Control of Unstable Power Swing using Modified Out-of-Step Tripping (OST) Method

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Author.

DEDICATION

To My Father

ABSTRACT

Disturbances in power systems are common and they result in electromechanical oscillations called power swing. The power swings could be harsh and may lead to loss of synchronism among the interconnected generators. This is referred to as out-of-step condition. The voltage and current swings during an out-of-step condition damage power system equipment and also cause unwanted operations of various protective devices. The protection systems require an effective algorithm for fast and accurate detection of out-of-step condition.

This thesis deals with Out-Of-Step conditions in a network, how to detect the events and how to make improvements on the protection devices. To achieve this, the research has gone through two distinct stages: development of an algorithm and simulation using MATLAB and PSCAD. The thesis includes the development of an algorithm that can detect power swings. The algorithm is programmed in MATLAB. This algorithm detects faults in the system and predicts loss of synchronism.

CHAPTER 1

INRODUCTION

1.1 Overview

This chapter expresses the overview of this thesis. First of all define the problems that have been solved, also explain the main purpose of this research work and at the end simply describe the thesis layout.

1.2 Definition of the Problem

If and when a disturbance takes place in a power system it is very essential to find out the changes as quickly as possible and to take precise actions against the fault. Modern power networks utilize distance relays with detection of power swing to identify out-of-step conditions. Preset tripping relays in electrical power system to get free of the oscillations and to continue important components operating without disturbances.

As an alternative of using distance relays to identify Out-Of-Step conditions, new measurement techniques are available where it is possible to detect phase angles in the complete power system with the same time and angle as a reference as shown on figure 1.1.

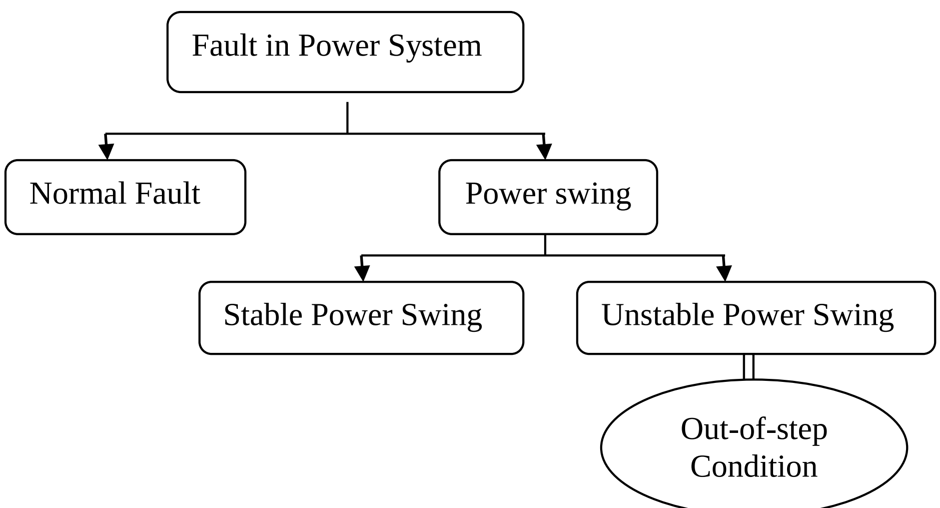


Figure 1.1 system block diagram

Studies have been done with the new technique to calculate voltages and currents in power systems and also measure the difference between mechanical rotor angle and electrical power. This thesis goes one step further in the way of making the new technique in the power system network to discover electric power swing oscillations and avoid Out of Step conditions.

1.3 Purpose of the Thesis

The aim of this thesis is to study power swing oscillations in electrical network, an electrical power transmission line and a generator component.

1.4 Thesis Layout

Chapter 2 describes the details of power swing. Fundamentals of power swings are discussed and phenomena of power swing also explained. This chapter answered the questions e.g how the power swing create and what will be effect on overall power system. Power swing detection methods and control are used and various types of power swing are discussed.

Chapter 3 discusses the details of relay; types of relays, distance relays, impedance relays and at the end explains the phenomena of out of step tripping in the distance relays.

Chapter 4 discusses the ideas and impressions related to out-of-step phenomena. The basics of out-of-step phenomena, OOS blocking and tripping and effect on protective relays are explained with a method which wants the information of them.

Chapter 5 contains the methodology of research work and brief of method to detect the out of step tripping (OST). Flow chart of algorithm used to explain the method of fault detection and at the end simple circuit is made on PSCAD to show the working of fault control scheme.

Chapter 6 summarizes the whole thesis, conclusions of all results and discussion about the technique used in the research work. At the end opens a discussion for future work.

CHAPTER 2

POWER SWING

2.1 Introduction

This chapter explains the fundamental of power swing, its characteristics and types is explained. This chapter also explained cause and effects of power swing ion the overall power system in also explained. Power swing detection methods and control are used and various types of power swing are discussed.

2.2 Power Swing Phenomenon

In steady state operating conditions, power systems operate on the nominal frequency (50Hz or 60Hz) ±0.02Hz and Voltage=Nominal voltage ± 5% [1]. During steady state condition a balance exists between consumed and generated active power that is essential for the stability of the electrical power system. There are various disturbances in the power system e.g. variation in the system loss in generation or transmission side and clearance of fault. Due to these variations in power system, imbalance created in the input and output of power. During steady state condition output is considered as electrical and input as a mechanical during, so electro-mechanical oscillations create due to imbalance of input and output and can result in electrical power flow swings. Theses oscillations affect the current and voltage waveforms of power system. Current and voltage waveform during steady state and power swing condition are shown in Figure 2.1 & 2.2 respectively [2].

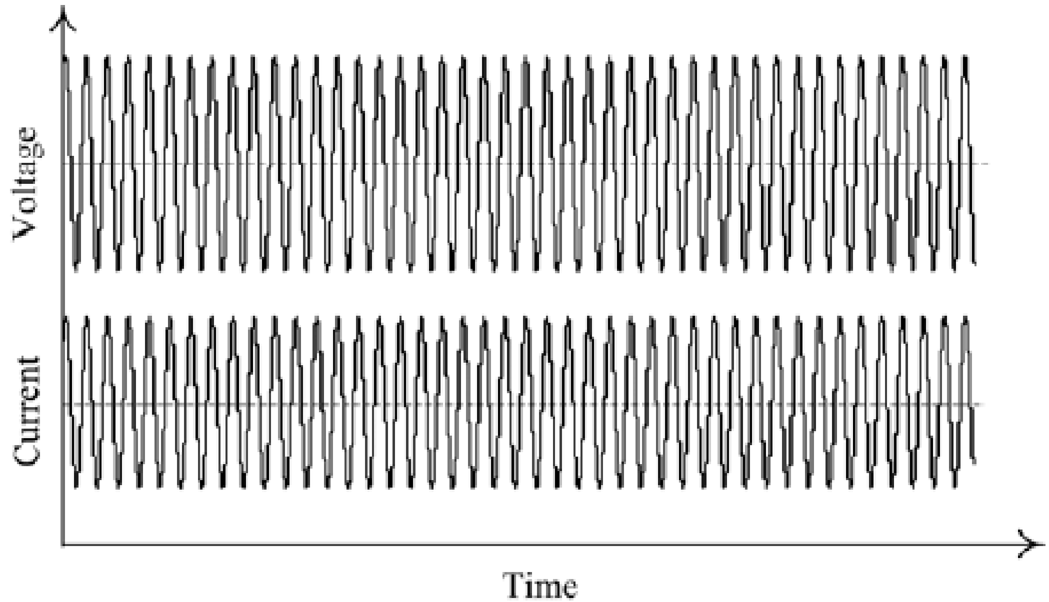


Figure 2.1 Current and voltage waveforms during steady state condition [2]

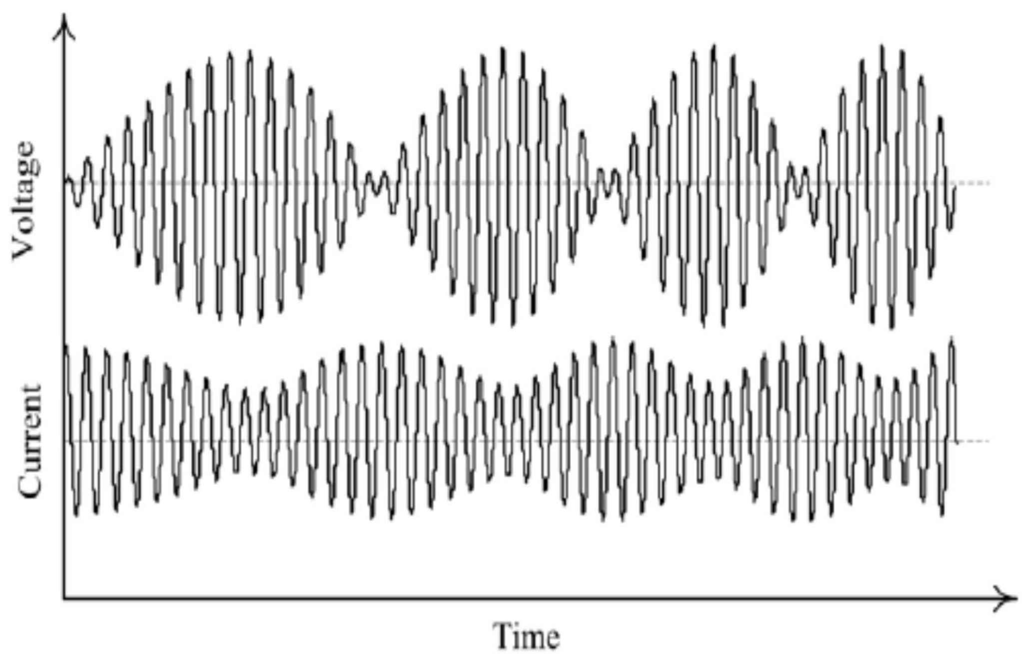


Figure 2.2 Current and voltage waveforms during electrical power swing [2]

Due to the reaction of disturbance, two types of power swings stable and unstable are produced in a power system.

When produced oscillations in power system returns to a steady state point, it is considered as a stable power swing. But if there is huge oscillations and it don't return to steady state point then it is considered as unstable power swing that is also called out-of-step situations. These out-of-step phenomena are cause of huge oscillations in current and voltage waveform which affect the stability of power system [3].

2.3 Power Swing Equation

The generated electrical power P_g transmitted from the generator to the load of electric machine is given by the equation: [4]

$$P_g = \frac{E_g E_l}{X} \, Sin\theta \qquad (2.1)$$

Where:

P_g = Electromagnetic Power output of the generating unit

E_g = Internal voltage and is proportional to the excitation current

E_l = Load Voltage

X = Reactance between the generator and the load

θ = Angle that the internal voltage leads the load voltage

$$P_a = P_m - P_g \qquad (2.2)$$

P_m = Mechanical Turbine Power of the generating unit

P_a = Accelerating Power

As turbine generates the electric power by using mechanical power, so according to electric power equation if one parameter will change due to disturbance in the power system, it will affect overall system. Electrical power changed due to two parameters one is reactance (X) and second is load voltage (E_l) of load side. Load voltage will be decreased due to short circuit and reactance will be increase due to opening of circuit breaker. When one of generator in power system is tripped, the load will have to shift on other generator units and this change will affect the stability of power system. In such conditions, instantaneous electrical power by the load is not equal to instantaneous mechanical power by the load [4]. So rotor angular velocity will be decrease due to sudden increase in load on other generator units. As a result, large power flow swings will produce due to oscillation in rotor angle.

The accelerating torque T_a is determined by the difference between electro-mechanical torque T_e and shaft torque T_m , in a machine as presented by Equation (2.3). In generators $T_a > 0$ accelerates the machine.

$$T_a = T_m - T_e \qquad (2.3)$$

We can denote power P as a function of torque T as shown in Equation (2.4) [4].

$$P = T * \omega \qquad (2.4)$$

Where,

P = Power in watt

T = torque in N.m

ω = Angular velocity in rad/s

It is cleared from Equation (2.5) that the change of the angular rotor position θ w.r.t time defines the angular velocity ω.

$$\omega = \frac{d\theta}{dt} \qquad (2.5)$$

The torque T depend the moment of inertia J as described Equation (2.6).

$$T = J * \alpha \qquad (2.6)$$

Where,

J = moment of inertia in kg.m^2

α = change of the angular velocity with w.r.t time in rad/s^2

Like torque, the angular momentum M is also function of the moment of inertia but in form of ω as described in Equation (2.7)

$$M = J * \omega \qquad (2.7)$$

From equation (2.8), we can denote the accelerating power P_a as a function of the angular acceleration α and as a function of the angular rotor position θ.

$$P_a = T_a * \omega = M * a = M * \frac{d^2\theta}{dt^2} \qquad (2.8)$$

The rotor angle position can be represented w.r.t a synchronous reference frame which rotates at synchronous speed ω_{syn}.

