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Power system stability

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CERTIFICATE OF RESEARCH

We do here by declaring this thesis has not been submitted else where for obtaining any degree, diploma or certificates or for publications.

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LIST OF SYMBOLS

Symbol	Meaning
δi	the power angle of the ith generator, in rad
ωi	the relative speed of the ith generator, in rad/s
Pmi	the mechanical input power, in p.u.
ω0	the synchronous machine speed, in rad/s
Di	the per unit damping constant
Hi	the inertia constant, in s
E2qi	the transient EMF in the quadrature axis, in p.u.
Pei	the electrical power, in p.u.
Eqi	the EMF in the quadrature axis, in p.u.
Efi	the equivalent EMF in the excitation coil, in p.u.
T2doi	the direct axis transient short-circuit time constant, in s
xdi	the direct axis reactance, in p.u.
x2di	the direct axis transient reactance, in p.u.
Bij	the ith row and jth column element of nodal suspectance matrix at the internal nodes after eliminating all physical buses, in p.u.
Qe Ifi	the excitation current, in p.u.
Idi	the direct axis current, in p.u.
Iqi	the quadrature axis current, in p.u.
kci	the gain of the excitation amplifier, in p.u.
ufi	the input of the SCR amplifier, in p.u.
xadi	the mutual reactance between the excitation coil and the stator coil, in p.u.
xTi	the transformer reactance, in p.u.
xij	the transmission line reactance between the ith generator and the jth generator, in p.u.
Vti	the terminal voltage of the ith generator, in p.u.

Xei	the steam valve opening of the ith generator, in p.u.
Pci	the power control input of the ith generator, in p.u.
Tmi	the time constant of the ith machine's turbine, in si
Kmi	the gain of the ith machine's turbine
Tei	the time constant of the ith machine's speed governor, in s
Kei	the gain of the ith machine's speed governor
Ri	the regulation constant of the ith machine, in p.u.

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ABSTRACT

The objective of this thesis project is to investigate and understand the stability of power system, with the main focus on stability theories and power system modeling. The thesis looked into the effects that advanced control techniques have on electrical power generation system and transmission system. The thesis first explained the definition of power system stability and the need for power system stability studies. It then proceeded to discuss on the various stability problems after which the thesis provided a brief introduction on basic control theory and study. Next the thesis examined the concept of system stability and some stability theories. The thesis then performed a power system modeling and simulation of a two-machine, three bus power systems. The performance of the power system was simulated with the proposed advanced control technique. The operating points and system parameters were varied to test the robustness of the power system and the effectiveness of the proposed controller. Examples of the parameters that were varied include the fault position λ, the power angle δ and the mechanical power input Pm. Lastly, a conclusion was made on the overall effect of the controller on the power system and the performance of the power system when its parameters were varied.

CHAPTER 1

INTRODUCTION AND BASIC STABILITY THEORY

CHAPTER 1

1.1 Overview of the Thesis Topic

An interconnected power system basically consists of several essential components. They are namely the generating units, the transmission lines, the loads, the transformer, static VAR compensators and lastly the HVDC lines [1]. During the operation of the generators, there may be some disturbances such as sustained oscillations in the speed or periodic variations in the torque that is applied to the generator. These disturbances may result in voltage or frequency fluctuation that may affect the other parts of the interconnected power system. External factors, such as lightning, can also cause disturbances to the power system. All these disturbances are termed as faults. When a fault occurs, it causes the motor to lose synchronism if the natural frequency of oscillation coincides with the frequency of oscillation of the generators. With these factors in mind, the basic condition for a power system with stability is synchronism. Besides this condition, there are other important condition such as steady-state stability, transient stability, harmonics and disturbance, collapse of voltage and the loss of reactive power

1.2 Definition of Stability of a System

The stability of a system is defined as the tendency and ability of the power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium [2].

Let a system be in some equilibrium state. If upon an occurrence of a disturbance and the system is still able to achieve the equilibrium position, it is considered to be stable.

The system is also considered to be stable if it converges to another equilibrium position in the proximity of initial equilibrium point. If the physical state of the system differs such that certain physical variable increases with respect to time, the system is considered to be unstable.

Therefore, the system is said to remain stable when the forces tending to hold the machines in-synchronism with one another are enough to overcome the disturbances. The system stability that is of most concern is the characteristic and the behavior of the power system after a disturbance.

1.3 Why the need for power system stability?

The power system industry is a field where there are constant changes. Power industries are restructured to cater to more users at lower prices and better power efficiency. Power systems are becoming more complex as they become inter-connected. Load demand also increases linearly with the increase in users. Since stability phenomena limits the transfer capability of the system, there is a need to ensure stability and reliability of the power system due to economic reasons.

1.4 Stability studies

The performance of a power system is affected when a fault occurs. This will result in insufficient or loss of power. In order to compensate for the fault and resume normal operation, corrective measures must be taken to bring the system back to its stable operating conditions. Controllers are used for this function. Some of the control methods used to prevent loss of synchronism in power systems are [19] [20]:

(1)Excitation control:

During a fault the excitation level of the generator drops considerably. The excitation level is increased to counter the fault.

(2) An addition of a variable resistor at the terminals of the generator. This is to make sure that the power generated is balanced as compared to the power transmitted.

(3) An addition of a variable series capacitor to the transmission lines. This is to reduce the overall reactance of the line. It will also increase the maximum power transfer capacity of the transmission line.

(4) Turbine valve control:

During a fault the electrical power output (Pe) of the generator decreases considerably. The turbine mechanical input power (Pm) is decreased to counter the decrease of Pe. Stability studies are generally categorized into two major areas: steady-state stability and transient stability [2]. Steady-state stability is the ability of the power system to regain synchronism after encountering slow and small disturbances. Example of slow and small disturbances is gradual power changes. The ability of the power system to regain synchronism after encountering small disturbance within a long time frame is known as dynamic stability. Transient stability studies refer to the effects of large and sudden disturbances. Examples of such faults are the sudden outrage of a transmission line or the sudden addition of removal of the loads. Transient stability occurs when the power system is able to withstand the transient conditions following a major disturbance.

When a major disturbance occurs, an imbalance is created between the generator and the load. The power balance at each generating unit (mechanical input power – electrical input power) differs from generator to generator. As a result, the rotor angles of the machines accelerate or decelerate beyond the synchronous speed of for time greater than zero ($t > 0$). This phenomenon is called the “swinging” of the machines. There are two possible scenarios when the rotor angles are plotted as a function of time:

(1) The rotor angle increases together and swings in unison and eventually settles at new angles. As the relative rotor angles do not increases, the system is stable and in synchronism.

(2) One or more of the machine angles accelerates faster than the rest of the others. The relative rotor angle diverges as time increase. This condition is considered unstable or losing synchronism.

These studies are important in the sense that they are helpful in determining critical information such as critical clearing time of the circuit breakers and the voltage level of the power system.

The main aim of this thesis project is to investigate the various power system stability problems, after which one important problem will be singled out for discussion and research. A proposed technique to solve the selected stability problem will also be explained in detail.

To maintain synchronism within the distribution system can proved to be difficult as most modern power system are very large. For the purpose of this thesis report, a simplified two machine infinite bus power system is studied.

1.5 Stability Theories

The aim of this thesis report is to investigate the various power system stability problems, the effect of a fault on the stability condition of the system and also the post-stability condition of the system. This section will discuss about the concept and theories of stability study. As mentioned previously, the main objective of stability studies is to determine whether the rotors of the machines being disturbed return to the original constant speed operation. There are three assumptions that are made in stability studies:

(i) We only consider the synchronous currents and voltages in the stator windings and the power system. DC offsets and harmonic components are also ignored.

(ii) To represent unbalanced faults, symmetrical components are used.

(iii) The generated voltage is considered to be unaffected by the speed variations of the machine.

1.6 Swing Equation

The Swing Equation governs the rotational dynamics of the synchronous machine in stability studies [2]. Under normal operating conditions, the relative position of the rotor axis and the resultant axis is fixed. The angle difference between the two axes is known as the power angle.

During disturbance to the machine, the rotor will accelerate or decelerate with respect to the synchronous rotating air gap mmf. The "Swing" equation describes this relative motion. If the rotor is able to resume its synchronous speed after this oscillation period, the generator will maintain its stability. The rotor will return to its original position if the disturbance is not created by any net changes in the power. However if the disturbance is created by a change in generation, load or network conditions, the rotor will be in a new operation power angle relative to the revolving field.

The Swing Equation (pu) is given as:

$2H\ d2\delta = Pm\ (pu) - Pe\ (pu)$

$Ws\ dt2$

Where H is pu inertia constant,

Ws is electrical synchronous speed

δ is electrical power angle

Pm is shaft mechanical power input

Pe is electrical power p

d2δ/ dt2 is angular acceleration or deceleration due to excess or deficit power

With this basic concept, we are now able to discuss and review the Equal Area Criterion concept in detail.

1.7 Equal Area Criterion

Equal Area Criterion is a stability method used for quick prediction of stability [16]. Based on the assumptions that the system is a purely reactive, a constant Pm and constant voltage behind transient reactance, it is found that if the transient stability limit is not exceeded, the electrical power angle δ oscillates around the equilibrium point with constant amplitude. Equal Area Criterion is the method which determines stability under transient conditions, without needing to solve the Swing Equation.

Originally the motor of the machine is operating at the synchronous speed with a torque angle of δ_0 . The mechanical power output P_{m0} is equal to the electrical power input P_e . When the mechanical load is suddenly increased so that the power output is P_{m1} , it is greater than the electrical power input at δ_0 . The difference in the power comes from the kinetic energy stored in the rotating system. Thus it results in a decrease in speed. When the speed decreases, it will cause the torque angle δ to increase.

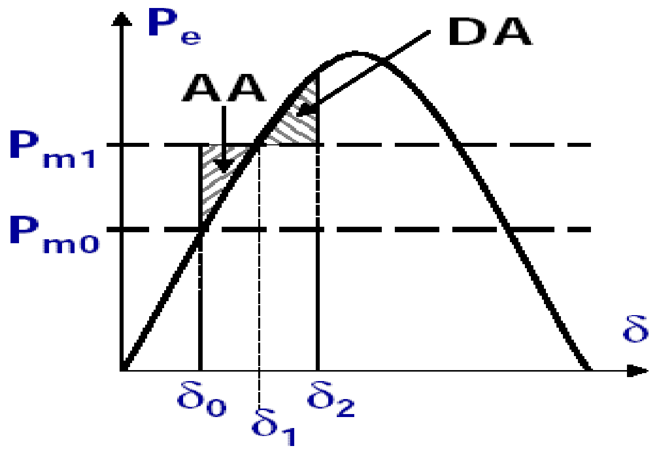


Figure 1: Electric power input to a motor as a function of torque angle δ

As δ increases, the electrical power received will increase to a point where $P_e = P_{m1}$. We shall name this Point B. After passing through Point B, the electrical power P_e is greater than P_{m1} . This will result in an increase in kinetic energy and speed. Thus between Point B and C, the speed will increase accordingly with δ , until the synchronous speed is again reached at Point C.

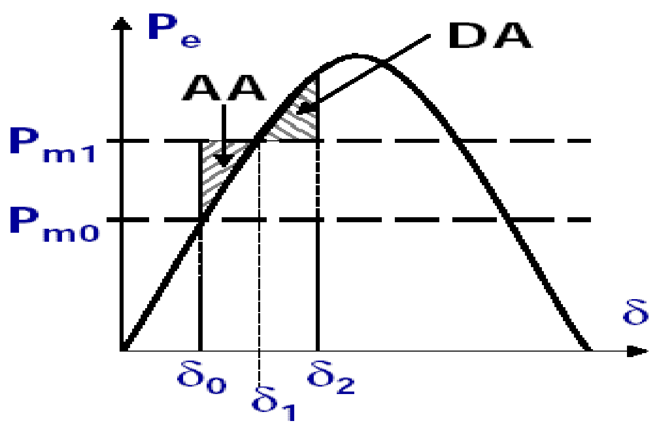


Figure 2: Electric power input to a motor as a function of torque angle δ . The diagram shows when the load is suddenly increased from P_{m0} to P_{m1} , the motor will oscillate around δ_1 and between δ_0 and δ_2 .

At Point C, the torque angle is δ_m . P_e is still greater than P_{m1} and the speed of the motor will continue to increase. However, δ will start to decrease as soon as the speed of the motor exceeds the synchronous speed. Therefore the maximum value of δ is at Point C.

As δ increases, Point B is reached again with the speed above the synchronous speed. The torque angle δ will continue to decrease until Point is achieved. This will imply that the motor is again operating at synchronous speed. The cycle is then repeated.

When the accelerating area (AA) is equal to the decelerating area (DA), the system is considered to be stable.

CHAPTER 2

ADVANCED STABILITY THEOREMS AND TECHNIQUES

CHAPTER 2

2.1 Lyapunov's Theorem

The stability of linear time-invariant systems can be determined by applying several known theorems such as Nyquist and Routh-Hurwitz. However, there was no systematic procedure to determine the stability of non-linear systems.

In 1892, A. M. Lyapunov founded the general framework for the solution for the stability of nonlinear systems. Lyapunov founded two approaches to the problem of stability. The first one was known as the Lyapunov's "First method" and the other was known as the "second method". The latter method is also commonly known as the Direct Method [12].

The principle idea of the Direct Method is as follow: If the rate of change dt/de of the energy $E(x)$of an isolated physical system is negative for every state x except for a single equilibrium state x_e ,then the energy will continue to decrease until it finally assumes its minimum value $E(x_e)$.

This idea was developed into a mathematical form by Lyapunov. The energy function of $E(x)$ was replaced by the scalar function $V(x)$. For a given system, if $V(x)$ is always positive except at $x = 0$ and its derivative $\dot{V}(x)$ is less than 0 except at $x = 0$, then we say that the system has returned to the origin if it is disturbed. The origin is said to be stable if there exist a scalar function $V(x) > 0$ in the neighborhood of the origin such that $\dot{V}(x)$ is less than or equal to 0 in that origin. The function $V(x)$ is known as the Lyapunov function. The system equations are as shown below:

$$x = f(x),\ f(0) = 0$$

$$\dot{V}(x) = \frac{\partial V}{\partial x_1}\frac{dx_1}{dt} + \frac{\partial V}{\partial x_2}\frac{dx_2}{dt} \ldots\ldots \frac{\partial V}{\partial x_n}\frac{dx_n}{dt}$$

$$= < \frac{\partial V}{\partial x}, \dot{x} >$$

$$= < \mathrm{GradV}, x > = < \mathrm{GradV}, f(x) >$$

2.2 Definition of stability

An undisturbed motion x_s is considered to be stable when the disturbed motion remains close to the undisturbed motion after encountering small disturbance. To elaborate on the above statement:

(1) If small disturbances were encountered and the effect on the motion is small, the undisturbed motion is considered to be stable

(2) If small disturbances were encountered and the effect on the motion is considerable, the undisturbed motion is termed “unstable”.

(3) If small disturbances were encountered and the effect tends to disappear, the disturbed motion is considered “asymptotically stable”.

(4) If regardless of the magnitude of the disturbances and the effect tends to disappear, the disturbed is considered “asymptotically stable in the large”.

2.2.1Definition 1

The origin is said to be stable in the sense of Lyapunov if for every real number $\varepsilon > 0$ and initial time $t_c > c$, there is a real number $\delta > 0$ which is dependent on ε and on t such that for all initial conditions it satisfy the following criteria:

$$\|x_0\| < \delta$$

And the motion satisfies.

$$\|x(t)\| < \varepsilon \quad \text{for all } t > t_0$$

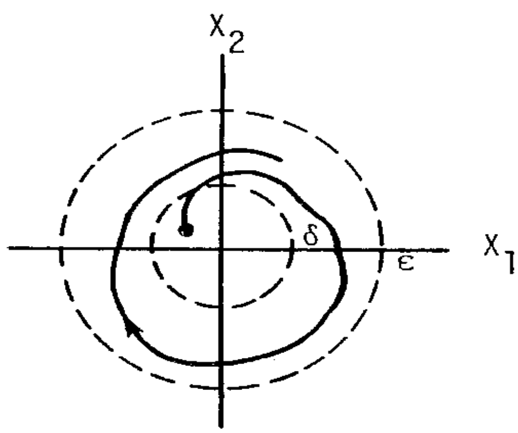


Figure 3: Geometrical illustration of Stability

The geometrical illustration of the definition is shown above. This stability concept of Lyapunov is a local concept as it does not indicate the value of δ that is to be chosen. The origin is considered to be unstable if the above condition is not satisfied.

2.2.2Definition 2

The origin is said to be asymptotically stable if it is stable and that every motion starts close to the origin and converges to the origin as t tends towards infinity.

$$\lim_{t \to \infty} \|x(t)\| \longrightarrow 0$$

However this definition does not indicate the magnitude of the disturbances in order for the motions to converge to the origin. This definition is also considered a local concept. The geometrical illustration of Asymptotic Stability is shown below.

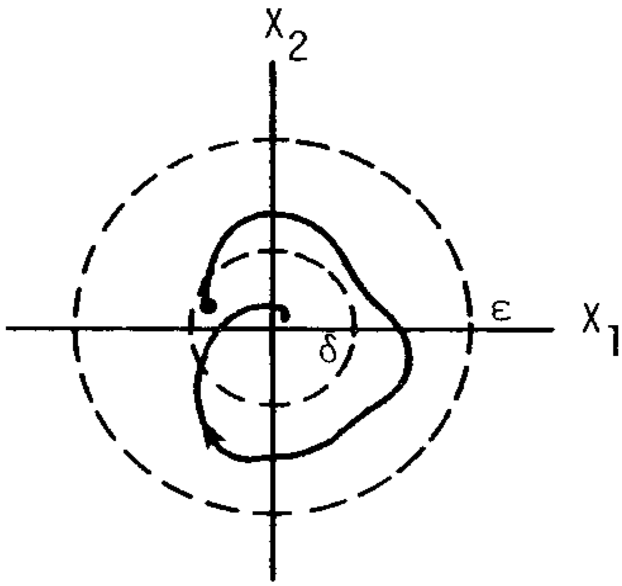


Figure 4: Geometrical illustration of Asymptotic Stability

2.2.3Definition 3

The origin is said to be asymptotically stable in the large when it is asymptotically stable and every motion starting at any point in the state space returns to the origin as t tends towards infinity. The geometrical illustration is shown below.

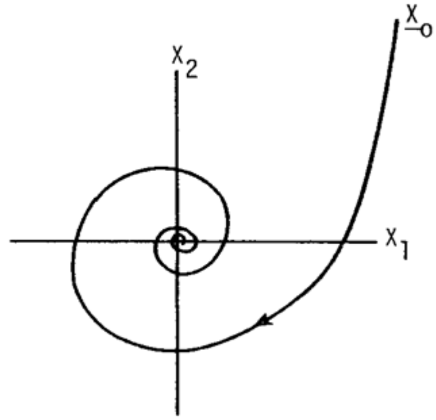


Figure 5: Geometric illustration of Asymptotic stability in the large

This definition is useful in power system as the magnitude of the disturbance need not be considered.

