STUDYING THE TURBINE-GENERATOR OSCILLATIONS

A CASE STUDY OF LAKVIJAYA POWER STATION

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Degree of Master of Science

Department of Electrical Engineering

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May 2024

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Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree

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DECLARATION

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

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L. U. N. de Silva

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

Signature of the supervisors: Date: 10.05.2024

Dr. W. D. Prasad

DEDICATION

My loving parents and my beloved wife who are nourishing and cherishing me and to my little adorable sons Ayuk and Anuk.

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I wish to express my warmest thanks to my family and friends for caring, bearing and providing me throughout while I was completely engaged in this research works.

Abstract

The Lakvijaya Power Station located in Narakkalliya, Norochcholai, Sri Lanka plays a crucial role in the nation's energy sector, contributing significantly by almost half of the load to the electricity grid at most of the year. However, similar to any large-scale power facility, it also faces operational challenges, including turbine-generator oscillations. This research study presents a comprehensive study focused mainly on understanding and help mitigating these oscillations for improved operational efficiency and grid stability.

This research inherits a good conjunction of theoretical analysis, numerical simulations, and practical measurements to characterize the nature and causes of turbine-generator oscillations at Lakvijaya Power Station. Through detailed modelling, factors such as turbine multi-stages dynamics, generator response characteristics, speed governor controls, excitation controls, and grid interactions are investigated to identify potential sources of oscillations.

Furthermore, advanced signal processing techniques are applied to real-time operational data to detect and analyze oscillatory patterns. This includes frequency domain analysis and modal analysis with modulation study to pinpoint dominant oscillation frequencies and modes.

The results of this study offer valuable insights for power plant operators, grid operators, and researchers involved in the operation and optimization of large-scale power generation facilities. By detailed in-depth evaluation of turbine-generator oscillations at Lakvijaya power station, this study contribute to the broader country's visionary policy of ensuring reliable and efficient electricity supply in Sri Lanka's energy landscape.

Keywords: Lakvijaya Power Station, turbine-generator oscillations, torsional interactions, power plant optimization, grid stability, small-signal assessment.

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ABBREVIATIONS

Shortened form	Interpretation
AM	Amplitude Modulation
AVR	Automatic Voltage Regulator
BB	Bus Bar
CCE	Cable Connection Enclosure
CEB	Ceylon Electricity Board
CMEC	China Machinery and Engineering Corporation
CT	Current Transformer
CVT	Capacitive Voltage Transformer
D-axis	Direct axis
DS	Disconnector Switch
ERA	Eigen system Realization Algorithm
ES	Earthing Switch
ESPRIT	Estimation of Signal Parameters via Invariance Technique
ET	Excitation Transformer
FES	Fast Earthing Switch
G	Generator
GIS	Gas Insulated Substation
GT	Generator Transformer
HIP	High & Intermediate Pressure
HV	High Voltage

HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IPB	Isolated Phase Bus
LA	Lightning Arrester
LP	Low Pressure
LV	Low Voltage
LVPP	Lakvijaya Power Plant
LVPS	Lakvijaya Power Station
MT	Main Transformer
NPB	Non-isolated Phase Bus
O&M	Operation and Maintenance
PM	Phase-angle Modulation
PSS	Power System Stabilizer
Q-axis	Quadrature axis
SCC	System Control Centre
SLD	Single Line Diagram
SST	Start-up Standby Transformer
SVC	Static Var Compensator
UAT	Unit Auxiliary Transformer
UKPS	Upper Kotmale Power Station
VD	Vision Device
VT	Voltage Transformer

Chapter 1

INTRODUCTION

OSCILLATIONS impose major threats to security and stability of power systems. Unless these oscillations are properly damped the power system can lose its stability when faced with a disturbance. The oscillatory instability which comes under small signal stability problem usually happens due to lack of proper damping torque. Depending on the behavior these are further classified in to several modes. These categories fall into five folds of Local, Inter machine, torsional, inter area and control modes. The frequency range of 0.2 to 0.5 Hz are related to local plant mode. In this mode set of generators in a local facility oscillating with respective to an outside network of a larger system. A higher frequency range of 1.5Hz – 3Hz corresponding to inter-machine mode. It is related to adjacent machines oscillating within each other. Oscillations exaggerated due to negative damping effects of control actions of control systems are usually treated as control modes. They are in a range of above 2Hz. According to literature [1] control modes are seen in SVC in bus voltage and similarly for HVDC lines control modes are visible in frequency as well as active power. And relative oscillations in-between generator shaft sections are commonly referred as torsional modes. Finally inter area modes can be identified in many network measurements around wide range of area across the total network considered. These are in the range of 0.2 and 0.5 Hz typically. The complicated nature of inter area modes sums up with in relation to network configuration, nature of loads, excitation systems' geography, fault levels etc. The classification of the oscillations are illustrated in Fig. 1-1.

1.1 Classification of Oscillatory Instability

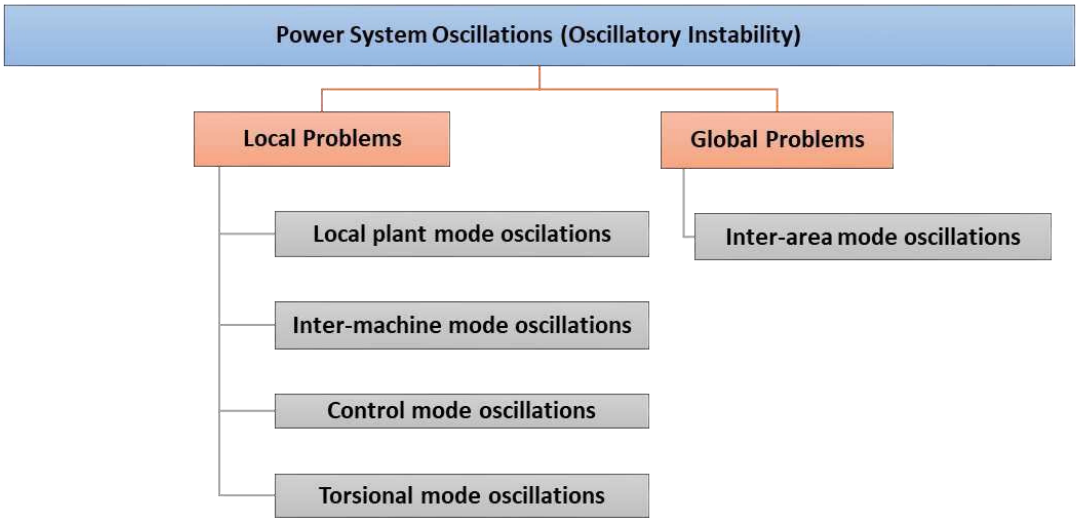


Fig. 1-1. Classification of power system oscillations which falls under oscillatory instability of small signal studies.

1.1.1 Local Plant and Inter-machine Mode Oscillations

This type of oscillation is the most common type of mode of oscillation among low frequency encounters [2]. This category of oscillations occur whence one synchronous machine or several synchronous machines oscillate against the rest of the generators in same facility or with respect to the external network. This mode of oscillation can cause serious problems in a situation where a power station with reactance tie lines and high load. This type of problems might be visible because of the maneuver of large excitation systems operating at high loads while delivering feeble network of transmission. Especially with the high response excitation systems it is more prominent. This common type of oscillation characteristics are properly identified and this can be effectively mitigated by the use of power system stabilizers which is an extra control mechanism of the excitation system nowadays.

1.1.2 Control Mode Oscillations

Even though various methods implemented to damp out different types of oscillations it can be affected by the unbalanced faults and various control methodologies. Such as control of static VAR compensator, control of HVDC converter, control of the governor and transmission with series capacitors. These contributions are termed as control mode of oscillations. Control mode of oscillations are related to the controls of generating machines and other subordinate systems. When Static Var Compensators, large HVDC converters, Automatic Voltage Regulators and Prime mover governors are not properly tuned for its control algorithms these types of modes results in oscillations. However most of the time tuning of such controlled is hard to achieve at desired damping levels.

1.1.3 Torsional Mode Oscillations

Usually this type of oscillations occur in steam turbine generators. Since the steam turbine generators have long mechanical shafts the relative motion between shaft sections leads to these torsional oscillations in the frequency of sub synchronous range which are originated by the variations of mechanical or electrical torques in the generators. This is more noticeable in the generators which are connected to long series compensated transmission lines. Turbine speed governors as well as the excitations systems by their controls which reacts on torsional modes might lead to instability situations. As these mode of oscillations are higher than the typical frequency range of power system stabilizer can identify in order to damp out, monitoring and controlling of these are much more difficult to the PSS. However flexible AC transmission systems were introduced as a solution for this problem [2]. When excited with these modes of oscillations where excitation system introduce high gains this might leads to critical shaft damages of turbine generator systems.

1.1.4 Inter-area Mode Oscillations

Similar to the local modes of oscillation the inter area mode of oscillation are also commonly referred power system oscillation by most of the authors. Further the local modes of oscillations can leads to large inter area oscillations as discussed in many literatures. This is the mode of oscillation where one part of power system oscillate with the another part of the same power system. In between these two parts there could be a weak electrical inter connection. These oscillations can be caused by more than one group of thoroughly coupled machines which are connected by weaker tie lines. However the characteristics of inter area mode of oscillation is more complicated and different compared to local modes of oscillations. The interaction of inter area mode of oscillation depends upon the location of the generator within the power system and connection of PSS. Therefore it should be properly studied and understood the characteristics specifically to the situation in order to implement monitoring and control actions for this purpose by means of PSS or other reliable controls.

1.2 Motivation for the Research

Power system oscillations are introduced to the system by means of events take place such as disturbances of the network, machines or loads. Fluctuation of the steady state operating point is also leading to the same. However it might happen around a stability margin. Persistence of these oscillations may happen over a lengths span. This is if it not properly damped so to exist several seconds. Occasionally many large generators are withdrawn from network due to oscillations. Because keeping the synchronism is affected. There are incidents where these oscillations exists for longer duration. This results in separation of power facilities equipment from network. This might extends to gradually developing total system failures. Even when these persisting oscillations don't produce disconnection of the network or sources still it can interrupt the healthy power system in many different ways. One such example in power systems is when there occur a power swing, an unacceptable voltage swing or frequency swing may realize within the network which will limit the power transfer capability of the entire network even though the stability is not a major concern. The local modes and inter area modes of oscillations hence exert risk to the safe operation of the system network whence not damped well. The inter area mode is more critical since the oscillation take place between two or more areas and present of individual generators might lead towards larger oscillations in tie lines. This problems finds relatively more attention since it directly affects commercial power transmission utilities between power markets. Inter area connections with bulk power can be significantly affected by this factor. The torsional modes which are poorly damped could trigger interruptions of the generators. This is because of the protective devices functioning in order to prevent serious damages to the shaft of turbine generator system. Therefore by the means of detailed analysis and modeling for scenarios at all possible operating points proper mitigate possibilities should be understood to these oscillations.

One of the first historical incident that leads to attention of researchers for the oscillatory studies is the one happened at Mohave power plant. This was located in United States Nevada region in 1970s at Laughlin town [3]. Which is identified as a case of a torsional oscillation interaction problem. The accident firstly felt as a slowly increasing vibration at the plant. Eventually this vibration was increased to level that resulted in fracture of the shaft between the generator and rotating exciter. Later a thorough detailed study was done and the analysis revealed that an electrical resonance produced a torque at 29.5 Hz with the resonance frequency at 30.5 Hz. The system operated at the frequency of 60 Hz. This electrical resonance frequency was nearly matched with the one of the torsional mode frequency of the turbine generator at the power station which was around at 30.1 Hz. Here the electrical network associate with the turbine shaft system. It is a torsional relationship and occur below at synchronous speed. Therefore it was identified and considered as sub synchronous resonance torsional incident later.

Fig. 1-2. Fracture of the shaft of generator at Mohave power station in 1970s [3].

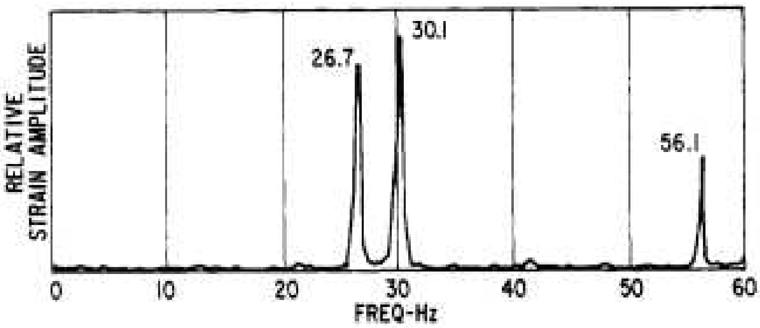


Fig. 1-3. Synchronization frequency analysis.

It might be inevitable going towards partial brownouts or total failure such as blackouts if power system oscillations are poorly damped. Even it can fall into unsafe operation conditions if not controlled correctly. Therefore a complete comprehension of this possible issues will help to find fruitful counter measures. The remedies could be taken by various measures and controls. There would be number of mechanism to alleviate the poor damping of oscillations in the power system.

Lakvijaya power station which was first commissioned in 2011 is the only coal fired power plant available in Sri Lanka delivering nearly 50% of national load during dry season. The plant which was built by China Machinery and Engineering Corporation (CMEC) consists 3X300MW subcritical thermal units. With the help of two grid substations these units are connected to national grid of transmission network. The names of two grid substations are New Chilaw and New Anuradhapura (Fig. 1-4). The plant is feeding to 220kV transmission lines using generator transformers and GIS located at the facility ultimately terminating at the above substations. The Country's load center is located at Colombo city. However LVPP is located far away from this load center. In a 120km distance radius. The following Power Station arrangement is extracted from single line diagram of Lakvijaya Power Station (Appendix A)

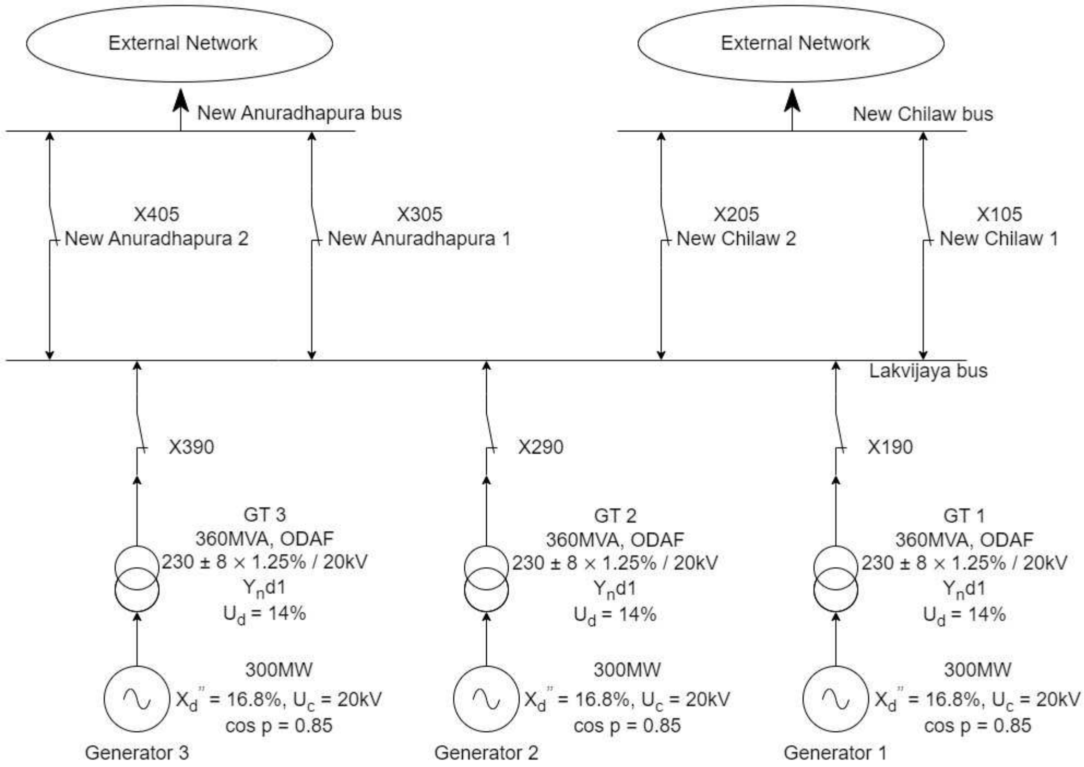


Fig. 1-4. Network and power equipment arrangement of the Lakvijaya Power Station

In this paper development and validation of a detailed linear model including turbine shaft dynamics of Lakvijaya power station is discussed. Electromechanical and torsional modes of oscillations associated with the thermal power plant were explored and their interactions with various sub-systems of the network were studied.

1.3 Objectives of the research

The broader goal of this research study is to support easing the operational challenges specifically related to power system oscillations which are faced by Lakvijaya Power Plant by studying turbine-generator oscillations. It focuses mainly on understanding and help operators and researchers mitigating these oscillations for improved operational efficiency and grid stability. Therefore this research is directed down towards the following important objectives.

- To develop a detailed linear model including turbine shaft dynamics of Lakvijaya Power Station and validate the performance.
- To analyze electromechanical and torsional modes of oscillations associated with Lakvijaya Power Station under different operating conditions.

Hence, the results of this study offer valuable insights not only for Lakvijaya power plant but also for other power plant operators, grid operators, and researchers involved in the operation and optimization of large-scale power generation facilities.

1.4 Thesis Outline

The rest of this thesis is ordered as explained below to present the entire scope carried out through this research study.

Chapter 2 starts by stating historical incidents related to oscillation study from the initial incident. Then it describes the outlined concepts related to spotlighted oscillation phenomena. Further the chapter introduce the analysis and monitoring of oscillatory modes using measurements and by estimation techniques in the literature.

Chapter 3 presents the fundamental concepts of the electromechanical and electromagnetic transients. Then it narrows down to more details of electromechanical phenomenon where amplitude modulation and phase angle modulation are discussed. Moreover the theories to extract oscillation frequencies in the modulated phasor using frequency domain analysis are highlighted.