The angular rotor position θ, is equal to the phase angle due to the synchronous rotating reference $\omega_{syn} * t$ and the angular displacement from the synchronous rotating reference δ as presented in Equation (2.9).

$$\theta(t) = \omega_{syn} * t + \delta \qquad (2.9)$$

While the angular velocity ω is:

$$\omega = \frac{d\theta}{dt} = \omega_{syn} + \frac{d\delta}{dt} \qquad (2.10)$$

Applying the derivative of the angular velocity, Equation (2.8) as a function of δ:

$$P_a = M * \frac{d^2\delta}{dt^2} \qquad (2.11)$$

We can represent Equation (2.11) as a function of the constant inertia 'H' with power denoted in per unit as follows:

$$P_a = P_m - P_e = \frac{2H}{\omega_{syn}} * \frac{d\omega}{dt} \qquad (2.12)$$

Where,

P_a = accelerating power

P_m = mechanical power delivered to the generator

P_e = electrical power supplied to the system

H is the constant of inertia

Equation (2.12) is the power swing equation that is one swing equation per machine is essential to model the network dynamics [5].

2.4 Impacts of Power Swing

2.4.1 Power Swing Effect on Distance Relay

Under steady state conditions, power swings can affect the load impedance, when impedance due to power swing matches with the operating impedance of distance relay, gives false tripping, as shown in Fig 2.3. Due to unwanted tripping in power system of transmission lines, power swing occurs during operation of these relays, this leads to weakening the system, cascading outages and the shutdown of important portions of the power system [5].

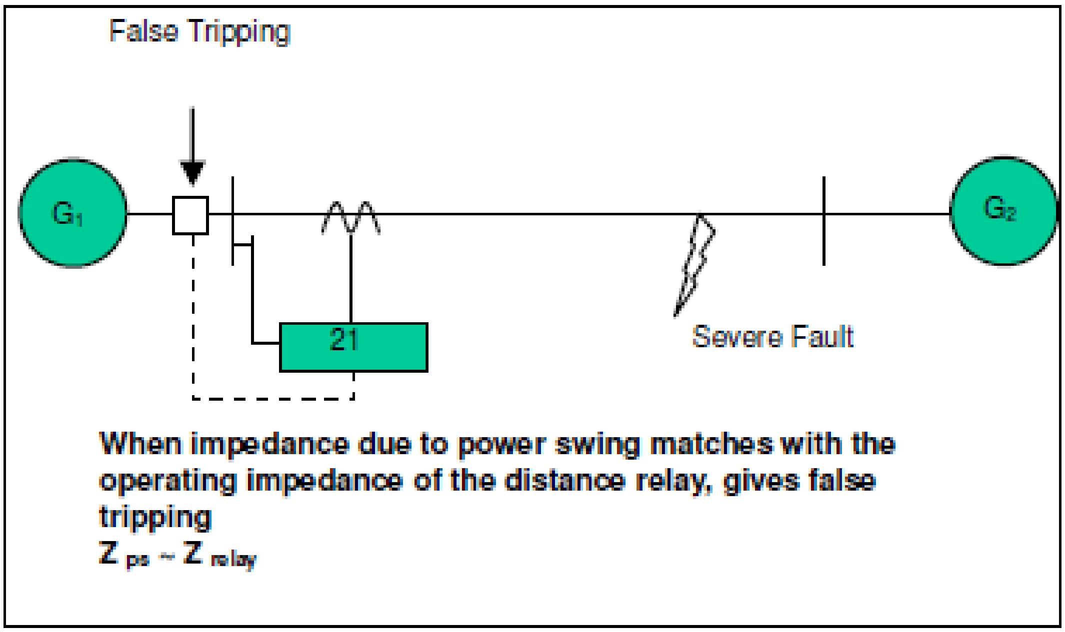


Figure 2.3 Wrong operation of distance relay due to electrical Power Swing [5]

In the modern relays, power swing blocking (PSB) method is used to prevent unwanted operation of distance relay element [5]. The main function of PSB is to differentiate between electrical power swing and normal fault, basic purpose is to block different relay especially distance relay from operation when power swing occurs. However, during electrical power swing, fault must be identified and cleared with accuracy and high degree of dependability and selectivity. Huge disorders in system could cause large separation of the rotor angles among different generators and ultimate loss of synchronism among different generators or between neighboring utility systems. Ideally, the systems should be separated in predetermined positions to maintain balance between load and generation in each of the parted location. System separation may not always attain the required balance between load and generation. In some circumstances, where the separated area load is in excess of local generation, some sort of load shedding is necessary to escape a complete shutdown of the zone. During an Out-of- Step (OOS) condition, uncontrolled tripping of circuit breakers could cause equipment damage, pose a safety needed for utility personnel, and further contribute to cascading outages and the blackout of larger regions of the electrical power system [5].

2.4.2 Power Swing Effect on Transmission Line

In any system, the loss due to unbalanced synchronism between different generators of power system disturbs transmission line relays settings, to avoid this situation several methods are used in power system. But in many applications, the required settings for the power swing blocking (PSB) and out-of- Step Trip (OST) elements could be difficult to calculate. For these applications, advanced stability studies must be performed with different operating methods to find the fastest rate of possible electrical power swings. So if possible power swing will not be determined properly, it will damage overall system by disturbing distance relay setting which is providing protection against faults in transmission lines [6].

2.5 Power Swing Detection Methods

There are many different methods that are used to detect power swings; each has its own merits and demerits. In this section different detection methods are described briefly.

2.5.1 Rate of Change of Impedance

Common used out-of- step protection method in commercial relays is the blinder method, which depends on the measurement of positive sequence impedance at the relay location. The out-of- step relay is normally a distance relay employing different protection algorithms in the impedance plane [7], [8].

A blinder scheme for out-of- step detection phenomena is shown in Figure 2.5, with two rectangular regions (outer and inner blinder). The two-blinder method differentiates between power swings and normal faults by measuring the rate-of-change of the impedance (*Z*). The measurements for the rate-of-change of *Z* are usually executed by determining the time, it takes the impedance to go through the two-blinder elements. During steady state conditions, the impedance seen by the relay is the normal load impedance, that lies away from the relay's rectangular blinders, shown as the load region in Figure 2.4.

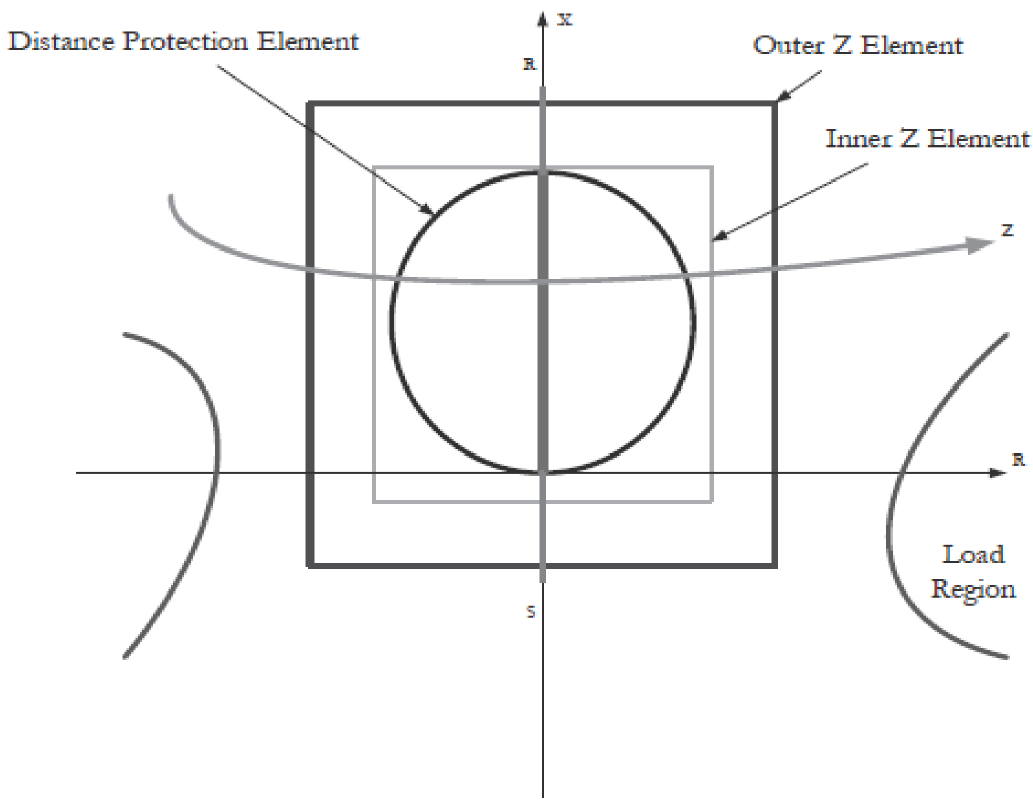


Figure 2.4 Blinder Scheme for Out-of-step Protection [9].

2.5.2 Swing Centre Voltage (SCV)

SCV calculates voltage at a near center in the two-machine equivalent power system. During steady state conditions, the swing center is located on the system where the voltage magnitude is zero for the power angle 180^o [10]. The equivalent two machine system is shown in Figure 2.5 is used to demonstrate the SCV method.

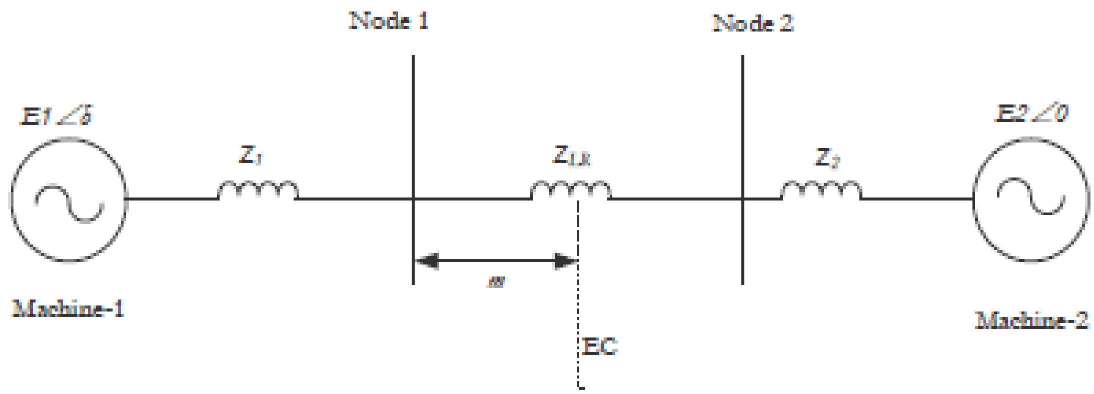


Figure 2.5 Two Machine Example for SCV [10]

If this system becomes out-of-step after a disturbance, the difference between two machine's angle, (t) would fluctuate. In Figure 2.5, E_1 and E_2 respectively represent terminal voltage of two machines; m is the electrical distance from 1 to 2.

The voltages of two machines are:

$$V_1 = E_1 \sin(\omega_1 t + \delta(t)) \quad (2.13)$$

$$V_2 = E_1 \sin(\omega_1 t) \quad (2.14)$$

Where, δ is the initial power angle at Node-1.

$$\delta(t) = \delta_o + \sin(\omega_1 t) \quad (2.15)$$

And the system impedance is:

$$Z = Z_1 + Z_2 + Z_{LR} \quad (2.16)$$

Thus, the swing center voltage is obtained as,

$$SCV = E_1 \sin\left[\omega_1 t + \frac{\delta(t)}{2}\right] \cos\left[\frac{\delta(t)}{2}\right] \quad (2.17)$$

The SCV could be simplified as,

$$SCV \approx E_1 \cos\left[\frac{\delta(t)}{2}\right] \quad (2.18)$$

Based on eq, (2.17) and (2.18), the maximum magnitude of the SCV occurs when the angle difference is equal to zero between two machines. During an electric power swing, change of SCV w.r.t time is compared as,

$$\frac{d(SCV)}{dt} = -\frac{E_1}{2}\sin\left[\frac{\delta(t)}{2}\right]\frac{d\delta}{2} \qquad (2.19)$$

2.5.3 Techniques Based on Fuzzy Logic and Neural Network

The fuzzy logic algorithm can be summarized as finding a group of appropriate signal sets to train the programmed inference system, developing stable and swing criteria to discriminate system status, and making a correct decision based on this. Figure 2.6 shows a typical diagram of fuzzy block detection system. Firstly power system signal are pre processed before sending into fuzzy interference network, where all this data arranges in groups, then it is compared will predefine standers and final decision could be made.