2.2.4Definition 4

A function V(x) is considered to be positive definite if V(x) = 0 and if it is around the origin V(x)

$$\geq 0 \text{ for } x \neq 0 .$$

2.2.5Definition 5

A function V(x) is considered to be positive semi-definite if V(0) = 0 and if it is around the origin

$$V(x) \geq 0.$$

2.3 Lyapunov function for Linear Time Invariant System

In this section we will examine the stability of linear time invariant system using the Lyapunov'smethod [12]. First let us consider a system:

$$X=Ax$$

Let the origin of the system be the only equilibrium point. The stability of the system can be examined by solving the eigenvalues of A and see whether any of it is in the right half plane. The stability of the system can also be determined by using the Routh Hurwitz method. However both methods failed to give insight into the class of A matrices that are stable, and the Lyapunov function is able to provide such information. By constructing the Lyapunov function of a quadratic form, we are able to obtain the conditions that affect the stability of the system.

Consider the following matrix equation:

$$A^T + PA = -Q$$

where $A = n \times n$ matrix

P and Q = symmetric n x n matrices

Let $\lambda_1, \lambda_2, \ldots \lambda_n$ be the eigen values of the matrix A. The above equation has a unique solution for P if and only if:

$$\lambda_i + \lambda_j \neq 0 \text{ for all I, j} = 1, 2, \ldots, n$$

This will indicate that when A has no zero eigenvalues and no real eigenvalues which are of opposite sign, there is a unique solution. The system will satisfy the Lyapunov matrix equation if the matrix A has no eigenvalues with positive real parts and has some distinct eigenvalues with zero real parts for a given $Q > 0$ and $P > 0$.

2.4 Lyapunov function for Nonlinear System

As we have examined in the previous section for a time linear invariant system, there is a systematic approach to solving for the stability of the system using the Lyapunov function. This section will attempt to examine a few different methods used to construct the Lyapunov functions for nonlinear systems [12]. The methods are as follow:

1. The method based on first integrals
2. The method based on quadratic forms
3. The method based on solving the partial differential equation
4. The method based on quadratic and integral of non-linearity type Lyapunov function

Several of the methods will be explained and discussed in details.

2.4.1Method based on first integrals

The basis of this method is to construct the Lyapunov functions using the linear combination of the first integrals of the system equations. Let us consider the following equation:

$$x_i = f_i(x_1, x_2, \ldots\ldots, x_n)$$

$$\text{we can also say that } f(x) = x$$

$$f(0) = 0$$

We understand that an integral is a differentiable function $G(x_1, x_2, \ldots.. x_n)$ defined in Domain D of the state space such that when $x2_i$s establish a solution, $G(x_1, x_2, \ldots.. x_n)$will have a constant value C. A conservative system can be defined by the existence of a first integral. A necessary condition to have a first integral is as follow.

$$\sum_{i=1}^{n} \frac{\partial f_i}{\partial x_i} = 0$$

2.4.2 Method based on quadratic form

The basis of this method is that the Lyapunov function is of the form of $x^T A(x)x$. This method is also known as the Krasovskii's method. Let us consider the autonomous system below:

$x = f(x), f(o) = 0$

Let us assume that f(x) has continues first partial derivatives. The Jacobian matrix is defined as follow

$$= \frac{\partial f}{\partial x} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} \cdots\cdots\cdots \frac{\partial f_1}{\partial x_n} \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ \frac{\partial f_n}{\partial x_1} \cdots\cdots\cdots \frac{\partial f_n}{\partial x_n} \end{bmatrix}$$

:

Let's define the Q(x) matrix is defined as Q(x) = P J(x) + J_T (x) P.

if a positive definite matrix P is obtained such that the Q(x) matrix is negative definite, then the Origin of the system is considered to be asymptotically stable in the large.

Let us consider the Lyapunov function below:

$$V(x) = f^{T} P F$$

The assumption is made that the function is positive definite in the f space. V(x) is also positive definite in the x space as there is a one to one mapping between the x space and the f space. The derivative of V(x) is as follow:

$$V(x) = \dot{f}^T Pf + f^T P\dot{f}$$

By applying chain rule,

$$\dot{f}(x) = J(x)\dot{x}$$
$$= J(x)\ f(x)$$

therefore,

$$\dot{V}(x) = f^T[J^T(x)P + PJ(x)]f$$

V& (x) is considered negative definite as the term inside the bracket of the equation above is negative definite. Therefore the origin is asymptotically stable in the large.

2.4.3 Methods based on Variable Gradient Method

The basis of this method is that a vector ∇V is assumed to have undetermined components. Both the V and V can be determined from the gradient function. Let's consider the following equation:

$$\frac{dV}{dt} = \frac{\partial V}{\partial x_1}\dot{x}_1 + \ldots\ldots \frac{\partial V}{\partial x_n}\dot{x}_n$$
$$= < \nabla V, \dot{x} >$$

And

$$V = \int_0^x < \nabla V, dx >$$

As the upper limit of the integral is x, it indicates that the line integral is to an arbitrary point in the x space. It is also independent of the path of the integration.

In order to determine the gradient ∇V, there are certain procedures to the construction of V(x).

They are as follow:

1. The n dimensional curl of ∇V is zero.
2. V and V is determined from ∇V for $V > 0$ and $V < 0$. If $V < 0$, then actions must be taken to ensure that it is not zero along any other solution other than the origin.

The matrix ∇V will be in the form of:

$$\nabla V = \begin{bmatrix} \alpha_{11}(X) & \alpha_{12}(X) & \cdots\cdots & \alpha_{1n}(X) \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ \alpha_{n1}(X) & \alpha_{n2}(X) & \cdots\cdots & \alpha_{nn}(X) \end{bmatrix} \begin{bmatrix} X_1 \\ . \\ . \\ . \\ X_n \end{bmatrix}$$

The αij s consist of a constant term αijk and a variable term αijv. The parameters may be considered to be constant unless cancellation or the generalized curl equations require a more complicated form. After obtaining the variable gradient the dV/dt equation will be formed, where

$$\frac{dV}{dt} = < \nabla V, f(x) >$$

The dV/dt equation is constrained to be negative semi-definite. This will also give some constraint on the coefficients. The curl equation is used to determine the remaining unknown coefficients. We are then able to determine V from the known gradient. Lastly by applying the necessary theorem, we are able to the condition of stability of the system.

2.4.4Method based on Zubov's Method

This method is not only able to generate the Lyapunov function but it is also able to construct a region of attraction or an approximation to it. The method is based on solving a linear partial differential equation. When the solution obtained is if a closed form, we would have a unique Lyapunov function and an exact stability region. However, if the solution obtained is not of closed form, we would then solve for a series solution. In this way we are also able to get an approximation to the exact stability region. The theorem of this method is explained in the following.

First we would let U be a set containing the origin. The conditions for U to be the exact domain of attraction such that the two functions V(x) and θ(x) are:

1) V(x) is defined and continuos in U. θ(x) is defined and continuos in the entire state space.

2) θ(x) is positive definite for all x.

3) V(x) is positive definite in U with V(0) = 0.

4) On the boundary of U, V(x) = 1.

5) The following partial differential equation is satisfied.

$$\sum_{i=1}^{n} \frac{\partial V}{\partial x_i} f_i(x) = -\theta(x)(1 - V(x))(1 + \|f\|^2)$$

As it is not possible to expect a closed form solution from the partial differential equation, the series solution is used to counter this problem. The equation x& = f(x)may be expanded into the following:

$$x = Ax + g(x)$$

Where A is the linear part of the equation and g(x) is of second degree or higher. A is assumed to be stable and has all eigenvalues with negative real parts. $\phi(x)$ is chosen to be a positive definite quadratic form. The solution of the partial differential equation is as follow:

$$\sum_{i=1}^{n} \frac{\partial V}{\partial x_i} f_i(x) = -\varphi(x)(1 - v(x)$$

and

$$V(x) = V2(x) + V3(x) + ...$$

where $V_2(x)$ is quadratic in x and $V_m(x)$, where m = 3,4,5, …, are homogenous in degree m, meaning V_m (© x) = $\gamma_m V(x)$ for any constant γ . In order to find $V_m(x)$, the original system differential equation is substituted with the above equation. Due to the assumption made on g(x) and Vm(x) , V2(x) is the Lyapunov function for the linear equation. Therefore,

$$x = Ax$$

Vm(x) can be obtained from:

$$\sum_{i=1}^{n} \frac{\partial V_m}{\partial x_i} f_i(x) = R_m(x)$$

2.4.5Other methods for nonlinear systems

Previously we have examined the various methods that are used to determine the stability of the nonlinear systems that have no restrictions on the nonlinearities. However there are some scenarios where there are restrictions to the nonlinearities. This occurs when the nonlinearity lies in the first and the third quadrant or in a section thereof. A systematic approach will then be possible to construct the Lyapunov function. This section will attempt to examine one of the methods that are used to obtain the stability of such system.

2.4.5.1Popov's Theorem

Let's consider the system below:

$$\dot{x} = Ax + b\xi$$
$$\xi = -\varphi(\sigma)$$
$$\sigma = c^T x$$

Where A is a n x n matrix,

x, b and c are n-vectors

$\phi(\sigma)$ is a nonlinearity which lies in the first and third quadrant

The block diagram of the system is shown below.

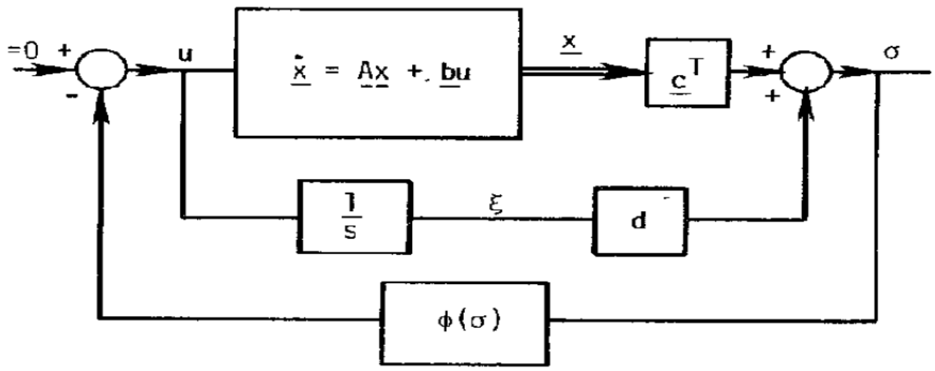


Figure 6: Block diagram of the system

The transfer function of the system is:

$$G(s) = \frac{\sigma(s)}{\xi(s)} = c^T(sI - A)^{-1}b$$

G(s) will have all poles with negative real parts if matrix A is a stable matrix. We will now look at the special cases where G(s) has poles which are on the imaginary axis. The case that we are examining is that G(s) has a single pole at the origin. This implies that matrix A has a zero eigenvalue. Therefore the state space is:

$$\begin{bmatrix} \dot{x} \\ \dot{\xi} \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \xi \end{bmatrix} + \begin{bmatrix} b \\ 1 \end{bmatrix} u$$

where $u = -\phi(\sigma)$

$\sigma = c^T x + d\xi$

The system is absolutely stable for all nonlinearities when the following sector condition is satisfied:

$0 < \phi(\sigma) < k\sigma^2$

or when a finite real q exist such that:

$$\frac{1}{k} + \mathrm{Re}\{(1 + j\omega q)G(j\omega)\} > 0 \qquad \text{for all } \omega \geq 0$$

$$\text{and } d > 0$$

One of the advantage of the Popov's method is that we are able to construct the Lyapunov function in a systematic manner if we can establish absolute stability. The Lyapunov function is the quadratic and the integral of the nonlinearity. The construction of the Lyapunov function through the solution of nonlinear algebraic equations is as follow:

$$A^T P + PA = -\varepsilon Q - uu^T$$

$$Pb = \frac{1}{2}\beta A^T c + \alpha dc + [\beta(c^T b + d)]^{\frac{1}{2}} u$$

where $q = \dfrac{\beta}{2\alpha d}$,

$\varepsilon \geq 0$ and small and

u is the (n-1) vector

We will be able to obtain the solution for q if the Popov's criterion is satisfied. Thus the solution of the Lyapunov function will be in the form of:

$$V(x) = x^T P x + \frac{1}{2} d\xi^2 + q\int_0^{\sigma} \varphi(\sigma) d\sigma$$

2.5 Continuation Method

The Continuation Method is used to determine proximity to saddle-node bifurcations in dynamic system [17]. The principle behind the Continuation Method is that if a set of equations is underdetermined, where a single parameter is free to vary and the system is under constrained, the results of the solution will be curves and not points. The purpose of the Continuation Method is to determine the curves. In this section, a brief explanation of this method will be discussed.

The continuation method uses a three-step approach to solve for the equilibrium points. As mentioned earlier, one of the parameter in the system is free to vary. The method is used to find the solution to the power flow equations for a given set of parameter values. The power flow equation is shown as follow:

$$f(z, \lambda) = 0$$

The loading factor λ is the varying parameter. However, the classical power flow Jacobian becomes unsatisfactory as the system gets closer to bifurcation. A parameterization will convert the Jacobian into non singular at the voltage collapse point.

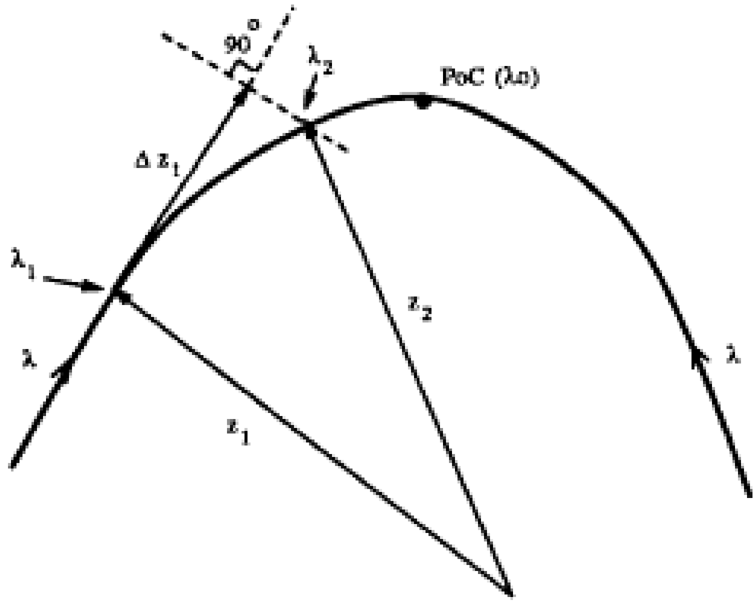


Figure 7: Continuation method in state space and parameter space

The figure above shows the Continuation method geometry in state space and parameter space. The boldface curve represents the system equilibria as the parameters of the system changes. Let's assume that the system is initially at the state (z_1, λ_1). The new equilibria (z_2, λ_2) can be predicted by using $\Delta\lambda$ and the scaled tangent vectorΔz_1 , where $\Delta\lambda$ and Δz is given by:

$$\Delta\lambda = \frac{k}{\|dz/d\lambda\|} \qquad \text{and}$$

$$\Delta z = \Delta\lambda \frac{dz}{d\lambda}$$

Where k = scaling constant

The following steps are used to obtain the actual values of z2 and λ2.

2.5.1 Predictor

The purpose of this procedure is to find the step Δz^ and Δp . The equation is given as below.

$$D_{\hat{z}} f(\hat{z}_1, p_1) \frac{d\hat{z}}{dp} = -\frac{\partial f}{\partial p}\bigg|$$

Therefore, by setting parameter p to λ and the state variable z^ to z,

$$\Delta p = \frac{k}{\left\| d\hat{z}/dp \right\|} \qquad \text{and}$$

$$\Delta \hat{z} = \Delta p \frac{d\hat{z}}{dp}\bigg|$$

The parameter p is likely to change to one of the bus voltage as the process approaches bifurcation and the loading factor λ will become part of *z*^ .

2.5.2 Corrector

The purpose of this procedure is to find the intersection between the perpendicular plane to the tangent and the branch. The equations are as follow.

f(z^,p) = 0

Δp(p p Δp) Δz^ (z^ z^1 Δz^) 0

The values of p_1 and $\hat{z}_1$ are obtained from the previous iteration. By setting the initial value of $\hat{z}$ to $\hat{z}_1 + \Delta\hat{z}$ and p to $p_1 + \Delta p$, the equations above can be solved by one or two iterations.

2.5.3 Parameterization

This procedure is to check the relative changes in all system variables. The parameter p is then traded with the variable that presents the largest change.

The Jacobian of equations is non-singular at the point of bifurcation. This is done by changing the parameter p from λ to a state variable $z_i \in z$. The tangent vector $dz/d\lambda$ is a scaled version of the right eigenvector v at the bifurcation point.

As the method naturally goes around the collapse point, we are able to find the unstable side of the branch.

CHAPTER 3

MODELLING OF POWER SYSTEM

CHAPTER 3

3.1 Basic Control Theory

In a control function block, the various parts of the system are broken down into the following function blocks.

(1) The plant, which is the transmission network

(2) The fault module

(3) The control system, which is the controller

The plant module consists of all the basic function of the transmission system. However it does not include the controller function. Thus the plant module is considered an open loop system as it has no feedback capability. The plant module will also only react to the faults with its own natural dynamics and damping system as it has not have any form of corrective functions.

The function of the fault module is to provide the new line impedances and voltages when the fault occurs. The fault module will only generate one value of the line impedance, depending on the location of the fault. The plant module will then receive this value when there is an occurrence of the fault. Otherwise, the plant module will use its original value of line impedance.

The controller module provides the feedback to the plant so that adjustment can be made to sustain the fault and regain its synchronism. The block diagrams of a system without controller and a system with control are shown as below.

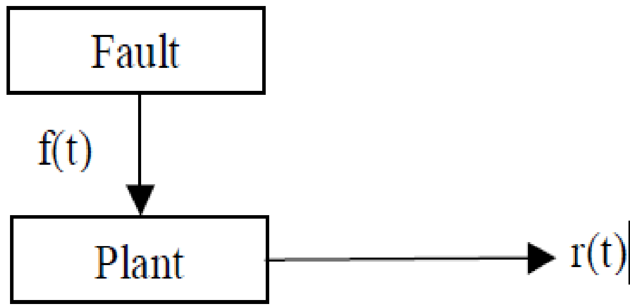


Figure 8: Block diagram of system without control module

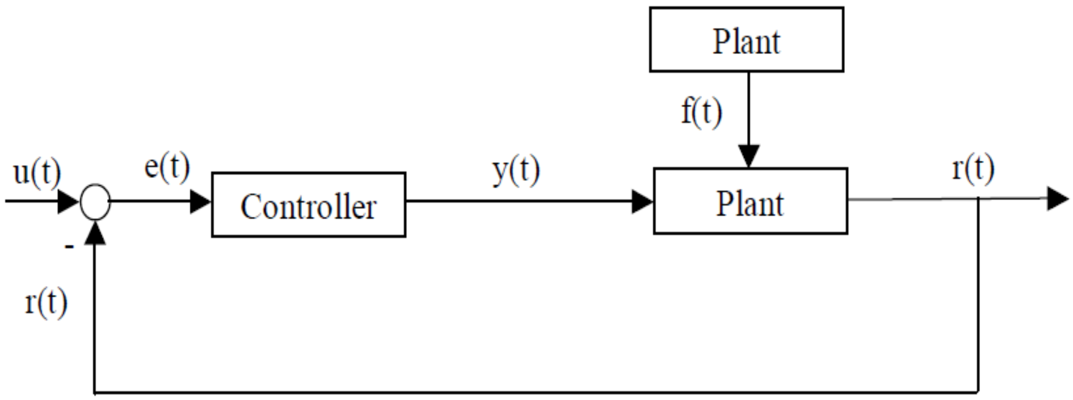


Figure 9: Block diagram of system with controller

The block diagram in Figure is a simplified closed loop control system. The output of the system r(t) is sent back to the comparator to be compared with the input u(t). The difference between the feedback and the input e(t) is then fed to the controller. The controller will perform and output the necessary control output y(t) to the plant module. The fault module, which acts as a disturbance, is also fed into the plant module. The cycle is then repeated.

