



Modeling of Synchronous generator for the simulation of Synchroconverter

A Thesis submitted to the

Dept. of Electrical & Electronic Engineering, BRAC University in
partial fulfillment of the requirements for the degree of Bachelor of
Science in Electrical and Electronic Engineering

by

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August 2014

Statement of originality

We do hereby declare that the thesis titled “**Modeling of Synchronous generator for the simulation of Synchroconverter**” is submitted to the Department of Electrical and Electronic Engineering of BRAC University in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical and Electronic Engineering. This is our original work and has not submitted elsewhere for the award of any other degree or diploma.

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Acknowledgements

We are extremely grateful to our Supervisor, Prof. Dr. S. M. Lutful Kabir for his ideas, advice, guidance and assistance. Without his continuous support the thesis work would not been possible.


18/10/2014

Sign of Supervisor

Abstract

From the very first age of invention, synchronous generator is dominating the power generation system. At present, new demand has been raised to get secured and stable power supply. For the increasing demand, renewable energy sources are started contributing in power supply. In this system inverter plays a vital role. But inverter cannot give smooth transition especially when it is connected in a large number. On the other hand, synchronous generator can provide smooth transition. By connecting this idea with inverter, synchroconverter concept has been developed. In this paper, concept, component and mathematical modeling of synchroconverter has shown for further implementation of this system. To know the behavior of synchronous generator it is necessary to model it and this behavior will be implemented in synchroconverter to mimic it as synchronous generator. So our main focus is to model and simulate synchronous generator. For modeling of generator, existing mathematical equations have been used and for the simulation MATLAB software has been used. This paper will help for further work in the implementation of synchroconverter by providing results carried out by the modeling of synchronous generator.

Table of Contents

Chapter 1 Introduction.....	1
1.1 Background.....	1
1.2 Literature survey.....	2
1.3 Scope of the present work.....	2
1.4 Thesis Layout.....	3
Chapter 2 Synchroconverter.....	4
2.1 concept	4
2.2 Mathematical Model.....	4
2.3 Component.....	9
Chapter 3 Generator Modeling.....	13
Chapter 4 Simulation Result.....	23
Chapter 5 Conclusion.....	54
5.1 Conclusion	54
5.2 Suggestions for further work.....	54
References.....	56
Appendix.....	57

MATLAB code

Chapter 1

Introduction

1.1 Background

Synchronous generator which is also known as alternator converts mechanical power to ac electric power. It is widely used converter in power generation. With the rapid development of new energy technologies more and more renewable energy sources are being used in power distribution. About 16% of global final energy consumption presently comes from renewable resources, with 10% of all energy from traditional biomass, mainly used for heating, and 3.4% from hydroelectricity [1]. In the national level, at least 30 nations around the world already use renewable energy contributing more than 20% of energy supply [2]. National renewable energy markets are projected to continue to grow strongly in the coming decade and beyond. Wind power is growing at the rate of 30% annually, with a worldwide installed capacity of 282,482 megawatts (MW) at the end of 2012 [1]. Therefore it is quite clear that power system is achieving a great revolution in changing power generation specially centralized to distributed generation. For this generation, renewable generators plays a vital role as it has variable frequency ac sources, high frequency ac sources, dc sources and an important device or mechanism which converts dc to ac and this device is known as inverter. To specify more about inverter, we can think about the renewable sources, for example in solar power generation, photovoltaic arrays need dc to ac conversion. That means inverter is essential equipment which is going to control or dominate power system as more inverters need to be connected into the grid [7].

Current from renewable sources is modeled in such a way that it can take out the maximum power from the power source and inject them all into the power grid. By injecting maximum power to the grid, it would be possible to supply more power to the consumer. The policy of injecting all available power to the grid is good as long as renewable power sources constitute a small part of the grid power capacity [7]. That means the less contribution of renewable sources in power generation, the more stable system we will get. As renewable sources are naturally variable it cannot contribute in a large scale if we want to avoid power imbalance. Now-a-days it is seen in many cases that, controller associated with large conventional generator compensate

the random power fluctuation of renewable power generator and it also takes care of total power system stability and fault [7].

With the advancement of power generation through renewable sources, new type of inverter demand has been raised to operate renewable power generators at the same way as conventional power generators. This type of inverters can behave like synchronous generators. Inverter that is operated in this way is called synchroconverter. Now before implementing the idea, we will have to execute such a method so that we can control the inverter like a synchronous generator. That means it has to be redesigned so that it can behave in such a manner that a synchronous generator does. For this we have to integrate the inverters into the existing system of the generation of power system. In this paper it has been focused mainly on modeling and the simulation of synchronous generator.

1.2 Literature Survey

There are papers related to the idea of synchroconverter. In [3], concept of virtual synchronous machine (VISMA) was proposed where it is found that, to calculate phase current of VISMA, voltages at the point of common coupling with grid are measured. This phase currents are used as reference current for inverter where it behaves as current source. While tracking the current, if it is found that the current tracking error is small, inverter will behave like synchronous machine. Tracking of reference current and voltage is the limitation of this work. On the other hand synchroconverter does not need to track reference current and voltage [7].

The idea of virtual synchronous generator (VSG) was proposed in [5], where short term energy storage system is added to the inverter which can provide virtual inertia to the system. Limitation of this idea is long term storage system cannot be used. In synchroconverter, short term energy storage function can be implemented using long term storage system [7].

1.3 Scope of the present work

The idea of the synchroconverter can be applied either to single distributed generators, or group of distributed generators. Single distributed generator may be more appropriate to individual owners of distributed generators on the other hand the group of distributed generators is more economical and easier to control from the point of view of the network operator [6]. In this

paper, synchronous generator model has been presented. If this behavior can be shown in the inverter, it will work like a synchronous generator. Synchronous generator's maintenance is very expensive. To operate synchronous generator it requires huge energy. If there is any problem in one synchronous generator, it will affect other generators in the system. On the other hand synchroconverter is a power electronic device with energy storage system which can filter the random fluctuations [7].

1.4 Thesis Layout

As we seen in chapter 1, it is organized with introduction part which includes background, literature survey, and scope of the present work and thesis layout of the paper. This paper portrays the concept of synchroconverter with necessary elements like component and mathematical modeling and in chapter 2 these materials are given. In Chapter 3 the modeling of synchronous generator is pictured by providing essential algebraic equation, model diagram and the algorithm of the program. Next, in Chapter 4 simulation results are shown by concerning twelve different cases on synchronous generator. All these cases are categorized into three parts like short circuit test, changing value of mechanical torque and variation of field current value. Conclusion has been provided with scope for further work in chapter 5.

Chapter 2

Synchroconverter

2.1 Concept

Before modeling and simulating the synchronous generator we would like to explain about the synchroconverter. Synchroconverter is basically an inverter which can behave like a synchronous generator.

As synchroconverter mimics the synchronous generator, it has all the advantages and disadvantages of synchronous generator. The good property of synchroconverter is that, it is liberal about choosing parameters and their values according to our desire. The parameters which we can choose are inertia, friction coefficient, field inductance, mutual inductance, no magnetic saturation and no eddy currents [7]. At the time of operating the system, these parameters can be varied. On the other hand in synchroconverter, loss of stability due to under excitation can occur which is also a bad property of synchronous generator. It has a tendency to hunt which means oscillations around the synchronous frequency [7].

To control the synchroconverter, algorithms which have been established and justified more than a century ago can be used. When synchroconverter is connected to a utility grid, it will behave like a conventional generator. Using the same mathematical equations, we can operate synchroconverter as synchronous motor. In high voltage dc transmission line synchroconverter will work as a motor by sending dc power and another synchroconverter will work as generator by receiving that dc power at the other end of the line. The reason behind this case is, according to the grid frequency, the direction of the energy flow between the dc bus and the ac bus can be automatically decided in a synchroconverter [7].

2.2 Mathematical modeling

It has been seen that researchers have made different assumptions on modeling of synchronous machine. In this paper, it has been followed a nonlinear passive dynamic system while making no assumptions on signals. It has been considered a round rotor machine to make all stator inductances constant [7].

2.2.1 Electrical part

The mutual inductance between field coil and all three stator coils can be varied with rotor angle, θ as follows:

$$M_{af} = M_f \cos \theta$$

$$M_{bf} = M_f \cos\left(\theta - \frac{2\pi}{3}\right)$$

$$M_{cf} = M_f \cos\left(\theta - \frac{4\pi}{3}\right)$$

Here $M_f > 0$. The flux linkages of the windings are-

$$\Phi_a = Li_a - Mi_b - Mi_c + M_{af}i_f$$

$$\Phi_b = Li_b - Mi_a - Mi_c + M_{bf}i_f$$

$$\Phi_c = Li_c - Mi_a - Mi_b + M_{cf}i_f$$

$$\Phi_f = M_{af}i_a + M_{bf}i_b + M_{cf}i_c + L_f i_f$$

In above equations, i_a , i_b and i_c represent stator phase currents and i_f represents rotor excitation current. Now, flux matrix Φ is formed by:

$$\Phi = \begin{bmatrix} \Phi_a \\ \Phi_b \\ \Phi_c \end{bmatrix} = \begin{bmatrix} L & -M & -M \\ -M & L & -M \\ -M & -M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + M_f i_f \widetilde{\cos \theta}$$

After adding $[M-M]$ with L we can get that,

$$\Phi = \begin{bmatrix} L + M - M & -M & -M \\ -M & L + M - M & -M \\ -M & -M & L + M - M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + M_f i_f \widetilde{\cos \theta}$$

Here L = self inductance and M = mutual inductance of coils of stator windings.

And
$$\widetilde{\cos \theta} = \begin{bmatrix} \cos \theta \\ \cos \left(\theta - \frac{2\pi}{3} \right) \\ \cos \left(\theta - \frac{4\pi}{3} \right) \end{bmatrix}$$

We are assuming that $L+M = L_S$. If we put this on above equation we can get that,

$$\Phi = \left(\begin{bmatrix} L_S & 0 & 0 \\ 0 & L_S & 0 \\ 0 & 0 & L_S \end{bmatrix} + \begin{bmatrix} -M & -M & -M \\ -M & -M & -M \\ -M & -M & -M \end{bmatrix} \right) * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + M_f i_f \widetilde{\cos \theta}$$

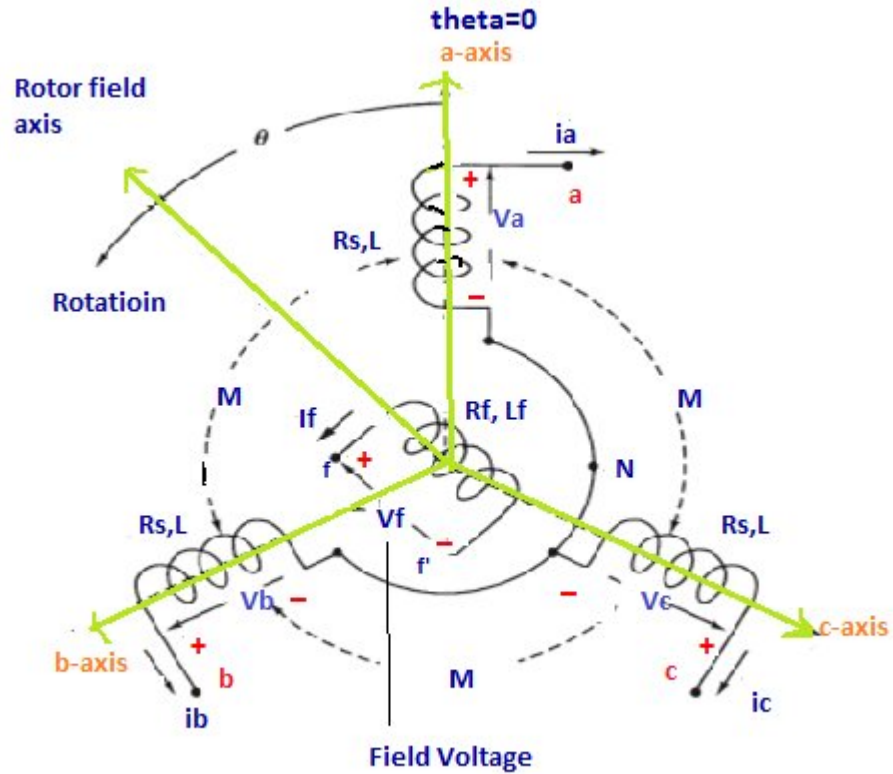


Figure 1: Structure of a three-phase round rotor SG.

Again we are assuming that neutral line is not connected. In that case,

$$i_a + i_b + i_c = 0$$

As a result we can find that $\begin{bmatrix} -M & -M & -M \\ -M & -M & -M \\ -M & -M & -M \end{bmatrix} * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = 0$. The equation of flux will be the following:

$$\Phi = L_s i + M_f i_f \widetilde{\cos \theta} \quad (1)$$

Here, $i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$. Now field flux linkage can be represented as

$$\begin{aligned} \Phi_f &= M_f \cos \theta i_a + M_f \cos \left(\theta - \frac{2\pi}{3} \right) i_b + M_f \cos \left(\theta - \frac{4\pi}{3} \right) i_c + L_f i_f \\ &\Rightarrow \Phi_f = L_f i_f + M_f \langle i, \widetilde{\cos \theta} \rangle \end{aligned} \quad (2)$$

Here $\langle i, \widetilde{\cos \theta} \rangle$ means dot product or inner product of “ i ” and “ $\widetilde{\cos \theta}$ ”.

From equation (1), Phase terminal voltage $v = [v_a \quad v_b \quad v_c]^T$ can be obtained as:

$$v = -R_s i - \frac{d\Phi}{dt} = -R_s i - L_s \frac{di}{dt} + e \quad (3)$$

In equation (3) resistance of stator windings is represented as R_s and $e = [e_a \quad e_b \quad e_c]^T$ is back electromotive force (emf) due to rotor movement given by the following equation:

$$\begin{aligned} e &= -M_f \frac{d}{dt} (i_f \widetilde{\cos \theta}) \\ &\Rightarrow e = +M_f i_f \dot{\theta} \widetilde{\sin \theta} - M_f \widetilde{\cos \theta} \frac{di_f}{dt} \end{aligned} \quad (4)$$

If i_f is constant then $M_f \widetilde{\cos \theta} \frac{di_f}{dt} = 0$

From equation (2) we can get field terminal voltage as given in the next page:

$$v_f = -R_f i_f - \frac{d\Phi_f}{dt} \quad (5)$$

2.2.2 Mechanical part

Mechanical part of the machine is governed by the following equation:

$$J\ddot{\theta} = T_m - T_e - D_p\dot{\theta} \quad (6)$$

In the above equation, moment of inertia, mechanical torque, electromagnetic torque, and damping factor are represented by J , T_m , T_e and D_p respectively. And

$$T_m = J \frac{d^2\theta}{dt^2} + D_p \frac{d\theta}{dt} + T_e$$

Electromagnetic torque can be found by Energy (E) which is the following:

$$\begin{aligned} E &= \frac{1}{2} \langle i, \Phi \rangle + \frac{1}{2} i_f \Phi_f \\ &= \frac{1}{2} \langle i, L_s i + M_f i_f \widetilde{\cos \theta} \rangle + \frac{1}{2} i_f (L_f i_f + M_f \langle i, \widetilde{\cos \theta} \rangle) \\ &= \frac{1}{2} \langle i, L_s i \rangle + \frac{1}{2} L_f i_f^2 + \frac{1}{2} M_f i_f \langle i, \widetilde{\cos \theta} \rangle + \frac{1}{2} M_f i_f \langle i, \widetilde{\cos \theta} \rangle \\ &= \frac{1}{2} \langle i, L_s i \rangle + M_f i_f \langle i, \widetilde{\cos \theta} \rangle + \frac{1}{2} L_f i_f^2 \end{aligned}$$

From simple energy considerations we can get electromagnetic torque as follows:

$$T_e = \left. \frac{\delta E}{\delta \theta} \right|_{\Phi, \Phi_f \text{ constant}} \quad . \text{ This is equivalent to,}$$

$$T_e = \left. \frac{\delta E}{\delta \theta} \right|_{i, i_f \text{ constant}}$$

Thus we can get the following equation of electromagnetic torque:

$$\begin{aligned} T_e &= -M_f i_f \langle i, \frac{\delta}{\delta \theta} \widetilde{\cos \theta} \rangle \\ &\Rightarrow T_e = M_f i_f \langle i, \widetilde{\sin \theta} \rangle \\ &\Rightarrow T_e = \langle i, M_f i_f \widetilde{\sin \theta} \rangle \quad (7) \end{aligned}$$

If $i = i_0 \widetilde{\sin \Phi}$ for arbitrary angle Φ , then electromagnetic torque will be:

$$T_e = M_f i_f i_0 \langle \widetilde{\sin \Phi}, \widetilde{\sin \theta} \rangle = \frac{3}{2} M_f i_f i_0 \cos(\theta - \Phi)$$

If i_f is constant, from equation (4) and (7) we can get that,

$$T_e \dot{\theta} = \langle i, e \rangle.$$

2.3 Components

Most essential component of synchroconverter is DC to AC converter which is used to convert DC power to AC power (three - phase). At the time of switching, voltage ripple may increase. In this case, it is needed to reduce voltage ripple. For this reason, it is essential to use three legs inverter which use pulse width modulation and LC filters for this reduction process. It can also be used in the reduction of current ripple. When it is connected in grid, it is needed to include the grid impedance with the inductors impedance. Now, it has been considered that we have an infinite bus after the circuit breaker section, at the same time neutral line is not connected in the system.