Chapter 4 is dedicated to explain historical events took pace in Lakvijaya power plant highlighting the requirement for this oscillation study. It majorly focus on two events occurred in 2019 and 2022. Where it was found a low frequency oscillation persisting in the LVPP power generation facility. Further development of a non-linear simulation model and validation of the same is also described.

Chapter 5 systematically explains the development of state space representation of the overall system. This includes modelling of each units having represented the dynamics of electrical generator stator and rotor, excitation system, turbine and speed governing system, shaft model representing its carrying multi masses of turbines with generator. And network and loads as well. Finally the model is validated against the simulation model explained in previous chapter.

Chapter 6 discuss the results of the study. This discussion firstly state the eigenvalue conclusions and then extends to two categories of methods to analyze the modes namely mode shapes and participation factors. There in each modes and states, various relationships and patterns are observed.

Chapter 7 presents the conclusions of this research work.

Chapter 2

LITERATURE REVIEW

Starting from the initial incident happened at Mohave power station in 1970 many researches were done extensively on oscillation studies. On top of that special attention was also given on oscillations that can lead to torsional interactions as there were many incidents took place which followed the original event at Mohave. These incidents lead to more disastrous situations of the power system together with permanent failures of equipment. Below Table 2-1 shows a list of such events found in historical records from 1970s to 2000s.

Table 2-1: HISTORICAL EVENTS OF MAJOR OSCILLATIONS [4]

Unit	Year	Rating	Failed components	Failure mechanism	Comments
Mohave Unit 2	1971	483MVA, 3600rpm	Generator shaft under collector ring	Two separate incidents due to SSR	The second incident occurred before the root cause discover
Prairie island Unit 1	1974	630MW, 1800rpm	LP turbine 1 and 2 turbine blades	High cycle fatigue	Two incidents due to torsional resonance near 120Hz
Maanshan	1985	1057MVA , 1800rpm	Eight last stage blades and alternator shaft	High cycle fatigue	Torsional resonance near 120Hz
Monticello Unit 1	1985	570MW, 1800rpm	Fatigue life consumption	Torsional oscillations-high stress	700MW oscillation at HVDC inverter substation. Unit required rebalancing.

Comanche Unit 2	1987	350MW, 3600rpm	Cracked generator shaft- Main coupling	Fretting fatigue	Postulated torsional oscillation at first torsional frequency due to nearby arc furnace SVC and unit PSS
Susquehann a Unit 1	1993	1050MW, 1800rpm	Two I-1 stage blade failures	High cycle fatigue	Torsional resonance near 120Hz
Comanche Unit 2	1994	350MW, 3600rpm	Generator retaining ring fracture	Torsional high cycle fretting fatigue	Interaction with nearby steel mill that stimulated torsional mode near 117Hz
South Texas project Unit 2	2002	1300MW, 1800rpm	One LP blade fracture. Other LP blade cracks	High cycle fatigue	Torsional natural frequency near 120Hz
Dresden Units 2 & 3	2004	912 MW, 1800rpm	Cracked generator shaft at main coupling	Hight cycle fatigue-fretting	Postulated intermittent oscillating torques due to system disturbances

2.1 Underlined power system oscillatory phenomena

Oscillatory phenomenon related to interaction between the electrical systems and mechanical modes of turbine-generator torsional characteristics can be identified as torsional interactions. It can be further diversified in to three below circumstances.

1. Resonance in sub synchronous domain
2. Oscillations depending on devices
3. Network switching associated torsional events and other events.

2.1.1 Resonance in sub synchronous domain

As mentioned earlier it was first observed at the Mohave generation station in 1970. . It is the resonance among transmission network natural frequencies and turbine generator shaft system's torsional mode frequencies f_m in the range of below synchronous power frequency. The resonance frequency f_n given by $f_n = f_0\sqrt{\frac{X_C}{X_L}}$. Usually this is less than nominal frequency f_0 denotes. Therefore pure resonance can be witnessed once the condition $f_n = f_0$ - f_m get satisfied. This circumstance is generally known as sub synchronous resonance.

2.1.2 Oscillations depending on devices

The first incident of this phenomena recorded at the Lambtan generating station, Ontario in Canada. It was in 1960s and reason was related to unstable PSS (power system stabilizer). Down the line year 1985 recorded similar interaction. It was reported in Canada and identified as due to action of turbine governor. In these both cases problem is associated to the speed signal taken from turbine-generator shaft which is affected by torsional mode oscillations. In this scenario the underline cause of torsional interference is due to the fast control system processes happening in large power electronic such as HVDC converters and SVC controllers. And also local controllers such as automatic voltage regulators and governors. In conclusion where this kind of oscillations take place the control actions of large power electronics exert negatively damped torques on torsional modes of the turbine generator shaft system. This is more commonly known as device dependent sub synchronous oscillations.

2.1.3 Network switching associated torsional events.

Transients happen as disturbance to power systems will excite natural modes of turbine-generator shaft. These transients include faults, breaker operations, automatic high speed reclosing, out of phase synchronization, cyclical or pulsating loads, switching of series capacitors etc. The impact to the turbine-generator is proportional to the severity of initial stimulus. It is understood that it is created large torque steps twice when an electrical fault happens. The first occurrence of fault and then tripping create it on the electrical generator. Further when high speed reclosing is applied another step will be experienced within short span before the previous stimulated oscillation is fully subsided. Normally a switching event only cause negligible fatigue life expenditure whereas faults could contribute fatigue life expenditure surpassing a level of 1%. There is a threshold to exceed in order to start off a crack on shaft by accumulation of fatigue life expenditure. Further there is a guideline published by IEEE to monitor/screen planned switching events. This is to minimize the harm. The same is given in references [5]. This is the underline principle of this kind of torsional interaction caused by network switching.

2.2 Modal Analysis Methods

In this section we briefly introduce some of the commonly available techniques in the literature for analysis of modes of oscillations.

1. Measurement based analysis

   In this method modes are determined by taking measurements by piezo-electric transducers and accelerometers etc. after exciting torques are applied using shakers and ratchets at turning gear of the turbo-generator [6].

   - Eigen System Realization Algorithm (ERA).
   - Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) [7], [1].
   - Prony's method.

2. State-space model based analysis

   This is the widely used approximation method for the real physical system where modes of oscillations are estimated using actual system parameters.

Following sub topics describes some of the above mentioned analysis methods in a definitive manner. Please note that the explanation of ESPRIT method is omitted here for the sake of objectivity of this thesis whereas it is explained in detailed in literature [7], [1].

2.2.1 Eigen System Realization Algorithm (ERA)

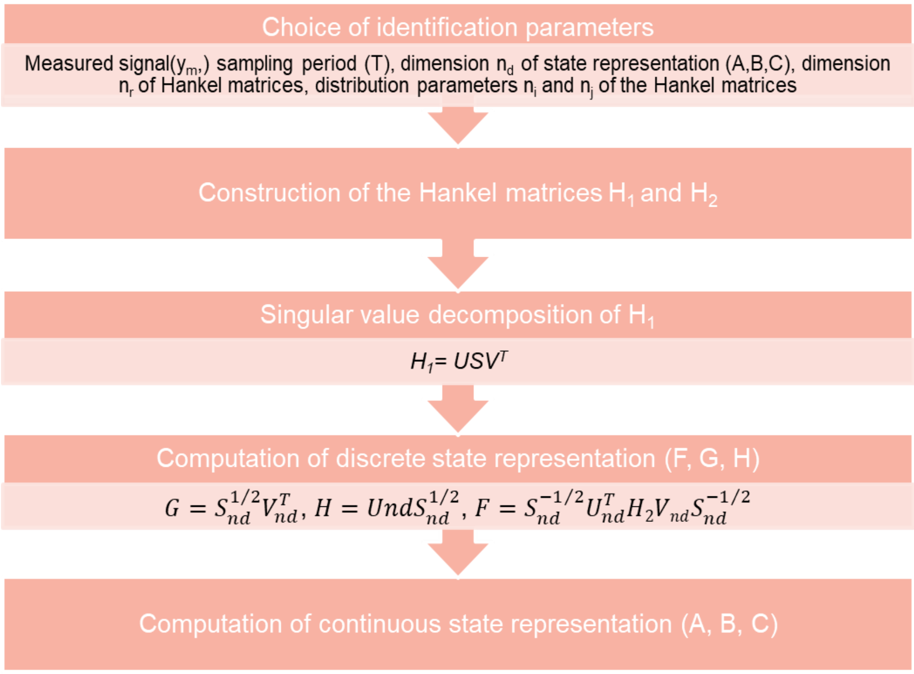


Fig. 2-1. Eigen system Realization Algorithm steps [8].

Fig. 2-1. illustrates the Eigen system Realization Algorithm. Development of Hankel matrices H_1 and H_2 is the main target of this algorithm. Firstly it needs to select identification parameters of the system. They are measured signal, dimensions of matrices, sampling period, dimensions of state representation, distribution parameters of the above H_1 and H_2 which decides window size. That is the identification time duration. Hankel matrices are constructed using elements which indicates measurements in the order of identification parameters. The difference of two Hankel matrices are the shifting of identification parameters by one position. That means there is one element offset between two matrices in measurement samples. The Hankel matrices are obtained as follows.

$$y_m = [y_m(0), y_m(T), \ldots, y_m(nT)] = [y(1), y(2), \ldots, y(n+1)] = \omega_f \tag{1}$$

$$H_k = \begin{pmatrix} y(k) & y(k+n_i) & \cdots & y(k+(n_r-1)n_i) \\ y(k+n_j) & y(k+n_j+n_i) & \cdots & y(k+n_j+(n_r-1)n_i) \\ \vdots & \vdots & \vdots & \vdots \\ y(k+(n_r-1)n_j) & \cdots & \cdots & y(k+(n_r-1)(n_j+n_i)) \end{pmatrix}$$

(2)

- The H_k matrices depend on the parameters T, n_r, n_i and n_j.
- If $n_i = n_j$ then H_1 and H_2 are symmetrical.
- If $n_i = n_j = 1$, adjacent data are used.
-The parameters n_r, n_i and n_j must be chosen so that $(n_r-1)(n_i+n_j) \leq n-1$ where n represents the number of samples.

The F, G and H matrices which are namely state, control and output respectively in the discrete domain are computed with the use of Hankel matrices. By decomposition of Hankel matrix 1 and arranging those singular values in descending order to the diagonal yields the diagonal S matrix. Further U and V matrices contains left and right singular vectors respectively. S_{nd} is deduced by considering the singular values at the highest that determined by the Hankel dimensions. The equations are given above to find the F, G and H system. From there onward using discrete to continuous transformation continuous system A, B and C is obtained [8].

2.2.2 Prony's Method

This method also measurement based technique which uses evenly spaced samples of the measured signal. Calculation of Eigen-values by Prony method in order to determine modes of power system is as follows.

Let f (t) be measured signal consisting of N evenly spaced samples.

$$f(t) = \sum_{i=1}^{M} A_i e^{\sigma_i t} \cos(\omega_i t + \emptyset_i)$$

(3)

$$= \sum_{i=1}^{M} \frac{1}{2} A_i (e^{j\emptyset_i} e^{\lambda_i^+ t} + e^{-j\emptyset_i} e^{\lambda_i^- t})$$

(4)

Where,

$\lambda_i^{\pm} = \sigma_i \pm j\omega_i$	; eigenvalues of the system
$\sigma_i = \omega_{0,i}\zeta_i$	; damping coefficients.
$\omega_i = \omega_{0,i}\sqrt{1 - \zeta_i^2}$	; angular velocities/frequencies
$\emptyset_i$	; phase angles
A_i	; amplitudes

Addition of p numbers of complex parameters as shown below gives the series of data sequence,

$$x\,[n] = \sum_{k=1}^{p} A_k e^{j\theta_k} \cdot e^{\left(\alpha_k + j2\pi f_k\right) T_s (n-1)} = \sum_{k=1}^{p} h_k \cdot z_k^{(n-1)}$$

(5)

It is understood that for a linear difference equation in fact which is homogeneous has a solution expressed in the above normally. As it is clear the above has p numbers of roots the linear difference equation can be deduced using characteristic equation below shown.

$$\varphi(z) = \prod_{k=1}^{p} (z - z_k) = \sum_{k=0}^{p} a\,[k]\, z^{p-k}; \qquad a\,[0] = 1$$

(6)

The above data sequence put into matrix form after rearranging gives below model of linear combination.

$$\begin{pmatrix} x[p] & x[p-1] & \cdots & x[1] \\ x[p+1] & x[p] & \cdots & x[2] \\ \vdots & \vdots & \ddots & \vdots \\ x[2p-1] & x[2p-2] & \cdots & x[p] \end{pmatrix} \begin{pmatrix} a[1] \\ a[2] \\ \vdots \\ a[p] \end{pmatrix} = - \begin{pmatrix} x[p+1] \\ x[p+2] \\ \vdots \\ x[2p] \end{pmatrix}$$

(7)

Using the above model roots of the characteristic equation can be identified. That is because as Vector a can be deduced from the above matrix form easily, the Prony polynomial can be derived. Once the roots are known frequency and damping factors are given by below formulae.

$$\alpha_k = \frac{\ln|z_k|}{T_s}$$

$$f_k = \frac{\tan^{-1}\left[\frac{\mathrm{Im}(z_k)}{\mathrm{Re}(z_k)}\right]}{2\pi T_s}$$

(8)

2.2.3 State Space Model based Modal Analysis

This is used to estimate the modes of a dynamic system. The system first has to be linearized using approximation methods such as Taylor expansion around initial steady state where the system operated initially. Here higher order terms are neglected in the approximation. More accurately it should incorporate all the dynamics of sub systems such as exciter, governor and shaft model etc. Ultimately leading to accurate estimation of the modes of the power system.

$$\Delta\dot{X} = A_{sys}\Delta X + B_{sys}\Delta U$$

(9)

$$\Delta Y = C_{sys}\Delta X$$

(10)

2.3 Chapter Summary

In this chapter the history of incidents happened due to oscillatory phenomena starting from the incident occurred at Mohave in 1970 were discussed. These incidents were the reasons that drew attention of the researchers regarding power system oscillations. Further the theories behind major oscillatory phenomena were explained. Those are namely sub synchronous resonance, Device dependent sub synchronous oscillations and torsional interactions due to switching and other events. Special attention was given to torsional oscillation since it is fairly the cause for the failure of most turbine-generators related to oscillation problem. Having explained that the next part describes the various methods to monitor and analyze oscillatory modes. These includes estimation of the oscillations and determining of oscillations as well. For both the case underline principle is mostly the state space representation of the system or developing an Eigen system. Whereas for monitoring various algorithms are in place namely such as Eigen system realization algorithm, Prony's method, Estimation of Signal Parameters via Rotational Invariance Techniques etc. Afterward some of these algorithms were briefly introduced for the completeness of this publication.

Chapter 3

POWER SYSTEM TRANSIENTS

Transients occur in a power system can either be electromagnetic or electromechanical which is more important for the present discussion. Electromagnetic transients are where sudden, temporary fluctuations mostly happen in voltage and current (i.e. electrical quantities). These can occur due to electrical switching operations, lightning strikes, faults in the network. In comparison to that reaction due to electrical elements' interrelationship with the mechanical counterparts cause electromechanical transients. Sudden changes in mechanical speed, mechanical torque or rotor angles initiated by disturbances are some phenomena for such transients. The type of transients related to a particular power system should be determined considering the system's components including transmission lines, transformers, power electronics, generators, transformers etc. Electromagnetic transients usually prevails in high voltage transmission systems on the other hand electromechanical transients are more relevant with large rotating machines predominantly generators and motors in a power system. However to conclude the applicable transient type detailed analysis is usually required using the data of system components, configuration and historical events.

3.1 Electromechanical Transients

The principle behind this types of transient is modulation of steady state phasors such as voltage and currents with low frequency signals. This signal is the modulating signal. Again this modulating signal is closely related to the electrical machine rotation. These large synchronous machines movements are hence associated to this type of transients. [9]. The said modulation can either be amplitude modulation or phase angle modulation or else both simultaneously. As a result these can be regarded as power system oscillations. Which cause frequency fluctuation in a cyclical manner. Sometimes leading to ramping of frequency. In general from 0.1Hz to 10Hz such oscillations can be present. Rotor angle at the beginning denoted by δ_0 as usual. The speed of rotor at any instance corresponds to angular frequency $\omega_1(t)$ at that instance. Therefore in usual notation terminal voltage of generator of positive sequence given by,

$$e_1(t) = \sqrt{2}E_1(t).\cos(\omega_1(t).t + \emptyset(t) + \delta_0) \tag{11}$$

The $\Delta\omega(t) = \omega_1(t) - \omega_0$, could denote rotor speed deviation from its nominal speed ω_0, at synchronism. This small deviation can either be ramp function or oscillatory function with respect to time. Here frequency $\omega_1(t)$ and magnitude $E_1(t)$ are relatively in accordance with empirical understanding. Whereas power frequency varies in relatively higher level.

When there are multiple machines in a power system they obviously have difference in their rotor speed when observed with respect to time. The result of such situation is the voltage and currents might have been modulated in their magnitude or phase angle or else both. . This happens due to superposition of sources operating at several rotor speed. Theories explained below describes the concept of magnitude modulation and phase angle modulation. And finally the simultaneous modulation by both methods.

3.1.1 Magnitude Modulation

In this type of modulation the modulated signal $e_1(t)$ can be represented as follows. Where the original signal $e(t)$ is modulated by a small amount 'x' having a modulating frequency of 'ω_m'.

$$e_1(t) = \sqrt{2}E_1(t).\{1 + \mathrm{x}\cos(\omega_m t)\}\cos(\omega_1(t).t + \emptyset(t) + \delta_0) \tag{12}$$

Expanding using trigonometry,

$$e_1(t) = \sqrt{2}E_1.\cos(\omega_1.t + \emptyset + \delta_0) + \frac{1}{2}\sqrt{2}E_1.x\cos(\{\omega_1 + \omega_m\}t + \emptyset + \delta_0) + \frac{1}{2}\sqrt{2}E_1.x\cos(\{\omega_1 - \omega_m\}t + \emptyset + \delta_0) \tag{13}$$

From the above equations we can understand that magnitude modulation adds mainly two elements to the nominal signal. One elements reflects a frequency of summing modulating frequency to original. Another element reflect frequency of difference between modulating and original. Further it is to be noted that this modulating frequency is minimal vis-à-vis nominal signal. Hence these added elements are also nearly similar frequency to original frequency in modulated signal.

