Application of Python for Power System Computation and Stability Analysis

A Project report submitted in partial fulfilment of the requirements for the degree of

B. Tech in Electrical Engineering

by

SRIJAN CHATTERJEE (EE/2017/009)

RONI BORAL(EE/2017/063)

ASIT KUMAR DAS (EE2017/053)

Under the Supervision of

Dr Debasish Mondal
Associate Prof. & HOD
Dept. of Electrical Engineering

श्रमम् बिना न किमपि साध्यम्

Department of Electrical Engineering
RCC INSTITUTE OF INFORMATION TECHNOLOGY
CANAL SOUTH ROAD, BELIAGHATA, KOLKATA - 700015, WEST BENGAL
Maulana Abul Kalam Azad University of Technology (MAKAUT)

CERTIFICATE

To whom it may concern

This is to certify that the project report entitled **APPLICATION OF PYTHON FOR POWER SYSTEM COMPUTATION AND STABILITY ANALYSIS** is a bonafide work carried out by **SRIJAN CHATTERJEE[117016170], RONI BORAL [11701617046]**, **ASIT KUMAR DAS [117016170]** students of B.Tech in the Dept. of Electrical Engineering**, RCC Institute of Information Technology Canal South Road, Beliaghata kol-700015,** affiliated to **Maulana Abul Kalam Azad University of Technology(MAKAUT),** West Bengal, India during the academic year of 2020-21 is an authentic work carried out by them under my supervision.

To the best of my knowledge the matter embodied in the report has not been submitted to any other university/institute for the award of any degree or diploma.

Dated: 15 /07/2021

HoD, Dept. of EE
RCC Institute of Information Technology
Kolkata-700015

(Dr. Debasish Mondal)

Project Supervisor and HOD
Department of Electrical Engineering
RCC Institute of Information Technology
Canal South Road, Beliaghata
Kolkata-700015

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Srijan Chatterjee

Place: Kolkata

Asit Kumar Das

Date: 15/07/21

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Name and Signature of the Students

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CHAPTER 1: INTRODUCTION

1.1 Abstract

***Abstract*—The computations and analysis of power systems are being executed for many years utilizing different toolbox in MATLAB environment. Special simulation software packages like ETAP, PSCAD, EMTP etc are also being popularly used for solving complex power system problems. Now a days there are various open-source software are available which are not only compatible but also highly effective for solution of different engineering problems. Among which Python is one of the most user friendly and easy to learn open-source software package. The objective of the present work is to developed a Python based programming to study power system stability problems for a single machine infinite bus (SMIB) test case with the application of PSS and a FACTS based controller. The simulations outcome by Python are compared with the MATLAB based results. It has been revealed that Python script is equally compatible and efficient like MATLAB to handle power system computational problems.**

Keywords—iPython, Power Systems Stability, Power System Stabilizer(PSS), Thyristor Controlled Series Compensators (TCSC),

1.2 Introduction

The basic requirements that a programming language has to satisfy to be eligible for scientific studies and, in particular, for power system analysis, are the availability of efficient and easy-to-use libraries for:

- Basic mathematical functions (e.g., trigonometric functions and complex numbers).

- Multi-dimensional arrays (e.g., element by element operations and slicing).

- Sparse matrices and linear algebra (e.g., sparse complete LU factorization).
- Eigen value analysis of non-symmetrical matrices.
- Advanced and publishing-quality plots.

The requirements above reduce the choice to a only a handful of programming languages. This is clearly captured by the software tools for power system analysis that are currently actively developed.

The main object of this project is to show that the Python language is mature enough for power system analysis. Moreover, the paper discusses how Python can be extended by means of open-source scientific libraries to provide a performance comparable to proprietary solutions. Specific contributions of the paper are:

1) To show that the Python language is an adequate tool for power system analysis studies.

2) To provide a comparison through power system simulations of the performance of MATLAB

1.3 Python as a Scripting Language for Power System Analysis

Python is a dynamically and safely typed language. Polymorphism, meta-programming, introspection and lazy evaluation are easy to implement and to use. Parallel programming, such as multi treading, concurrency and multiprocessing, is also possible even if with some limitations..Other relevant features of Python are the following.

• Python is a modern language fully based on well-structured classes (unlike most scientific languages such as MATLAB and R), which make easy creating, maintaining and reusing modular object-oriented code.
• As most recent scripting languages, Python inherits the best features and concepts of both system languages (such as C and FORTRAN) and structural languages (such as Haskell).
• Libraries such NumPy and CVXOPT provide a link to legacy libraries (e.g., BLAS, LAPACK, UMFPACK, etc.) for manipulating multidimensional arrays, linear algebra, eigen value analysis and sparse matrices. As the number crunching is done by efficient libraries, the slowness of the Python interpreter is not a bottle-neck.
• Thanks to graphical libraries such as Matplotlib, the ability of producing publication quality 2D figures in Python is as powerful as in MATLAB.
• The huge variety of free third-party libraries available for Python, allows easily and quickly extending the features of an application well beyond the scope of the original project (e.g., the Python profiler and the multiprocessing modules).
• Python is free and open source. Hence Python promotes the implementation and distribution of open projects.
• Python syntax is relatively simple, neat, compact and elegant. Hence, Python is particularly adequate for education and illustrative examples.

1.4 Main Objective

The main objective for this project is to implement python programming and MATLAB for computation and stability analysis in power system. It helps to understand mitigation of small signal stability problem employing P**ower System Stabilizer** and understand mitigation of small signal stability problem employing **Thyristor Controlled Series Compensator.**

CHAPTER 2: CONCEPT OF POWER SYSTEM STABILITY

2.1 BASIC CONCEPT OF POWER SYSTEM STABILITY

Power system stability may be broadly defined as the property of a power system that enables it to remain in a state of operating equilibrium or it is desirable for all elements in a power system to operate within a stable range of values under normal state of equilibrium after being subjected to a system disturbance such as when a change in load or generation occurs, or after a contingency such as a fault and/or outage occurs. Power system stability can be separated into two main categories, angle stability or rotor angle stability and voltage stability:

2.1.1 **ANGLE STABILITY:** angle stability or rotor angle stability can be defined as the ability of interconnected synchronous machines of a power system to remain in synchronism. The stability problem involves the study of electro-mechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotors oscillate.

2.1.2 **VOLTAGE STABILITY:** Voltage stability can be broadly defined as the ability of a system to maintain steady acceptable voltages at all buses following a system contingency or disturbance. A system enters a demand, or change in system condition causes a progressive and uncontrollable drop in voltage. The main factor causing instability is the inability of the power system to meet the demand for the reactive power. The heart of the problem is usually the voltage drop that occurs when active power and reactive power flow through inductive reactance associated with the transmission network. In this chapter we will mainly focus on the first of these two main categories of power system stability, angle stability.

2.2 CONCEPT OF SMALL SIGNAL STABILITY

2.2.1 INTRODUCTION

Small-signal (or small disturbance) stability is the ability of the power system to maintain synchronism under small disturbances such as small variations in loads and generations. Physically power system stability can be broadly classified into two main categories – *angle stability* or rotor angle stability and *voltage stability*.

1. ***Steady-state/dynamic***: This form of instability results from the inability to maintain synchronism and/or dampen out system transients and oscillations caused by small system changes, such as continual changes in load and/or generation.

2. ***Transient*****:** This form of instability results from the inability to maintain synchronism after large disturbances such as system faults and/or equipment outages. The aim of transient stability studies being to determine if the machines in a system will return to a steady synchronized state following a large disturbance. The literature of this book will focus in particular on the steady-state/dynamic stability subcategory and on the techniques that can be used to analyze and control the dynamic stability of a power system following a small disturbance.

2.3 SWING EQUATION

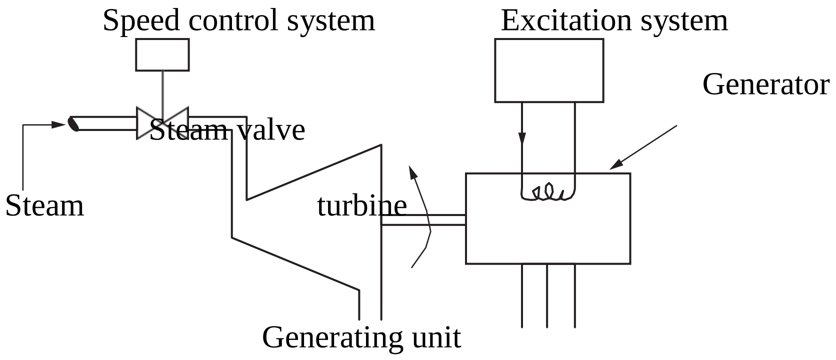
This equation bears the dynamics of oscillations of rotor of a synchronous generator. Consider a generating unit consisting of a three-phase synchronous generator and prime mover, as shown in Figure. The motion of the synchronous generator’s rotor is determined by Newton’s second law, which is given as

$$J\alpha_m(t) = T_m(t) - T_e(t) = T_a\text{(t)...2.3.1}$$

where J is the total moment of inertia of the rotating masses (prime mover and generator) (kg m^2), a_{m} is the rotor angular acceleration (rad/s^2), T_{m} is the mechanical torque supplied by the prime mover minus the retarding torque due to mechanical losses (e.g., friction) (N m), T_{e} is the electrical torque, accounting for the total three-phase power output and losses (N m), and T_{a} is the net accelerating torque (N m). The machine and electrical torques, T_{m} and T_{e}, are positive for generator operation .The rotor angular acceleration is given by

$$\alpha_m(t) = \frac{dw_m}{dt} = d^2\emptyset_m(t)/dt^2$$

$$\omega_m(t) = \frac{d\emptyset_m}{dt}$$



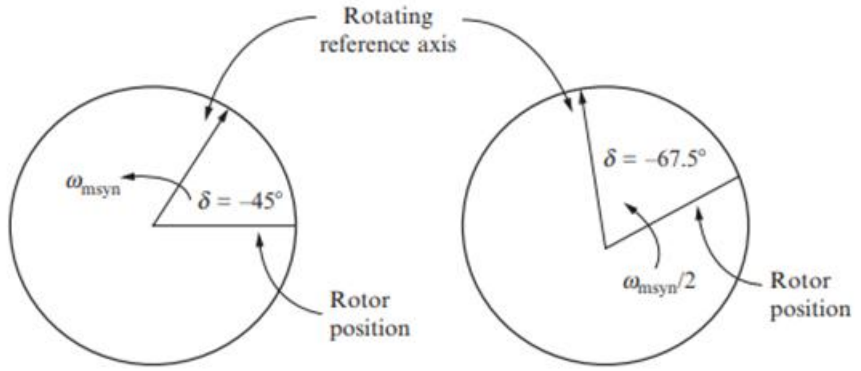
where ω_m is the rotor angular velocity (rad/s) and $\emptyset_m$ is the rotor angular position with respect to a stationary axis (rad). In steady-state conditions, the mechanical torque equals the electrical torque and the accelerating torque is zero. There is no acceleration and the rotor speed is constant at the synchronous velocity. When the mechanical torque is more than the electrical torque, then the acceleration torque is positive and the speed of the rotor increases. When the mechanical torque is less than the electrical torque, then the acceleration torque is negative and the speed of the rotor decreases. Since we are interested in the rotor speed relative to the synchronous speed, it is convenient to measure the rotor angular position with respect to a synchronously rotating axis instead of a stationary one. We therefore define

$$\emptyset_m(t) = \omega_{msyn}\, t + \delta_m(t)$$

where ω_{msyn} is the synchronous angular velocity of the rotor (rad/s) and dm is the rotor angular position with respect to a synchronously rotating reference. To understand the concept of the synchronously rotating reference axis, consider the diagram in Figure. In this example, the rotor is rotating at half the synchronous speed, $\omega_{msyn}/2$, such that in the time it takes for the reference axis to rotate 45^{0}, the rotor only rotates $22.5^{0}$and the rotor angular position with reference to the rotating axis changes from $-45^{0}$to -67.5^{0}. Using above equations in 2.3.1 we have

$$J\alpha_{m}(t) = J\frac{d^{2}\emptyset_{m}(t)}{dt^{2}} = J\frac{d^{2}\delta_{m}(t)}{dt^{2}} = T_{m}(t) - T_{e}(t) = T_{a}(t)\text{....2.3.2}$$

Being that we are analyzing a power system, we are interested in values of power more than we are in values of torque. It is therefore more convenient to work with expressions of power. Furthermore, it is convenient to consider this power in per unit rather than actual units.



Synchronously rotating reference axis.

