Steady State Stability Analysis and Improvement using Eigenvalues and PSS

A Case Study of a Thermal Power Plant in Jamshoro, Pakistan

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***Abstract*—The efficient handling and distribution of electrical power consist one of the most complex and appealing research problems. Due to the interconnection of different power plants and intensity of load, which gradually changes due to continuous change in load on generating units, careful treatment of the small disturbances in a power system which may lead to severe disturbance is necessary. Stability is an essential part in electrical power system operation and control. The stability problem is related with the behavior of synchronous machine after the power system is subjected to trouble. This work presents Steady State Stability (SSS) analysis of a Jamshoro Thermal Power Plant (JTPP) by using eigenvalue analysis of the different cases by varying load at three different positions. A mathematical model has been used for the JTPP with real data in order to examine the behavior of the system and to find the eigenvalues. A Simulink model of the JTTP for waveform analysis in MATLAB/Simulink has been used without and with Power System Stabilizer (PSS). Numerical quantification of the eigenvalues under the examined cases categorizes the stability of the system. The waveforms of the system are analyzed, and in cases of instability, the proposed procedure utilizing PSS helps in maintaining the system's usual working conditions. The eigenvalue analysis and simulation results show the behavior of synchronous machines when loading changes gradually. The existing system becomes stable after more swings, whereas by using PSS in the existing system, stable regimes are attained in less time. The obtained results demonstrate the effectiveness of the proposed solution for SSS examination and securing of the disturbances of the JTPP.**

Keywords-steady state stability; power plant; eigenvalues; power system stabilizer; MATLAB

I. INTRODUCTION

In an electrical power system, it is essential to transmit reliable, secure and free from disturbances power, but load and external faults are independent which may affect voltage and frequency values, or even cause loss of synchronism [1]. The ability of a power system to remain stable after facing a small or large disturbance, which occurs in the existing system, is called power system stability. Stability problems are divided into two categories: Transient Stability (TS) and Steady State Stability (SSS) [2]. In TS, the power system remains in normal condition when a large disturbance occurs such as a loss of excitation, fault on the system, a sudden outage of line, removal of large load, etc. [3]. On the other hand, in SSS, the power system remains in normal condition when small disturbances occur, such as gradual variation in electrical load [4]. Nowadays, electrical power systems grow day by day, with increase of interconnection, installation of very large units, and extra high voltage (EHV) tie-lines [5]. TS is usually analyzed through Euler method, modified Euler method, and Runge-Kutta (RK) methods whereas SSS of the power system is usually examined using eigenvalues [6]. Eigenvalues and wave-forms of synchronous machines were analyzed in [7]. The examination was carried out by varying faults at three different locations: generating point, middle of transmission line, and an infinite position. The fault near the machine appeared to be most severe. In [8], by varying instantaneous power disturbance, eigenvalues and wave forms were analyzed in power system generating units, disturbance of waveforms dependence on the amplitude and location of disturbance. According to [9] the SSS of power systems by increasing loads is complementary to the usual TS investigations. To study the SSS of a complex power system, eigenvalue analysis was used. In [10], analysis of SSS on the near connection between the already-connected Luzon-Visayas grid with the isolated Mindanao power grid was investigated in free and open-source software. There are not publicly available studies regarding this inter-connection. In [11], small signal stability analysis for a hybrid renewable energy system was conducted and an integrated hybrid system was analyzed with the help of Lyapurav's stability criteria and small signal stability disturbance with power system stabilizer (PSS) through MATLAB/Simulink.

Power flow and SSS of interconnected three isolated Philippine power grids was studied in [12]. Eigenvalues analysis was employed to find the SSS of the main power grid and a model was developed in MATLAB/Simulink. According to [13], if the quantity of perturbation is very small, in the initial stage when there is small perturbation in the load, the system remains in stable condition (SSS). Under small perturbation if the eigenvalues of the mathematical model have

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negative real parts, the system is under stable condition. In case the system becomes unstable, this means that the eigenvalues have positive real parts, while complex eigenvalues, produce oscillations in the system. In [14], the TS of a power system was verified by using time domain (TD) analysis, and eigenvalues analysis when the system was brought under small disturbances. The use of FACTS devices for TS was investigated in [15]. Other approaches like the use of fuzzy logic controllers [16] and harmonic function [17] have also been used to improve PSS under different conditions [18].