3.1.2 Phase Modulation (phase angle)

The nominal signal $e(t)$ modulated by a modulating frequency 'ω_m' having a little amplitude of 'y' under phase modulation is expressed as follows,

$$e_1(t) = \sqrt{2}E_1(t).\cos(\omega_1(t).t + \emptyset\{1 + y\cos(\omega_m t)\} + \delta_0) \tag{14}$$

Expanding using Taylor series expansion and trigonometry,

$$e_1(t) = \sqrt{2}E_1.\cos(\omega_1.t + \emptyset + \delta_0) + \frac{1}{2}\sqrt{2}E_1.y\sin(\{\omega_1 + \omega_m\}t + \emptyset + \delta_0) + \frac{1}{2}\sqrt{2}E_1.y\sin(\{\omega_1 - \omega_m\}t + \emptyset + \delta_0) \tag{15}$$

As same as magnitude modulation in phase modulation also adds two elements. One is addition of frequencies explained earlier and another is subtracts of frequencies. However here added elements are sine functions unlike cosine functions in counterpart.

The following Fig. 3-1. illustrates how magnitude modulation and phase modulation change the nominal phasor while rotating with respect to time. Magnitude modulation alter the phasor along the same axis whereas phase modulation alter perpendicular to phasor as shown.

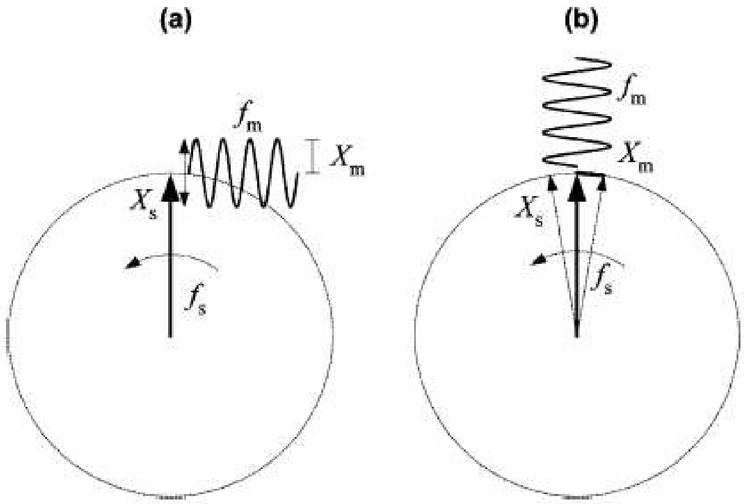


Fig. 3-1. Modulation of the phasor in (a) Amplitude and (b) Phase angle [9].

Having the understanding of the magnitude modulation technique and phase modulation technique it is straight forward that combination of both simultaneously give the combined results as well. That means this simultaneous modulation alter the phasor along the axis as well as perpendicular to axis at the same time while phasor rotation at nominal speed. Mathematically it is evident that the resulting modulated signal has cosine functions similar to magnitude modulation and sine functions similar to phase modulation ass additive elements. As explained earlier these additives may have frequencies of addition of nominal and modulating frequencies and subtraction of nominal and modulating frequencies. Whatever the case since this modulations are done using little amounts of 'x' and 'y' only. Therefore those all the additive elements are also have nearly the nominal phasor frequency. The graphical illustration of how the original nominal signal is affected after addition of additive signal is shown in Fig. 3-2. Please note that here this additive signal comprises of components having addition of nominal and modulating frequencies and subtraction of same frequencies.

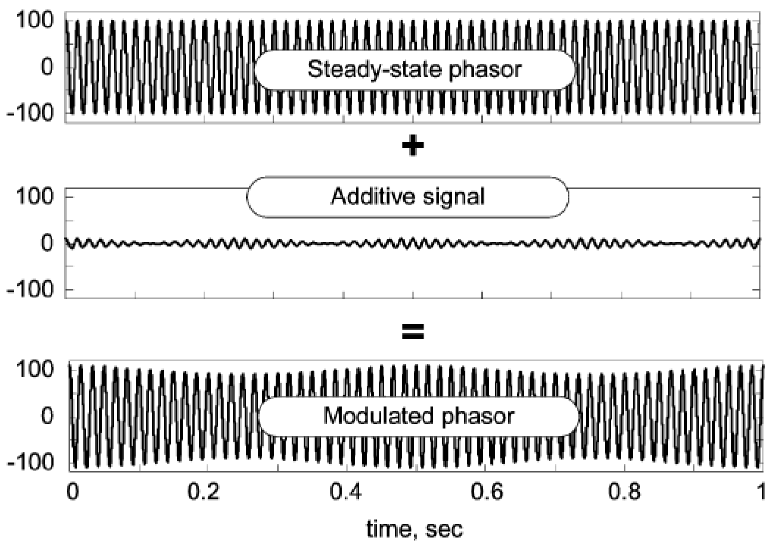


Fig. 3-2. Resultant modulated phasor after distortion of nominal phasor by additive signal [9].

3.2 Chapter Summary

Power System transients can be broadly categorized into electromagnetic transients and electromechanical transients. Electromagnetic transients are mostly sudden high frequency fluctuations of the voltage and currents whereas electromechanical transients are the modulation of steady-state voltage and current phasors with low frequency modulating signals corresponding to mechanical characteristic of the generator system. The underline theories were comprehensively explained in this chapter. The modulation incorporated with the electromechanical transients are two folds which are magnitude modulation and phase angle modulation or both. Whatever the case how the low frequency signal is mixed with the original phasor is explained and showed the possibility of extracting these signals using decomposition of components and explained the same. Finally the visual appearance of the measured signal after this phenomenon possibly on the fault recorder is illustrated.

Chapter 4

HISTORICAL INCIDENTS

Understanding its vital role as the largest power plant available in Sri Lanka for the integrity of the national power network, Lakvijaya power plant continuously improving and updating its systems to maintain the highest possible plant factor throughout the year. However during the last two decades it has intervene in to several nationwide blackouts and major cascading faults in the national network. For the purpose of this study the concern was given on two recent historical events recorded in plant fault recorders.

- Incident 1 – On 19th June 2019 unit 3 sync-breaker was suddenly opened due to a breaker malfunction isolating unit 3 from rest of the system.
- Incident 2 – On 12th December 2022 New Anuradhapura Line 1 was tripped due to a line fault.

Actual recorded windows by fault recorder (BEN 5000 model) are shown below Fig. 4-1. and Fig. 4-2.

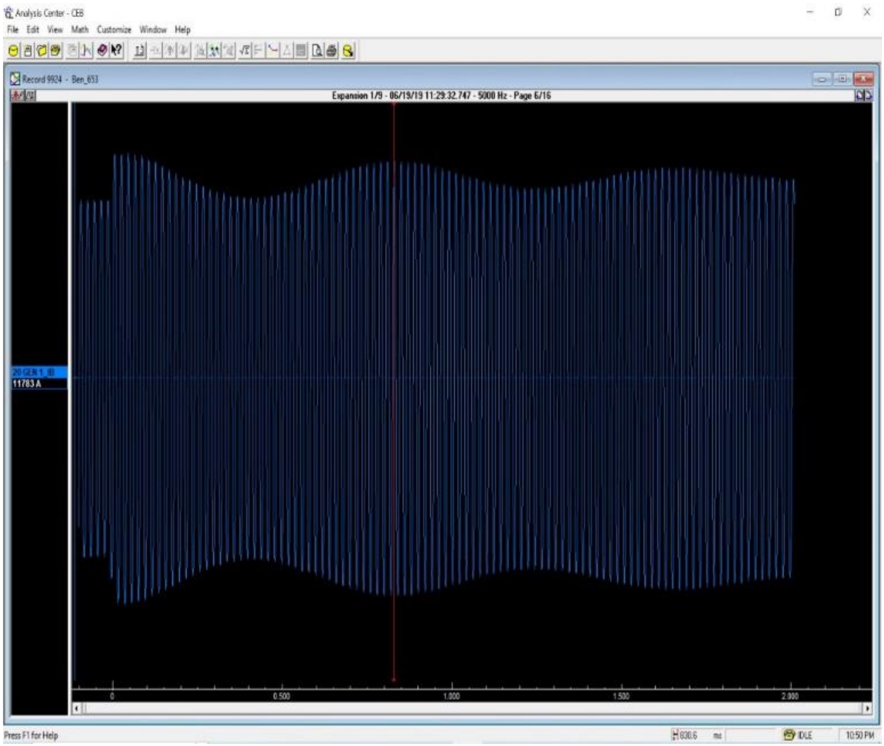


Fig. 4-1. Generator 1 terminal current (Phase B) recorded at fault recorder when incident 1 occurs.

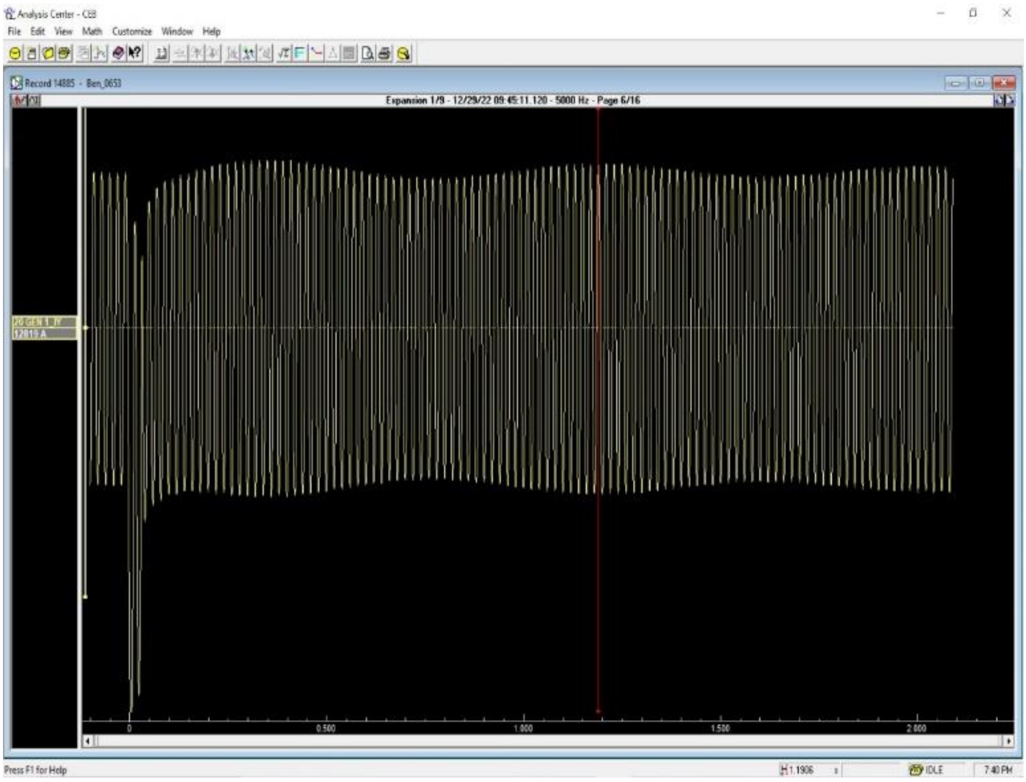


Fig. 4-2. Generator 1 terminal current (Phase Y) recorded at fault recorder when incident 2 occurs.

According to the theories explained in previous chapter here we notice similar snaps of modulated phasors that could be actual scenarios of such modulation of nominal phasors by low modulating frequencies. Therefore it was analyzed the frequency spectrum of these recorded signals. Similar results were obtained for all the incidents and the spectrum of the recorded signal on 19th Jun 2019 is illustrated here. Fig. 4-3.

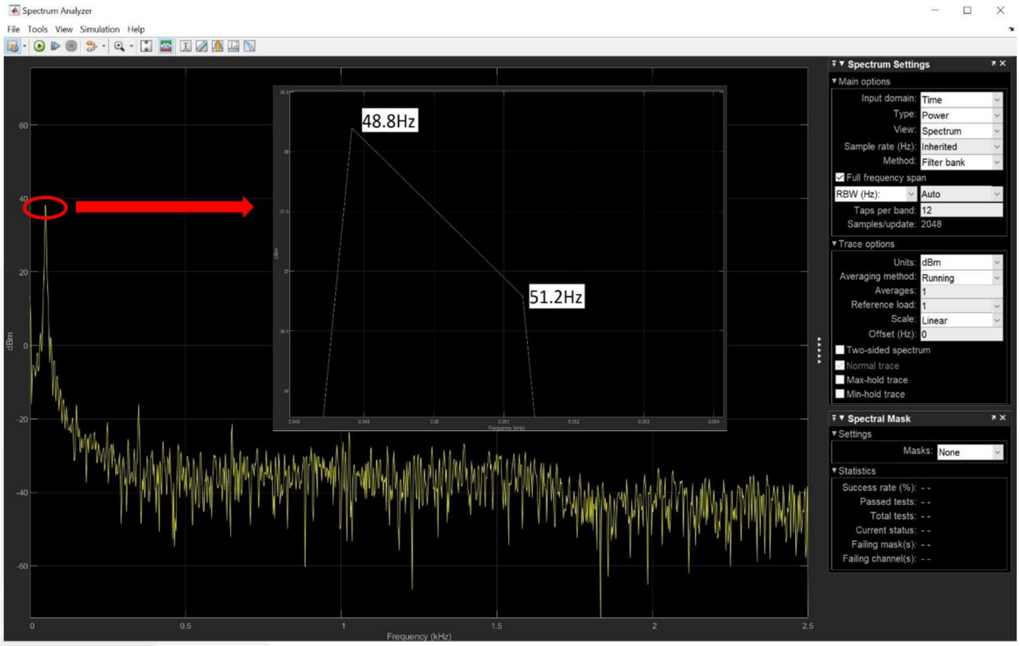


Fig. 4-3. Frequency spectrum of the recorded fault signal of incident 1 on 19th June 2019.

Since Eq. (13) and Eq. (15) includes sums and difference frequency components whereas systems nominal frequency ω_1 is assumed to be 50Hz, the two peaks observed on the spectrum at 48.8Hz and 51.2Hz are related to $\omega_1 - \omega_m$ and $\omega_1 + \omega_m$ respectively.

$$\omega_1 - \omega_m = 2\pi(f_1 - f_m) = 2\pi(48.8Hz) \tag{16}$$

$$\omega_1 + \omega_m = 2\pi(f_1 + f_m) = 2\pi(51.2Hz) \tag{17}$$

This yields,

Nominal frequency $f_1 = 50Hz$ as expected and low modulating frequency as $\boldsymbol{f_m = 1.2Hz}$.

In order to further analyze the noticed low frequency oscillation and to validate the performance of small signal stability study described later a nonlinear model of lakvijaya power station was developed in 'Matlab' simulation platform. This model incorporates the dynamics of Synchronous machines including shaft dynamics, Excitation systems, Turbine and Speed governing system, Transformers and dynamics of network nearby to the plant as shown in Fig. 1-4. In order to study power system oscillations 'Matlab' recommends to use phasor solution method. In this method large machines such as generators and motors are simulated in phasor domain. Which saves much computational time for large power systems comprise of such equipment and reach solutions fast. Therefore the phasor solver technique applied during the simulation. The system responses obtained from detailed simulations closely follow the recorded responses in fault recorders for the two incidents as shown in Fig. 4-4. and Fig. 4-5. It should be noted that 'Matlab' simulation outputs responses in magnitudes since Phasor simulation method is used. This concludes detailed model developed is accurate for further studies.

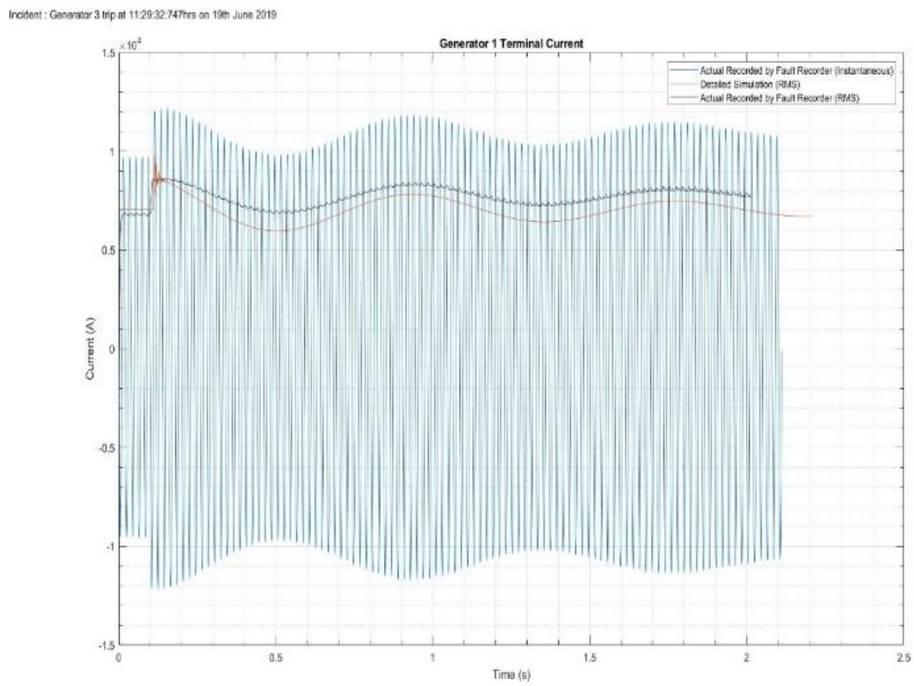


Fig. 4-4. Matlab and Actual magnitudes of the generator terminal current plus the original current waveform for disturbance incident 1, red curve – actual magnitude, black curve – Matlab magnitude, blue curve – original waveform.

