EIGENVALUE METHOD AND LINEARIZATION FOR THE STEADY STATE STABILITY ANALYSIS OF JAMSHORO THERMAL POWER PLANT (JTPP)

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Abstract

Electrical power system without interruption is the need of every consumer. Therefore, supplying electrical power which must be efficient, reliable and secure from any disturbance is the priority of power supply companies. But, due to changes in weather conditions and continuous load variations, small disturbances arise which may lead to severe disturbance. All electrical generating stations are interconnected, so a failure in any one unit can affect other generating units, therefore analysis is compulsory to solve the problem in the least time, and avoid a further big loss. Analysis of steady-state stability or transient stability plays a key role in a power system which helps to understand the behavior of a dynamic system. The stability problem is concerned with the behavior of the generating station when the system puts on either small or large disturbance. In this work, the steady-state stability (SSS) analysis of the Jamshoro thermal power plant (JTPP) is analyzed by using the eigenvalue method and linearization technique at four different reheat gain values. We develop a nonlinear mathematical model of JTPP and discuss its linearized form, and examine the behavior of the system stability using eigenvalues. The eigenvalue method analyzes the behavior of synchronous machine when system load varies continually. Numerical values of eigenvalues consist of either real part or real as well as imaginary parts. These eigenvalues help to understand the stability of the system, as to whether the system is stable or not.

Keywords: Eigenvalue, Steady-state, Stability, Power system, Nonlinear model, Synchronous machine.
I. Introduction

The potential of any electrical power system helps to produce restoring force that is identical or more than an interrupted force. To maintain the ability of the power system, some feedback controllers are used to understand the disturbance which occurs in any operating system [XV]. When any disturbance occurs in the operating system, to overcome that disturbance, a specific signal passes through the feedback system, and that signal overcomes disturbance through either governor or AVR (automatic voltage regulator), and the system then runs in a new equilibrium point [XV],[IV],[V]. Therefore, as a result, the operating system remains in a stable position, and the system does not undergo any critical condition. Whenever a disturbance occurs, either small or large, that disturbance hits the system equilibrium point. When the system becomes nonlinear, then afterward it comes in linear form through specific commands [IV],[IX], [X]. So, the system operating point is not the same as it was operating before disturbance, hence the new operating point is established which forms a new equilibrium point. The power system must remain in continuous operating point without any disturbance [I]. For continuous operation, it is necessary to understand the behavior of the existing power system, for understanding such behavior it is essential to analyze the system through particular analysis like eigenvalues, eigenvectors, equal-area criteria etc [XV], [IV], [X], [I], [VI]. Power system stability is a specific chief parameter that should be understood. This branch is very widely concerned with current research work [VIII]. For the sack of worth, it has been divided into two major branches, which are steady-state stability and other one is transient stability [VIII], [XVIII]. It is desired to keep the system in a normal state; there must be a considerable reduction in the influence of disturbances in the system [III]. But, disturbances bring serious and intolerable changes in the system. It creates a series of issues for industrial processes. It reduces the quantity and quality of industrial products [XVII].

A standard mathematical model of the doubly-fed induction generator (DFIG) and steady-state stability analysis was developed in [IV]. DFIGs operating under decoupled P–Q control and maintaining fixed real power outputs are expected to be unstable. The research was presented to sort out the issues through steady-state stability regions. The eigenvalues forecasting of the unstable regions have been settled by simulations [XI], [XVIII], and it was suggested to check the physical concept of steady-state systems at equilibrium. Such a concept must be generalized to narrate such systems, and determined precise conditions for the steady-state to exist as well as the requirements for it to be stable [XIX].

In this work, we analyze the operating system, particularly JTPP, that is either stable or not when the system is put on disturbance. This work assures us to take some remedies that help to run the system under the secure and reliable operation of the JTPP. Eigenvalues are very helpful to understand the behavior of the system. When the real part of eigenvalues is a negative system is stable, but if positive then the system is unstable. Eigenvalues are analyzed when a disturbance occurs in the system, either small disturbance or large disturbance, by changing different loads. We develop a nonlinear mathematical model and discuss its linearized form to examine eigenvalues. These eigenvalues are used to probe the behavior of the system, either

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The objective of this work is to analyze the stability of the power system under varying loads on the alternator side. By varying load at the alternator side, it has been analyzed that the running system is having more oscillations when having more gain values, but fewer oscillations at fewer gain values. This work implements the proposed eigenvalue method and linearization protocol by using MATLAB Software.