In this paper, stable and efficient operation of a JTPP have been considered. Stable operation, voltage stability, frequency stability, and rotor angle stability were studied. Voltage stability considered voltage control through an Automatic Voltage Regulator (AVR) for frequency stability. Focus was given on Primary Frequency Control (PFC) through governor, and rotor angle stability focus is on the deviation of rotor speed. This work analyzes small signal stability which can be modified by using PSS. In that way, the system becomes stable and will remain in stable condition for a long period of time. The proposed procedure assures the secure and reliable operation of the JTPP even in conditions when disturbance, either small or large, occurs in the system, by changing different loads. The objective of the current work is to analyze the stability of a power system under varying load at alternator side. By varying load at alternator side, it has been shown that the system has more swings when large load is connected on a power system. So, in order to remove more swings a PSS was used. By using PSS, the system became stable in less time. The main contribution of this work lies on the use of eigenvalues as indicators of the small signal stability in usual operation so that the unstable regimen may be analyzed and taken care of in order to retain stability. The use of PSS on usual operation has also been tested and found to improve the stability regimen.

II. MATERIALS AND METHODS

The JTPP has four units, one with 16.5KV rated voltage and three with 15.75KV rated voltage. Two transformers are used which step up from the rated voltage to 220KV transmission line voltage. A generating unit was developed in the mathematical model, at alternator side, at excitation side and at prime mover governing system side. The eigenvalues were found and the analyzed system's stability was improved by PSS.

A. Plant Overview

The plant was visited and all the necessary data, parameters, and specifications mentioned in Tables I-II were collected.

B. Small Signal Stability Analysis

The ability of the running power system to maintain synchronism after the occurrence of small interruption is known as Steady State Stability [1]. As variations occur in the system, they cause small unbalances. A dynamic equation model of the system will be developed and will be linearized to understand SSS.

TABLE I. SYSTEM PARAMETERS AND SPECIFICATIONS

Type	Units	
	1 Synchronous machine FTHRI 562/68-2	**2-4 Synchronous machines QFSN-210-2**
Connections	3-Phase star	3-Phase star
Power in MW	250	210
Rated current	10.294KA	9.056KA
Rated voltage	16.5KV	15.75KV
Visual power	294200KVA	247000KVA
Power factor	0.85	0.85
Speed	3000RPM	3000RPM
Critical speed second order	3590RPM	3494RPM
Critical speed first order	1200RPM	1263RPM
Rated excitation voltage	370V	489V
Rated excitation current	2020A	1867A
Efficiency	99.02%	98.66%
Pressure of h2	$3Kg/cm^2$	0.3MPa
Water flow for stator winding	----	$35m^3/h$
Insulation class	F	F

TABLE II. POWER TRANSFORMER PROPERTIES AND SPECIFICATIONS

Model	Units	
	1 AD69030T1	**2-4 SFP7-250000/220TA**
Rated power	294.2MVA	250000KVA
Rated current	772/10294A	656.1/9164.3A
Rated voltage	220/16.5KV	220±4X2.5%/15.75KV
Cooling type	Oil immersed, (ODAF) cooled	Oil immersed, (ODAF) cooled
Frequency	50Hz	50Hz
Poles	3	3
Temperature class	A	A
Connection of symbol	YN. d1	YN. d1
Noise level	90dB (A)	75dB
Load loss	<500KW	609.9KW
No load loss	<520KW	613.6KW
No load current	0.2%	0.12%
Impedance voltage	15%	13.5%

Under balanced condition, we may define the system as:

$$\Delta\dot{x} = A\Delta x \quad (1)$$

It is defined as the rate of change of each state variable with the linear composition of all thee states available in the system. To inscribe the small signal analysis problem, the modified state vector z is described in equation (2):

$$\Delta x = \phi z \quad (2)$$

The variable matrix Φ is the right modal matrix of vector A. A is consisting of n right eigenvectors φ_i;i∈n . Equation (3) is developed by combining (1) and (2):

$$\phi\dot{z} = A\phi z \quad (3)$$

By rearranging (3), we get:

