STUDY OF THE SETTINGS OF OVER SPEED PROTECTION FOR ENHANCING FREQUENCY STABILITY:
A CASE STUDY FOR LAKVIJAYA POWER STATION

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Degree of Master of Science

Department of Electrical Engineering

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

Signature of the supervisor:

Dr. W. D. Prasad **Eng. Rienzie Fernando**

DEDICATION

This work is dedicated to my beloved parents.

ACKNOWLEDGMENT

I owe my sincere gratitude to my supervisors, Dr. W.D. Prasad (Department of Electrical Engineering, University of Moratuwa) and Eng. Rienzie Fernando (Managing Director, Amithi Power Consultants Pvt. Ltd.) for their encouragement, support, and expert advice to make this research thesis a success.

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Abstract

The main target of the large interconnected Power Systems (PS) present today is to provide continuous and quality electricity supply to the consumers with highest possible reliability. “Fast Valving” (FV) action of Steam Turbines is one of the most effective elements for enhancing the transient stability of a power system in order to maintain a healthy power supply under the large and sudden disturbances. FV plays a significant role in mitigating the impact of sever disturbances by instantly decreasing steam turbine power, thus ensuring the Power System Stability (PSS).

Sri Lankan power system currently comprises 4,043 MW generation capacity consisting of 900 MW of coal power, 1,215 MW of oil burning thermal power, 1,720 MW of hydropower and 208 MW of non-conventional renewable energy sources such as wind, mini hydro, biomass, and solar power plants. Lak Vijaya Power Plant (LVPP) is the first and only coal power plant which is connected to Sri Lankan Power System and it contributes almost 45% of total power requirement of the nation. LVPP has three identical generating units driven by steam turbines each having 300MW capacity.

Main objective of this research was to study the behaviour of “Over Speed Protection Control” (OPC) unit of LVPP which has almost the same function of FV and to establish the main objective of the OPC function. This study further investigates the effects of FV scheme of LVPP on the transient stability of Sri Lankan Power System.

The study further explores the procedure to obtain the optimum valve actuation timing of the Intercepting Valves (IVs) for the FV scheme while proving that FV has much better control over transient stability than OPC. The results of the study further unveil that proper selection of actuation timings of IVs for FV scheme of LVPP steam turbines has a significant effect on enhancing the power system frequency stability under transient conditions.

As the main objective of this study, the optimum ranges for actuation timings of IVs for FV scheme of LVPP were found based on frequency stability of Sri Lankan power system under the transient conditions and a set of timings for FV scheme were recommended to set as actuation timings of IVs. The sensitivity of each time settings were also examined and the relationships were clearly established.

Keywords: Fast Valving (FV), Over speed Protection Control (OPC), Power System (PS), Lakvijaya Power Plant (LVPP), Large Disturbances, Optimum Time Settings, Transient Stability.

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List of Abbreviations

Abbreviation	Description
CEB	Ceylon Electricity Board
FV	Fast Valving
GV	Governor Valve
HP	High Pressure
IP	Intermediate Pressure
IPP	Independent Power Producers
IV	Intercept valve
LP	Low Pressure
LVPP	Lakvijaya Power Plant
OPC	Over Speed Protection Control
PS	Power System
PSS	Power System Stability
RE	Renewable Energy

1 INTRODUCTION

This chapter (Chapter 1) discusses about the requirement of FV scheme of steam turbines to improve the transient stability of a power system and OPC function of LVPP. Further this chapter presents the background for this study and objectives to be accomplished through this thesis.

1.1 Fast Valving (FV) for Power System Stability (PSS)

Today's world is highly dependent on electricity due to growth of needs and increased number of electrical appliances. Therefore the requirement to maintain a healthy and a reliable power system is much important now than ever. Hence a significant attention has been drawn to the topic of power system stability and various research studies are being conducted in this field.

Transient stability is an important aspect in maintaining a power system in a healthy condition throughout the day. FV is an accepted practice to enhance the transient stability of a power system, which employs power plants with steam turbines as prime movers [1]. FV control is rising in prominence since systems are operating near their stability limits and also due to difficulties in expanding the transmission system. It is a cost effective method to enhance the transient stability of a power system.

FV is used to decrease the turbine mechanical input power when the turbine speed is increased beyond the predefined limits. Rapid closing and opening of steam valves is activated in a prescribed manner to reduce the turbine acceleration following a severe fault in power system. Here the Intercept Valves (IV) of the steam turbines are fast closed, resulting in rapid reduction of mechanical power. This action must be initiated within a minimum time after the detection of a disturbance in the power system, followed by its reopening.

1.2 Sri Lanka Power System

Sri Lankan power system is currently serving a daily night peak of approximately 2.4 GW. It comprises 4,043 MW generation capacity. The mix of generation sources is as follows: Hydro (16%), Thermal (Thermal and Coal - 58%, Independent Power Plant (IPP) Thermal – 19%) and Non-Conventional Renewable Energy (NCRE) (7%). The high voltage transmission network is branched throughout the country with approximately 601 km of 220 kV lines and nearly 2,310 km of 132 kV lines, feeding approximately 60 grid substations. The medium voltage network of 33 kV and 11 kV distribution lines is spanned for 32,863 km, electrifying 99.7% of the nation [2]. Ceylon Electricity Board (CEB) has the sole authority over Sri Lanka's transmission network. The System Control Centre (SCC) operated by CEB, regulates the network within safe limits. SCC is used to have only the monitoring facility earlier, but by 2018, it is equipped with supervisory control as well.

LVPP is the first ever coal based steam machine which has been connected to Sri Lanka Power System. FV principle is used in the LVPP steam turbines and the unit which carries out this function has been named as the “Over speed Protection Controller (OPC)”.

With reference to power system stability, 2016 had been a tough year for Sri Lanka as she experienced two blackouts owing to system instabilities under transmission system transient fault conditions. Both of these incidents made the LVPP machines to over speed and initiated power swings as well as the triggering the OPC. But the response was not adequate to maintain the stability of the power system.

1.3 Lakvijaya Power Plant (LVPP)

LVPP is the largest and the first ever coal-fired power plant in Sri Lanka. This plant is located in Norochcholai, Puttalam on the Western shores of the Kalpitiya peninsula. With three units of 300 MW capacity, it generates a total power of 900MW at its peak. The first phase of the plant having one unit of 300 MW capacity was connected to the national grid on 22nd of March 2011. Second phase which comprises two units of 300 MW capacity was commissioned on 16th of September 2014 [3].

Steam turbine of LVPP consists of three stages named High Pressure (HP) turbines, Intermediate Pressure (IP) turbines and Low Pressure (LP) turbines. The arrangement of turbines and the path of steam flow to these turbines are shown in the Figure 01.

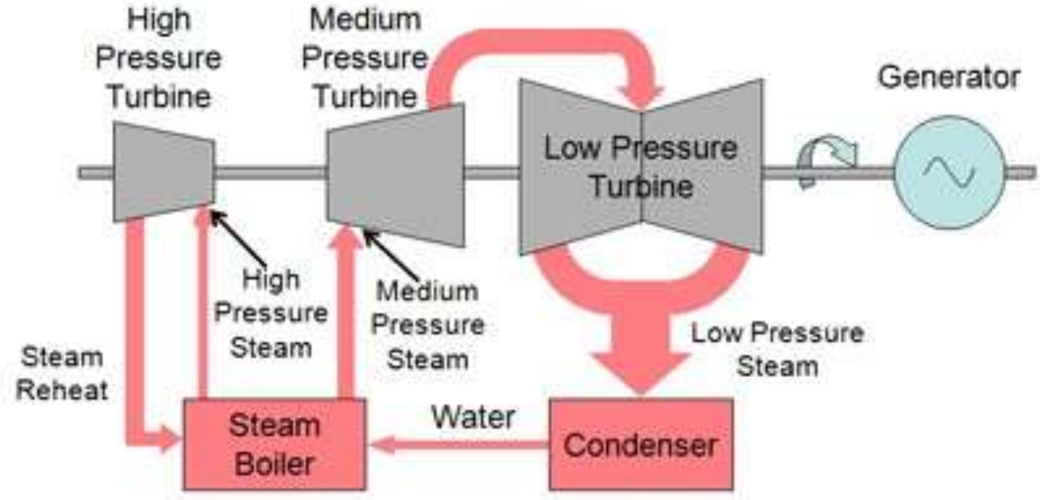


Figure 1: Steam Turbine Arrangement

The steam from the boiler enters the HP turbine through Main Steam Valves (MSV) and six GVs. The exhaust steam from the HP turbine goes back to boiler to reheater for a temperature boost and enters the IP turbine section through two Reheater Stop Valves (RSV) and two IVs. The exhaust steam from the IP turbine goes to the LP turbine section before being exhausted to the condenser for recycling. Figure 02 shows the arrangement of all four types of valves.

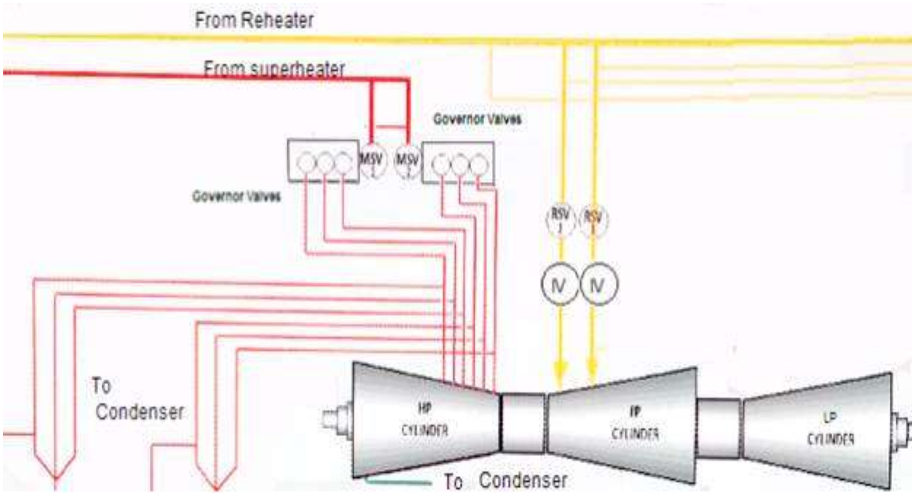


Figure 2: GVs and IVs Arrangement of Steam Turbine

The Digital Electro-Hydraulic (DEH) oil system supply oil to the actuators of valves. The oil in this system is fire resistance fluid based on the phosphate ester oil. Each inlet steam valves has an actuator to control its open/close, among which RSV actuators are of “ON-OFF” control type and others are of “proportional” control type.

1.4 Operation of Fast Valving

Neglecting losses, the difference between the mechanical and electrical torque of synchronous generator gives the net accelerating torque T_a. In the steady state, the electrical torque is equal to the mechanical torque and hence the accelerating power is zero. During this period the rotor moves at synchronous speed ω_0 in rad/s [4]. This rotor motion of synchronous machines is given by,

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e \text{ N-m}$$

Where:

- J is the total moment of inertia of the rotor mass in kg-m^2
- θ_m is the angular position of the rotor with respect to a stationary axis in (rad)
- t is time in seconds (s)
- T_m is the mechanical torque supplied by the prime mover in **N**-m
- T_e is the electrical torque output of the alternator in **N**-m
- T_a is the net accelerating torque, in **N**-m

There is an equilibrium between the mechanical input power of each generating unit and the sum of losses and electrical power output of that unit during the steady-state operation of a power system. Problems arise when there is a rapid fluctuation in the electrical power output of a generating unit due to a severe and sudden disturbance and this resulting sudden acceleration of the machines due to imbalance between input (mechanical) and output (Electrical) power. This rotor dynamic is described by the following equitation derived from above equation, known as swing equation [4].

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = (P_m - P_e),$$

where

P_m = electrical driving power input, in pu
P_e = electrical power output, in pu
H = inertia constant, in MW-s/ MVA
ω_0 = nominal speed, in electrical radian/ sec
δ = rotor angle, in electrical radian

It is not necessary to solve the swing equation to determine the stability limits. This can be obtained graphically by power angle diagram as shown in the figure 03. Although this is not applicable to multi machines systems with detailed representation of synchronous machines, it helps in understanding basic factors that influence the transient stability of any system [5].