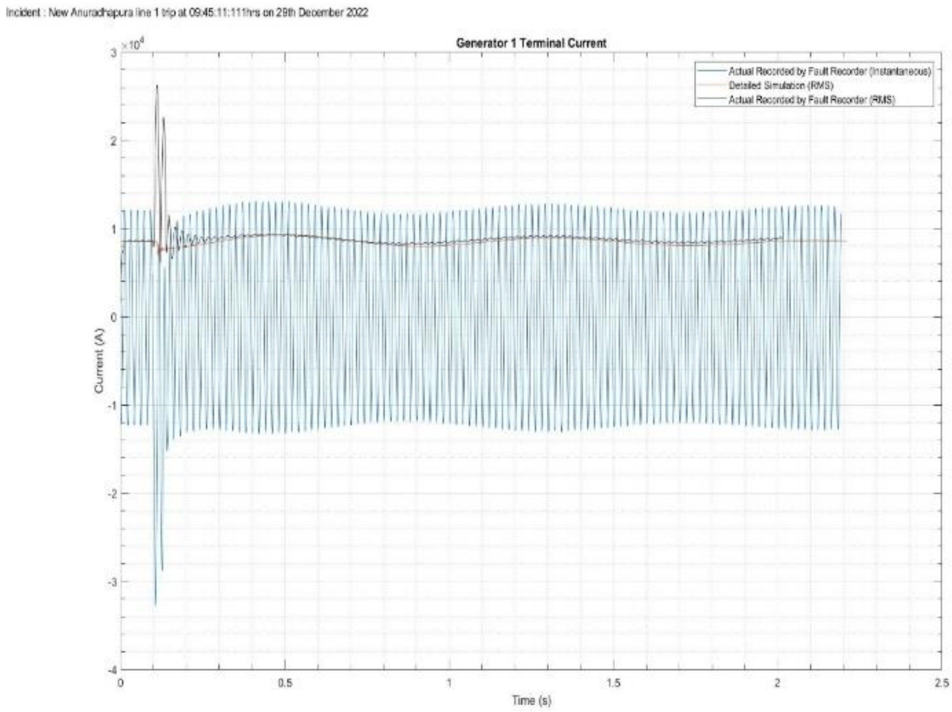


Fig. 4-5. Matlab and Actual magnitudes of the generator terminal current plus the original current waveform for disturbance incident 2, red curve – actual magnitude, black curve – Matlab magnitude, blue curve – original waveform.

4.1 Chapter summary

Being the largest power generation facility in Sri Lanka Lakvijaya power station is always prone to major disturbance events throughout the history. Most of the disturbances had a severe impact on total nation's electrical network. This entire chapter revolves around two major disturbance events took place within the power station's scope and found clearly recorded in Lakvijaya fault recorders. The two incidents occurred on 19th June 2019 and on 12th December 2022. Firstly these two incidents' responses were analyzed in frequency domain. This analysis gave an interesting finding which shows a low frequency oscillation inherent to this power generation facility which was obtained using the theories explained in Chapter 2. Then this chapter discussed how the power system of concern for this study was modeled in Matlab software tool for further analysis of the oscillations described later. The developed non-linear model in Matlab then validated against the real world responses for ensuring the accuracy of the model.

Chapter 5

SMALL SIGNAL STUDY

State space model (Eq. (18) and Eq. (19)) incorporate the synchronous machines; dynamics, Excitation system dynamics, Speed governing system and turbine dynamics, the network is represented by constant admittances. The system data required for this analysis are given in Appendix B. For the purpose of study, model is linearized around steady state operating point before fault happened on 19th June 2019.

$$\Delta\dot{X} = A_{sys}\Delta X + B_{sys}\Delta U \tag{18}$$

$$\Delta Y = C_{sys}\Delta X \tag{19}$$

5.1 Synchronous machines

The synchronous machine model used here incorporate dynamics of stator, rotor, field winding and damper windings. There are three damper windings where two windings are along q-axis and one damper winding along d-axis together with the field winding. It is a 6th order model. Following Fig. 5-1. illustrates the equivalent circuits along d-q axis whereas equations Eq. (20) to Eq. (25) show corresponding differential equations [10].

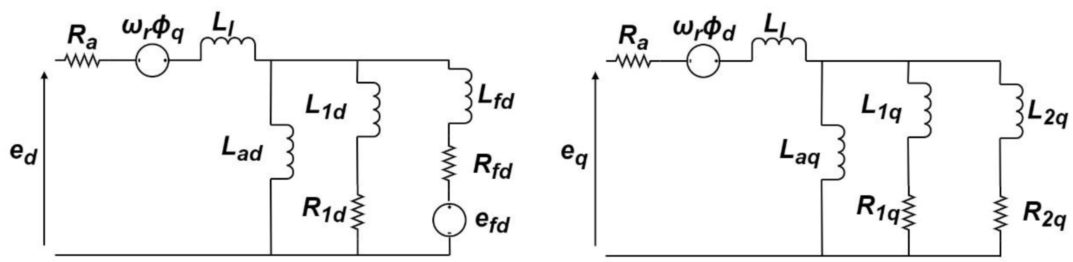


Fig. 5-1. Equivalent circuit (d-axis) - left and equivalent circuit (q-axis) - right.

$$\Delta\dot{\omega}_r = \frac{1}{2H}\left\{\overline{T}_m - \left(\psi_{ad}\imath_q - \psi_{aq}\imath_d\right) - K_D\Delta\omega_r\right\}$$

(20)

$$\dot{\delta} = \omega_0 \Delta\omega_r$$

(21)

$$\dot{\psi}_{fd} = \frac{\omega_0 R_{fd}}{L_{adu}} E_{fd} - \frac{\omega_0 R_{fd}}{L_{fd}} \psi_{fd} + \frac{\omega_0 R_{fd}}{L_{fd}} \left\{ L''_{ads} \left(-i_d + \frac{\psi_{fd}}{L_{fd}} + \frac{\psi_{1d}}{L_{1d}} \right) \right\}$$

(22)

$$\dot{\psi}_{1d} = \omega_0 \left\{ -\frac{R_{1d}}{L_{1d}} \psi_{1d} + \frac{R_{1d}}{L_{1d}} L''_{ads} \left(-i_d + \frac{\psi_{fd}}{L_{fd}} + \frac{\psi_{1d}}{L_{1d}} \right) \right\}$$

(23)

$$\dot{\psi}_{1q} = \omega_0 \left\{ -\frac{R_{1q}}{L_{1q}} \psi_{1q} + \frac{R_{1q}}{L_{1q}} L''_{aqs} \left(-i_q + \frac{\psi_{1q}}{L_{1q}} + \frac{\psi_{2q}}{L_{2q}} \right) \right\}$$

(24)

$$\dot{\psi}_{2q} = \omega_0 \left\{ -\frac{R_{2q}}{L_{2q}} \psi_{2q} + \frac{R_{2q}}{L_{2q}} L''_{aqs} \left(-i_q + \frac{\psi_{1q}}{L_{1q}} + \frac{\psi_{2q}}{L_{2q}} \right) \right\}$$

(25)

Where;

$$\psi_{ad} = L''_{ads} \left(-i_d + \frac{\psi_{fd}}{L_{fd}} + \frac{\psi_{1d}}{L_{1d}} \right)$$

$$\psi_{aq} = L''_{aqs} \left(-i_q + \frac{\psi_{1q}}{L_{1q}} + \frac{\psi_{2q}}{L_{2q}} \right)$$

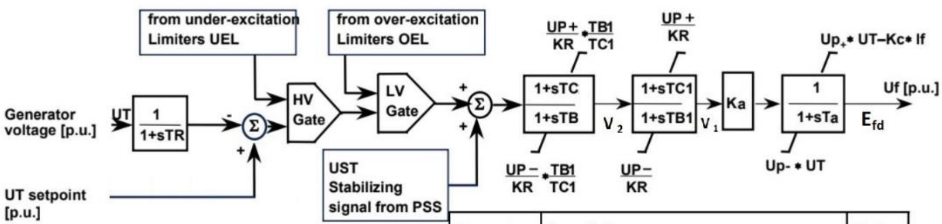
$$L''_{ads} = \frac{1}{\frac{1}{L_{ads}} + \frac{1}{L_{fd}} + \frac{1}{L_{1d}}}$$

$$L''_{aqs} = \frac{1}{\frac{1}{L_{aqs}} + \frac{1}{L_{1q}} + \frac{1}{L_{2q}}}$$

After linearization using Taylor expansion approximation and transforming to an common reference as explained shortly later this will be in $\Delta\dot{X} = f(\Delta X, \Delta U, \Delta I)$ format. The state variables used to represent a synchronous generator are $\boldsymbol{\Delta\omega}$, $\boldsymbol{\Delta\delta}$, $\boldsymbol{\Delta\psi_{fd}}$, $\boldsymbol{\Delta\psi_{1d}}$, $\boldsymbol{\Delta\psi_{1q}}$, $\boldsymbol{\Delta\psi_{2q}}$.

5.2 Excitation systems

IEEE 421-5 type ST1A excitation system [11] developed by ABB (UNITROL 5000 model) is operational at the power plant. The exciter model shown in Fig. 5-2. Considering the small changes associated with small signal stability studies, the linearized differential equation of the model listed in Eq. (26) to Eq. (28). In this type of system, K_a, T_a represents the exciter and T_R represents the terminal voltage measurement device whereas lead lag blocks represents the controller [12].



Parameter	Description	Unit
TR	Measuring filter time constant	s
Ts	Gate control unit and converter time constant	s
KR	Steady state gain	p.u.
Kc	Voltage drop due to commutation	p.u.
TB	Controller first lag time constant	s
TB1	Controller second lag time constant	s
TC	Controller first lead time constant	s
TC1	Controller second lead time constant	s
Up+	AVR output positive ceiling value	p.u.
Up-	AVR output negative ceiling value	p.u.

Fig. 5-2. Block diagram of IEEE ST1A type exciter model implemented at the power plant [13].

With the usual notations and the states shown in the above model,

$$\Delta\dot{V}_2' = \frac{-1}{T_b}\left\{\frac{e_d}{|E_t|}\left(-R_a I_R \cos\delta - R_a I_I \sin\delta - X'' I_R \sin\delta + X'' I_I \cos\delta\right)\right.$$
$$\left. + \frac{e_d}{|E_t|}\left(-X'' I_R \cos\delta - X'' I_I \sin\delta + R_a I_R \sin\delta - R_a I_I \cos\delta\right)\right\}\Delta\delta$$
$$- \frac{e_q L''_{ads}}{T_b|E_t|L_{fd}}\Delta\psi_{fd} - \frac{e_q L''_{ads}}{T_b|E_t|L_{1d}}\Delta\psi_{1d} + \frac{e_d L''_{aqs}}{T_b|E_t|L_{1q}}\Delta\psi_{1q}$$
$$+ \frac{e_d L''_{aqs}}{T_b|E_t|L_{2q}}\Delta\psi_{2q} - \frac{1}{T_b}\Delta V_2' + \frac{1}{T_b}\Delta V_{ref}$$
$$- \frac{1}{T_b}\left\{\frac{e_d}{|E_t|}\left(-R_a \sin\delta + X'' \cos\delta\right) + \frac{e_d}{|E_t|}\left(-X'' \sin\delta - R_a \cos\delta\right)\right\}\Delta I_R$$
$$- \frac{1}{T_b}\left\{\frac{e_d}{|E_t|}\left(R_a \cos\delta + X'' \sin\delta\right) + \frac{e_d}{|E_t|}\left(X'' \cos\delta - R_a \sin\delta\right)\right\}\Delta I_I$$

(26)

$$\Delta\dot{V}_1' = \frac{-T_c}{T_{b1}T_b}\left\{\frac{e_d}{|E_t|}\left(-R_a I_R \cos\delta - R_a I_I \sin\delta - X'' I_R \sin\delta + X'' I_I \cos\delta\right)\right.$$
$$\left. + \frac{e_d}{|E_t|}\left(-X'' I_R \cos\delta - X'' I_I \sin\delta + R_a I_R \sin\delta - R_a I_I \cos\delta\right)\right\}\Delta\delta$$
$$- \frac{T_c e_q L''_{ads}}{T_{b1}T_b|E_t|L_{fd}}\Delta\psi_{fd} - \frac{T_c e_q L''_{ads}}{T_{b1}T_b|E_t|L_{1d}}\Delta\psi_{1d} + \frac{T_c e_d L''_{aqs}}{T_{b1}T_b|E_t|L_{1q}}\Delta\psi_{1q}$$
$$+ \frac{T_c e_d L''_{aqs}}{T_{b1}T_b|E_t|L_{2q}}\Delta\psi_{2q} + \frac{1}{T_{b1}}\left[1 - \frac{T_c}{T_b}\right]\Delta V_2' - \frac{1}{T_b}\Delta V_1' + \frac{T_c}{T_{b1}T_b}\Delta V_{ref}$$
$$- \frac{T_c}{T_{b1}T_b}\left\{\frac{e_d}{|E_t|}\left(-R_a \sin\delta + X'' \cos\delta\right)\right.$$
$$\left. + \frac{e_d}{|E_t|}\left(-X'' \sin\delta - R_a \cos\delta\right)\right\}\Delta I_R$$
$$- \frac{T_c}{T_{b1}T_b}\left\{\frac{e_d}{|E_t|}\left(R_a \cos\delta + X'' \sin\delta\right) + \frac{e_d}{|E_t|}\left(X'' \cos\delta - R_a \sin\delta\right)\right\}\Delta I_I$$

(27)

$$\Delta\dot{E}_{fd} = \frac{-K_a T_{c1} T_c}{T_a T_{b1} T_b}\left\{\frac{e_d}{|E_t|}\left(-R_a I_R \cos\delta - R_a I_I \sin\delta - X^{"} I_R \sin\delta + X^{"} I_I \cos\delta\right)\right.$$
$$\left. + \frac{e_d}{|E_t|}\left(-X^{"} I_R \cos\delta - X^{"} I_I \sin\delta + R_a I_R \sin\delta - R_a I_I \cos\delta\right)\right\}\Delta\delta$$
$$- \frac{K_a T_{c1} T_c e_q L^{"}_{ads}}{T_a T_{b1} T_b |E_t| L_{fd}}\Delta\psi_{fd} - \frac{K_a T_{c1} T_c e_q L^{"}_{ads}}{T_a T_{b1} T_b |E_t| L_{1d}}\Delta\psi_{1d}$$
$$+ \frac{K_a T_{c1} T_c e_d L^{"}_{aqs}}{T_a T_{b1} T_b |E_t| L_{1q}}\Delta\psi_{1q} + \frac{K_a T_{c1} T_c e_d L^{"}_{aqs}}{T_a T_{b1} T_b |E_t| L_{2q}}\Delta\psi_{2q}$$
$$+ \frac{K_a T_{c1}}{T_a T_{b1}}\left[1 - \frac{T_c}{T_b}\right]\Delta V_2' + \frac{K_a}{T_a}\left[1 - \frac{T_{c1}}{T_{b1}}\right]\Delta V_1' - \frac{1}{T_a}\Delta E_{fd} + \frac{K_a T_{c1} T_c}{T_a T_{b1} T_b}\Delta V_{ref}$$
$$- \frac{K_a T_{c1} T_c}{T_a T_{b1} T_b}\left\{\frac{e_d}{|E_t|}\left(-R_a \sin\delta + X^{"} \cos\delta\right)\right.$$
$$\left. + \frac{e_d}{|E_t|}\left(-X^{"} \sin\delta - R_a \cos\delta\right)\right\}\Delta I_R$$
$$- \frac{K_a T_{c1} T_c}{T_a T_{b1} T_b}\left\{\frac{e_d}{|E_t|}\left(R_a \cos\delta + X^{"} \sin\delta\right) + \frac{e_d}{|E_t|}\left(X^{"} \cos\delta\right.\right.$$
$$\left.\left. - R_a \sin\delta\right)\right\}\Delta I_I \tag{28}$$

Therefore the excitation system adds three state variables (**$\Delta V'_2$** , **$\Delta V'_1$** , **ΔE_{fd}**) into the individual generator state space model.

5.3 Speed Governing system with steam turbine

Speed governing system consists proportional regulator and a speed relay similar to the model proposed in [14] as below Fig. 5-3. is functioning at the power station. First order models were used to represent the steam turbines (Fig. 5-4.). These transfer functions simulate the two main stages of the steam turbine at LVPP. They are High/Intermediate Pressure Turbine (HIP) stage and Low Pressure Turbine (LP) stage.

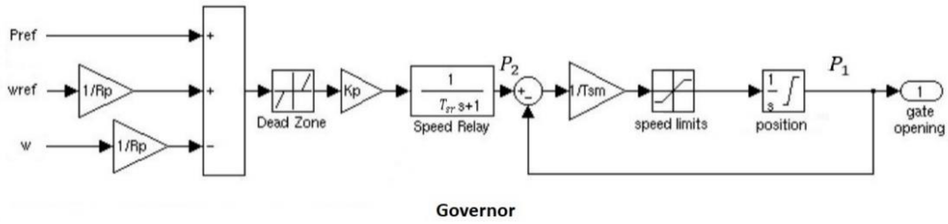


Fig. 5-3. Real power plant model of speed governor implemented.

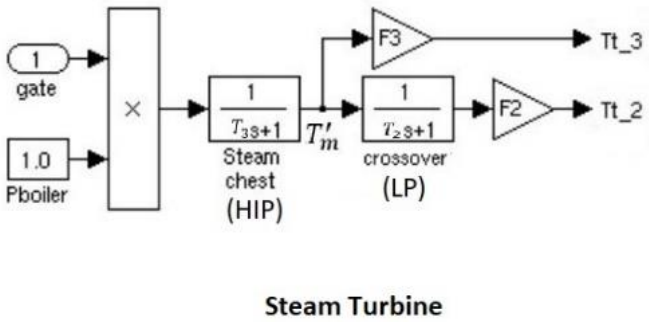


Fig. 5-4. Block diagram of multi-stage turbine model.

Linearized equations associated with the speed governing system and steam turbines are,

$$\Delta\dot{P}_2 = \frac{-K_p}{R_p T_{sr}}\Delta\omega - \frac{1}{T_{sr}}\Delta P_2 + \frac{K_p}{T_{sr}}\Delta P_{ref} \tag{29}$$

$$\Delta\dot{P}_1 = \frac{1}{T_{sm}}\Delta P_2 - \frac{1}{T_{sm}}\Delta P_1 \tag{30}$$

$$\Delta\dot{T}'_m = \frac{1}{T_3}\Delta P_1 - \frac{1}{T_3}\Delta T'_m \tag{31}$$

Hence the speed governor with steam turbine also add three state variables (**ΔP_2** , **ΔP_1** , **ΔT_m**) into the individual generator state space model

5.4 Multi-mass shaft system

As shown below turbine shaft has two masses. Since it is coupled to the generator there are total of three masses which is used to represent the turbine-generator shaft. (Fig. 5-5.)