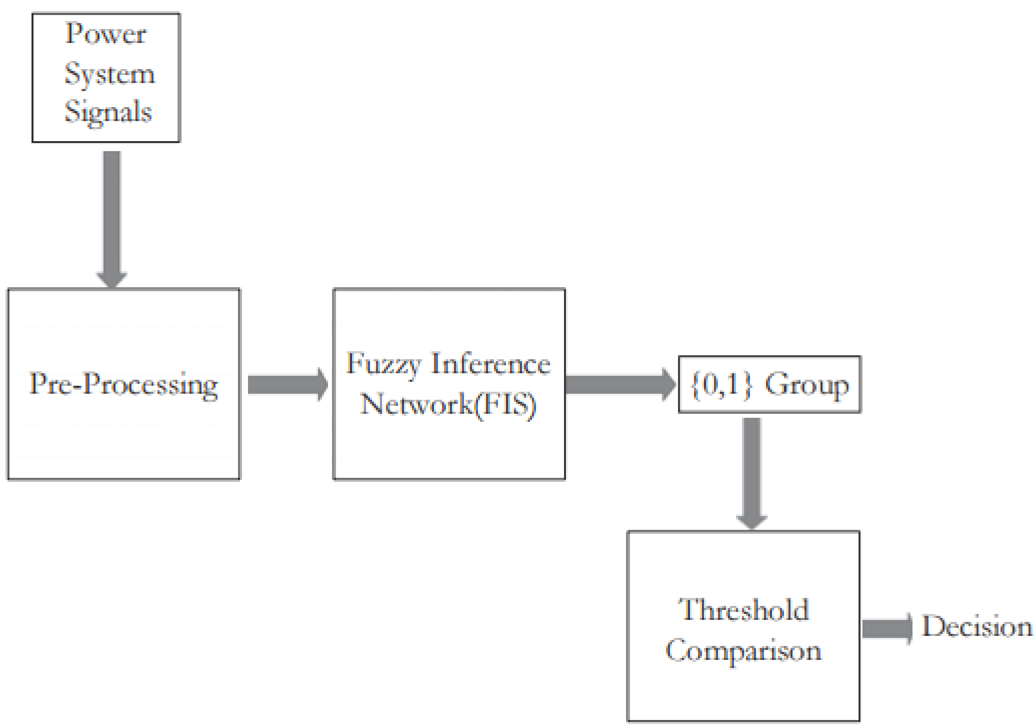


Figure 2.6 Fuzzy Algorithm for Out-of- Step Detection [11].

In second method, out-of- step detection depends on back propagation trained neural networks. This schematic is shown in Figure 2.7.

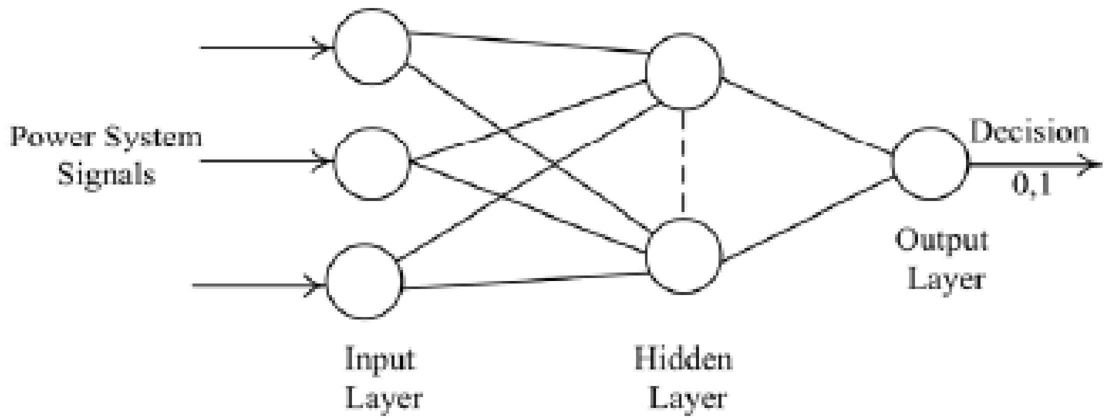


Figure 2.7 ANN Data Training Diagram for Out-of-step Detection [12]

2.6 Types of Power swing

2.6.1 Stable Power Swing

An electric power swing is called stable swing if the generators in power system do not slip poles and the power system gains a new state of equilibrium, that is suitable operating state.

For a stable power swing, this is possible which positive sequence impedance trajectory will traverse the working region of a distance element. In this case, the distance element needs to be blocked from operating using power swing blocking (PSB); otherwise, an unwanted operation of a distance element can occur, further weakening an already weakened system. Therefore, it is important that all power swing conditions be detected as rapidly as possible to prevent any unwanted operation of the protection system as shown in Figure 2.8 [13].

2.6.2 Unstable Power Swing

An electric power swing is called unstable if different generators in power system experience pole slipping for which some remedial action must be taken.

For unstable electric power swings (out-of- step situations), out-of- step tripping (OST) is implemented to separate the network with a generation-load balance. Stability studies determine the locations where it is best to identify the out-of-step conditions and separate the system into islands. All other locations need to implement PSB so as not to separate the system at unwanted locations. OST comes with its own challenges, such as when a trip command should be issued or if the system can regain stability after experiencing a pole slip [13].

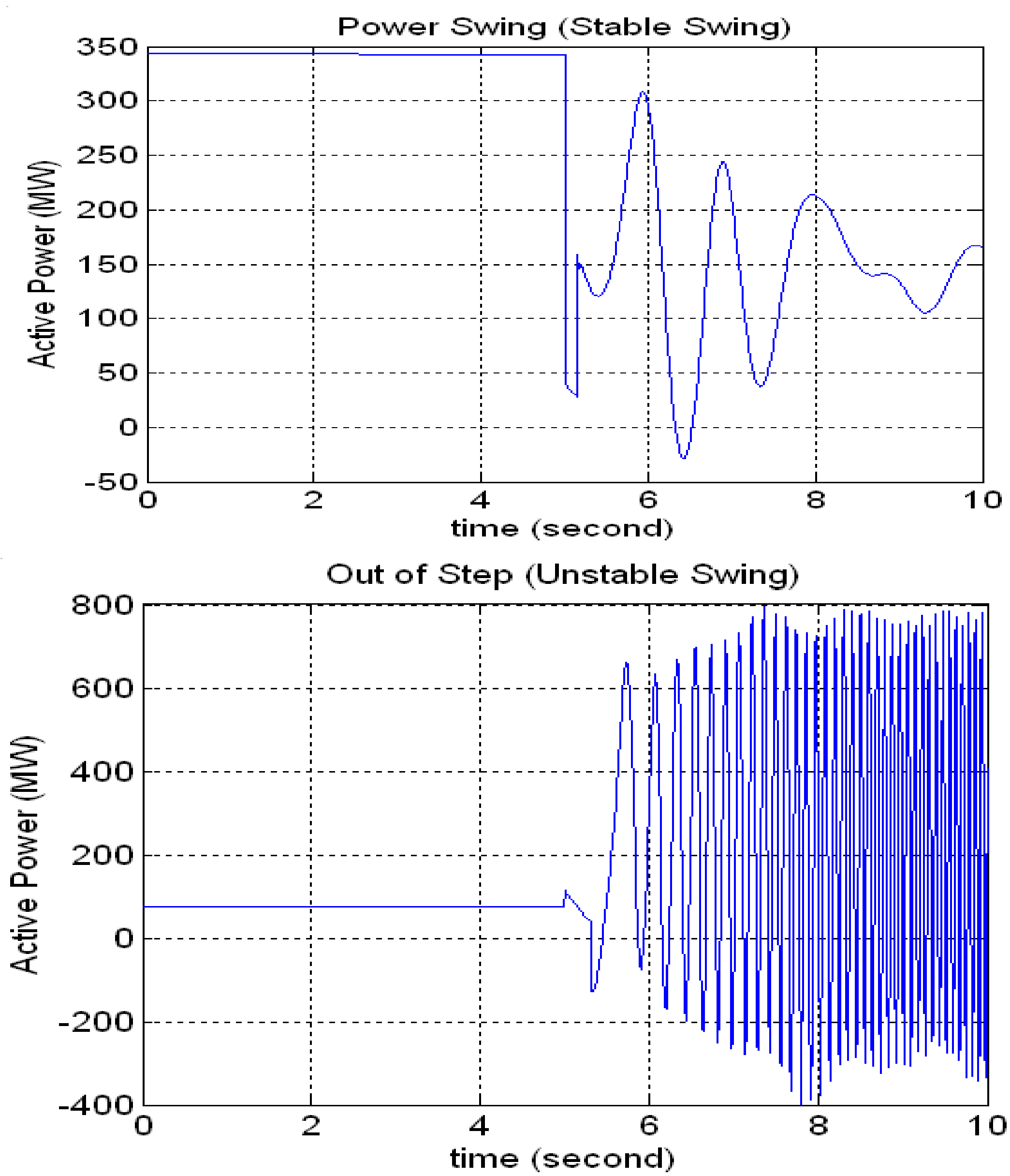


Figure 2.8 Time domain simulation illustrating a stable & unstable swing [13].

CHAPTER 3

PROTECTIVE RELAYS

3.1 Introduction

In electric power system, protective relays detect unusual power system circumstances that rise due to various faults that occur in the power system by constant observing of several variables of system such as power flow, system frequency and voltages [14]. There are many relays that identify and disconnect a component of the power system, working outside its regular range. The purpose of protective relays is to use for protecting numerous components in power system to deliver high reliability and safety. A protective relay which functions properly for all type of faults, that is intended to respond to, is said to have very high dependability [15]. Protective relays are of primary interests that are used in protection of power transmission line in this research work. Such protective relays clear the faults in the system by adjusting the closing and opening of circuit breakers when a normal fault happens in the power system. The relaying scheme used in power system is able to differentiate between usual loading methods, power swing situations, fault conditions and out-of- step situations [16].

3.2 Fault Clearing and Reclosing

In the power system, when a system fault happens on a portion of apparatus of a power system. It is necessary which is identified by the related relays and removed via the opening or closing of circuit breakers (CB) under the protective relay command [17].

The sum of the relay time determines the fault clearing time, also denoted as normal fault detection time, the signal transmission time and the required time by the circuit breakers (CB) to open. Alternatively, the protective relay time and the interrupting times basically depend on the voltages of power transmission line [18]. Table 3.1 illustrations the protective relay time and also interrupting time that is used for different transmission line voltage levels. Time is shown in frequency 60 Hz.

Line Voltage	Interrupting Time in Cycles of 60 Hz	Relay Time in Cycles of 60 Hz
≤ 69 kV	8	1 – 3
≥ 115 kV	5	1 – 3
230 kV	3	¼ - 1
345 kV	2	¼ - 1

Table 3.1 Interrupting time and Relay time for different line voltages [17]

Time required for protective relay to regain its predefined condition is called de-ionization time and it depends upon the voltage level, as much will voltage level that much will be de-ionization time. Table 3.2 illustrations the de-ionization time for the different transmission line voltages (cycles = 60 Hz).

Line Voltage in kV	Minimum De-ionization Time(in Cycles)
69	6
115	8.5
138	10
230	18
345	20

Table 3.2 Deionization times for different line voltages [17]

3.3 Distance Relays

The distance protective relays are the essential equipment that is used for line protection. For existing use, standard distance protection relays are impedance relays, mho relays, reactance relays, improved mho and improved impedance relays [17]. The impedance between the protective relay location and also the fault location, determined as the ratio of the measured current to measured voltage phasor [18].

The area in which relays observe the fault and clear it is called its zone. Basically distance protection relays protect three dissimilar zones for a certain line. The Zone 1 is usually set between 90% and 85% of the transmission line length for that the relay activates rapidly. The Zones 2 and 3 are adjusted for the back-up protection of the transmission line. For these two zones, a timer starts coordination delays that permit the primary protection to work first. Exactly, the coordination delay for Zone 2 is typically of the order of 0.3 seconds. Range of Zone 2 is mostly set from 120% to 150% of the length of transmission line. At this point, caution is taken that Zone 1 of the adjacent transmission line is activated before the Zone 2 for a protected transmission line. Regarding the Zone 3, it typically extends to 120% to 180% of the neighboring transmission line section. That is more essential that Zone 3 synchronizes in time and the distance with the Zone 2 of the neighboring circuit. Generally operating time for the Zone 3 is set at 1.0 second [18]. The zones denoted in distance relaying for 100% transmission line protection are shown in Figure 3.1(a &b)

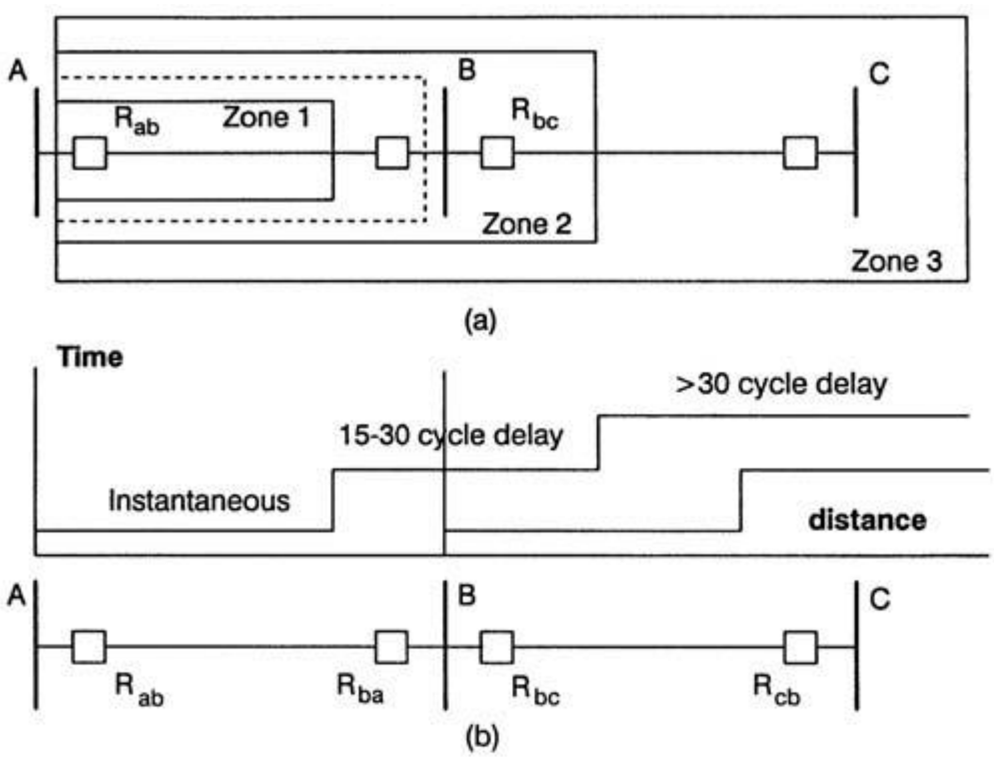


Figure 3.1 Three-zone step distance relaying and its clearing time [18]

3.3.1 Impedance Relays

A protective relay which activates on the value of a voltage to the current ratio is known as an impedance relay [19]. So the ratio is called as apparent impedance realized by the protective relay. This relay works when the value of magnitude of the apparent impedance is smaller than the set value of the operated relay. This kind of relay identifies faults in all the four quadrants of R-X plane. Consequently, for this type of relay, directional elements are unutilized. A normal impedance relay has a timer, three impedance elements and a directional element.