During the steady state operation, the power system is operated at equilibrium point A in curve 1 as shown in power angle diagram of figure 3. The electrical power is dropped to the point B due to a large disturbance of the system but mechanical input power remains constant at Po as illustrated in Figure 03.a. This causes to accelerate the machine until the operating point reaches point C in curve 2. When the fault is cleared up, operating point is shifted to point D in curve 3. When FV scheme is not present, the accelerating area 1 in Figure 3.a is greater than the decelerating area 2 and the system loses synchronism even after the fault is cleared up. But when FV is incorporated, input power is changed in accordance with the curve AG of Figure 03.b,

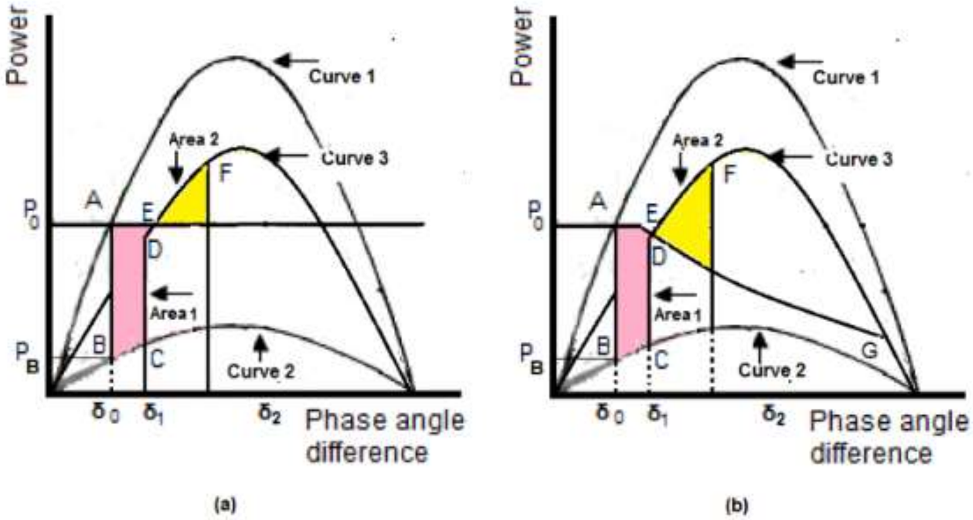


Figure 3: Power Angle Curves for Transient Stability with FV and without FV*1

Curve 1: Pre-fault Condition
Curve 2: During the Fault
Curve 3: After clearing the fault

As per the above figure 3.b, The FV operation helps the decelerating area (Area 2) to increase and accelerating area (Area 1) to decrease, without losing the machine from the system, thereby not allowing system inertia to drop, thus helping to achieve the basic requirement in transient stability. The shape of the curve AG when FV is incorporated will be determined by the valve opening and closing sequence and whether the valves remain closed or open.

Valve closing and opening sequence of FV scheme is shown in Figure 04. Upon the detection of pre-set speed of steam turbine following a severe power system disturbance, a signal will be generated to close the IVs controlling the steam to the turbine, at a pre-set rate and hold them closed for an adjustable period of time and then to reopen the same again at a pre-set rate.

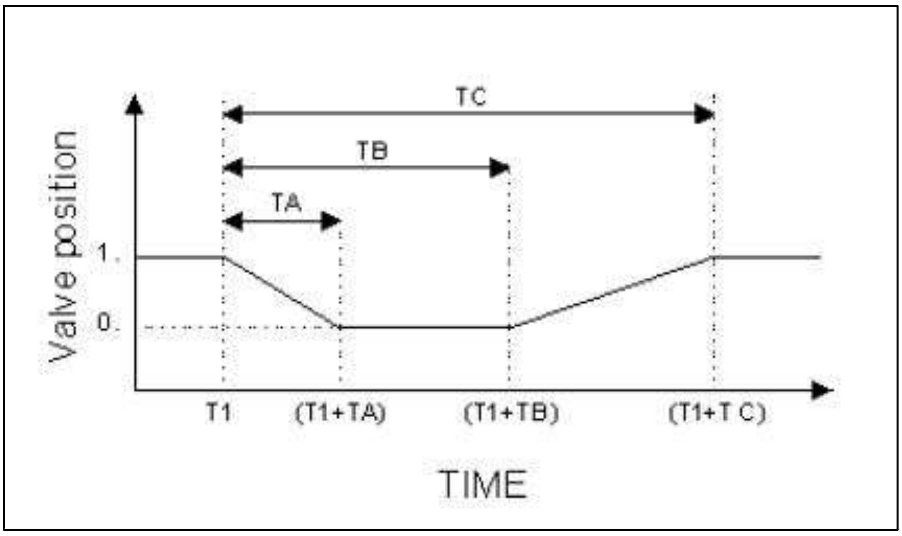


Figure 4: Valve Actuation Sequence of Typical Fast Valving Scheme

The settings for above valve timing needs to be determined in such a way that the system frequency is kept within the stable region. If these valve timings are not set with a proper system study, the stability will be lost under transient conditions, leading to a total system collapse [6]. For example, Figure 05 illustrates the system frequency variation under different time settings of valve dead time. It is clear that system frequency is not stable when dead time of valve increased.

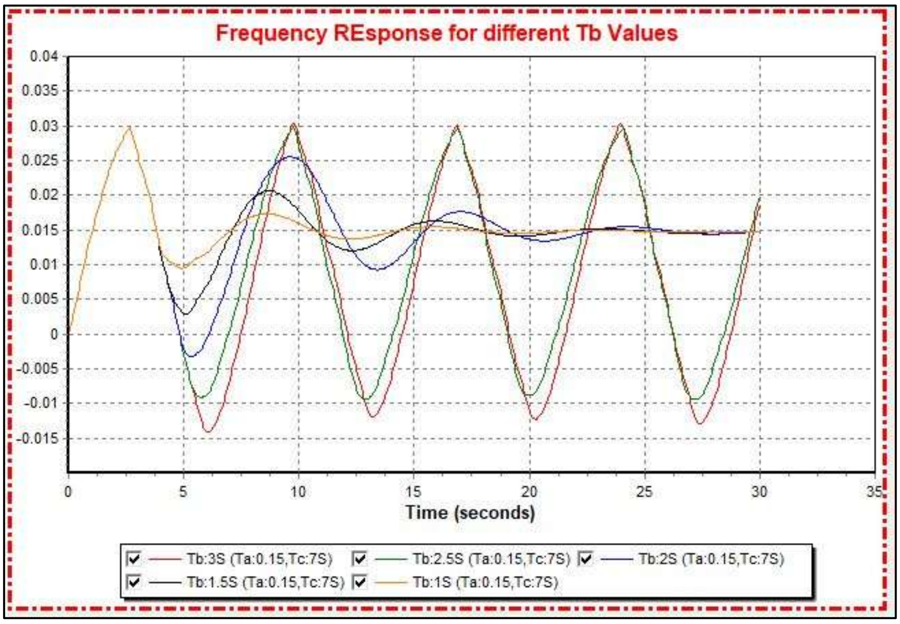


Figure 5: System Frequency Response for Different Valve Dead Times

1.5 OPC Unit of LVPP

As turbine manufacturer states, OPC unit of LVPP which has almost the same characteristics of FV, mainly focusing on the steam turbine protection on over speed detection [7].The only operational difference of FV action and OPC function is that FV controls the steam flow closing only the IVs, while OPC controls all six GVs and IVs .In terms of turbine power, OPC controls 100% of turbine power and FV controls only 70% of the total turbine power.

The LVPP machines normally operate at their synchronous speed of 3000 rpm and OPC setting has earlier been set to activate when machine speed exceeds 3090 rpm (103% of rated rpm). The OPC operation completely shuts all six GVs and the IVs to block the steam flow to the turbine, causing the machine to decelerate. When the speed subsequently decreases to 3030rpm due to OPC action, the OPC resets and GVs and IVs are reopened to let the steam back in.

1.6 Objectives of the Study

The OPC function of LVPP steam machine has been activated three times in the history up to now, following large disturbances of the power system. Out of these incidents, two incidents occurred in 2016 have led to power system blackouts and two other incidents have caused tripping of at least one steam machine out of three at LVPP.

As many researchers point out, FV is a vital element to enhance the transient stability of a power system [1]. But as Turbine manufacturer of LVPP has also stated, main objective of this OPC is to assist the turbine protection but not the system stability. Thus the OPC settings have been configured accordingly. Though it in fact controls the over speeding of the turbine, its main function is to assist to bring about the transient stability of the power system, which may arise as a result of a fault in the element of transmission system [7].

From all of above evidences, it is understood that there is a contradiction of manufacturer recommendations and the literature review done on primary objective of OPC function of steam turbine of LVPP. Under such circumstances, following objectives are clearly and concisely defined the purpose of this research,

a. Study the operation and behaviour of the Over Speed Protection Control Unit of the Lakvijaya Power Plant steam turbines
b. Establish the main objectives of OPC shall fulfil
c. Finding the best transient stability scheme out of Over Speed Protection control and Fast Valving
d. Determination of the steam valve closing time (TA), valve dead time (TB) and valve opening time (TC) in coordination with system stability studies.

e. Prove that the system reliability/transient stability will be improved with the proposed changes

1.7 Thesis Outline

In order to achieve the objectives mentioned in Section 1.6 above, the rest of the thesis is organized as follows:

Chapter 2 provides a comprehensive review on literature review related to FV scheme of steam turbines and OPC scheme of LVPP. Furthermore, the issues and drawback related to current settings of OPC function of LVPP, are also highlighted here.

Chapter 3 presents the methodology to find the optimum actuation timings of IVs for FV scheme of LVPP to enhance the transient stability of Sri Lanka Power System.

Chapter 4 presents results based analysis on the impact of varying different actuation timings of IVs on transient stability of Power System.

Chapter 5 presents the conclusions of the study.

2 LITERATURE REVIEW

This chapter presents a comprehensive review of the literature related to the OPC function of LVPP and importance of studying the subject area of FV for power system stability.

2.1 Fast Valving

FV plays a significant role in reducing the impact of large disturbances of the system and enhancing its stability by decreasing steam turbine power instantly [1]. FV is a technology applicable to thermal units, aimed at rapid closing and opening of steam valves to control the turbine driving power, following severe disturbances of power system. FV is a highly effective and a least cost method to improve the transient stability [8]. Benefits of FV on power system stability has been known since 1930s, followed by deep technical discussions, publications of papers and the implementation of FV in generating units since the 1960s [9].

2.2 History of OPC Activation and Settings of LVPP

The OPC function of LVPP has been activated at three different occasions up to now in the history.

INCIDENT 1

Date	25th of February 2016
Cause	A lightning stroke triggered earth fault on one phase of the 132 kV Seethawaka – Kolonnawa line
Behaviour Power System	As a result of these events, continuous increase of system frequency surpassed the setting of turbine overspeed limit to activate Over speed Protection Control (OPC) function of all three generators of LVPP

Table 1: OPC Activation Incident 01

INCIDENT 2

Date	13th of March 2016
Cause	The failure has initiated with the tripping of Biyagama 220/L32/33 kV transformer 01
OPC Activation	Tripping of above lines and transformers led to increase system frequency. Continuous increase of system frequency surpassed the setting of turbine over speed limit to activate Over speed Protection Control (OPC) function of all three generators of LVPP

Table 2: OPC Activation Incident 02

INCIDENT 3

Date	16th of September 2018
Cause	Earth Fault at 132 KV bus of Colombo Sub B
OPC Activation	This led to increase of system frequency. Continuous increase of system frequency surpassed the setting of turbine overspeed limit to activate Overspeed Protection Control (OPC) function of unit 2 steam turbine of LVPP.

