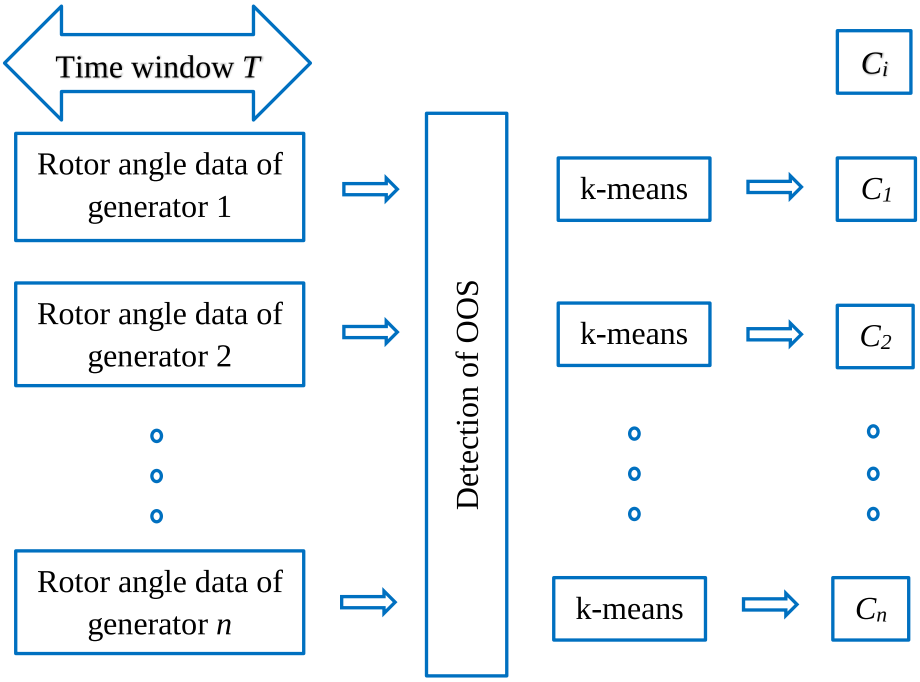


Figure 15 – Step 4 of proposed methodology explained

STEP (7) Clustering of data set C_i

Output from previous step is a $(n\times 1)$ array C containing centroids (C_i) of rotor angle data of all the generators. In this step, array C undergoes an iterative process for the generator clustering.

Initially, number of generator cluster m is set 2. Rotor angle centroids (C_i) representing each generator are clustered into groups by k-means algorithm as defined by m.

STEP (8) Application of Silhouette Criterion

Array C containing centroids (C_i) of rotor angle data of all generators are clustered into groups as defined by m, in the previous step. After the clustering, Average Silhouette value (S_m) is calculated for the given m.

Value of S_m indicates how well the generators are clustered into groups as defined by m. Closer the value of S_m to unity, better the clustering operation.

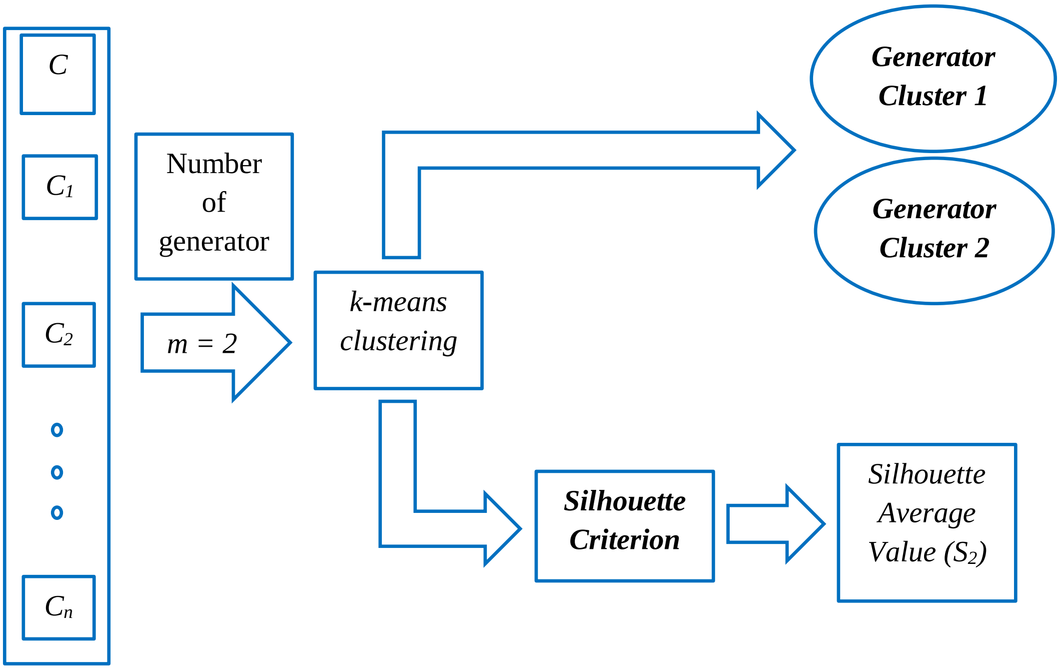


Figure 16 – Steps 5 & 6 of proposed methodology explained

STEP (9) Iterative process for generator clustering

Step 5 and Step 6 undergo an iterative process until $m = M$. Value of M is greater than 2 and should be decided based on practically possible maximum number of generator clusters within the power system. The knowledge of power system operators and the past experiences can be used to determine a practical value for M.

During this iterative process, array C containing centroids (C_i) of rotor angle data is clustered into groups ranging from 2 to M. At every iteration, Average Silhouette value (S_m) is calculated for values for m ranging from 2 to M. At the end of iterative process, a $((M\text{-}1) \times 1)$ array S containing Average Silhouette values is created.

STEP (10) Optimum number of clusters

Maximum value of Average Silhouette values (S_{max}) is obtained and corresponding value of m is selected as the optimum number of generator clusters (m_{opt}).

STEP (11) Identification of generators in clusters

Once the optimum number of generator clusters (m_{opt}) is found, clustering operation is done for m_{opt} by applying k-means algorithm and each generator is assigned to the relevant cluster as per the output of the algorithm.

STEP (12) Display results

Display the warning message "OUT OF STEP !!!" with the assignment of generators in relevant clusters.

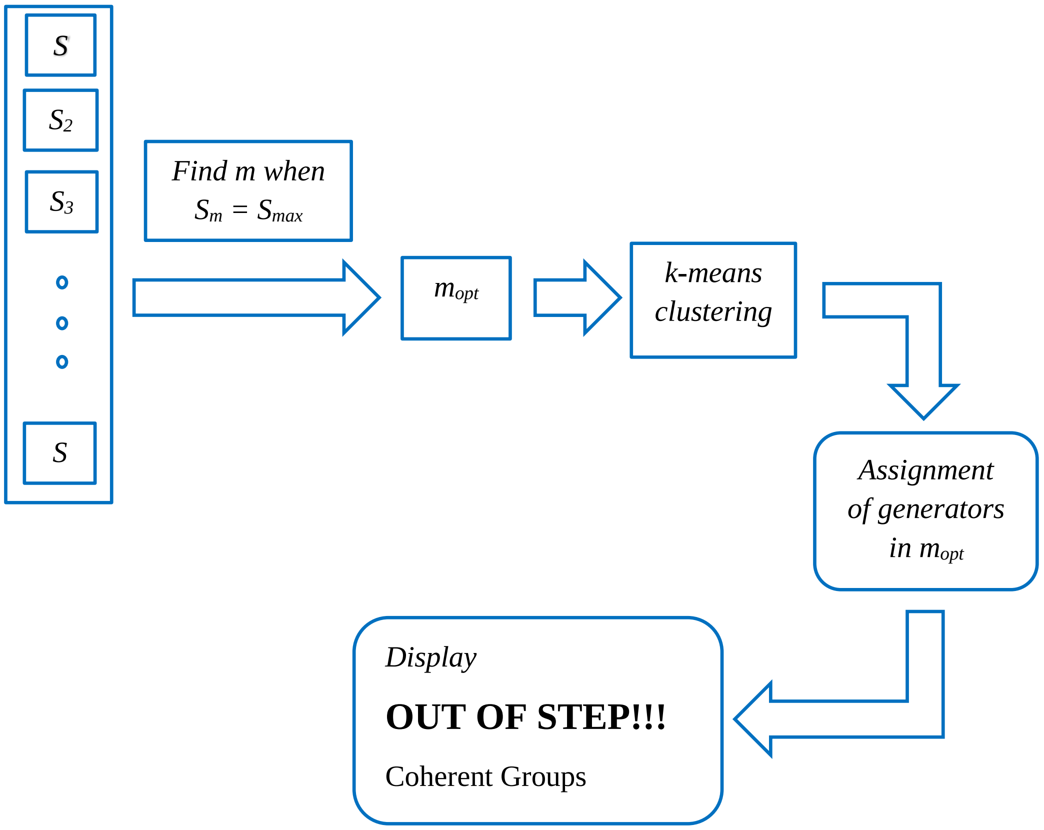


Figure 17 – Steps 7, 8, 9 & 10 of proposed methodology explained

Chapter Summary

This chapter introduced generalized methodology based on online measurements, which is to be adopted during OOS conditions in order to identify coherent groups of generators. In the next chapter, this methodology will be applied on contingencies created in a selected IEEE bench mark system and Sri Lankan power system.

4 VALIDATION OF THE PROPOSED METHODOLOGY

This chapter demonstrates the applicability of the proposed methodology in order to identify coherent generator groups. First, simulations of 2 area 4 generator system and IEEE 16 generator 68 bus system were used. 2 area 4 generator system includes 2 possible islands and 68 bus system includes 5 possible islands.

Contingencies have been applied on these benchmark systems covering possibilities of loss of a dominant generator, loss of a major load and loss of a backbone transmission line proceeded by a fault. Severities of the contingent events were decided such that the angular stability of the entire system is endangered and power system is about to be pulled apart.

Selected benchmark systems were built up and load flow simulations were done on PSS®E simulation environment. Dynamic simulations were done covering major aspects of possible contingencies after successful load flow simulations. Rotor angle plots and data recorded during these contingencies were fed into the proposed generator coherency identification scheme implemented on MATLAB. Coherent groups of generators were identified as the end result of this proposed methodology.

Results from the proposed generator coherency identification scheme on MATLAB were compared with the observations of PSS®E simulations.

4.1 2 area 4 generator system

This system comprises of two similar areas connected by a tie line from bus 7 to 9. Each area occupies 2 generators having a capacity of 700 MW nearly per each generator. A single line diagram of the test system is shown in Fig. 17.