Therefore, for all different impedance values, all three impedance components work to protect all three zones, at different time interval and should faults arise on the power line under their command. The tripping feature of an impedance relay and also with impedance elements and circle centered timer at the origin [19]. As there are two parts of impedance first is resistance and second is reactance. Reactance will be treated as positive component for capacitance and negative component for inductance; all this is shown in impedance circle in Figure 3.2.

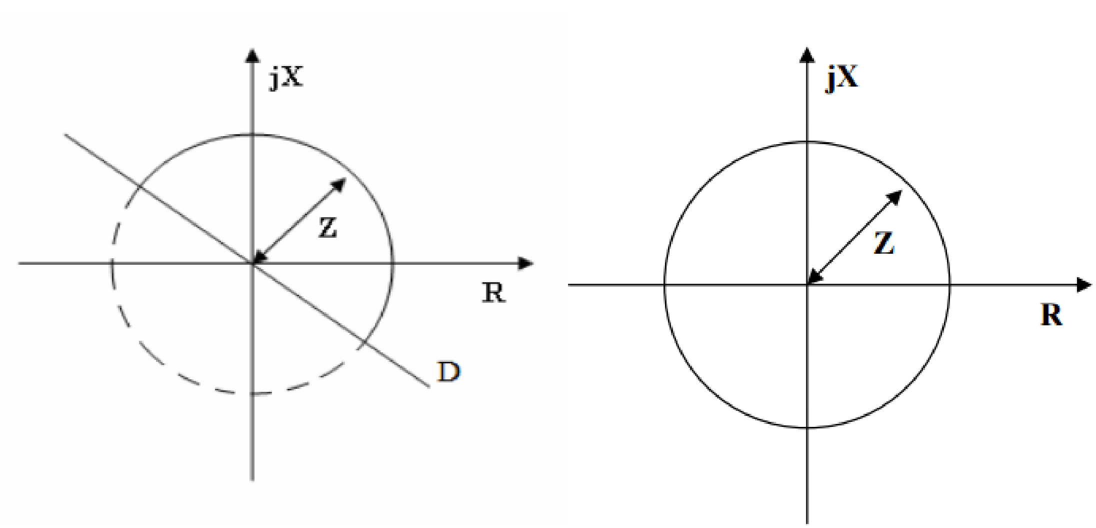


Figure 3.2 Impedance relay characteristics [18]

The relay operates, when the apparent impedance's value of relay falls inside the radius of circle. Alternatively, the directional element's characteristic is a straight line crossing from the origin that is vertical to the maximum torque line [18]. This tripping area is falling within the circle with the presence of a directional element and above a straight line. Specific of the impedance relay with the directional component and the zones is displayed in the Figure 3.3.

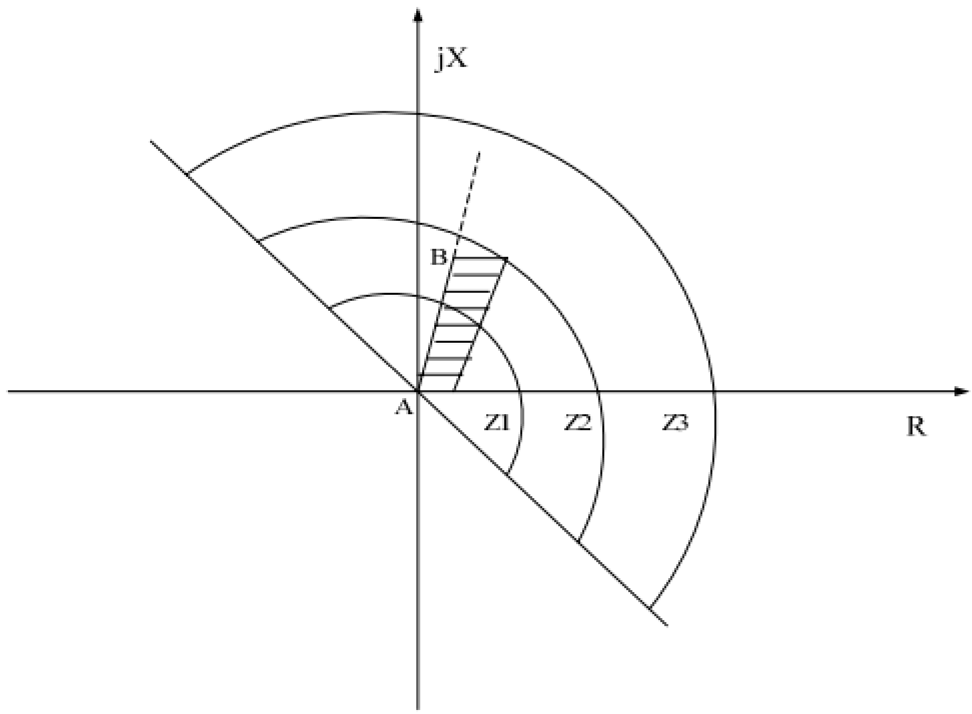


Figure 3.3 Impedance relay characteristics with three zones [18]

3.3.2 Mho Relay

Mho relay identifies the faults in system only in one path, appreciations to the availability of all three zone components and with a timer. It is to be noted that these are not required directional elements. The third zone of the impedance element of relay can be used to bring an offset feature for solution of back-up protection. It is important to note that usually, for protection of long transmission lines mho relays are used [19].

3.4 Out-of-Step Blocking and Tripping

In power system, due to fault, whenever the steady state symmetry of a power system is troubled, and power flow of generators starts swinging w.r.t others, that may result in the action of the distance relays. When protection relay operates wrong detection of unstable power swings, this may outcome in the opening of power transmission lines. Figure 3.4 shows the unstable and stable power swings. The control action is normally started to bring the system back into the stable symmetry with protecting actions. Such as, when unstable power swings (out-of- step) happen due to loss of synchronism between two generators, and these oscillations may be diminished by splitting the coherent machines into different groups, are called coherent areas [19].Therefore separation should follow the following points so that:

1) there is a marginal generation and load imbalance in each separated area
2) critical load is protected
3) Electric power system is brought back to protected state as soon as possible.

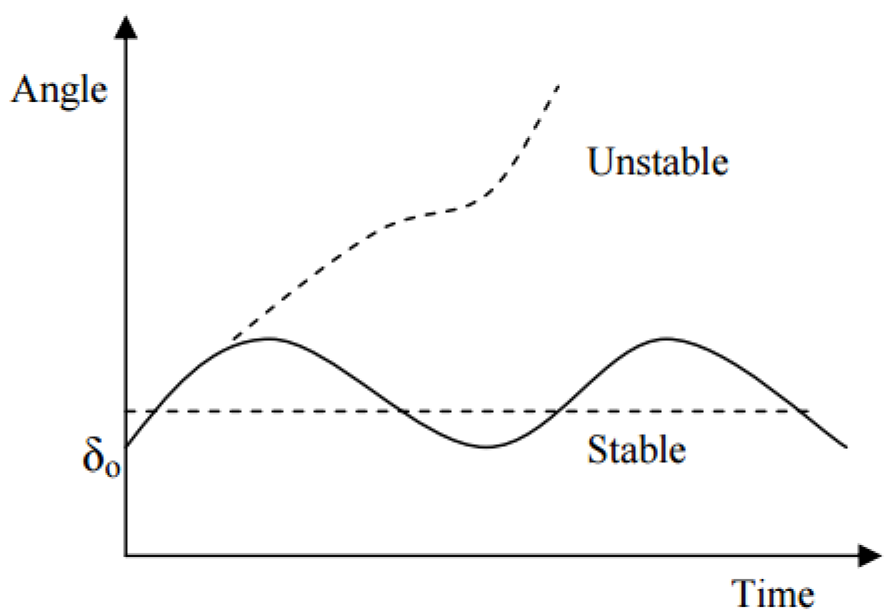


Figure 3.4 Stable and unstable swings [19]

3.4.1 Out -of- Step Relays

The out-of- step relays have various features. First of all, these relays successfully detect out-of- step situations due to the initial loss of synchronization. Secondly, whether the power swing is stable or the unstable, these relays do out-of-step tripping and blocking totally depending upon them. The conclusion is completed depend on the rate-of-change of locus of apparent impedance throughout system uncertainty. The rate-of-change is so slow for a stable power swing, whereas this is fast for an unstable power swing. The out-of-step relays contain the two relays which having spherical or perpendicular characteristics in R-X plane to do this detection [18]. The relay features are circular when the impedance protection relays are normally used and relay characteristic are vertical when mho relays are used. If the time is necessary by the apparent impedance locus to cross the two characteristics (buffer area) increases a definite value, then the out-of- step condition is started as shown in Figure 3.5

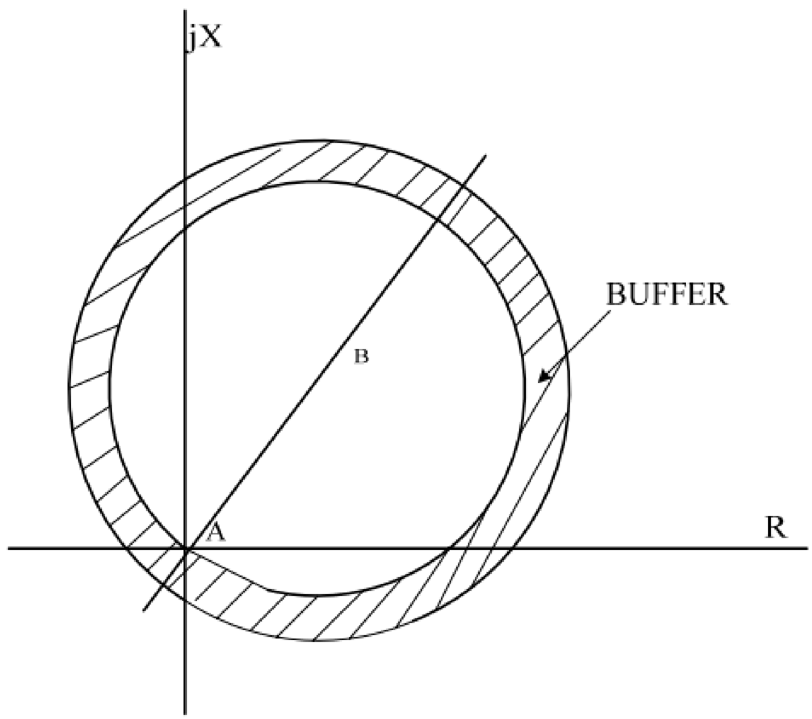


Figure 3.5 Circular characteristics of out-of- step relay [19]

Observably, blocking scheme of out-of-step method is desired to stop the distance relay’s tripping to escape unsuitable power system splitting during out-of- step situations that show high swings. These protective relays which may trip at unwanted areas are blocked while others out-of- step relays are permitted to trip [20]. For example demonstrated in Figures 3.6, the blocking-action is attained by adjacent the tripping location with the con-centric impedance relays or may be mho relays are establishing a buffer area. This apparent impedance passes, under fault condition, slowly over the buffer area into tripping area [20]. So the time taken by the apparent impedance to pass through the buffer area is equal or larger than pick up time (ΔT) of the auxiliary relay related to out-of- step relay, and therefore auxiliary relay activates to block the tripping the protective relay.