II. Stability of Kinetic System

When the system is linear, its stability is not completely related to the input, if there are no changes it means that it has zero input signal, therefore the system will remain in the original position of the state space, it will remain independent of the finite initial state. The stability of a nonlinear system relies on the type and value of the input. These values have to be considered for defining the nonlinear system stability [XV].

In the theory of control system, it is of frequent work to divide the stability of a nonlinear system into three categories: local, finite and global stability. The local stability is termed as a point of equilibrium when small disturbances occur, it is limited in a small region around the point of equilibrium. Local stability constraints can be examined by linearizing the nonlinear system equations about the equilibrium point. On the other hand, suppose that R is a defined region, if the state of the operating system remains in defined region R, the system is called stable when it remains in a defined region. When the system is in a state of disturbance, then it will deviate from its original position, again disturbed system will come back to its initial equilibrium point, this is called oscillatory finite stable within defined region R. The system will be in the category of globally stable if the region R consists on whole limited space [XV], [IV], [X].

III. Proposed Linearization and Eigenvalue Protocol to Examine Stability

In this section, we describe the main contributions and proposed protocol for stability analysis in general for a system. The main equations related to the linearization and computing eigenvalues are discussed here. The general form of a nonlinear system with \( x_o \) as the initial state vector and \( u_o \) as the input vector is described in (1). These are related to the equilibrium point where the performance of small-signal stability can be examined.

\[
\dot{x}_0 = f(x_o, u_o) = 0
\]  

Equation (1) represents that system is in equilibrium, when such type system is subjected on disturbance, then by assuming increment in the variables, we have:

\[
x = x_o + \Delta x
\]  

and

\[
u = u_o + \Delta u
\]  

In equations (2)-(3), the symbol \( \Delta \) defines a small deviation.

Hence, the disturbed system corresponding to (1) is:

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\[ \dot{x} = \dot{x}_o + \Delta \dot{x} = f([x_o + \Delta x], (u_o + \Delta u)] \]  

Here, the disturbances are taken as less in magnitude, when nonlinearity is introduced in the function \( f(x, u) \), this function may be written in the form of Taylor’s series, in its expansion with involvement of second and higher orders of \( \Delta x \) and \( \Delta y \) are considered as negligible. (4) can be written in expansion form as:

\[
\dot{x}_i = \dot{x}_{io} + \Delta \dot{x}_i = f_i([x_o + \Delta x], (u_o + \Delta u)]
\]

\[
= f_i(x_o, u_o) + \frac{\partial f_i}{\partial x_1} \Delta x_1 + \cdots + \frac{\partial f_i}{\partial x_n} \Delta x_n + \frac{\partial f_i}{\partial u_1} \Delta u_1 + \cdots + \frac{\partial f_i}{\partial u_r} \Delta u_r
\]

As, \( \dot{x}_{io} = f_i(x_o, u_o) \), we get

\[
\Delta \dot{x}_i = \frac{\partial f_i}{\partial x_1} \Delta x_1 + \cdots + \frac{\partial f_i}{\partial x_n} \Delta x_n + \frac{\partial f_i}{\partial u_1} \Delta u_1 + \cdots + \frac{\partial f_i}{\partial u_r} \Delta u_r
\]

Hence, \( i = 1, 2, \ldots, n \), likewise, we have:

\[
\Delta y_j = \frac{\partial g_j}{\partial x_1} \Delta x_1 + \cdots + \frac{\partial g_j}{\partial x_n} \Delta x_n + \frac{\partial g_j}{\partial u_1} \Delta u_1 + \cdots + \frac{\partial g_j}{\partial u_r} \Delta u_r
\]

As \( j = 1, 2, \ldots, m \), here we have linearized forms as in equations (5)-(6) respectively.

\[
\Delta \dot{x} = A \Delta x + B \Delta u
\]

\[
\Delta y = C \Delta x + D \Delta u
\]