[54], [55]. Threshold for deviation of rotor angles *D* for OOS detection was selected as 120^0. Value for *D* was decided after doing number of off-line simulations in PSS®E.

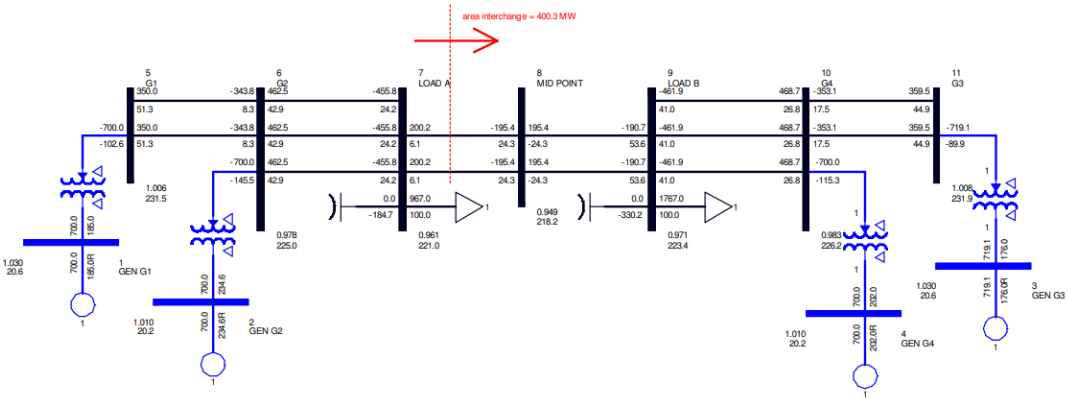
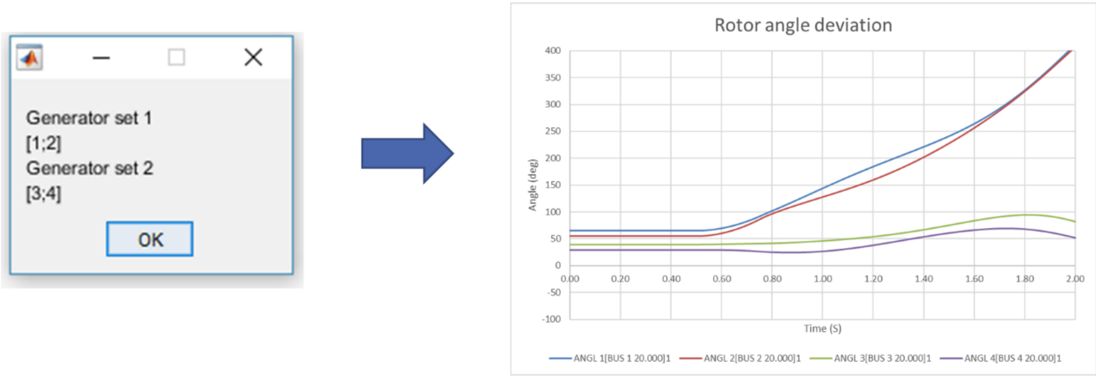


Figure 18 – 2 area 4 generator system [55]

A 3-phase fault lasting 200 ms was applied at bus 7 and the rotor angle deviation of the generators was observed after the fault as shown in Fig. 18.



(a) (b)

Figure 19 – (a) MATLAB output, (b) PSS®E rotor angle plot of 2 area 4 generator system

Plot of rotor angle deviation in above figure shows the loss of synchronism in 2 areas of the power system. Rotor angle data were fed into MATLAB for generator coherency identification and the result is shown in Fig. 18 (a). The two coherent generator groups are clearly visible in the simulations.

4.2 IEEE 16 generator 68 bus system

This benchmark system is a reduced order equivalent of the inter connected New England Test System (NETS) and New York Power System (NYPS). It has five geographic regions, in which NETS and NYPS are 2 areas and represented by several generators. Power import from other three areas are approximated by equivalent generators [56].

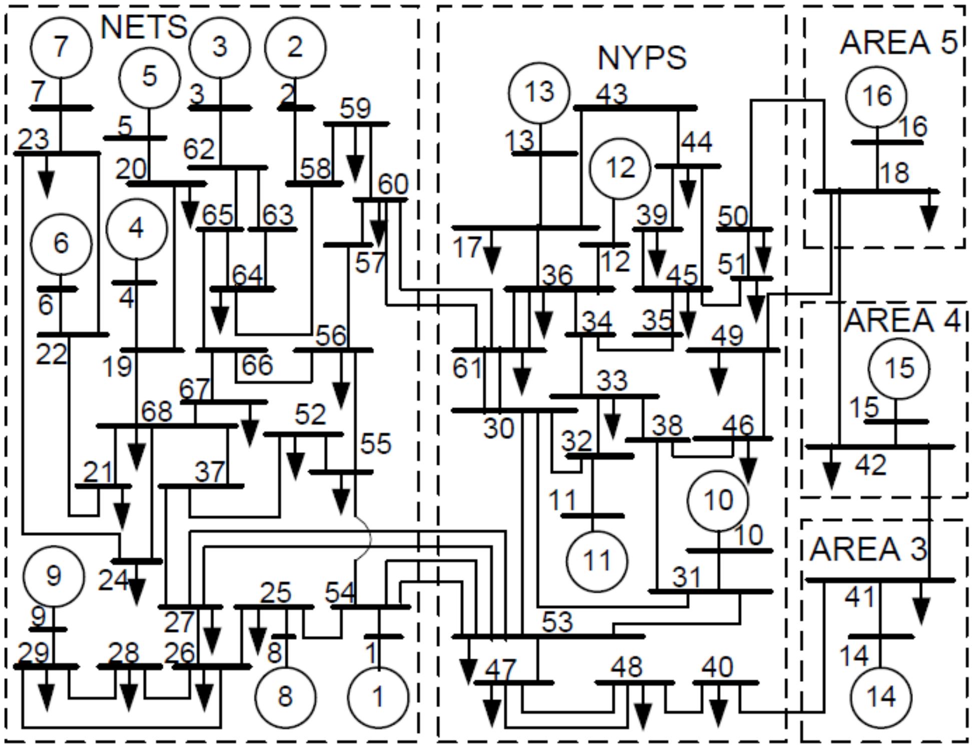


Figure 20 – 16 generator 68 bus system [56]

All the network data was extracted from Technical Report (PES-TR18) on August 2015 published by IEEE Power & Energy Society.

Power Flow data: Transmission line data is given in per unit values considering a system MVA base of 100 MVA. All the transmission lines are considered as π sections. All the transformers are rated at 900 MVA with an impedance voltage of 15% from the transformer rating. Winding resistance and the magnetizing currents are neglected. All the transmission line data, transformer data and load data are provided in ANNEXURE A [56].

Dynamics data: Generator model is considered to be round rotor unit for all the generators. GENROU generator model was used for this purpose in PSS®E. Exciters of generators from 1 to 12 were considered as DC Rotating Excitation system DC4B and that of generators from 13 to 16 as Static Excitation System ST1A in PSS®E. Governor models of the turbines were kept switched off for the simulations. All the data related to dynamic models are given in ANNEXURE B [56].

Three major tie lines can be observed between NETS and NYPS among the buses 60-61, 53-54 and 27-53, all being double circuit lines.

For the validation of the proposed methodology, 5 contingencies were simulated covering possibilities of loss of a dominant generator, loss of a major load and loss of a backbone transmission line proceeded by a fault.

Threshold for deviation of rotor angles D for OOS detection was selected as 180^0. Value for D was decided after doing number of off-line simulations in PSS®E.

4.2.1 Contingency 1 (Loss of a transmission line)

Tie line between the buses 60 & 61 was initially isolated and equilibrium was achieved in load flow studies.

A 3-phase solid fault was applied in No.1 transmission line between 53 and 54 buses. Fault lasted for 100 ms and cleared by isolating the faulty transmission line. Following figure shows the rotor angle behaviour of the generators during the incident.

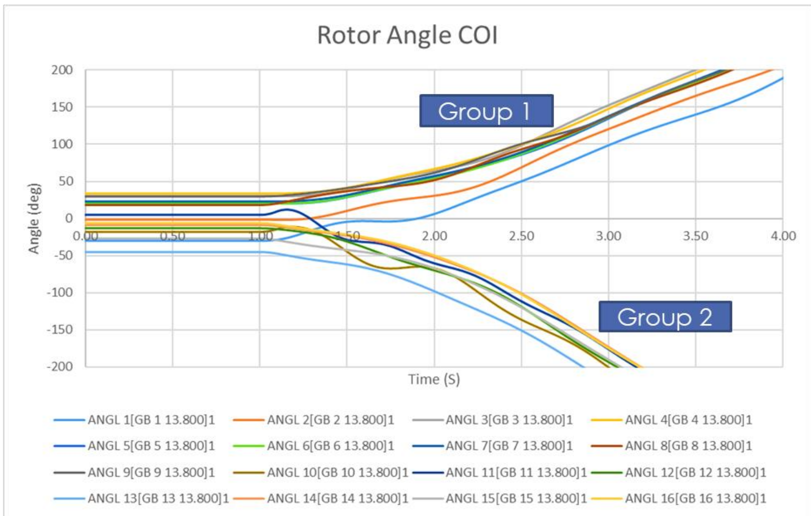
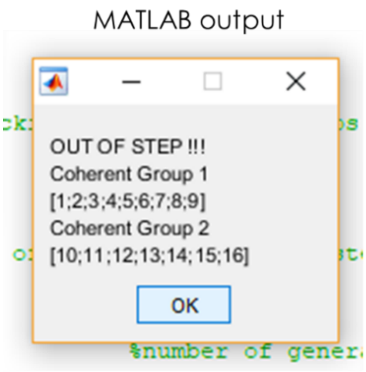


Figure 21 – PSS®E rotor angle plot of contingency 1 of 68 bus system

As per the simulation, above figure shows the separation of the total system into two sub systems. Generators 1 to 9 were oscillating against the generators 10 to 16, forming two coherent groups of generators.

Rotor angle data was fed into the proposed methodology in MATLAB for further analysis. Proposed methodology could identify the generators in relevant clusters as same as the observations in PSS®E simulations.



PSS/E simulation results

Group 1	Group 2
1[GB 1 13.800]	10[GB 10 13.800]
2[GB 2 13.800]	11[GB 11 13.800]
3[GB 3 13.800]	12[GB 12 13.800]
4[GB 4 13.800]	13[GB 13 13.800]
5[GB 5 13.800]	14[GB 14 13.800]
6[GB 6 13.800]	15[GB 15 13.800]
7[GB 7 13.800]	16[GB 16 13.800]
8[GB 8 13.800]	
9[GB 9 13.800]	

Figure 22 –MATLAB output of contingency 1 of 68 bus system

Table 2 – PSS®E simulation results of contingency 1 of 68 bus system

4.2.2 Contingency 2 (Loss of a tranmission line)

Tie line between buses 57 & 58 was initially isolated and equilibrium was achieved in load flow studies.