Power is equal to the angular velocity times the torque and per-unit power can be obtained by dividing byS_{rated} , so that

$$J\frac{\omega_{m}\, d^{2}\delta_{m}(t)}{S_{rated}\;\; dt^{2}} = \frac{\omega_{m}T_{m}(t) - \omega_{m}T_{e}(t)}{S_{rated}} = \frac{P_{m}(t) - P_{e}(t)}{S_{rated}} = P_{mpu}(t) - P_{epu}(t)$$

Pm (pu) is the mechanical power supplied by the prime mover minus mechanical losses (per unit), Pe (pu) is the electrical power output of generator plus electrical losses (per unit), and Stated is the generator volt-ampere rating. We here define a constant value known as the normalized inertia constant, or “H” constant:

$$\text{H} = \frac{\text{stored kinetic energy at synchronous speed}}{\text{generator volt ampere rating}}$$

$$=\frac{\frac{1}{2}J\,\omega_{msyn}^{2}}{S_{rated}} \text{ (J/VA per units second)}$$

Equation becomes,

$$2H\frac{\omega_{m}(t)d^{2}\delta_{m}(t)}{\omega_{msyn}^{2}\,dt^{2}} = P_{mpu}(t) - P_{epu}(t) = P_{apu}(t)$$

Where Pa (pu) is the accelerating power. We define per-unit rotor angular velocity as

$$\omega_{pu}(t) = \frac{\omega_m(t)}{\omega_{msyn}}$$

Equation becomes,

$$\frac{2H\omega_{pu}(t)}{\omega_{msyn}}\frac{d^2\delta_m(t)}{dt^2} = P_{mpu}(t) - P_{epu}(t) = P_{apu}(t)$$

When a synchronous generator has P poles, the synchronous electrical angular velocity,ω_{msyn} known more correctly as the synchronous electrical radian frequency, can be related to the synchronous mechanical angular velocity by the following relationship:

$$\omega_{syn} = \frac{P}{2}\omega_{msyn}$$

To understand how this relationship arises, consider that the number of mechanical radians in one full revolution of the rotor is 2p. If, for instance, a generator has four poles (two pairs) and there are 2p electrical radians between poles in a pair, then the electrical waveform will go through 4π electrical radians within the same revolution of the rotor. In general, the number of electrical radians in one revolution is the number of mechanical radians times the number of pole pairs (the number of poles divided by two)

The relationship shown in Equation also holds for the electrical angular acceleration α (t), the electrical radian frequency ω_r(t), and the electrical power angle $\delta(t)$

$$\alpha(t) = \frac{P}{2}\alpha_m(t)$$

$$\omega_r(t) = \frac{P}{2}\omega_m(t)$$

$$\delta(t) = \frac{P}{2}\delta_m(t)$$

From equation we have,

$$\omega_{pu}(t) = \frac{\omega_m(t)}{\omega_{msyn}} = \frac{\frac{2}{P}\omega_r(t)}{\frac{2}{P}\omega_{msyn}} = \frac{\omega_r(t)}{\omega_{syn}}$$

Therefore equation can be written in electrical terms rather mechanical ones,

$$\frac{2H}{\omega_{syn}}\omega_{pu}(t)\frac{d^2\delta(t)}{dt^2} = P_{mpu}(t) - P_{epu}(t) = P_{apu}(t)$$

Equation represents the equation of motion of synchronous machine. It is commonly referred to as the “swing equation” because it represents swing in rotor angle δ during disturbances and it is the fundamental equation in determining rotor dynamics in transient stability studies.

The swing equation is nonlinear because P_{epu}(t) is a nonlinear function of rotor angle δ and because of the $\omega_{pu}(t)$ term. The rotor speed, however, does not vary a great deal from the synchronous speed during transients, and a value of $\omega_{pu}(t)$= 1.0 is often used in hand calculations. Defining $M = \frac{2H}{\omega_{syn}}$, the equation in the preceding text becomes,

$$M\frac{d^2\delta(t)}{dt^2} = T_m - T_e$$

It is often desirable to include a component of damping torque, not accounted for in the calculation of Te, separately. This is accomplished by introducing a term proportional to speed deviation in the preceding equation. The equation of motion considering damping torque has been shown later in Equation.

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CHAPTER 3: MODELLING OF SMIB POWER SYSTEM

3.1 HEFFRON–PHILIPS MODEL OF SMIB POWER SYSTEM

The Heffron–Phillips model for small-signal oscillations in synchronous machines connected to an infinite bus was first presented in 1952. For small-signal stability studies of an SMIB power system, the linear model of Heffron–Phillips has been used for many years, providing reliable results [3, 4]. This section presents the small-signal model for a single machine connected to a large system through a transmission line (infinite bus) to analyze the local mode of oscillations in the range of frequency 1-3 Hz. A schematic representation of this system is shown in Figure.3.1.

The flux-decay model Figure. 3.2 of the equivalent circuit of the synchronous machine have been considered for the analysis.

The said model is known as the classical model of the synchronous machine. The following assumptions are generally made to analyze the small-signal stability problem an SMIB power system:

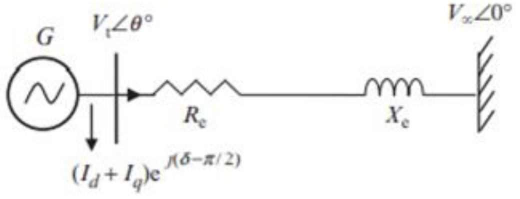
(i) The mechanical power input remains constant during the period of transient.

(ii) Damping or asynchronous power is negligible.

(iii) Stator resistance is equal to zero.

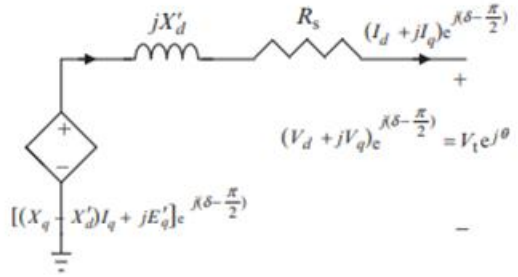
(iv) The synchronous machine can be represented by a constant voltage source (electrically) behind the transient reactance.

(v) The mechanical angle of the synchronous machine rotor coincides with the electric phase angle of the voltage behind transient reactance.

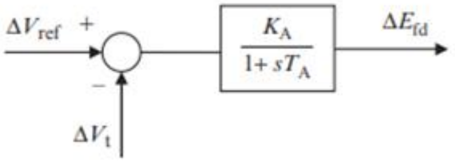


Single-machine infinite bus (SMIB) system. Here, $V_t\angle\theta°$, the terminal voltage of the synchronous machine; $V_\infty\angle 0°$, the voltage of the infinite bus, which is used as reference; R_e, X_e, the external equivalent resistance and reactance; and $\theta=\delta-\frac{\pi}{2}$, the angle by which V_t leads the infinite bus voltage V_∞.

Fig. 3.1


jX'_d
R_s
$(I_d + jI_q)e^{j(\delta - \frac{\pi}{2})}$
+
+
−
$(V_d + jV_q)e^{j(\delta - \frac{\pi}{2})} = V_t e^{j\theta}$
$[(X_q - X'_d)I_q + jE'_q]e^{j(\delta - \frac{\pi}{2})}$
−

Dynamic circuit for the flux-decay model of the machine.



Fast (static) exciter model.

Fig. 3.2

(vi) No local load is assumed at the generator bus; if a local load is fed at the terminal of the machine, it is to be represented by constant impedance (or admittance).

3.2 FUNDAMENTAL EQUATION

The differential algebraic equations of the synchronous machine of the flux-decay model with fast exciter can be represented as follows:

Differential equations

$$\frac{dE'_q}{dt} = \frac{1}{T'_{d0}}\left(E_q' + \left(X_q - X'_d\right)I_d - E_{fd}\right) \qquad (3.1)$$

$$\frac{d\delta}{dt} = \omega - \omega_a$$

$$\frac{d\omega}{dt} = \frac{\omega_s}{2H}\left[T_M - \left(E'_q I_q + \left(X_q - X'_d\right)I_d I_q + D(\omega - \omega_s)\right)\right]$$

$$\frac{dE_{fd}}{dt} = \frac{E_{fd}}{T_A} + \frac{K_A}{T_A}\left(v_{ref} - v_t\right) \tag{3.2}$$

Stator Algebraic Equation:

$$V_{\mathrm{t}}\sin(\delta - \theta) + R_{\mathrm{s}}I_d - X_q I_q = 0$$
$$E_q^{'} - V_{\mathrm{t}}\cos(\delta - \theta) - R_{\mathrm{s}}I_q - X_d^{'}I_d = 0$$

As it is assumed stator resistance Rs=0, Id and Vt denote the magnitude of the generator terminal voltage reduced to,

$$X_q I_q - V_{\mathrm{t}}\sin(\delta - \theta) = 0$$
$$E_q^{'} - V_{\mathrm{t}}\cos(\delta - \theta) - X_d^{'}I_d = 0$$

Now, $(V_d + jV_q)e^{(\delta - \frac{\pi}{2})} = V_t e^{j\emptyset}$

Hence, $(V_d + jV_q)e^{(\delta - \frac{\pi}{2})} = V_t e^{j\emptyset}$

Expansion of the right hand side result we get,

$$V_d + jV_q = V_t\sin(\delta - \emptyset) + V_t\cos(\delta - \emptyset) \quad (3.3)$$

Substitution of Equation we get,

$$X_q I_q - V_d = 0$$

$$E_q' - V_q - X_d' I_d = 0$$

Network Equation: The network equation assuming zero phase angle at the infinite bus:

$$\left(I_d + jI_q\right)\mathrm{e}^{j\left(\delta - \frac{\pi}{2}\right)} = \frac{V_{\mathrm{t}}\angle\theta^\circ - V_\infty\angle 0^\circ}{R_{\mathrm{e}} + jX_{\mathrm{e}}}$$
$$\left(I_d + jI_q\right)\mathrm{e}^{j\left(\delta - \frac{\pi}{2}\right)} = \frac{\left(V_d + jV_q\right)\mathrm{e}^{j\left(\delta - \frac{\pi}{2}\right)} - V_\infty\angle 0^\circ}{R_{\mathrm{e}} + jX_{\mathrm{e}}}$$

After cross multiplication when real and imaginary parts are separated, Equation becomes:

$$I_d R_{\mathrm{e}} + jI_q R_{\mathrm{e}} + jI_d X_{\mathrm{e}} - I_q X_{\mathrm{e}} = \left(V_d + jV_q\right) - V_\infty\,\mathrm{e}^{-j\left(\delta - \frac{\pi}{2}\right)}$$

Or

$$\left(R_{\mathrm{e}}I_d - X_{\mathrm{e}}I_q\right) + j\left(R_{\mathrm{e}}I_q + X_{\mathrm{e}}I_d\right) = \left(V_d + jV_q\right) - \left(V_\infty\cos\left(\delta - \frac{\pi}{2}\right) - jV_\infty\sin\left(\delta - \frac{\pi}{2}\right)\right)$$

$$\left(R_\mathrm{e}I_d - X_\mathrm{e}I_q\right) + j\left(R_\mathrm{e}I_q + X_\mathrm{e}I_d\right) = (V_d - V_\infty \sin\delta) + j\left(V_q - V_\infty \cos\delta\right)$$

$$\therefore\ R_\mathrm{e}I_d - X_\mathrm{e}I_q = V_d - V_\infty \sin\delta \qquad (3.4)$$

$$R_\mathrm{e}I_q + X_\mathrm{e}I_d = V_q - V_\infty \cos\delta$$

3.3 Linearization Process and State-Space Model

Step I: The linearization of the stator algebraic equations gives

$$X_q\Delta I_q - \Delta V_d = 0$$

$$\Delta E_q' - \Delta V_q - X_d'\Delta I_d = 0$$

Rearranging Equations gives, $X_q\Delta I_q = \Delta V_d$

$$\Delta V_q = -\Delta E_q' + X_d'\Delta I_d$$

Writing equations in matrix form we get,

$$\begin{bmatrix}\Delta V_d \\ \Delta V_q\end{bmatrix} = \begin{bmatrix}0 & X_q \\ -X_d' & 0\end{bmatrix}\begin{bmatrix}\Delta I_d \\ \Delta I_q\end{bmatrix} + \begin{bmatrix}0 \\ \Delta E_q'\end{bmatrix}$$