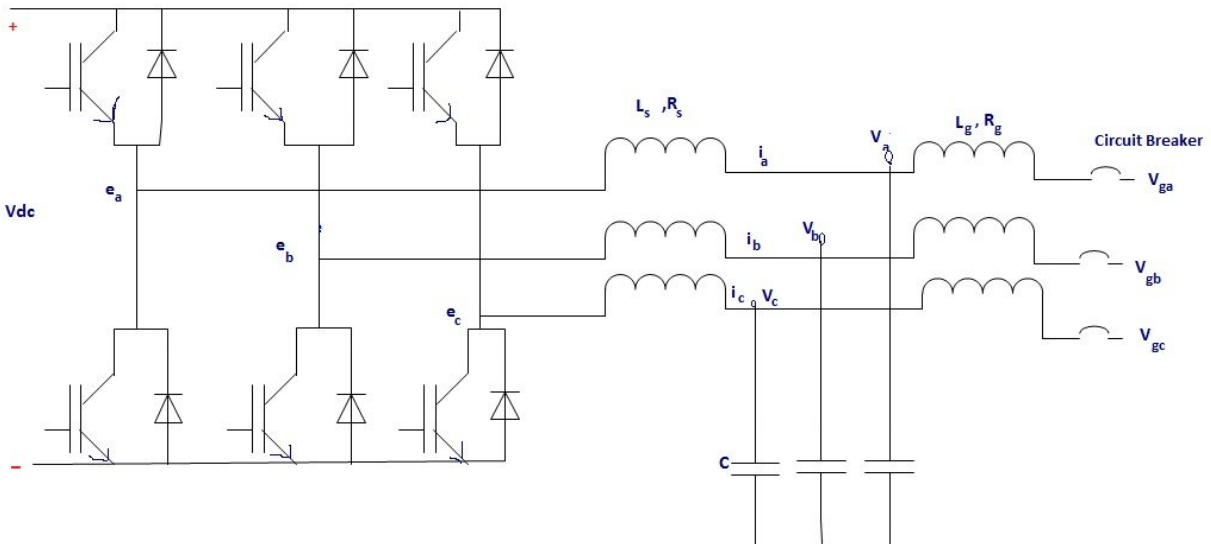


Figure 2: Power part of synchroconverter-a three phase inverter, including LC filters.

From the figure (2) we can see that, left side of the three parallel capacitors is the power part of synchroconverter. By controlling voltage and current ripple we can find that, power part of the

synchroconverter is behaving like synchronous generator. There must have an energy storage on the DC bus because the power absorbed from the DC bus is representing the power that has been taken both from the imaginary prime mover and the inertia of the rotating part of the imaginary synchronous generator. In switching control it is needed to use digital signal processing and its associated circuits which will run a special program to do this controlling job. DSP is called electronic part of synchroconverter and it is also known as the controller of the synchroconverter. For the electronic part, components like various voltage and current sensors, Analog/Digital convertor and signal conditioning circuits will be needed.

2.3.1 Power part

Power part consists of three phase legs and a three phase LC filter which are used suppress the switching noise. If the inverter is to be connected to be connected to the grid, the three more inductors L_g with series resistance and a circuit breaker are needed to interface with the grid. By not using voltage source v_f , adjustable dc current source i_f is used for the imaginary field rotor winding of synchroconverter [7]. If i_f is constant, then from (4) we can get that

$$e = M_f i_f \dot{\theta} \widetilde{\sin \theta} \quad (i)$$

2.3.2 Electronic part

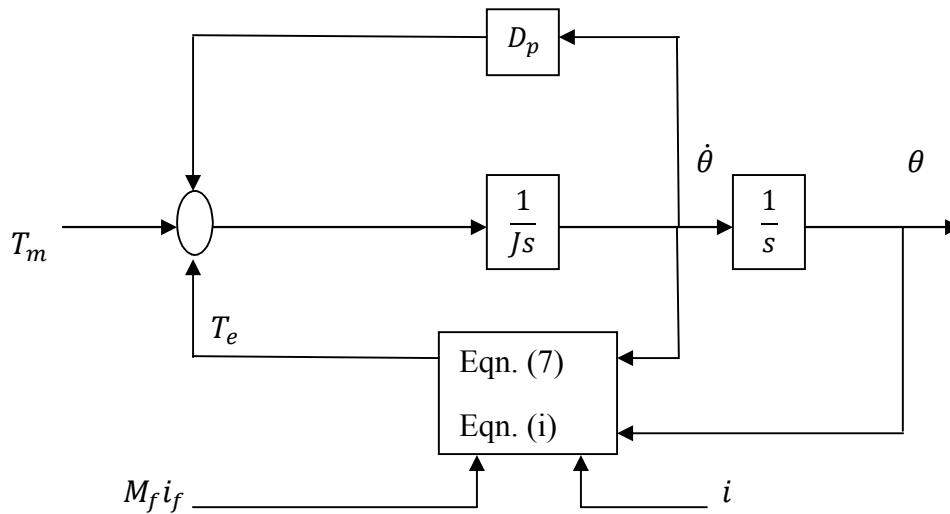


Figure 3: Electronic part of a synchroconverter (without control).

It has been seen from the inverter legs that the real power P can be defined as following:

$$p = \langle i, e \rangle$$

At the same time, reactive power Q can be defined as the following:

$$Q = \langle i, e_q \rangle$$

Here e_q can be represented as following:

$$e_q = \dot{\theta} M_f i_f \sin\left(\theta - \frac{\pi}{2}\right) = -\dot{\theta} M_f i_f \cos\theta$$

Using the above equation, real power P can be represented as:

$$p = \dot{\theta} M_f i_f \langle i, \sin\theta \rangle$$

And the reactive power can be represented as:

$$Q = -\dot{\theta} M_f i_f \langle i, \cos\theta \rangle$$

For $i = i_0 \sin\Phi$ then real power P can be written as:

$$p = \frac{3}{2} \dot{\theta} M_f i_f i_0 \cos(\theta - \Phi)$$

And reactive power can be written as:

$$Q = \frac{3}{2} \dot{\theta} M_f i_f i_0 \sin(\theta - \Phi)$$

We can write equation (6) as following:

$$\ddot{\theta} = \frac{1}{j} (T_m - T_e - D_p \dot{\theta})$$

Here the mechanical torque is a control input, at the same time electromagnetic torque is depending on inductor currents (i) and θ . This above equation along with the equation of reactive power Q has been implemented in electronic part. T_m , $M_f i_f$ are used as the control

input. A controller is needed which can generate the signal T_m and $M_f i_f$ for maintaining system stability.

CHAPTER 3

Generator Modeling

Synchronous generators can operate together which can form a large power system supplying electrical energy to the load side or consumers. In real life hundreds of generators are operating in parallel which are interconnected by transmission lines.

Model diagram

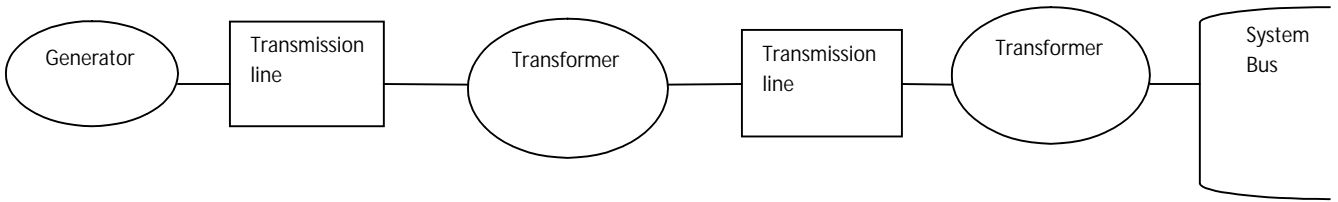


Figure 4: single line diagram for the system

At steady state condition,

$$P\dot{\Phi}_d = V_d - w_0\dot{\Phi}_q - R_a i_d + \Phi_q P\delta$$

Here, V_d = direct axis voltage, R_a = machine resistance, i_d = direct axis current.

In the steady state condition 2nd derivation of Φ_d and δ is zero.

$$\text{So,} \quad 0 = V_d - w_0\dot{\Phi}_q - R_a i_d$$

$$V_d = w_0\dot{\Phi}_q + R_a i_d$$

Again for steady state condition we can get the equation of next page,

$$P\dot{\Phi}_q = V_q + w_0\dot{\Phi}_d - R_a i_q - \Phi_d P\delta$$

Here, V_q indicates quadrature axis voltage, i_q means quadrature axis current.

Since at steady state condition 2nd derivation of Φ_d and δ is zero.

So from the above equation we can get,

$$0 = V_q + w_0 \Phi_d - R_a i_q$$

$$V_q = -w_0 \Phi_d + R_a i_q$$

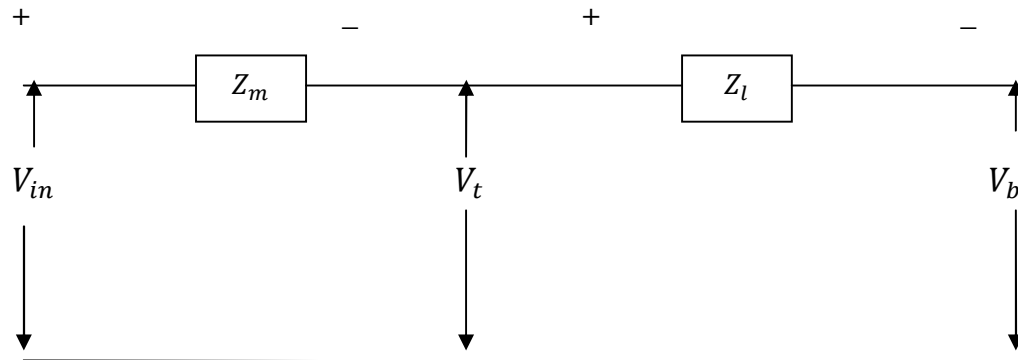


Figure 5: equivalent circuit of synchronous generator connected to infinite bus

From the circuit diagram we can find that,

Internal voltage is

$$V_{in} = V_t - I_t Z_m$$

And bus voltage is

$$V_b = V_t + I_t Z_t$$

Field voltage, $V_f = R_f i_f$

Power factor, $pf = \frac{P}{V_{tm} * I_{tm}}$

Here, p = power

V_{tm} = machine terminal voltage

I_{tm} = machine terminal current

Power factor angle, $\Phi = \cos^{-1}(pf)$

Terminal voltage, $V_t = V_{tm} + (0 * j)$

Terminal current, $I_t = [I_{tm} * \cos \Phi] + j * [I_{tm} * \sin \Phi]$

Machine impedance, $z_m = R_a + jX_d$

As $X_d > X_q$, so we use

Machine impedance, $z_m = R_a + jX_q$

Line impedance, $z_l = R + jx$

For the experiment, internal voltage has been used as the base voltage instead of terminal voltage. Following diagram shows phasor diagram which has been drawn for a lagging power factor condition of a system.

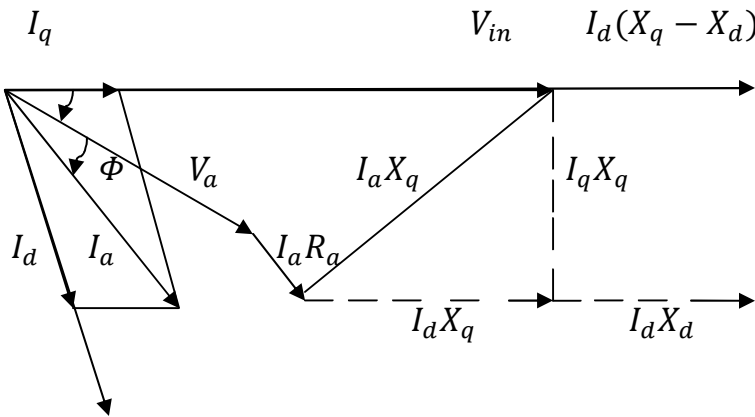


Figure 6: Phasor diagram

For changing the base we have to multiply all corresponding terms of phasor diagram by *rotate_vector*. Here *rotate_vector* will be following:

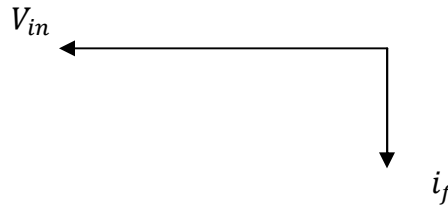
$$rotate_vector = \frac{conj(V_{in})}{abs(V_{in})}$$

Now we have to rotate the terminal current and bus voltage by the angle of rotate vector.

In conventional way, flux goes through the negative direction of voltage. So the direction of terminal current is negative [8]. Conventionally when internal voltage (V_{in}) goes to the positive direction, field current (i_f) will go in the upward direction.



In our case internal voltage (V_{in}) is going to the negative direction, so field current (i_f) will go in the downward direction [8].



Terminal current, $I_t = -(I_t * rotate_vector)$

Quadrature axis current, $I_q = real(I_t)$

Direct axis current, $I_d = img(I_t)$

As well as the equation of field current is in the next page,

$$i_f = -\frac{abs(V_{in})}{X_d - X_a}$$

Here, $X_d = X_a + X_{md}$

From the Phasor diagram we can get

$$V_{in} = V_{in} + (X_d - X_q) * I_d$$

Quadrature axis Bus voltage, $V_{bq} = real(V_b)$

Direct axis Bus voltage, $V_{bd} = img(V_b)$

Terminal voltage angle = $angle(V_t) = \delta_0$ (δ_0)

Bus voltage angle = $angle(V_b) = \delta$ (δ)

Rotor speed w is related to synchronous speed w_0 by the following equation

$$w = w_0 - p\delta$$

Terminal and infinite bus

We are assuming that bus voltage = V_b and terminal voltage = V_t

$$V_b = V_t + I_t z_l$$

Again, $V_b = V_{bq} + j V_{bd}$

After comparing these two equations we can get that,

$$V_{bq} + j V_{bd} = (V_q + jV_d) + (i_q + ji_d)(R + jX)$$

For steady state condition,

$$V_{bq} = V_q + Ri_q - Xi_d$$

$$V_{bd} = V_d + Ri_d + Xi_q$$

With transient we can get the following:

$$V_{bq} = V_q + Ri_q - Xi_d + \frac{X}{w} \frac{di_q}{dt} \quad (8)$$

$$V_{bd} = V_d + Ri_d + Xi_q + \frac{X}{w} \frac{di_d}{dt} \quad (9)$$

Terminal to machine's internal emf

Direct axis voltage has been denoted by V_d , quadrature axis voltage has been denoted by V_q and field voltage has been represented by V_f .