A 3-phase fault was applied in transmission line between 65 & 66 buses. Fault lasted for 100 ms and cleared by isolating the faulty transmission line. Following figure shows the rotor angle behaviour of the generators during the incident.

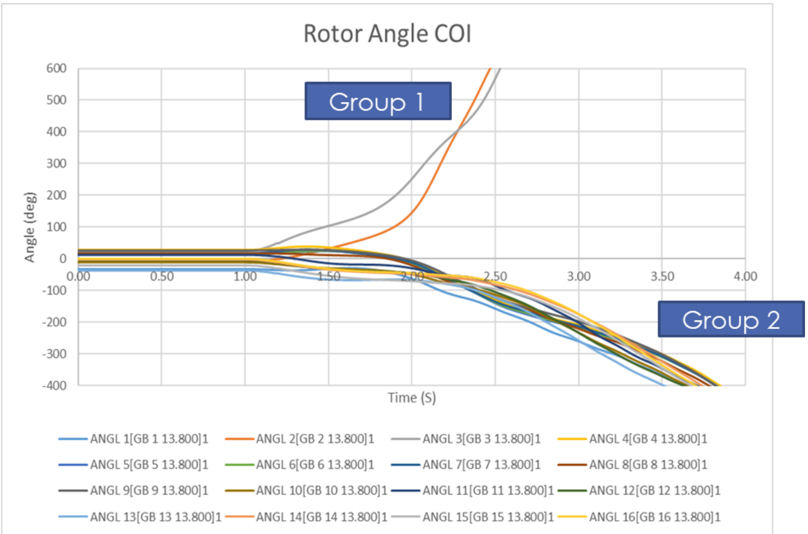
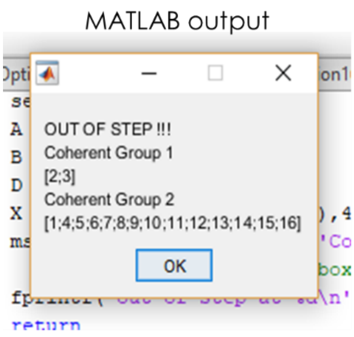


Figure 23 – PSS®E rotor angle plot of contingency 2 of 68 bus system

As per the simulation, above figure shows the separation of the total system into two sub systems. Generators 2 & 3 were oscilating against the rest of the generators in the entire system, forming two coherent groups of generators.

Rotor angle data was fed into the proposed methodology in MATLAB for further analysis. Proposed methodology could identify the generators in relevant clusters as same as the observations in PSS®E simulations.



PSS/E simulation results

Group 1	Group 2	
2[GB 2 13.800]	1[GB 1 13.800]	10[GB 10 13.800]
3[GB 3 13.800]	4[GB 4 13.800]	11[GB 11 13.800]
	5[GB 5 13.800]	12[GB 12 13.800]
	6[GB 6 13.800]	13[GB 13 13.800]
	7[GB 7 13.800]	14[GB 14 13.800]
	8[GB 8 13.800]	15[GB 15 13.800]
	9[GB 9 13.800]	16[GB 16 13.800]

Figure 24 –MATLAB output of contingency 2 of 68 bus system

Table 3 – PSS®E simulation results of contingency 2 of 68 bus system

4.2.3 Contingency 3 (Loss of a major load)

Tie line 42 – 41 & 42 – 18 were initially switched off and generator 15 was out of service due to above isolations. Equilibrium was achieved in load flow studies.

Load at bus 18 was dropped by 90% by an instant. Following figure shows the rotor angle behaviour of the generators during the incident.

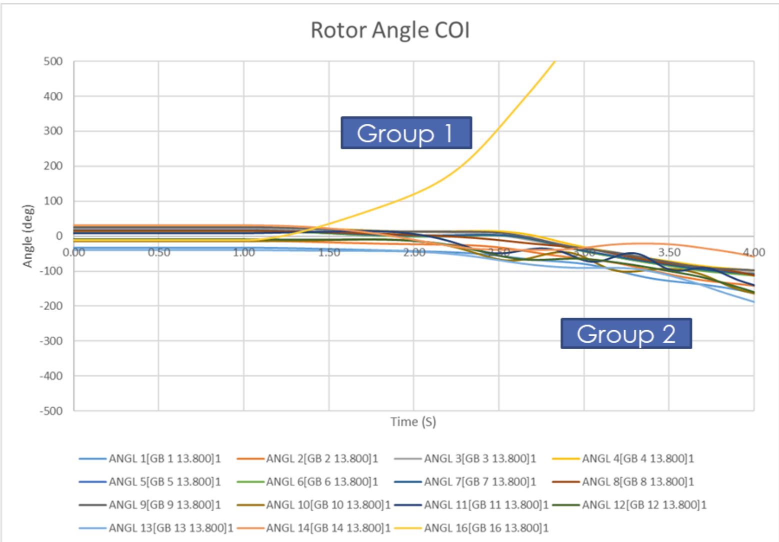
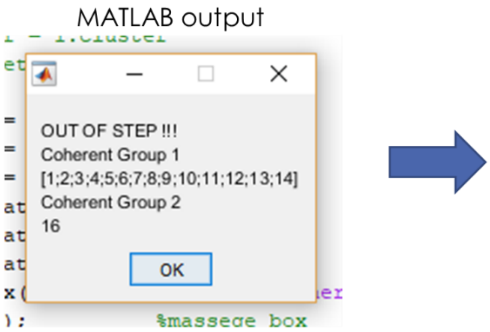


Figure 25 – PSS®E rotor angle plot of contingency 3 of 68 bus system

As per the simulation, above figure shows the separation of the total system into two sub systems. Generators 16 was oscillating against rest of the generators in the entire system, forming two coherent groups of generators.

Rotor angle data was fed into the proposed methodology in MATLAB for further analysis. Proposed methodology could identify the generators in relevant clusters as same as the observations in PSS®E simulations.



PSS/E simulation results

Group 1	Group 2	
16[GB 16 13.800]	1[GB 1 13.800]	8[GB 8 13.800]
	2[GB 2 13.800]	9[GB 9 13.800]
	3[GB 3 13.800]	10[GB 10 13.800]
	4[GB 4 13.800]	11[GB 11 13.800]
	5[GB 5 13.800]	12[GB 12 13.800]
	6[GB 6 13.800]	13[GB 13 13.800]
	7[GB 7 13.800]	14[GB 14 13.800]

Figure 26 –MATLAB output of contingency 3 of 68 bus system

Table 4 – PSS®E simulation results of contingency 3 of 68 bus system

4.2.4 Contingency 4 (Loss of a tranmission line)

Tie line between buses 60 & 61 was initially isolated and equilibrium achieved in load flow studies.

A 3-phase fault was applied in transmission line between 59 & 60 buses. Fault lasted for 200 ms and cleared by isolating the faulty transmission line. Following figure shows the rotor angle behaviour of the generators during the incident.

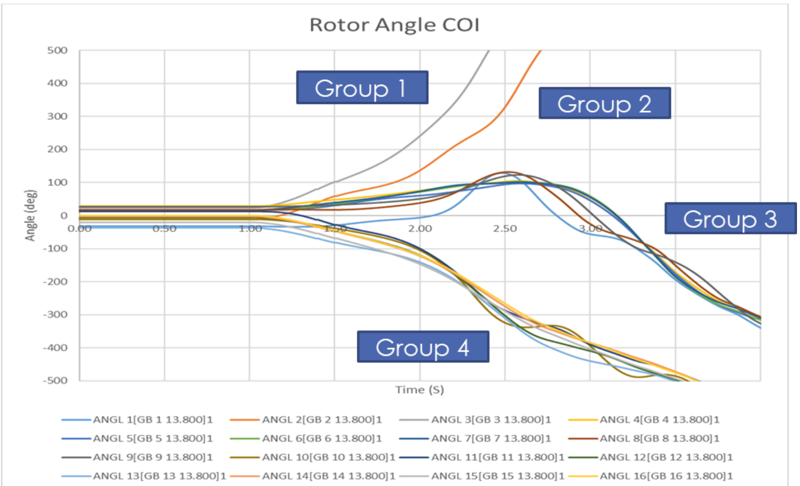
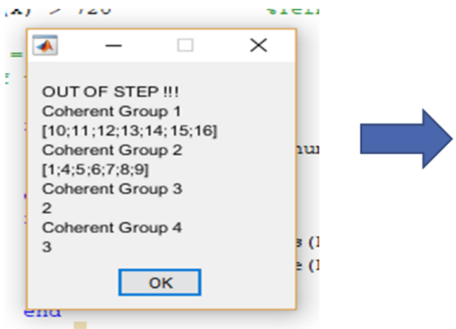


Figure 27 – PSS®E rotor angle plot of contingency 4 of 68 bus system

As per the simulation, above figure shows the separation of the total system into four sub systems. Generators 10 to 16 came under same coherent group. Generator 2 & 3 independently formed 2 separate groups, while rest of the generators formed a single group. Therefore, four coherent groups could be identified among the generators.

Rotor angle data was fed into the proposed methodology in MATLAB for further analysis. Proposed methodology could identify the generators in relevant clusters as same as the observations in PSS®E simulations.



PSS/E simulation results

Group 1	Group 2	Group 3	Group 4
10[GB 10 13.800]	1[GB 1 13.800]	2[GB 2 13.800]	3[GB 3 13.800]
11[GB 11 13.800]	4[GB 4 13.800]		
12[GB 12 13.800]	5[GB 5 13.800]		
13[GB 13 13.800]	6[GB 6 13.800]		
14[GB 14 13.800]	7[GB 7 13.800]		
15[GB 15 13.800]	8[GB 8 13.800]		
16[GB 16 13.800]	9[GB 9 13.800]		

Figure 28 –MATLAB output of contingency 4 of 68 bus system

Table 5 – PSS®E simulation results of contingency 4 of 68 bus system

4.2.5 Contingency 5 (Loss of a generator)

Tie line 40 – 41 & 60 – 61 were initially switched off and equilibrium achieved in load flow studies.

A 3-phase fault was applied in generator bus 1. Fault lasted for 200 ms and generator 1 was tripped together with the isolation of generator bus 1. Following figure shows the rotor angle behaviour of the generators during the incident.