$$\dot{z} = \Phi^{-1}A\Phi z = \Lambda z \quad (4)$$

Λ represents a matrix having diagonal elements of eigenvalues where λ=I belongs to n, so (5) represents n decoupled first order:

$$\dot{z}_i = \lambda_i z_i \quad (5)$$

The resolved form of (5) is:

$$z_i(t) = z_i(0)e^{\lambda_i t} \quad (6)$$

To obtain $z_i(0)$, (7), can be written as:

$$z(t) = \Phi^{-1}\Delta x(t) = \Psi\Delta x(t) \quad (7)$$

where Ψ is the left matrix of vector A, which consist of n left eigenvectors ψ_i, hence every variable of state and its starting condition are given as:

$$z_i(t) = \Psi_i\Delta x(t)\,; z_i(0) = \Psi_i\Delta x(0) \quad (8)$$

In accordance with (6), the actual state vector Δx(t) is written as:

$$\Delta x(t) = \sum_{i=1}^{n} \Psi_i c_i e^{\lambda_i t} \quad (9)$$

with c_i as $z_i(0)$. The actual state variable $\Delta x_i(0)$ can be extracted from (2) and (9):

$$\Delta x_i(t) = \Psi_{i1}c_1 e^{\lambda^1 t} + \Psi_{i2}c_2 e^{\lambda^2 t} + \cdots + \Psi_{in}c_n e^{\lambda^n t} \quad (10)$$

Free motion quickness of the power system is determined by the linear composition of eigenvalues, dynamic modes and left/right eigenvectors. The frequency behavior of the system can be successfully examined and evaluated by using the SSA in terms of the time-domain simulation (TDS). Linear analysis can be obtained by using DIgSILENT software and the non-linear TDS of the dynamic system, which makes it easy by software. The major benefits of the linear model are that it gives the opportunity for using the eigenvalues to adjust the frequency handling controllers and the use of eigenvectors to trace the contents of the frequency regulation mode. Generators' frequency shows the condition of the systems which may be scripted in the forms of entire eigenvalues and conditions of the system by using (10)[19]:

$$\omega_i(t) = \Psi_i^{1}c^{1e^{\lambda^1 t}} + \Psi_i^{2}c^{2e^{\lambda^2 t}} + \cdots + \Psi_i^{n}c^{n}e^{\lambda^n t} \quad (11)$$

C. General Mathematical Model

The electrical system exists on synchronous machines connected to an infinite bus bar. There are four conditions to sink the alternator with the infinite bus. It must have the same value of voltage, frequency, phase sequence, and phase angle difference. Every alternator has two main controllers, one for speed, called governor and another for voltage, the AVR. By varying load gradually at the alternator side through MATLAB/Simulink, we analyzed the small disturbances without PSS and with PSS. In the two axis model, the synchronous alternator consists of the transient and sub transient effect. The transient effects are taken into consideration and sub transient effects are considered as negligible, so the effects of transients are overcome with the rotor circuit which is the field circuit in the d-axis and q-axis formed by solid rotor [1].

1) Swing Equation

$$\dot{\omega} = \frac{1}{M_g}(P_m - D_g\omega - P_e) \quad (12)$$

2) Rotor Angle Equation

$$\dot{\partial} = (\omega - \omega_o) \quad (13)$$

3) Excitation System

Every alternator has an AVR. Through the AVR we can control the terminal voltage of an alternator by varying field current and maintain the terminal voltage as per our needs. Usually loop gain KA must be as per command of AVR, if the loop gain is very high the system will be unstable, if it is very low the system performance of AVR step response will be unsatisfactory. Therefore, to enhance the related stability and steady state behavior, the transformer is used for stabilizing.