Where, the matrices are defined as:

\[
A = \begin{bmatrix}
\frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\
\cdots & \cdots & \cdots \\
\frac{\partial f_n}{\partial x_1} & \cdots & \frac{\partial f_n}{\partial x_n}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{\partial f_1}{\partial u_1} & \cdots & \frac{\partial f_1}{\partial u_r} \\
\cdots & \cdots & \cdots \\
\frac{\partial f_n}{\partial u_1} & \cdots & \frac{\partial f_n}{\partial u_r}
\end{bmatrix}
\]

\[
C = \begin{bmatrix}
\frac{\partial g_1}{\partial x_1} & \cdots & \frac{\partial g_1}{\partial x_n} \\
\cdots & \cdots & \cdots \\
\frac{\partial g_m}{\partial x_1} & \cdots & \frac{\partial g_m}{\partial x_n}
\end{bmatrix}
\]

\[
D = \begin{bmatrix}
\frac{\partial g_1}{\partial u_1} & \cdots & \frac{\partial g_1}{\partial u_r} \\
\cdots & \cdots & \cdots \\
\frac{\partial g_m}{\partial u_1} & \cdots & \frac{\partial g_m}{\partial u_r}
\end{bmatrix}
\]

Hence, the above partial derivatives are extracted at the equilibrium point, where the small perturbation is being analyzed.

In equation (5)-(6),

\( \Delta x \) defines disturbance in state vector having \( n \) dimension,

\( \Delta y \) defines disturbance in output vector having \( m \) dimension,

\( \Delta u \) defines disturbance input vector having \( r \) dimension.

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A defines state matrix having nxn dimension
B defines an input matrix of size nxr,
C defines output matrix having dimension mnxn, and
D defines the feedback matrix, in this proportion of input shows directly in the output, having dimension mrxn.

By taking the Laplace transform of equation (5)-(6), where we can get the state equation in the frequency domain, we get:

\[ s\Delta x(s) - \Delta x(0) = A\Delta x(s) + B\Delta u(s) \]  \hspace{1cm} (7)
\[ \Delta y(s) = C\Delta x(s) + D\Delta u(s) \]  \hspace{1cm} (8)

The standard solutions can be obtained from the state equation by solving for \( \Delta x(s) \) and extracting \( \Delta y(s) \) as below. By rearranging equation (7), we can get:

\[ (sI - A)\Delta x(s) = \Delta x(0) + B\Delta u(s) \]

Here, we have

\[ \Delta x(s) = (sI - A)^{-1}[\Delta x(0) + B\Delta u(s)] \]  \hspace{1cm} (9)
\[ \Delta x(s) = \frac{\text{adj}(sI - A)}{\text{det}(sI - A)}[\Delta x(0) + B\Delta u(s)] \]

And similarly,

\[ \Delta y(s) = C \frac{\text{adj}(sI - A)}{\text{det}(sI - A)}[\Delta x(0) + B\Delta u(s)] + D\Delta u(s) \]  \hspace{1cm} (10)

The Laplace transform \( \Delta x \) and \( \Delta y \) are seen to have two parts, one part lies on the initial conditions and the second part lies on inputs parameters. All equations are considered in Laplace form. Here, we have taken the Laplace transform of the free and original components of the state and output vectors.

The poles of \( \Delta x(s) \) and \( \Delta y(s) \) are the resulting roots.

\[ \text{det} (sI - A) = 0 \]  \hspace{1cm} (11)

The values of \( s \) which justify the equation (11) are called eigenvalues of matrix \( A \), and this equation is also a known characteristic equation of matrix \( A \) [XIII].

The eigenvalues, of a square matrix, are scalar parameters \( \lambda \), which presents the non-trivial solution of equation (10). The basic definition is expressed in (12):

\[ A\phi = \lambda\phi \]  \hspace{1cm} (12)

Here in (12),

\( A \) is defined as a matrix having order nxn.
\( \phi \) is defined as a column vector having order nx1, also called eigenvector.

To investigate the eigenvalues, equation (12) can be expressed as in (13):

\[ (A - \lambda I)\phi = 0 \]  \hspace{1cm} (13)
For non-trivial solution, we must have:
\[
\det(A - \lambda I) = 0 \quad (14)
\]
Solution of the determinant equation provides the characteristics equation. For \( n \) solutions \( \lambda = \lambda_1, \lambda_2, \ldots, \lambda_n \) are taken as eigenvalues of \( A \) \([XIV], [IV], [X]\).

For small perturbation, we can analyze any nonlinearity of system by the nature of roots of the characteristics equation of the operating system, in the form of eigenvalues by the following procedure \([XIV], [IV], [X], [I], [VI]\):

- After solving a characteristic equation, we have got eigenvalues, if eigenvalues have negative real parts, the existing system is known as to be stable.
- In case, if eigenvalues have positive real parts, the operating system is said to be unstable.
- The real parts of eigenvalues are either positive or negative, if are zero, then it cannot be solved based on the first approximation.