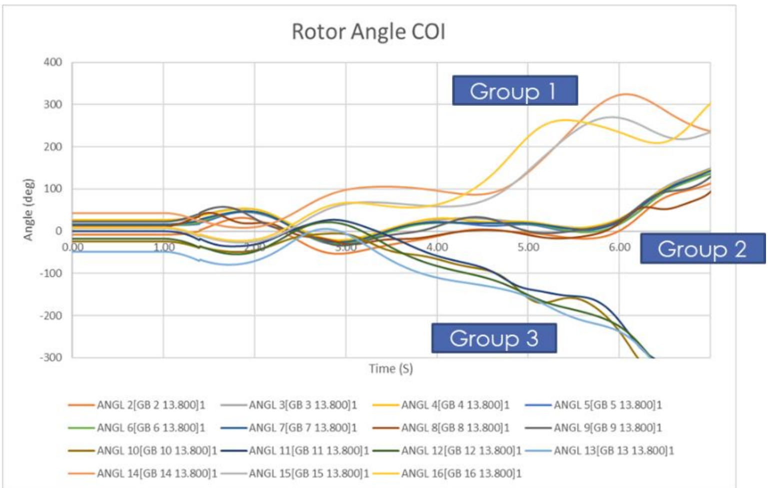
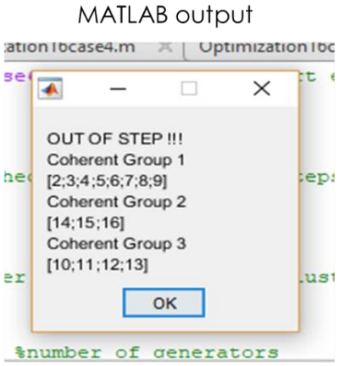


Figure 29 – PSS®E rotor angle plot of contingency 5 of 68 bus system

As per the simulation, above figure shows the separation of the total system into three sub systems. Generators 2 to 9 were found under single coherent group. Generators 10 to 13 formed another group, while rest of the generators formed another one.

Rotor angle data was fed into the proposed methodology in MATLAB for further analysis. Proposed methodology could identify the generators in relevant clusters as same as the observations in PSS®E simulations.



PSS/E simulation results

Group 1	Group 2	Group 3
2[GB 2 13.800]	10[GB 10 13.800]	14[GB 14 13.800]
3[GB 3 13.800]	11[GB 11 13.800]	15[GB 15 13.800]
4[GB 4 13.800]	12[GB 12 13.800]	16[GB 16 13.800]
5[GB 5 13.800]	13[GB 13 13.800]	
6[GB 6 13.800]		
7[GB 7 13.800]		
8[GB 8 13.800]		
9[GB 9 13.800]		

Figure 30 –MATLAB output of contingency 5 of 68 bus system

Table 6 – PSS®E simulation results of contingency 5 of 68 bus system

Chapter Summary

This chapter brings out the comparison of the results of the proposed methodology with the observations of contingencies simulated on benchmark power systems using PSS®E software. Aim of this chapter was to highlight the robustness the proposed methodology for generator coherency identification. Next chapter will focus on the case study on Sri Lankan power system and the analysis on results obtained.

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5 CASE STUDY ON SRI LANKAN POWER SYSTEM

This chapter defines the case study on possible OOS conditions on Sri Lankan Power System and involvement of suggested methodology in generator coherency identification.

Early events of the blackout on 25^{th} February 2016 in Sri Lankan power system were selected for the case study. Rotor angle data of conventional generators connected 220 kV and 132 kV networks were considered for the proposed methodology.

Initially, Sri Lankan Power System model was validated in PSS®E referring to selected events during last few years. Actual data recorded were compared with that of the simulation outputs. After achieving sufficient validity of the model, 25^{th} February 2016 was simulated for the generator coherency identification.

PSS®E software was used for load flow and dynamic simulations of the power system. Year 2016 & 2018 Sri Lankan Transmission Network were used for validation and simulations.

It is important to have accurate data in order get truthful results from the simulations. Network data was extracted from CEB Transmission Planning Division and from Original Equipment Manufacturer (OEM) documents. Case data was found from CEB System Control Centre (SCC). Event Reports, Digital Fault Recorder (DFR) records, Relay records and Power Plant Control Room records were used to find necessary event data for a particular contingency.

5.1 Preparation of Sri Lankan Power System model

Preparation of the model up the point of simulation of an event is a rigorous activity requiring vast amount of data related to network components, steady state, system dynamics and event data. Figure shows a flowchart which describes the process of preparation of the simulation model of Sri Lankan Power System.

a) Basic Network Model

Basic network model is built using generator, transformer and transmission line data. Impedance of above major components, transformer winding data, vector groups and generator capabilities should be specified for the initial simulation model.

Most of the data required for the initial model was found from CEB Transmission Planning Division and OEM documents.

b) Steady State Case

Steady state case is specific to a particular event. Thus, it is required to find the operating data of healthy power system prior to the contingency. Generator dispatch, load distribution and voltage profile over the system is essential for the steady state case to be built. Further, it is required to know the network components which are operational by the time of interest. Both active and reactive power should be considered in terms of generation and consumption. Also, swing bus should be identified and implement in the simulation model. Once the simulation is done for steady state case, comparison should be carried out with the measured data, before proceeding to system dynamics. Model should be re-defined if any unacceptable deviation.

Generation dispatch and voltage profile were found from CEB SCC. Power consumption data recorded at every Grid Sub Station (GSS) every half an hour was used for the necessary load distribution.

c) Combined model with system dynamics

After achieving sufficient amount of accuracy, steady state case can be incorporated with dynamics data. Dynamics of generator, exciter & governor should be accurately addressed for dynamic simulation and load shedding schemes should considered in order to get the actual response through the simulation.

Dynamics data was found from CEB Transmission Planning Division, CEB SCC and OEM documents.

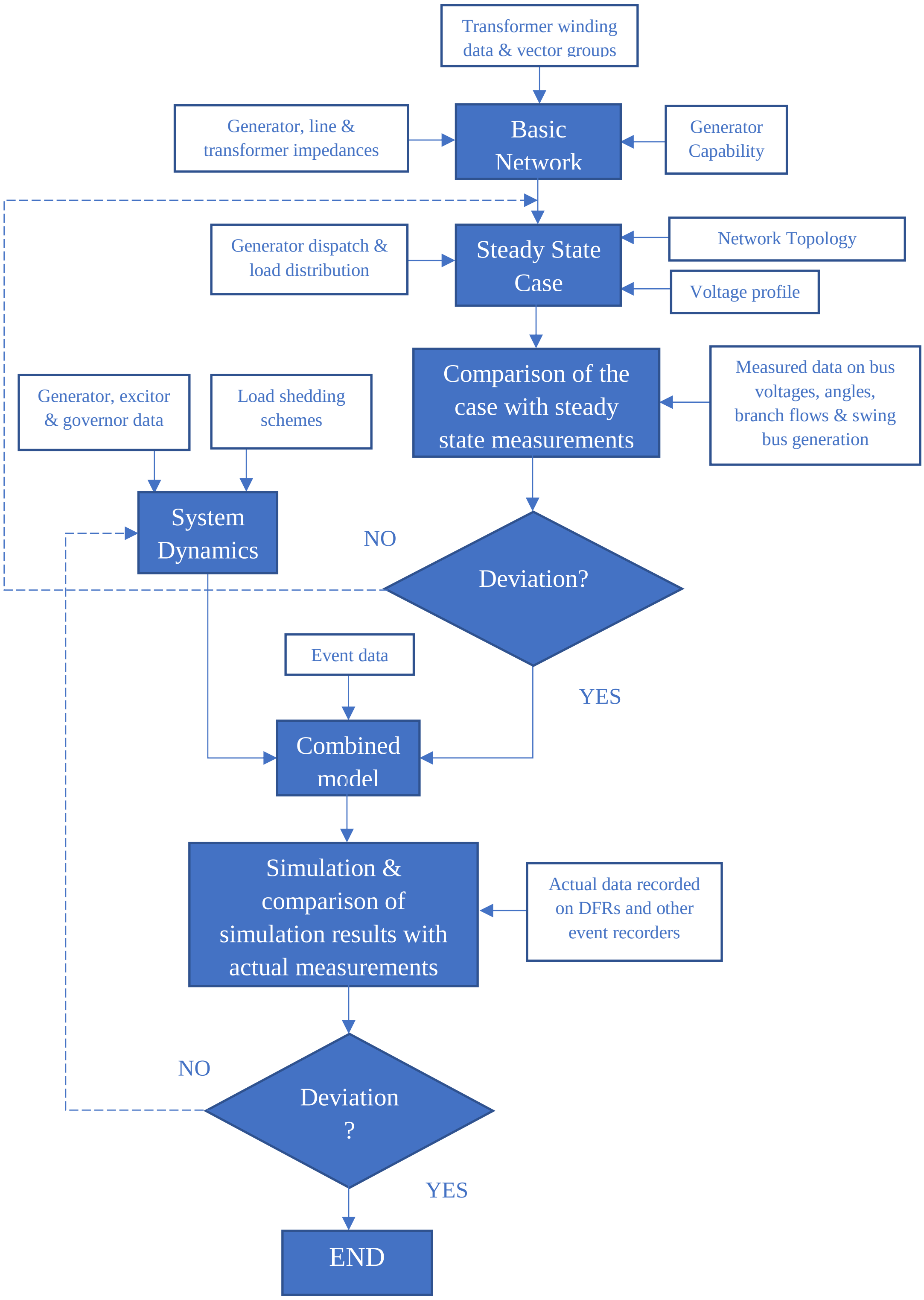
Generator, Exciter and Governor dynamic model assignment of each generator is given by ANNEXURE C. Under Frequency Load Shedding (UFLS) is applied for dynamic simulation referring to the UFLS scheme implemented in the actual Sri Lankan power system. Underfrequency Load Shedding Model (LDSHBL) which facilitates shedding of load at 3 stages of frequency and Rate of Frequency Load Shedding Model (DLSHBL) which enables shedding of load depending on the rate of frequency drop are adopted in dynamic simulations. Further, Under/Over Frequency Generator Trip Relay model (FRQTPA) is also adopted in dynamic simulation model in order to facilitate generator rejection during abnormal frequency conditions, referring to actual protection settings of the generators.

d) Simulation for system dynamics

Once the combined model of the power system is obtained, dynamics simulation is done for a particular event. Exact time, duration, location and the severity should be accounted for the event data to be simulated in the time domain. Responses of the simulation should be compared with actual measured data. System frequency is an ideal observation for validation of the power system model dynamics. In case of any unacceptable deviation from the actual responses, either steady state case or dynamics data should be re-addressed.