3.2 Power System Modeling

The power system modeling is based on a two-machine, three bus power system. The performance of the power system will be simulated with the proposed advanced control technique, Nonlinear Decentralized Controller [18]. The operating points and system parameters will be varied to test the robustness of the power system and the effectiveness of the proposed controller. The diagram of the model is shown below..

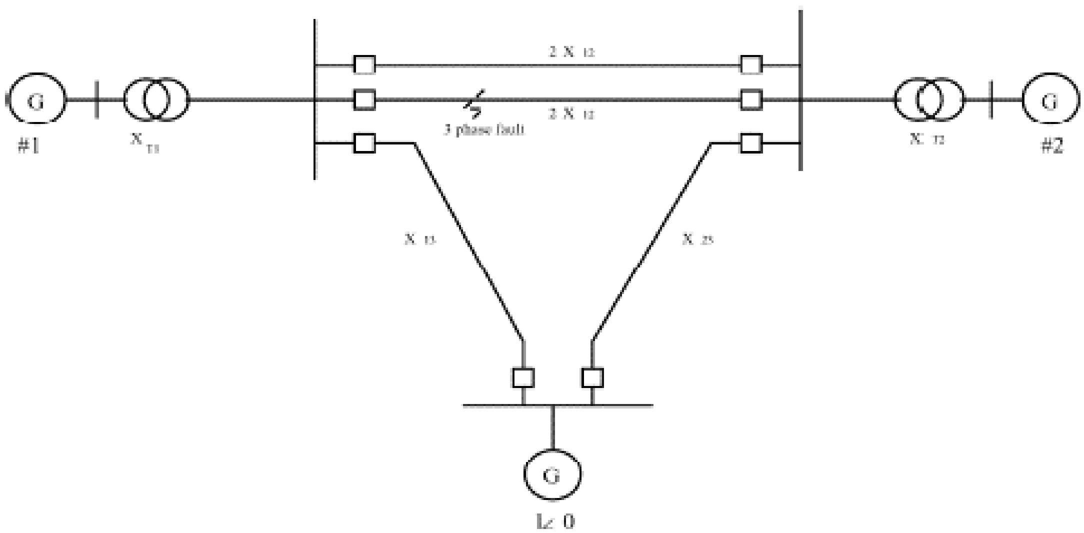


Figure 10: Two-machine infinite bus power system

3.3 Power system dynamic model

Power System Plant Model [18]

Mechanical Equations:

$$\delta_i = \omega_i \tag{1}$$

Swing equation:

$$\dot{\omega}_i = -\frac{D}{2H_i}\omega_i + \frac{\omega_0}{2H_i}\left(P_{mi} - P_{ei}\right) + d_i \tag{2}$$

Generator electrical dynamics:

$$\dot{E}'_{qi} = \frac{1}{T'_{doi}}\left(E_{fi} - E_{qi}\right) \tag{3}$$

Turbine Dynamics:

$$\dot{P}_{mi} = \frac{1}{T_{mi}}P_{mi} + \frac{K_{mi}}{T_{mi}}X_{ei} \tag{4}$$

Turbine valve control:

$$\dot{X}_{ei} = -\frac{K_{ei}}{T_{ei}R_i\omega_0}\omega_i - \frac{1}{T_{ei}}X_{ei} + \frac{1}{T_{ei}}P_{ci} \tag{5}$$

Electrical equations:

$$E_{qi} = E'_{qi} + \left(x_{di} - x'_{di}\right)I_{di}, \tag{6}$$

$$E_{fi} = K_{ci}u_{fi}, \tag{7}$$

$$P_{ei} = \sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\sin(\delta_i - \delta_j), \tag{8}$$

$$Q_{ei} = -\sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\cos(\delta_i - \delta_j), \tag{9}$$

$$I_{di} = -\sum_{j=1}^{n} E'_{qi}B_{ij}\cos(\delta_i - \delta_j), \tag{10}$$

$$I_{qi} = \sum_{j=1}^{n} E'_{qj}B_{ij}\sin(\delta_i - \delta_j), \tag{11}$$

$$E_{qi} = x_{adi}I_{fi}, \tag{12}$$

$$V_{ti} = \sqrt{(E'_{qi} - x'_{di}I_{di})^2 + (x'_{di}I_{qi})^2} \tag{13}$$

Excitation control loop:

By applying direct feedback linearization compensation,

$$\delta_i = \omega_i$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}\omega_i - \frac{\omega_0}{2H_i}\Delta P_{ei} + d_i$$

$$\Delta\dot{P}_{ei} = -\frac{1}{T'_{doi}}\Delta P_{ei} + \frac{1}{T'_{doi}}V_{fi} + \gamma_i(\delta, \omega), \tag{14}$$

where

$$\Delta P_{ei} = P_{ei} - P_{mi0}, \tag{15}$$

$$\gamma(\delta,\omega) = E'_{qi}\sum_{j=1}^{n} \dot{E}'_{qj}B_{ij}\sin(\delta_i-\delta_j) - E'_{qi}\sum_{j=1}^{n} \dot{E}'_{qj}B_{ij}\cos(\delta_i-\delta_j)\omega_j \qquad (16)$$

$$V_{fi} = I_{qi}K_{ci}U_{fi} - (x_{di} - x'_{di})I_{qi}I_{di} - P_{mi0} - T'_{d0i}Q_{ei}\omega_i \qquad (17)$$

Assuming no load condition,

$$\left|E'_{qi}E'_{qj}B_{ij}\right| \le \left|P_{ei}\right|_{max}, \qquad (18)$$

$$\left|\dot{E}'_{qj}\right| \le \left|\frac{1}{T'_{d0j}}[E_{fi} - E_{qi}]\right|_{max} \le 4\left|E_{qi}\right|_{max}\frac{1}{\left|T'_{d0j}\right|_{min}} \qquad (19)$$

which is followed by

$$\left|\gamma_i(\delta,\omega)\right| \le \sum_{j=1,j\ne i}^{n} \frac{4}{\left|T'_{d0j}\right|_{min}}\left|P_{ei}\right|_{max}\left|\sin(\delta_i-\delta_j)\right| + \sum_{j=1}^{n} \left|Q_{ei}\right|_{max}\left|\omega j\right|$$

$$\le \sum_{j=1,j\ne i}^{n} \frac{4P_{1ij}}{\left|T'_{d0j}\right|_{min}}\left|P_{ei}\right|_{max}(\left|\sin\delta_i\right| + \left|\sin\delta_j\right|) + \sum_{j=1}^{n} P_{2ij}\left|Q_{ei}\right|_{max}\left|\omega j\right|$$

$$= \sum_{j=1}^{n} (\gamma_{i1j}\left|\sin\delta_j\right| + \gamma_{i2}\left|\omega j\right|), \qquad (20)$$

where

$$\gamma_{i1j} \overset{\Delta}{=} \begin{cases} \sum_{j=1, j\neq i}^{n} \dfrac{4P_{1ij}}{|T'_{d0j}|_{min}} |P_{ei}|_{max} \\ \dfrac{4P_{1ij}}{|T'_{d0j}|_{min}} |P_{ei}|_{max} \end{cases}$$

$$\gamma_{i2} \overset{\Delta}{=} P_{2ij} |Q_{ei}|_{max} \tag{21}$$

Steam valve control loop:

$$\dot{\delta} = \omega_i$$

$$\dot{\omega}_i = -\frac{D_i}{2H_i}\omega_i + \frac{\omega_0}{2H_i}[P_{mi} - g_i(\delta)] + d_i$$

$$\dot{P}_{mi} = -\frac{1}{T_{mi}}P_{mi} + \frac{K_{mi}}{T_{mi}}X_{ei}$$

$$\dot{X}_{ei} = -\frac{K_{ei}}{T_{ei}R_i\omega_0}\omega_i - \frac{1}{T_{ei}}X_{ei} + \frac{1}{T_{ei}}u_i, \tag{22}$$

where

$$g_i(\delta) = \sum_{j=1}^{n} E'_{qi}E'_{qj}B_{ij}\sin(\delta_i - \delta_j), \tag{23}$$

$$u_i = P_{ei} \tag{24}$$

Using the parameters stated in (18), we can express $g_i(\delta)$ (the interconnected term) as the following nonlinear function regardless of uncertain $E2_{qi}, E2_{qj}$ and network parameters.

$$\begin{aligned} |g_i(\delta)| &\le \sum_{j=1, j\neq 1}^{n} |P_{ei}|_{max} |\sin(\delta_i - \delta_j)| \\ &\le \sum_{j=1, j\neq 1}^{n} P_{1ij} |P_{ei}|_{max} (|\sin\delta_i| + |\sin\delta_{j1}|) \\ &\le \sum_{j=1}^{n} g_{ij} |\sin x_{j1}|, \end{aligned} \tag{25}$$

where

$$g_{ij} \overset{\Delta}{=} \begin{cases} \sum_{j=1, j\neq 1}^{n} P_{1ij} |P_{ei}|_{max} & \text{when } j=1 \\ P_{1ij} |P_{ei}|_{max} & \text{when } j\neq 1 \end{cases} \tag{26}$$

The parameters that are used in the power system modeling are as shown below [18]:

ω_0 (rad/s) = 314.159

x_{12}(p.u.) = 0.55

x_{13}(p.u.) = 0.53

x_{23}(p.u.) = 0.6

Generator 1.

xd(p.u.) =1.863
x2d(p.u.) = 0.257
xT(p.u.) = 0.129
xad(p.u.) =1.712
T2d0(p.u.) = 6.9
H(s) = 4
D(p.u.) = 5
Tm(s) = 0.35
Te(s) = 0.1
R = 0.05
Km =1.0
Ke =1.0
kc =1

Generator 2.

xd(p.u.) = 2.36
x2d(p.u.) = 0.319
xT(p.u.) = 0.11
xad(p.u.) =1.712
T2d0(p.u.) = 7.96
H(s) = 5.1
D(p.u.) = 3
Tm(s) = 0.35
Te(s) = 0.1
R = 0.05
Km =1.0

Ke =1.0
kc =1

3.4 Nonlinear Decentralized Control Scheme

Power systems are often modeled as large nonlinear highly structured system. This is due to the fact that the function of conventional linear control is limited as it can only deal with small disturbances about an operating point. Due to the physical limitations on the system structure, information transfers between the subsystems are unfeasible. In order to solve this problem, decentralized controllers are applied.

The proposed controller that is used for the power system modeling is the Nonlinear Decentralized Controller [18]. The excitation control and steam valve control are designed to enhance the transient stability. The design of the excitation control of the controller involves the application of robust back stepping. By bounding the interconnections with nonlinear functions instead of bounding them with first-order polynomials, conservatism of the controller gain is reduced.

Persistent disturbances, such as permanent symmetrical three-phase short circuit fault and load changes, are applied to the system. The decentralized power controllers are then applied to restore and maintain the transient stability of the closed-loop system.

The equations of the nonlinear decentralized controller are as follow:

$$v_{f1} = 19.68(\delta_1 - \delta_{10}) + 20.60\omega_1 - 93.81(P_{e1} - P_{m10})$$

$$v_{f2} = 19.69(\delta_2 - \delta_{20}) + 21.45\omega_2 - 73.95(P_{e2} - P_{m20})$$

CHAPTER 4

Simulation results

CHAPTER 4

4.1 Overview

In this chapter, the power system model in Chapter 3 is simulated with the derived equations using the software MATLAB. The simulation results reflect the condition power system model when the fault occurs and the condition power system model with controller when the fault occurs. Various parameters are also varied and the results are catogorised into 5 different cases.

In each case, both the simulation of system without controller and system with controller are examined. The simulation results consist of the relative speed, the power angle, the control input, the electrical power Pe and the terminal voltage Vt. The results of the simulations and their effects are then discussed.

4.2 Simulation of system model

4.2.1CASE 1

The parameters of the transmission line are shown as below:
Reactance of transmission line X12 = 0.55p.u.
Reactance of transmission line X13 = 0.53p.u.
Reactance of transmission line X23 = 0.6p.u.
Power angle δ10 = 60.78
Power angle δ20 = 60.64
Mechanical power Pm10 =1.10p.u.
Mechanical power Pm20 =1.01p.u.
Terminal voltage of generator Vt10 = 1.0p.u.
Terminal voltage of generator Vt20 = 1.0p.u.
Fault position λ = 0.2

Simulation of results without Controller
Subsystem 1

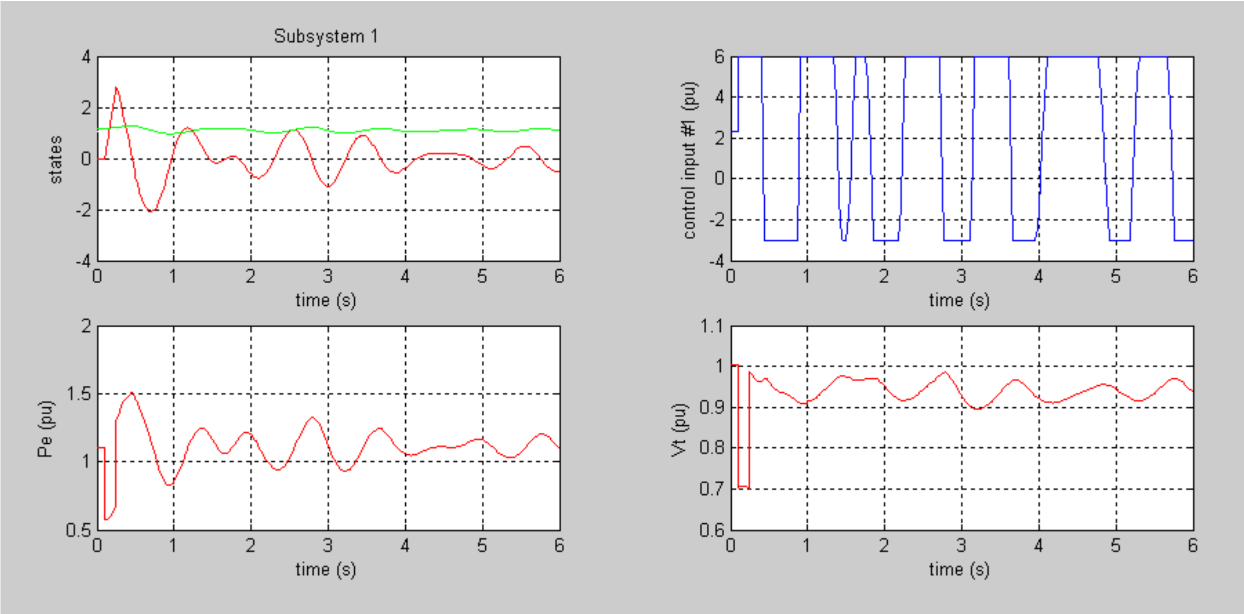


Figure 11: Case 1: Results of Subsystem 1 without controller

Subsystem 2

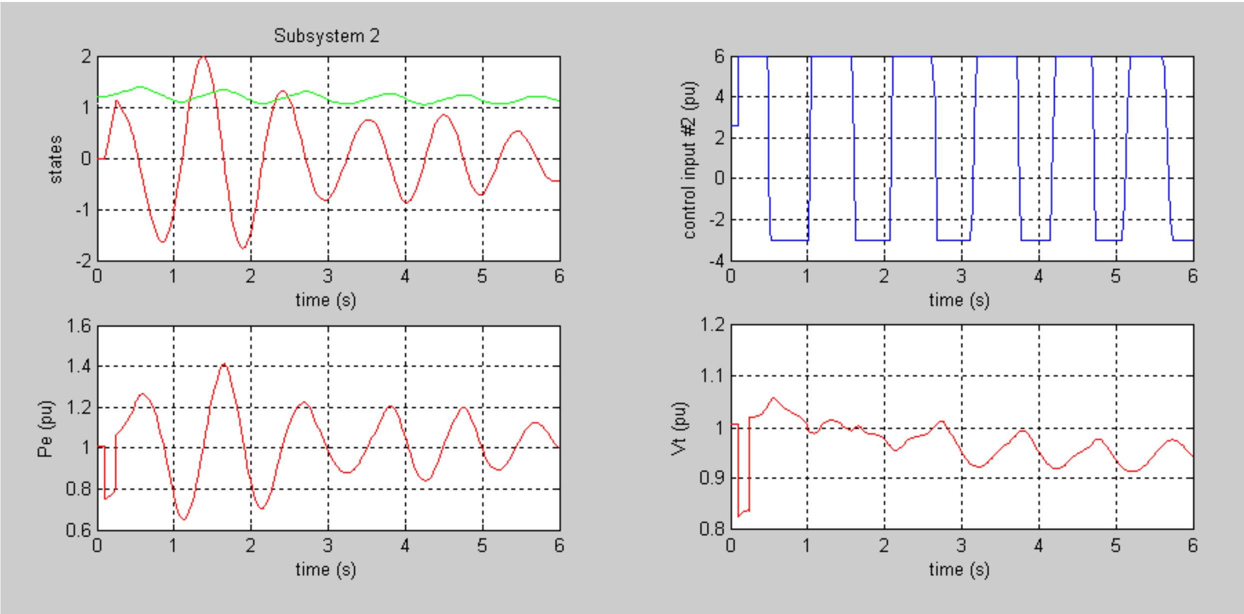


Figure 12: Case 1: Results of Subsystem 2 without controller

Firstly, the simulation result for the system model without the controller is examined. When the symmetrical three-phase short circuit fault occurs at the transmission line between Generator 1 and Generator 2 at $\lambda = 0.2$, the condition of the system is very unstable. The dynamics of the system is expected to change accordingly after occurrence of the fault. From the equations that were given in Chapter 3, we can see that when there are changes in the network impedances, there is an affect on the EMF in the quadrature axis Eq. This will in turn affect the value of the electrical power Pe. With the change in Pe, the swing equation will change accordingly and the acceleration of the system will be affected. Likewise, both the power angle δ and relative speed ω will be affected.

From Figure 5 and Figure 6, we can see that at the approximately t = 0.1 sec, there are changes to the system conditions. When the three phase symmetrical fault occurs at t = 0.1 sec, we can see a sudden drop in Pe due to the reduction in line impedances. Also, as the current at the line where the fault occur is able to find another route with relatively less impedance to flow, it results in the fluctuation in Vt. The oscillation shown in the relative speed and the power angle is the result of the natural damping of the system. The system tries to regain synchronism after encountering the fault.