IV. Stability Analysis of JTPP Using the Proposed Protocol, Results and Discussion

Nonlinear equations for the JTPP pertaining to the form described in \((5)-(6)\) have been used from \([XV]\). The linearized form of the nonlinear system has been considered now for the JTPP with ten variables as mentioned in equations \((15)-(24)\).

\[
M_g \Delta \dot{\omega} = \Delta P_m - D_g \Delta \omega - I d_{do} \Delta E_{d_d} - I d_{dqo} \Delta E_{d_q} - Ed_{do} \Delta I_d - Ed_{dqo} \Delta I_q \quad (15)
\]

\[
\Delta \dot{\theta} = \omega_o \Delta \omega \quad (16)
\]

\[
T_A \Delta E_{FD} = -\Delta E_{FD} + K_A(-\Delta V_s - f_1 \Delta E_{d_d} - f_2 \Delta E_{d_q} + f_3 \Delta I_d + f_4 \Delta I_q) \quad (17)
\]

\[
-K_F \Delta E_{FD} + T_{fd} \Delta \dot{V}_s = -\Delta V_s \quad (18)
\]

\[
T_{d_{dqo}} \Delta E_{d_d} = -\Delta E_{d_d} - (X_d - X_d_d) I_q \quad (19)
\]

\[
T_{d_{dqo}} \Delta E_{d_q} = \Delta E_{FD} - \Delta E_{d_q} + (X_d - X_d_d) \Delta I_d \quad (20)
\]

\[
T_{sr} \Delta P_R = -\Delta P_R - K_g \Delta \omega \quad (21)
\]

\[
T_{sm} \Delta P_h = -\Delta P_h + \Delta P_R \quad (22)
\]

\[
T_{ch} \Delta P_c = -\Delta P_c + \Delta P_h \quad (23)
\]

\[
-K_{rh} T_m \Delta P_c + T_m \Delta P_m = -\Delta P_m + \Delta P_c \quad (24)
\]

Where,

\[
f_1 = \frac{V_{do}}{V_{to}}, f_2 = \frac{V_{qo}}{V_{to}}, f_3 = f_2 X_{d_d} - f_1 r_a, \text{ and } f_4 = -f_1 X_{d_d} - f_2 r_a
\]

With the consideration,

\[V_{ref} = 1 \text{ p.u, } \omega_o = 1 \text{ p.u and } V_s = 0,\]

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Equations (15)-(24) can be written in matrix form as in (25):

\[ [F][\ddot{x}] = [B]\dot{x} + [D][I_{dq}] \]  

(25)

In (25), \( I_{dq} = L_G \dot{x} \)

\[ F \dot{x} = (B + DGL)x \]  

Or, \( \dot{x} = (F^{-1} (B + DGL)x ) \)  

(26)

Finally, \( \dot{x} = Ax \)  

(27)

The vector \( \dot{x} \) shows state variables that are \( \dot{\omega}, \dot{\delta}, \dot{E}_{FD}, \dot{V}_{s}, \dot{E}_{d}, \dot{E}_{dq}, \dot{P}_R, \dot{P}_h, \dot{P}_{ch}, \dot{P}_m \).

For eigenvalues, once we know the entries of matrix A, then the eigenvalues can be obtained using MATLAB R2017a with command eigs (A).

F, B and D matrices are obtained from the linearization of the nonlinear equation of the synchronous model, excitation and governor [XV], and are listed here.

\[
F = \begin{bmatrix}
M_g & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & T_A & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -K_f & T_f & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & T_{dqo} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & T_{dqo} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & T_{sr} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{sm} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{ch} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{rh} & T_{m} & T_{m} & T_{rh} & T_{m} & T_{m}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
D_g & 0 & 0 & 0 & -I_{dq} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & w_0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -K_A & -K_{Af1} & -K_{Af2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & T_f & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -K_f & -1 & T_{dqo} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1
\end{bmatrix}
\]

And

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The base matrix A of order 10 x 10 for the JTPP:

\[
A = \begin{bmatrix}
-E_{ddo} & -E_{dqq} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
K_A \ast f_3 & K_A \ast f_A & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -(X_q - X_{dd}) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