Event data was gathered from investigation reports related to the events, CEB SCC, DFR records and relay records. Actual data for the comparison was gained from DFR records and frequency plots recorded at GSSs and generating stations.

Figure 31 –Process of preparation of the PSS®E simulation model of Sri Lankan Power System



5.2 Validation of Sri Lankan Power System model

For the validation of power system model, process described in the previous sub topic was followed. Fast Cut Back (FCB) event of Unit 02 in Lak Vijaya Power Plant (LVPP) occurred on 16th September 2018 was simulated for the purpose of validation.

- **Pre-fault condition of the system**
  - ✓ Total demand – 1800 MW approximately
  - ✓ Frequency control by Victoria Unit 02

- **Event data**
  - ✓ Earth fault and isolation of Colombo Sub E 132 kV bus @ 09:52:29 h
  - ✓ Lak Vijaya Unit 02 FCB @ 09:52:33 h

Actual frequency variation recorded at Lakvijaya Unit 3 was compared with that of the simulation

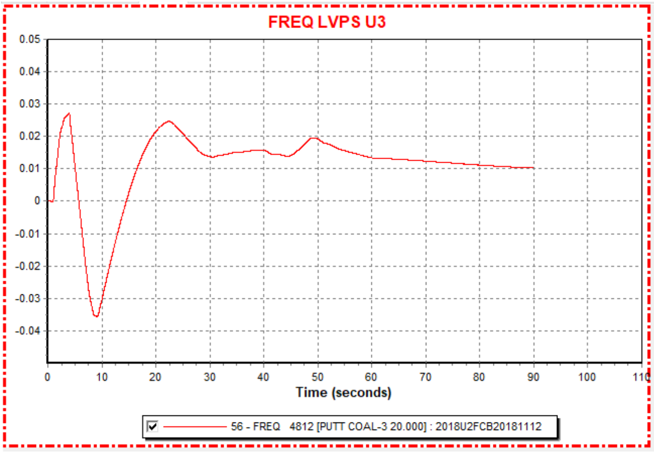


Figure 32 – Frequency response of PSS®E at LVPP unit 3

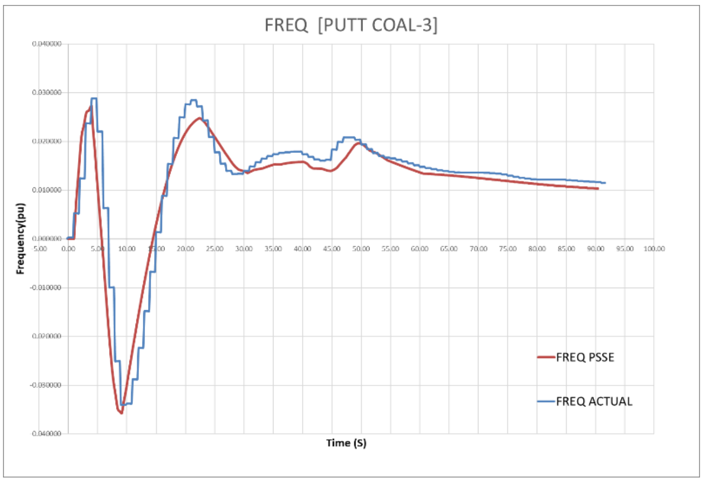


Figure 33 – Comparison of actual frequency vs PSS®E response at LVPP unit 3

As per the observations, frequency response of PSS®E simulation followed the same behaviour that of the actual response without any major deviation. This implies that the PSS®E Sri Lankan Power System model used for the simulation responds similar to the actual power system.

5.3 Case Study: Blackout in February 2016 in Sri Lankan power system

5.3.1 Background of the event

Immediately before the fault, the power system had been in an electrically stable condition and that is at 13:52 h on 25th February 2016. Weather conditions were rainy, windy with thundering during this time. Kolonnawa – Athurugiriya 132 kV double circuit line had been released for maintenance by this time, which was a violation of (n-1) reliability criterion. Except that, system operations were in accordance with CEB Policy on Power System Operations and Planning Standards [15].

Initial Event: Initiation of the fault was triggering of earth fault on R phase of Seethawaka – Kolonnawa 132 kV line due to a lightning stroke. Protection relays at both ends of the above line had correctly identified the fault and had tripped the line. High speed auto reclosing had correctly operated, but the line had been tripped permanently for the second time from both ends as the fault had not been self-cleared by the time. Soon after, Kosgama – Polpitiya 132 kV line had tripped from the Kosgama end due to a mal-operation of distance relay.

Cascading Failure: Stability of the power system has been endangered due to the disconnection of 132 kV link between Kolonnawa and Polpitiya. Result was some minor power swings in certain parts of the power system yet, the self-recovered. After certain time, Rantambe 220/132 kV inter transformer had tripped on over current for being an alternative route for the disconnected 132 kV link which was mentioned above. This had made the initiation of large power swings between 220 kV and 132 kV networks, mostly dominated LVPP machines as their electrical output being lowered. Results was the isolation of Ukuwela – Naula and Ukuwela – Habarana 132 kV lines due to excessive power swings as distance relays had seen them as zone 1 disturbances. End result was the separation of the system into two islands which were electrically unstable.

- **Pre-fault condition of the system**
    - ✓ Total demand – 1818 MW
    - ✓ Kolonnawa – Athurugiriya 132 kV double circuit line was out of service
    - ✓ Frequency controlling by Victoria unit 2

- **Event data**

  Series of events occurred during the initial stages of the blackout. Following data brings out the events with the time of occurrence.

No	Event/Tripping	Action	Time (h)
1	R phase LG fault Kolonnawa - Seethawaka 132 kV line at Kolonnawa end	-	13.52.08.512
2	Kolonnawa – Seethawaka CB	Zone 1 trip	13.52.08.537
3	Seethawaka – Kolonnawa CB	Zone 2 trip	13.52.08.617
4	Seethawaka – Kolonnawa CB	Auto Reclose	13.52.08.997
5	Seethawaka – Kolonnawa CB	Definite trip	13.52.09.563
6	Kosgama – Polpitiya CB	Zone 2 trip (mal-operation)	13.52.09.565
7	Rantambe transformer	Overcurrent trip	13.52.14.247
8	New Anuradhapura – Old Anuradhapura line II	Overcurrent trip	13.52.14.708
9	Ukuwela – Habarana & Ukuwela – Naula 132 kV lines	Zone 1 trip (Power Swing)	13.52.15.165
10	Polpitiya generator 1	under-frequency trip	13.52.17.823

Table 7 – Sequence of events during 25th February 2016 blackout [15]

Actual frequency recorded at Colombo substation C 132 kV bus during the event was compared with that of the simulation recording for further validation of the network model.

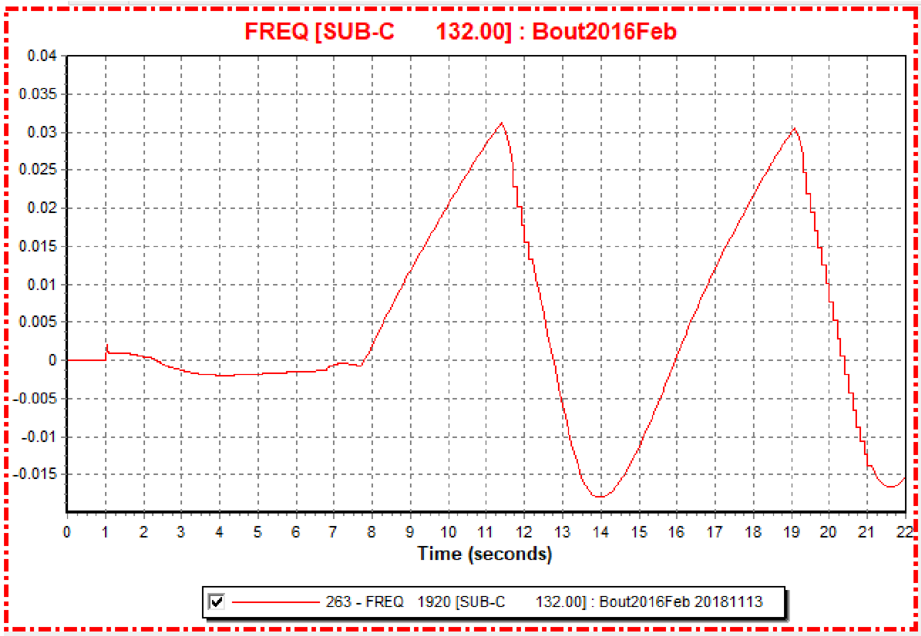


Figure 34 –Frequency response of PSS®E at Colombo Substation C 132 kV

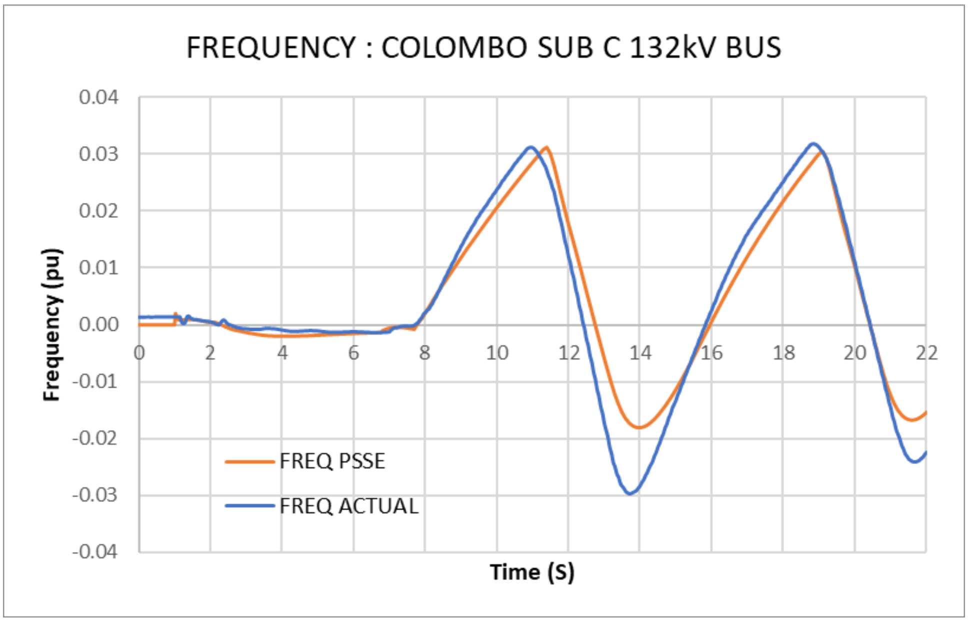


Figure 35 – Comparison of actual frequency vs PSS®E response at Colombo Substation C 132 kV

As per the above observation, it can be concluded that response of PSS®E simulations resembles that of the actual system.