Simulation of results with Nonlinear Decentralized Controller
Subsystem 1

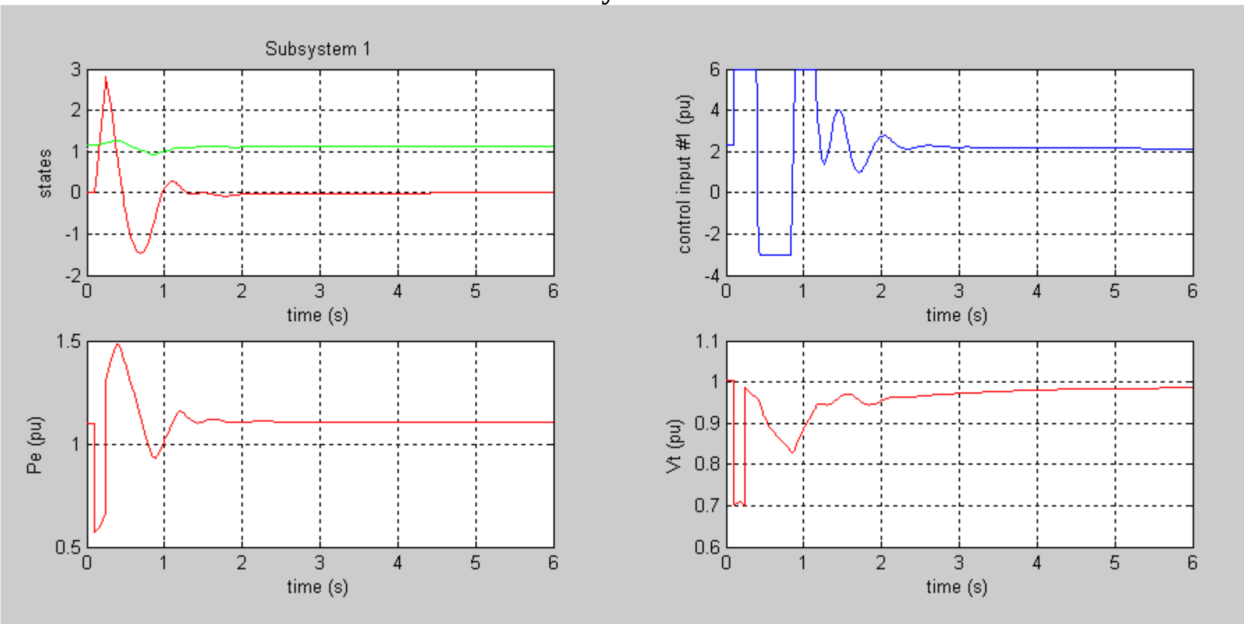


Figure 13: Case 1: Results of Subsystem 1 with controller

Subsystem 2

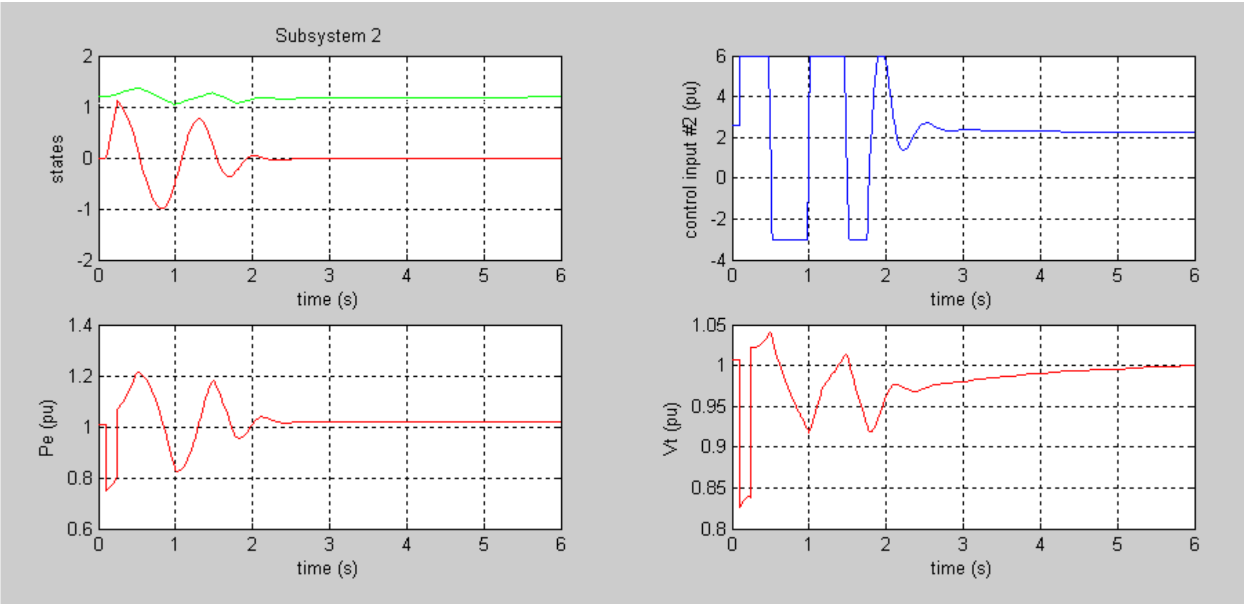


Figure 14: Case 1: Results of Subsystem 2 with controller

When the nonlinear decentralized controller is applied to the system model, there is a significant improvement in the condition of the system. The controller improved the transient stability of the system model. The disturbances caused by the fault are also reduced to a considerably small amount. The oscillations of the power angle are also dampened.

4.2.2 CASE 2: Variation of parameters

The system parameters are changed to simulate new results for the system model. This is to examine the robustness of the controller and its ability to adapt to new conditions.

The parameters of the transmission line are shown as below:
Reactance of transmission line $X_{12} = 0.55$p.u.
Reactance of transmission line $X_{13} = 0.53$p.u.
Reactance of transmission line $X_{23} = 0.6$p.u.
Power angle $\delta_{10} = 18.51$
Power angle $\delta_{20} = 23.68$
Mechanical power $P_{m10} = 0.32$p.u.
Mechanical power $P_{m20} = 0.42$p.u.
Terminal voltage of generator $V_{t10} = 1.0$p.u.
Terminal voltage of generator $V_{t20} = 1.0$p.u.
Fault position $\lambda = 0.05$

Simulation of results without Controller
Subsystem 1

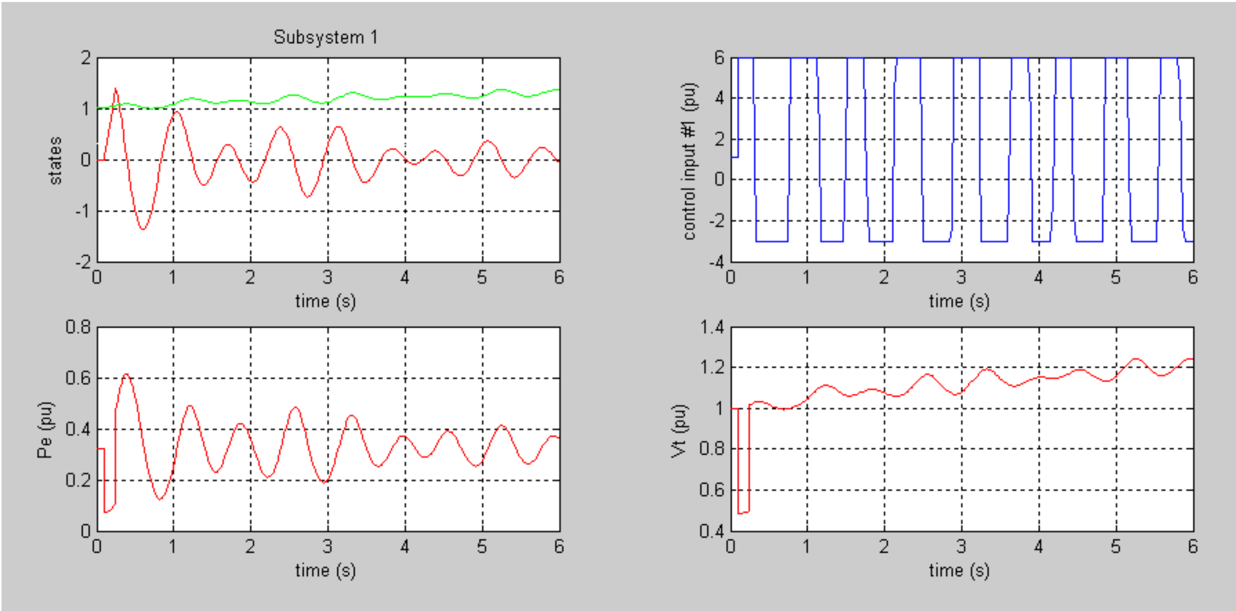


Figure 15: Case 2: Results of Subsystem 1 without controller

Subsystem 2

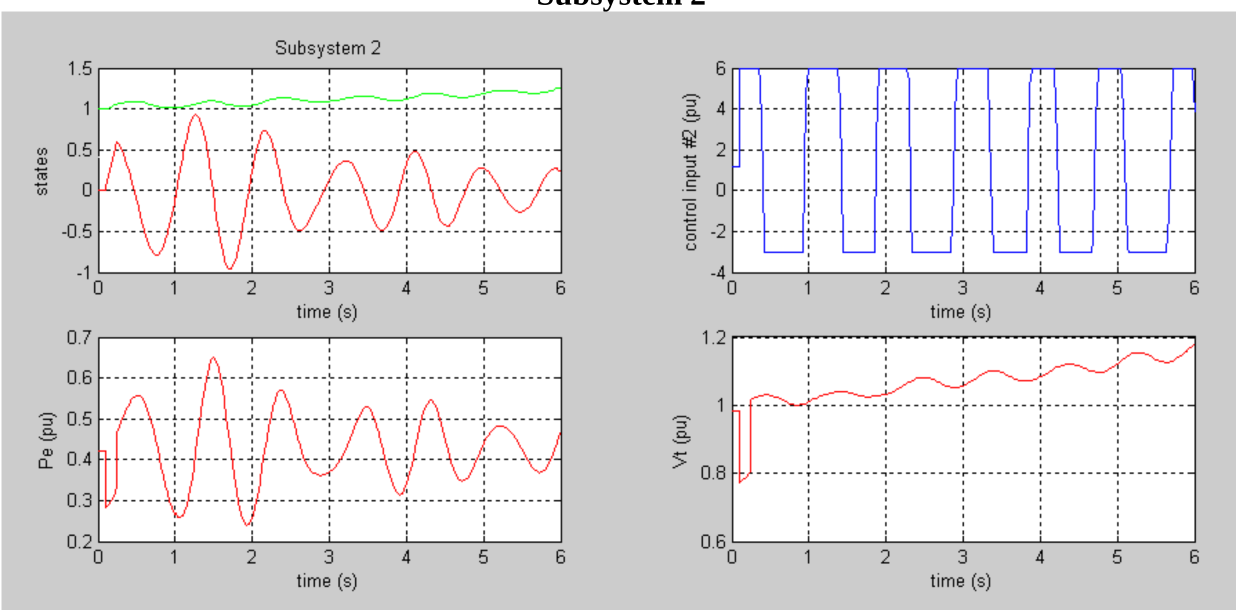


Figure 16: Case 2: Results of Subsystem 2 without controller

Without the nonlinear decentralized controller, the system model is again unable to regain its synchronism upon encountering the fault. The condition of the system is unstable.

Simulation of results with Nonlinear Decentralized Controller

Subsystem 1

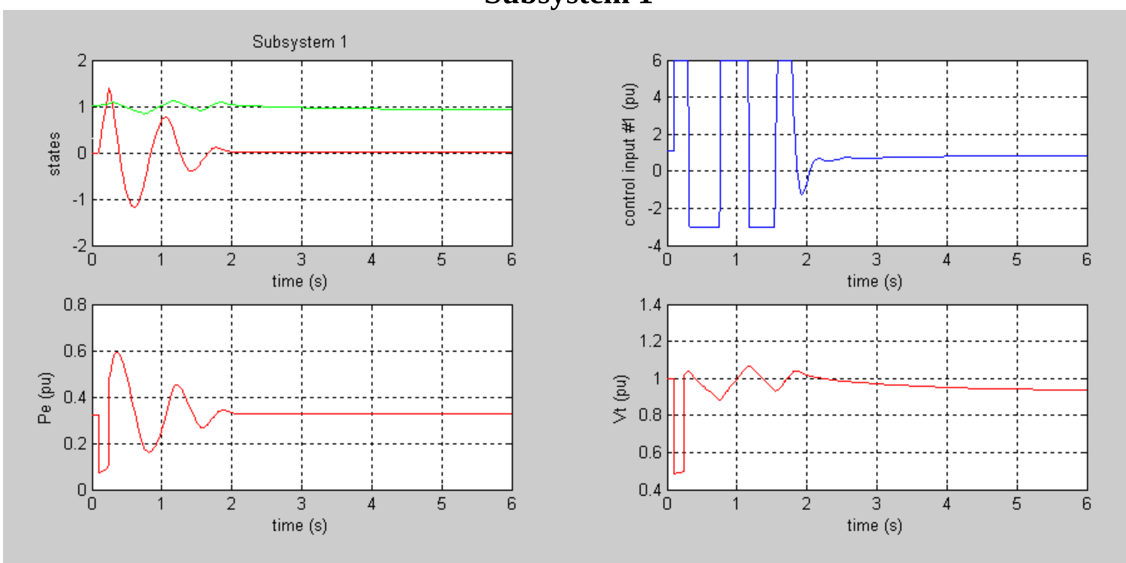


Figure 17: Case 2: Results of Subsystem 1 with controller

Subsystem 2

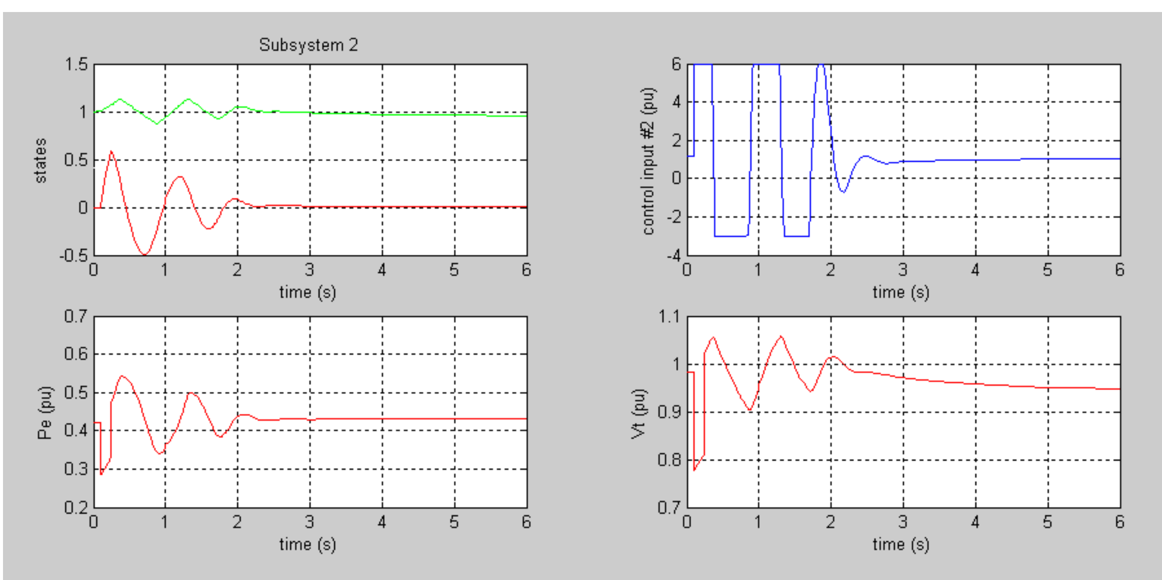


Figure 18: Case 2: Results of Subsystem 2 with controller

It is observed that even with different system parameters, the system is able to return to synchronism and stable conditions with the introduction of the nonlinear decentralized controller.

The controller is effective in enhancing the transient stability of the system model even with variations in system parameters, operating points and fault location.

4.2.3 CASE 3: Variation of parameters power angle δ and mechanical power P_m

For Case 3, four of the parameters are varied, namely the power angles δ_{10} and δ_{20}, and the mechanical input power P_{m10} and P_{m20}. The fault location remains the same as Case 2. The objective of Case 3 is to examine the condition of the system model when the system parameters are changed but with the fault occurring at the same fault location. The results will be then compared to Case 2 and discussion will be made.

The parameters of the transmission line are shown as below:

Reactance of transmission line $X_{12} = 0.55$p.u.
Reactance of transmission line $X_{13} = 0.53$p.u.
Reactance of transmission line $X_{23} = 0.6$p.u.
Power angle $\delta_{10} = 30.5$
Power angle $\delta_{20} = 32.5$
Mechanical power $P_{m10} = 0.57$p.u.
Mechanical power $P_{m20} = 0.56$p.u.
Terminal voltage of generator $V_{t10} = 1.0$p.u.
Terminal voltage of generator $V_{t20} = 1.0$p.u.
Fault position $\lambda = 0.05$