For steady state condition,

$$V_d = w\Phi_q + R_a i_d$$

$$V_q = -w\Phi_d + R_a i_q$$

$$V_f = R_f i_f$$

In transient state, V_d, V_q, V_f can be rearranged by follows

$$V_d = P\Phi_d + w\Phi_q + R_a i_d \quad (10)$$

$$V_q = P\Phi_q - w\Phi_d + R_a i_q \quad (11)$$

$$V_f = P\Phi_f + R_f i_f \quad (12)$$

Now, from equation (8) we get,

$$V_q = V_{bq} - R i_q + X i_d - \frac{X}{w} \frac{di_q}{dt} \quad (13)$$

And from equation (9) we get the new one which is the following:

$$V_d = V_{bd} - R i_d - X i_q - \frac{X}{w} \frac{di_d}{dt} \quad (14)$$

From equation (10) we can find the following:

$$\begin{aligned} V_d &= P\Phi_d + w\Phi_q + R_a i_d \\ &= \frac{1}{w_0} P [X_d i_d + X_{md} i_f] + X_q i_q + R_a i_d \end{aligned}$$

From equation (11) we can find the following:

$$\begin{aligned} V_q &= P\Phi_q - w\Phi_d + R_a i_q \\ &= \frac{1}{w_0} P [X_q i_q] - [X_{md} i_d + X_{md} i_f] + R_a i_q \end{aligned}$$

From equation (12) we can find the following:

$$\begin{aligned} V_f &= P\Phi_f + R_f i_f \\ &= \frac{1}{w_0} P[X_{md} i_d + (X_{md} + X_f) i_f] + R_f i_f \end{aligned}$$

Now after comparing equation (10) and (14) we get,

$$\begin{aligned} P\Phi_d + w\Phi_q + R_a i_d &= V_{bd} - \frac{X}{w} \frac{di_d}{dt} - X i_q - R i_d \\ \Rightarrow \frac{1}{w_0} P[X_d i_d + X_{md} i_f] + X_q i_q + R_a i_d &= V_{bd} - R i_d - X i_q - \frac{X}{w} \frac{di_d}{dt} \\ \Rightarrow \frac{1}{w_0} P(X_d i_d) + \frac{1}{w_0} P(X_{md} i_f) + X_q i_q + R_a i_d &= V_{bd} - R i_d - X i_q - \frac{X}{w} \frac{di_d}{dt} \\ \Rightarrow \frac{1}{w_0} P(X_d i_d) + \frac{X}{w} P(i_d) + \frac{1}{w_0} P(X_{md} i_f) &= -X_q i_q - R_a i_d + V_{bd} - R i_d - X i_q \\ \Rightarrow \frac{X_d}{w_0} P(i_d) + \frac{X}{w} P(i_d) + \frac{X_{md}}{w_0} P(i_f) &= -X_q i_q - R_a i_d + V_{bd} - R i_d - X i_q \\ \Rightarrow \left(\frac{X_d + X}{w}\right) P(i_d) + \left(\frac{X_{md}}{w}\right) P(i_f) &= -X_q i_q - R_a i_d + V_{bd} - R i_d - X i_q \\ \Rightarrow \left(\frac{X_d + X}{w}\right) P(i_d) + \left(\frac{X_{md}}{w}\right) P(i_f) &= V_{bd} - (R + R_a) i_d - (X + X_q) i_q \end{aligned} \quad (15)$$

Now after comparing equation (11) and (13) we get,

$$\begin{aligned} P\Phi_q - w\Phi_d + R_a i_q &= V_{bq} - R i_q + X i_d - \frac{X}{w} \frac{di_q}{dt} \\ \Rightarrow \frac{1}{w_0} P(X_q i_q) - (X_d i_d + X_{md} i_f) + R_a i_q &= V_{bq} - R i_q + X i_d - \frac{X}{w_0} P(i_q) \\ \Rightarrow \left(\frac{X_q + X}{w}\right) P(i_q) &= V_{bq} + X i_d - R i_q + X_d i_d + X_{md} i_f - R_a i_q \\ \Rightarrow \left(\frac{X_q + X}{w}\right) P(i_q) &= V_{bq} + (X + X_d) i_d + X_{md} i_f - (R + R_a) i_q \end{aligned} \quad (16)$$

We are assuming that,

$$X_d + X = X_{eqd}$$

$$R + R_a = R_{eq}$$

$$X_q + X = X_{eqq}$$

Equation (15) can be represented as follows:

$$\Rightarrow \frac{X_{eqd}}{w} P(i_d) + \left(\frac{X_{md}}{w}\right) P(i_f) = V_{bd} - R_{eq}i_d - X_{eqq}i_q \quad (17)$$

Equation (16) can be represented as follows:

$$\Rightarrow \frac{X_{eqq}}{w} P(i_q) = V_{bq} - R_{eq}i_q + X_{eqd}i_d + X_{md}i_f \quad (18)$$

Field voltage can be represented by follows from the equation (12):

$$V_f = P\Phi_f + R_f i_f$$

$$\Rightarrow V_f = \frac{X_{md}}{w} P(i_d) + \frac{X_{md} + X_f}{w} P(i_f) + R_f i_f$$

$$\Rightarrow V_f - R_f i_f = \frac{X_{md}}{w} P(i_d) + \frac{X_{fd}}{w} P(i_f) + R_f i_f \quad (19)$$

From the equation (17), (18), (19) it has been rearranged in matrix form as $[A] = [B] - [C]$ as follows:

$$\begin{bmatrix} \frac{X_{eqd}}{w} & 0 & \frac{X_{md}}{w} \\ 0 & \frac{X_{eqq}}{w} & 0 \\ \frac{X_{md}}{w} & 0 & \frac{X_{fd}}{w} \end{bmatrix} \begin{bmatrix} P i_d \\ P i_q \\ P i_f \end{bmatrix} = \begin{bmatrix} V_{bd} \\ V_{bq} \\ V_f \end{bmatrix} - \begin{bmatrix} +R_{eq} & +X_{eqq} & 0 \\ -X_{eqd} & +R_{eq} & -X_{md} \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_f \end{bmatrix} \quad (20)$$

[A]

[B]

[C]

(20)

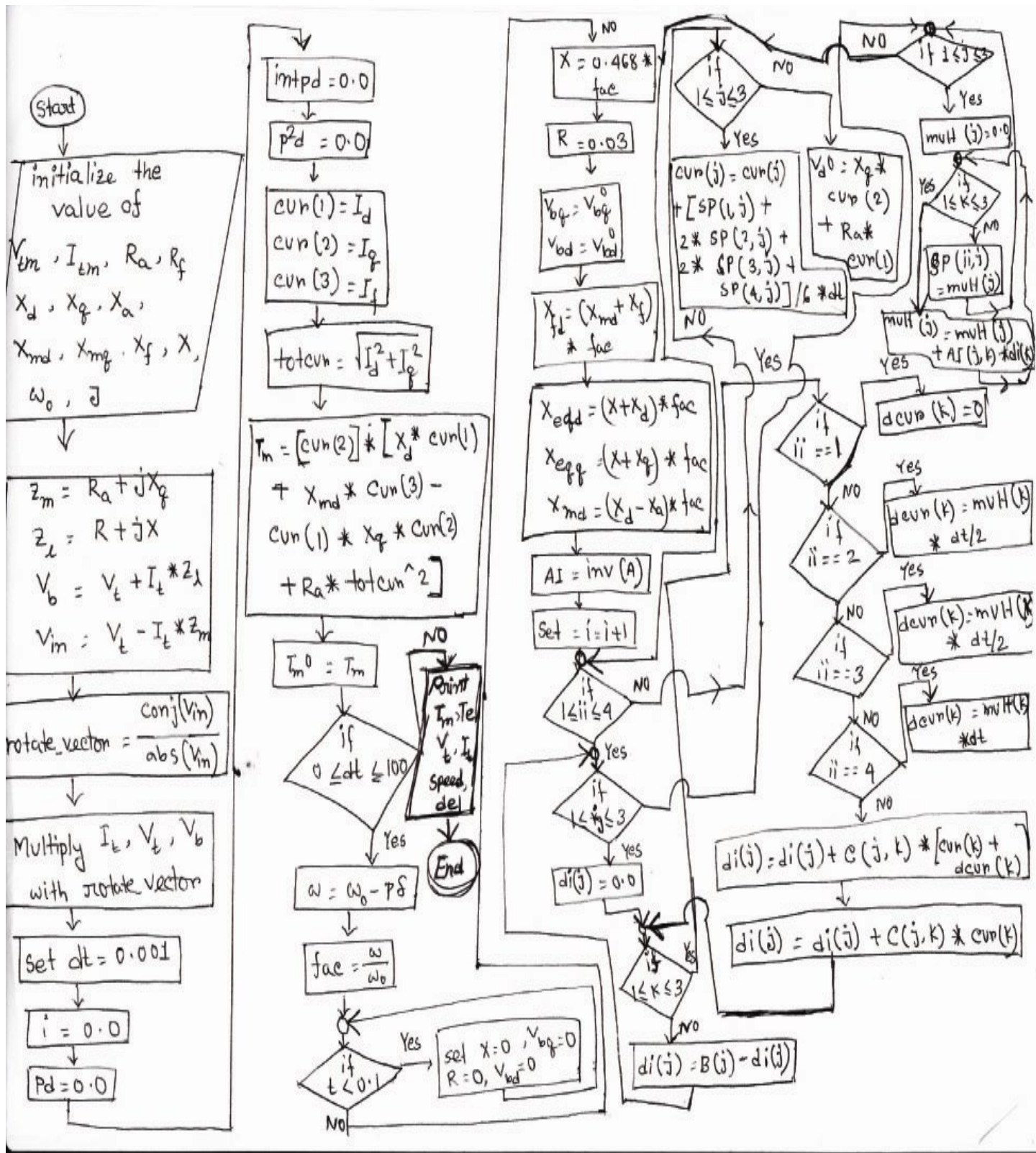
For rotor angle (δ) following matrix has been formed:

$$\begin{bmatrix} P\delta \\ P^2\delta \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta \\ \dot{\delta} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{T_e - T_m}{j} \end{bmatrix}$$

The electrical torque is represented by T_e which has been found by following equation:

$$\begin{aligned} T_e &= \frac{w_0[\Phi_d i_q - \Phi_q i_d]}{2} \\ &= \frac{[(w_0 \Phi_d) i_q - (w_0 \Phi_q) i_d]}{2} \\ &= \frac{[[X_d i_d + X_{md} i_f] i_q - (X_q i_q) i_d]}{2} \end{aligned}$$

For modeling, 4th order runga-kutta method has been used instead of Euler method. It has been used because it would give more accuracy in calculation than using Euler method. Simulation results are given in next chapter. Following flow chart describes the procedure of modeling synchronous generator.



CHAPTER 4

Simulation Result

For the convenience of our calculation it has been taken some certain value in our paper.

Here,

Name of Parameters	Symbol	Values of Parameters
Power	P	0.8
Terminal Voltage	V_t	1.0
Terminal Current	I_t	1.0
Mechanical Resistance	R_a	0.0006
Mechanical Reactance	X_d	2.159
Line Resistance	R	.03
Field Resistance	R_f	0.00105
Line Reactance	X	0.468
Mutual Reactance (Direct Axis)	X_{md}	2.046
Armature Reactance	X_a	0.113
Field Reactance	X_f	0.045
Angular Velocity	w_0	314.16
Moment of Inertia	J	3.36

Using the matrix we have built up a program and after simulation the program we have got some certain values of Mechanical, Electrical Torque, Terminal Voltage and current, torque angle delta, rotor speed.

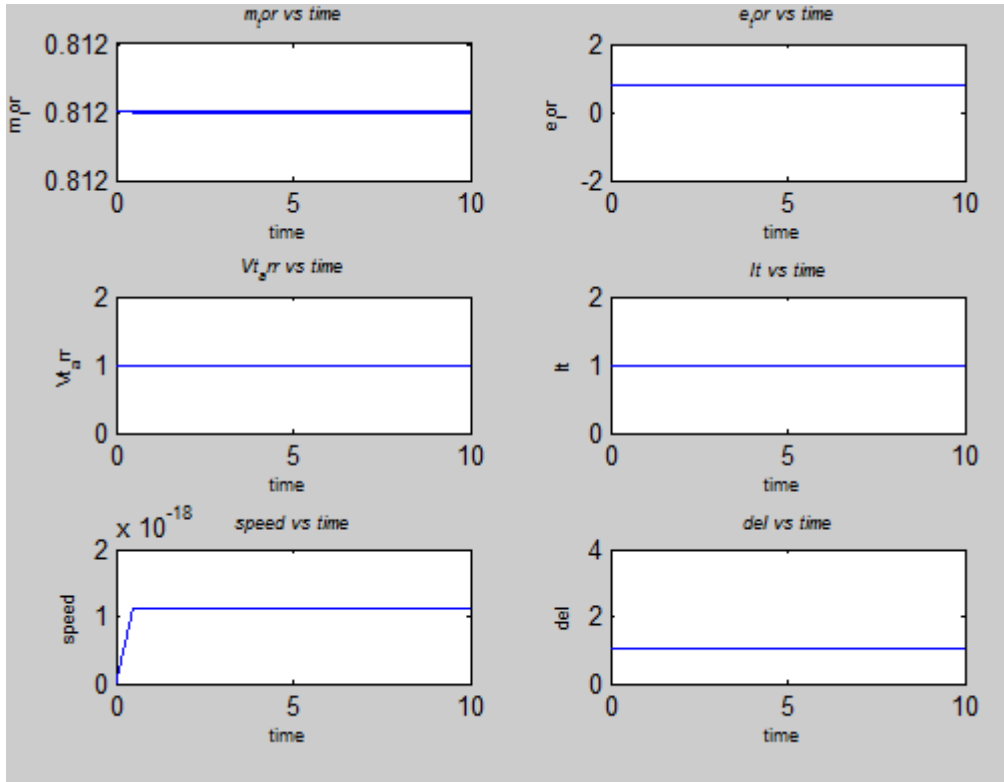


Fig: Mechanical torque, Electrical Torque, Terminal Voltage, Terminal Current, Torque speed, Torque angle delta

From our main code, we have got some certain values given as follows,

Mechanical Torque, $T_m = 0.8120$

Electrical Torque, $T_e = 0.8060$

Terminal Voltage, $V_t = 1$

Terminal Current, $I_t = 1$

Torque angle delta, $\delta = 1.0363$

Rotor speed, $\omega = 0.1108$

Case1: Mechanical torque is reduced to 0.9 of previous value when time duration, t=0 to 10sec at time step, dt= 0.0001

According to this case, Mechanical Torque, $T_m^0 = 0.9 * T_m$

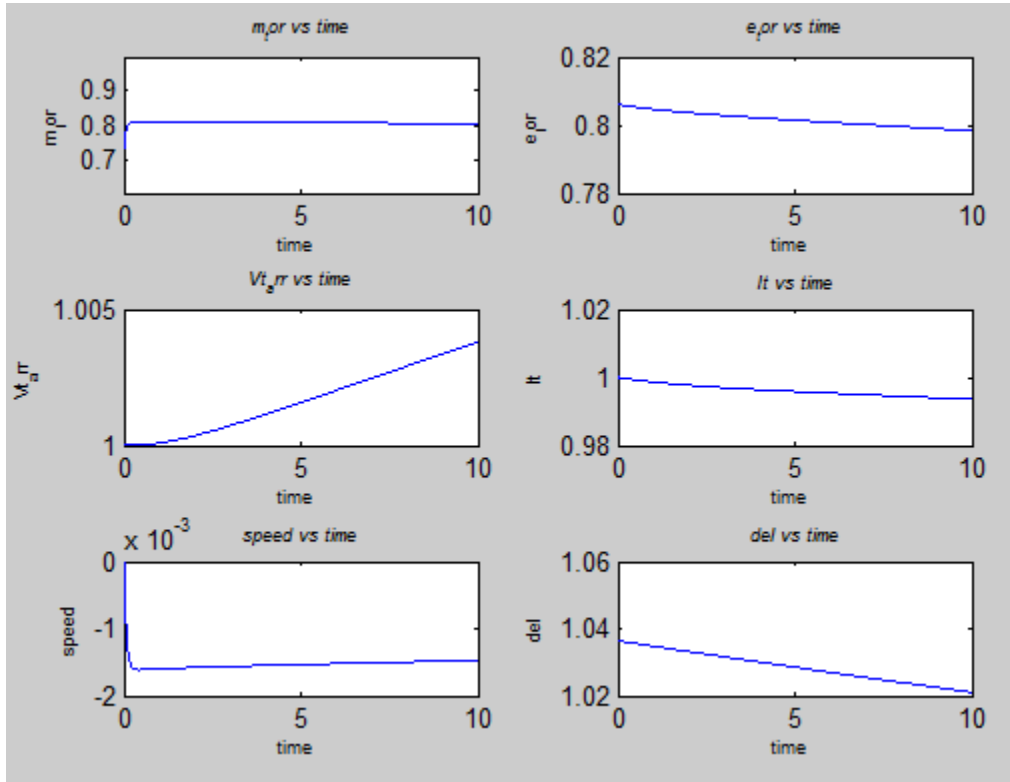


Fig 4.1.1: Time vs. Mechanical Torque, Fig 4.1.2: Time Vs. Electrical Torque, Fig 4.1.3: Time Vs. Terminal Voltage, Fig 4.1.4: Time Vs. Terminal Current, Fig 4.1.5: Time Vs. Speed, Fig 4.1.6: Time Vs. delta

In this case, Mechanical torque is reduced to 0.9 of its previous value. From the Torque equation the previous value of Mechanical Torque was 0.8120. From Fig 4.1.1 we can see that, the Mechanical Torque reduces from its previous value of 0.8120 to 0.7309 and after a certain time period the Mechanical Torque changes from its initial reduced value of 0.7309 to the final value of 0.8043

From Fig 4.1.2, the Electrical torque reduces from the value of 0.806 to the value of 0.7984 with the reduction of Mechanical Torque.

From Fig 4.1.3, Terminal Voltage increases from 0.1032 to 0.1038 as gaining the more power.

From Fig 4.1.4, Terminal Current reduces from 0.9942 to 0.9936.

Moreover,

$$P = T \cdot \omega$$

Again, Power, $P = V \cdot I$ where, $V =$ voltage and $I =$ Current.

So, $V \cdot I = T \cdot \omega$ where, $T =$ Torque and $\omega =$ angular velocity

So, the decrease of Torque will decrease Terminal Current.

From Fig 4.1.5, the Speed will be decreased with the reducing of Torque from the initial value of -0.5 to final increased value of -1.6.

In this case, with the change of the Synchronous speed the rotor angle delta also change. $\frac{d\delta}{dt}$ will be decreased if the rotor angle will goes high. On the other hand rotor angle will be decreased if the $\frac{d\delta}{dt}$ increases. It has happened for the balancing of machine's speed and it is controlled by the Governor (prime mover).

From Fig 4.1.6, if we take the absolute value of rotor angle delta, delta will be decreased from its initial value of 1.0363 to the final value of 1.0211.

Case 2: Mechanical torque is reduced to 0.9 of previous where time, $t=0$ to 500 sec at the step of time, $dt= 0.005\text{sec}$.