5.3.2 Application of the proposed methodology

Rotor angle data of all the generators connected to 220 kV and 132 kV networks were recorded. Trajectories of generator rotor angles were as per the following figure. Threshold for deviation of rotor angles *D* for OOS detection was selected as 150^0. Value for *D* was decided after doing number of off-line simulations in PSS®E.

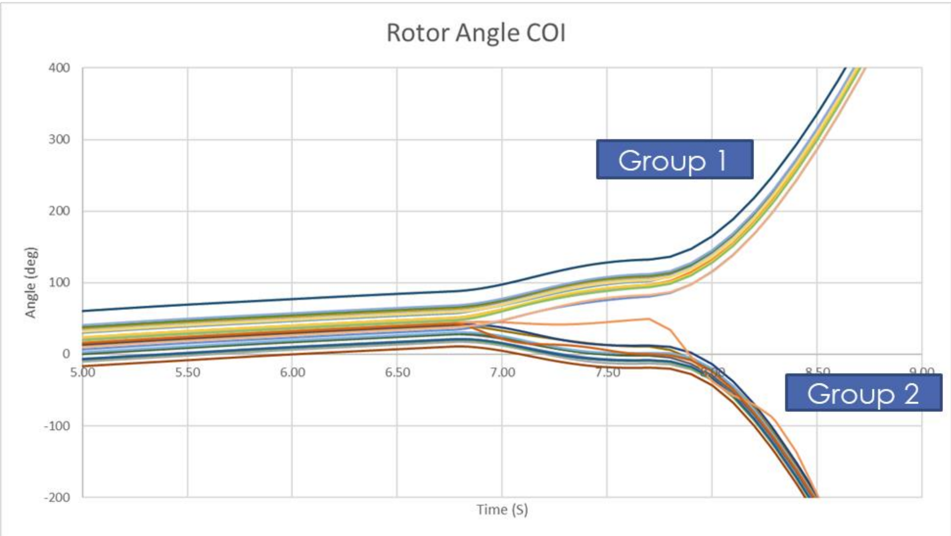


Figure 36 – PSS®E rotor angle plot of Sri Lankan Power System on February 2016 blackout

As per the simulation, above figure shows the separation of the total system into two sub systems. Seemingly, generators connected to 220 kV network had advanced relative to the generators connected to 132 kV network.

Rotor angle data was fed into the proposed methodology in MATLAB for further analysis. Proposed methodology could identify the generators in relevant clusters as same as the observations in PSS®E simulations.

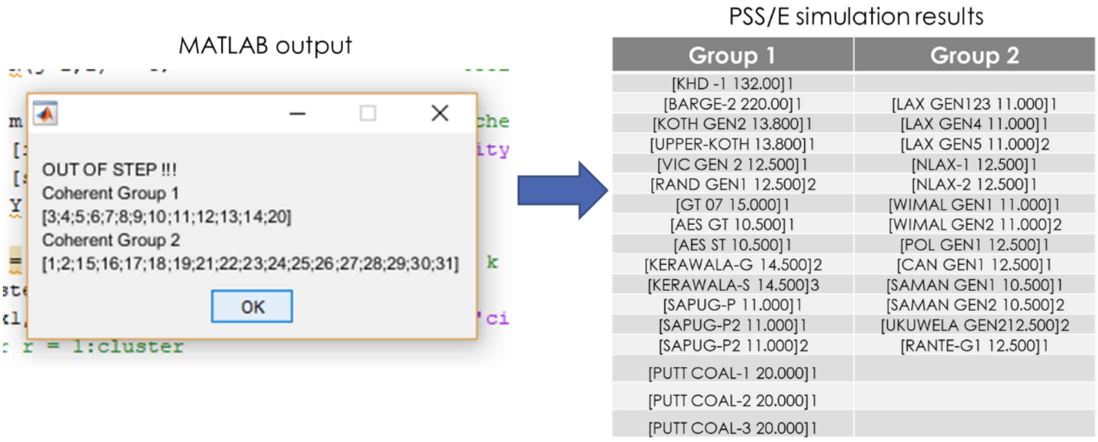


Figure 37 –MATLAB output of Sri Lankan power system on February 2016 blackout

Table 8 – PSS®E simulation results of Sri Lankan power system on February 2016 blackout

MATLAB ID	PSSE Name	Plant
1	[KHD -1 132.00]1	Asia Power
2	[BARGE-2 220.00]1	Colombo Barge
3	[LAX GEN123 11.000]1	Old Laxapana 1, 2 & 3
4	[LAX GEN4 11.000]1	Old Laxapana 4
5	[LAX GEN5 11.000]2	Old Laxapana 5
6	[NLAX-1 12.500]1	New Laxapana 1
7	[NLAX-2 12.500]1	New Laxapana 2
8	[WIMAL GEN1 11.000]1	Wimalasurendra 1
9	[WIMAL GEN2 11.000]2	Wimalasurendra 2
10	[POL GEN1 12.500]1	Polgolla 1
11	[CAN GEN1 12.500]1	Canyon 1
12	[SAMAN GEN1 10.500]1	Samanalawewa 1
13	[SAMAN GEN2 10.500]2	Samanalawewa 2
14	[UKUWELA GEN212.500]2	Ukuwela 2
15	[KOTH GEN2 13.800]1	Kothmale 2
16	[UPPER-KOTH 13.800]1	Upper Kothmale 1
17	[VIC GEN 2 12.500]1	Victoria 2
18	[VIC GEN 3 12.500]1	Victoria 3

MATLAB ID	PSSE Name	Plant
19	[RAND GEN1 12.500]2	Randenigala 2
20	[RANTE-G1 12.500]1	Rantambe 1
21	[GT 07 15.000]1	KPS GT 07
22	[AES GT 10.500]1	AES GT
23	[AES ST 10.500]1	AES ST
24	[KERAWALA-G 14.500]2	Kerawalapitiya GT
25	[KERAWALA-S 14.500]3	Kerawalapitiya ST
26	[SAPUG-P 11.000]1	Sapugaskanda Old Phase
27	[SAPUG-P2 11.000]1	Sapugaskanda New Phase 1
28	[SAPUG-P2 11.000]2	Sapugaskanda New Phase 2
29	[PUTT COAL-1 20.000]1	Lakvijaya Unit 1
30	[PUTT COAL-2 20.000]1	Lakvijaya Unit 2
31	[PUTT COAL-3 20.000]1	Lakvijaya Unit 3

Table 9 – MATLAB IDs of generators in Sri Lankan Power System

Following figure shows the geographic positioning of the Sri Lankan transmission network with generating stations. Generator connected to 220 kV network and in close electrical vicinity, which are circled in red came under a one coherent group. Most of the generator connected to 132 kV network, which are circled in blue formed another coherent group.

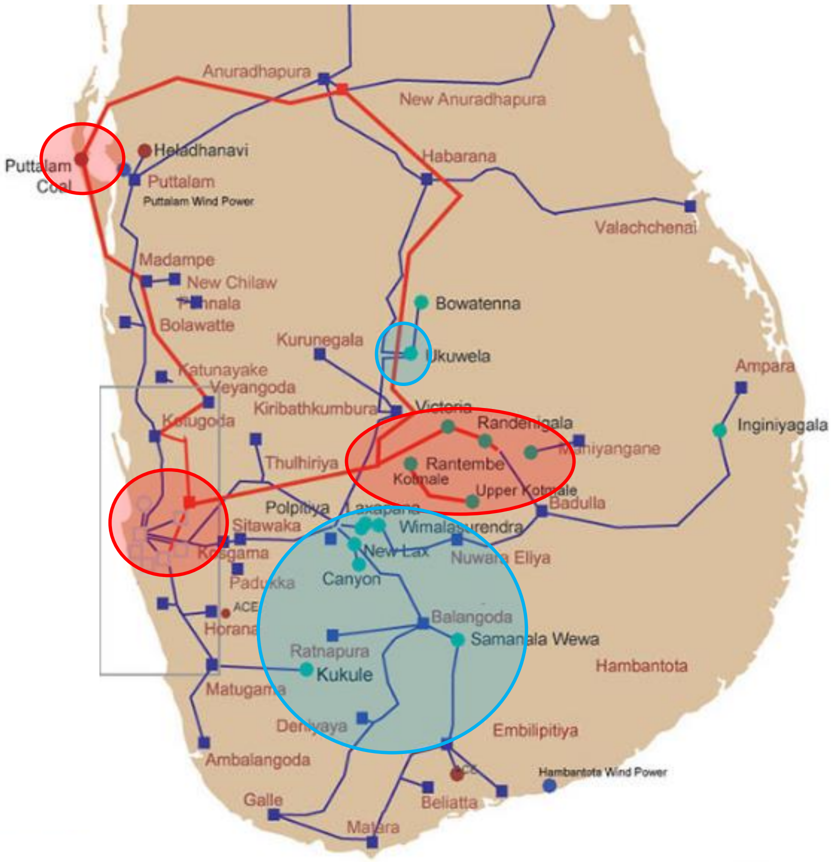


Figure 38 – Geographic locations of coherent generator groups in Sri Lankan power system [57]

Power Swings & Islanding: Power swings arise due to advancement of one set of machines relative to another in the same system. Propagation of a power swing may lead to loss of synchronism or OOS condition. In such cases, the affected areas must be separated in a controlled manner to avoid damages to personnel, equipment and to maintain the continuity of the supply. As per the above case, it is quite evident that the separation of the network is imminent. In such cases, asynchronously operating areas must be separated to ensure the safety of the personnel and equipment and it should be done in a controlled manner to maintain the continuity of the supply.

Chapter Summary

This chapter includes the case study on Sri Lankan Power System referring to a recent blackout incident. The proposed methodology has been applied on the generator rotor angle data of this incident to identify coherent groups of generators during the incident. Further, the model of Sri Lankan Power System has been validated by comparing with the actual responses related recent disturbances of the system. Next chapter will bring out the conclusions, future direction and the practical aspects of the thesis study.