Table 3: OPC Activation Incident 03

2.3 Primary Objective of OPC Function of LVPP

As explained in the chapter 01, FV is a vital element of steam turbines in terms of enhancing power system transient stability. The similar function used in LVPP steam machines is known as OPC. This OPC function of LVPP is activated when turbine speed exceeds a pre-set value following a sever disturbance in the power system. At the beginning, the speed settings of OPC of LVPP were set as follows,

	Enable (rpm)	**Disable (rpm)**	**Remarks**
Unit 01	3090	3030	103% of rated rpm
Unit 02	3090	3030	
Unit 03	3090	3030	

Table 4: OPC Settings of LVPP before 2017 [10]

Though FV uses only the IVs of steam turbines to cut off the steam to the turbine, LVPP uses all the GVs and IVs to cut off steam once OPC is activated. The current settings for actuation times of GVs and IVs of OPC scheme are as follows,

	TA (ms)	**TB (ms)**	**TC (ms)**
Governor Valves (GVs)	150	Not time based but based on rpm	7500
Intermediate Valves (IVs)	150	Not time based but based on rpm	7500

Table 5: Existing Valve Actuation Timings [11]

TA, TB and TC are as given in the figure 04

But there is no evidence that the manufacturer of LVPP steam turbine has set the actuation timing of GVs and IVs for OPC scheme with a proper system stability analysis.The manufacturer of the steam turbine has maintained that the OPC is simply as a device to prevent over speeding and has stated that there is no effect on the role of enhancing the system stability. The settings of OPC has also been set accordingly [7].

Though turbine manufacturer has stated that OPC as an over speed protection, LVPP machines have been provided two other methods for over speed protection called as electrical and mechanical over speed protection in addition to OPC. Following table shows the settings for these two protection schemes.

Electrical Tripping	3120 rpm for 5 seconds	52Hz	104%
	3300 rpm for 0.1 second	55Hz	110%
Mechanical Tripping	3300 rpm	55Hz	110%

Table 6: Over Speed Protection Settings of LVPP [10]

Manufacturer recommendation for OPC settings is 3090rpm (103%) and it is well below both the electrical and mechanical over speed protection settings. Having two other means of over speed protection for turbine further prove that the primary function of OPC is not only an over speed protection, though LVPP steam turbine manufacturer's recommendation is to keep OPC only as a mechanism to prevent over speeding of turbine. Instead, the primary objective of OPC should be assisting the transient stability of the power system. It has been emphasized on many research studies that FV which has the same function of OPC is an element to enhance the transient stability under severe disturbances of the power system.

2.4 Problems Associated with OPC Settings of LVPP

OPC settings of LVPP were as shown in Tables 04 & 05 when first two incidents occurred in 2016. In these two incidents, OPC function of all three machines of LVPP were triggered at the same time (at 3090rpm) following given settings due to power system disturbances. Under the OPC activation, machine loads fluctuated approximately between 300 MW and 60 MW following the speed of the steam turbines for few minutes. This happened as a result of OPC settings were not being able to bring the system to stable region from the transient condition.

As per the settings shown in the table 04, Once OPC activated at 3090rpm, the machine load will be reduced approximately to 60 MW from 300 MW. When machine speed reduces to 3030 rpm, OPC will be disabled and load will again be increased to 300 MW. Since various parameters such as temperature, pressure, vibration, water level of turbine, boiler, generator and balance of plant systems need to be maintained within the recommended values to avoid plant tripping and damaging the equipment, continuing to operate the power plant is not an easy task under the sever fluctuations due to OPC action. If system is not get stable quickly from this kind of situations, the possibility of tripping the machine is high, not because of power system conditions but protections activated due to deviating parameters of turbine, boiler, generator and balance of plant systems from design values.

Action taken by Operation Engineers while the incident 2 occurred on 13th of March 2016 are shown in the following table.

	Initial Condition	Triggered	Nature	Action Taken
Unit 01	Load – 160 MW Speed – 3000rpm	OPC triggered at 3090rpm at	Machine load fluctuated between 160MW and 60MW	Manually FCB activated
Unit 02	Load – 300 MW Speed – 3000rpm	OPC triggered at 3090rpm at	Machine load fluctuated between 270MW and 60MW	Manually FCB activated
Unit 03	Load – 300 MW Speed – 3000rpm	OPC triggered at 3090rpm at	Machine load fluctuated between 270MW and 60MW	Machine tripped due to under frequency

Table 7: LVPP Operation Action during the Incident on 13th of March 2016

It is clear that once OPC is activated for few minutes, it is very difficult to operate the machine. Best practice to protect the machine is to isolate it from main grid opening synchronous breaker to avoid this fluctuations as Operation Engineers have done in the incident on 13th of March 2016. This is known as activation of Fast Cut Back (FCB) mechanism. Once FCB activates, machine will be isolated from the main grid and will continue to supply only the house load (25-30 MW). To overcome these practical difficulties of plant operation due to OPC activation of all three machines at the same time, the OPC settings were changed as follows.

New Settings	**Enable (rpm)**	**Disable (rpm)**	**Remarks**
Unit 01	3100	3030	
Unit 02	3078	3030	FCB will be activated within 2 seconds
Unit 03	3110	3030	

Table 8: New OPC Settings of LVPP

Three different speeds were set to trigger the OPC function of three machines as shown in the above table. With these settings, OPC function of unit 02 will only be activated once machine speed exceeds 3078 rpm and if system frequency keeps increasing further, the OPC function of unit 01 and unit 03 will be activated at 3100 rpm and 3110 rpm respectively. One of the major changes made was, once OPC function of unit 2 is activated, it will go directly to house load, isolating the unit from main grid by activating FCB. Main reason for this change is to keep at least one machine without getting tripped due to the load fluctuation as a result of OPC activation.

All these changes were done based on the power plant operational perspective and there is no evidence to prove that these settings of OPC are determined based on a system stability study.

2.5 Main Differences of FV and OPC

The main difference between FV and OPC is that FV uses only the IVs (70% of the turbine power) to control the turbine power while OPC uses all GVs and IVs (100% of total power) for this purpose. As many research studies recommend, FV is the least complicated way to reduce turbine power rapidly by using only the intermediate valves which controls approximately 70% of total unit power [12].

Further the effect of FV and OPC on transient stability has been analyzed using the simulation results in chapter 4.

2.6 Need for Finding the Optimum Timing

Machine speed and load of Unit 2 varied as follows during the event on 25th of February 2016.

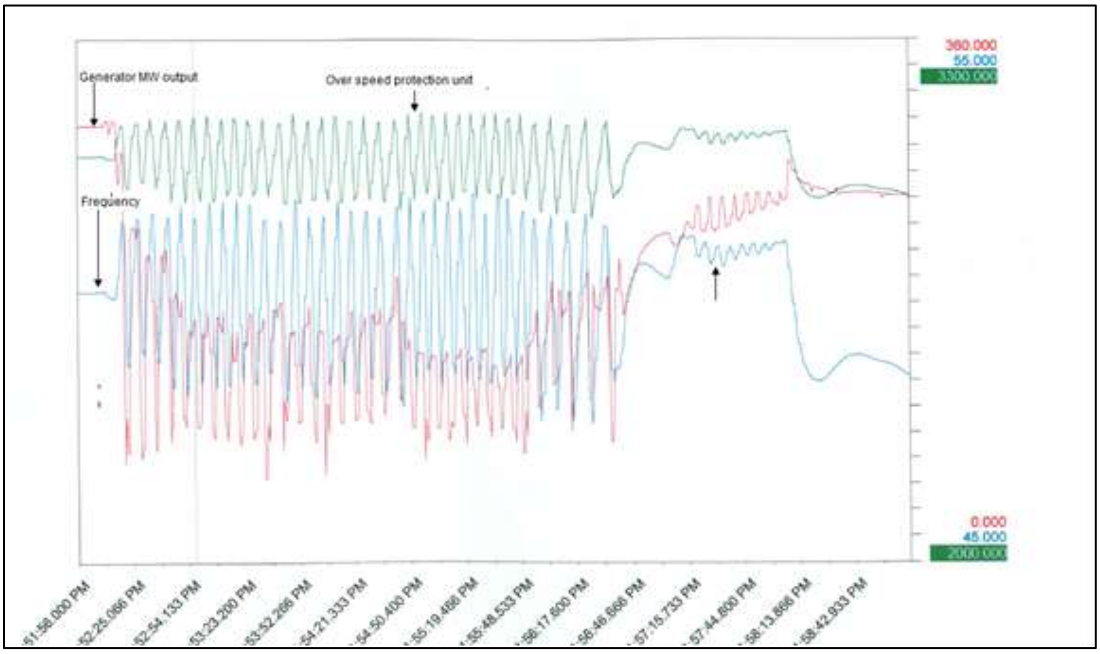


Figure 6: Frequency/ Load Fluctuation during OPC Activation

The above graph shows the pattern of fluctuation of the system frequency and load (MW) of LVPP machine during the time of OPC activation of all three units. This fluctuation continued for few minutes and led to a blackout since OPC function was not capable to maintain the system stability.

There are many research studies evaluating the impact of FV on transient stability, and all these technical literature suggest that it is quite important to determine the steam valve closing time (TA), dead times (TB) and opening times (TC) in coordination with power system transient stability studies. Valve timings cannot be ad-hoc and needs to be determined based on power system stability studies. If the valve actuation times are not appropriate, it can lead to aggravation of the system disturbance

Chapter Summary

This chapter discussed the history of OPC function activation of LVPP, the behaviour of three machines during OPC activated incidents in the history and the primary objective of OPC. Further this chapter discussed the present and previous OPC settings of LVPP and requirement of a proper study for determination of the OPC settings. Next chapter will describe the methodology for determining optimum valve actuation timings based on simulation results.

3 PROPOSED METHODOLOGY FOR FINDING OPTIMUM TIMINGS FOR FV OF LVPP

3.1 Modelling the Sri Lankan Power System

For the purpose of this study, PSS/E (33) software tool was used to model the Sri Lanka power system. This models developed for this task include all the main components of electrical power systems including synchronous generators, excitation systems, power transformers, transmission lines (220 kV and 132 KV), systems loads and the electrical network. It has been used throughout the research to provide the simulation results presented later.

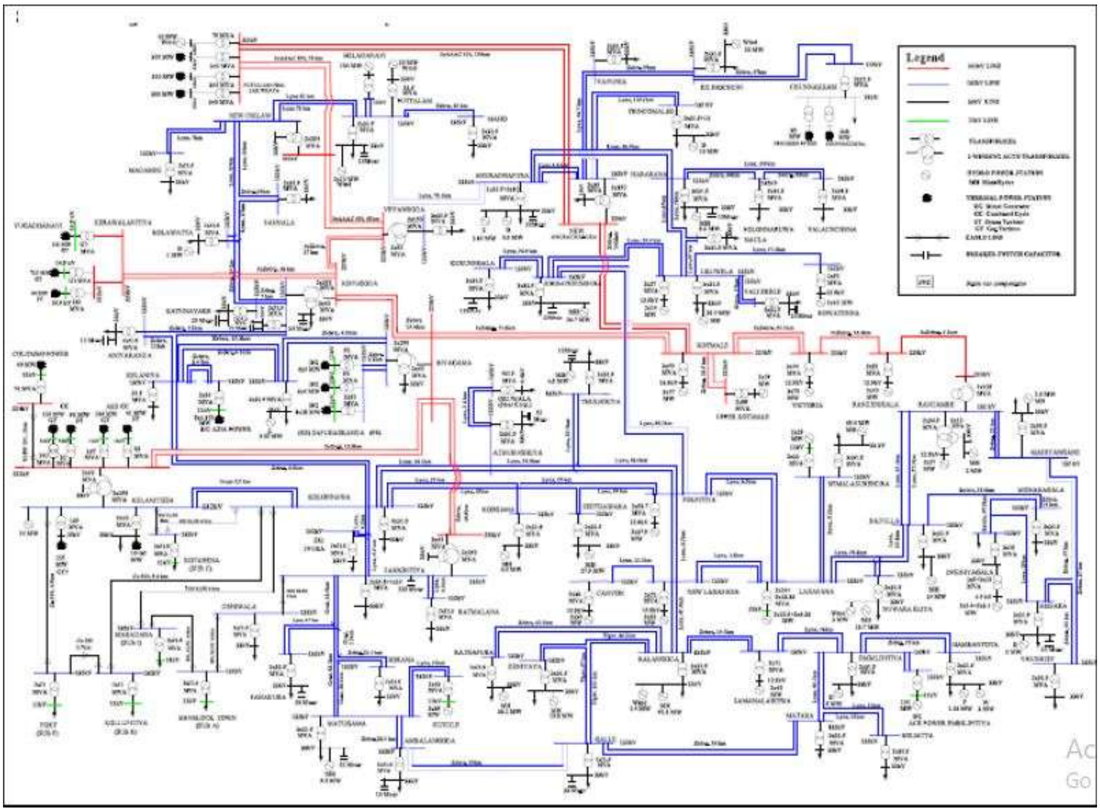


Figure 7: Schematic Diagram PSS/E Model of Sri Lankan Power Transmission System

3.2 Modelling LVPP Steam Governor

The steam turbines of LVPP are modelled with the TGOV3 governor model which has the in-built Fast Valving action. The governor model used for simulating the steam turbine of LVPP is shown in Figure 08.