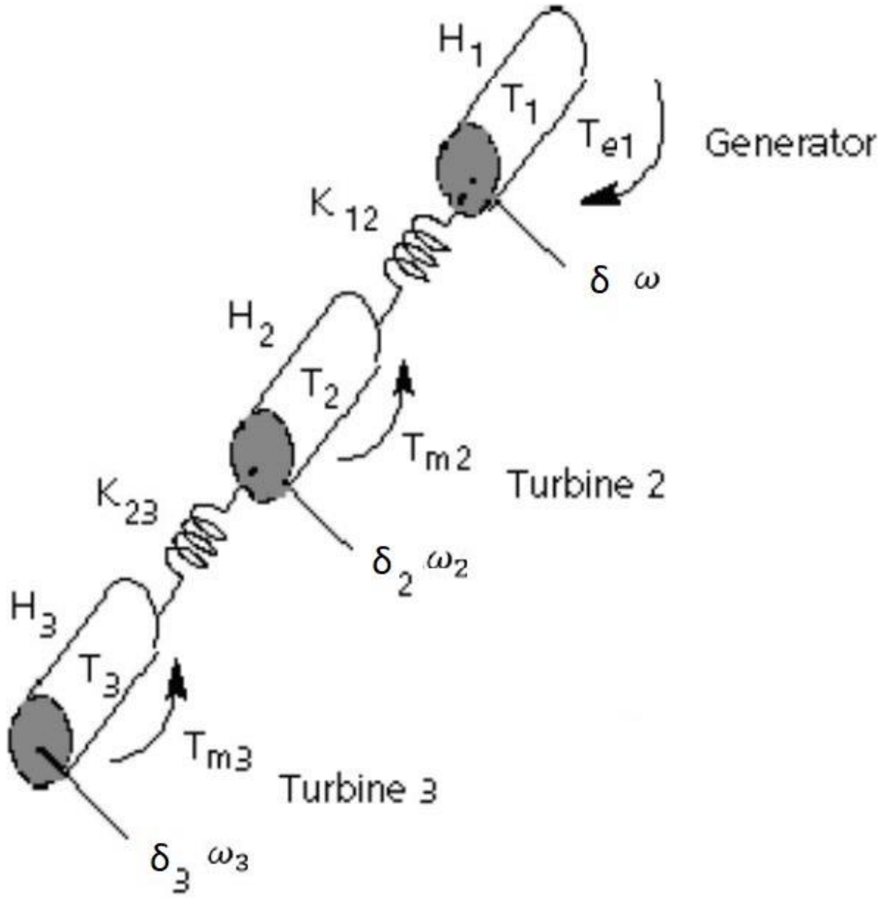


Fig. 5-5. Multi-mass shaft system model which includes three shaft sections of two turbine stages and generator.

Linearized equations of the multi-mass system model are,

$$\Delta\dot{\omega}_3 = \frac{F_3}{2H_3}\Delta T'_m - \frac{D_3}{2H_3}\Delta\omega_3 - \frac{K_{23}}{2H_3}\Delta\delta_3 + \frac{K_{23}}{2H_3}\Delta\delta_2 \tag{32}$$

$$\Delta\dot{\delta}_3 = \omega_0\Delta\omega_3 \tag{33}$$

$$\Delta\dot{\omega}_2 = \frac{K_{12}}{2H_2}\Delta\delta + \frac{F_2}{2H_2}\Delta T'_m + \frac{K_{23}}{2H_2}\Delta\delta_3 - \frac{D_2}{2H_2}\Delta\omega_2 - \left(\frac{K_{23}+K_{12}}{2H_2}\right)\Delta\delta_2 \tag{34}$$

$$\Delta\dot{\delta}_2 = \omega_0\Delta\omega_2 \tag{35}$$

Thus the multi-mass model adds four more state variables (**$\Delta\omega_3$** , **$\Delta\delta_3$** , **$\Delta\omega_2$** , **$\Delta\delta_2$**) into the individual generator state space model.

5.5 Development of small signal model and validation

Considering all sub systems' state space representations explained previously each generating unit is represented by 16 no's of distinct state variables as shown below Fig. 5-6. Finally considering all three units at the power station there are 48 no's of state variables which follows $\Delta\dot{X} = \mathrm{f}\,(\Delta\mathrm{X}, \Delta\mathrm{U}, \Delta\mathrm{I})$ relationship.

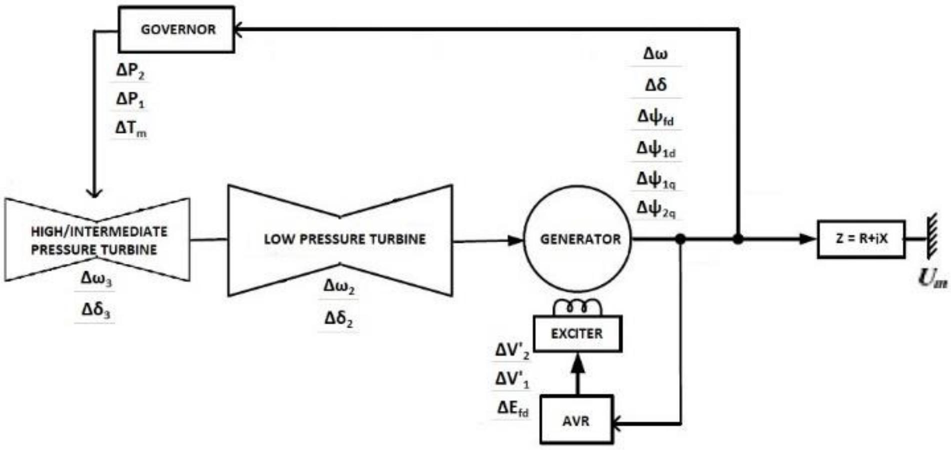


Fig. 5-6. Summary of state variables to represent a generating unit.

Table 5-1: SUMMARY OF STATE VARIABLES

System	**State Variables**	**No's**
Synchronous Generator	$\Delta\omega$, $\Delta\delta$, $\Delta\psi_{fd}$, $\Delta\psi_{1d}$, $\Delta\psi_{1q}$, $\Delta\psi_{2q}$	6
Excitation System	$\Delta V'_2$, $\Delta V'_1$, ΔE_{fd}	3
Speed Governing system with Steam Turbine system	ΔP_2 , ΔP_1 , ΔT_m	3
Multi-mass Shaft system	$\Delta\omega_3$, $\Delta\delta_3$, $\Delta\omega_2$, $\Delta\delta_2$	4
Total		**16**

From the explanations done in previous sections it was explained that each machines are represented using a reference d-q frame. But it is to be noted that these frames are corresponding to that individual machine only. Rotation of this each d-q frame corresponds to their own rotor movement. Therefore one might argue we cannot associate different machines in separate domains to have an overall understanding. This problem is solved by putting them all in a common domain by means of a common synchronously rotating reference. So that to compare all machines and network with respect to this reference. This common reference hereafter named as R-I frame. Eq. (36) and Eq. (37) gives the relationship between d-q frames and R-I frame. These are used to transform voltages and currents between the frames. The linearization of these equations to be done accordingly in order to incorporate with the small signal analysis of this study.

$$\begin{bmatrix} e_q \\ e_d \end{bmatrix} = \begin{bmatrix} \cos\delta & \sin\delta \\ \sin\delta & -\cos\delta \end{bmatrix} \begin{bmatrix} E_R \\ E_I \end{bmatrix}$$

(36)

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \cos\delta & \sin\delta \\ \sin\delta & -\cos\delta \end{bmatrix} \begin{bmatrix} I_R \\ I_I \end{bmatrix}$$

(37)

Following algebraic equations are used to represent the relationship of stator terminal currents to stator terminal voltages of the synchronous machines [15].

$$e_q = -R_a i_q + \omega_r \psi_d = -R_a I_q - X_d'' i_d + E_q''$$

(38)

$$e_d = -R_a i_d - \omega_r \psi_q = -R_a I_d - X_q'' i_q + E_d''$$

(39)

Where,

$$E_d'' = -\omega_r L_{aq}'' \left[\frac{\psi_{1q}}{L_{1q}} + \frac{\psi_{2q}}{L_{2q}} \right]$$

$$E_q'' = -\omega_r L_{ad}'' \left[\frac{\psi_{fd}}{L_{fd}} + \frac{\psi_{1d}}{L_{1d}}\right]$$

After transformation from d-q frame to common reference frame R-I and linearization around an operating point this can be written as $\Delta I = g(\Delta X, \Delta V)$ and since the network equation is $\Delta I = Y\Delta V$ as usual, then $\Delta\dot{X} = A_{sys}\Delta X + B_{sys}\Delta U$ represents the all-inclusive total system in state space model.

The step response for 10% step input obtained from small signal model closely follows the step response of Matlab detailed simulation as shown in Fig. 5-7. This concludes the small signal model developed is accurate enough for further analysis.

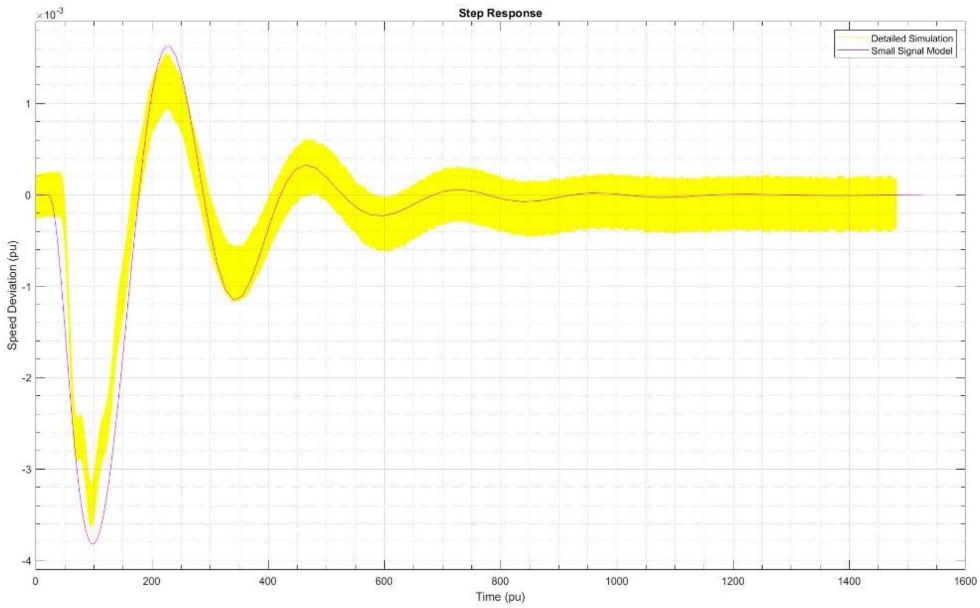


Fig. 5-7. Generator speed response comparison for 10% step input signal.

5.6 Chapter summary

This chapter systematically derived the small signal model for the overall system of concern. Considering the normal steady state operation the three generating units' models were linearized. All the synchronous generators were modelled using equations given and then it is linearized using Taylor expansion approximation.

Similarly the excitation system which is installed at the facility which is an IEEE standard model ST1A also modelled for each generator giving three state variables. Then speed governing system model of first order differential equations yields three more state variables to the state space representation. The model used to express the turbine generator shafts having multiple masses incorporate four state variables for single generating unit. This model helps in extracting torsional modes. Therefore one single generating unit represent by sixteen numbers of state variable. All the three units combined represented by forty eight numbers of state variables.

The algebraic equations which gives the relationship of stator terminal voltage and current are then used to reduce the number of variables of the system. The network is presented by a constant admittance model which could represent low frequency transients such as electromechanical oscillations fairly accurate. At the end the validation of small signal model was done against the Matlab simulation model explained in chapter 3. This proves model accuracy for further analysis.

Chapter 6

DETAILED STABILITY ANALYSIS RESULTS

The location of eigenvalues in the complex plane determines the relative stability of a system in conventional approach. Hence for a small signal study which assess the stability around steady state, the location of eigenvalues should be at negative real side of the complex plane. Then only we can say the power system is stable for little disturbances. Since there are 48 distinct state variable to represent the system of interest, obtained 48 no's of eigenvalues of the entire system and all satisfy the above criterion. Out of this 48 there are 12 no's of pairs of oscillatory modes which are shown here (Table 6-1) along with their natural frequencies and damping ratios. It is to be noted that for a physical system oscillatory modes occur in complex conjugate pairs.

Table 6-1: DETAILS OF OSCILATORY MODES

Oscillatory mode	**Eigenvalue**	**f (Hz)**	**D (%)**
1	-0.0006 ± 1.9863i	99.3188	0.0303
2	-0.0006 ± 1.9863i	99.3188	0.0303
3	-0.0006 ± 1.9863i	99.3188	0.0303
4	-0.0521 ± 0.0535i	3.7349	69.7599
5	-0.0060 ± 0.0250i	1.2878	23.5004
6	-0.0072 ± 0.0365i	1.8641	19.4227

7	-0.0060 ± 0.0369i	1.8719	16.1414
8	-0.0538 ± 0.0207i	2.8838	93.3045
9	-0.0541 ± 0.0161i	2.8245	95.8008
10	-0.0002 ± 0.6503i	32.5152	0.0414
11	-0.0002 ± 0.6503i	32.5152	0.0414
12	-0.0002 ± 0.6503i	32.5152	0.0414

It is accepted that oscillatory modes should be well damped. If it is less than 5 % those modes can be critical if they are electromechanical oscillations. Otherwise whence these modes get excited it will dominate over system stability [16]. Note that the mode 5 has nearly the same frequency of 1.2Hz (~0.25pu) of low frequency modulating signal noticed with actual fault incidents mentioned earlier. This is probably the excited mode in those disturbances.

Not only there are the above mentioned straightforward method of using the eigenvalues, there are other interesting sophisticated ways to analyze the power system stability. The coming sections will explain such techniques further. These might be very useful in determining control strategies for secure operation in further studies. Modes with lowest damping ratios are considered for further analysis.

6.1 Participation of dominant oscillatory modes

At this section participation factors are calculated. Which is indicative of relative participation of each states to the modes of concerned. That is to realize how the critical modes are contributed highly by the states in net values. For this purpose we create a participation matrix. It is a combination of Eigen matrices right and left. Elements in each matrix multiplied by other matrix element in a way that gives the association. The right eigenvector is an indication of behavior of various states in a particular mode. On the other hand left eigenvector gives the allowance of each states to excite a mode. In combination of these two represent the net participation between modes and states [15]. As a concluding note participation factors are a measure of relative participation. Participation of states to modes.

Fig. 6-1., Fig. 6-2., Fig 6-3., and Fig. 6-4. are used to illustrate the participation factors graphically at mode 1, mode 5, mode 7, and mode 10 respectively. These participation factors are normalized for more clarity. It is clear for mode 1 highly contributing states are of unit 1. Similarly mode 2 and mode 3 are highly contributed by unit 2 and unit 3. Mode 5 which is a local pant mode is contributed by states of all the units as expected. Mode 7 is highly participated by the states of unit 2 and unit 3 whereas mode 6 is mostly by the unit 1. States of the unit 1 majorly contributed in mode 10 and for the mode 11 and mode 12, unit 2 and unit 3 are participating respectively.

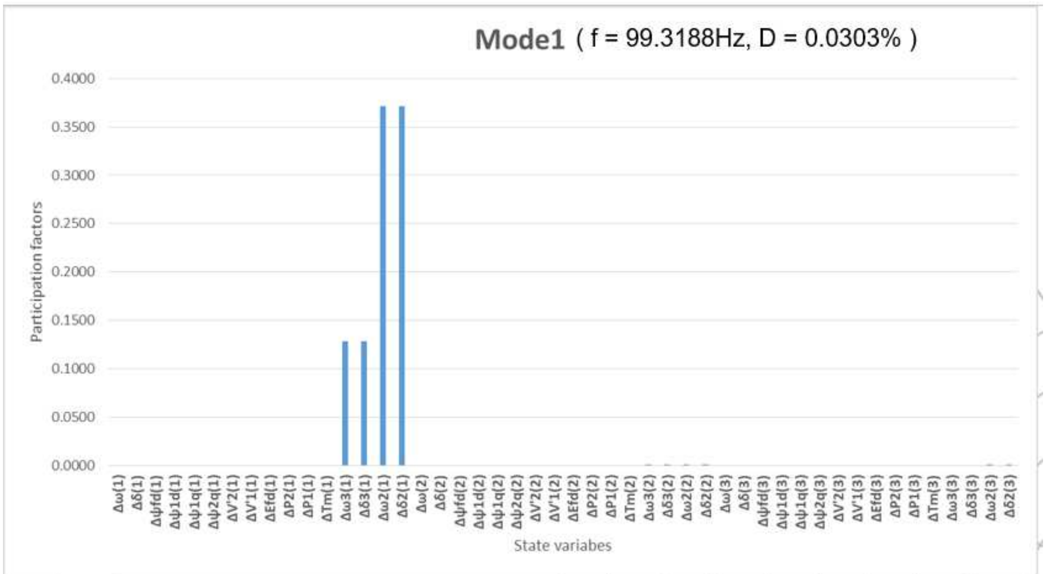


Fig. 6-1. Participation factors of Oscillatory mode 1, Δω3 (1) - High / Intermediate Pressure turbine (HIP) speed deviation (Unit 1), Δδ3 (1) - High / Intermediate Pressure turbine (HIP) rotor angle deviation (Unit 1), Δω2 (1) - Low Pressure (LP) turbine speed deviation (Unit 1), Δδ2 (1) - Low Pressure turbine (LP) rotor angle deviation (Unit 1).