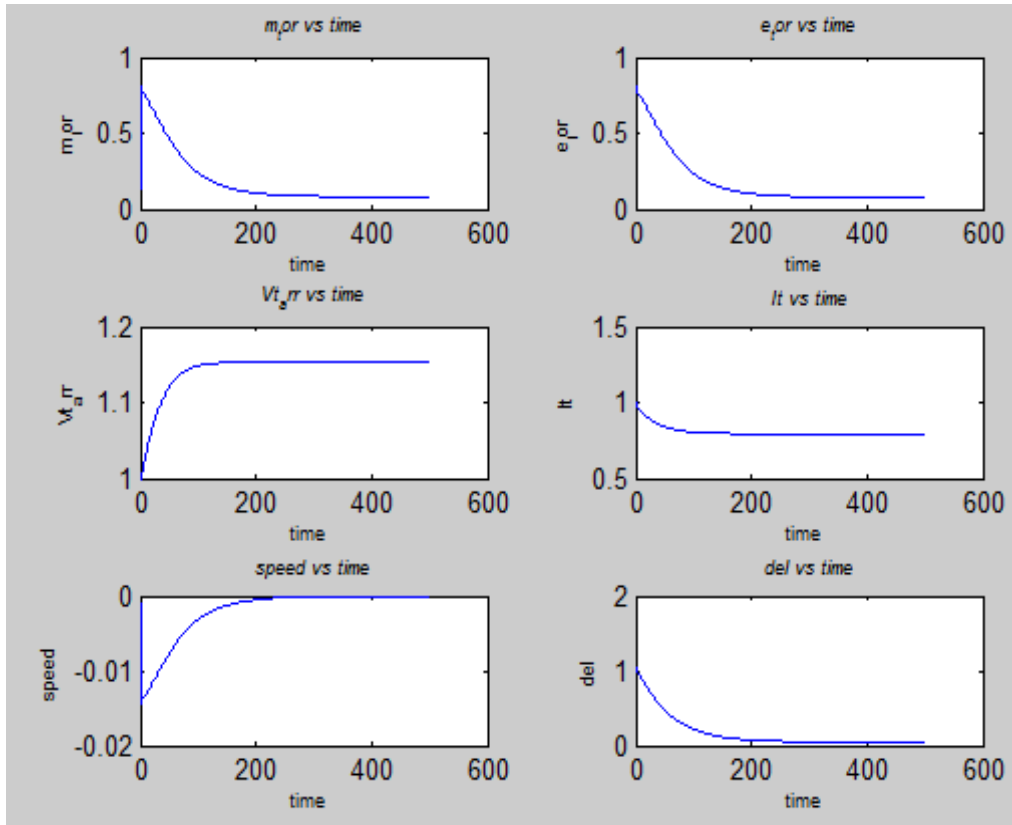


Fig4.2.1: Time vs. Mechanical Torque, Fig 4.2.2: Time Vs. Electrical Torque, Fig 4.2.3: Time Vs. Terminal Voltage, Fig 4.2.4: Time Vs. Terminal Current, Fig 4.2.5: Time Vs. Speed, Fig 4.2.6: Time Vs. delta.

In this case, Fig 4.2.1, Mechanical torque is reduced from 0.7368 to 0.7313. Same as case 1 Mechanical torque is reduced even in the long time duration and small step size of time and the wave shape stable in the value of 0.7313.

From Fig 4.2.2, Electrical torque will also be reduced with the reducing mechanical torque. Electrical torque reduced from initial value of 0.8060 to the final steady state value of 0.7259.

From Fig 4.2.3, with the gaining of more power Terminal Voltage increases from the value of 1 to 1.0465. Even for the high duration of time and sort step of time the terminal voltage will be increased.

From Fig 4.2.4, with the change of terminal voltage, terminal current also become changing from the value of 1 to 0.9488. So, the terminal current reduces.

Moreover,

$$P = T * \omega \quad \text{again,}$$

Power, $P = V * I$ where, $V =$ voltage and $I =$ Current.

So, $V * I = T * \omega$ where, $T =$ Torque and $\omega =$ angular velocity

So, the decrease of torque will also be decreased terminal current.

From Fig 4.2.5, as speed is inversely proportional to the torques so, with the decrease of torque, the speed will be increased from its initial value of

$-1.2083 * 10^{-4}$ to the final value of $-9.23 * 10^{-6}$.

From Fig 4.2.6, with the decreasing of Torque, rotor angle also going to decrease from the value of -1.0363 (take absolute value) to -0.8684 (take absolute value). As, the speed increases, the rotor angle will be decreased cause angle is inversely proportional to speed.

Case 3: Mechanical torque is increased to 1.1 of previous value where time duration is, $t=0$ to 10 sec and the step of time duration is, $dt= 0.001$ sec.

According to this case,

$$\text{Mechanical Torque, } T_m = 1.1 * T_m$$

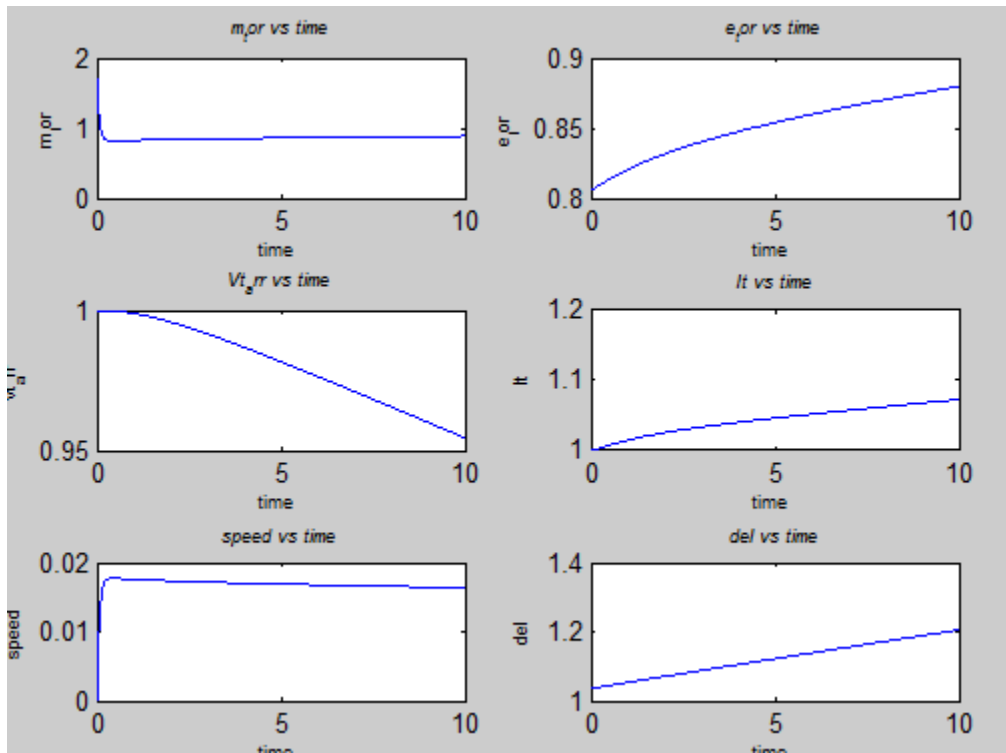


Fig4.3.1: Time vs. Mechanical Torque, Fig 4.3.2: Time Vs. Electrical Torque, Fig4.3.3: Time Vs. Terminal Voltage, Fig 4.3.4: Time Vs. Terminal Current, Fig 4.3.5: Time Vs. Speed, Fig 4.3.6: Time Vs. delta.

In this case, from fig 4.3.1, mechanical torque is increased to 1.1 from its previous value. From the torque equation, the previous value of mechanical Torque is 0.8120. So, the mechanical torque is increased from its previous value of 0.8120 to 0.8932 and after a certain time period, the mechanical torque changes from its initial increased value of 0.8932 to the final value of 0.8195.

From Fig 4.3.2, with the increase of mechanical torque from its previous value, electrical torque also increases from its previous value. For the time being electrical torque increases from the initial value of 0.8060 to the final value of 0.8135.

From Fig 4.3.3, with the increase of mechanical torque, terminal voltage is decreased from its initial value of 1 to the final value of 0.9962.

From Fig 4.3.4, torque is increased from its previous value. Torque is proportional to the terminal current. So, terminal current increases from the initial value of 1 to the final value of 1.0065.

From Fig 4.3.5, speed will be increased from its previous value of 2.4×10^{-6} to the final value of 0.0015.

From Fig 4.2.6, rotor angle delta increases with the increase of mechanical torque. It increases from the initial value of 1.0363 to the final value of -1.0516.

Case 4: Mechanical torque is increased to 1.1 from the previous value where time duration is, $t=0$ to 500 and the time step duration is, $dt= 0.005$.

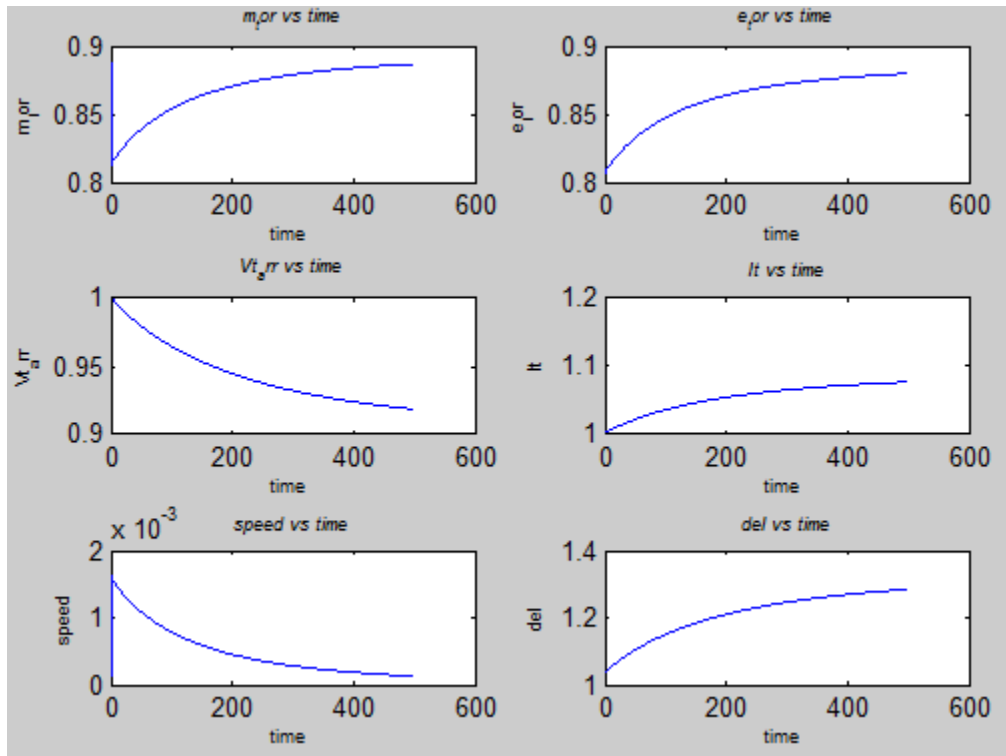


Fig4.4.1: Time vs. Mechanical Torque, Fig 4.4.2: Time Vs. Electrical Torque, Fig 4.4.3: Time Vs. Terminal Voltage, Fig 4.4.4: Time Vs. Terminal Current, Fig 4.4.5: Time Vs. Speed, Fig 4.4.6: Time Vs. delta.

In this case, Fig 4.4.1, mechanical torque increases to 1.1 from its previous value. From the torque equation, the previous value of mechanical torque is 0.806. So, the mechanical torque increased from its previous value of 0.806 to 0.8872 and after a certain time period the mechanical torque changes from its initial increased value of 0.8872 to the final value of 0.8868.

From Fig 4.4.2, with the increase of mechanical torque, electrical torque is also increased from its previous value. Electrical torque increases from the value of 0.8060 to the final value of 0.8798.

From Fig 4.4.3, with the increases of mechanical torque, terminal voltage decreases from its initial value of 1 to the value of 0.9187.

From Fig 4.4.4, terminal current increases with the increases of mechanical torque. The terminal current increases from the value of 1 to the final value of 1.0772.

From Fig 4.4.5, with the increases of mechanical torque, speed also decreases from its initial value of 1.20×10^{-4} to the final value of 1.28×10^{-4} .

Rotor angle (δ) changes with time. As, the rotor speed is inversely proportional to δ and since the mechanical torque increases, δ also increases from its initial value of 1.0363 to the final value of 1.2848 as the rotor speed also decreases with time.

For the short circuit test we have presented five conditions in this response paper.

For getting more accuracy, we have taken short time duration ($t=0$ to 10sec) with short step size of time ($dt= 0.0001$)

Resistance, $R=0$ and Reactance, $X=0$.

In the short circuit cases initial value will remain the same. Final value will be changed for different given cases.

Case 5: Short Circuit at the Machine Terminal for 0.1sec and same line afterwards when time is, $t= 0$ to 10sec at step of time duration is, $dt = 0.0001\text{sec}$.

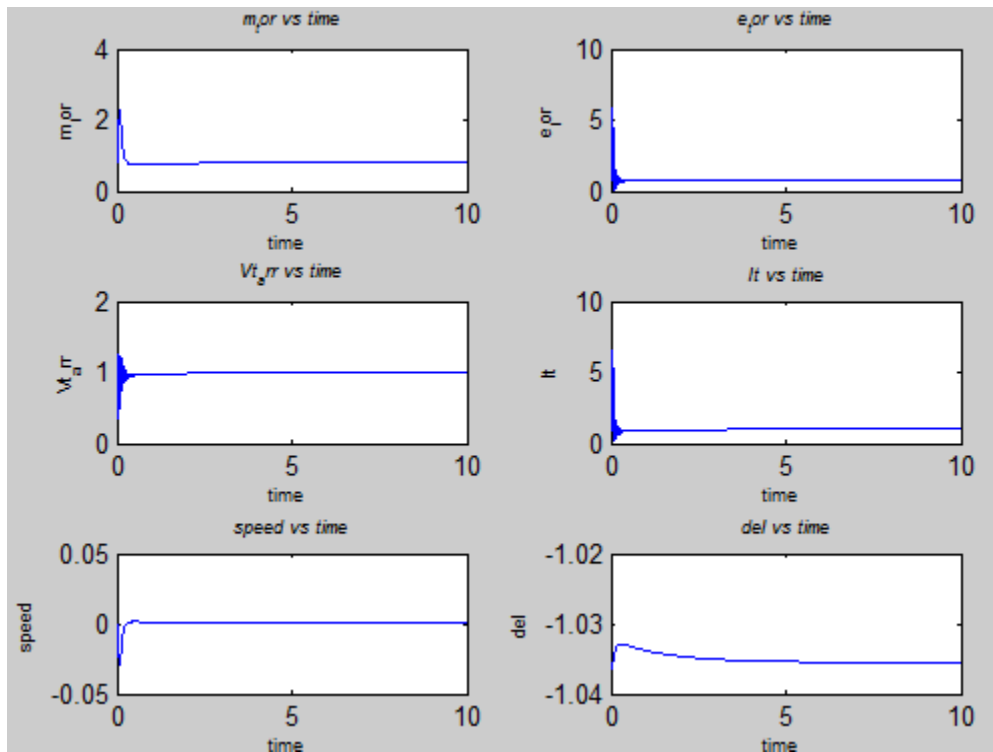


Fig4.5.1: Time vs. Mechanical Torque, Fig 4.5.2: Time Vs. Electrical Torque, Fig 4.5.3: Time Vs. Terminal Voltage, Fig 4.5.4: Time Vs. Terminal Current, Fig 4.5.5: Time Vs. Speed, Fig 4.5.6: Time Vs. delta

From Fig 4.5.1 we can see that, for the certain period of time ($t=0$ to 10sec), the initial value is fixed all the time and the initial value of Mechanical Torque is, T_m (initial) = 0.8120 . But in this condition, same line exists after the short circuit period. So, the line becomes loaded with the

previous impedance. As, the line is loaded after the short circuit period, the Synchronous generator Torque is decreased as it is needed more power to rotate. Finally, the Mechanical Torque decreases from its initial fixed value to the final value of 0.8115.

From Fig 4.5.2, for the certain time period (t=0 to 10sec), the electrical torque at the short circuit period is same for all short circuit cases. So, the electrical torque has fixed value for this certain period (t=0 to 10sec) and the value is 0.8141.

Mechanical Torque is proportional to Electrical Torque.

$$T_m \propto T_e$$

So, the Electrical Torque is also decreased after the short circuit period with the decrease of Mechanical Torque. So, the Electrical Torque is decreased from its fixed initial value to final value of 0.8056.

From Fig 4.5.3, for the certain period of time (t= 0 to 10sec), for the short circuit period, initial value is fixed all the time and the Fixed value of terminal voltage in this case is 1.011.

After the short circuit period, the terminal voltage gets changed from its initial fixed value to final value of 1, which is same as the given value of terminal voltage in the simulation. So, in the short circuit period, the value of voltage is changed, but after the short circuit period, the same line exists and for this reason, we get the same voltage gain after the short circuit period.

From Fig 4.5.4, for the certain period of time (t=0 to 10sec), the initial value of the terminal current for all short circuit cases are fixed and the fixed initial value for the terminal current is, $I_t = 0.9789$. But after the short circuit period, the same line exists. So, the current will be same as the given value in the Simulation. And the final value of the current is 0.9996 which is approximately 1. On the other hand, terminal voltage is decreased from its initial fixed value to final value, so the Terminal Current is increased and reaches to the final increased value of 0.9996. After the short circuit period, the same line exists and the voltage decreases, so finally the current is increased from its initial value.