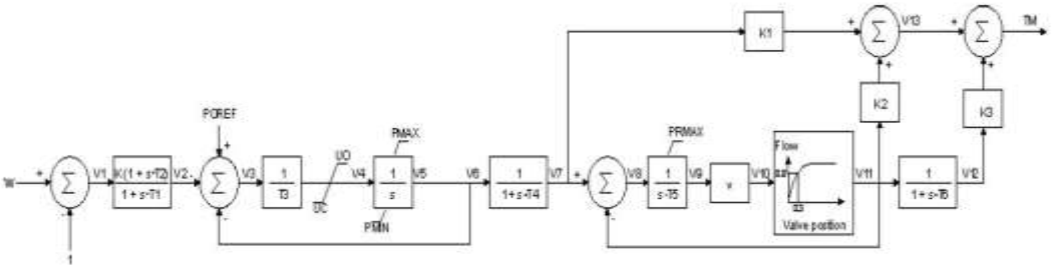
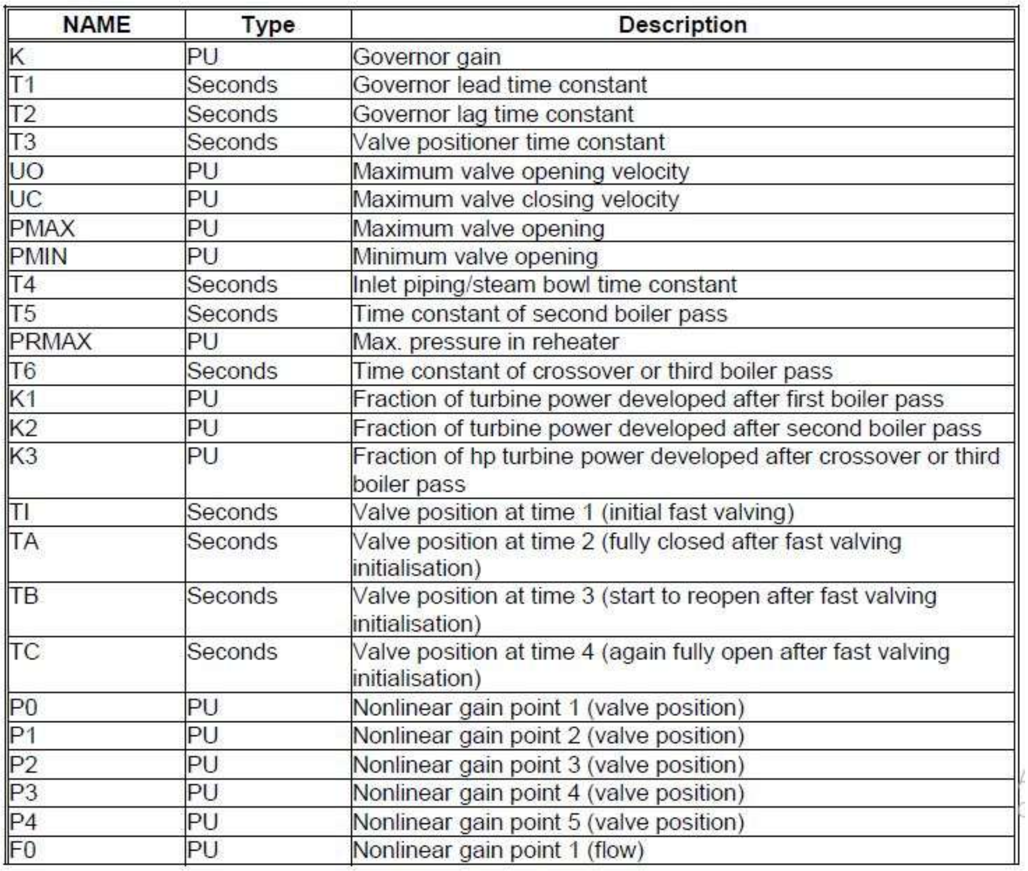


Figure 8 : TGOV3 Steam Turbine Governor Model with FV [13]

The model shown in Figure 08 is applicable for fossil fuel steam turbines like LVPP with the appropriate choice of constants. These constants are given in Figure 09.



NAME	Type	Description
K	PU	Governor gain
T1	Seconds	Governor lead time constant
T2	Seconds	Governor lag time constant
T3	Seconds	Valve positioner time constant
UO	PU	Maximum valve opening velocity
UC	PU	Maximum valve closing velocity
PMAX	PU	Maximum valve opening
PMIN	PU	Minimum valve opening
T4	Seconds	Inlet piping/steam bowl time constant
T5	Seconds	Time constant of second boiler pass
PRMAX	PU	Max. pressure in reheater
T6	Seconds	Time constant of crossover or third boiler pass
K1	PU	Fraction of turbine power developed after first boiler pass
K2	PU	Fraction of turbine power developed after second boiler pass
K3	PU	Fraction of hp turbine power developed after crossover or third boiler pass
TI	Seconds	Valve position at time 1 (initial fast valving)
TA	Seconds	Valve position at time 2 (fully closed after fast valving initialisation)
TB	Seconds	Valve position at time 3 (start to reopen after fast valving initialisation)
TC	Seconds	Valve position at time 4 (again fully open after fast valving initialisation)
P0	PU	Nonlinear gain point 1 (valve position)
P1	PU	Nonlinear gain point 2 (valve position)
P2	PU	Nonlinear gain point 3 (valve position)
P3	PU	Nonlinear gain point 4 (valve position)
P4	PU	Nonlinear gain point 5 (valve position)
F0	PU	Nonlinear gain point 1 (flow)

Figure 9: Constants for TGOV3 Governor Model [13]

3.3 Modifications to PSS/E Governor Model

The FV action of this governor model (TGOV3) were customized using the python programming to simulate the effect of LVPP machines. Following Changes were carried out,

3.3.1 OPC Effect

Primary objective of this research is to analyse the behaviour of OPC function of LVPP. But the governor model available in PSS/E software, only the FV function is provided. FV function of TGOV3 triggers only the IVs which contributes to 70% of the turbine power. But OPC of LVPP triggers all GVs and IVs which contributes 100% of the turbine power as shown in the figure 02. The turbine power controlled by GVs and IVs can be changed by varying the power ratio constants of three stages of steam turbines.

K1 – Power gain of HP turbine

K2 – Power gain of IP turbine

K3 – Power gain of LP turbine

Power ratio constant of three stages of steam turbines of LVPP machines are K1 – 0.3, K2 – 0.4 and K3 – 0.3 [10].These constants of governor model were changed as K1 – 0, K2 – 0.6 and K3 – 0.4 in such a way that IVs has control of 100% of turbine power (K2+K3=100%) in order to simulate the effect of OPC action from this governor model. This changes give a close effect of OPC action from FV action of TGOV3 governor model.

3.3.2 Speed Based Triggering

The activation of the FV scheme of this selected governor model is based on time. But under actual circumstances, it is needed to activate and deactivate the FV action based on speed of turbine (frequency). See the Annex 1 for the complete python code which was developed to activate and deactivate the Fast Valving action based on frequency.

3.4 Model Validation

The developed PSS/E model of the Sri Lankan Power system with LVPP steam turbine, was validated for the OPC activated incident on 13th of March 2016

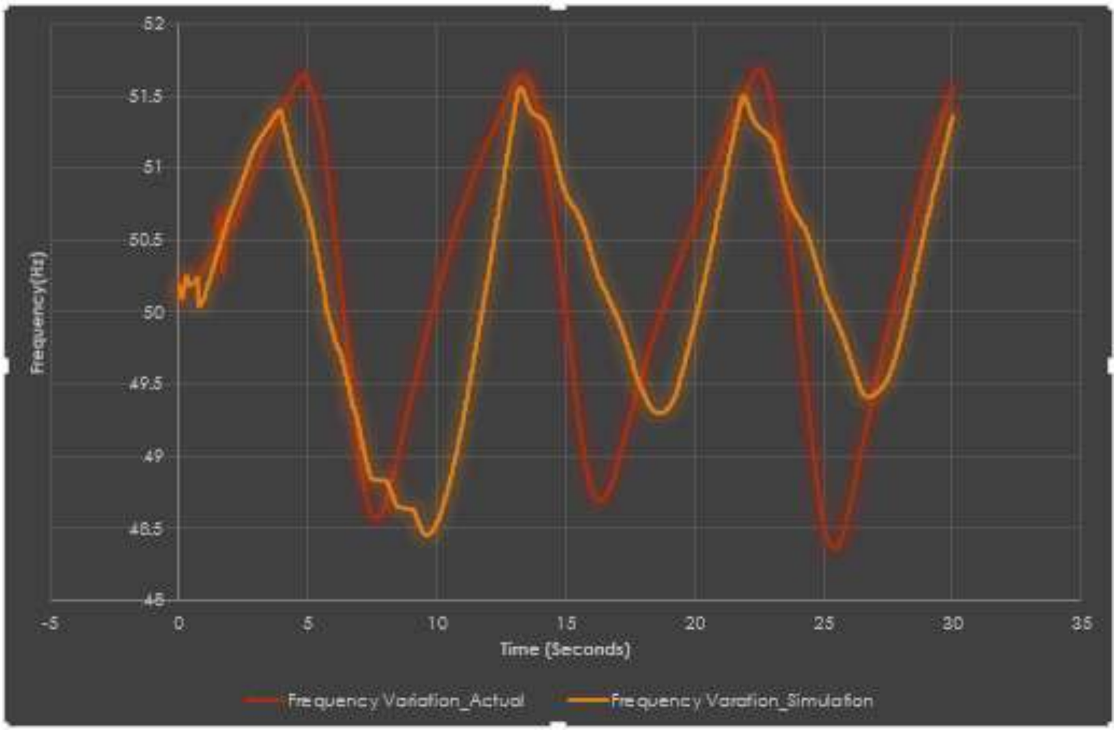


Figure 10: Comparison of Actual and Simulation Frequency Variation on 13th March 2016 Incident

3.5 Methodology to Find Optimum Timings for FV of LVPP

As many research papers emphasize, the determining the valve actuation times for FV scheme is paramount important for transient stability. This study follows the developed methodology given below, to find the optimum actuation timings for IVs once FV is activated.

As shown in the below diagram, there are four stages of this process. The proposed methodology is shown in Figure 12.