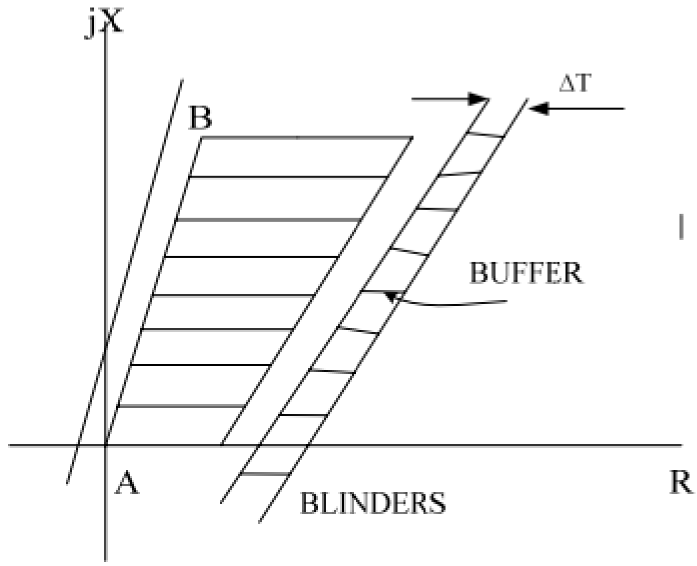


Figure 3.6 Out-of- step relay with blinders (Ohm unit relay) [20]

3.4.2 Ohm Unit Relays

Ohm unit relays have linear characteristics, also known as angle impedance relays, which mark these protective relays appropriate for protection of the long power transmission lines, here quick tripping needs to be prohibited to allow greater swings to happen. Actually, they protective relays are prepared with blinders to regulator the tripping activities during out-of- step or power swing situations. The angular range of the distance protection relays can be measured and narrowed to any required lower angles as shown in Figure 3.7. Shaded area f the fault impedance locus is between two lines at the angles 75^0 and 60^0. Path of apparent impedance or power swing impedance locus is applied at various power swing angles, overlapping the line impedance. The distance protective relays will trip, generally used without blinders, for the power swing angles of ranging from 240^0 to 90^0, while distance relays will trip, which used with blinders, for the power swing angles of ranging from 195^0 to 135^0 [20]. Therefore circular features characterize the tripping area boundary whereas the blinders explain different angular range.

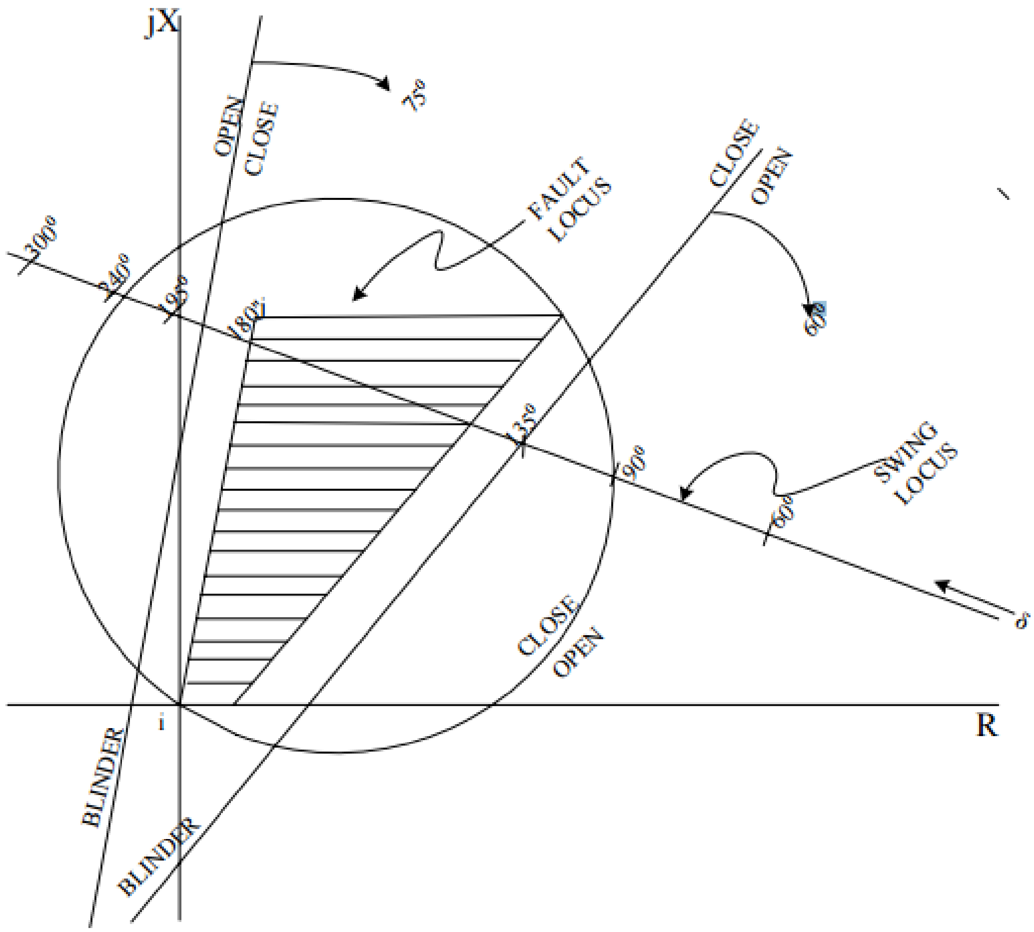


Figure 3.7 Swing blocking relaying [20]

CHAPTER 4

OUT-OF-STEP BASICS

4.1 Introduction

This chapter discusses the ideas and impressions associated to out-of-step phenomena. The basics of out-of-step phenomena, OOS blocking and tripping and effect on protective relays are explained with a method which wants the information of them.

4.2 Out-of-Step Phenomena

Abrupt change in load in the electrical power system affected by a fault, by an auto reclose forces the generators or disconnection of loaded lines to adjust this new load condition. So, due to mass of the generators, the adjustment will not be instantaneous, but it is not in the form of oscillations. Generally this will be a damped fluctuation and generators will be able to return back to its normal steady state form. In other cases, where the generators lose synchronism and run out-of-step, this state can lead to a shutdown of the whole power grid [21].

4.2.1 Out-of-Step Blocking

During power swings, a function of power swing blocking (PSB) exists in the modern distance relay to avoid undesired operation of distance relay component. Main purpose of the PSB function is to separate normal faults from electric power swings and also block the operation of distance relay or other relay components during an electrical power swing. Though, during a power swing fault that occurs, it must be identified and also cleared with a high degree of reliability and selectivity. In this condition, the PSB function must be clear and allow the operation of distance protection relay components and clear all faults that happen in their protection zone during an electric power swing situation. Most of power swings blocking (PSB) components depend on traditional methods that observe the rate-of-change of positive-sequence impedance. The necessary settings for the PSB components could be difficult to determine in various applications, mostly those where fast power swings can be predictable. In these situations, to define the fastest rate of possible power swings, extensive stability studies are necessary [22].

For a stable power swing, this is possible which positive sequence impedance trajectory will traverse the operating region of a distance element. In this case, the distance element needs to be blocked from operating using power swing blocking (PSB); otherwise, an unwanted operation of a distance element can occur, further weakening an already weakened system. Therefore, it is important that all power swing conditions be detected as rapidly as possible to prevent any unwanted operation of the protection system [23].

4.2.2 Out-of-Step Tripping

The function of the out-of- step tripping (OST) mechanism is found in modern distance relays, to distinguish between unstable and also stable power swings. The function of OST condition controls the tripping of circuit breakers at preset power network positions during unstable swings and separates the system rapidly for the purpose of maintain power system stability. Conventionally, the function of OST is to observe the rate-of-change of the positive-sequence impedance. So, the necessary settings for the OST functions are difficult to analyze, and in maximum applications, a wide number of power network system stability studies with different operating situations must be implemented. It is an expensive exercise, and anyone can never be sure that all possible situations and operating circumstances were measured [24].

For unstable power swings (out-of- step conditions), out-of- step tripping (OST) is implemented to separate the network into islands with a generation-load balance. Stability studies determine the locations where it is best to identify the out-of-step situations and separate the system into islands. All other locations need to implement PSB so as not to separate the system at unwanted locations. OST comes with its own challenges, such as when trip command should be issued or if system can regain stability after experiencing a pole slip [25].

4.3 Out-of-Step Tripping Protection

In spite of the stable power swing or out-of- step situation, the relays are lying to power swing works if all the parameter are identified by the protective relay enters the operating zone of an protective relay. In figure 4.1 distances relay works for the cases ‘b’ and ‘c’ as the impedance shown by protective relay goes into the operating zone. During stable swing case 'b', the tripping of relay is not necessary. The distance protection relay should allow the electric power system to return back to new steady state situation for the stable power swing. Therefore, the out-of- step relays must be matched with the protective relays lying to the power swing, to send them signal showing not to trip during a stable power swing. The out-of- step relay sends tripping signal only to the selected relays in case of an out-of-step condition [26].

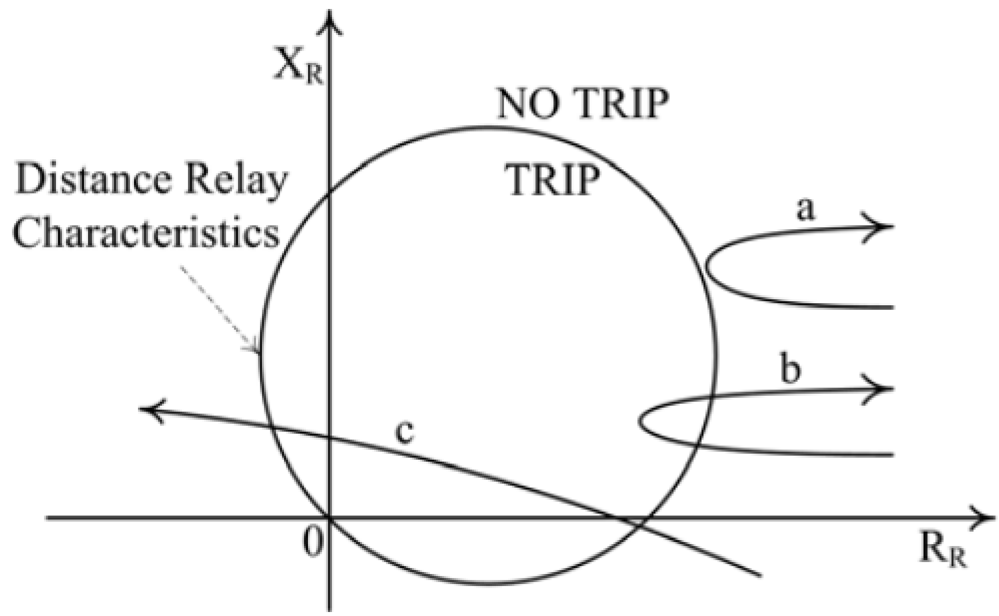


Figure 4.1 Operating characteristics of distance relay for different power swings [26]

Above discussion, it is clear that there are fundamentally two purposes which an out-of- step relaying system has to execute. Function of out-of- step blocking (OSB) is first, OSB function must block protective relays prone to power swing, whatever whether this is a stable or unstable (out-of-step) swing. Function of out-of- step tripping (OST) is next, which differentiates between stable and unstable swings (out-of- step) and starts the power system separation only during the out-of- step situation. Ideas of out-of-step relaying are denoted in [26] and are shortened below:

- Block the tripping at all settings for a stable power swing.

- Protect the components of power system network by guaranteeing rapid separation for each out-of-step situation to avoid destruction of equipment and shutdown of main areas of the electric power system.
- Isolate the electric power system effectively, sustaining a load-generation equilibrium in each location.
- Controlled tripping of definite power network components to protect from damage of apparatus.

4.3.1 Out-of-Step Detection Techniques

There is lots of detection of out-of-step methods that are used and are described in the literature. For the out-of-step detection, the most general approaches include rate-of-change of impedance technique (blinder technique), use of fuzzy logic, SCV technique, neural network, and artificial intelligence, out-of- step detection using frequency deviation of voltage, detection of out-of- step technique depend on wavelet transform, and detection of out-of- step technique based on angle already discussed in Chapter 2.

4.4 Effect on Protective Relays

4.4.1 Effect on Differential Relays

The current differential relaying applied for the protection of transformer, generators, buses and lines (like that pilot wire relays or phase comparison relays) will not be exaggerated by an out-of- step power swing. During a loss of synchronism between systems A and B of Fig. 4.2 where A swings fast than of B, there a current will be flow for A to B. It will be a "through" current and consequently, the swing appear as an external fault state to a current differential arrangement. C and D denoted the circuit breaker. Swing locus occurs to go through a bus, a transmission line or transformer which has pilot wire or phase comparison relaying and system separation is required at the point, there are some other kind of relaying either for standby or additional, will have to be provided to identify the power swing.