For the certain period of time (t= 1 to 10sec) from Fig 4.5.5, in the short circuit cases, the initial value of Speed is unchanged and its initial fixed value is -2.32×10^{-7} . After the short circuit

period, torque is decreased at the same line which comes afterwards. So, the impedance is increased from the short circuit position. After the short circuit period, the machine gives more speed than before to rotate the rotor winding. So, the speed increases from its initial fixed value to final increased value of $9.0058 * 10^{-6}$.

For the certain period of time ($t=0$ to 10sec) in the short circuit cases, from Fig 4.5.6, the initial value is fixed and the fixed value for the rotor angle Delta is 1.0363. But after the short circuit period, the rotor angle decreases with the decrease of Torque. The final decreased value of delta is 1.0355.

Case 6: Short Circuit at Machine Terminal for 0.1 sec and line of 1.5 of previous afterwards when time duration, $t=0$ to 10sec and step duration of time, $dt= 0.0001$ sec.

In this case, after the short circuit period,

Resistance, $R= 1.5*0.03$ and
 Reactance, $X=1.5*0.468*fac$

For the short circuit cases, all the initial value is fixed for the certain time period.

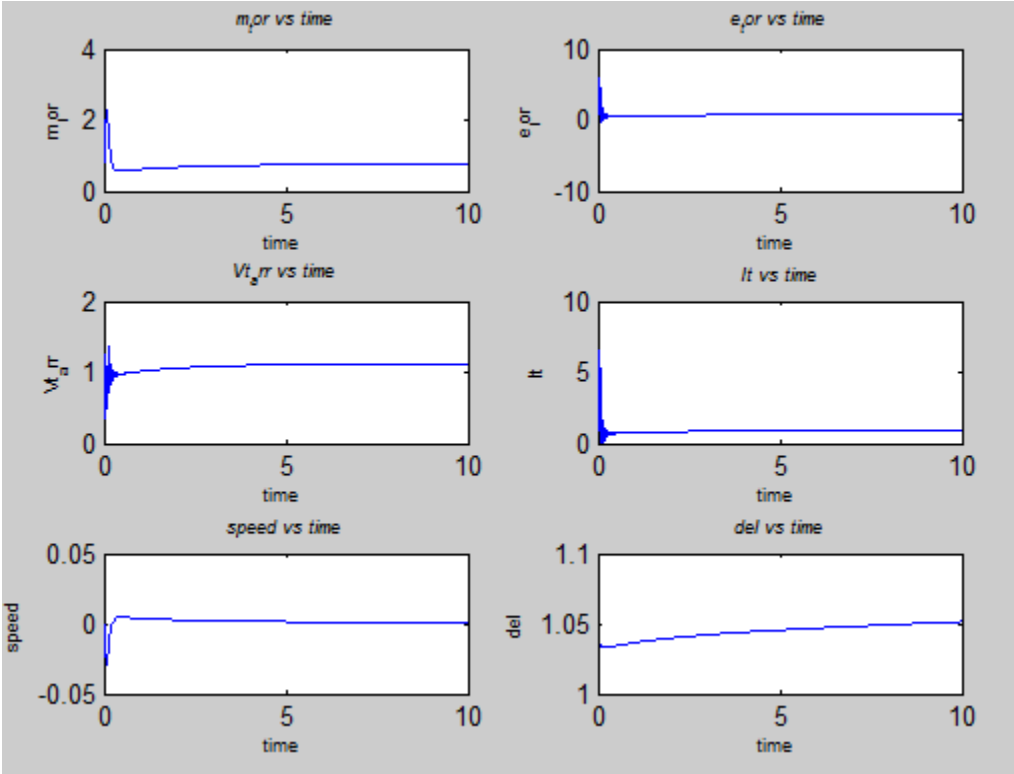


Fig4.6.1: Time vs. Mechanical Torque, Fig 4.6.2: Time Vs. Electrical Torque, Fig 4.6.3: Time Vs. Terminal Voltage, Fig 4.6.4: Time Vs. Terminal Current, Fig 4.6.5: Time Vs. Speed, Fig 4.6.6: Time Vs. delta

For the certain value of time ($t= 0$ to 10sec) in the short circuit cases, From Fig 4.6.1, the initial value in the short circuit period is unchanged. So, the initial value of the mechanical torque is same as the initial value of mechanical torque in the previous case (case 5). So, the unchanged fixed value of mechanical torque in the short circuit period is 0.8120. In this case, after the period of short circuit, the impedances increase 1.5 from its previous value. So, the load is increased on the Machine and the rotor rotates with a reduced value. The mechanical torque decreases from its

initial short circuit period value to the final decreased value of 0.7578. Comparing with Case 5, in this case after the short circuit period, the line impedance is increased. So, the Mechanical Torque is decreased more than the Mechanical Torque in the condition of same line exists after the short circuit period (case 5).

For the certain period of time ($t= 0$ to 10sec) in the short circuit condition, from Fig 4.6.2, the initial value is fixed and the initial value of electrical torque in the short circuit condition is 0.8141. After the short circuit period, impedances are increased from its initial value. So, the electrical torque is reduced from its initial value of 0.8141 to the final value of 0.7527.

For the certain period of time ($t=0$ to 10sec) in the short circuit condition, From Fig 4.6.3, initial value of terminal voltage is unchanged and its value is 1.0111. After the short circuit period, the impedances increase 1.5 from its previous value before the short circuit period. So, the potential difference increases with the increases of impedance. So, the voltage increases from its initial value of 1.0111 to final value of 1.01180.

For all the short circuit condition in a certain value of time ($t= 0$ to 10sec), from Fig 4.6.4 the initial value is unchanged and the value of terminal current is 0.9789 which is already mentioned in case 5. After the short circuit period, the terminal current decreases with the increase of impedance. So, the Terminal Current changes from its initial value of 0.9789 to the final decreased value of 0.9196.

In the short circuit condition the speed is unchanged in a certain value of time duration ($t= 0$ to 10sec). The initial value of Speed in Fig 4.6.5 is -2.32×10^{-7} . After the short circuit period, the impedance increases from its initial value, so the Torque decreases and Speed increases to rotate the rotor. So, the rotor needs much speed to rotate with loaded impedance than before. Speed increases from its initial value of -2.32×10^{-7} to final value of 0.0011.

For the short circuit condition in the same time period ($t=0$ to 10sec), the initial value of delta in Fig 4.6.6, in the short circuit period is 1.0363. After the short circuit period, the rotor angle is changed from its fixed initial value of 1.0363 to the final value of 1.0515.

Case 7: Short circuit Machine Terminal for 0.1sec and line will be 0.5 of the previous value afterwards when time duration is, $t= 0$ to 10sec and the step time duration is, $dt=0.0001$.

In this case, during short circuit period,

Resistance, $R= 0.5*0.03$ and

Reactance, $X=0.5*0.468*fac$.

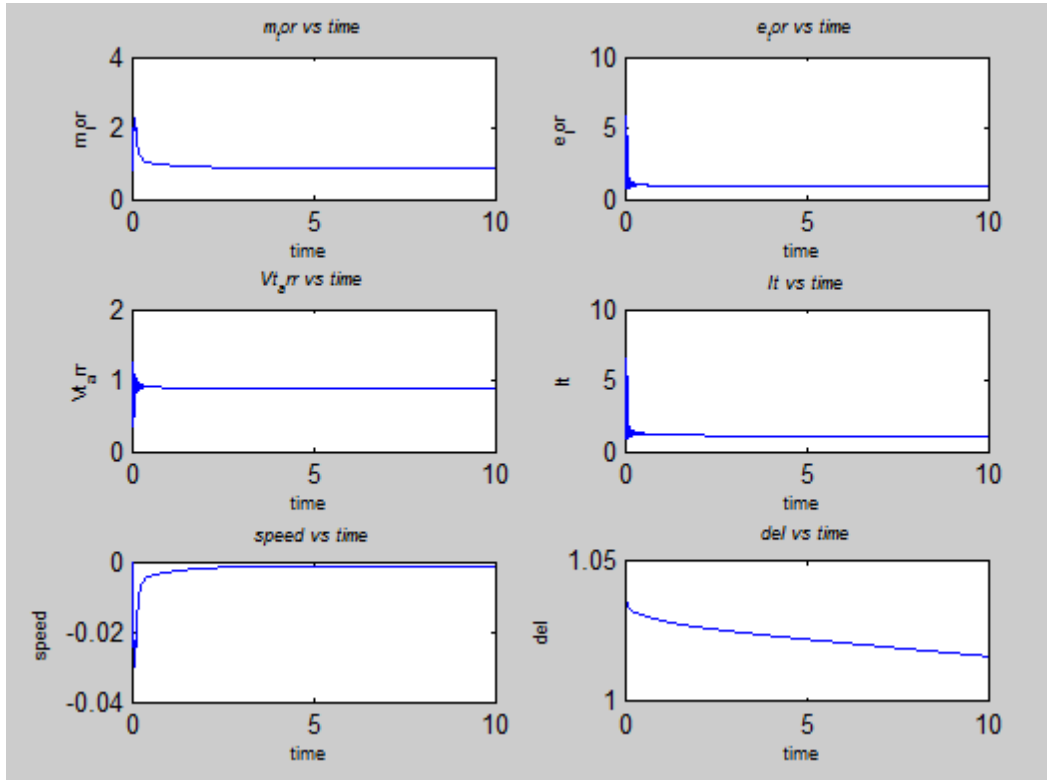


Fig4.7.1: Time vs. Mechanical Torque, Fig 4.7.2: Time Vs. Electrical Torque, Fig 4.7.3: Time Vs. Terminal Voltage, Fig 4.7.4: Time Vs. Terminal Current, Fig 4.7.5: Time Vs. Speed, Fig 4.7.6: Time Vs. delta

For the certain value of time ($t= 0$ to 10sec) in the short circuit cases, the initial value in the short circuit period remains unchanged. So, the initial value of mechanical torque is same as the initial value of mechanical torque in the previous cases (case 5 & case 6). So, the unchanged fixed value of mechanical torque in the short circuit period is 0.8120.

In this case, after the period of short circuit, the impedances decrease 0.5 from its previous value. So, the load decreases on the Machine and the rotor rotate with an increased value than before

cases (case5 & case 6). In fig 4.7.1 the mechanical torque increases from its initial short circuit period value of 0.8120 to the final increased value of 0.8714. Comparing with Case 5 and Case 6, in this case, after short circuit period line impedance decreases by 0.5. So, the mechanical torque increases than the mechanical torque of the cases 5(after short circuit period same line exists) and Case 6 (after short circuit period, impedance increases 1.5 than pervious value).

For the certain period of time ($t= 0$ to 10sec) in the short circuit condition, the initial value is fixed and the initial value of Electrical Torque in the short circuit condition is 0.8141.

After the short circuit period, impedances decrease from its initial value. So, the Electrical Torque in fig 4.7.2is increased from its initial value of 0.8141 to the final value of 08642.

For the certain period of time ($t=0$ to 10sec) in the short circuit condition, initial value of the Terminal Voltage is unchanged and its value is 1.0111. After the short circuit period, the impedances are decreased by 0.5 from its previous value before the short circuit period. So, the potential difference decreases with the decreases of impedance.

In fig 4.7.3 voltage decreases from its initial value of 1.0111 to final value of 0.8806. Comparing with the previous cases (case 5 & case 6), in this case impedance decreases so, the terminal voltage decreases than the case 5(same line exists after the short circuit period) and Case 6 (impedance increases by 1.5 after the short circuit is removed).

For all the short circuit condition in a certain value of time ($t= 0$ to 10sec), the initial value is unchanged and the value of Terminal Current is 0.9789 which is already mentioned in case 5 and case 6.

After the short circuit period the terminal current increases with the decreases of impedance by 0.5. In fig 4.7.4, the terminal current changes from its initial value of 0.9789 to the final increased value of 1.0932.

In the short circuit condition the speed is unchanged in a certain value of time duration ($t= 0$ to 10sec). The initial value of Speed in the short circuit period is -2.32×10^{-7} .

After the short circuit period, the impedance decreases from its initial value, so the Torque increases and Speed decreases to rotate the rotor. So, the rotor needs less speed than before to rotate with reduced impedance than before.

With the increases of torque, the speed will be decreasing from its previous value. In fig 4.7.5, the Speed decreases from its initial value of -2.32×10^{-7} to final value of -0.0012 .

For the short circuit condition in the same time period ($t=0$ to 10sec) the initial value of delta in the short circuit period is 1.0363. After the short circuit period, from fig 4.7.6, the rotor angle is changed from its fixed initial value of 1.0363 to the final value of 0.0162.

Case 8: Short Circuit at Machine Terminal for the 0.1sec and same line afterwards where $t=0$ to 600sec and $dt= 0.005$ sec.

During the short circuit period,

Resistance, $R=0$ and

Reactance, $X=0$. In previous case (Case 5) of short circuit condition we have taken the same condition with time period of $t=0$ to 10sec. But now we have taken the long time period, $t= 0$ to 600sec.

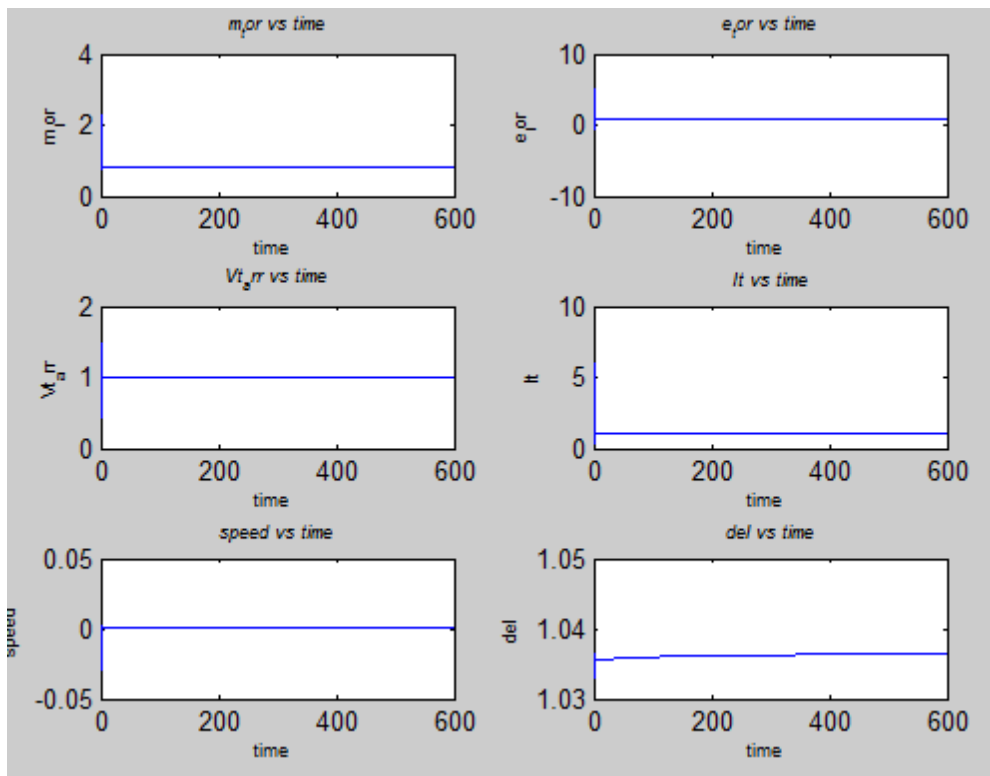


Fig4.8.1: Time vs. Mechanical Torque, Fig 4.8.2: Time Vs. Electrical Torque, Fig 4.8.3: Time Vs. Terminal Voltage, Fig 4.8.4: Time Vs. Terminal Current, Fig 4.8.5: Time Vs. Speed, Fig 4.8.6: Time Vs. delta

As, we have taken the long step size of time ($dt= 0.05$ sec), so the simulation responses the initial value of Mechanical Torque at the short circuit period is 1.0157.

For the certain time period ($t= 0$ to 600sec) in the short circuit condition, the initial value is unchanged and the value is 1.0157.

But in this condition, same line exists after the short circuit period. So, the line becomes loaded with the previous impedance. As, the line is loaded after the short circuit period, the Synchronous generator Torque decreases as, it needs much power to rotate. So, finally, in fig 4.8.1, the Mechanical Torque decreases from its initial fixed value 1.0157 to the final value of 0.8120.

As, we have taken the long step size of time ($dt= 0.05\text{sec}$) so the simulation responses the initial value of Electrical Torque at the short circuit period is 3.4982.

For the certain time period ($t=0$ to 600sec), Electrical Torque at the short circuit period is same for all short circuit cases. So, Electrical Torque fixed value for this certain period ($t=0$ to 600sec) is 3.4982.

Mechanical Torque is proportional to Electrical Torque.

$$T_m \propto T_e$$

So, the Electrical Torque also decreases after the short circuit period with the decrease of Mechanical Torque. So, the electrical torque in fig 4.8.2 decreases from its fixed initial value 3.4982 to final value of 0.806.