Simulation of results without Controller

Subsystem 1

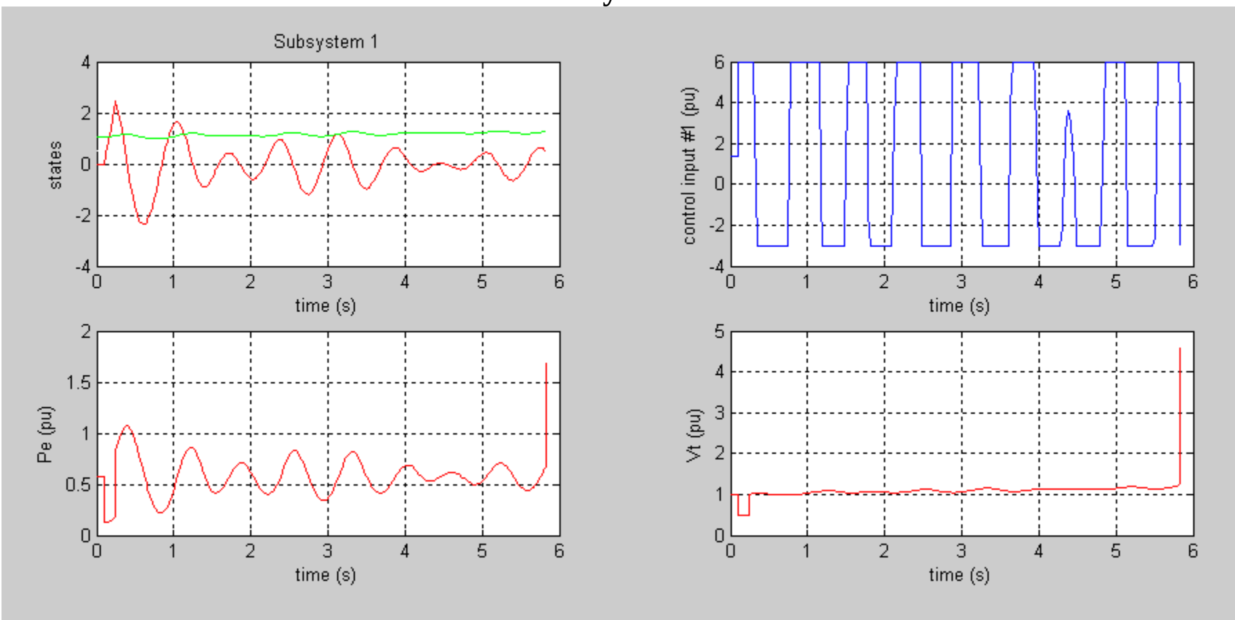


Figure 19: Case 3: Results of Subsystem 1 without controller

Subsystem 2

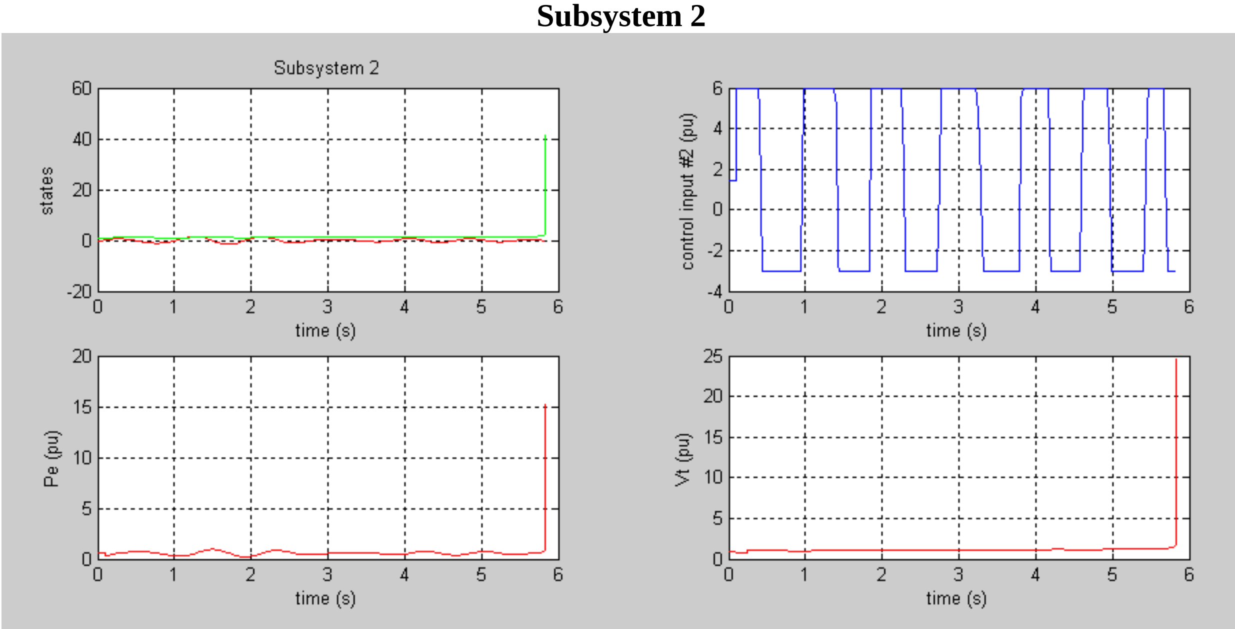


Figure 20: Case 3: Results of Subsystem 2 without controller

The results yield from Case 3 is similar to the results from Case 1 and 2. The system model is unable to regain its synchronism upon the occurrence of a fault. However comparing the above results with the results from Case 2, it can assume that the level of disturbance in Case 3 is highersince the relative speed ω, the power angle δ, the mechanical power input Pe and the terminal voltage Vt produced a zero value for Subsystem 2.

Simulation of results with Nonlinear Decentralized Controller
Subsystem 1

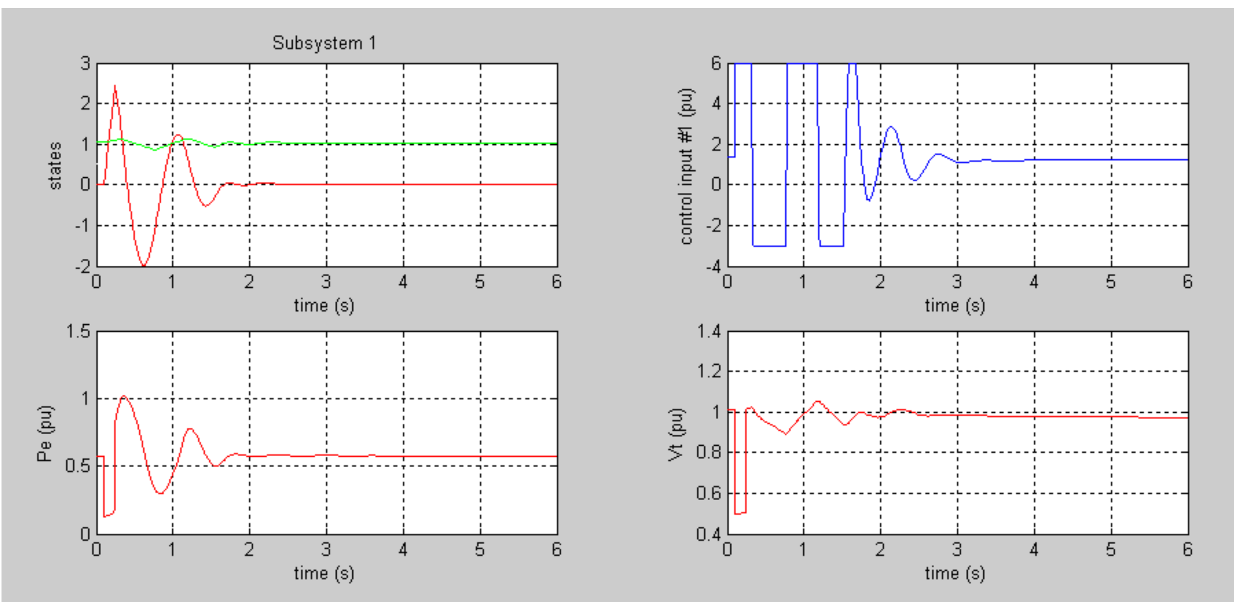


Figure 21: Case 3: Results for Subsystem 1 with controller

Subsystem 2

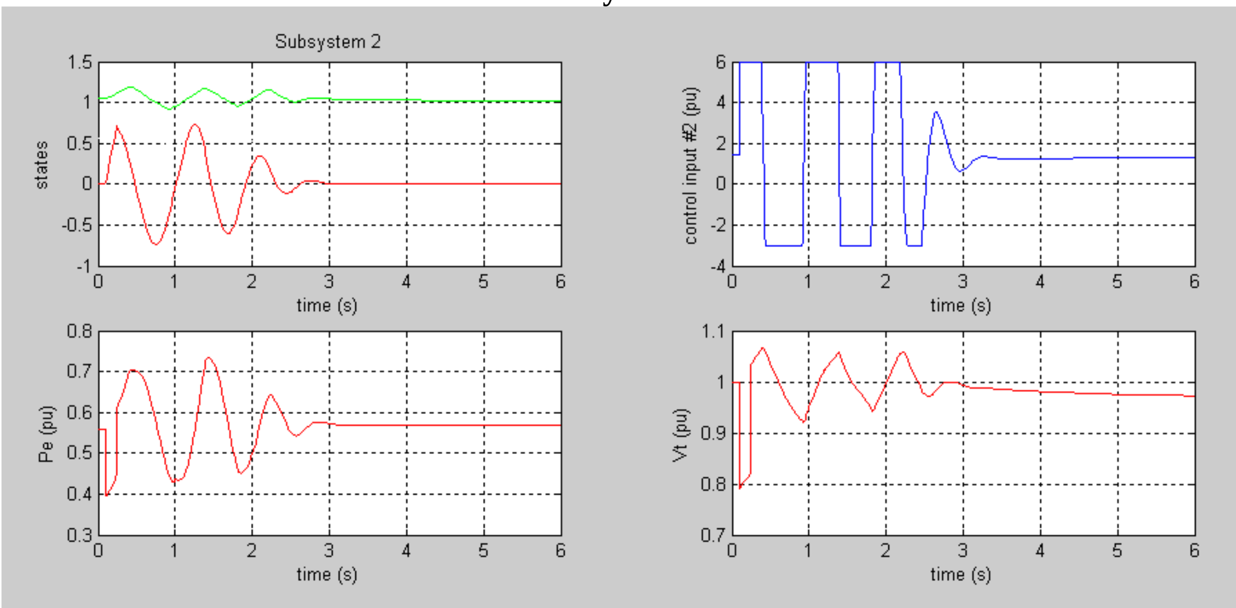


Figure 22: Case 3: Results for Subsystem 2 with controller

From the above results, we can see that the system model is able to regain synchronism and equilibrium with the aid of the nonlinear decentralized controller. The result also proved that the controller is capable and robust enough to handle the occurrence of the fault and the variation in the system parameters.

4.2.3.1 Comparison of Case 2 and Case 3

The effects of varying the power angle δ and mechanical power Pm on the system are as follow:

4.2.3.1.1 Effect on ω and δ

CASE2 **CASE3**

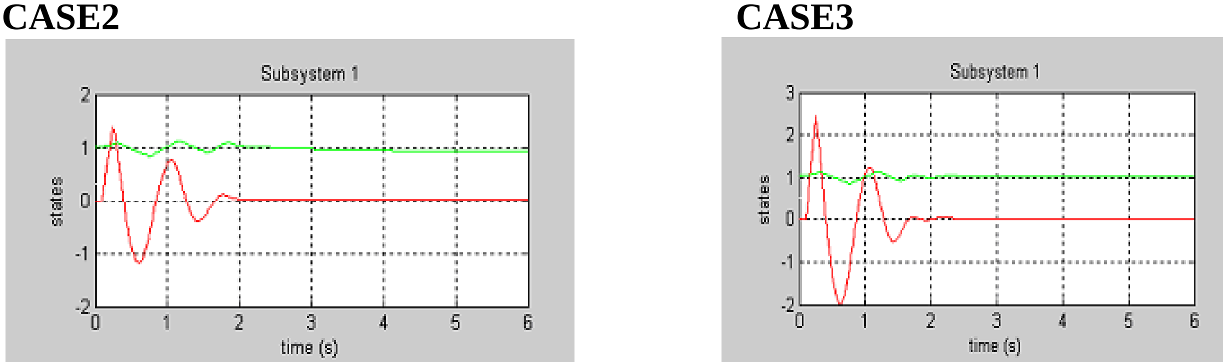


Figure 23: Comparing ω and δ of Subsystem 1 for Case 2 and Case 3

CASE 2 **CASE 3**

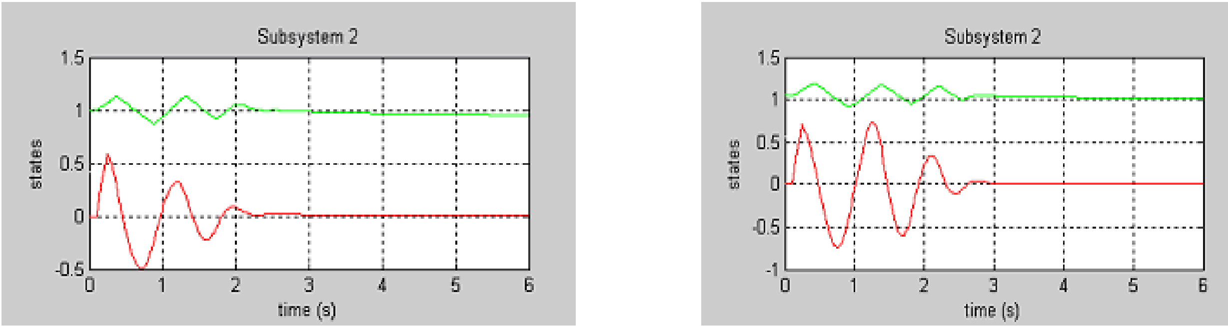


Figure 24: Comparing ω and δ of Subsystem 2 for Case 2 and Case 3

Firstly, the effect on the δ is examined. From the figures above, it can be seen that the oscillation is smaller with smaller initial power angles (Case 2) as compared to larger initial power angles

(Case 3). The rate of damping is also considerably faster.

Next, the effect on the ω is observed. It can be seen that the amplitude of the oscillations reduces as the initial angle is smaller.

4.2.3.1.2 *Effect on Pe*

CASE 2 **CASE 3**

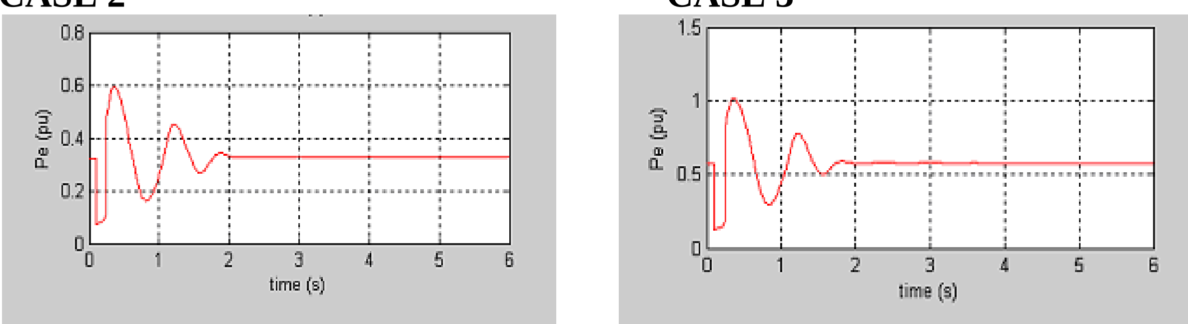


Figure 25: Comparing Pe of Subsystem 1 for Case 2 and Case 3

CASE 2 **CASE 3**

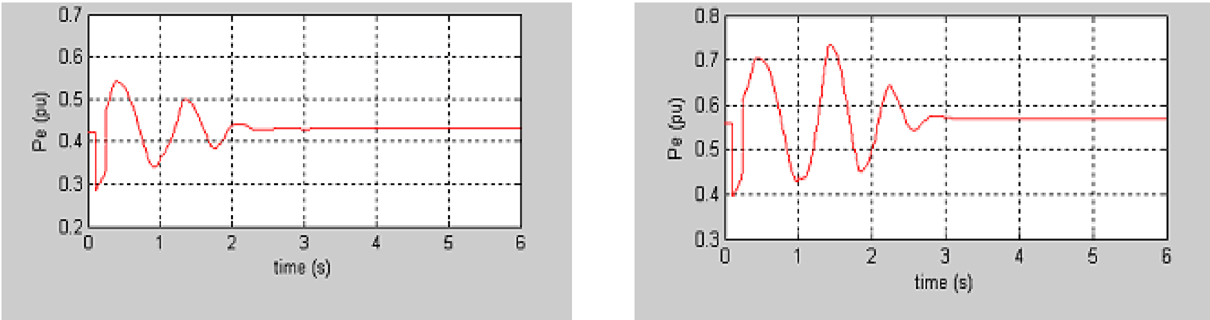


Figure 26: Comparing Pe of Subsystem 2 for Case 2 and Case 3

From the figures above, it can be seen that the oscillations after the occurrence of the fault tends to be larger with larger initial values of δ (Case 3). The rate of damping of Case 2 is also faster as compared to Case 3 as Case 2 has a smaller value of δ. The value of the electrical power Pe is also approximately the same as the value of the mechanical input power Pm.

4.2.4CASE 4: Variation of fault position λ

For Case 4, the network parameters are identical to Case 3 but the fault location is changed. This is to examine the effect of the fault location of the performance of the system. The results will be then compared to Case 2 and discussion will be made.

The parameters of the transmission line are shown as below:

Reactance of transmission line $X_{12} = 0.55$p.u.

Reactance of transmission line $X_{13} = 0.53$p.u.

Reactance of transmission line $X_{23} = 0.6$p.u.

Power angle $\delta_{10} = 30.5$

Power angle $\delta_{20} = 32.5$

Mechanical power $P_{m10} = 0.57$p.u.

Mechanical power $P_{m20} = 0.56$p.u.

Terminal voltage of generator $V_{t10} = 1.0$p.u.

Terminal voltage of generator $V_{t20} = 1.0$p.u.

Fault position $\lambda = 0.5$

Simulation of results without Controller
Subsystem 1

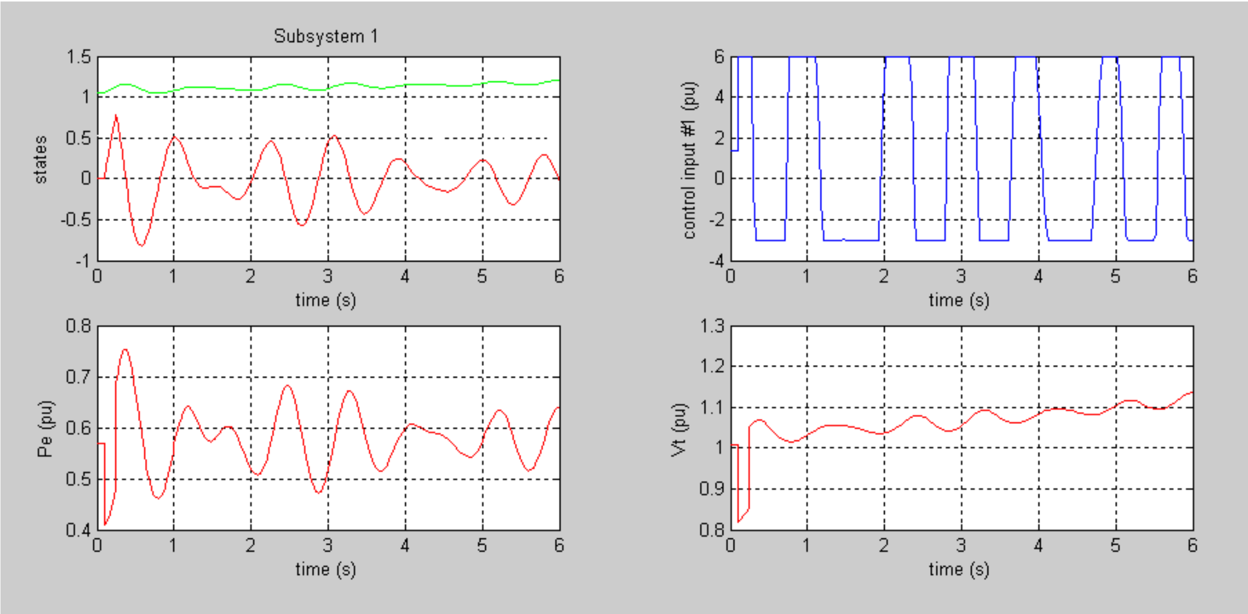


Figure 27: Case 4: Results of Subsystem 1 without controller

Subsystem 2

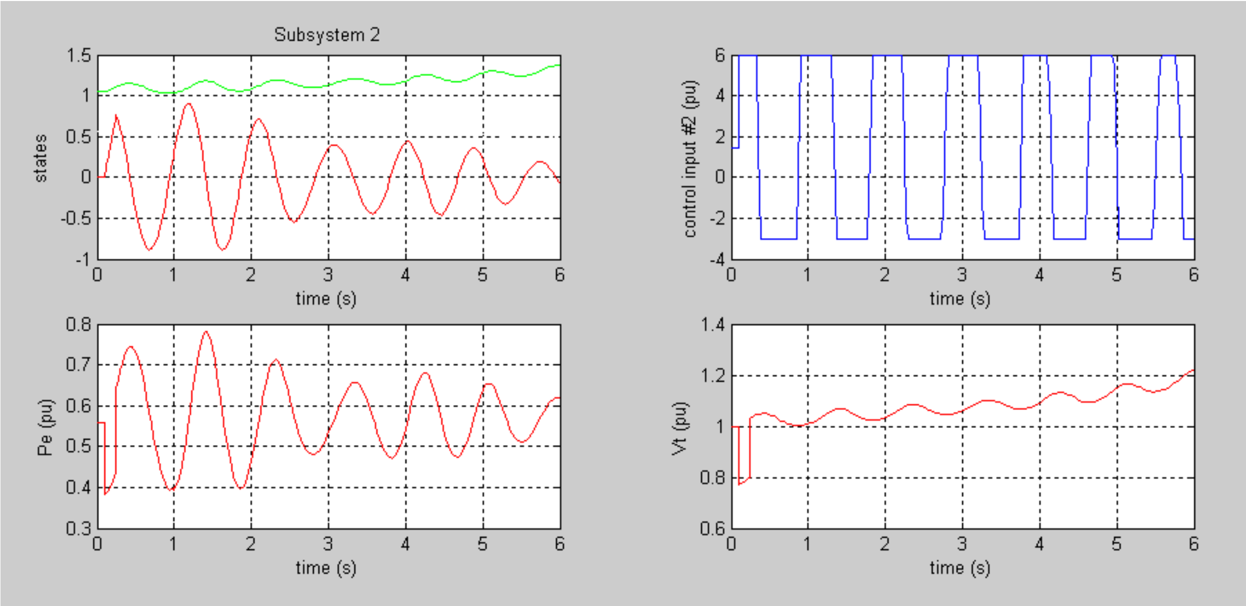


Figure 28: Case 4: Results of Subsystem 2 without controller

The results shown above are again similar to the previous cases that were discussed earlier. The system model is unable to sustain the fault and loses its synchronism.