$$\dot{E}_{FD} = \frac{1}{T_A}[-E_{FD} + (V_{ref} - V_t - V_s)K_A] \quad (14)$$

$$\dot{V}_s = \frac{1}{T_F}[-V_s + E_{FD}] \quad (15)$$

The transient voltage of armature on d and q-axes may be indicated like:

$$\dot{E}d_d = \frac{1}{Td_{qo}}\left[-Ed_d + (X_q - Xd_d)I_q\right] \quad (16)$$

$$\dot{E}d_q = \frac{1}{Td_{do}}[E_{FD} - Ed_d + (X_d - Xd_d)I_d] \quad (17)$$

4) Governor System

When the load on alternator increases suddenly, it causes rapid change in the governor intake. The deficient power is delivered by the kinetic energy of the rotary system. So, the depletion in kinetic energy decreases the alternator speed, hence change in new operating speed is identified by the governor which will act to adjust the intake valve to generate the mechanical power output which will counterbalance the normal operating position. The equations that express the prime-mover governing system are:

$$\dot{P}_R = \frac{1}{T_{sr}}\left[-P_R + K_g(\omega_{ref} - \omega)\right] \quad (18)$$

$$\dot{P}_h = \frac{1}{T_{sh}}[-P_h + P_R] \quad (19)$$

$$\dot{P}_{ch} = \frac{1}{T_{ch}}[-P_{ch} + P_h + P_{mo}] \quad (20)$$

$$\dot{P}_m = \frac{1}{T_{rh}}\left[-P_m + \dot{P}_{ch} + \frac{K_{rh}T_{rh}}{T_{ch}}(-P_{ch} + P_h + P_{mo})\right] \quad (21)$$

The standard action for small faults is basically that the disturbed system may be linearized near quiescent operating point.

$$M_g\Delta\dot{\omega} = \Delta P_m - D_g\Delta\omega - Id_{do}\Delta Ed_d - Id_{qo}\Delta Ed_q - Ed_{do}\Delta I_d - Ed_{qo}\Delta I_q \quad (22)$$

$$\Delta\dot{\partial} = \omega_o\Delta\omega \quad (23)$$

$$T_A\Delta\dot{E}_{FD} = -\Delta E_{FD} + K_A(-\Delta V_s - f_1\Delta Ed_d - f_2\Delta Ed_q + f_3\Delta I_d + f_4\Delta I_q) \quad (24)$$

$$-K_F\Delta\dot{E}_{FD} + T_F\Delta\dot{V}_s = -\Delta V_s \quad (25)$$

$$Td_{qo}\Delta\dot{E}d_d = -\Delta Ed_d - (X_q - X_d)I_q \quad (26)$$

$$Td_{qo}\Delta\dot{E}d_q = \Delta E_{FD} - \Delta Ed_q + (X_d - Xd_d)\Delta I_d \quad (27)$$

$$T_{sr}\dot{\Delta P}_R = -\Delta P_R - K_g\Delta\omega \quad (28)$$

$$T_{sm}\dot{\Delta P}_h = -\Delta P_h + \Delta P_R \quad (29)$$

$$T_{ch}\dot{\Delta P}_c = -\Delta P_c + \Delta P_h \quad (30)$$

$$-K_{rh}T_m\dot{\Delta P}_C + T_m\dot{\Delta P}_m = -\Delta P_m + \Delta P_c \quad (31)$$

where $f_1 = \frac{V_{do}}{V_{to}}$, $f_2 = \frac{V_{qo}}{V_{to}}$, $f_3 = f_2 Xd_d - f_1 r_a$,

and $f_4 = -f_1 Xd_d - f_2 r_a$.

We consider $V_{ref} = 1p.u$ $\omega_o = 1p.u$ and $V_s = 0$.

D. Proposed Stability Snalysis of the JTPP

The flowchart given in Figure 1 represents the work division in two parts. One part consists of the mathematical model, in which stability is analyzed through eigenvalues. If the eigenvalues are negative, the system is in stable state. If the obtained eigenvalues are positive, the system is in state of instability, and it will be stabilized by the PSS. In the other part, the developed MATLAB/Simulink model, stability is analyzed through waveforms, and is also improved by PSS.