In the previous case (Case 5) of short circuit condition, we have taken the same condition with time period of $t=0$ to 10sec . But now we have taken the long time period, $t= 0$ to 600sec .

As, we have taken the long step size of time ($dt= 0.05\text{sec}$), so the simulation responses the initial value of Terminal Voltage at the short circuit period is 1.2007.

For the certain period of time ($t= 0$ to 600sec) for the short circuit period, the initial value is fixed all the time and the Fixed value of Terminal Voltage in this case is 1.2007.

After the short circuit period, the terminal voltage changes from its initial fixed value to the final value of 1 which is same as given value of terminal voltage in the simulation. So, in the short circuit period, the voltage changes, but after the short circuit period, same line exists and for this reason, same voltage gain is seen after the short circuit period.

As, we have taken the long step size of time ($dt= 0.05\text{sec}$) and time duration , $t= 0$ to 600sec , so the simulation responses the initial value of terminal current at short circuit period is 2.9415.

For the certain period of time ($t= 0$ to 600sec) for the short circuit period, the initial value is fixed all the time and the fixed value of terminal current in this case is 2.9415.

But after the short circuit period, same line exists. So, the current will remain the same as the given value in the simulation. And the final value of the current is 1.

On the other hand, the terminal voltage is decreased from its initial fixed value to final value, so the terminal current increases and reaches to final value of 1. As, in this case we have taken the long time period with long step size of time, so the initial value of the terminal current is high. After the short circuit period, the same line exists and the voltage decreases, so finally the current is increased from its initial value.

For the certain period of time ($t= 0$ to 600sec) for the short circuit period, the initial value is all time fixed and the fixed value of speed in this case is -0.0041 .

After the short circuit period the torque become decreases as the same line comes afterwards. So, the impedance increases from the short circuit position. For the same line exists after the short circuit period; the machine needs much speed to rotate in the synchronous speed. For this reason after the short circuit period, the machine gives much speed than before to rotate the rotor winding. So, the speed in fig 4.8.5 increases from its initial fixed value to final increased value of $5.3982 * 10^{-8}$.

For the certain period of time ($t= 0$ to 600sec) for the short circuit period, initial value is all time fixed and the fixed value of delta in this case is 1.0363. The final value will be the same as the initial value of 1.0363 as it is a synchronous generator and the condition is same line will be exists after short circuit period.

Case 9: Short circuit at Machine terminal for 0.1sec and line will be 1.5 of previous value afterwards where time $t= 0$ to 600sec at $dt= 0.005$ sec.

After the short circuit period,

Resistance, $R= 1.5*0.03$

Reactance, $X=1.5*0.468*fac$

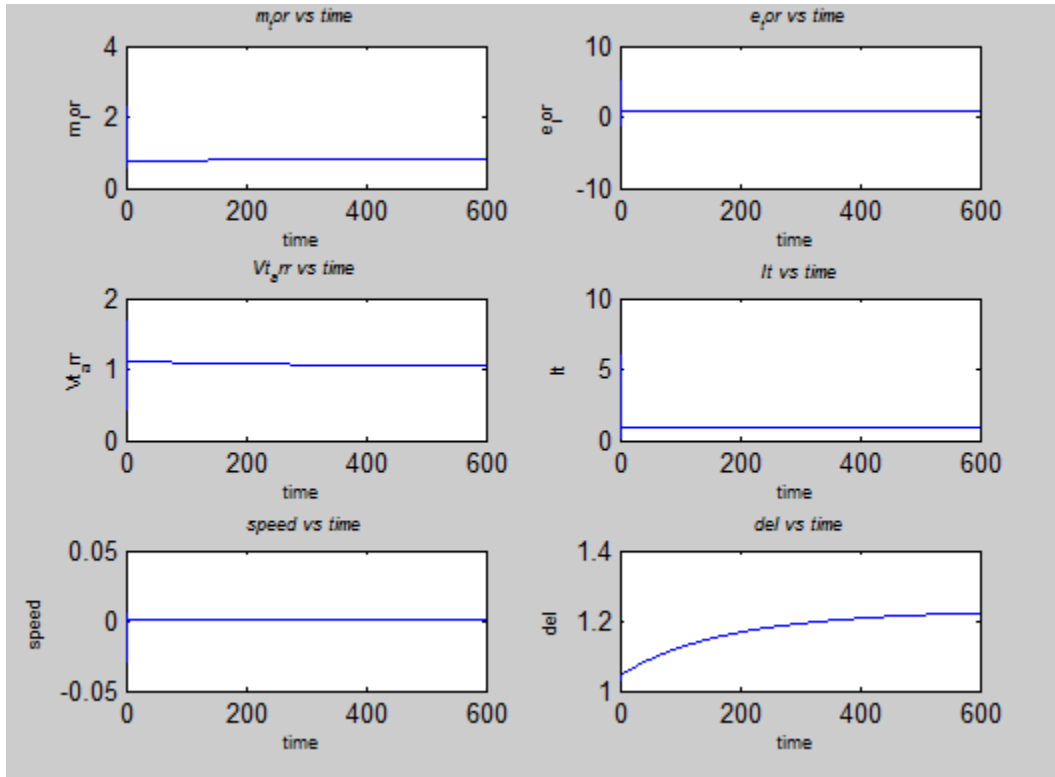


Fig4.9.1: Time vs. Mechanical Torque, Fig 4.9.2: Time Vs. Electrical Torque, Fig 4.9.3: Time Vs. Terminal Voltage, Fig 4.9.4: Time Vs. Terminal Current, Fig 4.9.5: Time Vs. Speed, Fig 4.9.6: Time Vs. delta

For the certain value of time ($t= 0$ to 600sec) in the short circuit cases, the initial value in the short circuit period remains unchanged. So, the initial value of Mechanical Torque is same as the initial value of Mechanical Torque in the previous case (case 8). So, the unchanged fixed value of Mechanical Torque in the short circuit period is 1.0157.

In this case, after the period of short circuit, the impedances are increased 1.5 times from its previous value. So, the load increases on the machine and the rotor rotate with a reduced value.

So, from fig 4.9.1, the mechanical torque decreases from its initial short circuit period value to the final decreased value of 0.8097. Comparing with Case 8, in this case, after the short circuit period, the line impedance is increased. So, the mechanical torque is decreased more than the mechanical torque in the condition of same line exists after the short circuit period (case 8).

For the certain value of time ($t= 0$ to 600sec) in the short circuit cases, the initial value in the short circuit period remains unchanged. So, the initial value of electrical torque is same as the initial value of mechanical torque in the previous case (case 8). So, the unchanged fixed value of electrical torque in the short circuit period is 1.0157.

After the short circuit period, impedances increase from its initial value. So, the electrical torque in fig 4.9.2, reduced from its initial value of 1.0157 to the final value of 0.8041

Comparing with the previous case (Case 8), in this case impedance increases, so, the final value of electrical torque will be decreasing more than the final value of the previous case (Case 8).

For the certain period of time ($t=0$ to 600sec) in the short circuit condition, the initial value of terminal voltage is unchanged and its value is 1.2007

After the short circuit period, the impedances increase 1.5 times from its previous value before the short circuit period. So, the Potential difference increases with the increase of the impedance.

So, the terminal voltage decreases in fig 4.9.3, from its initial value of 1.2007 to the final value of 1.0569. But, comparing with the previous case (case 8), in this case impedance increases, so, the terminal voltage increases more than that of the same line exists after the short circuit period in case 8. So, the terminal voltage changes from its initial value to final value of 1.0569.

For all the short circuit condition in a certain value of time ($t= 0$ to 600sec), the initial value is unchanged and the value of terminal current is 2.9415, which is already mentioned in case 8. For the long time period and long duration of step size, the simulation all time shows the high initial value of terminal current.

After the short circuit period the terminal current decreases with the increases of impedance. So, the terminal current changes in fig 4.9.4, from its initial value of 2.9415 to the final decreased value of 0.9683.

In the short circuit condition the speed remains unchanged in a certain value of time duration ($t=0$ to 600sec). The initial value of speed in the short circuit period is -0.0041 .

After the short circuit period, the impedance increases from its initial value, so the torque decreases and speed increases to rotate the rotor. So, the rotor needs more speed to rotate with loaded impedance than before. With the decrease of torque, the speed in fig 4.9.5 will be increased from its previous value. The speed increases from its initial value of -0.0041 to final value of 4.59×10^{-5} . For the short circuit condition in the same time period ($t=0$ to 600sec), the initial value of delta in the short circuit period is 1.0363 . After the short circuit period, the rotor angle in fig 4.9.6 is changed from its fixed initial value of 1.0363 to the final value of 1.2221 .

Case 10: Short Circuit at Machine Terminal for 0.1sec and the line will be 0.5 of the previous value afterwards where time period, $t= 0$ to 600sec and $dt= 0.005$ sec.

After the short circuit period,

Resistance, $R=0.5*0.03$

Reactance, $X= 0.5*0.468*fac$

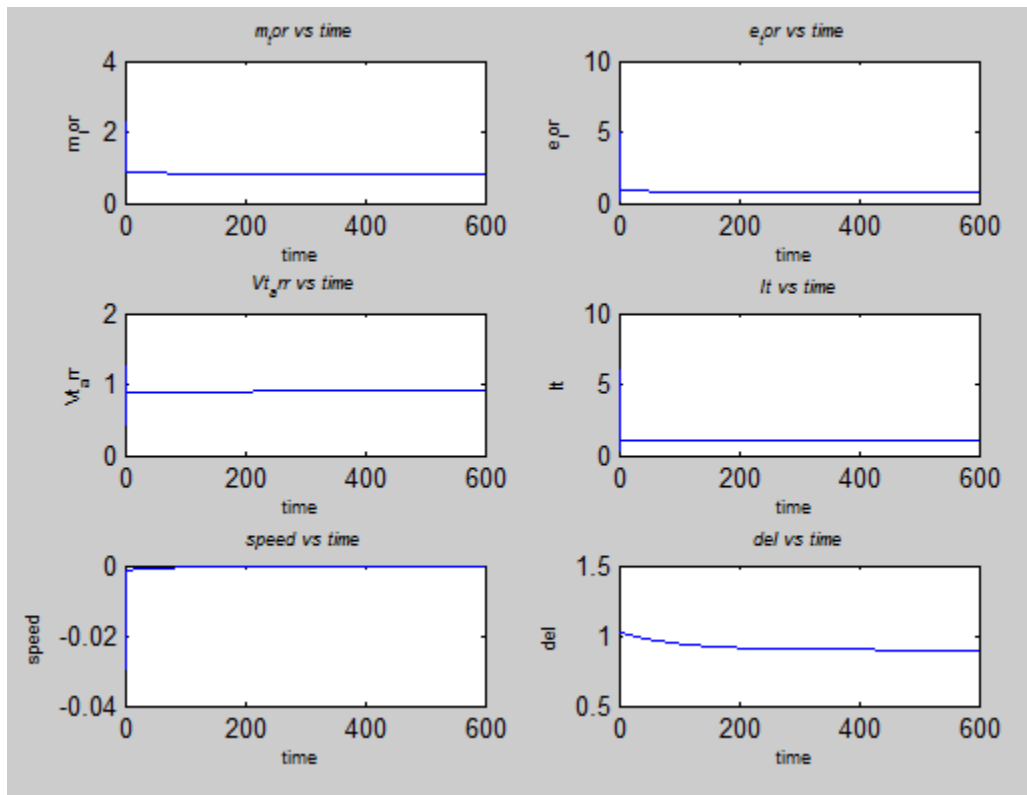


Fig4.10.1: Time vs. Mechanical Torque, Fig 4.10.2: Time Vs. Electrical Torque, Fig 4.10.3: Time Vs. Terminal Voltage, Fig 4.10.4: Time Vs. Terminal Current, Fig 4.10.5: Time Vs. Speed, Fig 4.10.6: Time Vs. delta

For the certain value of time ($t= 0$ to 600sec) in the short circuit cases, the initial value in the short circuit period remains unchanged. So, the initial value of mechanical torque is same as the initial value of mechanical torque in the previous cases (case 8 & case 9). So, the unchanged fixed value of mechanical torque in the short circuit period is 1.0157.

In this case, after the period of short circuit, the impedances decrease 0.5 times from its previous value. So, the load decreases on the machine and the rotor rotate with an increased value than before cases (case 8 & case 9). Because of the long time period and long period of step sizes, the initial value is all time higher than the final value. So, the mechanical torque in fig 4.10.1 decreases from its initial short circuit period value of 1.0157 to the final value of 0.8127.

For the certain period of time ($t= 0$ to 10sec) in the short circuit condition, the initial value is fixed and the initial value of electrical torque in the short circuit condition is 3.4982. After the short circuit period, impedances are decreased from its initial value. So, the electrical torque increases but for the long time period and the long duration of step sizes, initial value is all time higher than the final value . Comparing with the initial value, the final value is decreased from initial high value of 3.4982 to final decreased value of 0.8054.

For the certain period of time ($t=0$ to 600sec) in the short circuit condition, the initial value of terminal voltage remains unchanged and its value is 1.2007

After the short circuit period, the impedances are decreased by 0.5 from its previous value before the short circuit period. So, the potential difference decreases with the decrease of impedance, compare with the Case 8 and Case 9. So, the voltage decreases from its initial value of 1.2007 to final value of 0.9038.

For all the short circuit condition in a certain value of time ($t= 0$ to 600sec), the initial value remains unchanged and the value of terminal current is 2.9415, which is already mentioned in case 8 and case 9. After the short circuit period, the terminal current increases with the decrease of the impedance by 0.5 comparing with the Case 8 (same line exists after short circuit period) and Case 9 (impedance increase by 1.5 after the short circuit period).

But, because of the long time period ($t= 0$ to 600sec) and long duration of step size ($dt= 0.05$ sec), the initial value is time higher than the final value. So, comparing with the initial value, the terminal current is decreased from its initial value of 2.9415 to the final value of 0.9683.

In the short circuit condition, the speed remains unchanged in a certain value of time duration ($t= 0$ to 600sec). The initial value of speed in the short circuit period is -0.0041. After the short circuit period, the impedance decreases from its initial value, so the torque increases and speed

decreases to rotate the rotor. So, the rotor needs less speed than before to rotate with reduced impedance than before.

On the other hand, speed is inversely proportional to the torque. So,

$$T \propto \frac{1}{\omega}$$

So, with the increase of torque, the speed will be decreasing from its previous value. The speed decreases from its initial value of -0.0041 to final value of $-1.94 * 10^{-6}$.

Comparing with the Case 8 and Case 9 the speed will be decreased much more in this case. For the short circuit condition in the same time period (t=0 to 600sec), the initial value of delta in the short circuit period is 1.0363. After the short circuit period the rotor angle changed from its fixed initial value of 1.0363 to the final value of 0.8990.

Case 11: Field current is increased by 20% where, time $t= 0$ to 600sec at duration of step size of time, $dt= 0.005$ sec.

In this case,

$$\text{Field Current, } I_f = I_{f0} + (0.2 * I_{f0})$$

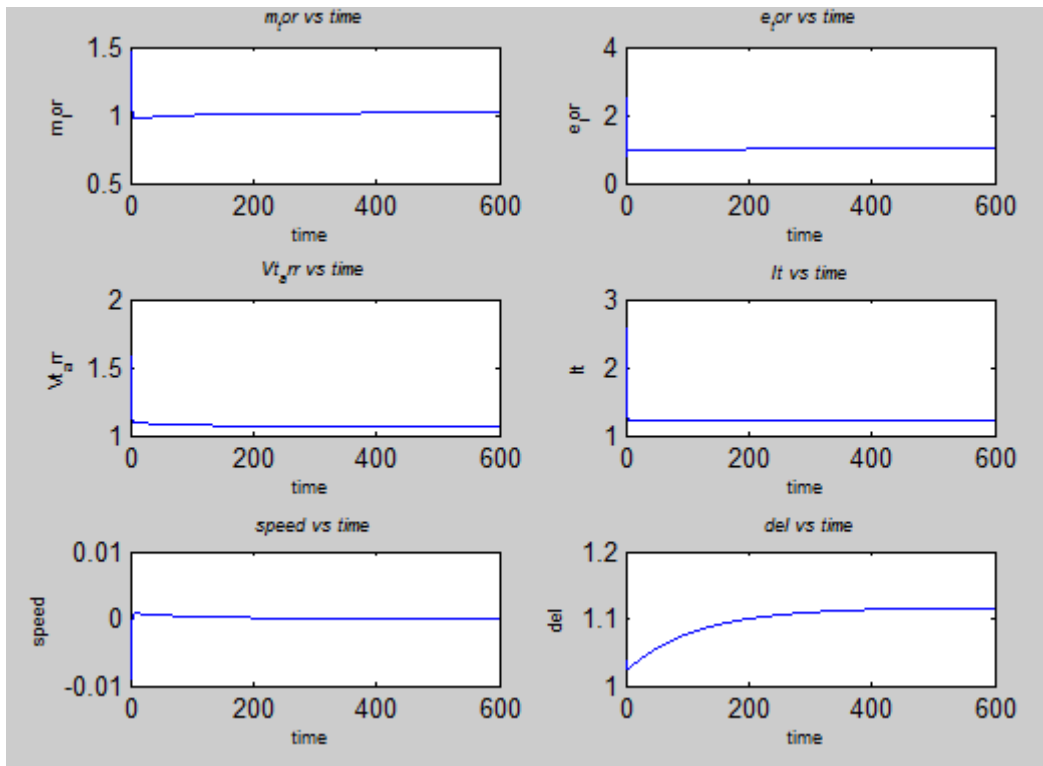


Fig4.11.1: Time vs. Mechanical Torque, Fig 4.11.2: Time Vs. Electrical Torque, Fig 4.11.3: Time Vs. Terminal Voltage, Fig 4.11.4: Time Vs. Terminal Current, Fig 4.11.5: Time Vs. Speed, Fig 4.11.6: Time Vs. delta

In this case, field current increases 20% from its previous value. So, the mechanical torque decreases from its initial value of 1.1278 to the final value of 1.0161.