Step II: The linearization of the load-flow equations results in,

$$R_\mathrm{e}\Delta I_q - X_\mathrm{e}\Delta I_d = \Delta V_q - V_\infty \cos\delta\Delta\delta$$

$$R_\mathrm{e}\Delta I_q + X_\mathrm{e}\Delta I_d = \Delta V_q + V_\infty \sin\delta\Delta\delta$$

Rearranging Equations give

$$R_\mathrm{e}\Delta I_q - X_\mathrm{e}\Delta I_d + V_\infty \cos\delta\Delta\delta = \Delta V_q$$

$$R_\mathrm{e}\Delta I_q + X_\mathrm{e}\Delta I_d - V_\infty \sin\delta\Delta\delta = \Delta V_q$$

Writing Equations in matrix form gives

$$\begin{bmatrix}\Delta V_d \\ \Delta V_q\end{bmatrix} = \begin{bmatrix}R_\mathrm{e} & -X_\mathrm{e} \\ X_\mathrm{e} & R_\mathrm{e}\end{bmatrix}\begin{bmatrix}\Delta I_d \\ \Delta I_q\end{bmatrix} + \begin{bmatrix}V_\infty\cos\delta \\ -V_\infty\sin\delta\end{bmatrix}\Delta\delta \qquad (3.5)$$

Step III: Equating the right-hand side of Equations gives

$$\begin{bmatrix}R_\mathrm{e} & -X_\mathrm{e} \\ X_\mathrm{e} & R_\mathrm{e}\end{bmatrix}\begin{bmatrix}\Delta I_d \\ \Delta I_q\end{bmatrix} + \begin{bmatrix}V_\infty\cos\delta \\ -V_\infty\sin\delta\end{bmatrix}\Delta\delta = \begin{bmatrix}0 & X_q \\ -X_d' & 0\end{bmatrix}\begin{bmatrix}\Delta I_d \\ \Delta I_q\end{bmatrix} + \begin{bmatrix}0 \\ \Delta E_q'\end{bmatrix}$$

$$\left(\begin{bmatrix} R_{\mathrm{e}} & -X_{\mathrm{e}} \\ X_{\mathrm{e}} & R_{\mathrm{e}} \end{bmatrix} - \begin{bmatrix} 0 & X_q \\ -X_d' & 0 \end{bmatrix}\right)\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta E_q' \end{bmatrix} + \begin{bmatrix} -V_\infty \cos\delta \\ V_\infty \sin\delta \end{bmatrix}\Delta\delta$$

$$\begin{bmatrix} R_{\mathrm{e}} & -\left(X_{\mathrm{e}} + X_q\right) \\ \left(X_{\mathrm{e}} + X_d'\right) & R_{\mathrm{e}} \end{bmatrix}\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} - \begin{bmatrix} 0 \\ \Delta E_q' \end{bmatrix} + \begin{bmatrix} -V_\infty \cos\delta \\ V_\infty \sin\delta \end{bmatrix}\Delta\delta \qquad (3.6)$$

Now,

$$\begin{bmatrix} R_{\mathrm{e}} & -\left(X_{\mathrm{e}} + X_q\right) \\ \left(X_{\mathrm{e}} + X_d'\right) & R_{\mathrm{e}} \end{bmatrix}^{-1} = \frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} R_{\mathrm{e}} & \left(X_{\mathrm{e}} + X_q\right) \\ -\left(X_{\mathrm{e}} + X_d'\right) & R_{\mathrm{e}} \end{bmatrix}$$

$$\Delta_{\mathrm{e}} = R_{\mathrm{e}}^2 + \left(X_{\mathrm{c}} + X_q\right)\left(X_{\mathrm{e}} + X_d'\right)$$

Solving for ΔId and ΔIq from Equation (3.6) results in

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \begin{bmatrix} 0 \\ \Delta E_q' \end{bmatrix}\begin{bmatrix} R_{\mathrm{e}} & -\left(X_{\mathrm{e}} + X_q\right) \\ \left(X_{\mathrm{e}} + X_d'\right) & R_{\mathrm{e}} \end{bmatrix}^{-1}$$

$$+\begin{bmatrix} -V_\infty \cos\delta \\ V_\infty \sin\delta \end{bmatrix}\Delta\delta \cdot \begin{bmatrix} R_{\mathrm{e}} & -\left(X_{\mathrm{e}} + X_q\right) \\ \left(X_{\mathrm{e}} + X_d'\right) & R_{\mathrm{e}} \end{bmatrix}^{-1}$$

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} 0 \\ \Delta E_q' \end{bmatrix}\begin{bmatrix} R_{\mathrm{e}} & \left(X_{\mathrm{e}} + X_q\right) \\ -\left(X_{\mathrm{e}} + X_d'\right) & R_{\mathrm{e}} \end{bmatrix}$$

$$+\frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} -V_\infty \cos\delta \\ V_\infty \sin\delta \end{bmatrix}\Delta\delta\begin{bmatrix} R_{\mathrm{e}} & \left(X_{\mathrm{e}} + X_q\right) \\ -\left(X_{\mathrm{e}} + X_d'\right) & R_{\mathrm{e}} \end{bmatrix}$$

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} \left(X_{\mathrm{e}} + X_q\right)\Delta E_q' \\ R_{\mathrm{e}}\Delta E_q' \end{bmatrix}$$

$$+\frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} -R_{\mathrm{e}}V_\infty \cos\delta + V_\infty \sin\delta\left(X_{\mathrm{e}} + X_q\right) \\ R_{\mathrm{e}}V_\infty \sin\delta + V_\infty \cos\delta\left(X_{\mathrm{e}} + X_d'\right) \end{bmatrix}\Delta\delta$$

Therefore,

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} \left(X_{\mathrm{e}} + X_q\right) & -R_{\mathrm{e}}V_\infty \cos\delta + V_\infty \sin\delta\left(X_{\mathrm{e}} + X_q\right) \\ R_{\mathrm{e}} & R_{\mathrm{e}}V_\infty \sin\delta + V_\infty \cos\delta\left(X_{\mathrm{e}} + X_d'\right) \end{bmatrix}\begin{bmatrix} \Delta E_q' \\ \Delta\delta \end{bmatrix} \qquad (3.7)$$

Step IV: The linearizations of the differential equations are as follows. Here, the frequency is normalized throughout our study:

$$\dot{\Delta E_q'} = -\frac{1}{T_{\mathrm{d_o}}'} - \Delta E_q' - \frac{1}{T_{\mathrm{do}}'}\left(X_d - X_d'\right)\Delta I_d + \frac{1}{T_{\mathrm{dc}}'}\Delta E_{\mathrm{fd}}$$

$$\dot{\Delta\delta} = \omega_{\mathrm{s}}\Delta v$$

$$\dot{\Delta v} = \frac{1}{2H}\Delta T_{\mathrm{M}} - \frac{1}{2H}\Delta E'_q I_q - \frac{1}{2H}E'_q\Delta I_q - \frac{\left(X_q - X'_d\right)}{2H}\Delta I_d I_q - \frac{\left(X_q - X'_d\right)}{2H}I_d\Delta I_q - \frac{D\omega_{\mathrm{s}}}{2H}\Delta v$$

$$T_{\mathrm{A}}\dot{\Delta E}_{\mathrm{fd}} = -\Delta E_{\mathrm{fd}} + K_{\mathrm{A}}(\Delta V_{\mathrm{ref}} - \Delta V_{\mathrm{t}})$$

Writing Equations in matrix form, the state-space model of the SMIB system without exciter is

$$\begin{bmatrix}\dot{\Delta E'_q}\\ \dot{\Delta\delta}\\ \dot{\Delta v}\end{bmatrix} = \begin{bmatrix}-\frac{1}{T'_{\mathrm{do}}} & 0 & 0\\ 0 & 0 & \omega_{\mathrm{s}}\\ -\frac{I_q}{2H} & 0 & -\frac{D\omega_{\mathrm{s}}}{2H}\end{bmatrix}\begin{bmatrix}\Delta E'_q\\ \Delta\delta\\ \Delta v\end{bmatrix} + \begin{bmatrix}-\frac{\left(X_d - X'_d\right)}{T'_{\mathrm{do}}} & 0\\ 0 & 0\\ \frac{I_q\left(X'_d - X_q\right)}{2H}\frac{\left(X'_d - X_q\right)}{2H} - \frac{E'_q}{2H} & \end{bmatrix}\begin{bmatrix}\Delta I_d\\ \Delta I_q\end{bmatrix} + \begin{bmatrix}\frac{1}{T'_{\mathrm{do}}} & 0\\ 0 & 0\\ 0 & \frac{1}{2H}\end{bmatrix}\begin{bmatrix}\Delta E_{\mathrm{fd}}\\ \Delta T_{\mathrm{M}}\end{bmatrix} \qquad (3.8)$$

Step V: Obtain the linearized equations in terms of the K constants. The expressions for ΔI_d and ΔI_q obtained from Equation (3.8) are

$$\Delta I_d = \frac{1}{\Delta_{\mathrm{e}}}\left[\left(X_{\mathrm{e}} + X_q\right)\Delta E'_q + \left\{-R_{\mathrm{e}}V_\infty\cos\delta + \left(X_{\mathrm{e}} + X_q\right)V_\infty\sin\delta\right\}\Delta\delta\right]$$

$$\Delta I_q = \frac{1}{\Delta_{\mathrm{e}}}\left[R_{\mathrm{e}}\Delta E'_q + \left\{R_{\mathrm{e}}V_\infty\sin\delta + \left(X_{\mathrm{e}} + X'_d\right)V_\infty\cos\delta\right\}\Delta\delta\right]$$

On substitution of ΔId and ΔIq in Equation, the resultant equations relating the constants K1, K2, K3, and K4 can be expressed as

$$\dot{\Delta E'_q} = -\frac{1}{K_3T'_{\mathrm{do}}}\Delta E'_q - \frac{K_4}{T'_{\mathrm{do}}}\Delta\delta + \frac{1}{T'_{\mathrm{do}}}\Delta E_{\mathrm{fd}}$$

$$\dot{\Delta\delta} = \omega_{\mathrm{s}}\Delta v$$

$$\dot{\Delta v} = -\frac{K_2}{2H}\Delta E'_q - \frac{K_1}{2H}\Delta\delta - \frac{D\omega_{\mathrm{s}}}{2H}\Delta v + \frac{1}{2H}\Delta T_{\mathrm{M}} \qquad (3.9)$$

Step VI: The linearization of generator terminal voltage is as follows:

The magnitude of the generator terminal voltage is

$$V_1 = \sqrt{V}_d^{2} + V_q^2$$
$$\therefore V_{\mathrm{t}}^2 = V_d^2 + V_q^2$$

The linearization of the above Equation gives

$$2V_{\mathrm{t}}\Delta V_{\mathrm{t}} = 2V_d\Delta V_d + 2V_q\Delta V_q$$
$$\Delta V_{\mathrm{t}} = \frac{V_d}{V_{\mathrm{t}}}\Delta V_d + \frac{V_q}{V_{\mathrm{t}}}\Delta V_q$$

Now, substituting Equations we get,

$$\left[\begin{matrix} \begin{bmatrix}\Delta V_d \\ \Delta V_q\end{bmatrix} = \frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} 0 & X_q \\ -X_d^{'} & 0 \end{bmatrix} \\ \begin{bmatrix} (X_{\mathrm{e}} + X_q) & -R_{\mathrm{e}}V_\infty\cos\delta + V_\infty\sin\delta(X_{\mathrm{e}} + X_q) \\ R_{\mathrm{e}} & R_{\mathrm{e}}V_\infty\sin\delta + V_\infty\cos\delta(X_{\mathrm{e}} + X_d^{'}) \end{bmatrix}\end{matrix}\right.\begin{bmatrix}\Delta E_q^{'} \\ \Delta\delta\end{bmatrix} + \begin{bmatrix} 0 \\ \Delta E_q^{'}\end{bmatrix}$$

$$\begin{bmatrix}\Delta V_d \\ \Delta V_q\end{bmatrix} = \frac{1}{\Delta_{\mathrm{e}}}\begin{bmatrix} R_{\mathrm{e}}X_q & X_q\left(R_{\mathrm{e}}V_\infty\sin\delta + V_\infty(X_d^{'} + X_{\mathrm{e}})\cos\delta\right) \\ -X_d^{'}(X_{\mathrm{e}} + X_q) & -X_d^{'}\left(-R_{\mathrm{e}}V_\infty\cos\delta + V_\infty(X_{\mathrm{e}} + X_q)\sin\delta\right)\end{bmatrix}\begin{bmatrix}\Delta E_q^{'} \\ \Delta\delta\end{bmatrix} + \begin{bmatrix} 0 \\ \Delta E_q^{'}\end{bmatrix}$$

$$\Delta V_d = \frac{1}{\Delta_{\mathrm{e}}}\left[R_{\mathrm{e}}X_q\Delta E_q^{'} + X_qR_{\mathrm{e}}V_\infty\sin\delta + V_\infty X_q\left(X_d^{'} + X_{\mathrm{e}}\right)\cos\delta\Delta\delta\right] \tag{3.10}$$

and

$$\Delta V_q = \frac{1}{\Delta_{\mathrm{e}}}\left[-X_d^{'}(X_{\mathrm{e}} + X_q)\Delta E_q^{'} + (X_d^{'}R_{\mathrm{e}}V_\infty\cos\delta - V_\infty X_d^{'}(X_{\mathrm{e}} + X_q)\sin\delta\Delta\delta\right] + \Delta E_q^{'} \tag{3.11}$$