6 CONCLUSIONS AND FUTURE DIRECTIONS

6.1 Conclusions

In the event of power swings, voltages and currents undergo an oscillatory behaviour and once these power swings grow beyond capability of self-dampening of the power system, an OOS condition where the separation of the power system is unavoidable. Even the most reliable system should be prepared to deal with OOS as achieving 100% reliability is practically impossible. Therefore, asynchronously operating areas should be separated in a controlled manner to achieve the above. Generators, which swings together showing similar rotor dynamics during a power swing conditions tend to form separate sub systems within the main power system. Thus, it is important to identify coherency of the generators to facilitate controlled islanding, if the separation of the power system is imminent. Studying the behaviour of the rotor angle during an OOS condition is a fine direction towards generator coherency identification as the power swings are translations of the oscillations of rotor angles of the generators. However, as each OOS situation have their unique identities and the coherency of the generators follow the same. This fact should be accounted when deciding on a methodology to identify generator coherency. Online approach based on real time data is an ideal solution to eliminate the difficulties brought by the uniqueness of OOS conditions. Typically, WAMS based OOS protection and generator coherency identification provide a greater observability over the power system and the situational awareness for contingency. This thesis brought out a generalized methodology of online approach for generator coherency identification using real time data. Further, the proposed methodology has been applied on a recent blackout event in Sri Lankan Power System to identify coherent groups of generators.

Propose methodology for generator coherency identification is empowered by a data clustering algorithm; k-means clustering, which is simple, efficient and guaranteed to converge into a realistic solution. If the deviation of rotor angles of any two generators exceeds the given threshold at a time, OOS condition is declared. Clustering operation of rotor angle data starts at the point of detection of OOS. For the clustering operation, latest N data samples within time window T is used at the point of OOS detection. Silhouette criterion is applied on top of k-means clustering in order to achieve the optimum number of generator clusters. Output of the proposed methodology is the identification optimum number of generator clusters with assignment of generators in the groups based on the coherency related to rotor angle dynamics. Proposed methodology was established on MATLAB.

Proposed methodology was tested on benchmark power systems; 2 area 4 generator system and IEEE 16 generator 68 bus system. Different types of contingencies were applied on these benchmark power systems in PSS®E simulation environment and the observations of the simulations were compared with results of the proposed methodology. Robustness and the convergence of the results of the proposed methodology were confirmed.

The case study on Sri Lankan Power System was oriented a blackout event in February 2016. The PSS®E network model was validated referring to recent contingencies of the power system. Proposed methodology was applied on rotor angle data from the simulations and 2 groups of coherent generators were identified. As per the observations, generators of the 220 kV network had advanced relative to the generators of 132 kV network.

As per the above results of the case study, geographic positioning of the generators is immaterial when it comes to the process of controlled islanding. For generators to be under the same coherent group, electrical distance between the generators plays a vital role than the geographic remoteness.

6.2 Future Directions

6.2.1 Practical Implementation

Wide Area Measurement System (WAMS)

WAMS is established on a reliable communication network connecting power stations, grid substations and system control centres and it acquires data from data resources and forward them to the control centres via communication link for further processing in real time. Decisions are made on power system operations based on collected data with immediate effect. If necessary, WAMS may command the remote actuators of the power system to perform the required action based on the information gathered. Task oriented applications and algorithm at control centres help to take decisions as per the necessity.

WAMS occupies a multi-layered architecture, in which the bottom layer consists Phaser Measurement Units (PMUs). PMUs provide voltage and current phasors in a common time reference relying on GPS [58]. The next layer is made up of Local Protection Centres (LPCs). Main task of the LPC is to align the time stamps from PMUs to provide a coherent data stream. Further, localized control and monitoring function can be integrated at this level. System Protection Centre is the top layer which acts as overall coordinator of LPCs and PMUs. Centralized decisions are made and control actions are sent to relevant parts of the power system [2], [25]. Communication link is the backbone of WAMS and it is responsible for the delivery of data from PMUs to control centres. Reliability and quickness are essential in communication of data [24].

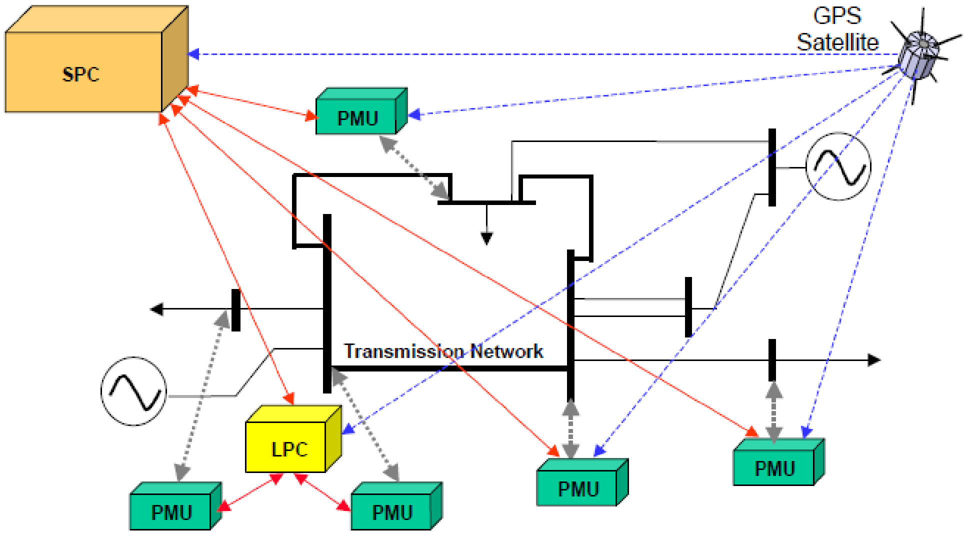


Figure 39 –Typical WAMS architecture [2]

Opportunities to implement WAMS in Sri Lankan Power System

- **Optical Ground Wire (OPGW) for communication**

When it comes to the phase of implementation, communication network is the most important layer and the backbone of the WAMS. Optical fibre is fast reliable form of data transmission due to the immunity to power line and lightning induction, external electrical noise and cross-talk.

In Sri Lankan Power System, most of the overhead transmission lines are provided shielding with OPGW which occupies fibre optics. With the availability of OPGW, supervisory control has become a reality in the recent past and the voice and data communication has become much reliable. Further, for the protection applications, only line differential protection is utilized using fibre optics.

Most of the OPGWs used in the transmission network occupy 24 fibres and those fibres are not fully utilized even with the above-mentioned applications. Currently used OPGW has the capacity for more applications related to data transmission. Therefore, OPGW can be used as the communication link between PMUs and SPC in WAMS enabling dynamic monitoring, protection & control.

- **Phasor Measurement Units (PMUs)**

Currently, PMUs are deployed Kothmale and Biyagama substations which can be incorporated in the bottom line of the WAMS. Yet, more PMUs should be deployed covering critical generating stations, GSSs in order to collect vital information for dynamic monitoring of the system.

Further, modern relays come with integrated PMUs which can be utilized for phasor measurements. Old relays can be replaced with these novel relays, such that dynamic data measurement function is achieved together with the protection features.

- **Supervisory Control and Data Acquisition (SCADA)**

SCC used to have only the monitoring facility and it is equipped with supervisory control since 2018. SCADA system has become a reality due to the establishment of fibre network. With the implementation of SCADA system, system operators can monitor the steady state condition of the power system and can remotely operate beakers and isolators. As per the development of the infrastructure, this can be turned into a SPC with the deployment of sufficient number of PMUs at selected locations and proper utilization of OPGWs.

With the evolvement of WAMS, online generator coherency identification schemes have become much more promising. Data measured by PMUs can be time stamped with the aid of GPS, which eliminates the barrier of measured data not being in a common time frame due to diversity of geographic location. With the availability of fast and reliable networking technologies and dedicated computers, measured data can be quickly processed at the remedial actions can be taken in time.

6.2.2 Studies on OOS in Sri Lankan Power System

The thesis was only focussed on identifying the generator coherency of Sri Lankan Power System which is subjected to OOS condition. Identifying the generators showing similarities in rotor dynamics will come in handy when deciding on controlled islanding on the system. More studies are needed to be carried out on Sri Lankan Power System for successful implementation of OOS protection scheme. Following are the key areas to be covered when doing further studies.

- Power swing detection
- OOS detection
- Network separation or controlled islanding
- Post stability control in islands

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ANNEXURE A – Power Flow Data of 68 bus system

Transmission line data on 100MVA base

From Bus Number	To Bus Number	Id	Resistance (pu)	Reactance (pu)	Total charging (pu)
7	23	1	0.0005	0.0272	0
17	36	1	0.0005	0.0045	0.32
17	43	1	0.0005	0.0276	0
18	42	1	0.004	0.06	2.25
18	49	1	0.0076	0.1141	1.16
18	50	1	0.0012	0.0288	2.06
19	68	1	0.0016	0.0195	0.304
21	22	1	0.0008	0.014	0.2565
21	68	1	0.0008	0.0135	0.2548
22	23	1	0.0006	0.0096	0.1846
23	24	1	0.0022	0.035	0.361
24	68	1	0.0003	0.0059	0.068
25	26	1	0.0032	0.0323	0.531
25	54	1	0.007	0.0086	0.146
26	27	1	0.0014	0.0147	0.2396
26	28	1	0.0043	0.0474	0.7802
26	29	1	0.0057	0.0625	1.029
27	37	1	0.0013	0.0173	0.3216
27	53	1	0.032	0.32	0.41
28	29	1	0.0014	0.0151	0.249
30	31	1	0.0013	0.0187	0.333
30	32	1	0.0024	0.0288	0.488
30	53	1	0.0008	0.0074	0.48
30	61	1	0.00095	0.00915	0.58
31	38	1	0.0011	0.0147	0.247
31	53	1	0.0016	0.0163	0.25
32	33	1	0.0008	0.0099	0.168
33	34	1	0.0011	0.0157	0.202
33	38	1	0.0036	0.0444	0.693
34	36	1	0.0033	0.0111	1.45
35	45	1	0.0007	0.0175	1.39
36	61	1	0.0011	0.0098	0.68
37	52	1	0.0007	0.0082	0.1319
37	68	1	0.0007	0.0089	0.1342
38	46	1	0.0022	0.0284	0.43
39	44	1	0	0.0411	0
39	45	1	0	0.0839	0
40	41	1	0.006	0.084	3.15
40	48	1	0.002	0.022	1.28

41	42	1	0.004	0.06	2.25
43	44	1	0.0001	0.0011	0
44	45	1	0.0025	0.073	0
45	51	1	0.0004	0.0105	0.72
46	49	1	0.0018	0.0274	0.27
47	48	1	0.00125	0.0134	0.8
47	53	1	0.0013	0.0188	1.31
50	51	1	0.0009	0.0221	1.62
52	55	1	0.0011	0.0133	0.2138
53	54	1	0.0035	0.0411	0.6987
54	55	1	0.0013	0.0151	0.2572
55	56	1	0.0013	0.0213	0.2214
56	57	1	0.0008	0.0128	0.1342
56	66	1	0.0008	0.0129	0.1382
57	58	1	0.0002	0.0026	0.0434
57	60	1	0.0008	0.0112	0.1476
58	59	1	0.0006	0.0092	0.113
58	63	1	0.0007	0.0082	0.1389
59	60	1	0.0004	0.0046	0.078
60	61	1	0.0023	0.0363	0.3804
62	63	1	0.0004	0.0043	0.0729
62	65	1	0.0004	0.0043	0.0729
65	66	1	0.0009	0.0101	0.1723
66	67	1	0.0018	0.0217	0.366
67	68	1	0.0009	0.0094	0.171