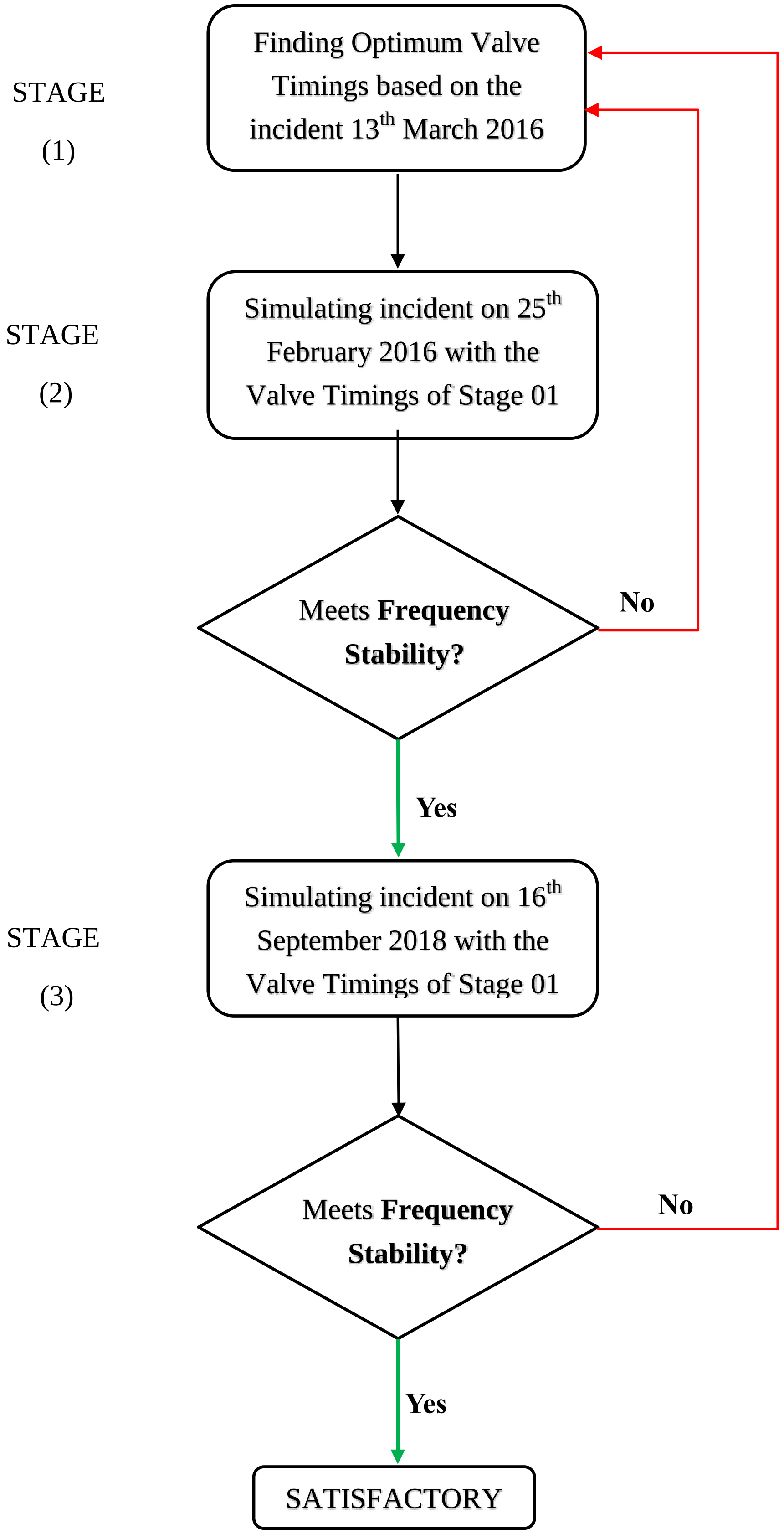
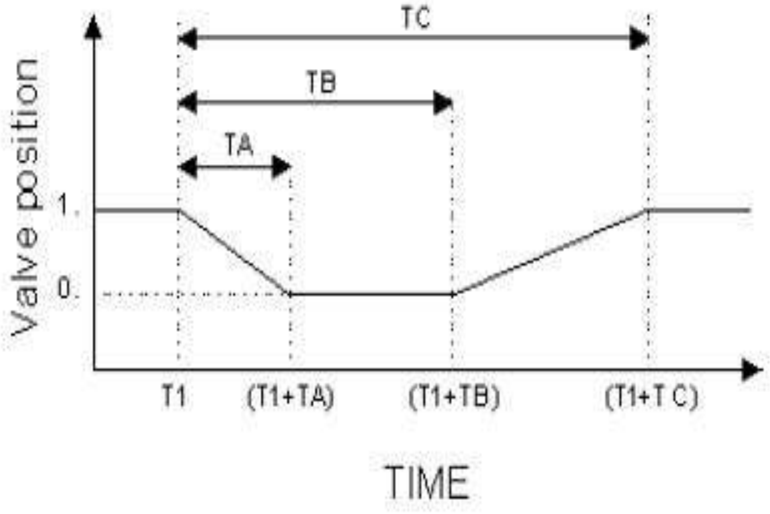


Figure 11: Proposed Methodology

Each step of the aforementioned methodology is explained in detail following section.

Stage 01

The optimum ranges for valve timing of the Intercept Valves were found in this stage. Figure 13 shows the intermediate valve travel sequence and defines the different valve actuation times.



TA-Closing Time

TB-Dead Time

TC-Opening Time

Figure 12: Intermediate Valve Sequence of FV scheme [13]

TA, TB and TC were varied to determine the sensitivity of the FV on transient conditions to the actuation times of IVs. The incident occurred on 13th of March 2016 with valve times equal to existing timing of LVPP is identified as the base case. Each one of the three valve times was changed keeping the other two fixed.

The effects of changing closing time, dead time, and opening time of IVs for the incident occurred on 13th of March 2016 were analysed one by one in following steps.

- Step 01: Check the frequency stability (Frequency of swing bus) for different TB values and find a range for TB
- Step 02 : Check the frequency stability for different TC values with TB values found in step 1 and find a range for TC
- Step 03 : Check the frequency stability for different TA values with Tb and Tc values found in step 1 and Step 2

- Step 04: Pick up an appropriate value set for TA, TB and TC from values found in step 1, 2 and 3

Step 01-Finding TB: TA and TC kept at their default values, (TA=0.15s and TC=7s) and change the TB from 3 to 1 second. It was identified that system frequency stabilizes for TB values below 2 seconds. Figure 14 shows the effect of changing TB from 3s to 1s on system frequency.

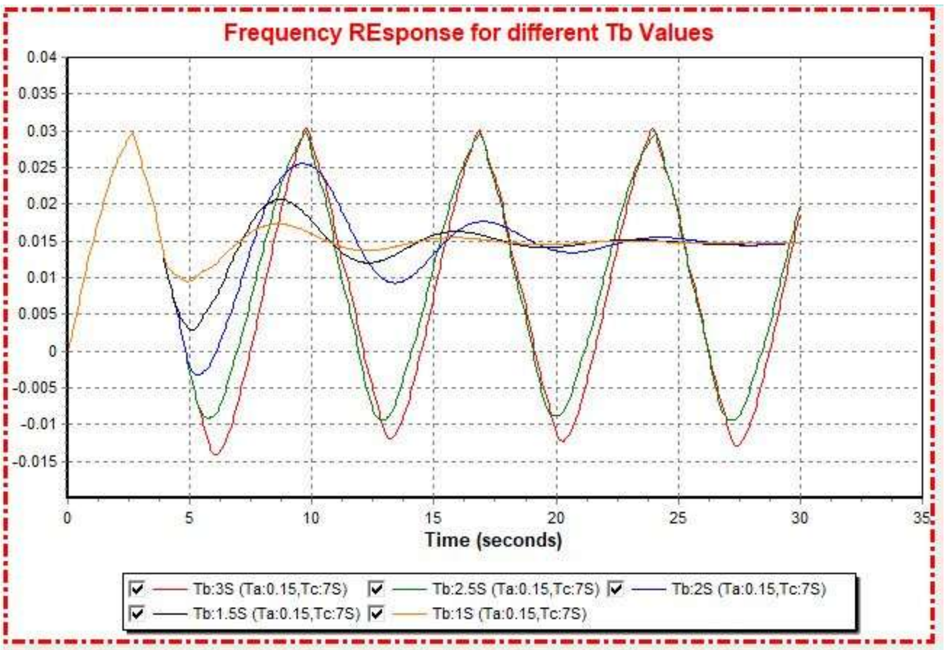


Figure 13: Frequency Variation for TB Values between 3s and 1s

TB value were further changed from 2.5 s to 2 s in steps of 0.1 s in order to get precise values for the stable region. It was found that system get stable for the TB values below the 2.2 s.

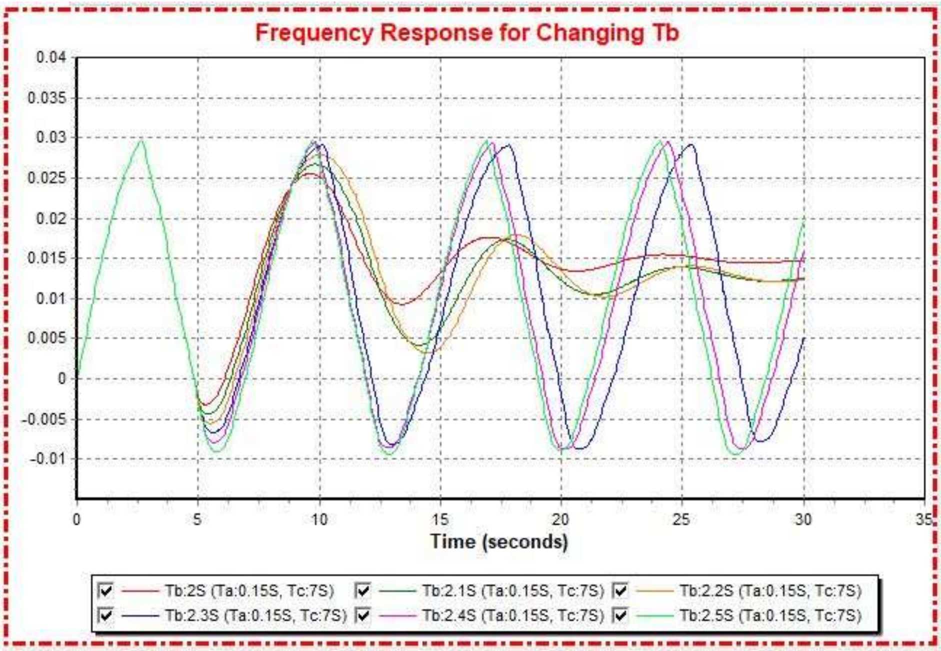


Figure 14: Frequency Variation for TB Values between 2.5s and 2s

The results of above two analyses shows that system frequency stabilizes for this particular incident within the time range of **1 s < TB < 2.2 s**.

Step 02-Finding TC: Effect of frequency stability for different TC values were analysed in this step for the different TB values within the range found in the step 01. Stability for different TC values were checked as the following chart.

Cases	**TB** **TC**	**5 s**	**7 s**	**9 s**	**13 s**
Case I	**2 s**	Stable	Stable	**Unstable**	**Unstable**
Case II	**1.5 s**	Stable	Stable	Stable	**Unstable**
Case III	**1 s**	Stable	Stable	Stable	Stable

Table 9 : Different Cases for Finding TC

Simulation results for each case are shown in Figure 16, 17 and 18.

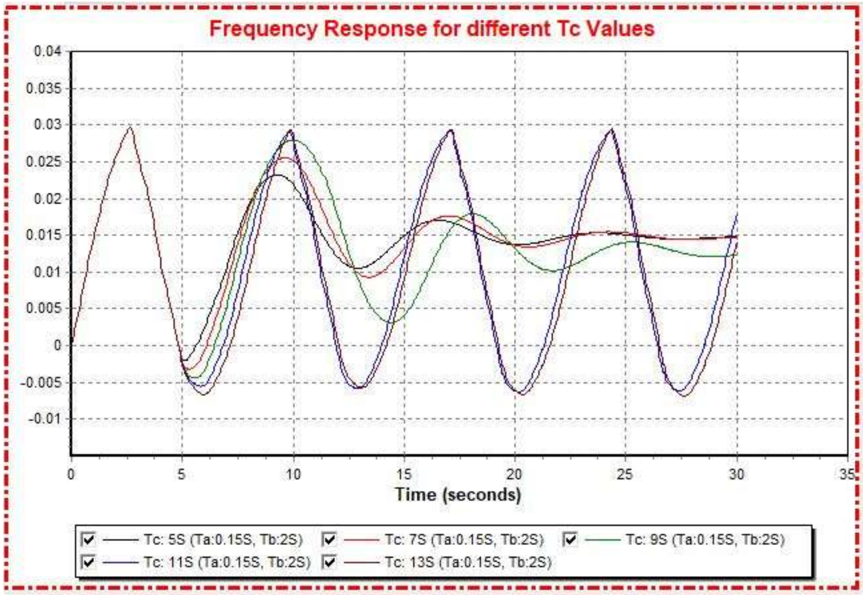


Figure 15: Case I – Frequency Variation for Different TC Values for TB=2 s

The TC were varied keeping TB at 1seconds which is picked from the stable region of TB found in step 1. The system stabilizes only for TC values below 7 s.