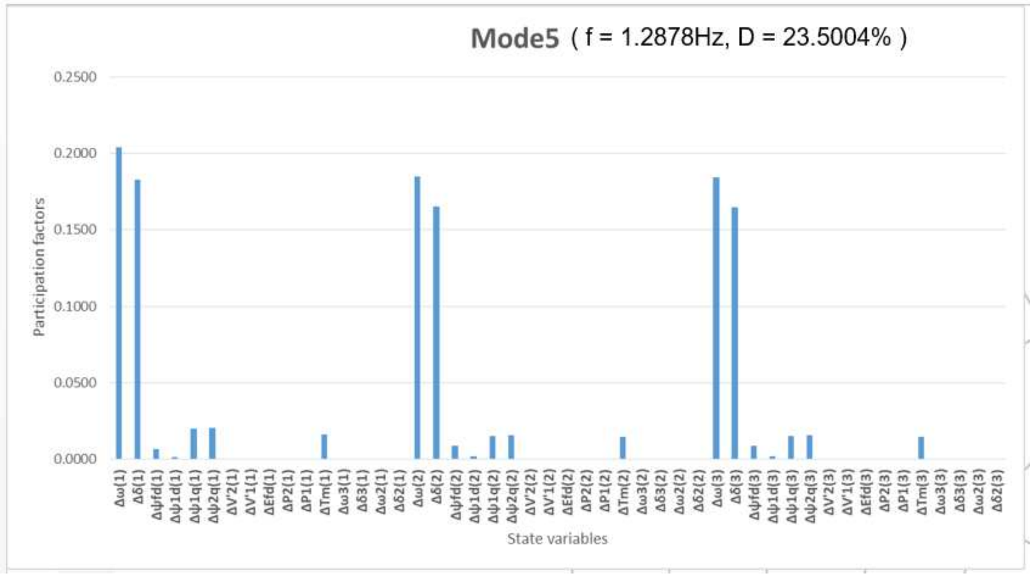


Fig. 6-2. Participation factors of Oscillatory mode 5, Δω (1) - Generator speed deviation (Unit 1), Δδ (1) - Generator rotor angle deviation (Unit 1), Δω (2) - Generator speed deviation (Unit 2), Δδ (2) - Generator rotor angle deviation (Unit 2), Δω (3) - Generator speed deviation (Unit 3), Δδ (3) - Generator rotor angle deviation (Unit 3).

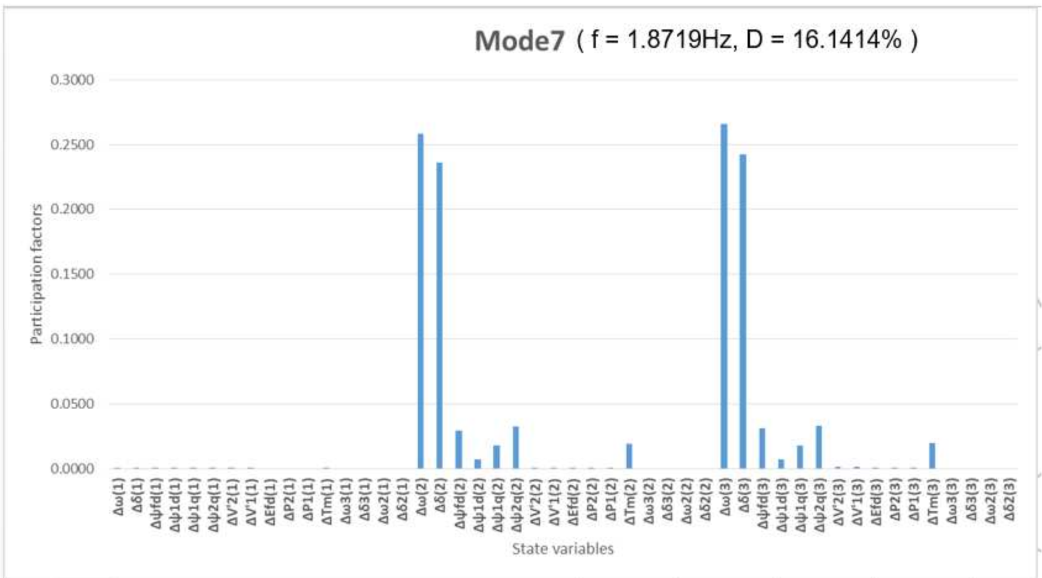


Fig. 6-3. Participation factors of Oscillatory mode 7, Δω (2) - Generator speed deviation (Unit 2), Δδ (2) - Generator rotor angle deviation (Unit 2), Δω (3) - Generator speed deviation (Unit 3), Δδ (3) - Generator rotor angle deviation (Unit 3).

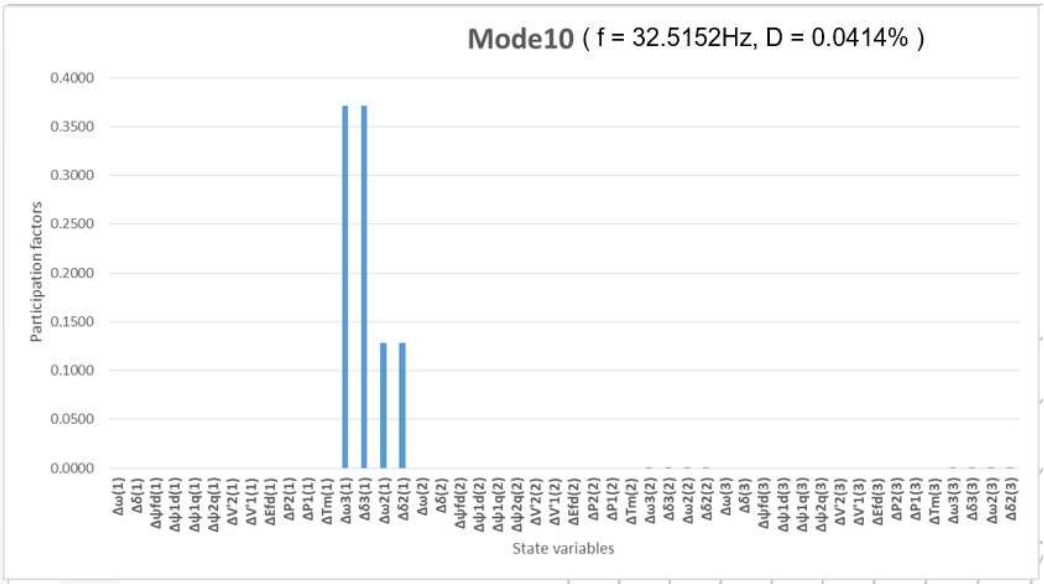


Fig. 6-4. Participation factors of Oscillatory mode 10, Δω3 (1) - High / Intermediate Pressure turbine (HIP) speed deviation (Unit 1), Δδ3 (1) - High / Intermediate Pressure turbine (HIP) rotor angle deviation (Unit 1), Δω2 (1) - Low Pressure (LP) turbine speed deviation (Unit 1), Δδ2 (1) - Low Pressure turbine (LP) rotor angle deviation (Unit 1).

The normalized participation factors of remaining oscillatory modes 2, mode 3, mode 6, mode 11, and mode 12 are also shown below Fig. 6-5., Fig. 6-6., Fig 6-7., and Fig. 6-8.. These will help to understand the respective states behavior at each of those modes as well.

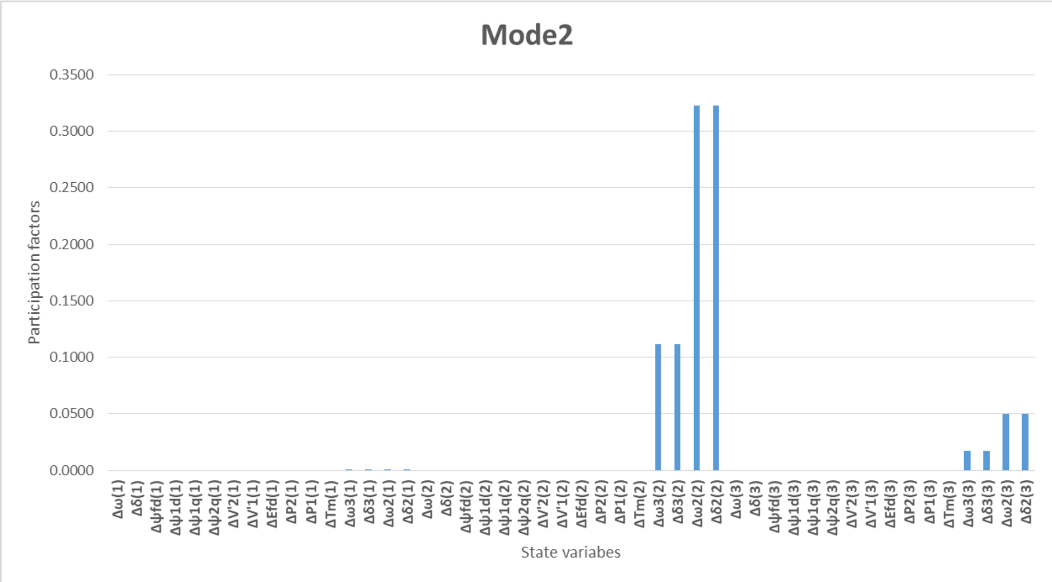


Fig. 6-5. Participation factors of Oscillatory mode 2, Δω3 (2) - High / Intermediate Pressure turbine (HIP) speed deviation (Unit 2), Δδ3 (2) - High / Intermediate Pressure turbine (HIP) rotor angle deviation (Unit 2), Δω2 (2) - Low Pressure (LP) turbine speed deviation (Unit 2), Δδ2 (2) - Low Pressure turbine (LP) rotor angle deviation (Unit 2).

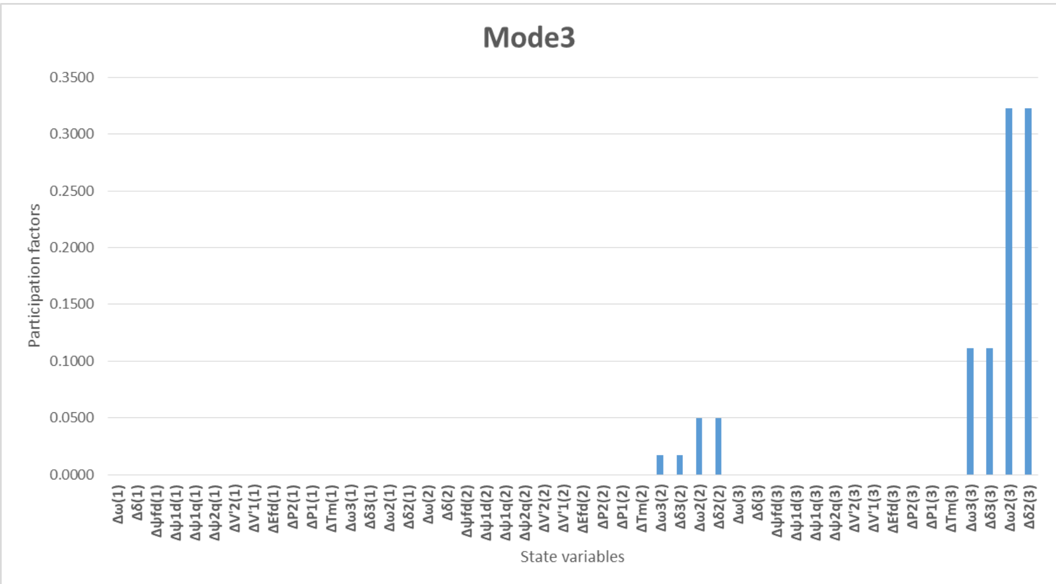


Fig. 6-6. Participation factors of Oscillatory mode 3, Δω3 (3) - High / Intermediate Pressure turbine (HIP) speed deviation (Unit 3), Δδ3 (3) - High / Intermediate Pressure turbine (HIP) rotor angle deviation (Unit 3), Δω2 (3) - Low Pressure (LP)

turbine speed deviation (Unit 3), Δδ2 (3) - Low Pressure turbine (LP) rotor angle deviation (Unit 3).

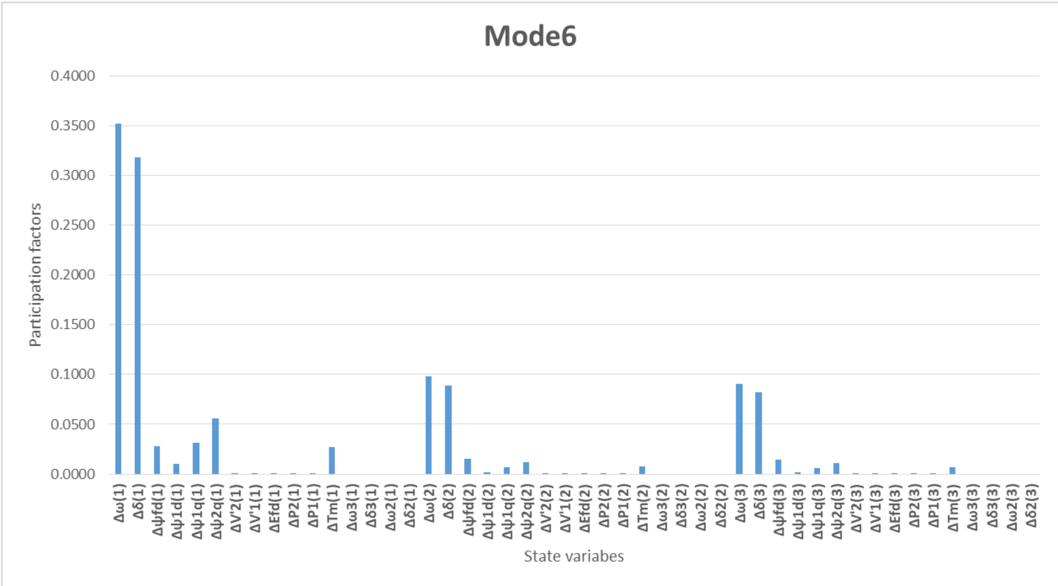


Fig. 6-7. Participation factors of Oscillatory mode 6, Δω(1) - Generator speed deviation (Unit 1), Δδ(1) - Generator rotor angle deviation (Unit 1), Δω(2) - Generator speed deviation (Unit 2), Δδ(2) - Generator rotor angle deviation (Unit 2), Δω(3) - Generator speed deviation (Unit 3), Δδ(3) - Generator rotor angle deviation (Unit 3).

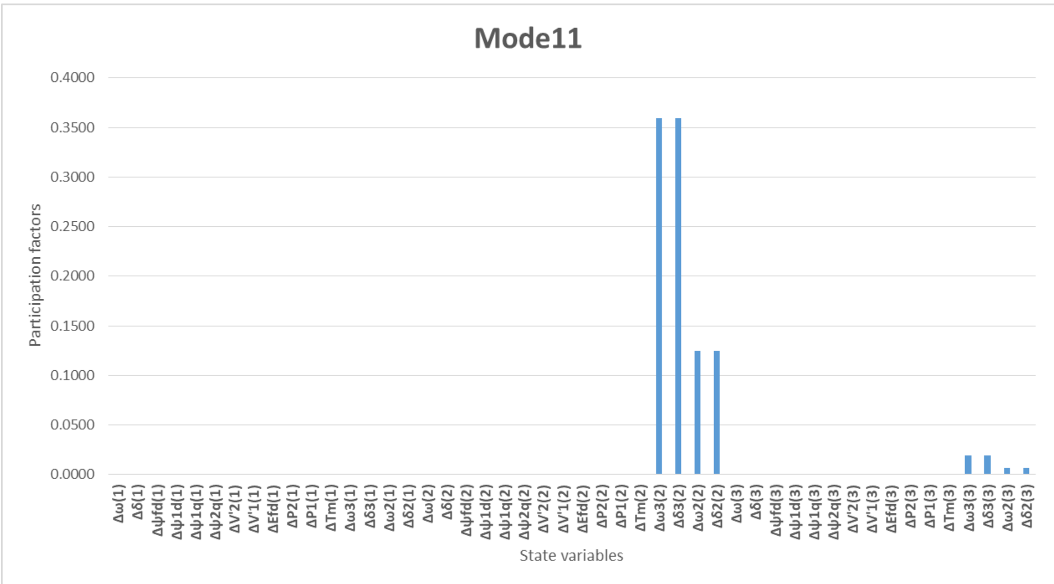


Fig. 6-8. Participation factors of Oscillatory mode 11, Δω3 (2) - High / Intermediate Pressure turbine (HIP) speed deviation (Unit 2), Δδ3 (2) - High / Intermediate

Pressure turbine (HIP) rotor angle deviation (Unit 2), Δω2 (2) - Low Pressure (LP) turbine speed deviation (Unit 2), Δδ2 (2) - Low Pressure turbine (LP) rotor angle deviation (Unit 2).

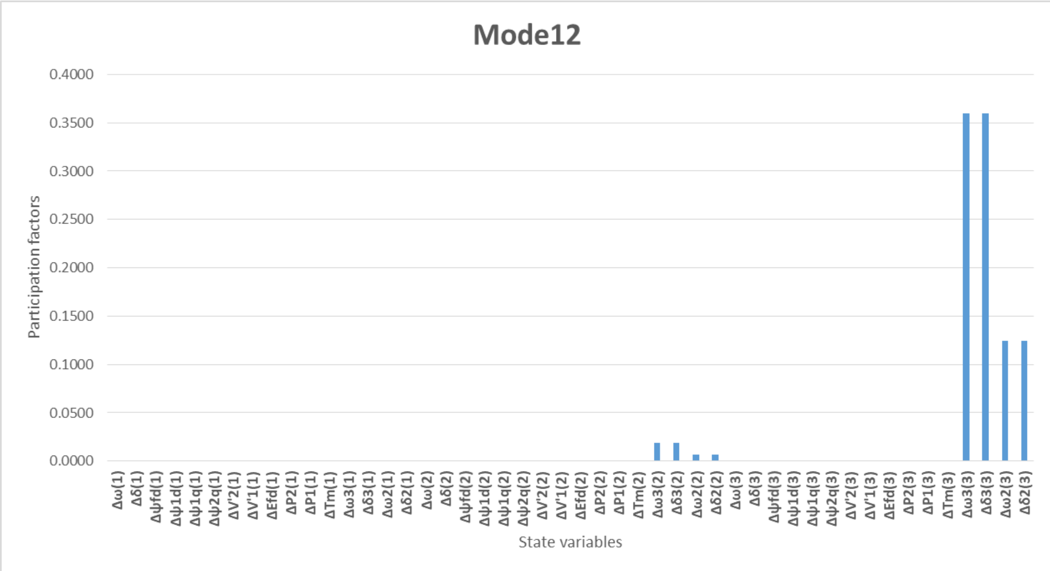


Fig. 6-9. Participation factors of Oscillatory mode 12, Δω3 (3) - High / Intermediate Pressure turbine (HIP) speed deviation (Unit 3), Δδ3 (3) - High / Intermediate Pressure turbine (HIP) rotor angle deviation (Unit 3), Δω2 (3) - Low Pressure (LP) turbine speed deviation (Unit 3), Δδ2 (3) - Low Pressure turbine (LP) rotor angle deviation (Unit 3).