Replacing ΔVd and ΔVq from Equations (3.10) and (3.11) in Equation results in

$$\Delta V_{\mathrm{t}} = K_5\Delta\delta + K_6\Delta E_q^{'}$$

3.4 Derivation of K constants: K1, K2, K3, K4, K5, and K6

From Equation , the expression of $\Delta E_q^{'}$ on substitution of ΔI_d is

$$\Delta\dot{E}_q' = -\frac{1}{T_{dc}'}\Delta E_q' - \frac{1}{T_{do}'}\left(X_d - X_d'\right)\left(\frac{1}{\Delta_e}\left[\left(X_e + X_q\right)\Delta E_q' + \{-R_e V_\infty \cos\delta\right.\right.$$

$$\left.\left.+\left(X_e + X_q\right)V_\infty \sin\delta\}\Delta\delta\right]\right) + \frac{1}{T_{do}'}\Delta E_{fd}$$

$$\Delta\dot{E}_q = -\frac{1}{T_{do}'}\left[1 + \frac{\left(X_d - X_d'\right)\left(X_e + X_q\right)}{\Delta_e}\right]\Delta E_q'$$

$$-\frac{1}{T_{do}'}\frac{V_\infty\left(X_d - X_d'\right)}{\Delta_e}\left\{\left(X_e + X_q\right)\sin\delta - R_e \cos\delta\right\}\Delta\delta + \frac{1}{T_{de}'}\Delta E_{fd}$$

$$\therefore \Delta\dot{E}_q' = -\frac{1}{K_3 T_{do}}'\Delta E_q' - \frac{K_4}{T_{do}'}\Delta\delta + \frac{1}{T_{do}'}\Delta E_{fd}$$

ere

$$\frac{1}{K_3} = 1 + \frac{\left(X_d - X_d'\right)\left(X_q + X_e\right)}{\Delta_e}$$

$$K_4 = \frac{V_\infty\left(X_d - X_d'\right)}{\Delta_e}\left[\left(X_q + X_e\right)\sin\delta - R_e \cos\delta\right]$$

$$\Delta\dot{v} = -\frac{1}{2H}\Delta E_q' I_q - \frac{\left(X_q - X_d'\right)I_q}{2H}\frac{1}{\Delta_e}\left[\left(X_e + X_q\right)\Delta E_q' + \{-R_e V_\infty \cos\delta\right.$$

$$\left.+\left(X_e + X_q\right)V_\infty \sin\delta\}\Delta\delta\right]$$

$$+\left(\frac{\left(X_d' - X_q\right)}{2H}I_d - \frac{1}{2H}E_q'\right)\frac{1}{\Delta_e}\left[R_e \Delta E_q' + \{R_e V_\infty \sin\delta\right.$$

$$\left.+\left(X_e + X_d'\right)V_\infty \cos\delta\}\Delta\delta\right] - \frac{D\omega_s}{2H}\Delta v + \frac{1}{2H}\Delta T_M$$

$$\Delta\dot{v} = -\frac{1}{2H}\frac{1}{\Delta_e}\left[I_q \Delta_e - I_q\left(X_d' - X_q\right)\left(X_e + X_q\right) - R_e I_d\left(X_d' - X_q\right) + R_e E_q'\right]\Delta E_q'$$

$$+\frac{V_\infty I_q}{2H\Delta_e}\left(X_d' - X_q\right)\left[\left(X_e + X_q\right)\sin\delta - R_e \cos\delta\right]\Delta\delta$$

$$+\frac{V_\infty}{\Delta_e}\left[\left\{I_d\left(X_d' - X_q\right) - E_q'\right\}\left\{\left(X_e + X_d'\right)\cos\delta + R_e \sin\delta\right\}\right]$$

$$-\frac{D\omega_s}{2H}\Delta v + \frac{1}{2H}\Delta T_M$$

This can be written in terms of K constants as

$$\Delta\dot{v} = -\frac{\Lambda_2}{2H}\Delta E_q' - \frac{\Lambda_1}{2H}\Delta\delta - \frac{D\omega_s}{2H}\Delta v + \frac{1}{2H}\Delta T_{\mathrm{M}}$$

ere

$$K_2 = \frac{1}{\Delta_{\mathrm{e}}}\left[I_q\Delta_{\mathrm{e}} \quad - I_q\left(X_d' - X_q\right)\left(X_q + X_{\mathrm{e}}\right) - R_{\mathrm{e}}\left(X_d' - X_q\right)I_d + R_{\mathrm{e}}E_q'\right]$$

$$K_1 = \qquad -\frac{1}{\Delta_{\mathrm{e}}}\left[I_q V_\infty\left(X_d' - X_q\right)\left\{\left(X_q + X_{\mathrm{e}}\right)\sin\delta - R_{\mathrm{e}}\cos\delta\right\}\right.$$
$$\left. + V_\infty\left\{\left(X_d' - X_q\right)I_d - E_q'\right\}\left\{\left(X_d' + X_{\mathrm{e}}\right)\cos\delta + R_{\mathrm{e}}\sin\delta\right\}\right]$$

On substitution

$$\Delta V_{\mathrm{t}} = \frac{V_d}{V_{\mathrm{t}}}\left[\frac{1}{\Delta_2}\left\{R_{\mathrm{e}}X_q\Delta E_q' + X_q R_{\mathrm{e}}V_\infty\sin\delta + V_\infty X_q\left(X_d' + X_{\mathrm{e}}\right)\cos\delta\Delta\delta\right\}\right]$$
$$+ \frac{V_q}{V_{\mathrm{t}}}\left[\frac{1}{\Delta_{\mathrm{e}}}\left\{-X_d'\left(X_{\mathrm{e}} + X_q\right)\Delta E_q'\right.\right.$$
$$\left.\left. + \left(X_d' R_{\mathrm{e}} V_\infty \cos\delta - V_\infty X_d'\left(X_{\mathrm{e}} + X_q\right)\sin\delta\Delta\delta\right\} + \Delta E_q'\right]$$
$$\Delta V_{\mathrm{t}} - \left[\frac{1}{\Delta_{\mathrm{e}}}\left\{\frac{V_d}{V_{\mathrm{t}}}R_{\mathrm{e}}X_4 - \frac{V_d}{V_{\mathrm{t}}}X_d'(X_4 + X_{\mathrm{c}})\right\} + \frac{V_d}{V_{\mathrm{t}}}\right]\Delta E_q'$$
$$+ \left[\frac{1}{\Delta_{\mathrm{e}}}\left\{\frac{V_d}{V_{\mathrm{t}}}X_q\left(R_{\mathrm{e}}V_\infty\sin\delta + V_\infty\cos\delta\left(X_d' + X_{\mathrm{e}}\right)\right)\right.\right.$$
$$\left.\left. + \frac{V_q}{V_{\mathrm{t}}}X_d'\left(R_{\mathrm{e}}V_\infty\cos\delta - V_\infty\left(X_{\mathrm{e}} + X_q\right)\sin\delta\right)\right\}\right]\Delta\delta$$

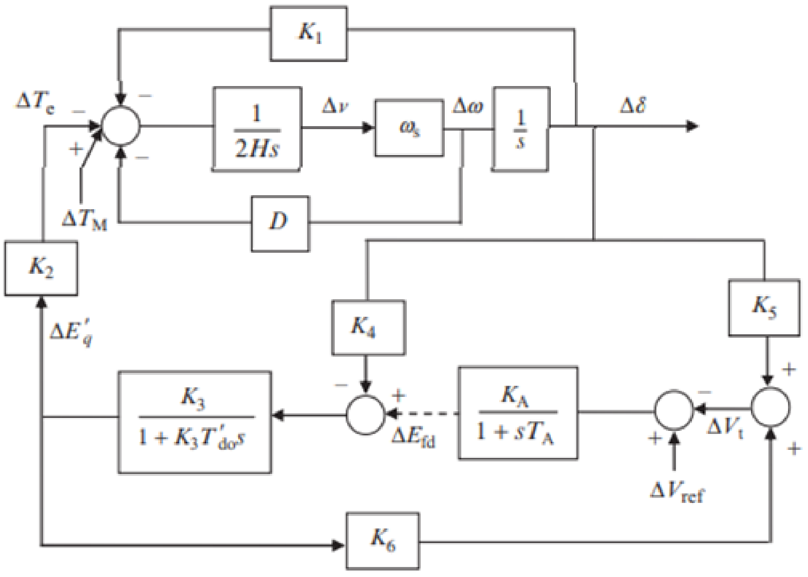
Therefore, this equation can be written in terms of K constants as

$$\Delta V_{\mathrm{t}} = K_5\Delta\delta + K_6\Delta E_q'$$

$$K_5 = \frac{1}{\Delta_{\mathrm{e}}}\left[\frac{V_d}{V_{\mathrm{t}}}X_q\left\{R_{\mathrm{e}}V_\infty\sin\delta + V_\infty\cos\delta\left(X_d' + X_{\mathrm{e}}\right)\right\}\right.$$
$$\left. + \frac{V_q}{V_{\mathrm{t}}}X_d'\left\{R_{\mathrm{e}}V_\infty\cos\delta - V_\infty\left(X_{\mathrm{e}} + X_q\right)\sin\delta\right\}\right]$$

$$K_6 = \frac{1}{\Delta_{\mathrm{e}}}\left[\frac{V_d}{V_{\mathrm{t}}}R_{\mathrm{e}}X_q - \frac{V_d}{V_{\mathrm{t}}}X_d'\left(X_q + X_{\mathrm{e}}\right)\right] + \frac{V_d}{V_{\mathrm{t}}}$$

Now, the overall linearized machine differential equations and the linearized exciter equation together can be put in a block diagram shown in Figure 3.3. In this representation, the dynamic characteristics of the system can be expressed in terms of the K constants. These constants (K1–K6) and the block diagram representation were developed first by Heffron–Phillips and later by de Mello in to study the synchronous machine stability as affected by local low-frequency oscillations and its control through excitation system.



Block diagram representation of the synchronous machine flux-decay model.

Fig. 3.4

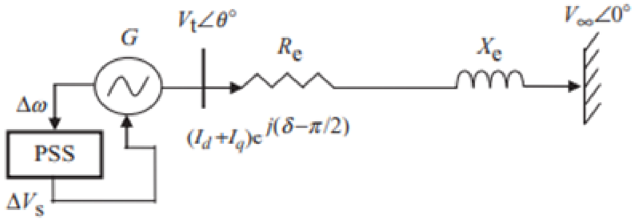
It is evident that the K constants are dependent on various system parameters such as system loading and the external network resistance (Re) and reactance (Xe). Generally, the value of the K constants is greater than zero (>0), but under heavy loading condition (high generator output) and for high value of external system reactance, K5 might be negative, contributing to negative damping and causing system instability. This phenomenon has been discussed in the following sections based on state space model.

CHAPTER 4: MITIGATION OF SMALL SIGNAL STABILITY USING PSS

It has been discussed the need of installing a power system stabilizer (PSS) in a power system in order to introduce additional damping to the rotor oscillations of the synchronous machine. The enhancement of damping in power systems by means of a PSS has been a subject of great attention in the past three decades. It is much more significant today when many large and complex power systems frequently operate close to their stability limits. In this chapter, the problem of small-signal stability has been investigated by applying the conventional PSS. A speed input single-stage PSS has been applied in the linearized model of a SMIB power system, and then, the application of PSS has been extended in a multimachine network. In both cases, investigation is carried out by studying the behaviour of the critical eigen value or the critical swing mode.