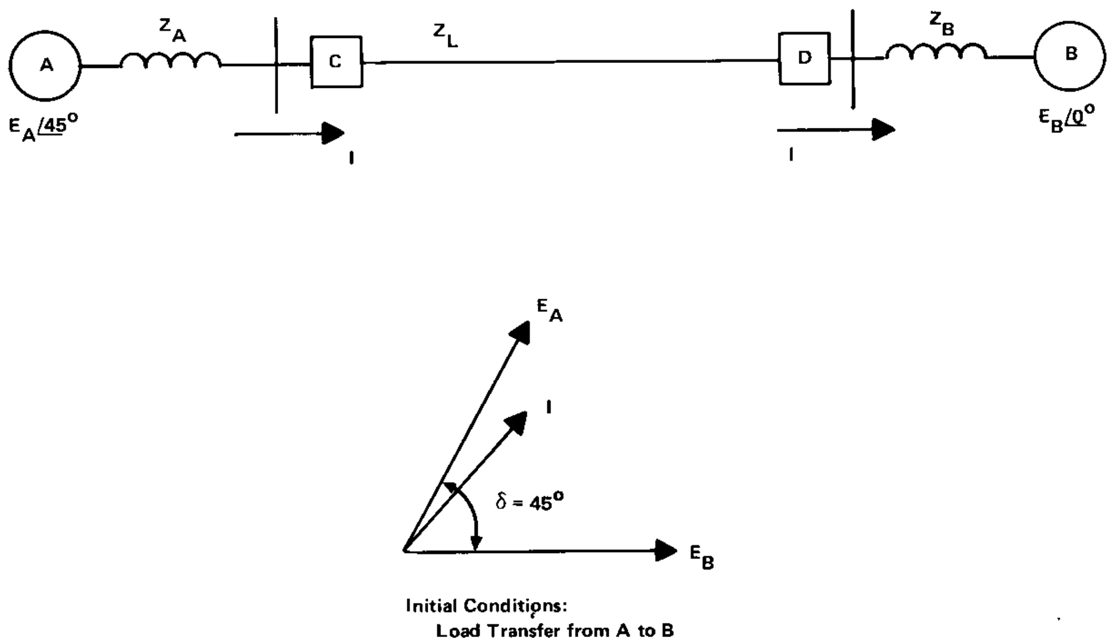


Figure 4.2 Equivalent system used to determine loss of synchronization [27]

4.4.2 Effect on Over-current Relays

It should be observable that for protection of phase fault in system, over-current and directional over-current relays are used and these will work if "swing currents" increase the spontaneous locations of these relays. Therefore, one of the limitations of this type of protective relay is which may work during power swings from which the power network may improve and stay stable.

4.4.3 Effect of Distance Relays

The distance relay which determines positive-sequence impedance all through 3-phase faults will work when the power swing locus enters into operating location. The protective relay will execute the process and trip its circuit breaker depends on the zone of distance relay, involved and the length of time it proceeds for the power swing locus to cross the relay characteristic. In common, only the distance protection relay backup time is likely to contain sufficient time delay to avoid tripping during a power swing.

CHAPTER 5

METHODOLOGY & SIMULATION

This chapter contains the methodology of research work and brief purpose method to detect the out of step tripping (OST). Flow chart of algorithm used to explain the method of fault detection and at the end simple circuit is made on PSCAD to show the working of fault control scheme.

5.1 Proposed Method

The proposed approach is basically categorized into three conjectures, (I) First define the three conditions when fault occur at different angles of rotor of generator, which show that how to power system response and behavior of swing curves during three conditions are pre-fault, during fault and post fault. (II) Secondly explain why a threshold value of rotor angle is set to determine the faults type, either it is normal fault or power swing. Compare the rotor angles value if the gap is more than 0.1 than fault move to power swing region, otherwise this normal fault that easily detect with normal relay operation. (III) Thirdly differentiate between stable and unstable fault by comparing the mechanical power of rotor and electrical power of generator. If the electrical power greater than mechanical power and curve will not come back to under the mechanical power line, than algorithm will work and show the out-of-Step condition.

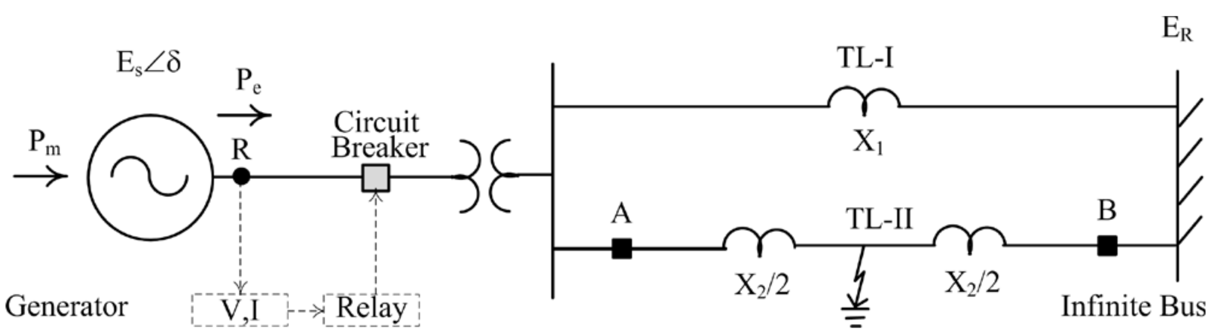


Figure 5.1 single-machine infinite buses system (SMIB)

Figure 5.1 shows the single-machine power system and parallel transmission line TL-1 and TL-2 with impedance X_1 and X_2 respectively. The electrical power from generator to motor is given by,

$$P_e = P_{max} \sin\delta \qquad (5.1)$$

The maximum power transferred from generation to motor end is given by,

$$P_{max} = \frac{E_S E_R}{X} \qquad (5.2)$$

δ = phase angle between E_S and E_R

X = total impedance

Power changes due to change of impedance during fault in the system in three cases are pre-fault, during fault and post fault.

5.2 For Stable system

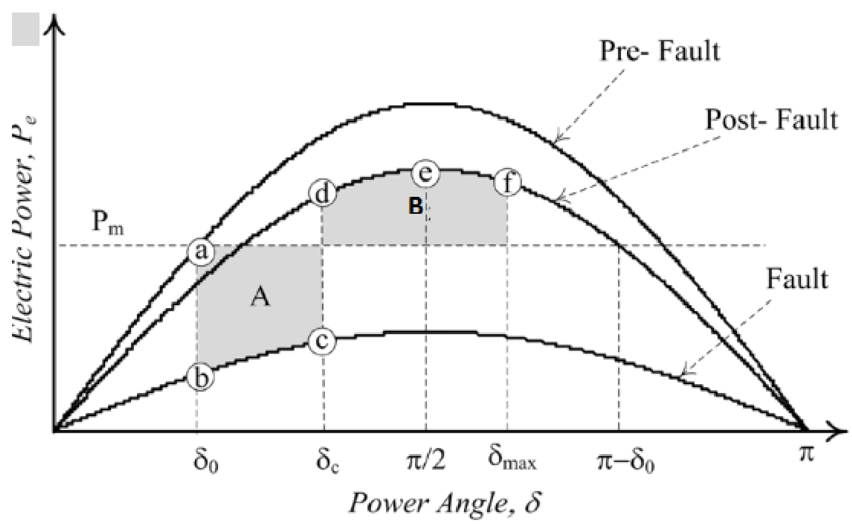


Figure 5.2 P- δ curves showing a stable condition [28]

Figure 5.2 shows that mechanical power (P_m) is equal to electrical power (P_e) at angle δ_o at the pre-fault steady state condition. Electrical output power suddenly drops and follows the fault curve when fault is applied on the power system as shown in figure 5.2. Output electrical power suddenly changes and follows the post-fault curve when fault is cleared at δ_o. The area **A** and area **B** represent the transient energy for $P_m > P_e$ and $P_m \leq P_e$ respectively.

$$\mathbf{A} = \int_{\delta_0}^{\delta_c} \frac{\omega_s}{H} (P_m - P_e) d\delta \qquad (5.3)$$

$$\mathbf{B} = \int_{\delta_c}^{\delta_{max}} \frac{\omega_s}{H}(P_m - P_e)d\delta \qquad (5.4)$$

A will be equal to and less than **B** for stable power system

5.3 For Unstable system

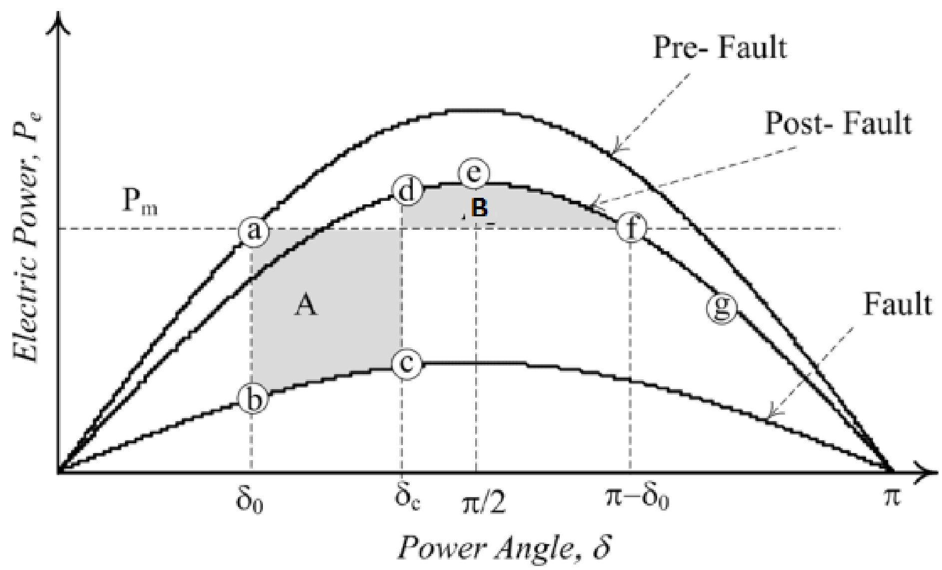


Figure 5.3 P- δ curves showing a unstable condition **[**28]

As shown in Figure 5.3, the power angle δ swings up to δ_{max} where $\delta_{max} = \pi - \delta_o$. **A** will be greater than **B** for unstable power system.

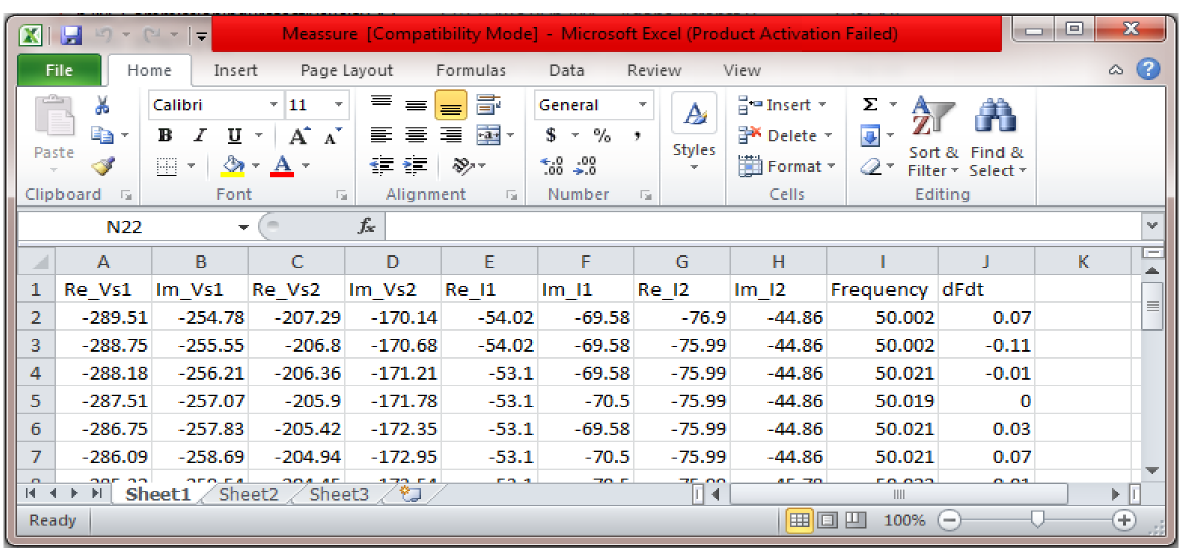


Figure 5.4 Excel sheet with measured value of single-machine infinite buses system (SMIB)

Figure 5.4 shows the real and imaginary values of current and voltage of two buses and also shows the phase difference between two buses of single-machine infinite buses system (SMIB)

5.4 Flowchart

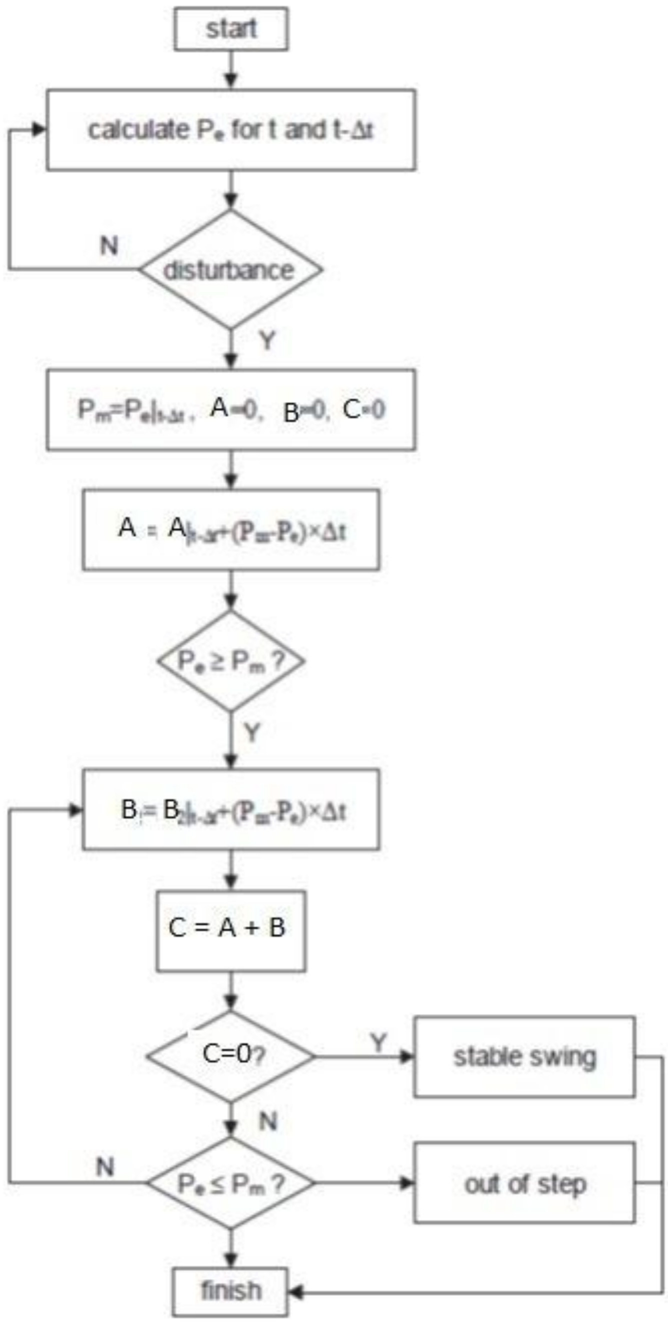


Fig 5.5 Flow chart of algorithm [29]

Figure 5.5 shows the flow chart of common algorithm and following table 5.1 shows the result of this algorithm.