6.2 Mode shapes of oscillatory modes

Mode shape calculations are good indicative of relative activities of states in a particularly activated mode. The activation of such a mode can be reasoned due to disturbance happen in the system [16]. Mode shapes calculations consider mainly two things of right eigenvectors. Those are magnitudes and angles of vector elements. The magnitude gives you the extent of activity of states at a particular mode. The angle indicates the phase angle displacement of the activity compared to the mode.

Here for mode shape calculations the state variable selected is the speed deviation. It is a good indicative of understanding the behavior of modes physically in electromechanical oscillations. Fig. 6-10., Fig. 6-11., Fig. 6-12., and Fig. 6-13.

illustrate the mode shapes of mode 1, mode5, mode7 and mode 10 in order. Shape of mode 1 verifies that in this mode shaft of LP turbine of unit 1 is oscillating against HIP turbine shaft of the same unit. Hence this can be considered as a torsional mode [17]. Similarly mode 2 and mode 3 are torsional modes as well which exhibit such phenomenon in unit 2 and unit 3. As explained earlier mode 5 is a local plant where all the generators and turbines are oscillating nearly the same direction with respect to the large external power system. Mode 7 probably an inter-machine mode which is visible within the power plant where turbine-generator of second unit shows an oscillation opposed to turbine-generator of third unit. In a same way once mode 6 gets excited due to a disturbance unit 1 turbine-generator is oscillating against unit 2 and unit 3 turbine-generators showing characteristics of inter-machine modes. As seen in the mode shape it is clear that mode 10 is also a torsional mode where LP turbine shaft and HIP turbine shaft are oscillating with respect to generator shaft within the unit 1 once the mode gets excited. Similarly mode 11 and mode 12 are also torsional modes where such torsional oscillation occur within unit 2 and unit 3 respectively.

- G speed = Generator speed deviation
- HIP speed = High & Intermediate Pressure turbine speed deviation
- LP speed = Low Pressure turbine speed deviation
- Mode shapes of Unit 1 are shown in blue color
- Mode shapes of Unit 2 are shown in red color
- Mode shapes of Unit 3 are shown in green color

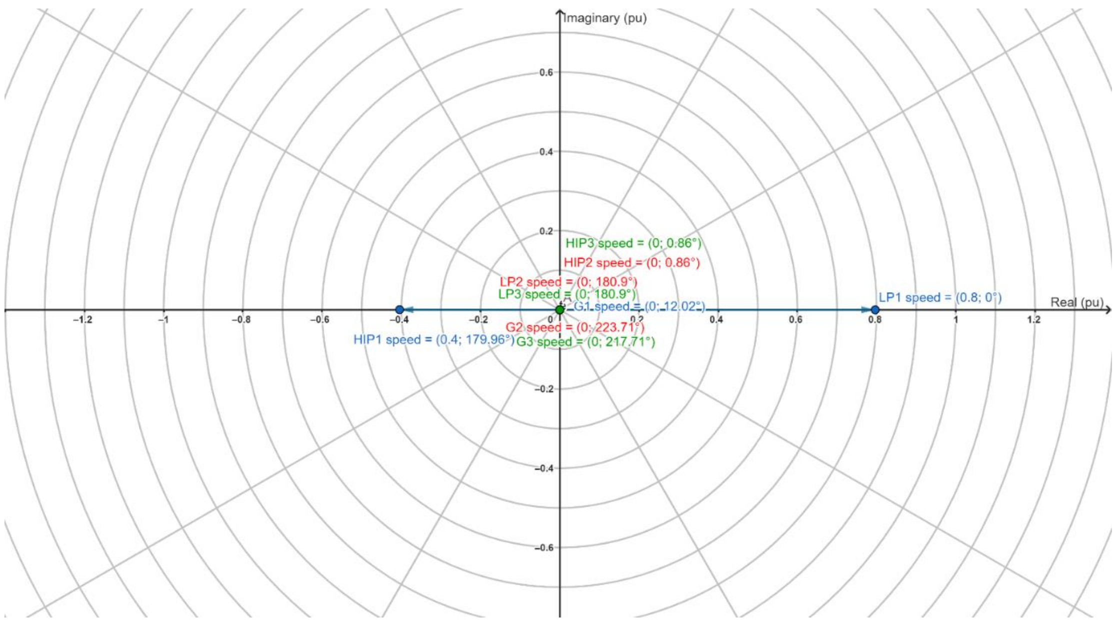


Fig. 6-10. Mode shape of oscillatory mode 1.

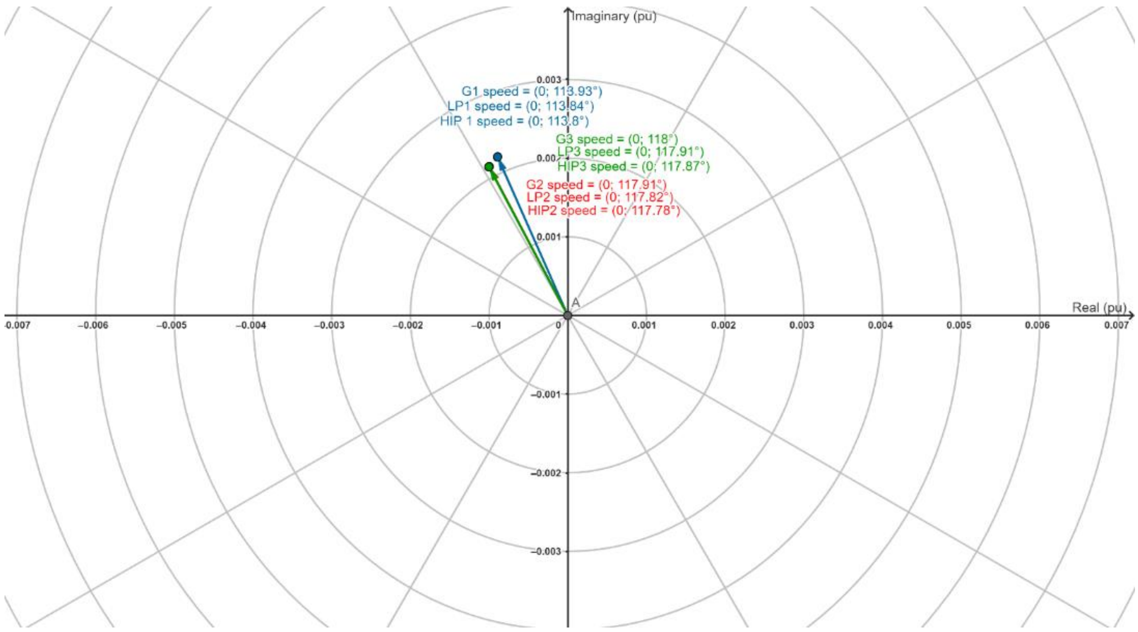


Fig. 6-11. Mode shape of oscillatory mode 5.

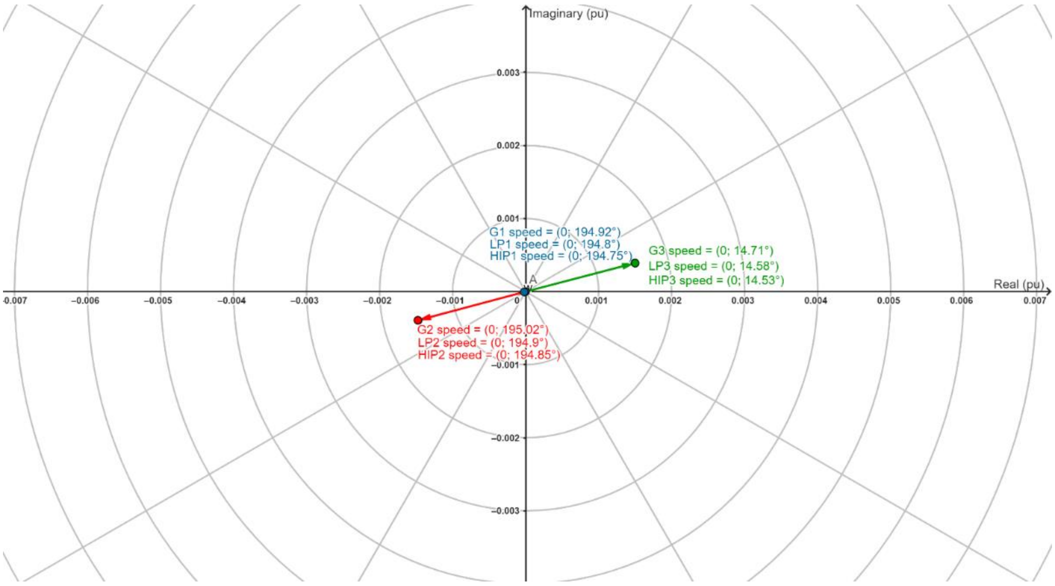


Fig. 6-12. Mode shape of oscillatory mode 7.

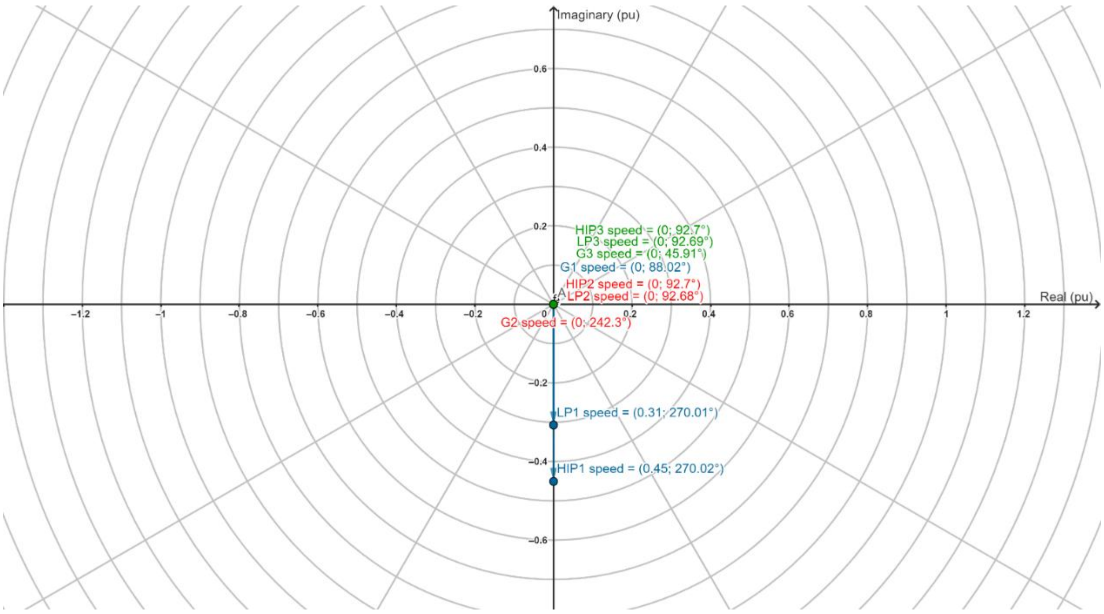


Fig. 6-13. Mode shape of oscillatory mode 10.

The mode shapes of remaining oscillatory modes 2, mode 3, mode 6, mode 11, and mode 12 are also shown below Fig. 6-14., Fig. 6-15., Fig. 6-16., and Fig. 6-17.. These will help to understand the relative activity of states at respective modes by showing graphically for each of those modes as well.

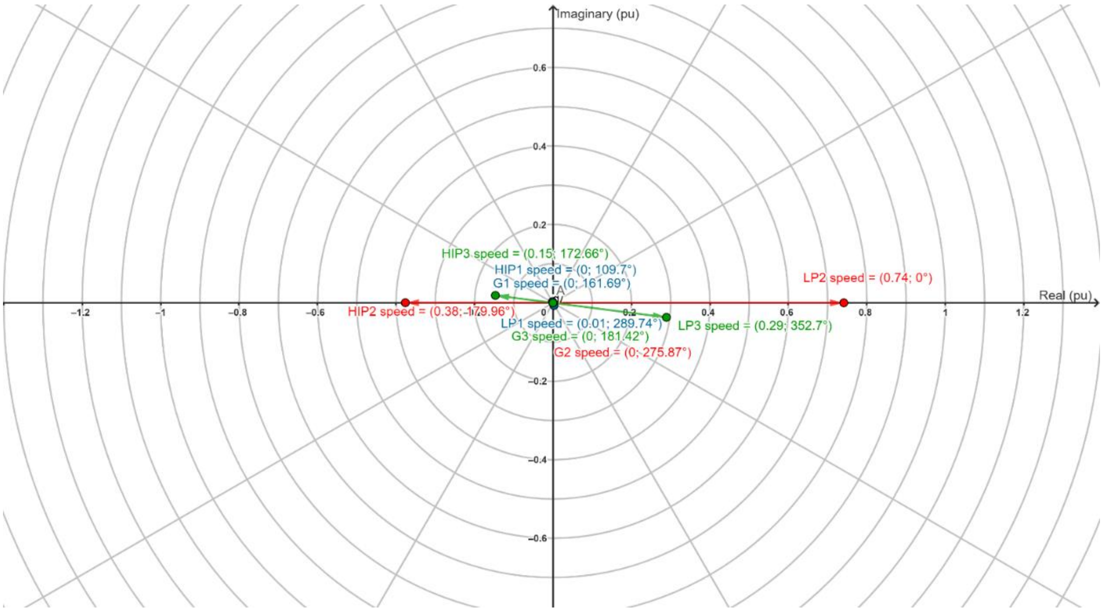


Fig. 6-14. Mode shape of oscillatory mode 2.

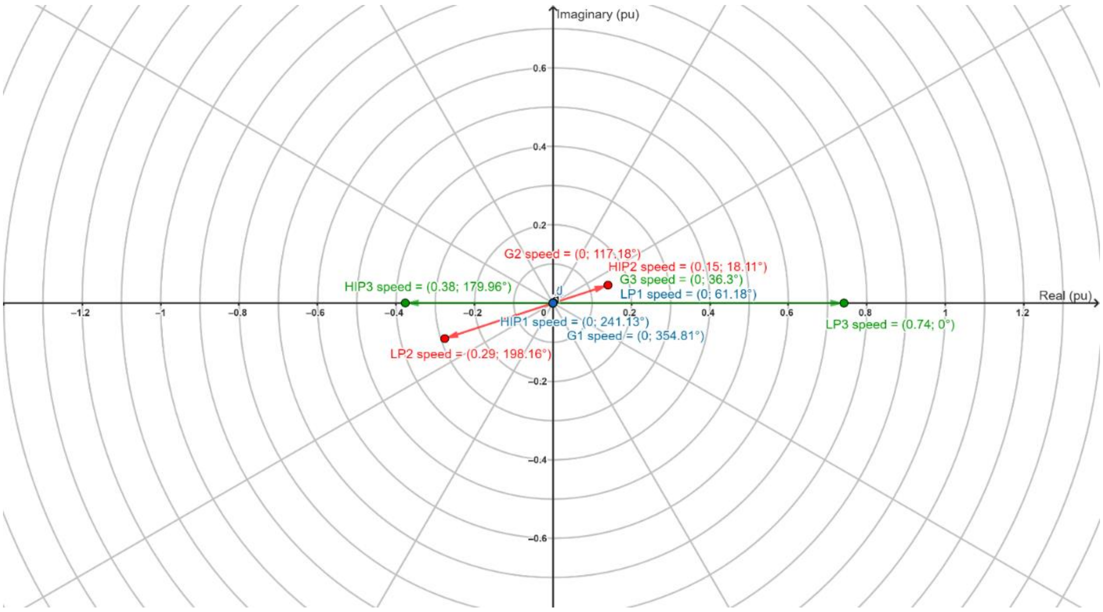


Fig. 6-15. Mode shape of oscillatory mode 3.

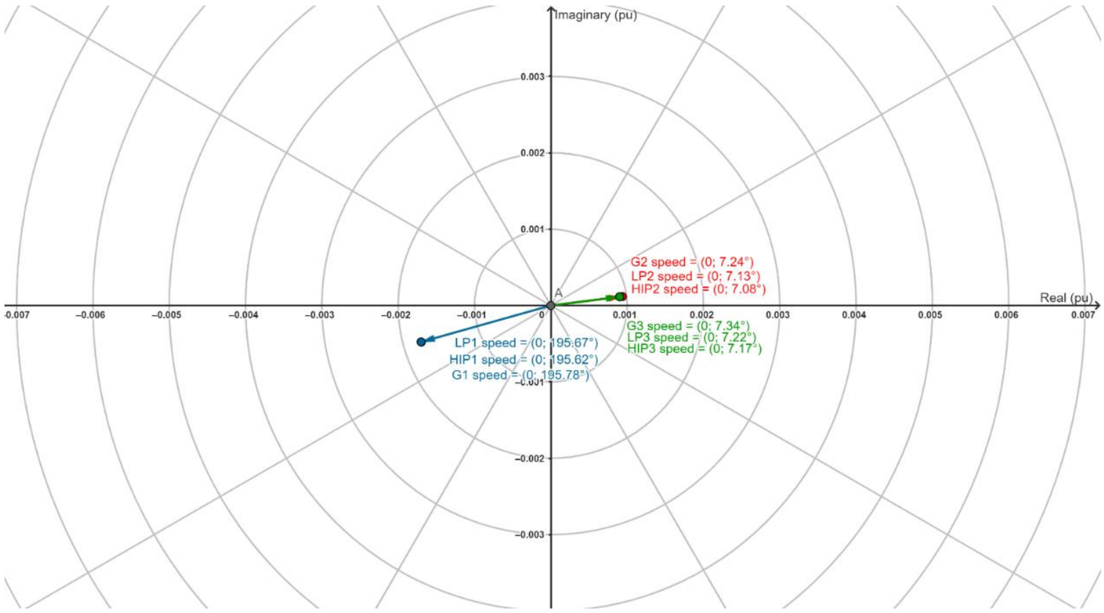


Fig. 6-16. Mode shape of oscillatory mode 6.