4.1THE APPLICATION OF PSS IN A SMIB SYSTEM

A simple single-machine infinite bus (SMIB) system has been shown in Figure 4.1. It is assumed that the machine is equipped with a fast exciter. In order to improve small-signal oscillations, a PSS is incorporated in this system



Single-machine infinite bus system with PSS.

Fig. 4.1

4.2 Combined model of SMIB system with PSS

A PSS is a lead-lag compensator, which produces a component of electric torque to damp generator rotor oscillations by controlling its excitation. The basic block diagram of a speed input single-stage PSS, which acts through excitation system, is depicted in Figure 4.2.

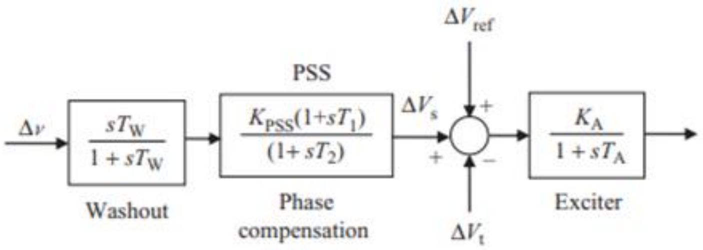
Neglecting washout stage, the linearized Heffron–Phillips model of the SMIB system, including PSS dynamics, can be represented by the following state-space equation

$$\Delta\dot{E}_q' = -\frac{1}{K_3 T_{\mathrm{do}}'}\Delta E_q' - \frac{K_4}{T_{\mathrm{do}}'}\Delta\delta + \frac{1}{T_{\mathrm{do}}'}\Delta E_{\mathrm{fd}}$$

$$\Delta\dot{\delta} = \omega_{\mathrm{s}}\Delta v$$

$$\Delta\dot{v} = -\frac{K_2}{2H}\Delta E_q' - \frac{K_1}{2H}\Delta\delta - \frac{D\omega_{\mathrm{s}}}{2H}\Delta v + \frac{1}{2H}\Delta T_{\mathrm{M}}$$

$$\Delta\dot{E}_{\mathrm{fd}} = -\frac{1}{T_{\mathrm{A}}}\Delta E_{\mathrm{fd}} - \frac{K_{\mathrm{A}}K_5}{T_{\mathrm{A}}}\Delta\delta - \frac{K_{\mathrm{A}}K_6}{T_{\mathrm{A}}}\Delta E_q' + \frac{K_{\mathrm{A}}}{T_{\mathrm{A}}}\Delta V_{\mathrm{ref}}$$


ΔV_{ref}
PSS
Δv
$\frac{sT_{\mathrm{W}}}{1+sT_{\mathrm{W}}}$
Washout
$\frac{K_{\mathrm{PSS}}(1+sT_1)}{(1+sT_2)}$
Phase compensation
ΔV_{s}
+
+
−
ΔV_{t}
$\frac{K_{\mathrm{A}}}{1+sT_{\mathrm{A}}}$
Exciter

Exciter with PSS.

Fig. 4.2

$$\Delta\dot{V}_{\mathrm{s}} = -\frac{1}{T_2}\Delta V_{\mathrm{s}} - \frac{K_{\mathrm{PSS}}\,T_1}{T_2}\frac{K_2}{2H}\Delta E_q' - \frac{K_{\mathrm{PSS}}\,T_1}{T_2}\frac{K_1}{2H}\Delta\delta + \left(\frac{K_{\mathrm{PSS}}}{T_2} - \frac{K_{\mathrm{PSS}}\,T_1}{T_2}\frac{D\omega_{\mathrm{s}}}{2H}\right)\Delta v \qquad (4.1)$$

Where $K_2 = \frac{\partial P_e}{\partial E_q'}$ and $K_1 = \frac{\partial P_e}{\partial \delta}$. Assuming the stator resistance Rs=0, the electric power $P_e = \frac{V_\infty E_q'}{X_T}\, sin\delta$ where $X_T = X_d' + X_c$

Here, Equation (4.1) is added to the general equations written above of the SMIB system because of the installation of a PSS. The system matrix (A_PSS) of this combined model has been presented in Equation (4.2). The system matrix without PSS can be easily obtained by excluding the PSS output state (Vs):

$$A\_PSS = \begin{bmatrix} -\frac{1}{K_3 T_{d0}^{'}} & -\frac{K_4}{T_{\mathrm{do}}^{'}} & 0 & \frac{1}{T_{\mathrm{do}}^{'}} & 0 \\ 0 & 0 & \omega_{\mathrm{s}} & 0 & 0 \\ -\frac{K_2}{2H} & -\frac{K_1}{2H} & -\frac{D\omega_{\mathrm{s}}}{2H} & 0 & 0 \\ -\frac{K_{\mathrm{A}}K_6}{T_{\mathrm{A}}} & -\frac{K_{\mathrm{A}}K_5}{T_{\mathrm{A}}} & 0 & -\frac{1}{T_{\mathrm{A}}} & \frac{K_{\mathrm{A}}}{T_{\mathrm{A}}} \\ -\frac{K_2 T_1}{T_2}\left(\frac{K_{\mathrm{PSS}}}{2H}\right) & -\frac{K_1 T_1}{T_2}\left(\frac{K_{\mathrm{PSS}}}{2\mathrm{H}}\right) & \left(\frac{K_{\mathrm{PSS}}}{T_2} - \frac{K_{\mathrm{PSS}}\, T_1}{T_2}\frac{D\omega_{\mathrm{s}}}{2\mathrm{H}}\right) & 0 & -\frac{1}{T_2} \end{bmatrix} \quad (4.2)$$

The washout filter stage is neglected here, since its objective is to offset the dc steadystate error and not have any effect on phase shift or gain at the oscillating frequency. The application of washout stage is not a critical task. Its dynamics can be included easily with suitable choice of the parameter TW. The value of TW is generally set within 10-20 s

4.3 Results and discussion

- **Eigen value Analysis**

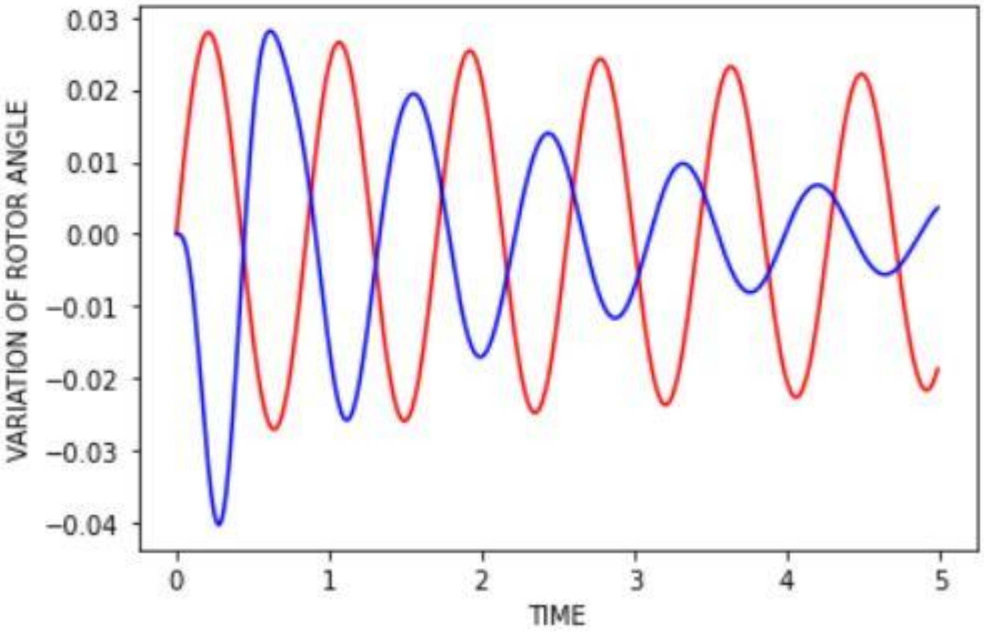
In this section, eigenvalues and the electromechanical swing modes of a SMIB system are computed in MATLAB from the system matrix, A_PSS, presented in Equation (4.2). The eigenvalues of the system without and with PSS are listed in Table 4.1. It is evident that the damping ratio of the electromechanical swing mode #2 (second row, third column) is small compared to the other mode; therefore, the behavior of this mode is more important to study the small-signal stability problem of this system and this mode has been referred to as the critical mode. When a PSS is installed in the system, the damping ratio of this critical mode #2 is enhanced significantly. The value of the damping ratio with PSS has been shown in the second row, column six of Table 4.1.

Table 4.1 Eigenvalues and damping ratio without and with PSS

Before applying PSS		**PSS PARAMETERS**	**After applying PSS**	
Eigenvalue	**Damping ratio**		**Eigenvalue**	**Damping ratio**
-2.6626±j15.136	**0.1733**	**K_pss=1.0**	**-2.054±j15.3253**	**0.1328**
-0.05265±j7.3426	**0.0072**	**T1=0.5s**	**-0.04116±j7.110**	**0.0578**
-	**-**	**T2=0.5s**	**-10.4989**	**1.0**

Time domain analysis

The small-signal stability response of this system has been examined further by plotting the rotor angle deviation under different values of the PSS gain (KPSS) for a unit change in mechanical step power input with a reasonable simulation time of 500 s. Thus, it may be reasonable to remark that the installation of PSS in a SMIB system not only damps the rotor angle oscillations effectively but also enhances its performance with increasing PSS gain.

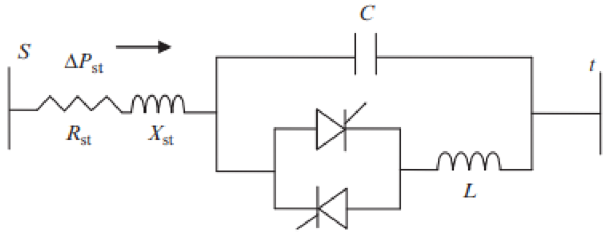


The red colour graph shows the graph of system before applying PSS to system. The blue colour graph shows the graph of system after applying PSS to system.

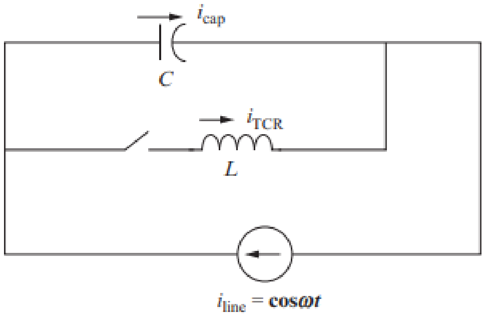
CHAPTER 5: APPLICATION OF TCSC FOR SMALL SIGNAL STABILITY ANALYSIS

5 .1Thyristor Controlled Series Compensator

The basic Thyristor controlled series compensator (TCSC) configuration consists of a fixed series capacitor bank C in parallel with a TCR as shown in Figure 5.1. This simple model utilizes the concept of a variable series reactance. The series reactance is adjusted through appropriate variation of the firing angle (α), to allow specified amount of active power flow across the series-compensated line.



TCSC module.



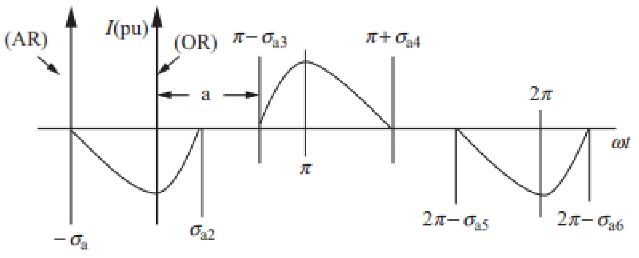
Equivalent circuit of a TCSC module.

Fig. 5.1

The simplified TCSC equivalent circuit is shown in above figure .The transmission line current is assumed to be the independent input variable and is modelled as an external current source, line (t). It has been assumed that a loop current is trapped in the reactor-capacitor circuit and that the power system can be represented by an ideal, sinusoidal current source. Under these assumptions, the TCSC steady-state voltage and current equations that can be obtained from the analysis of a parallel LC circuit with a variable inductance are shown in Figure 5.1, and the asymmetrical current pulses through the TCSC thyristors are shown schematically in Figure 5.2. However, the analysis presented in the following text may be erroneous to the extent that the line current deviates from a purely sinusoidal nature. The original time reference (OR) is taken to be the positive going zero crossing of the voltage across the TCSC inductance. Also, an auxiliary time reference (AR) is taken at a time when the thyristor starts to conduct.

The line current is

$$i_{\text{line}} = \cos \omega t$$



Asymmetrical thyristor current.