Simulation of results with Nonlinear Decentralized Controller
Subsystem 1

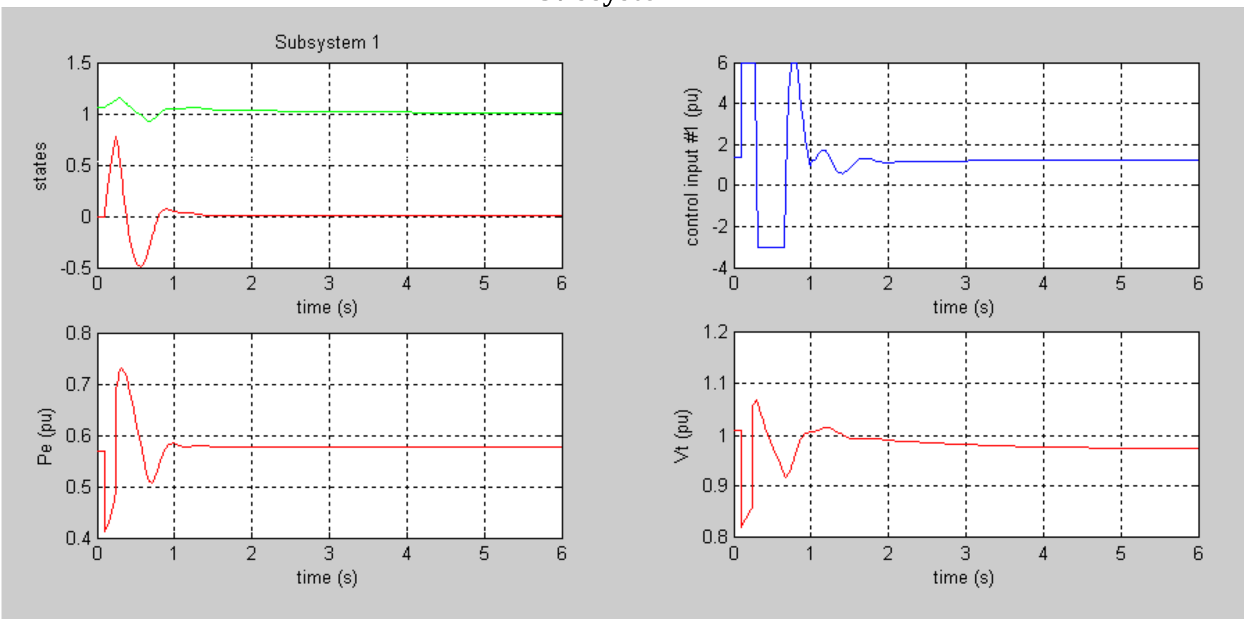


Figure 29: Case 4: Results for Subsystem 1 with controller

Subsystem 2

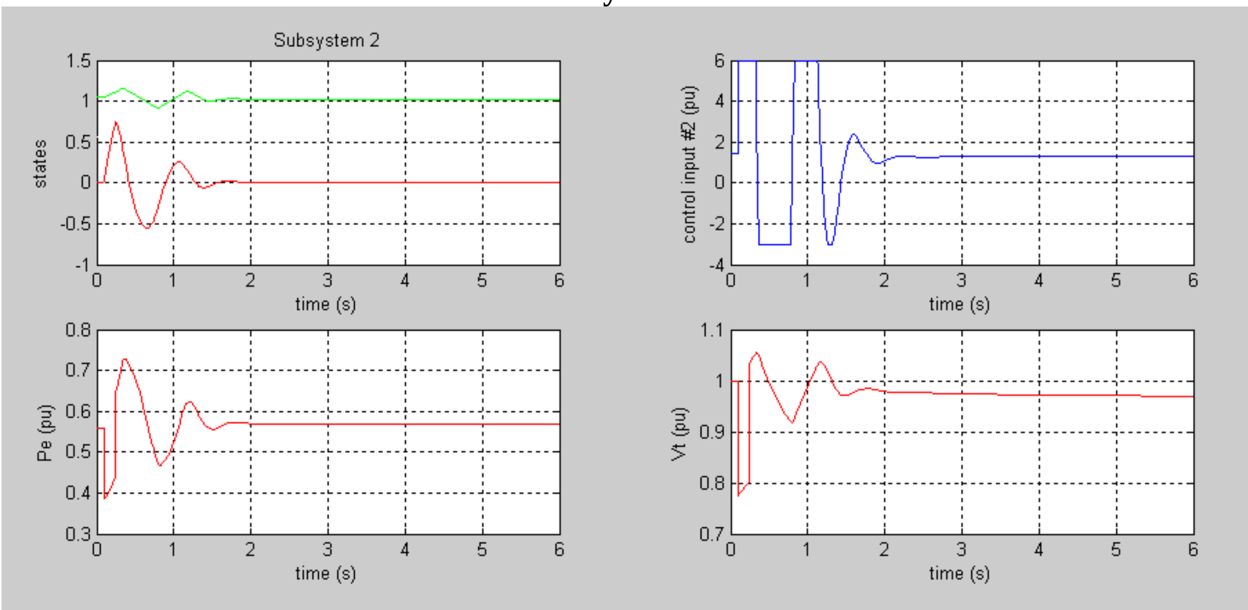


Figure 30: Case 4: Results for Subsystem 2 with controller

The introduction of the nonlinear decentralized controller is able to improve and enhance the transient stability of the system model even with a variation in the fault location λ.

4.2.4.1 Comparison of Case 3 and Case 4

The effects of varying the fault location λ on the system are as follow:

4.2.4.1.1 Effect on ω and δ

CASE 2 **CASE3**

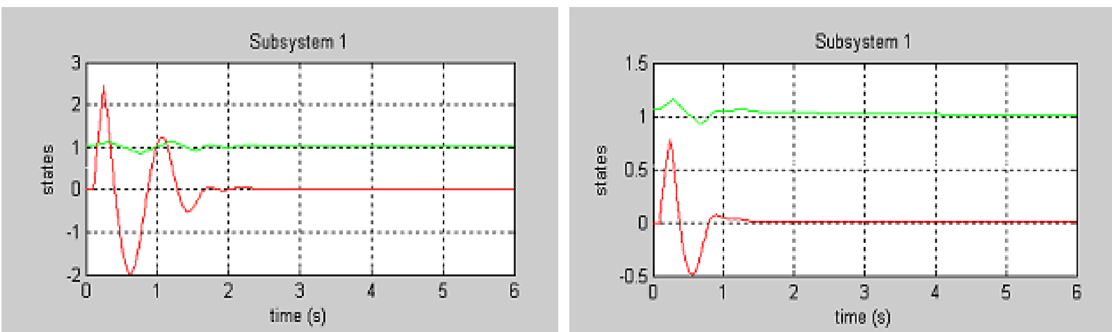


Figure 31: Comparing ω and δ of Subsystem 1 for Case 3 and Case 4

CASE 2 **CASE 3**

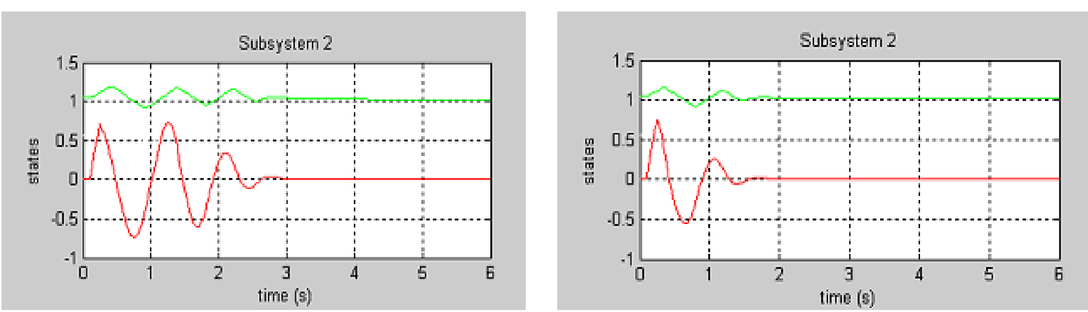


Figure 32: Comparing ω and δ of Subsystem 2 for Case 3 and Case 4

It is observed from the figures above that a smaller λ (Case 3) produced more oscillation in the Wave form of ω. This shows that faults which are nearer to the generator bus are more disruptive as compared to faults further down the transmission line. The variation of the fault location seems to have little effect on δ.

4.2.4.1.2 Effect on Pe

CASE 2 **CASE 3**

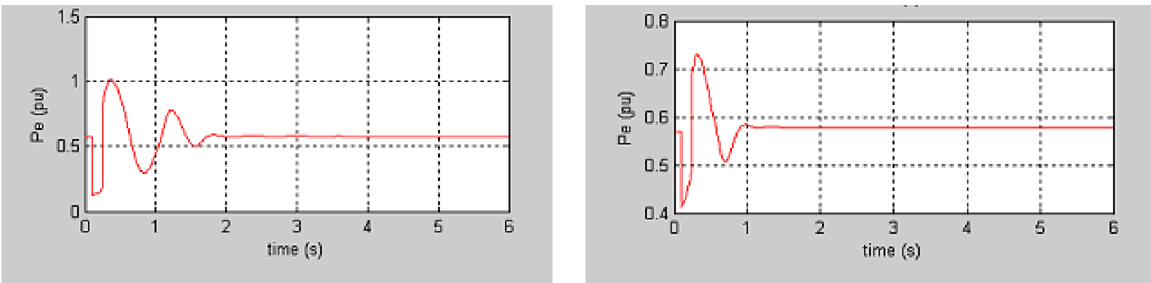


Figure 33: Comparing Pe of Subsystem 1 for Case 2 and Case 3

CASE 2 **CASE 3**

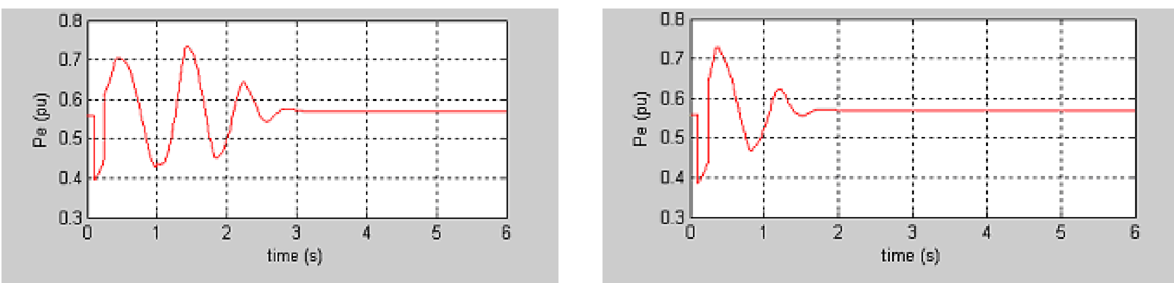


Figure 34: Comparing Pe of Subsystem 2 for Case 3 and Case 4

From the figures above, it can be seen that there are more fluctuations in the waveform for a smaller value of λ (Case 3). When the fault location is nearer to the generator bus, the Pe of the system model will take a longer time to regain stability.

4.2.5CASE 5

For Case 5, all the systems parameters are changed except for the terminal voltage of the generators and the reactance of the transmission lines.

The parameters of the transmission line are shown as below:

Reactance of transmission line $X_{12} = 0.55$p.u.

Reactance of transmission line $X_{13} = 0.53$p.u.

Reactance of transmission line $X_{23} = 0.6$p.u.

Power angle $\delta_{10} = 64.08$

Power angle $\delta_{20} = 65.33$

Mechanical power $P_{m10} = 0.95$p.u.

Mechanical power $P_{m20} = 0.95$p.u.

Terminal voltage of generator $V_{t10} = 1.0$p.u.

Terminal voltage of generator $V_{t20} = 1.0$p.u.

Fault position $\lambda = 0.5$

Simulation of results without Controller
Subsystem 1

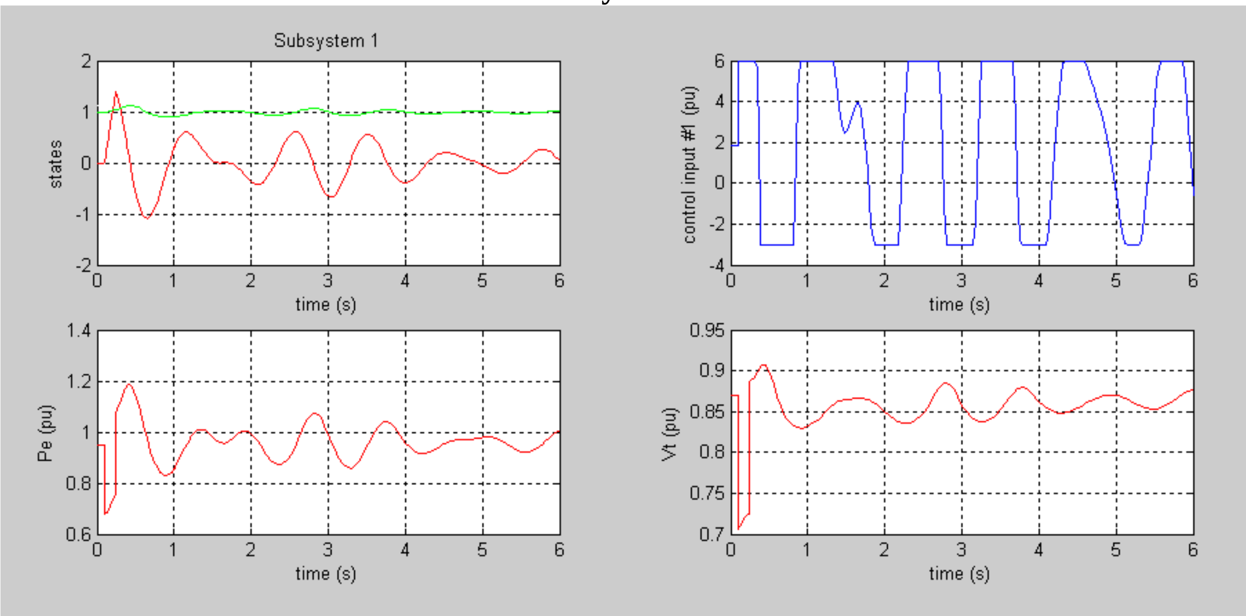


Figure 35: Case 5: Results of Subsystem 1 without controller

Subsystem 2

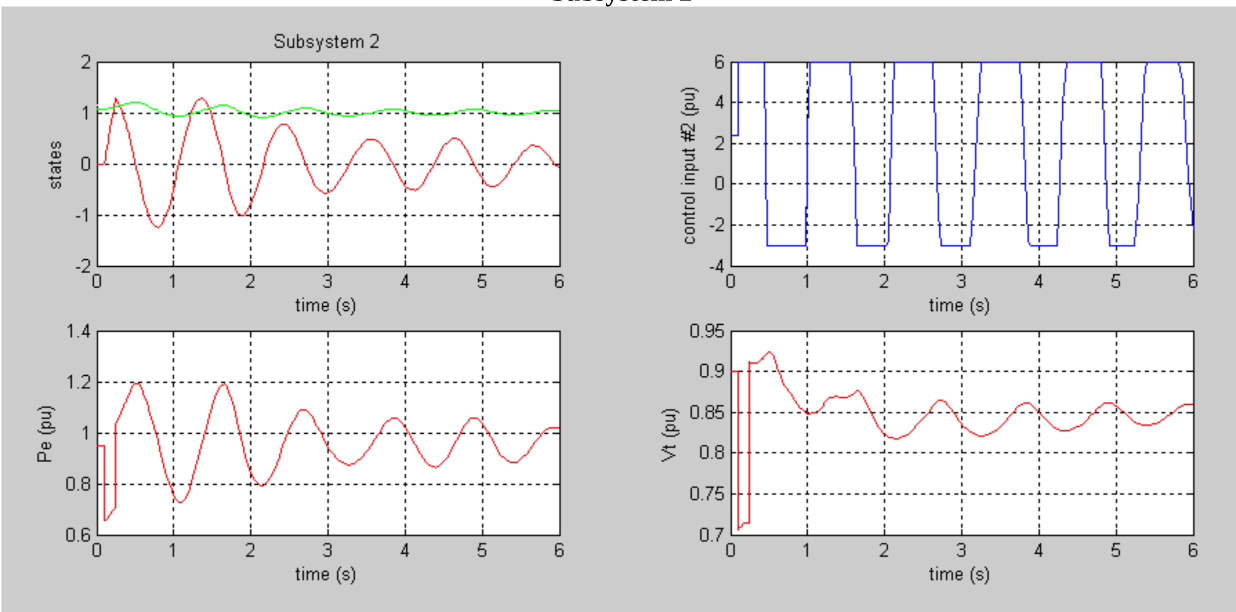


Figure 36: Case 5: Results of Subsystem 2 without controller

Without the aid of the controller, the condition of the system model is unstable. The system is unable to sustain its equilibrium and after the occurrence of the fault.