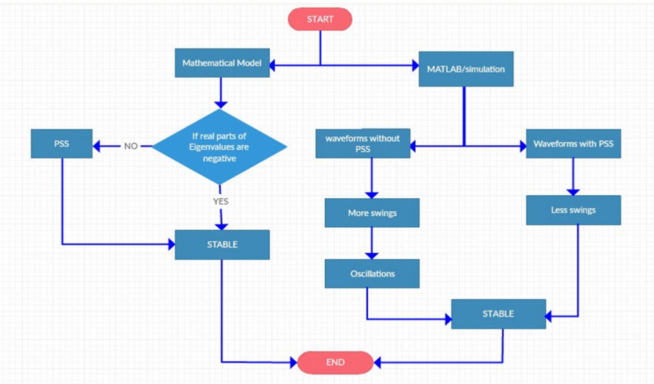

Fig. 1. Flow chart of the proposed identification by eigenvalues and PSS

The equation for a system under an instability state can be given in matrix form as follows, here we can determine eigenvalues.

$$[F][\dot{x}] = [B][X] + [D][I_{dq}] \quad (32)$$

$$I_{dq} = LGX$$

$$\therefore F\dot{x} = (B + DGL)X$$

$$\therefore \dot{x} = (F^{-1}(B + DGL)X) \quad (33)$$

$$\therefore \dot{x} = AX \quad (34)$$

The values of A matrix are known. Finally, the eigenvalues are obtained with MATLAB R2017a. Eigenvalues play an important part in determining power system stability. Two real separate eigenvalues have the same symbols. Both may be positive or negative. Positive values will show that the system is unstable and negative will show that the system is stable. Nodal real eigenvalues with two eigenvectors are unstable if these are positive and the opposite if they are negative. Saddle points with two distinct real eigenvalues of opposite signs are always unstable [6]. On the spiral chart, there are complex eigenvalues with non-zero and real parts. The system is unstable if the real part is positive and stable if the real part is negative. On the other hand, improper node represents unstable condition if it is positive and asymptotically stable if it is negative [19]. Figure 2 shows an existing electrical power system with generating unit, circuit breakers, transformer, and infinite bus. Three different loads are applied at generating stations and the waveforms are monitored. Severe disturbance occurs when more loads are applied. Figure 3, similarly, shows the developed MATLAB/Simulink model modified by PSS. Stability is analyzed by changing load after modification. It has been concluded that the system becomes stable in a very short time after the modification when compared to the system of Figure 2.

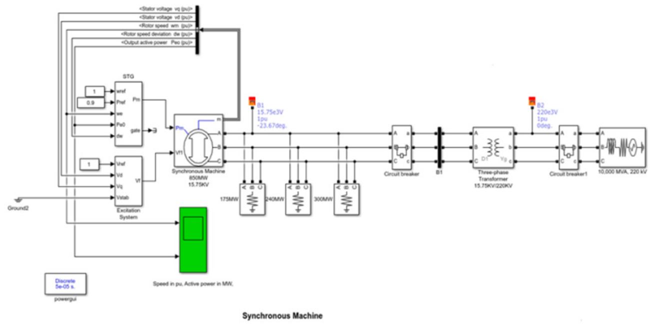

Fig. 2. MATLAB/Simulink model without PSS

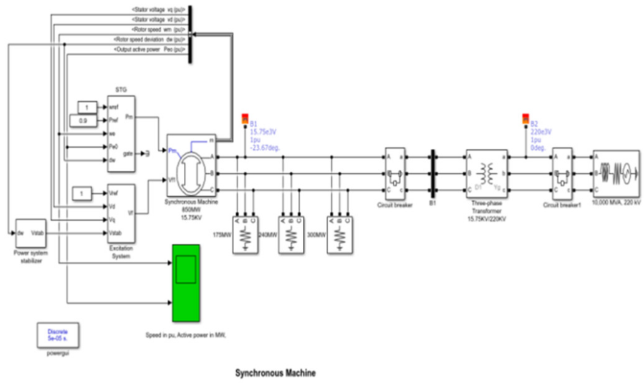

Fig. 3. MATLAB/Simulink model with PSS

The data regarding the parameters of the simulation model defined in (11)-(20) were obtained from the JTPP and are given in p.u. in Table III.

III. Results and Discussion

By varying reheat system prime mover gain K_{rh}=0.3, 2, 2.5, and 10, we find that at K_{rh}=10 the system is unstable. Figures 4-7 represent the system's eigenvalues. In normal condition, the system is stable with constant speed (no deviation), constant output voltage, and constant output power. When load changes, small disturbances occur.