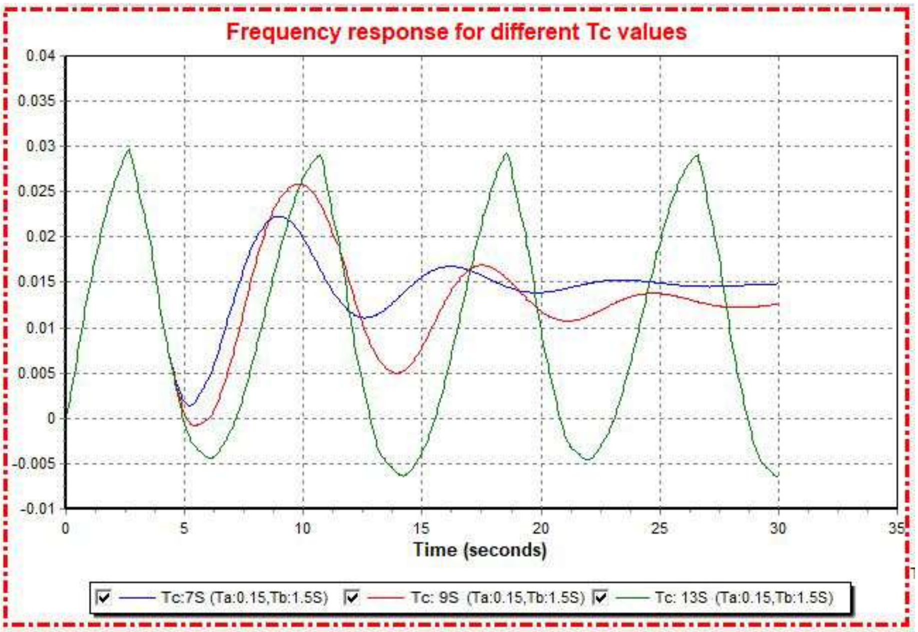


Figure 16: Case II – Frequency Variation for Different TC Values for TB=1.5s

The TC were varied keeping TB at 1.5 s which is picked from the stable region of TB found in step 1.The system get stable only for TC values below 9 s.

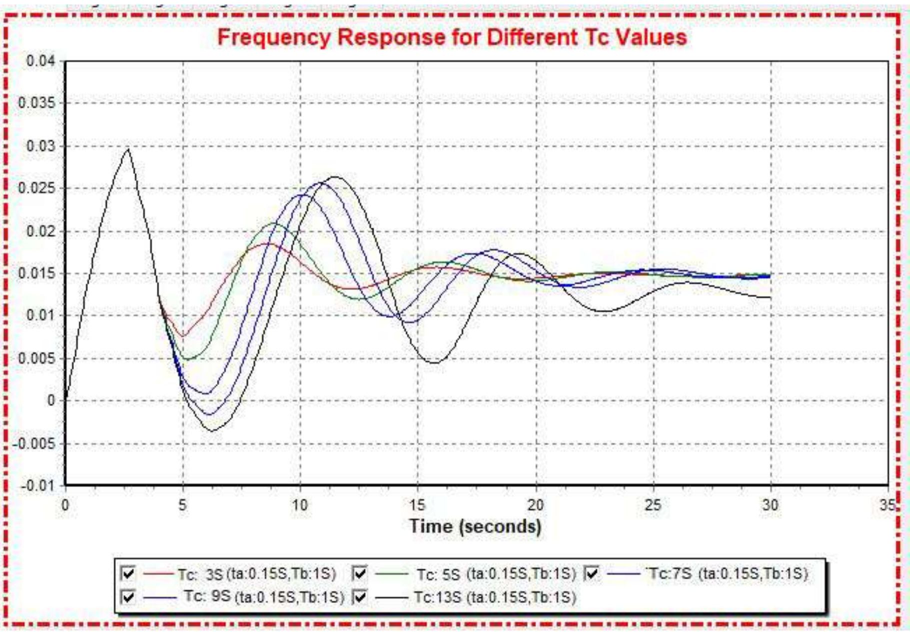


Figure 17: Case III – Frequency Variation for Different TC values for TB=1 s

The TC were varied keeping TB at 2 s which is picked from the stable region of TB found in step 1. The system stabilizes only for TC values below 9 s.

The results of three cases of the above analysis shows that system frequency stabilizes for this particular incident within the time range of **3 s <TC < 7 s** while keeping TB within the stable time region found in step 1.

Step 03 – Finding Ranges for TA: Manufacturer has recommended to keep the closing time of IVs below 0.3 s in emergency conditions. IVs currently takes around 0.15 s to fully close in emergency conditions. So the possible range for TA values is between 150mS and 0.250 s. System stability was checked for this range of TA. TB and TC values picked from derivative value regions of step 01 and Step 02.

Figure 19 shows the frequency response for randomly picked up values of this optimum time range of TA.

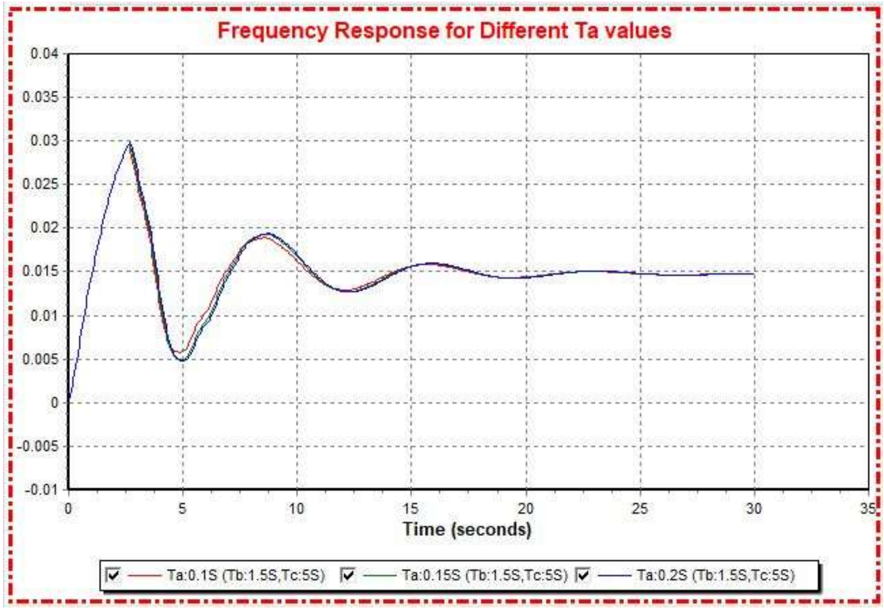


Figure 18: Frequency Variation for TA values between 0.1 s and 0.25 s

From above three steps of stage 01 of methodology, following time ranges were found as the optimum time ranges for Fast Valving action to keep system stable under serious disturbances of the power system.

Comparison table of optimum valve actuation timing ranges:

		Fixed Time	**Variable Time**	**Optimum Time Range**
Step 01	**Finding TB Dead Time**	TA-0.15 s TC-7.5 s	TB-1,1.5,2,2.5,3 s	**1 s<TB<2 s**
Step 02	**Finding TC Opening Time**	TA-0.15 s TB- 1,1.5,2 s	TC-5,7,9,11,13 s	**3 s<TC<7 s**
Step 03	**Finding TA Closing Time**	TA-1.5 s TC-5 s	TA-0.1,0.15,2.5 s	**0.1 s<TA<0.25 s**

Table 10: Optimum Valve Actuation Timing ranges for FV

From these optimum time ranges for Fast Valving action, one set of values were picked as the valve actuation timing for further analysis. They are,

TA = 0.15 s

TB = 1.5 s

TC = 5 s

Stage 02

The values found for valve timings in the stage 01 were used to simulate the incident occurred on 25th of February 2016 (Table 01). As the first step of stage 02, the incident in February 2016 was validated and results of simulation and actual frequency variation were compared.

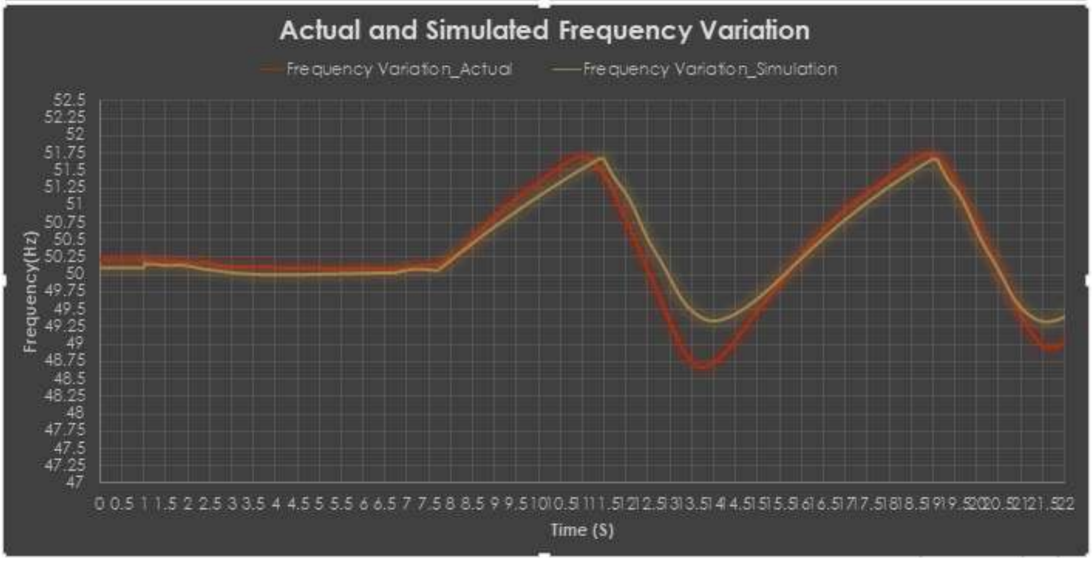


Figure 19: Actual and Simulated Frequency Variation_25th of February 2016

Same incident was simulated enabling FV action with the valve actuation timings found in the stage one. The results are as follows.

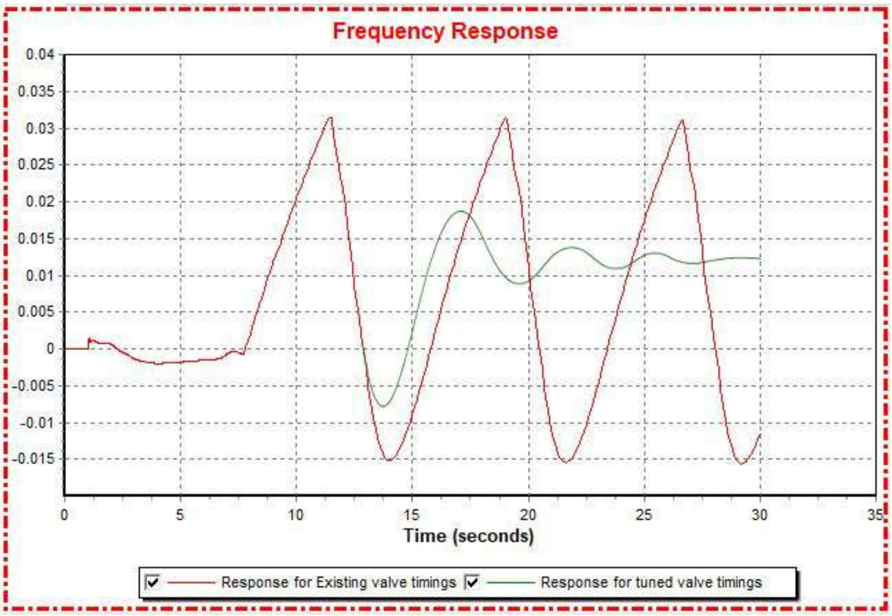


Figure 20: Frequency Response for Existing and Prosed time Settings_25th of February 2016

The system stabilizes without sever fluctuation for the valve actuation timings picked up from stage 01.