Table 5.1 Summary of stable and out-of-step swing of a single-machine infinite-bus system (SMIB) [29]

Case	*1*	*2*	*3*	*4*
Power Angle (δ_0)	30°	30°	30°	30°
Fault Duration Time, s	0.167	0.20	0.233	0.267
Area (A) pu-s	0.048	0.054	0.061	0.067
Area (B) pu-s	-0.048	-0.054	-0.027	-0.016
A + B	0	0	0.034	0.051
Decision Time, s	0.640	0.850	0.598	0.504
Decision	Stable	Stable	OS	OS

OS: Out-of-step

The following flow chart shows the proposed algorithm. Figure 5.6 explain as, in the beginning of algorithm, at t=0 consider that initial condition is stable and just check the value of mechanical power and rotor angle as well.

In the second step iteration start and go through all the each next value of angle. The IF statement in this section compares the difference of two values next to each other in the phase angel vector, if the values differ too much the part of the algorithm that detect power swings will start. Here assume a threshold value which is equal to 0.1, if the value is greater than threshold than algorithm will start and go to next step. Similarly in opposite cause algorithm goes back step.

After calculating the value of angles, IF statement is used to measure value of change in angle and electric power output. This IF statement is the most important part of the algorithm, If the angle has changed too much and the electric power output has decreased to a level below the mechanical power input, it is for sure that the system will experience a power swing. This algorithm start to observing the value of electrical power (P_e) and mechanical power (P_m) and also compare all of these values to differentiate between normal condition and power swing fault.

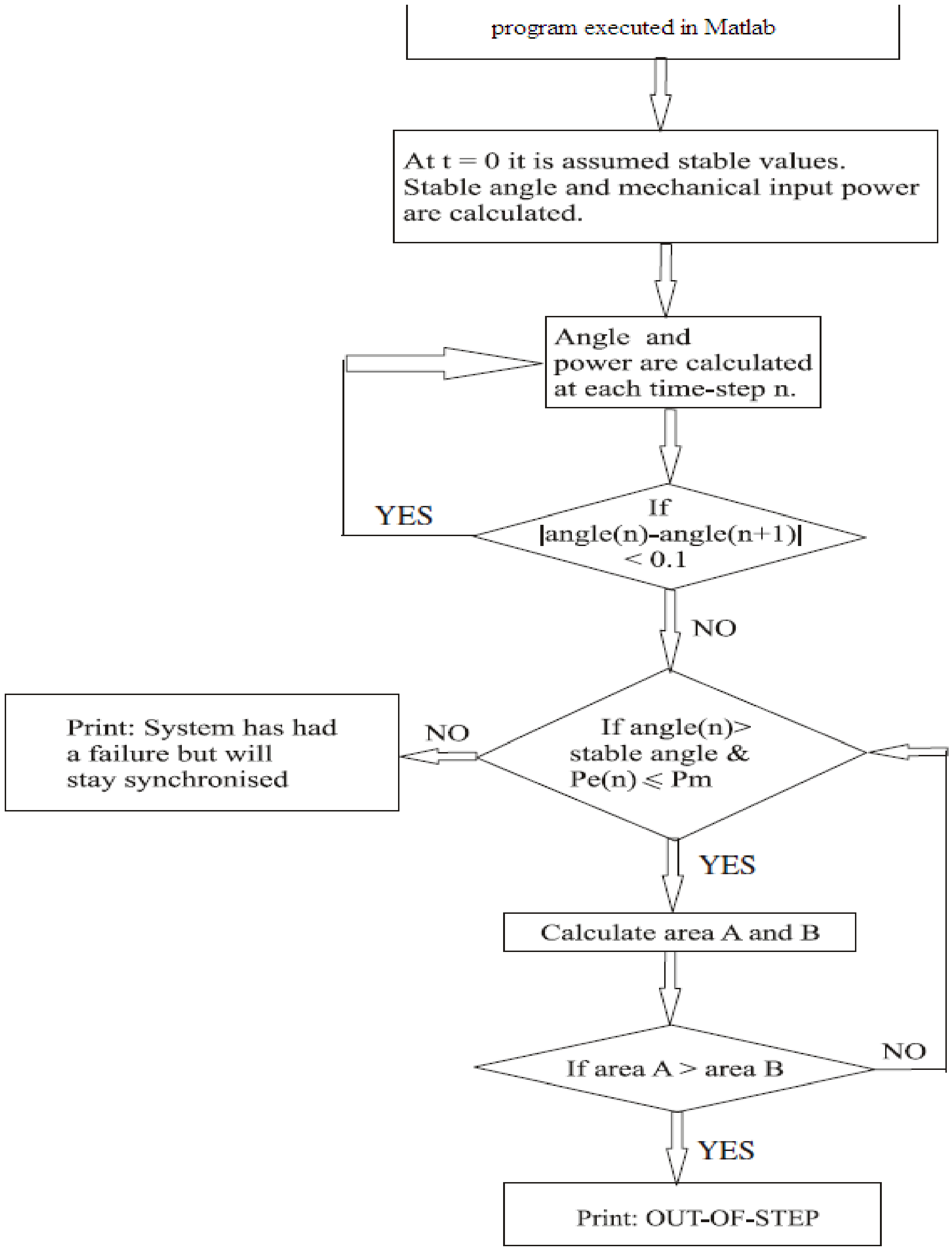


Figure 5.6 Flow chart of algorithm proposed

Therefore if statement is decide at the end, this IF statement compares the areas as shown on Figure 5.7. As long as area A is lesser than area B the IF statement will receive NO and the algorithm continues but if the angle grows too large and area A is greater than area B the IF statement receive a YES and the algorithm stops.

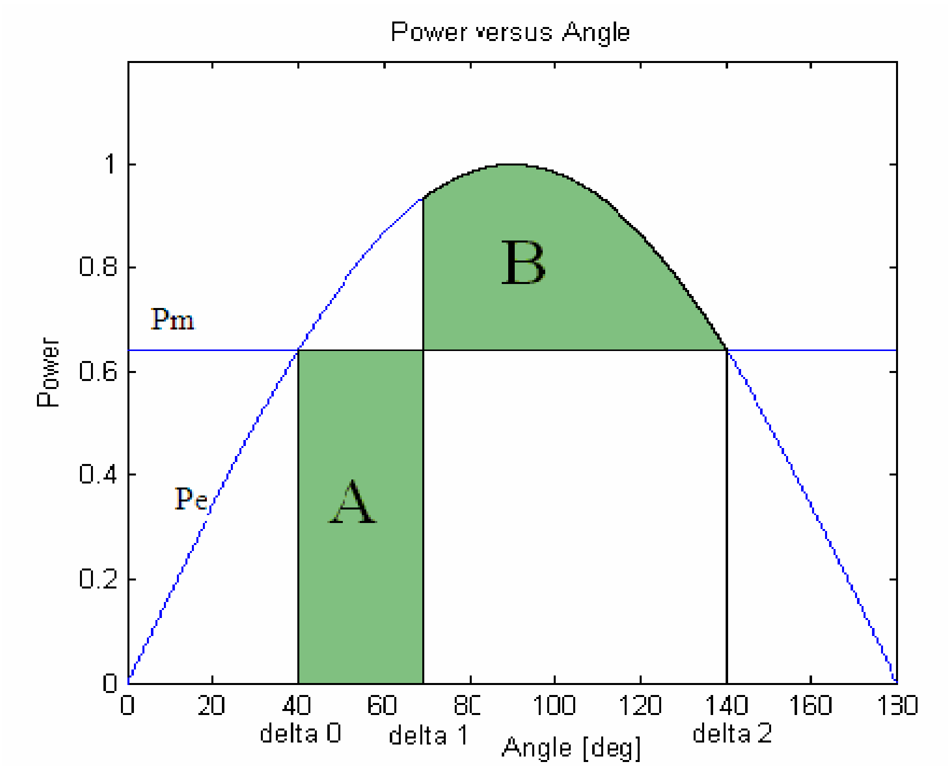


Figure 5.7 Differences between Electrical and Mechanical Power
By acceleration area A and a decelerating area B

Table 5.2 Summary of stable and out-of-step swing of a single-machine infinite-bus system

Case	**1**	**2**	**3**	**4**	**5**	**6**
Power Angle (δ)	40	40	40	40	40	40
Fault Duration Time, s	0.133	0.167	0.20	0.23	0.26	0.30
Critical angle (delta1)	70^0	70^0	70^0	$>70^0$	$>70^0$	$>70^0$
Area A, pu-s	0.1013	0.1038	0.1300	0.1661	0.4583	0.4656
Area B, pu-s	-0.1013	-0.1038	-0.1300	-0.0009	-0.031	-0.0298
Decision	**Stable**	**Stable**	**Stable**	**Out-of-step**	**Out-of-step**	**Out-of-step**

The pre-fault power angle δ is set at 40. A three phase fault is applied at the middle of TL-II and four different simulations are carried out with fault duration times of 0.167, 0.20, 0.233 and 0.267 s. The fault duration times of 0.167 and 0.20 s make the system stable whereas the fault duration times of 0.233 and 0.267 s result in an out-of-step condition as shown in Table 5.2

5.5 Results

The main goal of this research is that first of all we differentiate between normal fault and power swing and then differentiate between stable and unstable power swing (out-of-step condition). Define the three conditions to describe the different steps of pre-fault, during fault and after fault condition using formula:

$$P = \frac{E \times V}{X} \text{Sin\&}$$

F = 50Hz generator 50 MVA supplying 50 MW with inertia constant 'H' = 2.7 MJ/MVA at rated speed. E = 1.05 pu, V = 1 pu,

X1 = X2 = 0.4 pu three phase fault at line 2.