TABLE III. DATA OBTAINED FROM JTPP

Parameters			
Symbols	**Values**	**Symbols**	**Values**
Mg	8	**Tdq_o**	0.3
Dg	0	**Xq**	1.58
Iddo	0.39	**Xdd**	0.32
Idqo	0.6329	**Xd**	1.67
Eddo	0.1248	**Tsr**	0.1
Edqo	0.9999	**Kg**	4
Wo	1	**Tsm**	0.2
T_A	0.05s	**Tch**	0.2 to 0.5s
K_A	50	**Krh**	0.3,2,2.4 and 15
f_1	0.9523	**Tm**	0.93
f_2	0.9523	**P_o**	0.8
f_3	0.2322	**Vd_o**	1
f_4	0.2344	**Vt_o**	1.05
Kf	0.11	**Vq_o**	0.999
Tf	0.7	**r_a**	0.0023

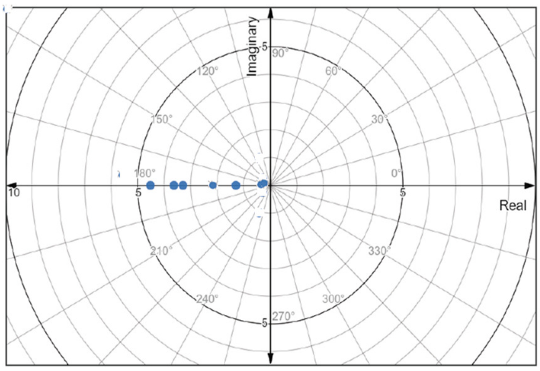

Fig. 4. Stable condition at K_{rh}=0.3

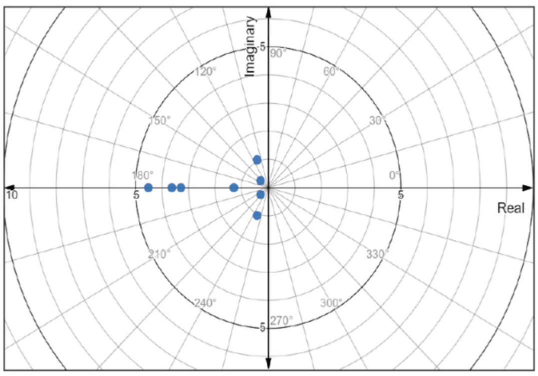

Fig. 5. Stable condition at K_{rh}=2

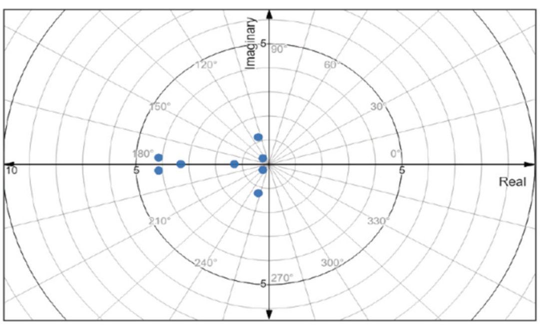

Fig. 6. Stable condition at K_{rh}=2.5

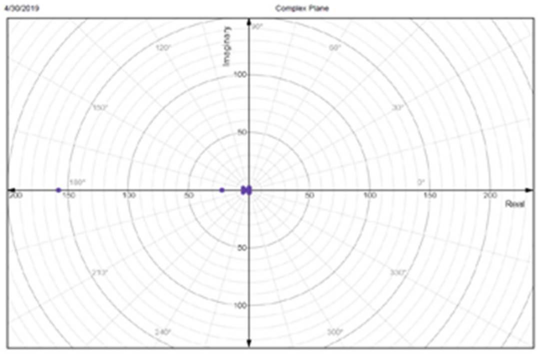

Fig. 7. Unstable condition at K_{rh}=10

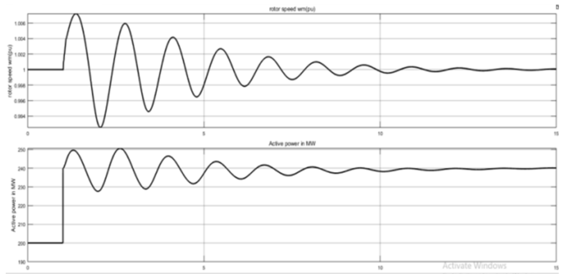

Fig. 8. Without PSS when 240MW load is connected

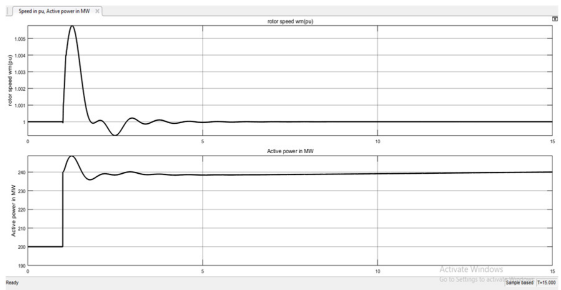

Fig. 9. With PSS when 240MW load is connected

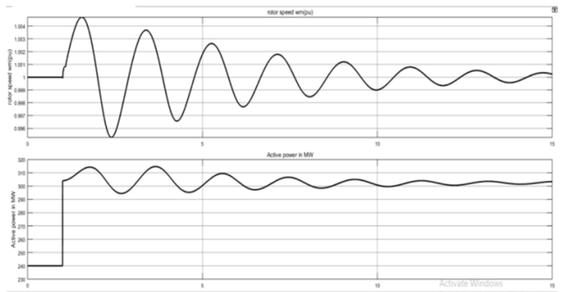

Fig. 10. Without PSS when 300MW load is connected

The behavior of a synchronous machine with small disturbances has been analyzed with the help of MALTAB/Simulink, when 240MW, 300MW, and 175MW load changes. The respective waveforms are shown in Figures 8, 10, and 12 with PSS and in Figures. 9, 11, and 13 without PSS. The instabilities were identified using eigenvalues, as shown in Figures 4-7, they have been overcome and quickly minimized with the help of PSS.