As, electrical torque is proportional to the mechanical torque, with the decrease of the mechanical torque, the electrical torque in fig 4.11.2 is decreased from its initial value of 2.4923 to the final value of 1.0070.

In this case, with the increase of field current by 20%, Terminal Voltage in fig 11.3 decreases from its initial value of 1.5864 to the final decreased value of 1.0633.

In this case, with the increase of field current, Terminal current in fig 4.11.4 will be decreased from its initial value of 1.8940 to the final value of 1.2318.

In this case, with the increase of field current, speed will also be increasing. Speed in fig 4.11.5 will be increasing from its initial value of -0.0022 to the final value of 5.3044×10^{-6} .

With the increase of field current, torque angle delta in fig 4.11.6 will be increasing from its initial value of 1.0363 to the final value of 1.1164.

Case 12: Field Current decreased by 20 % when the time period, $t=0$ to 600sec and duration of step size of time, $dt= 0.005$ sec.

In this case,

Field current, $I_f = I_f - (0.2 * I_f)$

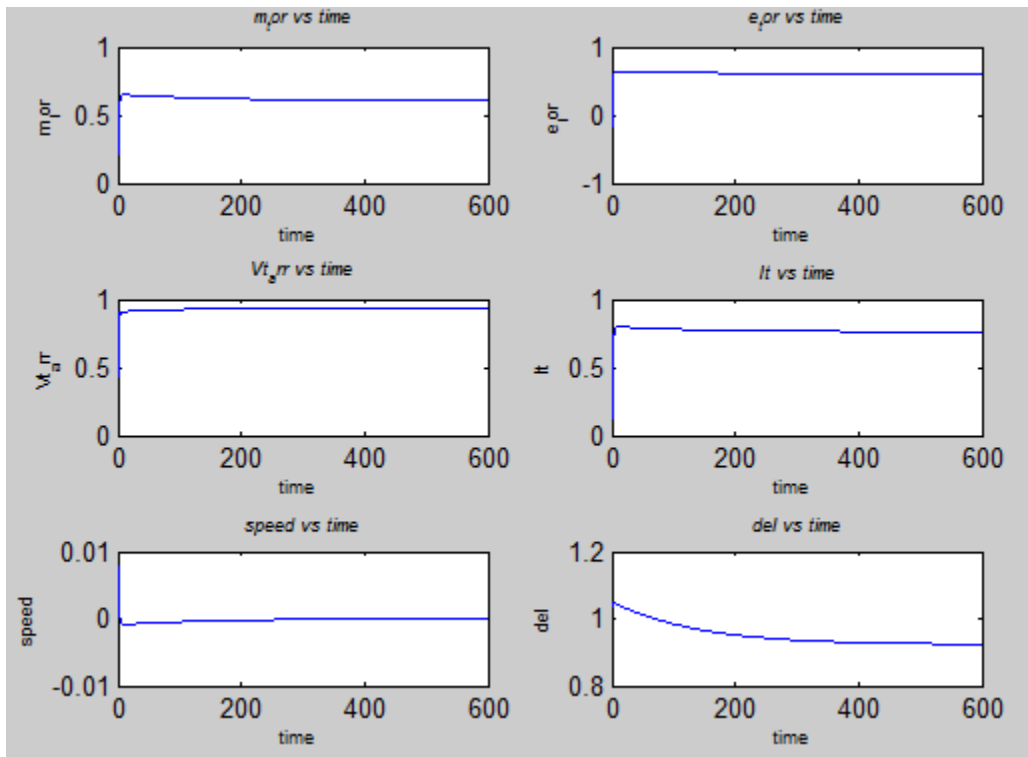


Fig4.12.1: Time vs. Mechanical Torque, Fig 4.12.2: Time Vs. Electrical Torque, Fig 4.12.3: Time Vs. Terminal Voltage, Fig 4.12.4: Time Vs. Terminal Current, Fig 4.12.5: Time Vs. Speed, Fig 4.12.6: Time Vs. delta

With the decrease of field current, mechanical torque in fig 4.12.1 increases from its initial value of 0.5659 to the final value of 0.6081.

As, electrical torque is proportional to mechanical torque, in this case, with the increase of mechanical torque, the electrical torque in fig 4.12.2 also increases from its initial value of 0.0470 to the final value of 0.6046.

In this case, with the decrease of field current by 20%, terminal voltage in fig 4.12.3 increases from its initial value of 0.4302 to the final increased value of 0.9410.

With the decrease of the field current, terminal current in fig 4.12.4 will be decreasing from its initial value of 0.1196 to the final value of 0.7628.

With the decrease of field current, speed will also be decreasing. Speed in fig 4.12.5 will be decreasing from its initial value of $8.3417 * 10^{-4}$ to the final value of $-1.0013 * 10^{-5}$.

With the decrease of the field current, the torque angle delta in fig 4.12.6 will be decreasing from its initial value of 1.0363 to the final value of 0.9243.

Chapter 5

Conclusion

5.1 Conclusion

In this paper, a modeling of Synchronous Generator has been developed and tested which will help to simulate synchroconverter. It has been tested on MATLAB to get results of terminal voltage, terminal current, speed, mechanical and electrical torque and rotor angle of generator. Using the already established equations, mathematical modeling of generator has been done. Our focus was to model synchronous generator so that a comparison can be done between synchronous generator and inverter. Modeling of inverter has not been provided in this paper. If the behavior of synchronous generator can be implemented by comparing synchronous generator with inverter, then a synchroconverter will work like a synchronous generator in the high voltage dc transmission line. So, this synchroconverter can take part in regulations of frequency and voltage of power system by frequency and voltage dropping. It has potential to disconnect from the grid as well as it can automatically reconnect. In this paper concept and mathematical modeling of synchronous generator has been provided. The concept and results can be work on inverter so that it behaves like a synchronous generator which will help in real life implementation.

5.2 Suggestions for further work

- In this paper, modeling of inverter has not been provided due to short time period. It has been kept for further research to establish synchroconverter.
- In the model of synchroconverter, it has been assumed that damper winding is not being used in the rotor. It is needed to do more research to find out whether using of damper windings in the rotor is worthwhile or not to implement a synchroconverter.
- Research on use of synchroconverter in different applications is needed. Due to short time period, details explanation of different wave shapes hasn't been done and has been

kept for future research of the 12 case studies of synchronous generator which have been done here.

- Having large inertia with synchronous generator is not necessary if synchroconverter is used instead of synchronous generator, but this large inertia helps to store more energy mechanically. Again, small inertia is good for power system stability but it is unknown that where this short inertia could be used in the large power grid. It is not presented here that which inertia is more advantageous.
- By using the mathematical model provided in the paper, investigation can be done on the stability of power systems by inverters operating in parallel.

References

- [1] "[Renewables 2014: Global Status Report](#)". pp. 13, 17, 21, 25. Archived from [the original](#) on 4 September 2014
- [2] Steve Leone (25 August 2011). "[U.N. Secretary-General: Renewables Can End Energy Poverty](#)". Renewable Energy World.
- [3] H.-P.Beck and R.Hesse, "Virtual synchronous machine," in Proc.9th int. conf.EPQU,2007,pp 1-6.
- [4] Q. C.Zhong and G. Weiss, "Static synchronous generators for distributed generation and renewable energy,"in Proc.IEEE PES PSCE, Washington, DC, Mar.2009, pp.1-6
- [5]J.Driesen and K. Visscher, "Virtual synchronous generators," in Proc. IEEE Power Energy Soc.Gen. Meeting-Conversion and Delivery of Electrical energy in the 21st Century, Jul.2008,pp.1-3.
- [6] K. Visscher and S.W.H. De Haan, "virtual synchronous machines (VSG's) for frequency stabilization in future grids with a significant share of decentralized generation," in Proc. IET-CIRED Semin. Smart -Grids Distrib.Jun. 2008, pp 1-4.
- [7] Q. C. Zhong and G. Weiss, "Synchronverters: Inverters that Mimic Synchronous Generators," IEEE Transactions on Industrial Electronics,vol.58,No.4,April. 2011.
- [8] A. E. Fitzgerald, Charles Kingsley,Jr., Stephen D. Umans , Synchronous Machines, Electric Machinery,Sixth Edition.

Appendixes

The following code was developed in MATLAB:

Case 1:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);
```

```

Vf=Rf*If;

dt=0.0001;
i=0;
pd=0;
intpd=0.0;
p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=0.9*Tm;
Tm=Tm0;

for t=0:dt:10
    W=W0-pd;
    fac=W/W0;

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;
for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;
end
    di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

```

```

end
    di(j)=B(j)-di(j);
end
for j=1:3
    mult(j)=0.0;
for k=1:3
    mult(j)=mult(j)+AI(j,k)*di(k);
end
    sp(ii,j)=mult(j);
end
end

for j=1:3
    cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;

end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

xlabel('time ','FontSize',7)

```



```
ylabel('m_tor', 'FontSize', 7)
title('\it{m_tor vs time}', 'FontSize', 7)
```

```
subplot(3,2,2),plot(time,e_tor);
```

```
xlabel('time ', 'FontSize', 7)
ylabel('e_tor', 'FontSize', 7)
title('\it{e_tor vs time}', 'FontSize', 7)
```

```
subplot(3,2,3),plot(time,Vt_arr);
```

```
xlabel('time ', 'FontSize', 7)
ylabel('Vt_arr', 'FontSize', 7)
title('\it{Vt_arr vs time}', 'FontSize', 7)
```

```
subplot(3,2,4),plot(time,It);
```

```
xlabel('time ', 'FontSize', 7)
ylabel('It', 'FontSize', 7)
title('\it{It vs time}', 'FontSize', 7)
```

```
subplot(3,2,5),plot(time,speed);
```

```
xlabel('time ', 'FontSize', 7)
ylabel('speed', 'FontSize', 7)
title('\it{speed vs time}', 'FontSize', 7)
```

```
subplot(3,2,6),plot(time,del);
```

```
xlabel('time ', 'FontSize', 7)
ylabel('del', 'FontSize', 7)
title('\it{del vs time}', 'FontSize', 7)
```

Case 2:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.005;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=0.9*Tm;
Tm=Tm0;

for t=0:dt:500
    W=W0-pd;
    fac=W/W0;

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;
for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;
end
    di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
    di(j)=B(j)-di(j);
end
for j=1:3
    mult(j)=0.0;

```

```

for k=1:3
    mult(j)=mult(j)+AI(j,k)*di(k);
end
    sp(ii,j)=mult(j);
end
end

for j=1:3
    cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;

end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=delta;
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

xlabel('time ','FontSize',7)
ylabel('m_tor','FontSize',7)
title('\it{m_tor vs time}','FontSize',7)

subplot(3,2,2),plot(time,e_tor);

```

```
    xlabel('time ', 'FontSize', 7)
    ylabel('e_tor', 'FontSize', 7)
    title('\it{e_tor vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 3), plot(time, Vt_arr);
```

```
        xlabel('time ', 'FontSize', 7)
        ylabel('Vt_arr', 'FontSize', 7)
        title('\it{Vt_arr vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 4), plot(time, It);
```

```
        xlabel('time ', 'FontSize', 7)
        ylabel('It', 'FontSize', 7)
        title('\it{It vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 5), plot(time, speed);
```

```
        xlabel('time ', 'FontSize', 7)
        ylabel('speed', 'FontSize', 7)
        title('\it{speed vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 6), plot(time, del);
```

```
        xlabel('time ', 'FontSize', 7)
        ylabel('del', 'FontSize', 7)
        title('\it{del vs time}', 'FontSize', 7)
```

Case 3:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.0001;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=1.1*Tm;
Tm=Tm0;

for t=0:dt:10
    W=W0-pd;
    fac=W/W0;

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;
for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;
end
    di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
    di(j)=B(j)-di(j);
end
for j=1:3
    mult(j)=0.0;

```

```

for k=1:3
    mult(j)=mult(j)+AI(j,k)*di(k);
end
    sp(ii,j)=mult(j);
end
end

for j=1:3
    cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;

end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

    time(i)=t;
    e_tor(i)=Te;
    m_tor(i)=Tm;
    int_pd(i)=intpd;
    speed(i)=pd;
    del(i)=abs(delta);
    It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

    xlabel('time ','FontSize',7)
ylabel('m_tor','FontSize',7)
title('\it{m_tor vs time}','FontSize',7)

subplot(3,2,2),plot(time,e_tor);

```



```
    xlabel('time ', 'FontSize', 7)
    ylabel('e_tor', 'FontSize', 7)
    title('\it{e_tor vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 3), plot(time, Vt_arr);
```

```
    xlabel('time ', 'FontSize', 7)
    ylabel('Vt_arr', 'FontSize', 7)
    title('\it{Vt_arr vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 4), plot(time, It);
```

```
    xlabel('time ', 'FontSize', 7)
    ylabel('It', 'FontSize', 7)
    title('\it{It vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 5), plot(time, speed);
```

```
    xlabel('time ', 'FontSize', 7)
    ylabel('speed', 'FontSize', 7)
    title('\it{speed vs time}', 'FontSize', 7)
```

```
    subplot(3, 2, 6), plot(time, del);
```

```
    xlabel('time ', 'FontSize', 7)
    ylabel('del', 'FontSize', 7)
    title('\it{del vs time}', 'FontSize', 7)
```

Case 4:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.005;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=1.1*Tm;
Tm=Tm0;

for t=0:dt:500
    W=W0-pd;
    fac=W/W0;

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;
for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;
end
    di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
    di(j)=B(j)-di(j);
end
for j=1:3
    mult(j)=0.0;

```

```

for k=1:3
    mult(j)=mult(j)+AI(j,k)*di(k);
end
    sp(ii,j)=mult(j);
end
end

for j=1:3
    cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;
end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);
    xlabel('time ','FontSize',7)
ylabel('m_tor','FontSize',7)
title('\it{m_tor vs time}','FontSize',7)

subplot(3,2,2),plot(time,e_tor);

    xlabel('time ','FontSize',7)
ylabel('e_tor','FontSize',7)

```

```

title('\it{e_tor vs time}', 'FontSize', 7)

    subplot(3,2,3),plot(time,Vt_arr);
        xlabel('time ', 'FontSize', 7)
ylabel('Vt_arr', 'FontSize', 7)
title('\it{Vt_arr vs time}', 'FontSize', 7)

    subplot(3,2,4),plot(time,It);

        xlabel('time ', 'FontSize', 7)
ylabel('It', 'FontSize', 7)
title('\it{It vs time}', 'FontSize', 7)

    subplot(3,2,5),plot(time,speed);

        xlabel('time ', 'FontSize', 7)
ylabel('speed', 'FontSize', 7)
title('\it{speed vs time}', 'FontSize', 7)

    subplot(3,2,6),plot(time,del);

        xlabel('time ', 'FontSize', 7)
ylabel('del', 'FontSize', 7)
title('\it{del vs time}', 'FontSize', 7)

```

Case 5:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.0001;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:10
    W=W0-pd;
    fac=W/W0;
if t<0.1

    X=X*fac/2;
    R=R/2;
    Vbd=0;
    Vbq=0;
    X=0;
    R=0;
else

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;
end

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3

    di(j)=0.0;

for k=1:3
if (ii==1)

    dcur(k)=0;
elseif (ii==2)

    dcur(k)=mult(k)*dt/2;
elseif (ii==3)

    dcur(k)=mult(k)*dt/2;
elseif (ii==4)

    dcur(k)=mult(k)*dt;

```

```

end
        di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
        di(j)=B(j)-di(j);
end
for j=1:3
        mult(j)=0.0;
for k=1:3
        mult(j)=mult(j)+AI(j,k)*di(k);
end
        sp(ii,j)=mult(j);
end
end

for j=1:3
        cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;
end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=delta;
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

```