Fig. 5.2

or, in the AR plane,

$$i_{line} = \cos(\omega t - \sigma_a) = cos\omega t cos\sigma_a + sin\omega t sin\sigma_a$$

Applying Kirchhoff current law (KCL) to the circuit shown in Figure 5.2

$$i_{line} = i_{TCR} + i_{cap}$$

During the conduction period, the voltage across the TCSC inductive reactance and capacitive reactance coincides:

$$L\frac{di_{TCR}}{dt} = \frac{1}{C}\int i_{cap}\,dt + V_{cap}^{+}$$

where V_{cap}^{+} is the voltage across the capacitor when the thyristor turns on. Taking Laplace transformation of equations above,

$$I_{\text{line}} = \cos\sigma_{\text{a}}\frac{s}{s^2+\omega^2} + \sin\sigma_{\text{a}}\frac{\omega}{s^2+\omega^2}$$

$$I_{\text{line}} = I_{\text{TCR}} + I_{\text{cap}}$$

$$I_{\text{cap}} = s^2 LC I_{\text{TCR}} - CV_{\text{cap}}^{+}$$

Solving for I_{TCR}

$$I_{\mathrm{TCR}} = \omega_0^2 \cos \sigma_{\mathrm{a}} \frac{s}{(s^2 + \omega_0^2)(s^2 + \omega^2)} + \omega_0^2 \omega \sin \sigma_{\mathrm{a}} \frac{1}{(s^2 + \omega_0^2)(s^2 + \omega^2)} + \frac{\omega_0^2 C V_{\mathrm{cap}}^{+}}{s^2 + \omega_0^2}$$

where ω^2 = 1/LC. Expressing above equation in the time domain leads to

$$i_{\mathrm{TCR}} = A\cos(\omega t - \sigma_{\mathrm{a}}) - A\cos \sigma_{\mathrm{a}} \cos \omega_0 t$$
$$-B\sin \sigma_{\mathrm{a}} \sin \omega_0 t + D V_{\mathrm{cap}}^{+} \sin \omega_0 t$$

Where $A = \frac{\omega_0}{\omega_0^2 - \omega^2}, B = \frac{\omega_0 \omega}{\omega_0^2 - \omega^2},$ and $D = \omega_0 C$

The TCSC fundamental impedance is

$$Z_{\mathrm{TCSC}} = R_{\mathrm{TCSC}} + jX_{\mathrm{TCSC}} = \frac{V_{\mathrm{TCSC}}}{I_{\mathrm{line}}}$$

The voltage isV_{TCSC} equal to the voltage across the TCSC capacitor and the above equation can be written as

$$Z_{\mathrm{TCSC}} = \frac{-jX_{\mathrm{C}} I_{\mathrm{cap}}}{I_{\mathrm{line}}}$$

If the external power network is represented by an idealized current source, as seen from the TCSC terminals, this current source is equal to the sum of the currents flowing through the TCSC capacitor and inductor. The TCSC impedance can then be expressed as

$$Z_{\mathrm{TCSC}} = \frac{-jX_{\mathrm{C}}(I_{\mathrm{line}} - I_{\mathrm{TCR}})}{I_{\mathrm{line}}}$$

Substituting the expression for I_{TCR} from above and assuming $I_{line} = lcos\omega t$

$$Z_{\mathrm{TCSC}} = -jX_{\mathrm{C}} + \frac{-jX_{\mathrm{C}}}{1\cos \omega t}\Bigg[\frac{A}{\pi}(2\sigma_{\mathrm{a}} + \sin(2\sigma_{\mathrm{a}}))$$
$$- \frac{4A\cos^2 \sigma_{\mathrm{a}}}{(\varpi^2 - 1)}\left[\frac{\varpi \tan(\varpi\sigma_{\mathrm{a}}) - \tan(\sigma_{\mathrm{a}})}{\pi}\right]\Bigg]$$

Let $U_1 = \frac{-jX_{\mathrm{C}}}{1\cos \omega t}\left[\frac{A}{\pi}\left(2\sigma_{\mathrm{a}} + \sin(2\sigma_{\mathrm{a}})\right)\right]$ and $U_2 = \frac{4AX_{\mathrm{C}}\cos^2 \sigma_{\mathrm{a}}}{(\varpi^2 - 1)1\cos \omega t}\left[\frac{\varpi \tan(\varpi\sigma_{\mathrm{a}}) - \tan(\sigma_{\mathrm{a}})}{\pi}\right]$

Therefore,

$$Z_{\mathrm{TCSC}} = -jX_{\mathrm{C}} + U_1 + U_2$$

Using the expression for $A = \frac{\omega_0^2}{\omega_0^2 - \omega^2}, \omega_0^2 = \frac{1}{LC},$ and $\sigma_{\mathrm{a}} = \pi - \alpha$

$$U_1 = \frac{X_C}{\pi\omega C\left(\frac{1}{\omega C - \omega L}\right)}[2(\pi - \alpha) + \sin(2(\pi - \alpha))], [\because \cos\omega t|_{\max} = 1]$$

$$= \frac{X_C + X_{LC}}{\pi}[2(\pi - \alpha) + \sin(2(\pi - \alpha))]$$

$$= C_1(2(\pi - \alpha) + \sin(2(\pi - \alpha)))$$

$$\text{where } C_1 = \frac{X_C + X_{LC}}{\pi} \text{ and } X_{LC} = \frac{X_C X_L}{X_C - X_L}$$

Again,

$$U_2 = \frac{4AX_C\cos^2\sigma_a}{(\varpi^2 - 1)1\cos\omega t}\left[\frac{\varpi\tan(\varpi\sigma_a) - \tan(\sigma_a)}{\pi}\right]$$

$$\text{Replacing the expression for } A = \frac{\omega_0^2}{\omega_0^2 - \omega^2} \text{ and } \sigma_a = \pi - \alpha\,,$$

$$= \frac{4X_C\omega_0^2\cos^2(\pi - \alpha)}{(\omega_0^2 - \omega^2)(\varpi^2 - 1)}\left[\frac{\varpi\tan\big(\varpi(\pi - \alpha)\big) - \tan(\pi - \alpha)}{\pi}\right]$$

$$\left[\because \cos\omega t|_{\max} = 1, \because \varpi = \frac{\omega_0}{\omega}, \omega_0^2 = \frac{1}{LC}\right]$$

$$= \frac{4X_{LC}^2\cos^2(\pi - \alpha)}{\pi X_L}\big[\varpi\tan\big(\varpi(\pi - \alpha)\big) - \tan(\pi - \alpha)\big]$$

$$= C_2\cos^2(\pi - \alpha)\big[\varpi\tan\big(\varpi(\pi - \alpha)\big) - \tan(\pi - \alpha)\big]$$

$$X_{LC} = \frac{X_L X_C}{(X_C - X_L)} \text{ and } C_2 = \frac{4X_{LC}^2}{\pi X_L}.$$

Combining above equations, the TCSC fundamental impedance can be obtained,

$$Z_{TCSC} = j(-X_C + C_1(2(\pi - \alpha) + \sin 2(\pi - \alpha))$$
$$-C_2\cos^2(\pi - \alpha)\left(\varpi\tan\big(\varpi(\pi - \alpha)\big) - \tan(\pi - \alpha)\right)\Big)$$

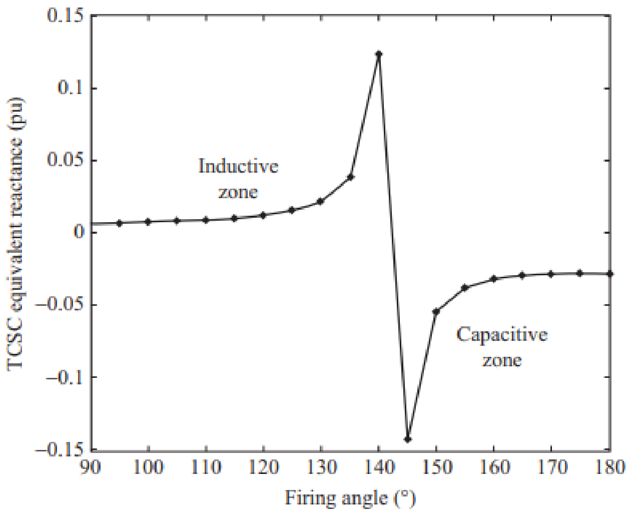
Therefore, the TCSC equivalent reactance, as a function of the TCSC firing angle (a), which can be expressed from above equation, is

$$Z_{TCSC} = (-X_C + C_1(2(\pi - \alpha) + \sin 2(\pi - \alpha))$$
$$-C_2\cos^2(\pi - \alpha)\left(\varpi\tan\big(\varpi(\pi - \alpha)\big) - \tan(\pi - \alpha)\right)\Big)$$

The TCSC linearized equivalent reactance, which can then be obtained as

$$\Delta X_{TCSC} = \Big\{-2C_1(1 + \cos(2\alpha)) + C_2\sin(2\alpha)\left(\varpi\tan\big(\varpi(\pi - \alpha)\big) - \tan\alpha\right)$$
$$+C_2\left(\varpi^2\frac{\cos^2(\pi - \alpha)}{\cos^2\big(\varpi(\pi - \alpha)\big)} - 1\right)\Big\}\Delta\alpha$$

For a typical value X_C and X_L at a base frequency of 50 Hz, its equivalent reactance (X_{TCSC}) as a function of the firing angle (a) has been plotted in Figure



Variation of TCSC reactance (X_{TCSC}) with firing angle (α).

5.2 APPLICATION OF A TCSC CONTROLLER IN AN SMIB SYSTEM

This section describes the application of a TCSC controller in an SMIB system in order to improve small-signal stability through series compensation. Simulation results established the superiority of the TCSC controller over PSS and SVC controllers. With changes in the firing angle of the Thyristors, the TCSC can change its apparent reactance smoothly and rapidly. Because of its rapid and flexible regulation ability, it can improve transient stability and dynamic performance and is capable of providing positive damping effect to the electromechanical oscillation modes of the power systems.

5.3 **Model of an SMIB system with a TCSC controller**

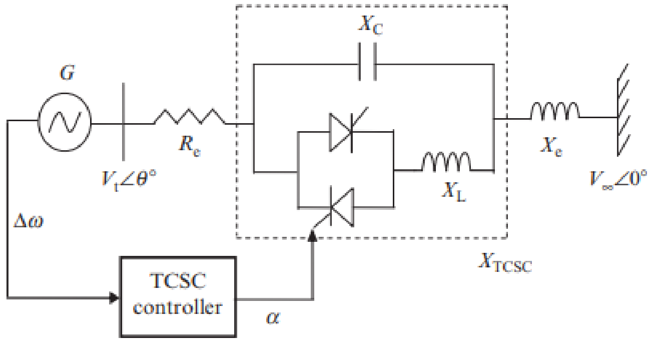
A simple SMIB system with TCSC controller has been shown in Figure. The small-signal model of the TCSC controller has been described. The state-space model of SMIB system with a TCSC controller can be formulated by adding the state variables $\Delta x_{\text{tesc}} = [\Delta\alpha \quad \Delta X_{\text{TCSC}}\,]^{\text{T}}$ corresponding to the TCSC controller in the general Heffron-Phillips model of

SMIB system. Therefore, combined state-space model of the SMIB system with a TCSC controller can be represented by the following equations:

$$\Delta\dot{E}_q' = -\frac{1}{K_3 T_{\mathrm{do}}'}\Delta E_q' - \frac{K_4}{T_{\mathrm{d}}'}\Delta\delta + \frac{1}{T_{\mathrm{dc}}'}\Delta E_{\mathrm{fd}}$$

$$\Delta\dot{\delta} = \omega_{\mathrm{s}}\Delta v$$

$$\Delta\dot{E}_{\mathrm{fd}} = -\frac{1}{T_{\mathrm{A}}}\Delta E_{\mathrm{fd}} - \frac{K_{\mathrm{A}}K_5}{T_{\mathrm{A}}}\Delta\delta - \frac{K_{\mathrm{A}}K_6}{T_{\mathrm{A}}}\Delta E_q' + \frac{K_{\mathrm{A}}}{T_{\mathrm{A}}}\Delta V_{\mathrm{ref}}$$



SMIB system with TCSC.