Stage 03

The values found for valve timings in the stage 01 were used to simulate the incident happened on 16th of September 2018 (Table 03). This incident occurred after OPC settings were changed as explained in Chapter 2. After these changes, OPC was activated on 16th of September 2018.

As the first step of stage 02, the incident in September 2018 was validated and results of simulation and actual frequency variation were compared.

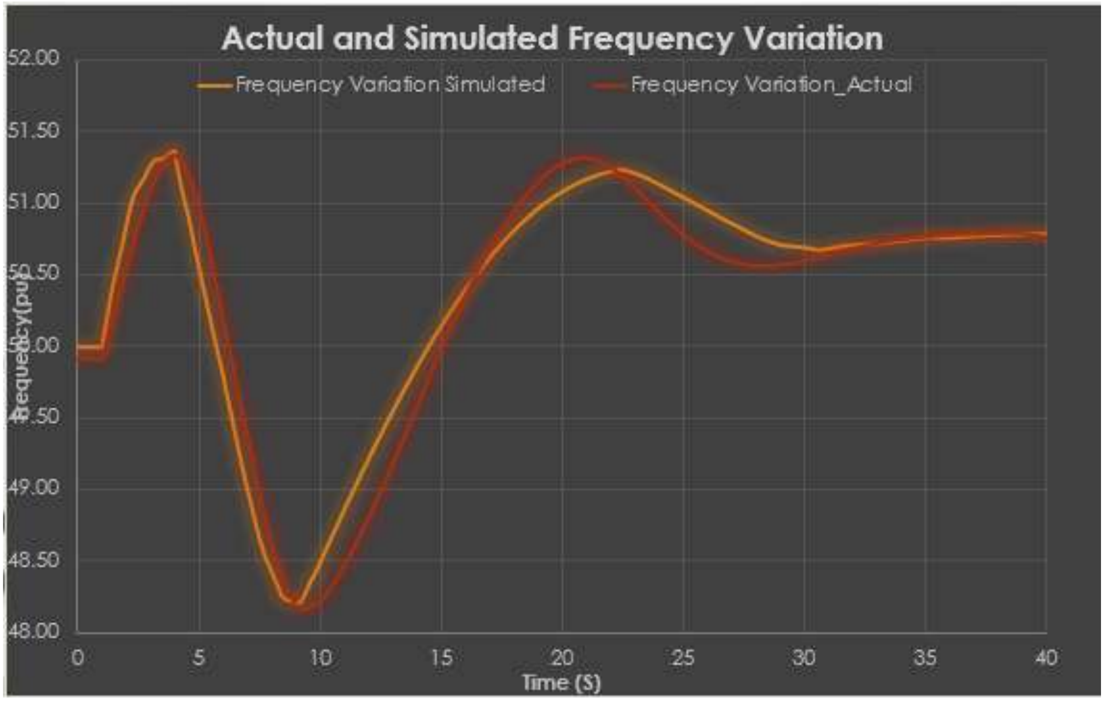


Figure 21: Actual and Simulated Frequency Variation_Incident 16th of September 2018

Same incident was simulated enabling FV action with the valve actuation timings found in the stage one. The results are as follows.

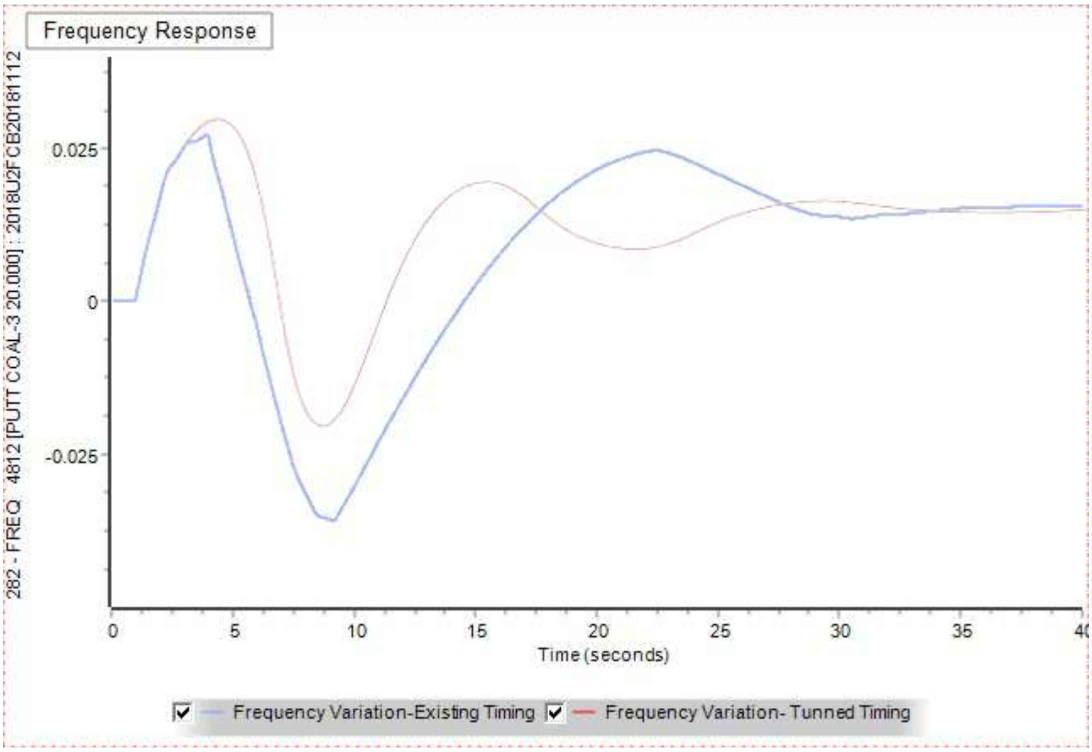


Figure 22: Frequency Response for Existing and Proposed Time Settings_16th of September 2018

The system stabilizes without sever fluctuation for the valve actuation timings picked up from stage 01.

Chapter Summary

This chapter proposed a methodology to find the optimum timings for IVs of FV scheme of LVPP. Further this chapter found the optimum actuation timings for IVs of FV scheme of LVPP to enhance the Sri Lankan power system frequency stability transient conditions based on the results of simulations.

4 RESULTS AND ANALYSIS

4.1 Comparing OPC and FV Schemes

In the chapter 03, the incidents validations were done enabling the OPC action of LVPP and optimum timings were checked for the FV action as many research papers has recommended. Following simulation results further verify that FV action has control on transient stability over the OPC.

The effect of OPC and FV were compared separately for the incident occurred on 13th of March 2016 with the optimum valve actuation timings found in the chapter 3.

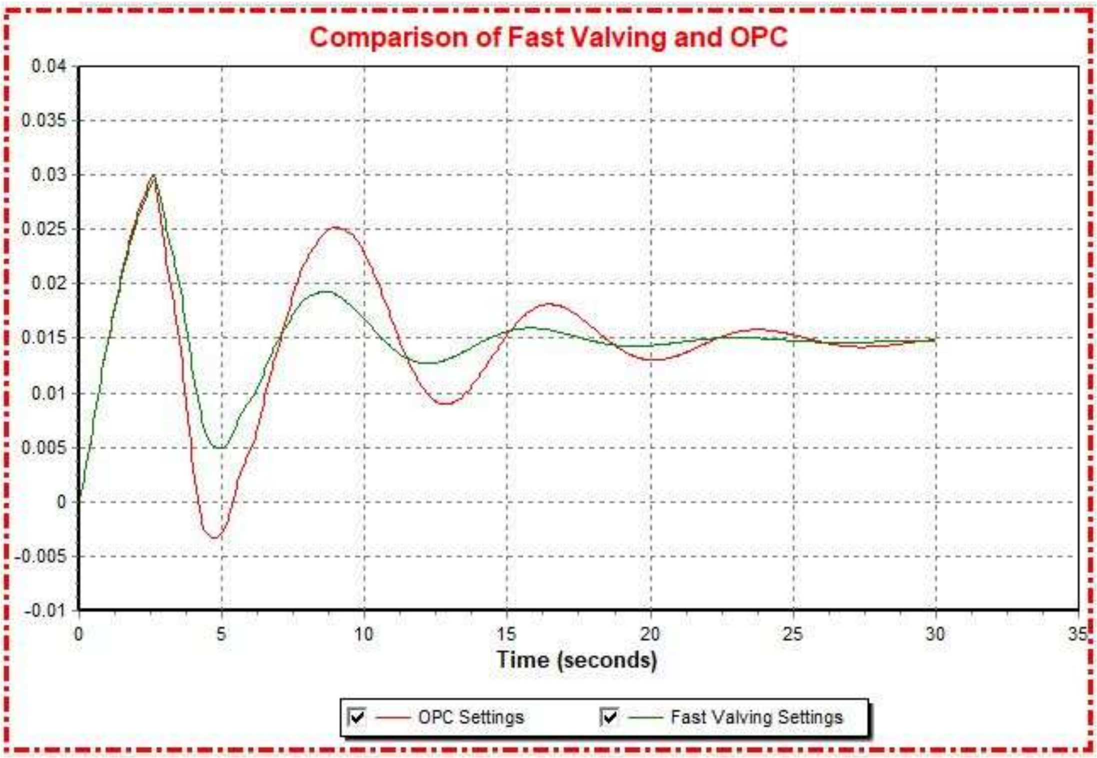


Figure 23: Comparison of Frequency Variation under OPC and FV Action

As results shows, the fluctuation of frequency under OPC action is higher than FV action. As most of the research papers has recommended, FV is recommended to use as a transient stability enhancement element of LVPP steam turbine.

4.2 Recommended FV Settings for LVPP

From the results of this study and manufacturer recommendations, following values are recommended for the fast valving settings of LVPP,

	FV Enable Speed (rpm)	**FV Disable Speed (rpm)**
Unit 01	3090	3030
Unit 02	3090	3030
Unit 03	3090	3030

Table 11: Proposed Speed settings for FV

Intermediate Valve Actuation Timing	**Range**	**Optimum Settings**
TA	0.1 s<TA<0.25 s	0.15 s
TB	1 s<TB<2.2 s	1.5 s
TC	3 s<TC<9 s	5 s

Table 12: Proposed Intermediate Valve Actuation Timings for FV

These settings are within the optimum range of valve actuation timings found in the chapter 3 and machine speed limits recommended by the manufacturer.

4.3 Analysis of Effect of the Different Valve Actuation Timings

After determining the optimum time ranges for the actuation timings of IVs, the effects of changing TA, TB and TC were investigated. The system frequency responses with different values of TA, TB and TC from optimum time ranges found in chapter 03 have been examined here.

4.3.1 Changing TA within Recommended Range

Due to the manufacturer recommendations and mechanical constraints the time range for TA of IVs is very narrow. System get stable within the recommended range of TA (0.1 s< TA < 0.25 s) as shown in the figure 25.

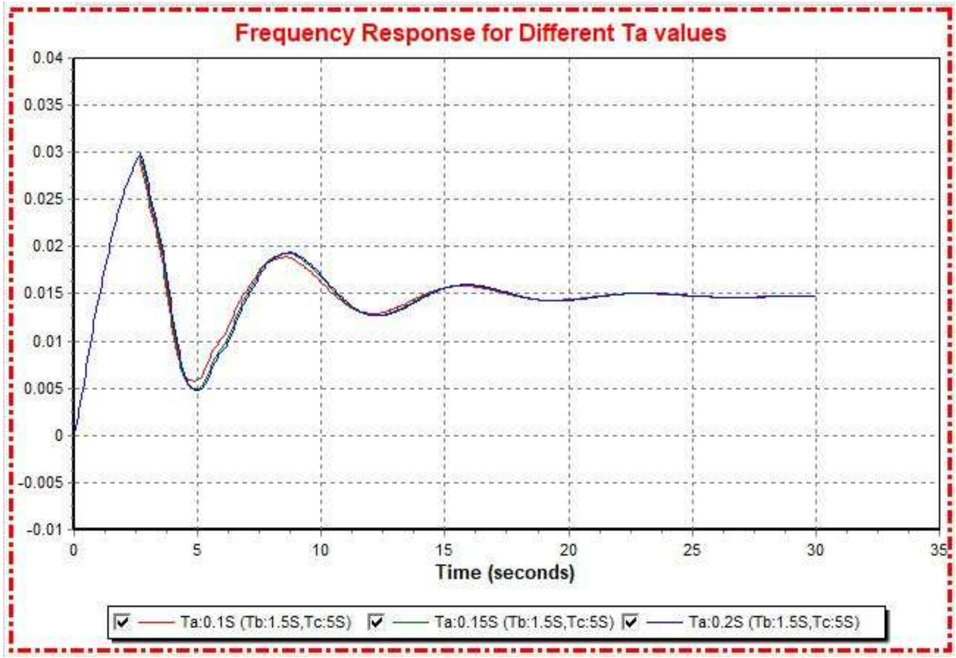


Figure 24: Frequency Response for Different TA of Proposed Optimum Time Range

Three different TA values (0.1 s, 0.15 s and 0.2 s) were randomly picked up from the recommended timing range of TA in chapter 03. System gets stable for this recommended range of TA as shown in the figure 25.