Simulation of results with Nonlinear Decentralized Controller

Subsystem 1

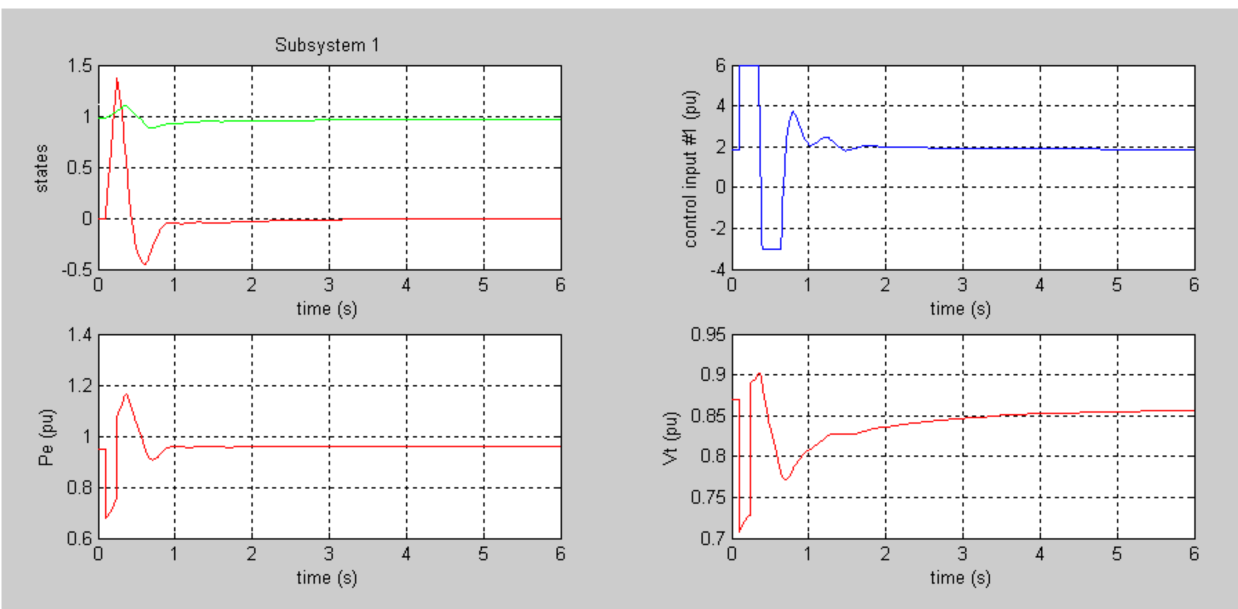


Figure 37: Case 5: Results of Subsystem 1 with controller

Subsystem 2

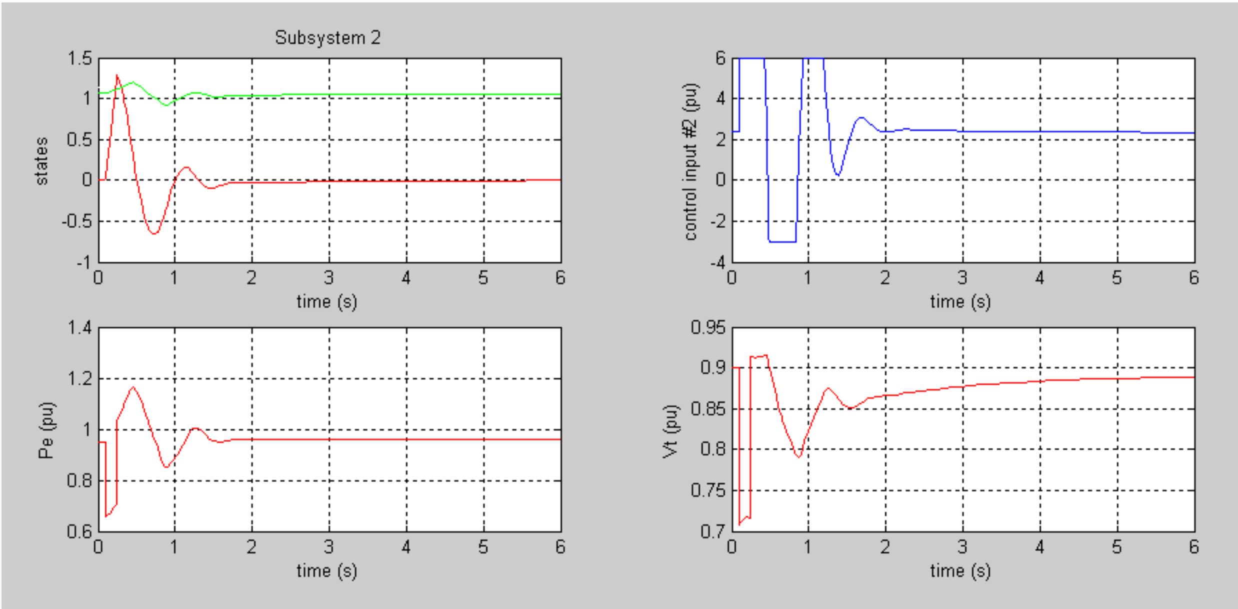


Figure 38: Case 5: Results of Subsystem 2 with controller

The results yield above is similar to the previous cases. With the aid of the controller, the transient stability of the system is enhanced. It has also proven once again that the nonlinear decentralized controller is robust enough to handle any uncertain network parameters.

4.2.6 CASE 6: Variation of parameters system reactance x_{12}, x_{13} and x_{23}

For Case 6, the system parameters are similar to Case 5 but the reactances of the transmission lines are altered. The results of Case 5 and Case 6 will be compared to examine the effect on the system due to the different reactance.

The parameters of the transmission line are shown as below:

Reactance of transmission line $X_{12} = 0.7$p.u.

Reactance of transmission line $X_{13} = 0.7$p.u.

Reactance of transmission line $X_{23} = 0.7$p.u.

Power angle $\delta_{10} = 64.08$

Power angle $\delta_{20} = 65.33$

Mechanical power $P_{m10} = 0.95$p.u.
Mechanical power $P_{m20} = 0.95$p.u.
Terminal voltage of generator $V_{t10} = 1.0$p.u.
Terminal voltage of generator $V_{t20} = 1.0$p.u.
Fault position $\lambda = 0.5$

Simulation of results without Controller
Subsystem 1

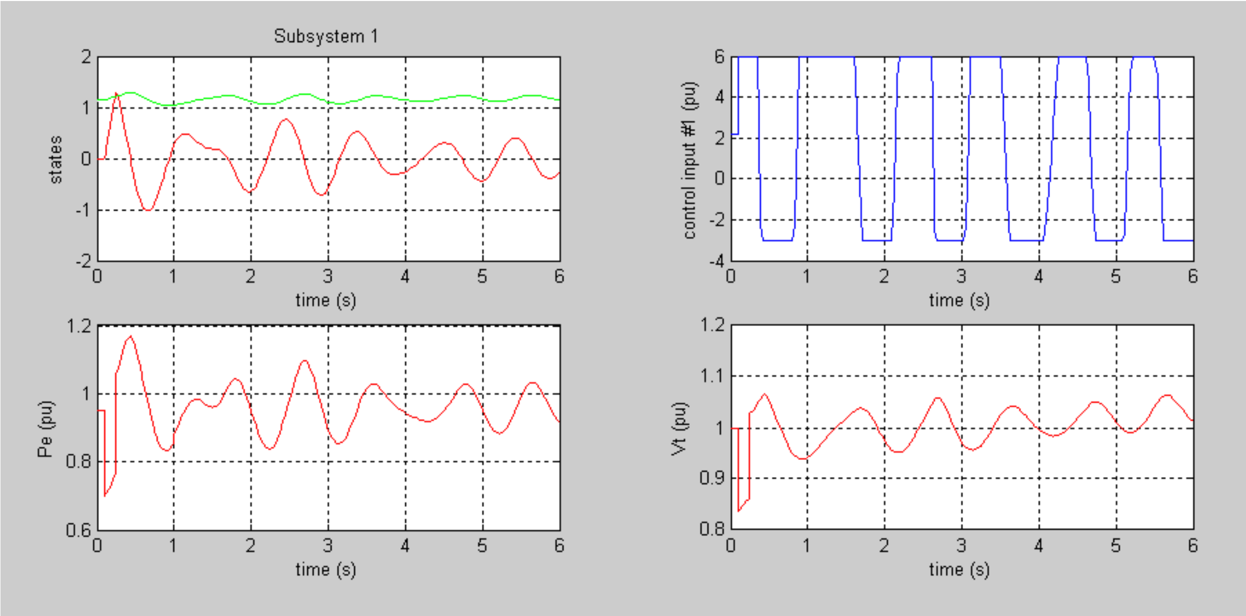


Figure 39: Case 6: Results of Subsystem 1 without controller

Subsystem 2

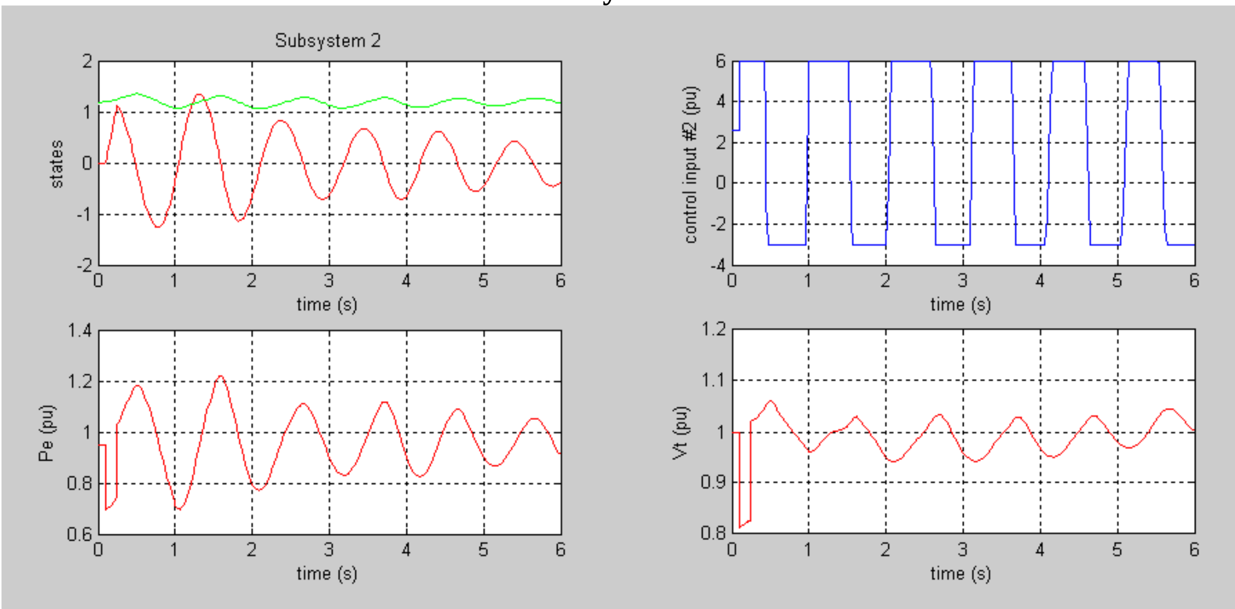


Figure 40: Case 6: Results of Subsystem 2 without controller

Simulation of results with Nonlinear Decentralized Controller
Subsystem 1

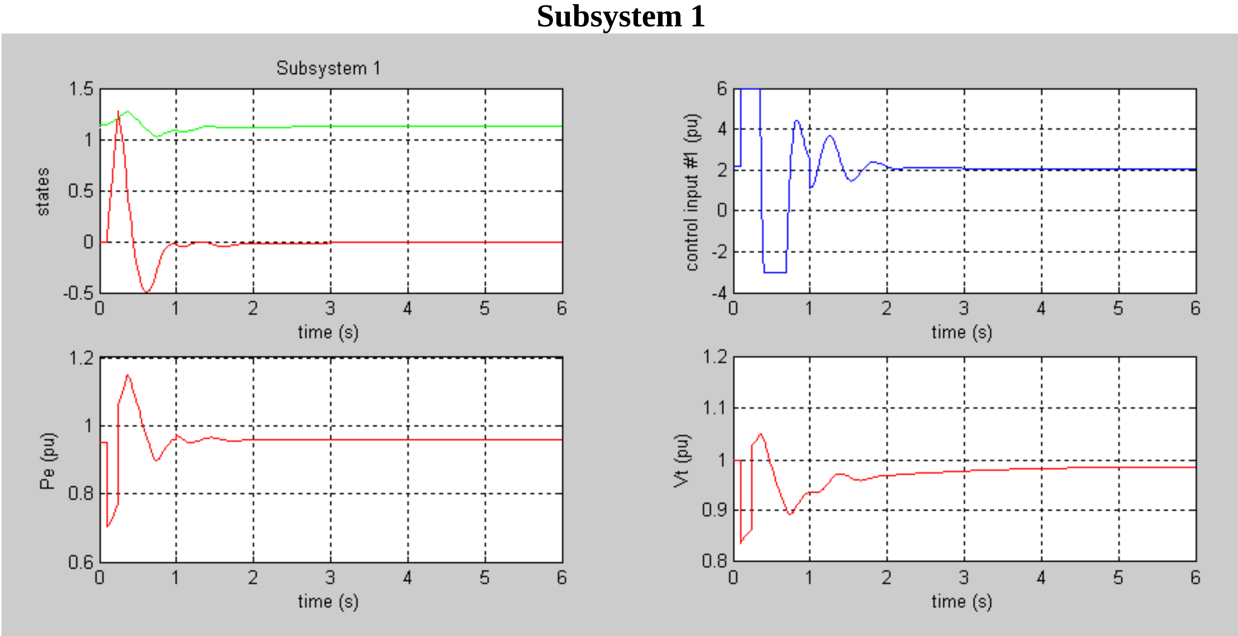


Figure 41: Case 6: Results of Subsystem 1 with controller

Subsystem 2

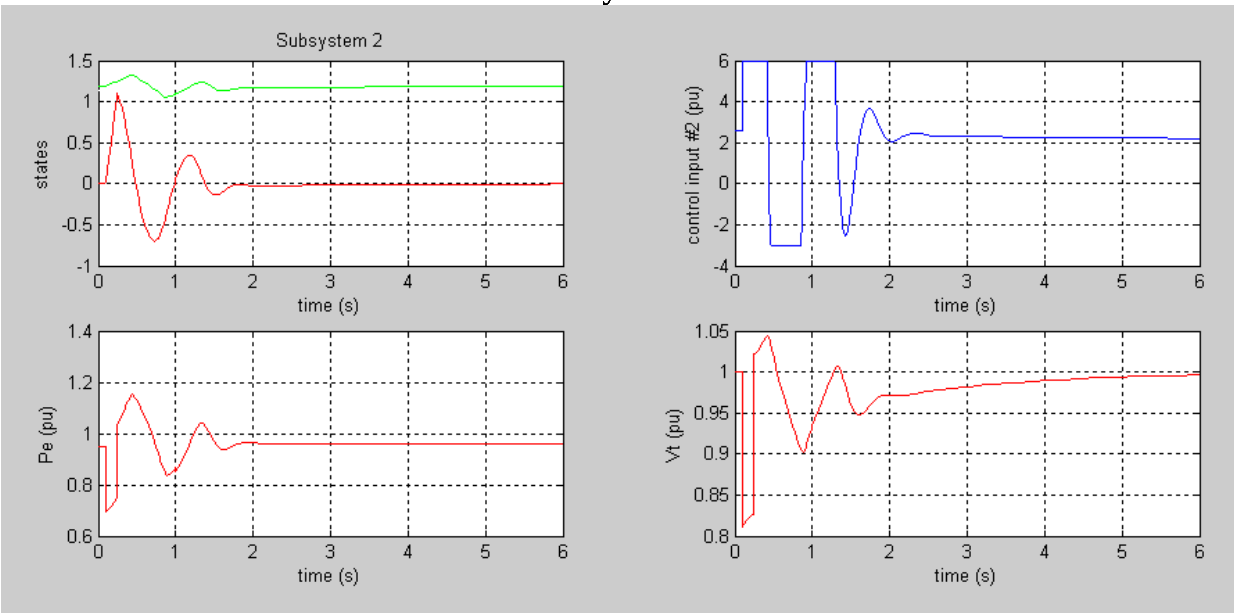


Figure 42: Case 6: Results of Subsystem 2 with controller

4.2.6.1 Comparison of Case 5 and Case 6

From the figures, it can be seen that when the reactance of the transmission line is varied, there is not much effect on the performance of the system model that is running on the same network parameters. This shows that even when there are sudden changes to the reactance of the transmission lines, the controller is able to sustain the fault and bring the system back to the stable condition. Thus the nonlinear decentralized controller is robust and is able to adapt to any uncertain network conditions.

4.3 MULTI-MACHINE SYSTEM

Multimachine equation can be written similar to the one-machine system connected to the infinite Bus. In order to reduce the complexity of the transient stability analysis, similar simplifying are mode as Follows.

1. Each synchronous machine is represented by a constant voltage source behind the direct axis transient reactance. This representation neglects the effect of saliency and constant flux linkage.
2. The governor's actions are neglected and the inputs are assumed to remain constant during the period of simulation.
3. Using the Perrault bus voltage , all loads are converted to equivalent admittances to ground and are assumed to remain constant
4. Damping or asynchronous power are ignored
5. The mechanical rotor angle of each machine coincides with the angle of the voltage behind the machine reactance.
6. Machines belonging to the same station swing together and are said to be coherent. A group of Coherent machine is represented by one equivalent machine.