$$\begin{aligned}\Delta\dot{\alpha} &= \frac{K_{\mathrm{TCSC}}\,T_1}{T_2}\frac{K_2}{2H}\Delta E_q' + \frac{K_{\mathrm{TCSC}}\,T_1}{T_2}\frac{K_1}{2H}\Delta\delta \\ &+ \left(-\frac{K_{\mathrm{TCSC}}}{T_2} + \frac{K_{\mathrm{TCSC}}\,T_1}{T_2}\frac{D\omega_{\mathrm{s}}}{2H}\right)\Delta v \\ &+ \left(-\frac{1}{T_2} + \left(\frac{-K_{\mathrm{TCS}}\,T_1 K_\alpha}{2HT_2}\right)\right)\Delta\alpha - \frac{K_{\mathrm{TCSC}}\,T_1}{2HT_2}\Delta T_{\mathrm{M}}\end{aligned}$$

$$\Delta\dot{X}_{\mathrm{TCSC}} = -\frac{1}{T_{\mathrm{TCSC}}}\Delta\alpha - \frac{1}{T_{\mathrm{TCSC}}}\Delta X_{\mathrm{TCSC}}$$

The above equations are added due to the installation of the TCSC. Here $K_2 = \frac{\partial P_{\mathrm{e}}}{\partial E_q'}, K_1 = \frac{\partial P_{\mathrm{e}}}{\partial\delta}$, and $K_\alpha = \frac{\partial P_{\mathrm{e}}}{\partial\alpha}$. The electrical power (Pe) assuming the stator resistance $R_{\mathrm{s}} = 0$ is $P_{\mathrm{e}} = \frac{E_q' V_\infty}{X_{\mathrm{T}}}\sin\delta$, where $X_{\mathrm{T}} = X_d' + X_{\mathrm{eff}}$ and $X_{\mathrm{eff}} = X_{\mathrm{e}} - X_{\mathrm{TCSC}}(\alpha)$. "$\alpha$" is the firing angle of the Thyristors. The system matrix (*A_TCSC*) of the corresponding model is

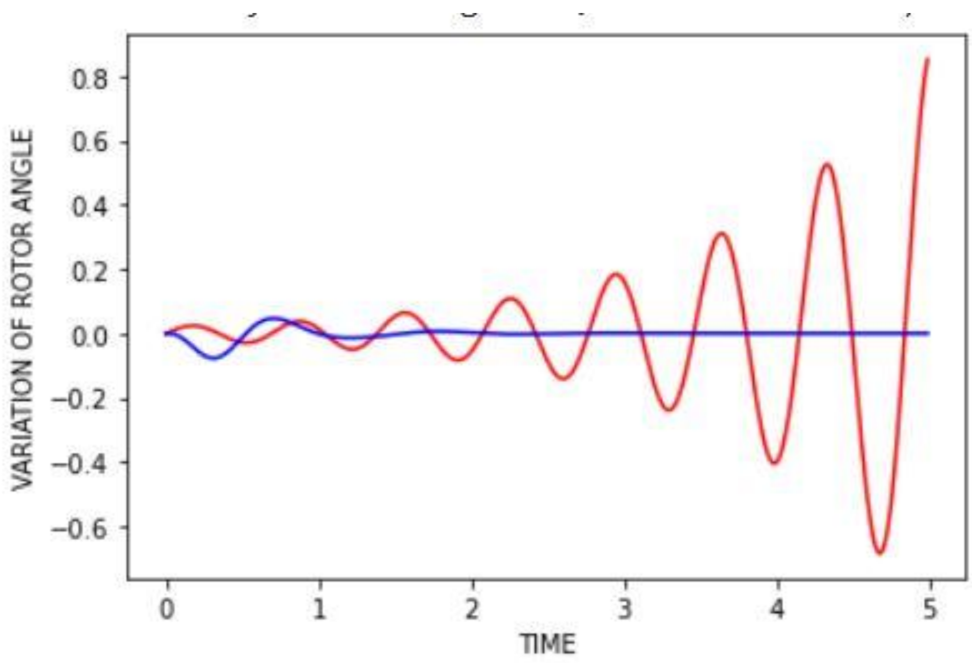
$$\text{A\_TCSC} = \begin{bmatrix} -\frac{1}{K_3 T_{\mathrm{do}}^{'}} & -\frac{K_4}{T_{\mathrm{do}}^{'}} & 0 & \frac{1}{T_{\mathrm{do}}^{'}} & 0 & 0 \\ 0 & 0 & \omega_{\mathrm{s}} & 0 & 0 & 0 \\ -\frac{K_2}{2H} & -\frac{K_1}{2H} & -\frac{D\omega_{\mathrm{s}}}{2H} & \frac{K_z}{2H} & 0 & 0 \\ -\frac{K_{\mathrm{A}}K_6}{T_{\mathrm{A}}} & -\frac{K_{\mathrm{A}}K_5}{T_{\mathrm{A}}} & 0 & -\frac{1}{T_{\mathrm{A}}} & \frac{K_{\mathrm{A}}}{T_{\mathrm{A}}} & 0 \\ \frac{K_2 T_1}{T_2}\left(\frac{K_{\mathrm{TCSC}}}{2\mathrm{H}}\right) & \frac{K_1 T_1}{T_2}\left(\frac{K_{\mathrm{TCSC}}}{2H}\right)\left(-\frac{K_{\mathrm{TCSC}}}{T_2} + \frac{K_{\mathrm{TCSC}}\, T_1 D\omega_{\mathrm{s}}}{T_2}\right) & 2\mathrm{H} & 0 & -\frac{1}{T_2} + \left(\frac{-K_{\mathrm{TCSC}}\, T_1 K_x}{2\mathrm{HT}_2}\right) & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_{\mathrm{TCSC}}} & -\frac{1}{T_{\mathrm{TCSC}}} \end{bmatrix}$$

5.4 Eigenvalue Computation and Time Domain Analysis

The system matrix of an SMIB system with a TCSC controller is simulated in Python. The eigen values of the system are computed without and with the TCSC and PSS. It is found that the damping ratio of the critical mode #2 (second row and third column) is improved satisfactorily with the application of the TCSC controllers, but the improvement is reasonably more with the application of the TCSC. The eigenvalues before and after applying TCSC are shown in a Table 5.1 for firing angle(at resonance) $\alpha = 140\text{degree}$

Table 5.1 Eigenvalues without and with TCSC

Before applying TCSC		**After Applying TCSC**	
Eigenvalue	**Damping ratio**	**Eigenvalue**	**Damping ratio**
-2.6626±j15.136	**0.1733**	**-2.9411±j10.655**	**0.2661**
-0.05265±j7.3426	**0.0072**	**-1.6436±j5.9836**	**0.2653**
-	**-**	**-40.00000**	**1.0**



The red colour response shows the system behaviour before applying TCSC to the system whereas the blue colour graph indicates the system response after applying TCSC

CHAPTER 6: CONCLUSION & FUTURE SCOPE

6.1 Conclusion

In this work Python has been used for simulation of power system small signal stability problem. Python programming has been used to calculate eigenvalue and time domain analysis. The same problem has been already solved applying MATLAB and available in standard literature. However, application of Python is a novel concept presented in this project report. Comparing the result before using PSS & TCSC and after applying PSS & TCSC, it has been observed that the results executed in MATLAB are identically same with the results obtained in Python. So it is possible to conclude that the Python programming can also be used as an alternative of MATLAB for simulation of power system stability problems.

6.2 Future Scope:

For the simplicity of solution, in this project the case of single machine system has been studied. But this approach can be applied for the multi-machine problems also. Moreover other FACTS device like SVC, STATCOM can also be used too.

APPENDIX

A.1 System parameters

Td=5.90

H=2.37

TA=0.2

DX=0.0

Ws=314

KA=400

Xq=1.64

Xd=1.70

X_d=0.245

Re=0.02

Xe=0.7

Vinf=1.0

Rs=0.0

A.2 PROGAM FOR SYSTEM WITH0UT PSS

```
import numpy as np
from scipy import linalg,signal
 import matplotlib.pyplot as plt
#PARAMETERS OF THESYSTEM#
Td=5.90
H=2.37
TA=0.2
DX=0.0
Ws=314
KA=400
Xq=1.64
Xd=1.70
X_d=0.245
Re=0.02
Xe=0.7
Vinf=1.0
Rs=0.0
Xeff=Xe
XT=X_d+Xeff
THETA1=(np.pi*19.31)/180
THETA2=(np.pi*0)/180
Vi=1.172
 V1=Vi*np.exp(complex(0,THETA1))
V2=Vinf*np.exp(complex(0,THETA2))
IG = (V1 - V2) / complex(Re,Xeff)
print("V1,V2,IG=",V1,V2,IG)
#step1#
 Mag = abs(IG)
 ANG = (180 * np.angle(IG)) / 3.14
print("Mag,ANG=",Mag,ANG)
 #step2#
 E = abs(V1 + complex(Rs , Xq) * IG)
 delta = (180 * np.angle(V1 + complex(Rs,Xq) * IG)) / 3.14
print("E,delta=",E,delta)
#step3#
 Idq = IG * np.exp(complex(0,-((3.14 * delta / 180) - (3.14 / 2))))
 Id = np.real(Idq)
Iq = np.imag(Idq)
Vdq = V1 * np.exp(complex(0,-((3.14 * delta / 180) - (3.14 / 2))))
 Vd = np.real(Vdq)
Vq = np.imag(Vdq)
print("Idq,Iq,Vdq,Vd,Vq=",Idq,Iq,Vdq,Vd,Vq)
 #step4#
 E_q = Vq + Rs * Iq + X_d * Id
print("E_q=",E_q)
#step5#
 Efd = E_q + (Xd - X_d) * Id
print("Efd=",Efd)
  #step6#
 Vref = Vi + Efd / KA
 TM = E_q * Iq + (Xq - X_d) * Id * Iq
print("Vref,TM=",Vref,TM)
  #CALCULATION OF K-CONSTANTS#+++++++++++++++++++++
 DEL = Re * Re + (Xeff + Xq) * (Xeff + X_d)
 K3_1 = 1 + (Xd - X_d) * (Xq + Xeff) / DEL
 K3 = 1 / K3_1
 K4 = (Vinf * (Xd - X_d) / DEL) * ((Xq + Xeff) * np.sin(3.14 * delta / 180) - Re * np.cos(3.14 *
delta / 180))
 K2 = (1 / DEL) * (Iq * DEL - Iq * (X_d - Xq) * (Xq + Xeff) - Re * (X_d - Xq) * Id + Re * E_q)
 K1 = (-1 / DEL) * (
           Iq * Vinf * (X_d - Xq) * ((Xq + Xeff) * np.sin(3.14 * delta / 180) - Re * np.cos(3.14 *
delta / 180)) + Vinf * (
               (X_d-Xq) * Id - E_q) * ((X_d + Xeff) * np.cos(3.14 * delta / 180) + Re * np.sin(3.14 *
delta / 180)))
 K5 = (1 / DEL) * (
((Vd * Xq / Vi) * (Re * Vinf * np.sin
 (3.14 * delta / 180) + Vinf * np.cos(3.14 * delta / 180) * (X_d + Xeff)) + (Vq / Vi) *
 (X_d * (Re * Vinf * np.cos(3.14 * delta / 180) - Vinf * (Xq + Xeff) * np.sin(3.14 * delta /
180)))))
 K6 = (1 / DEL) * ((Vd * Xq * Re) / Vi - (Vq * X_d * (Xq + Xeff)) / Vi) + Vq / Vi
 #SYSTEM MATRIX 'A' WITHOUT PSS#
 A=[ [-1/(K3*Td), -K4/Td, 0 ,1/Td ],[ 0 ,0 ,Ws ,0] ,[(-Vinf*np.sin(3.14*delta/180))/(2*H*XT) ,(-
E_q*Vinf*np.cos(3.14*delta/180))/(2*H*XT), -DX*Ws/(2*H) ,0],[-KA*K6/TA ,-KA*K5/TA ,0
,-1/TA ]]
  #EIGEN VALUES OF A#
eig_val1=linalg.eigvals(A)
```

```
print("eig_val1=",eig_val1)
#INPUT MATRIX 'B' #
B=[[0, 0],[0, 0],[1/(2*H), 0 ],[0 ,KA/TA ]]
  #OUTPUT MATRIX 'C' #
C=[0 ,0, 1, 0 ]
#TRANSITION MATRIX 'D' #
D=[0 ,0]
 #CLOSED LOOP TRANSFER FUCTION OF THE SYSTEM EXCITER#
[NUM1,DEN1]=signal.ss2tf(A,B,C,D)
print(NUM1)
T=np.arange(0,5,0.01)
 lti=signal.lti(NUM1,DEN1)
 t,r=signal.step(lti,0,T)
```