```

        xlabel('time ', 'FontSize',7)
ylabel('m_tor', 'FontSize',7)
title('\it{m_tor vs time}', 'FontSize',7)

        subplot(3,2,2),plot(time,e_tor);

        xlabel('time ', 'FontSize',7)
ylabel('e_tor', 'FontSize',7)
title('\it{e_tor vs time}', 'FontSize',7)

        subplot(3,2,3),plot(time,Vt_arr);

        xlabel('time ', 'FontSize',7)
ylabel('Vt_arr', 'FontSize',7)
title('\it{Vt_arr vs time}', 'FontSize',7)
        subplot(3,2,4),plot(time,It);
        xlabel('time ', 'FontSize',7)
ylabel('It', 'FontSize',7)
title('\it{It vs time}', 'FontSize',7)

        subplot(3,2,5),plot(time,speed);

        xlabel('time ', 'FontSize',7)
ylabel('speed', 'FontSize',7)
title('\it{speed vs time}', 'FontSize',7)

        subplot(3,2,6),plot(time,del);

        xlabel('time ', 'FontSize',7)
ylabel('del', 'FontSize',7)
title('\it{del vs time}', 'FontSize',7)

```

Case 6:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.0001;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:10
    W=W0-pd;
    fac=W/W0;
if t<0.1

    X=X*fac/2;
    R=R/2;
    Vbd=0;
    Vbq=0;
    X=0;
    R=0;
else

    X=1.5*0.468*fac;
    R=1.5*0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;
end

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;

for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;

```

```

end
        di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
        di(j)=B(j)-di(j);
end
for j=1:3
        mult(j)=0.0;
for k=1:3
        mult(j)=mult(j)+AI(j,k)*di(k);
end
        sp(ii,j)=mult(j);
end
end

for j=1:3
        cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;
end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

```

```

        xlabel('time ', 'FontSize', 7)
ylabel('m_tor', 'FontSize', 7)
title('\it{m_tor vs time}', 'FontSize', 7)

        subplot(3,2,2),plot(time,e_tor);
        xlabel('time ', 'FontSize', 7)
ylabel('e_tor', 'FontSize', 7)
title('\it{e_tor vs time}', 'FontSize', 7)

        subplot(3,2,3),plot(time,Vt_arr);

        xlabel('time ', 'FontSize', 7)
ylabel('Vt_arr', 'FontSize', 7)
title('\it{Vt_arr vs time}', 'FontSize', 7)

        subplot(3,2,4),plot(time,It);

        xlabel('time ', 'FontSize', 7)
ylabel('It', 'FontSize', 7)
title('\it{It vs time}', 'FontSize', 7)

        subplot(3,2,5),plot(time,speed);

        xlabel('time ', 'FontSize', 7)
ylabel('speed', 'FontSize', 7)
title('\it{speed vs time}', 'FontSize', 7)

        subplot(3,2,6),plot(time,del);

        xlabel('time ', 'FontSize', 7)
ylabel('del', 'FontSize', 7)
title('\it{del vs time}', 'FontSize', 7)

```

Case 7:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.0001;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:10
    W=W0-pd;
    fac=W/W0;
if t<0.1

    X=X*fac/2;
    R=R/2;
    Vbd=0;
    Vbq=0;
    X=0;
    R=0;
else

    X=0.5*0.468*fac;
    R=0.5*0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;
end

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3

    di(j)=0.0;

for k=1:3
if (ii==1)

    dcur(k)=0;
elseif (ii==2)

    dcur(k)=mult(k)*dt/2;
elseif (ii==3)

    dcur(k)=mult(k)*dt/2;
elseif (ii==4)

    dcur(k)=mult(k)*dt;

```

```

end
        di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
        di(j)=B(j)-di(j);
end
for j=1:3
        mult(j)=0.0;
for k=1:3
        mult(j)=mult(j)+AI(j,k)*di(k);
end
        sp(ii,j)=mult(j);
end
end

for j=1:3
        cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;

end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

```



```

        xlabel('time ', 'FontSize',7)
ylabel('m_tor', 'FontSize',7)
title('\it{m_tor vs time}', 'FontSize',7)

        subplot(3,2,2),plot(time,e_tor);
        xlabel('time ', 'FontSize',7)
ylabel('e_tor', 'FontSize',7)
title('\it{e_tor vs time}', 'FontSize',7)

        subplot(3,2,3),plot(time,Vt_arr);

        xlabel('time ', 'FontSize',7)
ylabel('Vt_arr', 'FontSize',7)
title('\it{Vt_arr vs time}', 'FontSize',7)

        subplot(3,2,4),plot(time,It);

        xlabel('time ', 'FontSize',7)
ylabel('It', 'FontSize',7)
title('\it{It vs time}', 'FontSize',7)

        subplot(3,2,5),plot(time,speed);

        xlabel('time ', 'FontSize',7)
ylabel('speed', 'FontSize',7)
title('\it{speed vs time}', 'FontSize',7)

        subplot(3,2,6),plot(time,del);

        xlabel('time ', 'FontSize',7)
ylabel('del', 'FontSize',7)
title('\it{del vs time}', 'FontSize',7)

```

Case 8:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.005;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:600
    W=W0-pd;
    fac=W/W0;
if t<0.1

    X=X*fac/2;
    R=R/2;
    Vbd=0;
    Vbq=0;
    X=0;
    R=0;
else

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;
end

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3

    di(j)=0.0;

for k=1:3
if (ii==1)

    dcur(k)=0;
elseif (ii==2)

    dcur(k)=mult(k)*dt/2;
elseif (ii==3)

    dcur(k)=mult(k)*dt/2;
elseif (ii==4)

    dcur(k)=mult(k)*dt;

```

```

end
        di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
        di(j)=B(j)-di(j);
end
for j=1:3
        mult(j)=0.0;
for k=1:3
        mult(j)=mult(j)+AI(j,k)*di(k);
end
        sp(ii,j)=mult(j);
end
end

for j=1:3
        cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;

end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

```

```

        xlabel('time ', 'FontSize', 7)
ylabel('m_tor', 'FontSize', 7)
title('\it{m_tor vs time}', 'FontSize', 7)

        subplot(3,2,2),plot(time,e_tor);
        xlabel('time ', 'FontSize', 7)
ylabel('e_tor', 'FontSize', 7)
title('\it{e_tor vs time}', 'FontSize', 7)

        subplot(3,2,3),plot(time,Vt_arr);

        xlabel('time ', 'FontSize', 7)
ylabel('Vt_arr', 'FontSize', 7)
title('\it{Vt_arr vs time}', 'FontSize', 7)

        subplot(3,2,4),plot(time,It);

        xlabel('time ', 'FontSize', 7)
ylabel('It', 'FontSize', 7)
title('\it{It vs time}', 'FontSize', 7)

        subplot(3,2,5),plot(time,speed);
        xlabel('time ', 'FontSize', 7)
ylabel('speed', 'FontSize', 7)
title('\it{speed vs time}', 'FontSize', 7)

        subplot(3,2,6),plot(time,del);

        xlabel('time ', 'FontSize', 7)
ylabel('del', 'FontSize', 7)
title('\it{del vs time}', 'FontSize', 7)

```

Case 9:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.005;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:600
    W=W0-pd;
    fac=W/W0;
if t<0.1

    X=X*fac/2;
    R=R/2;
    Vbd=0;
    Vbq=0;
    X=0;
    R=0;
else

    X=1.5*0.468*fac;
    R=1.5*0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;
end

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;

for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;

```

```

end
        di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
        di(j)=B(j)-di(j);
end
for j=1:3
        mult(j)=0.0;
for k=1:3
        mult(j)=mult(j)+AI(j,k)*di(k);
end
        sp(ii,j)=mult(j);
end
end

for j=1:3
        cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;
end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

```



```

        xlabel('time ', 'FontSize', 7)
ylabel('m_tor', 'FontSize', 7)
title('\it{m_tor vs time}', 'FontSize', 7)
        subplot(3,2,2), plot(time, e_tor);
        xlabel('time ', 'FontSize', 7)
ylabel('e_tor', 'FontSize', 7)
title('\it{e_tor vs time}', 'FontSize', 7)

        subplot(3,2,3), plot(time, Vt_arr);

        xlabel('time ', 'FontSize', 7)
ylabel('Vt_arr', 'FontSize', 7)
title('\it{Vt_arr vs time}', 'FontSize', 7)

        subplot(3,2,4), plot(time, It);
        xlabel('time ', 'FontSize', 7)
ylabel('It', 'FontSize', 7)
title('\it{It vs time}', 'FontSize', 7)

        subplot(3,2,5), plot(time, speed);
        xlabel('time ', 'FontSize', 7)
ylabel('speed', 'FontSize', 7)
title('\it{speed vs time}', 'FontSize', 7)

        subplot(3,2,6), plot(time, del);

        xlabel('time ', 'FontSize', 7)
ylabel('del', 'FontSize', 7)
title('\it{del vs time}', 'FontSize', 7)

```

Case 10:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);

Vf=Rf*If;

dt=0.005;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:600
    W=W0-pd;
    fac=W/W0;
    if t<0.1

        X=X*fac/2;
        R=R/2;
        Vbd=0;
        Vbq=0;
        X=0;
        R=0;
    else

        X=0.5*0.468*fac;
        R=0.5*0.03;
        Vbd=Vbd0;
        Vbq=Vbq0;
    end

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;

for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;

```

```

end
        di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
        di(j)=B(j)-di(j);
end
for j=1:3
        mult(j)=0.0;
for k=1:3
        mult(j)=mult(j)+AI(j,k)*di(k);
end
        sp(ii,j)=mult(j);
end
end

for j=1:3
        cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;

end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

```

```

subplot(3,2,1),plot(time,m_tor);

xlabel('time ','FontSize',7)
ylabel('m_tor','FontSize',7)
title('\it{m_tor vs time}','FontSize',7)

subplot(3,2,2),plot(time,e_tor);

xlabel('time ','FontSize',7)
ylabel('e_tor','FontSize',7)
title('\it{e_tor vs time}','FontSize',7)

subplot(3,2,3),plot(time,Vt_arr);

xlabel('time ','FontSize',7)
ylabel('Vt_arr','FontSize',7)
title('\it{Vt_arr vs time}','FontSize',7)

subplot(3,2,4),plot(time,It);

xlabel('time ','FontSize',7)
ylabel('It','FontSize',7)
title('\it{It vs time}','FontSize',7)

subplot(3,2,5),plot(time,speed);

xlabel('time ','FontSize',7)
ylabel('speed','FontSize',7)
title('\it{speed vs time}','FontSize',7)

subplot(3,2,6),plot(time,del);

xlabel('time ','FontSize',7)
ylabel('del','FontSize',7)
title('\it{del vs time}','FontSize',7)

```

Case 11:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);
If= If+(0.2*If);
Vf=Rf*If;

dt=0.005;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:600
    W=W0-pd;
    fac=W/W0;

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;

for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;
end
    di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
    di(j)=B(j)-di(j);
end
for j=1:3

```

```

                                mult(j)=0.0;
for k=1:3
                                mult(j)=mult(j)+AI(j,k)*di(k);
end
                                sp(ii,j)=mult(j);
end
end

for j=1:3
                                cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;
end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=- (pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

xlabel('time ','FontSize',7)
ylabel('m_tor','FontSize',7)
title('\it{m_tor vs time}','FontSize',7)

```



```

subplot(3,2,2),plot(time,e_tor);

xlabel('time ','FontSize',7)
ylabel('e_tor','FontSize',7)
title('\it{e_tor vs time}','FontSize',7)

subplot(3,2,3),plot(time,Vt_arr);

xlabel('time ','FontSize',7)
ylabel('Vt_arr','FontSize',7)
title('\it{Vt_arr vs time}','FontSize',7)

subplot(3,2,4),plot(time,It);

xlabel('time ','FontSize',7)
ylabel('It','FontSize',7)
title('\it{It vs time}','FontSize',7)

subplot(3,2,5),plot(time,speed);

xlabel('time ','FontSize',7)
ylabel('speed','FontSize',7)
title('\it{speed vs time}','FontSize',7)

subplot(3,2,6),plot(time,del);

xlabel('time ','FontSize',7)
ylabel('del','FontSize',7)
title('\it{del vs time}','FontSize',7)

```

Case 12:

```
clear all;
clc;
P=0.8;
lag_lead=-1;
Vtm=1.0;
Itm=1.0;
Ra=0.006; % machine resistance
Xd=2.159; % machine reactance
Xq=0.7*Xd;
R=0.03;% line resistance(0.016+0.002+0.012)=0.03
Rf=0.00105;
Xmd=2.046;
Xa=0.113;
Xmq=Xq-Xa;
Xf=0.045;
X=0.468;%line reactance(0.18+0.028+0.26)=0.468
W0=314.16;% angular velocity
J=3.36;
pf=P/(Vtm*Itm);%power factor
theta=lag_lead*acos(pf);% power factor angle
Vt=Vtm+0*j; % terminal voltage
It=-[(Itm*cos(theta)+j*Itm*sin(theta))];
Zm=Ra+j*Xq; % machine impedance
Zl=R+j*X; % line impedance
Vin=Vt-It*Zm; % internal voltage
Vb=Vt+It*Zl
rotate_vector=conj(Vin)/abs(Vin);
Vin=Vin*rotate_vector;
It=It*rotate_vector
Vt=Vt*rotate_vector
Vb=Vb*rotate_vector
Vbm=abs(Vb);
Iq=real(It);
Id=imag(It);
Vbq=real(Vb);
Vbd=imag(Vb);
Vbd0=Vbd;
Vbq0=Vbq;

delta=angle(Vb);
delta0=delta;
Vq=real(Vt);
Vd=imag(Vt);

Vin=Vin+(Xd-Xq)*Id;
If=-abs(Vin)/(Xd-Xa);
If=If-(0.2*If);
Vf=Rf*If;

dt=0.005;
i=0;
pd=0;
intpd=0.0;
```

```

p2d0=0;

cur(1)=Id;
cur(2)=Iq;
cur(3)=If;

totcur=sqrt(cur(1)^2+cur(2)^2);
Tm=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2))+Ra*totcur^2;
Tm0=Tm;

for t=0:dt:600
    W=W0-pd;
    fac=W/W0;

    X=0.468*fac;
    R=0.03;
    Vbd=Vbd0;
    Vbq=Vbq0;

    Xfd=(Xmd+Xf)*fac;
    Xeqd=(X+Xd)*fac;
    Xeqq=(X+Xq)*fac;
    Req=R+Ra;
    Xmd=(Xd-Xa)*fac;

    A=[Xeqd/W 0 Xmd/W;0 Xeqq/W 0;Xmd/W 0 Xfd/W];
    AI=inv(A);

    B(1)=Vbm*sin(delta);
    B(2)=Vbm*cos(delta);
    B(3)=Vf;

    C=[Req Xeqq 0;-Xeqd Req -Xmd;0 0 Rf];
    i=i+1;
for ii=1:4
for j=1:3
    di(j)=0.0;
for k=1:3
if (ii==1)
    dcur(k)=0;
elseif (ii==2)
    dcur(k)=mult(k)*dt/2;
elseif (ii==3)
    dcur(k)=mult(k)*dt/2;
elseif (ii==4)
    dcur(k)=mult(k)*dt;
end
    di(j)=di(j)+C(j,k)*(cur(k)+dcur(k));

end
    di(j)=B(j)-di(j);
end
for j=1:3

```

```

        mult(j)=0.0;
for k=1:3
        mult(j)=mult(j)+AI(j,k)*di(k);
end
        sp(ii,j)=mult(j);
end
end

for j=1:3
        cur(j)=cur(j)+((sp(1,j)+2*sp(2,j)+2*sp(3,j)+sp(4,j))/6)*dt;

end

Vd0=Xq*cur(2)+Ra*cur(1);
Vq0=-Xd*cur(1)-Xmd*cur(3)+Ra*cur(2);
Vt=sqrt(Vq0*Vq0+Vd0*Vd0);
Vt_arr(i)=Vt;
totcur=sqrt(cur(1)^2+cur(2)^2);
Te=(cur(2)*(Xd*cur(1)+Xmd*cur(3))-cur(1)*Xq*cur(2));
Tl=Ra*totcur^2;
p2d=(Tm-Te-Tl)/J;
pd=pd+p2d*dt;
delta=delta-pd*dt;
intpd=intpd+pd*dt;

Tm=-(pd)/0.02+Tm0;

time(i)=t;
e_tor(i)=Te;
m_tor(i)=Tm;
int_pd(i)=intpd;
speed(i)=pd;
del(i)=abs(delta);
It(i)=totcur;

end
Te+Tl
Tm
cur(1)
cur(2)
delta
Vd0
Vq0
B(1)
B(2)

subplot(3,2,1),plot(time,m_tor);

xlabel('time ','FontSize',7)
ylabel('m_tor','FontSize',7)
title('\it{m_tor vs time}','FontSize',7)

```

```
subplot(3,2,2),plot(time,e_tor);

xlabel('time ','FontSize',7)
ylabel('e_tor','FontSize',7)
title('\it{e_tor vs time}','FontSize',7)
```

```
subplot(3,2,3),plot(time,Vt_arr);

xlabel('time ','FontSize',7)
ylabel('Vt_arr','FontSize',7)
title('\it{Vt_arr vs time}','FontSize',7)
```

```
subplot(3,2,4),plot(time,It);

xlabel('time ','FontSize',7)
ylabel('It','FontSize',7)
title('\it{It vs time}','FontSize',7)
```

```
subplot(3,2,5),plot(time,speed);

xlabel('time ','FontSize',7)
ylabel('speed','FontSize',7)
title('\it{speed vs time}','FontSize',7)
```

```
subplot(3,2,6),plot(time,del);

xlabel('time ','FontSize',7)
ylabel('del','FontSize',7)
title('\it{del vs time}','FontSize',7)
```