4.3.2 Changing TB within Recommended Range

TB has a direct relationship with the accumulation of steam in the reheater. Accumulation of steam in the reheater will be higher when TB is increased. The stored steam in the reheater produce more mechanical driving power as the intercepts valve reopens completely. The release of stored steam in the reheater causes to increase the mechanical driving power from the nominal value and it affects the subsequent swings and the transient stability of the system.

The effect of different TB from the determined optimum time ranges (1 s < TB < 2 s) are shown in the figure 27,

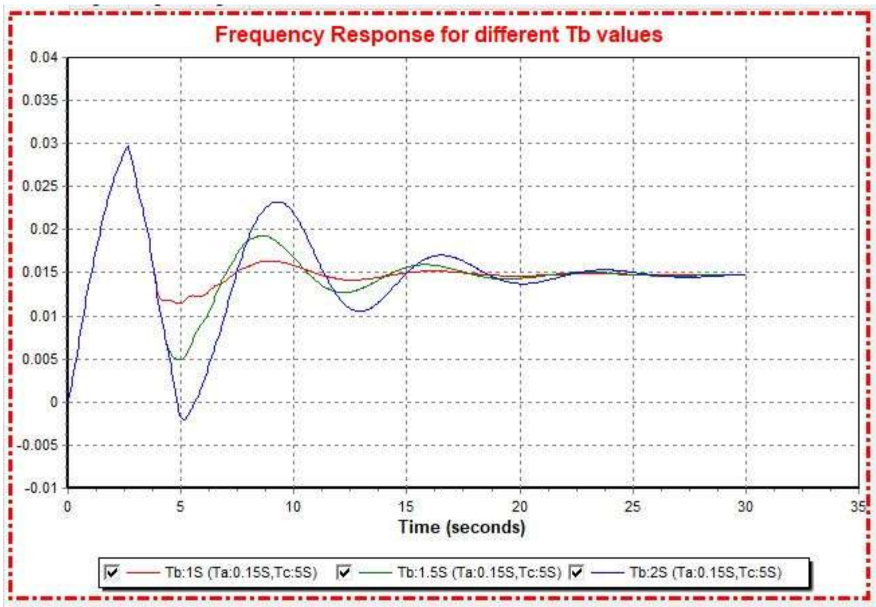


Figure 25 : Frequency Response for Different TB of Proposed Optimum Time Range

Three different TB values (1 s, 1.5 s and 2 s) were randomly picked up from the recommended timing range of TB in chapter 03. System gets stable for this recommended range of TB as shown in the figure 26.

As explained when TB is increased, the accumulation of steam in reheater considerably affects the second swing stability as shown in the figure 26. The second swing is much controllable when the dead time reduced to nearly 1 s from 2 s

4.3.3 Changing TC within Recommended Range

The valve actuation time for different reopening times (TC) are considered. When TA and TB are not varied, the mechanical driving power decay occur at same rate for all values of TC within the range as shown in the figure 27. The changing of TC is mainly affected to vary the rate of rise of mechanical power to the nominal value. As per the figure 27, it is clear that TC has no effect on first swing stability of the system but on the second swing and subsequent swing stability. This causes due to time taken for reopening of IVs decides the accumulation of steam in the reheater and rate of release of accumulated.

The effect of different TC from the determined optimum time range (3 s < TB < 7 s) are shown in the figure 27,

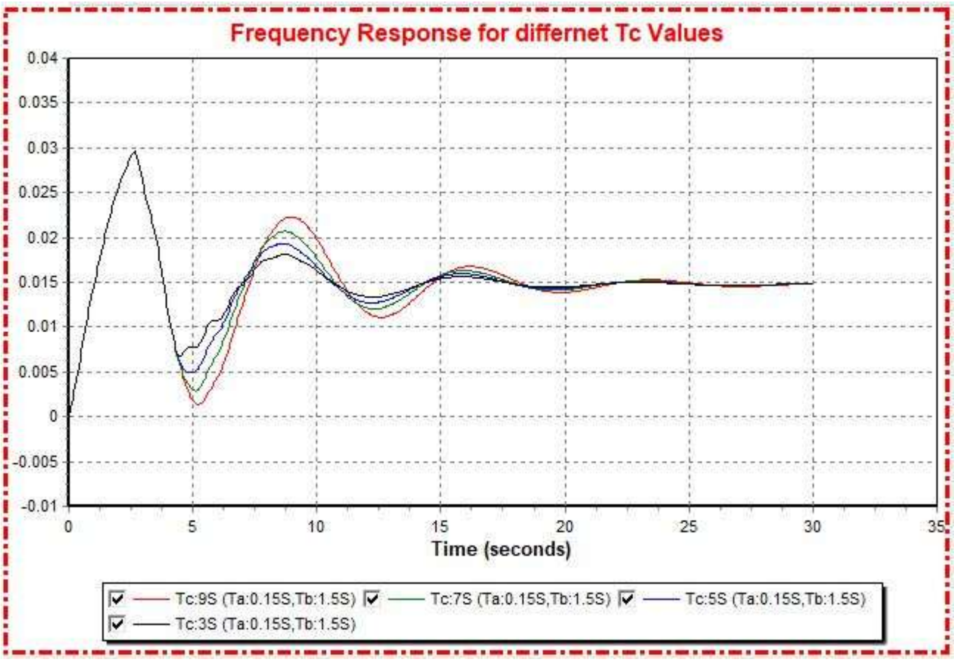


Figure 26: Frequency Response for Different TC from Optimum Time Range

Three different TC values (3 s, 5 s and 7 s) were randomly picked up from the recommended timing range of TB in chapter 03. System gets stable for this recommended range of TB as shown in the figure 27.

As explained when TC is increased, the accumulation of steam in reheater considerably affects the second swing and subsequent stability as shown in the figure 26. The second swing is much controllable when TC reduced to nearly 3 s from 7 s

As per the results of simulations, closing time (TA) mainly affect first swing but dead time (TB) has large effect on second swing. Also the valve opening time (TC) has effect on the stability of second swing and subsequent swings but not on first swing stability.

Chapter Summary

This chapter carried out a detailed analysis on the results obtained from the PSS/E simulations. Next chapter will bring out the conclusions of the thesis study.

5 CONCLUSIONS

5.1 Conclusions

Coal based steam turbines are still young to the Sri Lankan Power system. More coal based generation plants will be integrated to the system in the future to cater the rising electricity demand in the country. In this context, it is very important to study the “Fast Valving” (FV) function which is used for steam turbines as a transient stability enhancement tool. This thesis presents results based analysis showing the effectiveness of setting optimum timings for FV scheme of steam turbines to improve the transient stability of the power system.

This study has revealed that though the steam turbine manufacturer of LVPP has stated that primary objective of OPC which has a similar function to FV is designed only to protect the steam turbine from over speeding, the application of OPC can be used to improve the power system frequency stability margins and reduces the possibility of unit tripping due to sever power system disturbances.

This study has further demonstrated that the use of FV has more control over transient stability than OPC and FV is one of the commonly used schemes for steam turbines worldwide. The results of the studies carried out on these two schemes clearly showed that the effectiveness of FV in improving transient stability is higher than OPC and controlling 70% of the turbine power is enough to enhance the transient stability under large disturbance of the system.

The simulation results of this study has clearly showed that finding the optimum time settings for valve actuations of FV is of paramount important to enhance the transient stability. It is proven that the possibility of a first swing, second swing and subsequent swings instability is very high under a large disturbance of the power system when these valve actuation timings are out of the range.

Results of this study finally showed that the all three incidents which triggered OPC function of LVPP could be stabilized by enabling the FV schemes of LVPP machines with proposed settings.

6 REFERENCES

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[11] Lakvijaya Power Plant, *Commissining Values.*

[12] Jan Machowski, Adam Smolarczyk and J.W. Bialek, “Power System Transient Stability Enhancement By Cordinated Fast Valving and Excitation Control of Synchronous Generator,” in *CIGRE Symposium on Working Plant and Systems*

Harder, London, 1999.

[13] NEPLAN AG, TURBINE-GOVERNOR MODELS, Küsnacht ZH.

7 ANNEXES

7.1 Python Code

```
import math

t=0

psspy.case(r"""C:\Users\User\Desktop\MSc PSSE for Final\Janaka Biyagama \Biyagama Failure.cnv""")

psspy.rstr(r"""C:\Users\User\Desktop\MSc PSSE for Final\Janaka Biyagama \Biyagama Failure1.snp""")


psspy.change_plmod_var(4810,r"""1""",r"""TGOV3""",2, 99999.)

psspy.change_plmod_var(4811,r"""1""",r"""TGOV3""",2, 99999.)

psspy.change_plmod_var(4812,r"""1""",r"""TGOV3""",2, 99999.)


#OPC action by defining K1=0,K2=0.6 and K3=0.4


psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",10, 0.0)

psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",10, 0.0)

psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",10, 0.0)


psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",12, 0.6)

psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",12, 0.6)

psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",12, 0.6)


psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",14, 0.4)
```

```
psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",14, 0.4)

psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",14, 0.4)


psspy.strt(0,r"""C:\Users\User\Desktop\MSc PSSE for Final\Janaka Biyagama
\biyagamatcdampingfinal.out""")

psspy.run(0,t,0,50,0)


psspy.dist_3wind_trip(2570,1570,3570,r"""2""")

psspy.dist_bus_trip(2570)

while t<30:

    t=t+0.05

    psspy.run(0,t,0,50,0)

    f1=psspy.chnval(45)

    freq1=f1[1]

    ActF1=50*(1+freq1)


    #Enabling OPC at turbine speed of 3090rpm


    if ActF1>51.5 :


        psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",15, 0.15)

        psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",15, 0.15)

        psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",15, 0.15)


        psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",16, 1.5)

        psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",16, 1.5)

        psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",16, 1.5)
```

```
        psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",17, 5)
        psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",17, 5)
        psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",17, 5)

        psspy.change_plmod_var(4810,r"""1""",r"""TGOV3""",2, t)
        psspy.change_plmod_var(4811,r"""1""",r"""TGOV3""",2, t)
        psspy.change_plmod_var(4812,r"""1""",r"""TGOV3""",2, t)

#Disabling OPC at turbine speed 3030rpm

    f2=psspy.chnval(45)
    freq2=f2[1]
    ActF2=50*(1+freq2)
    Diff=ActF2-ActF1
    print("Difference ",Diff)

    if ActF1<50.5 & Diff<0:

        psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",15, 1000)
        psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",15, 1000)
        psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",15, 1000)

        psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",16, 0.001)
        psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",16, 0.001)
        psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",16, 0.001)

        psspy.change_plmod_con(4810,r"""1""",r"""TGOV3""",17, 1)
```

```
    psspy.change_plmod_con(4811,r"""1""",r"""TGOV3""",17, 1)
    psspy.change_plmod_con(4812,r"""1""",r"""TGOV3""",17, 1)

    psspy.change_plmod_var(4810,r"""1""",r"""TGOV3""",2, 99999.)
    psspy.change_plmod_var(4811,r"""1""",r"""TGOV3""",2, 99999.)
    psspy.change_plmod_var(4812,r"""1""",r"""TGOV3""",2, 99999.)

else:

    print("freq within limit",ActF)
```