Transformer data on 100 MVA base

From Bus Number	To Bus Number	Id	Resistance (pu)	Reactance (pu)	Tap (pu)
1	54	1	0	0.0181	1.025
2	58	1	0	0.025	1.07
3	62	1	0	0.02	1.07
4	19	1	0.0007	0.0142	1.07
5	20	1	0.0009	0.018	1.009
6	22	1	0	0.0143	1.025
8	25	1	0.0006	0.0232	1.025
9	29	1	0.0008	0.0156	1.025
10	31	1	0	0.026	1.04
11	32	1	0	0.013	1.04
12	36	1	0	0.0075	1.04
13	17	1	0	0.0033	1.04
14	41	1	0	0.0015	1
15	42	1	0	0.0015	1
16	18	1	0	0.003	1

20	19	1	0.0007	0.0138	1.06
34	35	1	0.0001	0.0074	0.946
63	64	1	0.0016	0.0435	1.06
65	64	1	0.0016	0.0435	1.06

Load Data

Bus Number	P (MW)	Q (Mvar)
17	6000	300
18	2470	123
20	680	103
21	274	115
23	248	85
24	309	-92
25	224	47
26	139	17
27	281	76
28	206	28
29	284	27
33	112	0
36	102	-19.46
39	267	12.6
40	65.63	23.53
41	1000	250
42	1150	250
44	267.55	4.84
45	208	21
46	150.7	28.5
47	203.12	32.59
48	241.2	2.2
49	164	29
50	100	-147
51	337	-122
52	158	30
53	252.7	118.56
55	322	2
56	200	73.6
59	234	84
60	208.8	70.8
61	104	125
64	9	88
67	320	153
68	329	32

ANNEXURE B – Dynamics data of 68 bus system

Dynamic model data for round rotor units from 1 to 7

	Gen	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Rated apparent power	MVA BASE	600	600	700	700	600	800	600
d-axis open circuit transient time constant	T'_{do}	10.2	10.2	5.7	5.69	5.4	7.3	5.66
d-axis open circuit sub-transient time constant	T''_{do}	0.05	0.05	0.05	0.05	0.05	0.05	0.05
q-axis open circuit transient time constant	T'_{qo}	1.5	1.5	1.5	1.5	0.44	0.4	1.5
q-axis open circuit sub-transient time constant	T''_{qo}	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Inertia	H	7	7	5.1143	4.0857	4.3333	4.35	4.4
Speed damping	D	0	0	0	0	0	0	0
d-axis synchronous reactance	X_d	0.6	0.6	1.7465	1.834	1.98	2.032	1.77
q-axis synchronous reactance	X_q	0.414	0.414	1.659	1.806	1.86	1.928	1.752
d-axis transient reactance	X'_d	0.186	0.186	0.3717	0.3052	0.396	0.4	0.294
q-axis transient reactance	X'_q	0.25	0.25	0.5	0.41	0.53	0.54	0.4
sub-transient reactance (X"d=X"q)	X"	0.15	0.15	0.315	0.245	0.3	0.32	0.24
Leakage reactance	X_l	0.075	0.075	0.2128	0.2065	0.162	0.1792	0.193
Saturation factor at 1.0 pu voltage	S (1.0)	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Saturation factor at 1.2 pu voltage	S (1.2)	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Dynamic model data for round rotor units from 8 to 16

Gen	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
MVA BASE	600	900	650	1700	1500	10000	8700	8700	8000
T'_{do}	6.7	4.79	9.37	4.1	7.4	5.9	4.1	4.1	7.8
T''_{do}	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
T'_{qo}	0.41	1.96	1.5	1.5	1.5	1.5	1.5	1.5	1.5
T''_{qo}	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
H	4.05	3.8333	4.7692	1.6588	6.153	4.96	3.4483	3.448	5.625
D	0	0	0	0	0	0	0	0	0
X_d	1.74	1.8954	1.0985	2.176	1.515	1.48	1.566	1.566	1.424
X_q	1.68	1.845	0.7475	2.091	1.425	1.43	1.5051	1.505	1.336
X'_d	0.342	0.513	0.297	0.306	0.465	0.275	0.248	0.248	0.284
X'_q	0.46	0.69	0.4	0.41	0.63	0.37	0.33	0.33	0.38
X''	0.27	0.405	0.26	0.204	0.375	0.2	0.2001	0.2	0.22
X_l	0.168	0.2682	0.075	0.075	0.075	0.075	0.075	0.075	0.075
S (1.0)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
S (1.2)	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Dynamic model data for DC rotating excitation systems DC4B for units from 1 to 12

Description	Symbol	Value	Unit
Voltage transducer time constant	TR	0.01	s
AVR proportional gain	KP	200	pu
AVR integral gain	KI	50	pu
AVR derivative gain	KD	50	pu
AVR derivative time constant	TD	0.01	s
Max. AVR output	VRmax	10	pu
Min. AVR output	VRmin	–10	pu
thyristor bridge equivalent gain	KA	1	pu
thyristor bridge equivalent time constant	TA	0.02	s
Exciter feedback time constant	KE	1	pu
Exciter time constant	TE	0.785	s
Stabilizer feedback gain	KF	0	pu
Stabilizer feedback time constant	TF	1	s
Minimum exciter output	VEmin	0	
Exciter saturation point 1	E1	3.9267	pu
Exciter saturation factor at point 1	SE(E1)	0.07	–
Exciter saturation point 2	E2	5.2356	pu
Exciter saturation factor at point 2	SE(E2)	0.91	–

Dynamic model data for static excitation systems ST1A for units from 13 to 16

Description	Symbol	Value	Unit
Voltage transducer time constant	TR	0.01	s
Max. voltage error	VImax	99	pu
Min. voltage error	VImin	–99	pu
TGR block 1 numerator time constant	TC	1	s
TGR block 1 denominator time constant	TB	1	s
TGR block 2 numerator time constant	TC1	1	s
TGR block 1 denominator time constant	TB1	1	s
AVR steady state gain	KA	200	pu
Rectifier bridge equivalent time constant	TA	0.01	s
Max. AVR output	VAmax	5	pu
Min. AVR output	VAmin	–5	pu
Max. rectifier bridge output	VRmax	5	pu
Min. rectifier bridge output	VRmin	–5	pu
Commutation factor for rectifier bridge	KC	0	pu
Stabilizer feedback gain	KF	0	pu
Stabilizer feedback time constant	TF	1	s
Field current limiter gain	KLR	0	pu
Field current instantaneous limit	ILR	3	pu

ANNEXURE C – PSS®E Dynamic model assignment for SL Power System

PSS®E Dynamic model assignment of each generator in Sri Lankan Power System

Plant	Generator Model	Exciter Model	Governor Model
Asia Power	GENSAL	IEEET1	-
Colombo Barge	GENSAL	SEXS	-
Old Laxapana 1, 2 & 3	GENSAL	SEXS	HYGOV
Old Laxapana 4	GENSAL	SEXS	HYGOV
Old Laxapana 5	GENSAL	SEXS	HYGOV
New Laxapana 1	GENSAL	SEXS	HYGOV
New Laxapana 2	GENSAL	SEXS	HYGOV
Wimalasurendra 1	GENSAL	SEXS	HYGOV
Wimalasurendra 2	GENSAL	SEXS	HYGOV
Polgolla 1	GENSAL	SEXS	HYGOV
Polgolla 2	GENSAL	SEXS	HYGOV
Canyon 1	GENSAL	SEXS	HYGOV
Canyon 2	GENSAL	SEXS	HYGOV
Samanalawewa 1	GENSAL	SEXS	HYGOV
Samanalawewa 2	GENSAL	SEXS	HYGOV
Ukuwela 1	GENSAL	SEXS	HYGOV
Ukuwela 2	GENSAL	SEXS	HYGOV
Kothmale 1	GENSAL	SEXS	HYGOV
Kothmale 2	GENSAL	SEXS	HYGOV
Kothmale 3	GENSAL	SEXS	HYGOV
Upper Kothmale 1	GENSAL	SEXS	HYGOV
Upper Kothmale 2	GENSAL	SEXS	HYGOV
Victoria 1	GENSAL	SEXS	HYGOV
Victoria 2	GENSAL	SEXS	HYGOV
Victoria 3	GENSAL	SEXS	HYGOV
Randenigala 1	GENSAL	SEXS	HYGOV
Randenigala 2	GENSAL	SEXS	HYGOV
Rantambe 1	GENSAL	SEXS	HYGOV
Rantambe 2	GENSAL	SEXS	HYGOV
KPS GT 07	GENROU	SEXS	GAST
KCCP GT	GENROU	SEXS	GAST
KCCP ST	GENROU	SEXS	TGOV1
AES GT	GENROU	SEXS	GAST
AES ST	GENROU	SEXS	TGOV1

Plant	Generator Model	Exciter Model	Governor Model
Kerawalapitiya GT	GENROU	SEXS	GAST
Kerawalapitiya ST	GENROU	SEXS	TGOV1
Sapugaskanda Old Phase	GENROU	SEXS	-
Sapugaskanda New Phase 1	GENROU	SEXS	-
Sapugaskanda New Phase 2	GENROU	SEXS	-
Kukule Ganga 1	GENSAL	SCRX	-
Kukule Ganga 2	GENSAL	SCRX	-
Lakvijaya Unit 1	GENROU	EXST1	TGOV3
Lakvijaya Unit 2	GENROU	EXST1	TGOV3
Lakvijaya Unit 3	GENROU	EXST1	TGOV3

PSS®E Dynamic model description

Dynamics model	Description
GENROU	Round rotor synchronous generator with quadratic saturation in d-q axis
GENSAL	Hydroelectric generators were modelled with Salient pole synchronous machine with quadratic saturation in d axis
IEEET1	IEEE type 1 excitation control system
SEXS	Simplified Excitation system
SCRX	Simple excitation system model representing generic characteristics of many excitation systems
EXST1	IEEE type ST1 excitation system model
HYGOV	Hydraulic turbine and governor
GAST	Gas turbine and governor
TGOV1	Steam turbine and governor with reheat
TGOV3	Modified IEEE type 1 speed-governing model with Fast Valving

ANNEXURE D – PSS®E Single Line Diagram of SL Power System (2016)