The matrices F, B and D yield the base matrix A of order 10 x 10 for the JTPP:

The base matrix gives basic information about the stability of the system, in terms of eigenvalues. To obtain eigenvalues, we put all variable parameters [XV] in MATLAB/Simulink, then formed three different matrices as shown F, B and D, after that in MATLAB/Simulink, we obtained base matrix 10×10. By using the characteristic equation, we get the eigenvalues of the system analytically and verified the results using the eigs (A) command in MATLAB. Through these eigenvalues, we can understand the behavior of the operating system. If all real parts of eigenvalues are found to be negative then, it shows that system is way forward to stabilization, in case if eigenvalues have positive real parts, the system is way backward to destabilization. Eigenvalues help determine the stability and instability of operating systems without any labor workout or expensive security checkups, the analysis through eigenvalues is simplest and requires less calculation hence the complexity is avoided, this property of the eigenvalues method ideally suits among other methods. Eigenvalues play an important part in determining the power system stability. Two real separate eigenvalues having the same symbols, both may be positive or negative. The positive values will show that the system is unstable and the negative will show that the system is stable.

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By varying reheat system, prime mover gain $K_{rh} = 0.3, 2, 2.5$ and $10$, we found that at $K_{rh} = 10$ system is unstable because of the real parts of some eigenvalues become positive numbers. Table 1 represents the system eigenvalues, whereas in Fig. 1, the signs of real parts of all eigenvalues of 10 state variables are displayed. For state variables labelled as 5 and 6, the instability is evident from Tables 1 and Fig. 1 at reheat gain equal to 10p.u. In normal condition, system is in stable position, it must have constant speed (means no deviation), constant output voltage and constant output power. When load changes, then as per load small disturbance occurs.

V. Main contributions and Conclusion

In this research work, steady state stability of JTPP has been discussed and analyzed in detail using the proposed eigenvalue and linearization protocol. This all analysis has been done by using MATLAB software. For analysis, we developed tenth order nonlinear state space mathematical model of JTPP, and converted that in linearized mathematical form. Further for eigenvalues this tenth order linearized form yields the base matrix. Base matrix was used to form characteristic equation for eigenvalues calculation. At four different conditions, eigenvalues have been determined. This all was done in MATLAB software. If eigenvalues have negative real parts, it shows that system is stable, and in case if one or more eigenvalue has positive real part, then it shows that system is unstable. At a higher gain value unstable case was successfully outlined using the proposed protocol.

Table 1: Eigenvalues at different gain values

| State variables | $K_{rh}=0.3$ | $K_{rh}=2$ | $K_{rh}=2.5$ | $K_{rh}=10$ |
|-----------------|--------------|------------|-------------|-------------|
| $\omega$        | -158.06      | -158.06    | -158.06     | -158.06     |
| $\delta$        | -22.51       | -22.51     | -22.51      | -22.51      |
| $\dot{E}_{FD}$  | -4.99        | -4.53      | -4.15 + 0.27i | -4.89 + 1.86i |
| $V_s$           | -3.34        | -3.64      | -4.15 - 0.27i | -4.89 - 1.86i |
| $\dot{E}_{dq}$  | -0.08 + 0.66i | -3.30      | -3.32       | 0.17 + 2.12i |
| $\dot{E}_{dq}$  | -0.08 + 0.66i | -0.42 + 0.99i | -0.40 + 1.12i | 0.17 - 2.12i |
| $P_R$           | -0.27        | -0.42 - 0.99i | -0.40 - 1.12i | -3.33       |
| $P_h$           | -2.06 + 0.56i | -0.29 + 0.25i | -0.23 + 0.24i | -0.05 + 0.14i |
| $P_{ch}$        | -2.06 + 0.56i | -0.29 + 0.25i | -0.23 + 0.24i | -0.05 + 0.14i |
| $P_m$           | -1.30        | -1.30      | -1.30       | -1.30       |

In summary, following are the main contributions of the present work.

- Brief literature related to the steady-state stability has been discussed such as synchronous generator, which is very important component of the power plant. It’s working principles, components, mathematical equations and its various parameters which get affected when problems related to steady-state stability occur were discussed. Ten different equations of system were discussed including swing equation and power angle. Through all these equations, behavior of synchronous machine can be probed, when its
equilibrium state is perturbed either by varying load or very short duration of fault. In this work, different type of loads was applied at generating station to observe the performance.