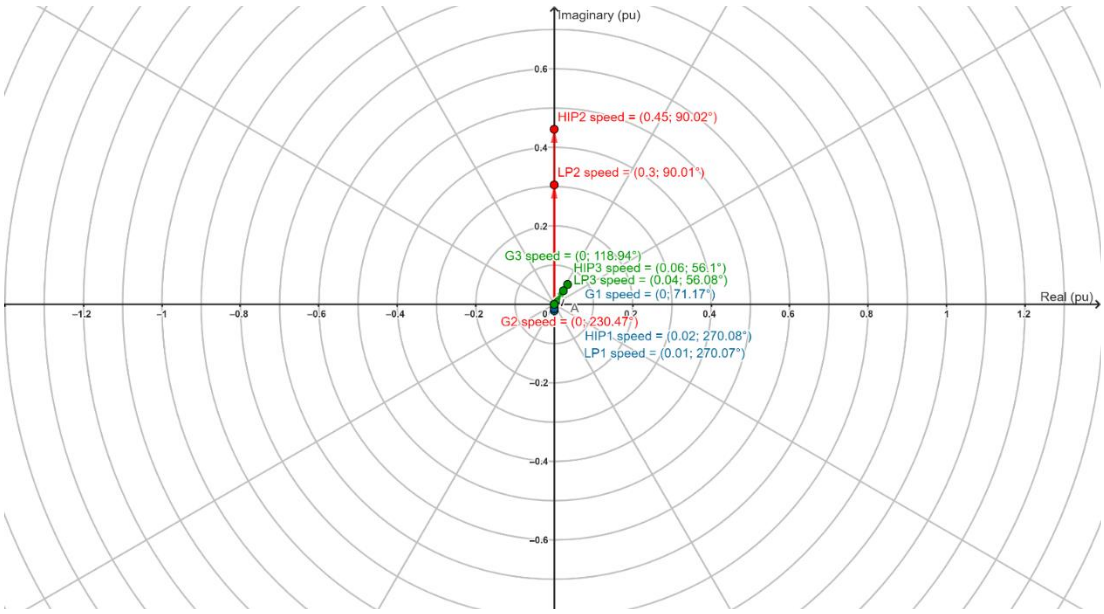


Fig. 6-17. Mode shape of oscillatory mode 11.

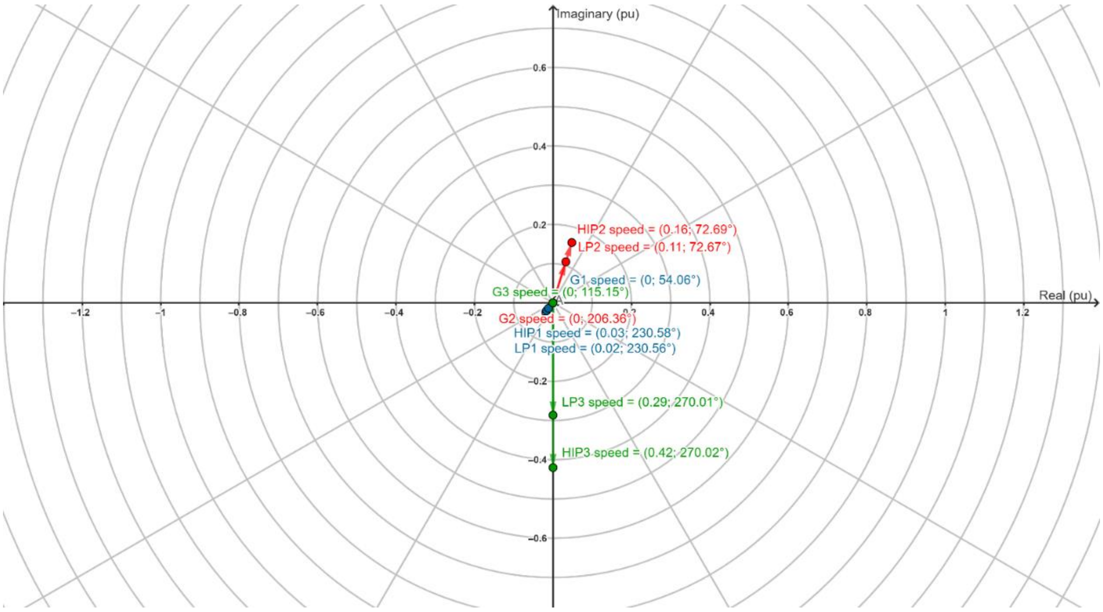


Fig. 6-18. Mode shape of oscillatory mode 12.

6.3 Chapter summary

Most of the time small signal stability is determined by simply the location of eigenvalues in complex coordinates in studies. There the location should be confirmed in the left side of the complex plane where real part is negative. Then it will be the determining condition for stability for a little fluctuations margin around steady state due to disturbances.

Despite of this conventional approach the stability analysis can be derived in more detail by using the two categories explained namely participation factors and mode shapes in order to derive useful conclusions. These outcomes will help understanding suitable controller strategies to maintain expected functionality of the total system.

Participation factor analysis explain that for mode 1 highly contributing states are of unit 1. Similarly mode 2 and mode 3 are highly contributed by unit 2 and unit 3. Mode 5 which is a local pant mode is contributed by states of all the units as expected. Mode 7 is highly participated by the states of unit 2 and unit 3 whereas mode 6 is mostly by the unit 1. States of the unit 1 majorly contributed in mode 10 and for the mode 11 and mode 12, unit 2 and unit 3 are participating respectively.

Mode shape analysis shows that shape of mode 1 verifies that in this mode shaft of LP turbine of unit 1 is oscillating against HIP turbine shaft of the same unit. Hence this can be considered as a torsional mode. Similarly mode 2 and mode 3 are torsional modes as well which exhibit such phenomenon in unit 2 and unit 3. As explained earlier mode 5 is a local plant where all the generators and turbines are oscillating nearly the same direction with respect to the large external power system. Mode 7 probably an inter-machine mode which is visible within the power plant as the total turbine generator system of second unit shows an oscillation opposed to that of the third unit. Similarly once mode 6 gets excited due to a disturbance unit 1 turbine-generator is oscillating against unit 2 and unit 3 turbine-generators showing characteristics of inter-machine modes. As seen in the mode shape it is clear that mode 10 is also a torsional mode where LP turbine shaft and HIP turbine shaft are oscillating with respect to generator shaft within the unit 1 once the mode gets excited. Similarly mode 11 and mode 12 are also torsional modes where such torsional oscillation occur within unit 2 and unit 3 respectively.

Chapter 7

CONCLUSIONS

This study developed a method for understanding the existence of low frequency oscillation in the real system of Lakvijaya power plant which was observed with the actual fault records and explained its causes such as participation of various state variables from differing generating units and behavior of such possible oscillations geared by excitation of modes. Further during this study it was developed a detailed simulation model and validated with the actual real world system which includes dynamics of all the subsystems of the plants and the adjacent network. Moreover it was identified possible other modes such as torsional and inter-machine modes and their characteristics which is required to taking mitigating measures having developed a validated small signal model. The mitigation techniques to be studied and discuss accordingly in future scope of work. Therefore in summary following points are to be emphasized regarding this research.

- Analyzed and understood existence of a low-frequency oscillation in the real system which is observed with the fault records and explained which generating units, state variables contribute to this oscillation. And recognized the factors on which this mode depends.
- Developed a detailed simulation model which includes dynamics of synchronous machines, excitation systems, turbine speed governing systems, multi-mass shaft systems and network of Lakvijaya Power Station having validated with the real systems' recordings.
- Studied and identified the characteristics of twelve (12) oscillatory modes associated with the station using a small signal study.
- Recognized six (6) torsional modes each participate only within a single generating unit. Three of them are with frequency close to twice the grid frequency.

It might be important to understand as explained in the literature [17] if the generator terminal outputs an unbalance load the negative sequence current exerts an electrical torque on generator. This torque is in a way that can negatively damp a torsional mode which has twice grid frequency. If the turbine generator shaft has similar mode closer to double frequency that might lead to a torsional resonance event. Additionally studied transmission lines might be modeled using dynamic phasors instead of constant admittance used in this study to represent transmission lines. This will give more accurate results for higher frequency oscillations in-between units or between units and the network if they present with the system. However such oscillations were not found with this study. Power system stabilizers (PSS) might be beneficial in many ways in damping out the power oscillations. However the effect of PSS installed at plant not studied in this research. If studied as future work it will be beneficial to the Lakvijaya power plant operators in order to activate the power system stabilizer which is available but currently inactive at the facility. Moreover the developed dynamic models can be used to study various aspects of the power generation facility and nearby network.

Finally this study could be further extended up to Upper Kotmale Power Station (UKPS) within the Sri Lankan network in order to analyze and understand the oscillatory behavior in between the two power plants if connected as a separate grid isolated from the rest of the Sri Lankan network during a blackout restoration. This will greatly contributes to understand network dynamics of the current ongoing experiments at Ceylon Electricity Board to facilitate an external grid supply to LVPP from UKPS in order to keep plant subsystems in running state during a blackout for more speedy total restoration.

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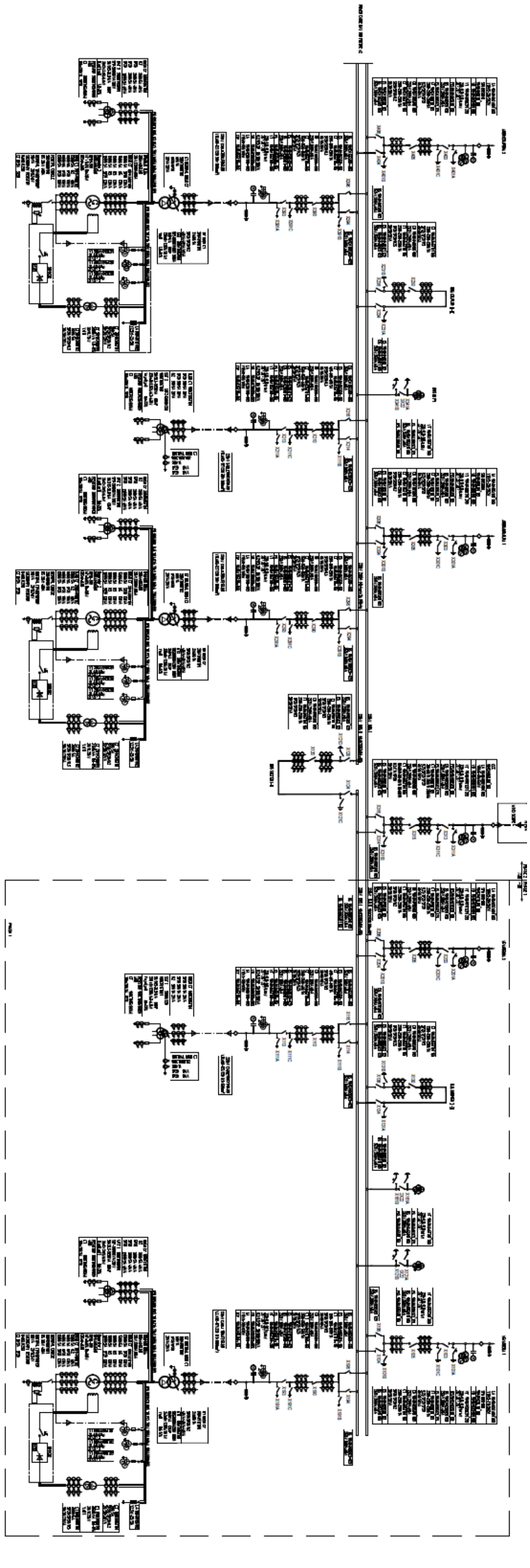
APPENDIX A
SINGLE LINE DIAGRAM OF LVPP



ABBREVIATIONS: 缩写:

CB: CIRCUIT BREAKER 断路器
CCE: CABLE CONNECTION ENCLOSURE(CABEL TERMINATION) 电缆连接终端
CT: CURRENT TRANSFORMER 电流互感器
DS: DISCONNECTING SWITCH 隔离开关
ES: EARTHING SWITCH 接地开关
FES: FAST EARTHING SWITCH 快速接地开关
LA: LIGHTNING ARRESTER 避雷器
VD: VISION DEVICE 带电显示装置
VT: VOLTAGE TRANSFORMER 电压互感器
G: GENERATOR 发电机
GT: GENERATOR TRANSFORMER 主变压器
UAT: UNIT AUXILIARY TRANSFORMER 厂用高压变压器
ET: EXCITATION TRANSFORMER 励磁变压器
SST: START STANDBY TRANSFORMER 起动/备用变压器

As Built
CMEC

DOCUMENT STATUS	AB

REV.	DATE	DRAWN	DESIGNED	CHECKED	REVIEWED	APPROVED	DESCRIPTION
A	2014.05						

EMPLOYER	CEYLON ELECTRICITY BOARD PÖYRY POYRY ENERGY LTD
CONTRACTOR	CHINA NATIONAL MACHINERY & EQUIPMENT IMPORT & EXPORT CORPORATION
SUBCONTRACTOR	NORTHWEST ELECTRIC POWER DESIGN INSTITUTE

Nwepdi 西北电力设计院

PHASE II 2X300MW PUTTALAM COAL POWER PROJECT | DETAILED | DESIGN STAGE

MAIN ELECTRICAL SYSTEM SINGLE LINE DIAGRAM PHASE I & PHASE II
电气主接线图

UNITS	mm	SCALE	1:1	DAWG. NO.	F5222S-D0101-02	SHEET 1 OF 1	REV.	A

APPENDIX B
SYSTEM DATA

Generator dynamic data

Generator is hydrogen cooled three phase cyndrical rotor 2 poles YY with 6 terminals of stator windings synchronous generator with the following rated data

Apparent power	= 353 MVA
Active power	= 300 MW
Maximum continuous output (MCR)	= 332 MW
Rated power factor	= 0.85 lag
Rated stator voltage	= 20 kV
Rated stator current	= 10190 A
Exciting voltage	= 365 V
Exciting current	= 2642 A
Efficiency	= 98.9 %
Frequency	= 50 Hz
Rotate speed	= 3000 rpm
Inertia constant (H)	= 4.2 s

Reactances	**Direct axis (pu)**		**Quadrature axis (pu)**	
	Saturation	**Unsaturation**	**Saturation**	**Unsaturation**
Sub-transient (X'')	15.5%	16.8%	15.2%	16.57%
Transient (X')	20%	22.75%	33.3%	37.8%
Synchronous (X)	-	183%	-	179%
Negative-phase	15.4%	16.7%	-	-
Zero-phase	7.3%	7.7%	-	-

Time constants (short circuit)	**Direct axis (s)**	**Quadrature axis (s)**
Sub-transient (T'')	0.035	0.035
Transient (T')	0.91	0.17
Time constants (open circuit)	**Direct axis (s)**	**Quadrature axis (s)**
Transient (T_0')	8.47	0.94

Stator winding caculating resistance at 25°C, per phase (R_a) = 0.00228Ω

Field winding calculating resistance at 25°C (R_f) = 0.125Ω

Neutral grounding is done through a 50kVA 20/0.24kV transformer and secondary side resistance is 0.46 Ω.

Stator winding leakage reactance (X_{la}) = 12.4% pu

Exciter dynamic data

Parameter	Description	Unit	Value
TB	Controller first lag time constant	s	1
TB1	Controller second lag time constant	s	1
TC	Controller first ead time constant	s	0.01
TC1	Controller second lead time constant	s	0.01
K_a	Voltage regulator gain	pu	400
T_a	Excitation time constant	s	0.004
T_r	Measuring time constant	s	0.02

Governor with turbine dynamic data

Parameter	Description	Unit	Value
T_{SR}	Speed relay time constant	s	0.001
T_{SM}	Hydrauic servo time constant	s	0.15
K_p	Proportional gain		1
T_3	HIP steam chest time constant	s	10
T_2	LP crossover time constant	s	negligible

Multi-mass shaft data

Parameter	Description	Unit	Value
K_{12}	Stiffness coefficient	Pu/rad	250.57
H_2	Coefficient of inertia	s	0.31
K_{23}	Stiffness coefficient	Pu/rad	356.01
H_3	Coefficient of inertia	s	0.42

Main Transformer rated data

Transformer type = SFPZ-360000/20

No. of Phase = 3

Rated power = 360000 kVA

Rated frequency = 50 Hz

Rated voltage = (230 ± 8 x 1.25 %) / 20 kV

Connection symbol = YNd1

Coolinf method = ONAN / ONAF / ODAF (30/60/100%)

Short-circuit impedance = 13.98 %

No-load current = 0.067 %

No-load loss = 152.17 kW

Load loss = 727.48 kW

Transmission line details

Line section	**Voltage (kV)**	**Ccts.**	**Conductor**	**Length (km)**	**Positive/Zero impedance (Ω/km)**	**Mutual impedance (Ω/km)**
New Chillaw - Norochcholai	220	2	630AAAC	73.3	0.02378 + j0.2818	0.167 + j1.199
Anuradhapura - Norochcholai	220	2	400AAAC	100	0.03663 + j0.2961	0.1798 + j1.214

Steady state power flow data

Bus No.	Bus Type	Voltage (pu)	P_G (MW)	Q_G (Mvar)	$-P_L$ (MW)	$-Q_L$ (Mvar)
1	P-V	1.000∠-19.66°	197.1	12.458		
2	P-V	1.000 ∠-17.98°	271.9	16.045		
3	P-V	1.000 ∠-17.94°	273.7	16.025		
4	P-V	0.995 ∠5.95°	-	-	-	-
5	P-Q	0.960 ∠-2.26°			234.8	15.5
6	swing	1.000 ∠0°	494.548	-84.565		