The first step in the transient stability analysis is to solve the initial load flow and to determine the initial bus voltage magnitudes and phase angle. The machine current prior to disturbance are Calculated from

$$I_i = \frac{S_{i*}}{V_{i*}} = \frac{P_i - jQ_i}{V_{i*}} \qquad i=1,2,\ldots,m$$

Where m is the number of generator. is the terminal voltage of the i_{th} generator, and are the generator real and reactive powers. All unknown values are determined from the initial power flow solution. The generator armature resistances are usually neglected and the voltage behind the transient reactance is then obtained.

$$E'_i = V_i + jX'_d I_i$$

Next, all loads are converted to equivalent admittances by relation

$$y_{i0} = \frac{Si*}{|V_i|^2} = \frac{P_{i-jQ_i}}{|V_i|^2}$$

4.4 MUULTIMACHINE TRANSIENT STABILITY

The classical transient stability study is based on the application os a three-phase fault. A solid three-phase fault at bus k in the network result in =0. This is simulated by removing the kth row and column from the Perrault bus admittance matrix. The newbus admittance matrix is reduced by eliminating all nodes except the internal generator nodes. The generator excitation voltage during the fault and post fault modes is assumed to remain constant. The electrical power of the i_{th} generator in terms of the new reduced bus admittances matrices are obtained from the swing equation with damping neglected for machine i becomes.

$$\frac{H_i}{\pi f_0}\frac{d^2\delta_i}{dt^2} = P_{mi} - \sum_{j=1}^{m}|E'_i||E'_j||Y_{ij}|\cos(\theta_{ij-}\ \delta_{i+}\delta_j)$$

Where are the elements of the fault reduced bus admittance matrix, and is the inertia constant of machine expressed on the common MVA base . if is the inertia costant of machine expressed on the machine rated MVA then is given by

$$H_i=\frac{S_{Gi}}{S_B}H_{Gi}$$

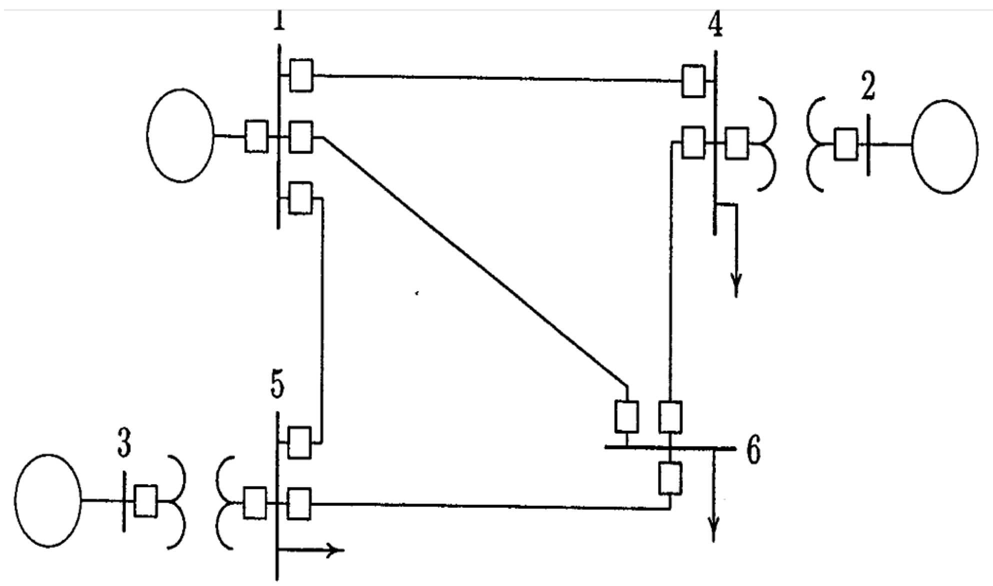
Showing the electrical power of the generator by and transforming into state Variable mode yield.

$$\frac{d\delta_i}{dt} = \Delta w_i \qquad i=1,....,m$$

$$\frac{d\Delta\omega_i}{dt} = \frac{\pi f_0}{Hi}\left(P_{m-P_e^f}\right)$$

4.5 MULTIMACHINE TRANSIENT STABILITY

System consideration with 6 buses



LOAD DATE

Bus No.	MW	Mvar
1	0	0
2	0	0
3	0	0
4	100	70
5	90	30
6	160	110

GENERATION SCHEDULE

Bus No.	Voltage Mag	Generation MW	Min	Max
1	1.06			
2	1.04	150	0	140
3	1.03	100	0	90

LINE DATA

Bus No.	Bus No.	R, PU	X, PU	$\frac{1}{2}$B, PU
1	4	0.035	0.225	0.0065
1	5	0.025	0.105	0.0045
1	6	0.040	0.215	0.0055
2	4	0.000	0.035	0.0000
3	5	0.000	0.042	0.0000
4	6	0.028	0.125	0.0035
5	6	0.026	0.175	0.0300

Phase fault occurs on line 4-1 near bus 1

Fault clearing time at 0.4s system is unstable

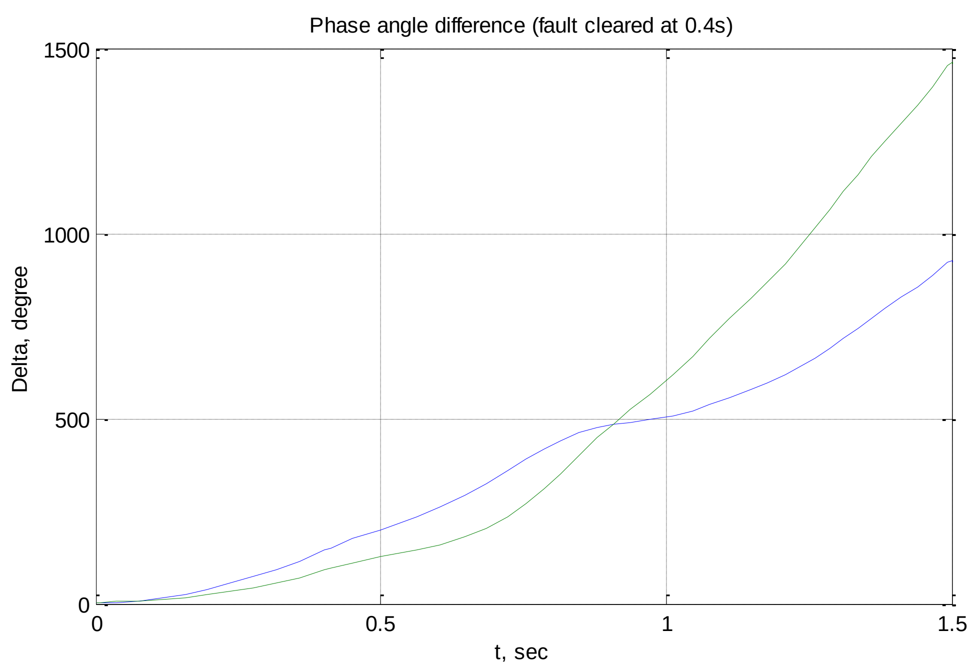


Figure 43: Plots of angle differences

By removing the line 4-1

Fault clearing time at .35s system is stable

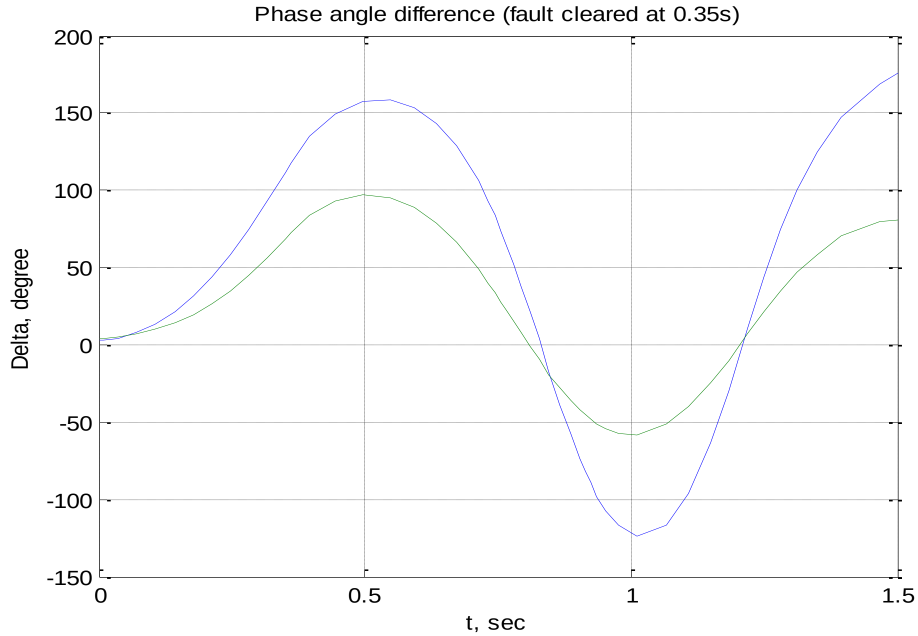


Figure 44: Plots of angle differences

Critical clearing time is 0.36s

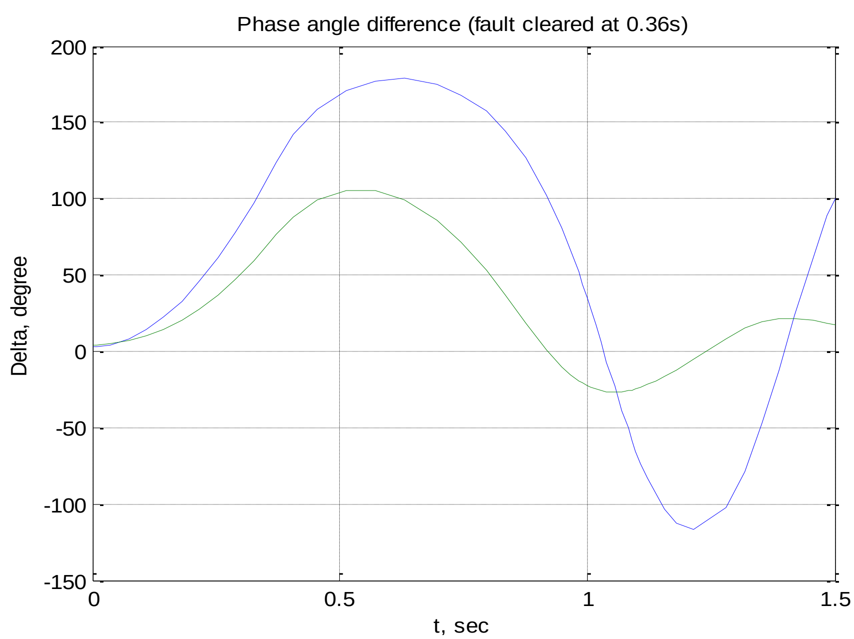


Figure 45: Plots of angle differences

Phase fault occurs on line 1-5 near bus 5 Fault Clearing time at 0.4s system is unstable

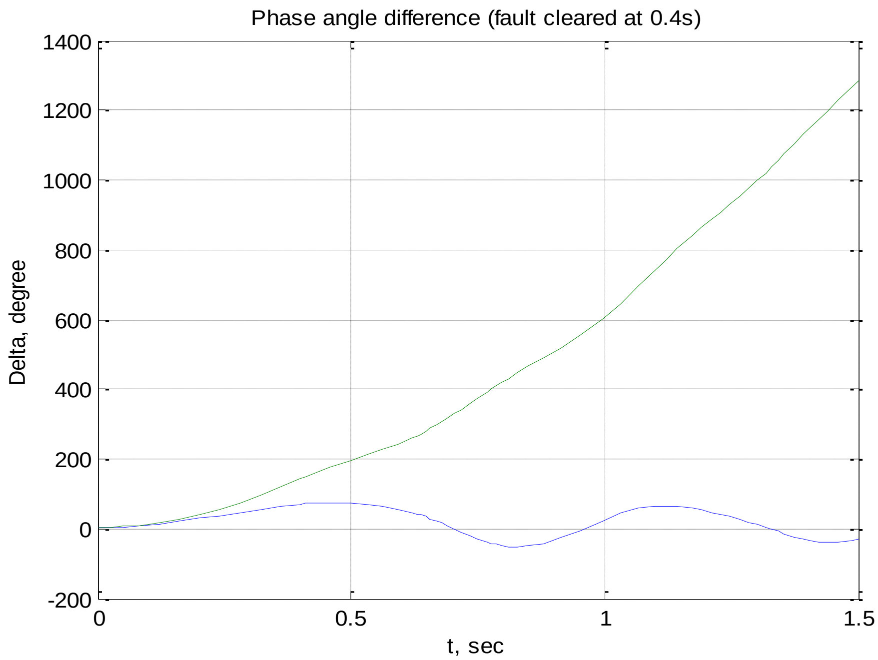


Figure 46: Plots of angle differences

By Removing the line 1-5 Fault Clearing time at 0.33s system is stable

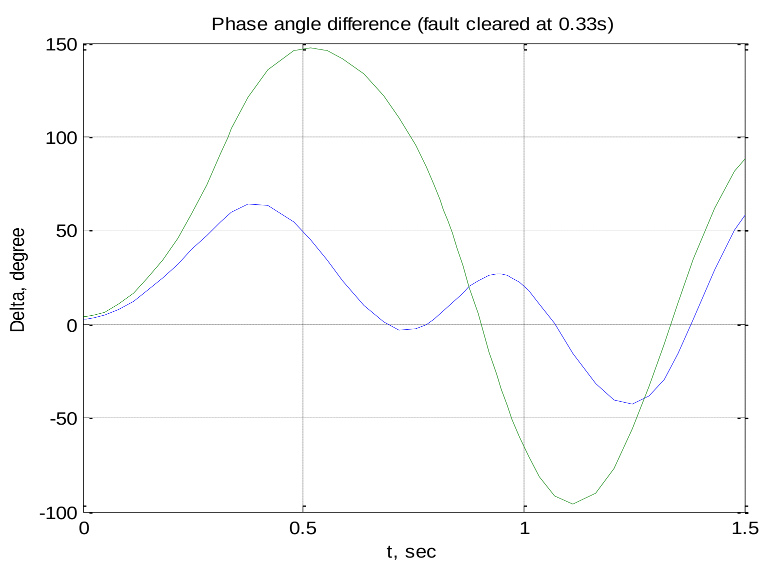


Figure 47: Plots of angle differences

Critical clearing time is 0.335s

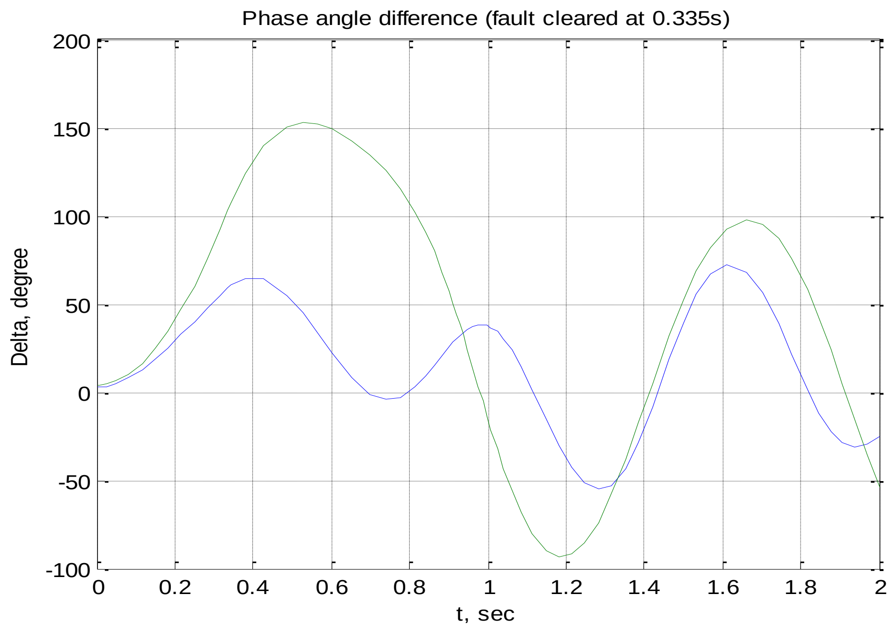


Figure 48: Plots of angle differences

CHAPTER 5

Conclusion

CHAPTER 5

5.1 Conclusion

As the economic demand and environmental pressure continues to mount, large-scale power system around the world are getting more and more interconnected. The modern power systems are also much more complex. The ability to maintain system stability in a deregulated power system environment is a major challenge. Stability phenomena can cause significant damage economically, thus the limits of stability and the reliability and efficiency of the power system are much sought after issues.

This thesis attempted to provide an insight into the various power system stability issues. In the first part of the thesis, the definition of power system stability was discussed. Several reasons were also provided to justify the need to study the area power system stability. Some basic stability theorems were discussed briefly in order to aid understanding in the topic. In the second part of the thesis, several advanced stability theorem and techniques were examined. These techniques were useful in determining the stability of complex power systems.

In the latter part of the thesis, a power system modelling was attempted. Simulations were performed on the power system model to acquire the conditions of the system model in an event of an occurrence of a three phase symmetrical fault. A proposed nonlinear decentralized control scheme was then implemented to the power system model. Comparisons were then made to examine the effect of the controller. Various system operating points were also varied to test the robustness of the controller.

From the various simulation results, it can be seen that the nonlinear decentralized controller is effective in enhancing the transient stability of the system model. The proposed controller ensured the overall stability of the system model. It is also robust enough to withstand uncertain network parameters. The simulation results showed that the transient stability of the system model was enhanced and synchronism regained regardless of the location of the three-phase symmetrical fault, the variations in the system operating points and network parameters and the persistent disturbances.

In conclusion, as power systems are growing at a tremendous rate and are getting more interconnected, transient stability is an important area of study. The financial gain and economic pressure also encourage the exploration of methods to maintain and enhance the transient stability of the power systems.

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APPENDIX

APPENDIX

FUNCTION PROGRAME OF SINGLE MACHINE INFINITE BUS

```
     %program for transient stability of
single machine connected to infinite
     %bus this program simulates Example
12.10 using point by point method
     clear
     t=0
     tf=0
     tfinal=0.5
     tc=0.125
     tstep=0.05
     M=2.52/(180*50)i=2
     delta=21.64*pi/180
     ddelta=0
     time(1)=0
     ang(1)=21.64
     pm=0.9
     pmaxbf=2.44
     pmaxdf=0.88
     pmaxaf=2.00

    while t<tfinal,
    if  (t==tf),
    paminus=0.9-pmaxbf*sin(delta)
    paplus=0.9-pmaxdf*sin(delta)
    paav=(paminus+paplus)/2
    pa=paav
    end
    if(t==tc),
    paminus=0.9-pmaxdf*sin(delta)
    paplus=0.9-pmaxaf*sin(delta)
    paav=(paminus+paplus)/2
    pa=paav
    end
    if(t>tf& t<tc),
    pa=pm-pmaxdf*sin(delta)
    end
    if(t>tc),
    pa=pm-pmaxaf*sin(delta)
    end
    t,pa
```

```
ddelta=ddelta+(tstep*tstep*pa/M)
delta=(delta*180/pi+ddelta)*pi/180
deltadeg=delta*180/pi
t=t+tstep
pause
time(i)=t
ang(i)=deltadeg
ang(i)=deltadeg
i=i+1
end
axis([0 0.6 0 160])
plot(time,ang
```

FUNCTIN PROGRAM OF MULTIMACHINE TRANSIENT STABILITY

```
% This function forms the bus admittance
matrix including load
% admittances after removal of faulted
line. The corresponding reduced
% bus admittance matrix is obtained for
transient stability study.
% Copyright (c) 1998 by H. Saadat
function   [Yaf]=ybusaf(linedata,   yload,
nbus1,nbust, nbrt);
global Pm f H E  Y thngg

nl=linedata(:, 1);  nr=linedata(:, 2);
remove = 0;

rtn=1;
while remove ~= 1
fprintf('\nFault is cleared by opening a
line. The bus to bus nos. of the\n')
fprintf('line  to  be  removed  must  be
entered within brackets, e.g. [5, 7]\n')
fline=input('Enter the bus to bus Nos. of
line to be removed -> ');
nrmv=length(fline);
rtn=isempty(fline);
while (rtn==1 | nrmv~=2)
fline=input('Enter the bus to bus Nos. of
line to be removed -> ');
rtn=isempty(fline);
nrmv=length(fline);
end
nlf=fline(1); nrf=fline(2);
for k=1:nbrt
ifnl(k)==nlf& nr(k)==nrf
remove = 1;
   m=k;
else, end
end
if remove ~= 1
fprintf('\nThe  line  to  be  removed  does
not   exist   in   the   line   data.   Try
again.\n\n')
end
end
```

```
 linedat2(1:m-1,:)= linedata(1:m-1,:);
 linedat2(m:nbrt-
 1,:)=linedata(m+1:nbrt,:);

linedat0=linedata;
linedata=linedat2;
lfybus

for k=1:nbust
Ybus(k,k)=Ybus(k,k)+yload(k);
end

YLL=Ybus(1:nbus1, 1:nbus1);
YGG = Ybus(nbus1+1:nbust, nbus1+1:nbust);
YLG = Ybus(1:nbus1, nbus1+1:nbust);
Yaf=YGG-YLG.'*inv(YLL)*YLG;
linedata=linedat0;
```