➢ Formed mathematical model of JTPP to calculate eigenvalues.

➢ Eigenvalues analysis is very helpful to understanding the behavior of the system. In this work, we found out ten eigenvalues at four different gains, and successfully examined the four cases for stability.

Figure 1: Real part eigenvalue signs in state variables at different reheat gains

Conflict of Interest:
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References
I. Amin, M., & Molinas, M. (2017). Small-signal stability assessment of power electronics based power systems: A discussion of impedance- and eigenvalue-based methods. IEEE Transactions on Industry Applications, 53(5), 5014-5030.
II. Azizipanah-Abarghoee, et al (2018, October). Small Signal Based Frequency Response Analysis for Power Systems. In 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe) (pp. 1-6). IEEE.

III. Balu, Neal, et al. "On-line power system security analysis." Proceedings of the IEEE 80.2 (1992): 262-282.

IV. Banakar, H., Luo, C., & Ooi, B. T. (2006). Steady-state stability analysis of doubly-fed induction generators under decoupled P–Q control. IEE Proceedings-Electric Power Applications, 153(2), 300-306.

V. Bhan, V., Hashmani, A. A., & Shaikh, M. M. (2019). A new computing perturb-and-observe-type algorithm for MPPT in solar photovoltaic systems and evaluation of its performance against other variants by experimental validation. Scientia Iranica, 26(Special Issue on machine learning, data analytics, and advanced optimization techniques in modern power systems [Transactions on Computer Science & Engineering and Electrical Engineering (D)]), 3656-3671.

VI. Biswas, M. M., et al (2011). Steady State Stability Analysis of Power System under Various Fault Conditions. Global Journal of Research in Engineering, 11(6-F).

VII. Choo, Y. C, et al. (2006). Assessment of small disturbance stability of a power system. In Australasian Universities Power Engineering Conference (AUPEC) (pp. 1-

VIII. Himaja K., et al. (2012). Steady State Stability Analysis of a single machine power system by using MATLAB SOFTWARE. International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181

IX. Khoso, A. H., Shaikh, M. M., & Hashmani, A. A. (2020). A New and Efficient Nonlinear Solver for Load Flow Problems. Engineering, Technology & Applied Science Research, 10(3), 5851-5856.

X. Liverpool, T. B. (2020). Steady-state distributions and nonsteady dynamics in nonequilibrium systems. Physical Review E, 101(4), 042107.

XI. Martins, N. (1986). Efficient eigenvalue and frequency response methods applied to power system small-signal stability studies. IEEE Transactions on Power Systems, 1(1), 217-224.

XII. M. A. Huda, Md. Harun-or-Roshid, A. Islam and Mst. Mumtahinah, : SENSITIVITY AND ACCUARACY OF EIGENVALUES RELATIVE TO THEIR PERTURBATION, J. Mech. Cont. & Math. Sci., Vol.-6, No.-1, July (2011) Pages 780-796
XIII. Muhammad Aamir Aman, Muhammad Zulqarnain Abbasi, Murad Ali, Akhtar Khan. : To Negate the influences of Underdeterministic Dispersed Generation on Interconnection to the Distributed System considering Power Losses of the system, J. Mech. Cont. & Math. Sci., Vol.-13, No.-3, July-August (2018) Pages 117-132

XIV. Pruski, P., and Paszek, S. (2011). Analysis of calculation accuracy of power system electromechanical eigenvalues based on instantaneous power disturbance waveforms.

XV. Shahani, Z. A., Hashmani, A. A., & Shaikh, M. M. (2020). Steady state stability analysis and improvement using eigenvalues and PSS. Engineering, Technology & Applied Science Research, 10(1), 5301-5306.

XVI. Sidhu, T. S., et al. "Protection issues during system restoration." IEEE Transactions on Power Delivery 20.1 (2005): 47-56.

XVII. Singh, Bindeshwar. "Applications of FACTS controllers in power systems for enhance the power system stability: a state-of-the-art." International Journal of Reviews in Computing 6 (2011)

XVIII. Slootweg, J. G., et al. "A study of the eigenvalue analysis capabilities of power system dynamics simulation software." Proc. 14th Power Systems Computation Conference. 2002.

XIX. Song, Y., & Wang, B. (2013). Survey on reliability of power electronic systems. IEEE Transactions on Power Electronics, 28(1), 591-604