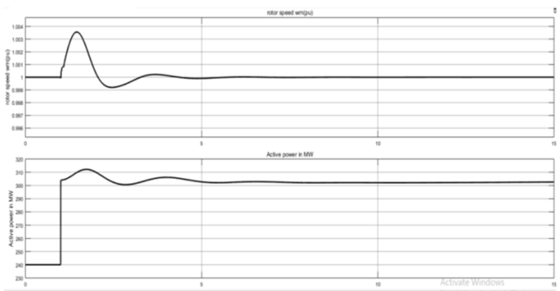

Fig. 11. With PSS when 300MW load is connected

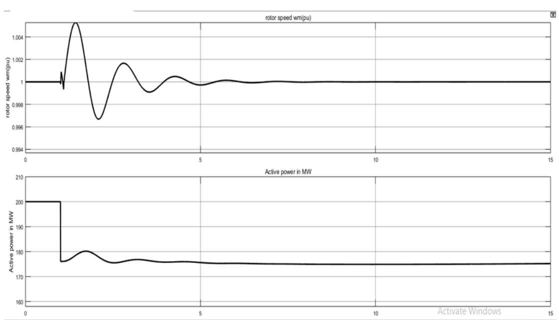

Fig. 12. Without PSS when 175MW load is connected

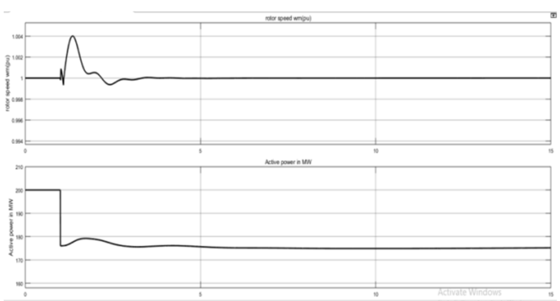

Fig. 13. Without PSS when 175MW load is connected

IV. CONCLUSION

Nowadays, electrical power systems are more complex in nature and widely interconnected. Continuous changes in load cause deviation in frequency and voltage. These changes result in small disturbances in the power system posing instability problems. Hence, steady state stability is important for generating stations. This work proposes a mathematical model and a MATLAB/Simulink model. Eigenvalues are found and employed for finding whether the system is stable or unstable. When they are negative the system stable and vice versa. MATLAB/Simulink model demonstrates the variations in the waveform by varying load, and then improves by applying PSS. This work promotes fast recovery in stable condition when unstable conditions occur in a system when the load gradually changes. This method is helpful for improving the reliability and stability of the system and small disturbances can be rectified without further isolation.

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