A.3 PROGAM FOR SYSTEM WITH PSS

```
#SYSTEM MATRIX 'A' WITH PSS#
 KP= 1   #PSS gain#
T1=0.5 #time constants of PSS#
T2= 0.1
A_pss =[ [-1/(K3*Td) ,-K4/Td ,0 ,1/Td ,0 ],[ 0, 0, Ws, 0 ,0 ],[(-
Vinf*np.sin(3.14*delta/180))/(2*H*XT) ,(-E_q*Vinf*np.cos(3.14*delta/180))/(2*H*XT), -
DX*Ws/(2*H), 0 ,0],[(-KA*K6)/TA, (-KA*K5)/TA ,0 ,-1/TA ,KA/TA] ,
[(-KP*T1*Vinf*np.sin(3.14*delta/180))/(2*H*T2*XT) ,(-
KP*T1*E_q*Vinf*np.cos(3.14*delta/180))/(2*H*T2*XT), (KP/T2)-(KP*T1*DX*Ws)/2*H*T2
,0 ,(-1/T2)]]
 #EIGEN VALUES OF A_PSS#
eig_val2=linalg.eigvals(A_pss)
print("eig_val2=",eig_val2)
 #INPUT MATRIX B_PSS#
B_pss=[[0 ,0],[0 ,0],[1/(2*H), 0],[0 ,KA/TA],[KP*T1/(2*H*T2), 0]]
 #OUTPUT MATRIX C_PSS#
C_pss=[0 ,0 ,1 ,0, 0 ]
#TRANSITION MATRIX D_PSS#
D_pss=[0, 0]
#CLOSED LOOP TRANSFER FUCTION OF THE SYSTEM WITH PSS#
[NUM2,DEN2]=signal.ss2tf(A_pss,B_pss,C_pss,D_pss,1)
lti1=signal.lti(NUM2,DEN2)
t1,r1=signal.step(lti1,0,T)
```

```
plt.plot(T,r1,'b')
plt.plot(T,r,'r')
# Set the x axis label of the current axis.
plt.ylabel('VARIATION OF ROTOR ANGLE')
# Set the y axis label of the current axis.
plt.xlabel('TIME')
plt.show()
```

A.4 PROGRAM TO FIND VARIATION OF TCSC WITH FIRING ANGLE

```
import numpy as np
from scipy import linalg,signal
import matplotlib.pyplot as plt
pi=3.14
omega=2*np.pi*50
# XL1 inductive reactance ; XC1 capacitive reactance#
import numpy as np
import matplotlib.pyplot as plt
beta=[90,95,100,105,110,115,120,125,130,135,136,137,138,139,140,141,142,143,144,145,146,147,148,149,150,155,160,165,170,175,180]
omega=2*np.pi*50
XL1=2.6
XC1=15
L=XL1/omega
C=1/(omega*XC1)
omega_zero=np.sqrt(1/(L*C))
omega_bar=omega_zero/omega
XL=XL1/529.02
XC=XC1/529.02
XLC=XC*XL/(XC-XL)
C1=(XC+XLC)/XL*np.pi
C2=(4*XLC*XLC)/XL*np.pi
XTCS=[]
for m in range(0,len(beta)):
    XTCS.append(-XC+C1*(2*(np.pi-beta[m]*np.pi/180)+np.sin(2*(np.pi-beta[m]*np.pi/180)))-C2*((np.cos(np.pi-beta[m]*np.pi/180))**2)*(omega_bar*np.tan(omega_bar*(np.pi-beta[m]*np.pi/180))-np.tan(np.pi-beta[m]*np.pi/180)))
plt.plot(beta,XTCS)
plt.show()
```

A.5 PROGAM FOR SYSTEM WITH TCSC

```
import numpy as np
from scipy import linalg,signal
 import matplotlib.pyplot as plt
#DETERMINATION OF TCSC REACTANCE AT A PARTICULAR VALUE OF FIRING
ANGLE
#Resonance occured at beta=140deg
beta_in= 150                    # initial value of firing angle
beta=(beta_in*np.pi)/180
print(beta)
delt=np.pi-beta
print(delt)
omega=2*np.pi*50
print(omega)
# XL inductive reactance ; XC capacitive reactance%
XL1=2.6; XC1=15.0;      #Assumed value %
# XL1=1.2 ; XC1=9.0;
L=XL1/omega
C=1/(omega*XC1);
omega_zero=np.sqrt(1/(L*C));
omega_bar=omega_zero/omega;
XL=XL1/529.02
XC=XC1/529.02  #Expressed in pu , where base impedance =529.02
   XLC=XC*XL/(XC-XL)
C_1=(XC+XLC)/np.pi
C_2=(4*XLC*XLC)/XL*np.pi
XTCSC=-XC+C_1*(2*(delt)+ np.sin(2*(delt)))-
C_2*(np.cos(delt))**2*(omega_bar*np.tan(omega_bar*(delt))-np.tan(delt))
print("XTCSC=",XTCSC)
 #CACULATION OF delta(YTCSC)
part1= -2*C_1*(1+np.cos(2*beta))+ C_2*np.sin(2*beta)*(omega_bar*np.tan(omega_bar*(np.pi-
beta))-np.tan(beta));
part2= (((omega_bar)**2)*((np.cos(np.pi-beta))**2))/((np.cos(omega_bar*(np.pi-beta)))**2) ;
dXTCSC= part1+C_2*(part2-1)
print("dXTCSC=",dXTCSC)
#PARAMETERS OF THESYSTEM#
Td=5.90
```

```
H=2.37
TA=0.2
DX=0.0
Ws=314
KA=40
Xq=1.64
Xd=1.70
X_d=0.245
Re=0.02
Xe=0.7
Vinf=1.00
Rs=0.0
TCSC=0.025
Xeff=Xe+XTCSC     # WITHOUT TCSC#
XT=X_d+Xeff
THETA1=(np.pi*19.31)/180
THETA2=(np.pi*0)/180
Vi=1.172
V1=Vi*np.exp(complex(0,THETA1))
V2=Vinf*np.exp(complex(0,THETA2))
 IG = (V1 - V2) / complex(Re,Xeff)
print("V1,V2,IG=",V1,V2,IG)
 #step1#
 Mag = abs(IG)
 ANG = (180 * np.angle(IG)) / 3.14
print("Mag,ANG=",Mag,ANG)
  #step2#
 E = abs(V1 + complex(Rs , Xq) * IG)
 delta = (180 * np.angle(V1 + complex(Rs,Xq) * IG)) / 3.14
print("E,delta=",E,delta)
#step3#
 Idq = IG * np.exp(complex(0,-((3.14 * delta / 180) - (3.14 / 2))))
 Id = np.real(Idq)
 Iq = np.imag(Idq)
 Vdq = V1 * np.exp(complex(0,-((3.14 * delta / 180) - (3.14 / 2))))
 Vd = np.real(Vdq)
 Vq = np.imag(Vdq)
print("Idq,Iq,Vdq,Vd,Vq=",Idq,Iq,Vdq,Vd,Vq)
 #step4#
 E_q = Vq + Rs * Iq + X_d * Id
```

```
print("E_q=",E_q)
  #step5#
 Efd = E_q + (Xd - X_d) * Id
print("Efd=",Efd)
  #step6#
 Vref = Vi + Efd / KA
 TM = E_q * Iq + (Xq - X_d) * Id * Iq
print("Vref,TM=",Vref,TM)
 #CALCULATION OF K-CONSTANTS#++++++++++++++++++++++
 DEL = Re * Re + (Xeff + Xq) * (Xeff + X_d)

  K3_1 = 1 + (Xd - X_d) * (Xq + Xeff) / DEL
 K3 = 1 / K3_1
 K4 = (Vinf * (Xd - X_d) / DEL) * ((Xq + Xeff) * np.sin(3.14 * delta / 180) - Re * np.cos(3.14 *
delta / 180))
 K2 = (1 / DEL) * (Iq * DEL - Iq * (X_d - Xq) * (Xq + Xeff) - Re * (X_d - Xq) * Id + Re * E_q)
 K1 = (-1 / DEL) * (
            Iq * Vinf * (X_d - Xq) * ((Xq + Xeff) * np.sin(3.14 * delta / 180) - Re * np.cos(3.14 *
delta / 180)) + Vinf * (
                (X_d-Xq) * Id - E_q) * ((X_d + Xeff) * np.cos(3.14 * delta / 180) + Re * np.sin(3.14 *
delta / 180)))
 K5 = (1 / DEL) * (
((Vd * Xq / Vi) * (Re * Vinf * np.sin
 (3.14 * delta / 180) + Vinf * np.cos(3.14 * delta / 180) * (X_d + Xeff)) + (Vq / Vi) *
 (X_d * (Re * Vinf * np.cos(3.14 * delta / 180) - Vinf * (Xq + Xeff) * np.sin(3.14 * delta /
180)))))
 K6 = (1 / DEL) * ((Vd * Xq * Re) / Vi - (Vq * X_d * (Xq + Xeff)) / Vi) + Vq / Vi
 #SYSTEM MATRIX 'A' WITHOUT TCSC#
 A=[ [-1/(K3*Td), -K4/Td, 0 ,1/Td ],[ 0 ,0 ,Ws ,0] ,[(-Vinf*np.sin(3.14*delta/180))/(2*H*XT) ,(-
E_q*Vinf*np.cos(3.14*delta/180))/(2*H*XT), -DX*Ws/(2*H) ,0],[-KA*K6/TA ,-KA*K5/TA ,0
,-1/TA ]]
  #EIGEN VALUES OF A#
eig_val1=linalg.eigvals(A)
print("eig_val1=",eig_val1)
#INPUT MATRIX 'B' #
B=[[0, 0],[0, 0],[1/(2*H), 0 ],[0 ,KA/TA ]]
  #OUTPUT MATRIX 'C' #
C=[0 ,0, 1, 0 ]
#TRANSITION MATRIX 'D' #
D=[0 ,0]
```

```
 #CLOSED LOOP TRANSFER FUCTION OF THE SYSTEM EXCITER#
[NUM1,DEN1]=signal.ss2tf(A,B,C,D)
print(NUM1)
T=np.arange(0,5,0.01)
 lti=signal.lti(NUM1,DEN1)
 t,r=signal.step(lti,0,T)
 # SYSTEM MATRIX 'A' WITH TCSC
#^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^^
KP= 1.0;           # TCSC controller gain%
T1=0.5 ; T2= 0.1;  # Time constants of TCSC controller
A_tcsc=[[-1/(K3*Td) ,-K4/Td  ,0 , 1/Td ,0 ,0],[0  ,0 , Ws, 0 , 0 , 0],[(-
Vinf*np.sin(3.14*delta/180))/(2*H*XT), (-E_q*Vinf*np.cos(3.14*delta/180))/(2*H*XT) , -
DX*Ws/(2*H) , 0 , (E_q*Vinf*dXTCSC*np.sin(3.14*delta/180))/(2*H*XT*XT) ,0],[-
KA*K6/TA  , -KA*K5/TA  ,0 , -1/TA  ,0
,0],[(KP*T1*Vinf*np.sin(3.14*delta/180))/(2*H*T2*XT) ,
(KP*T1*E_q*Vinf*np.cos(3.14*delta/180))/(2*H*T2*XT) ,  (-
KP/T2)+(KP*T1*DX*Ws)/(2*H*T2) ,  0 ,  (-1/T2)+(-
KP*T1*E_q*Vinf*dXTCSC*np.sin(3.14*delta/180))/(2*H*T2*XT*XT) ,0],[ 0, 0 ,0 ,0 ,-
1/TCSC ,-1/TCSC]]
 #EIGEN VALUES OF A_TCSC#
eig_val2=linalg.eigvals(A_tcsc)
print("eig_val2=",eig_val2)
 #INPUT MATRIX B_TCSC#
B_tcsc=[[0 ,0],[0 ,0],[1/(2*H), 0],[0 ,KA/TA],[-KP*T1/(2*H*T2), 0],[0,0]]
 #OUTPUT MATRIX C_TCSC#
C_tcsc=[0 ,0 ,1 ,0, 0,0 ]
#TRANSITION MATRIX D_TCSC#
D_tcsc=[0, 0]
[NUM2,DEN2]=signal.ss2tf(A_tcsc,B_tcsc,C_tcsc,D_tcsc,1)
lti1=signal.lti(NUM2,DEN2)
t1,r1=signal.step(lti1,0,T)
plt.plot(T,r,'r')
plt.plot(T,r1,'b')
# Set the x axis label of the current axis.
plt.ylabel('VARIATION OF ROTOR ANGLE')
# Set the y axis label of the current axis.
plt.xlabel('TIME')
plt.show()
```