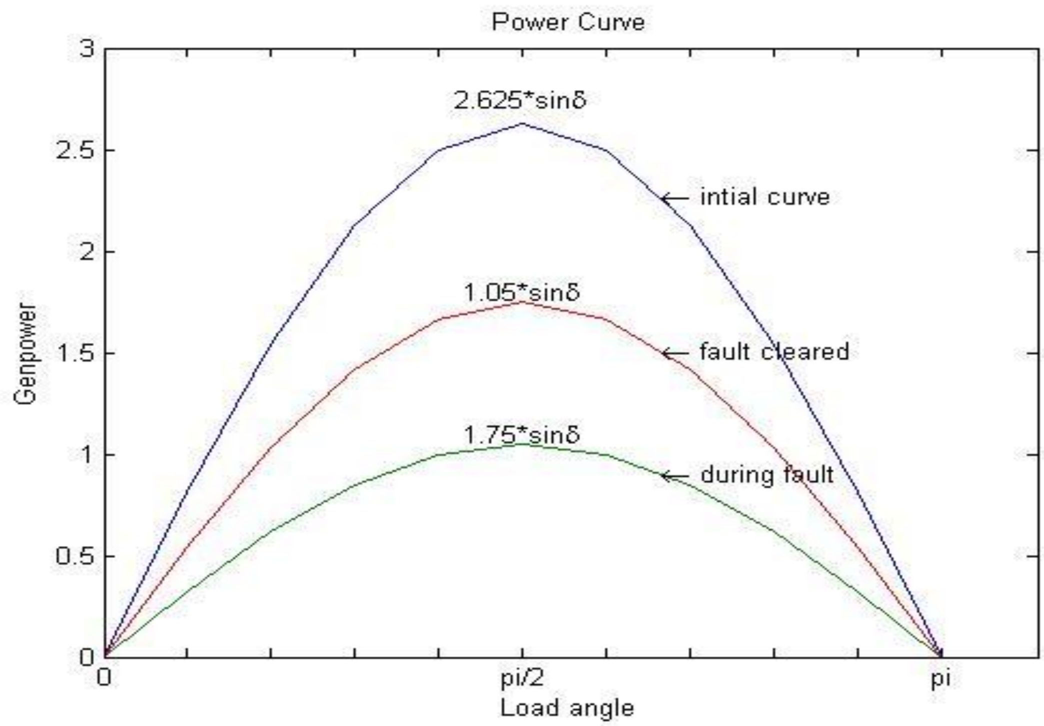
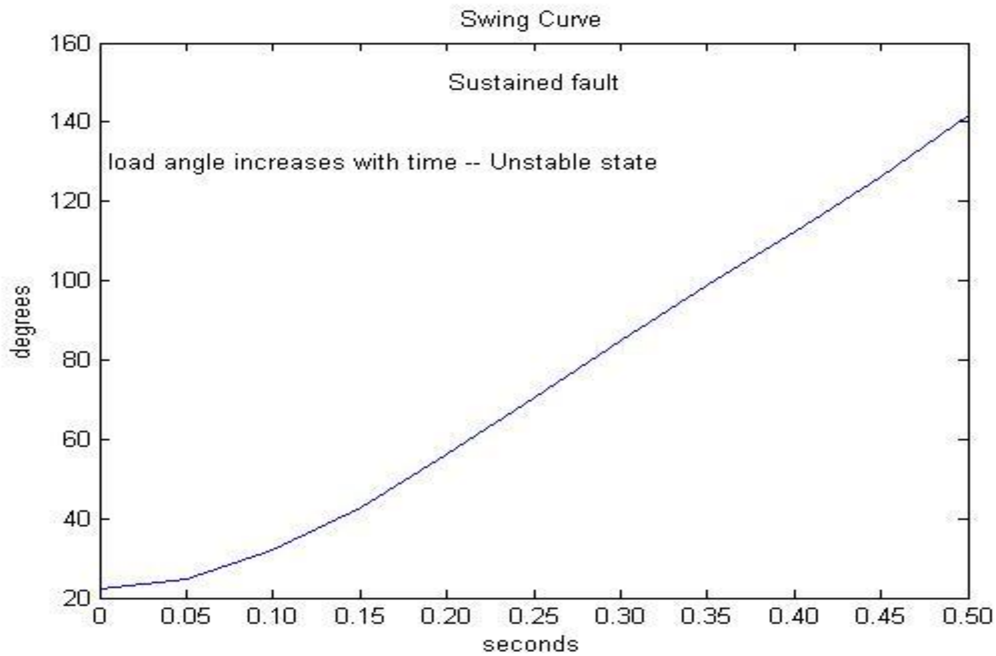


Figure 5.8 Power curve w.r.t load angle during fault

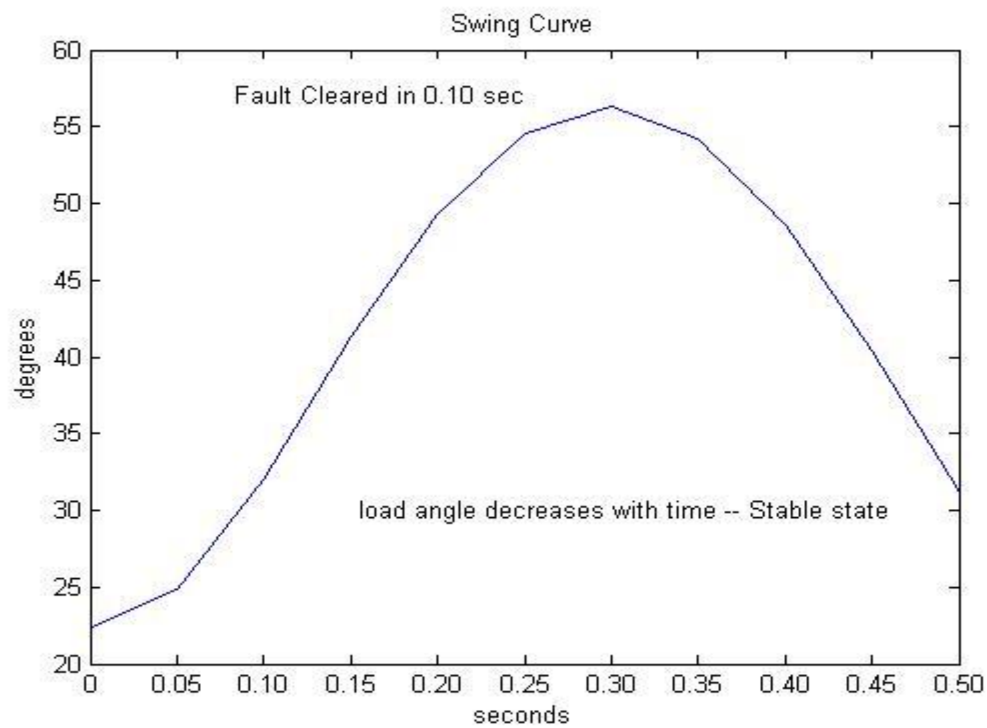
Figure 5.8 shows that how the power system response and behavior of swing curves during three conditions are pre-fault, during fault and post fault. Power changes due to change of impedance during fault in the system. When fault occur in system, power curve shows three conditions during fault.

Figure 5.9 (a) shows swing curve for a sustained fault up to a time of 5 secs. When fault occurs in system, angle changes with respect to time. This power curve shows the unstable condition because fault sustained in system for few seconds.

Figure 5.9 (b) shows swing curve if fault is cleared by isolating line in 0.1 seconds. Similarly during fault, angle changes with respect to time. This power curve shows the stable condition because fault is cleared by isolating line in 0.1 seconds.



(a)



(b)

Figure 5.9 Swing Curve for stable and unstable.

5.6 Simple AC system

A simple single line AC system is drawn in PSCAD to perform an experiment to detect the fault in transmission line. Fault “Flt1” is created in a system; in which breaker “Brk1” detect the ground fault for a limit time.

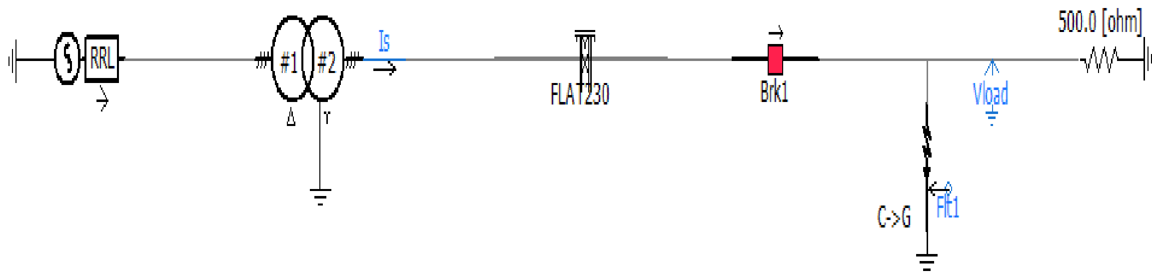


Figure 5.10 Simple AC System

230 kV transmission line systems with a passive load are shown in Figure 5.10. This demonstrates the use of the single line of a transmission line directly connected with the sending and receiving ends. Three phase transformer of value 100 MVA is used to conversion from delta (Δ) to star (Y). Three phase impedance type source is used. Its value is 100 MVA with base voltage is 13.8 kV. Set the input voltage constant time of source is 0.05 sec.

The sending end currents are measured on the transformer secondary windings inside the transformer component.

A timed phase C to ground fault is applied at **0.25 sec** and lasts 50 msec. The timed breaker logic is set to trip at **0.26 sec** and reconnects at **0.31 sec**.

After setting the values of each components and set the fault duration and fault time, run the system and below figures show the result that is easy to understand the concept of detection of fault in transmission line of power system.

Figure 5.11 shows the disturbance in current when fault occur in system for 50 msec. similarly behavior of breaker current and load voltage during fault condition are shown in Figures 5.12 and 5.13 respectively.

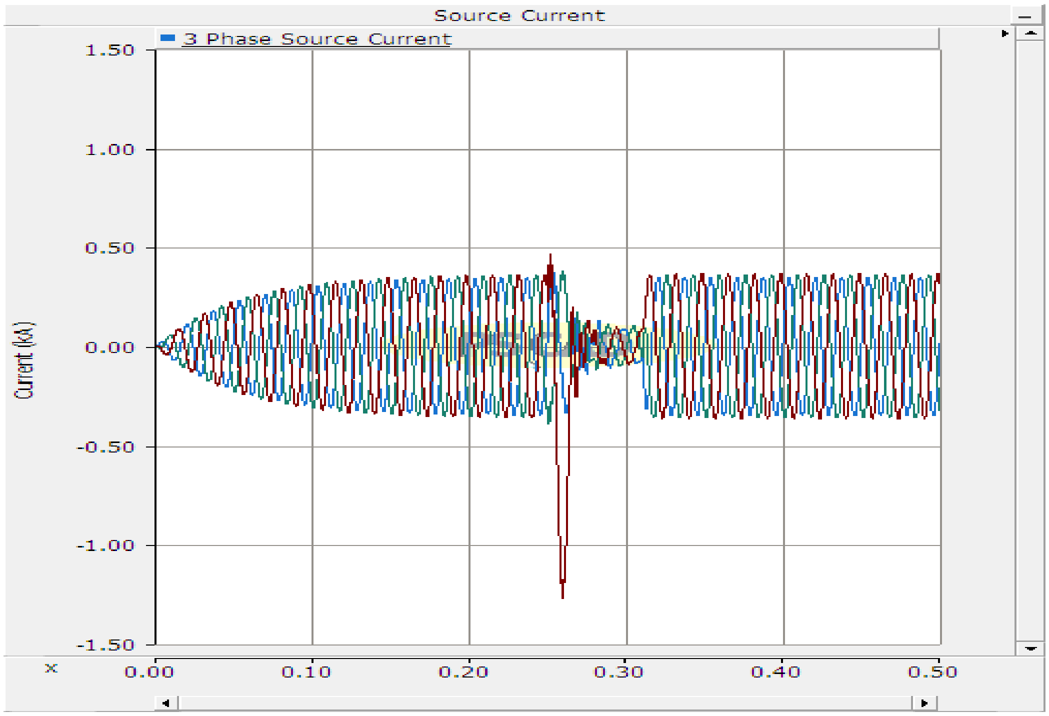


Figure 5.11 Three Phase Source Current w.r.t time

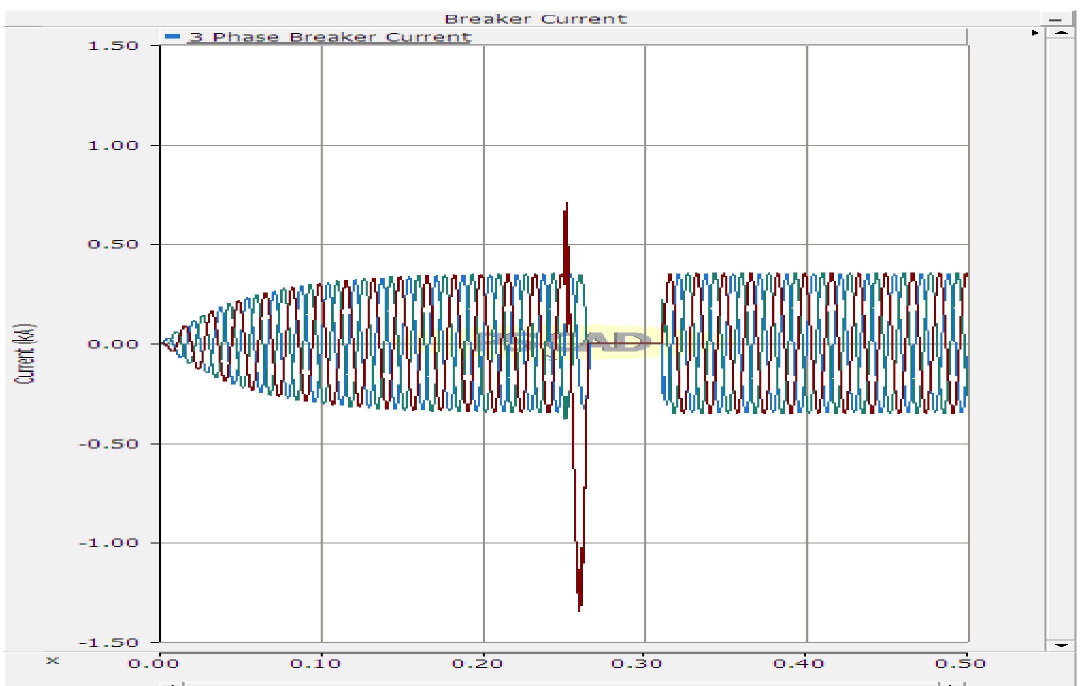


Figure 5.12 3 Phase Breaker Current w.r.t time

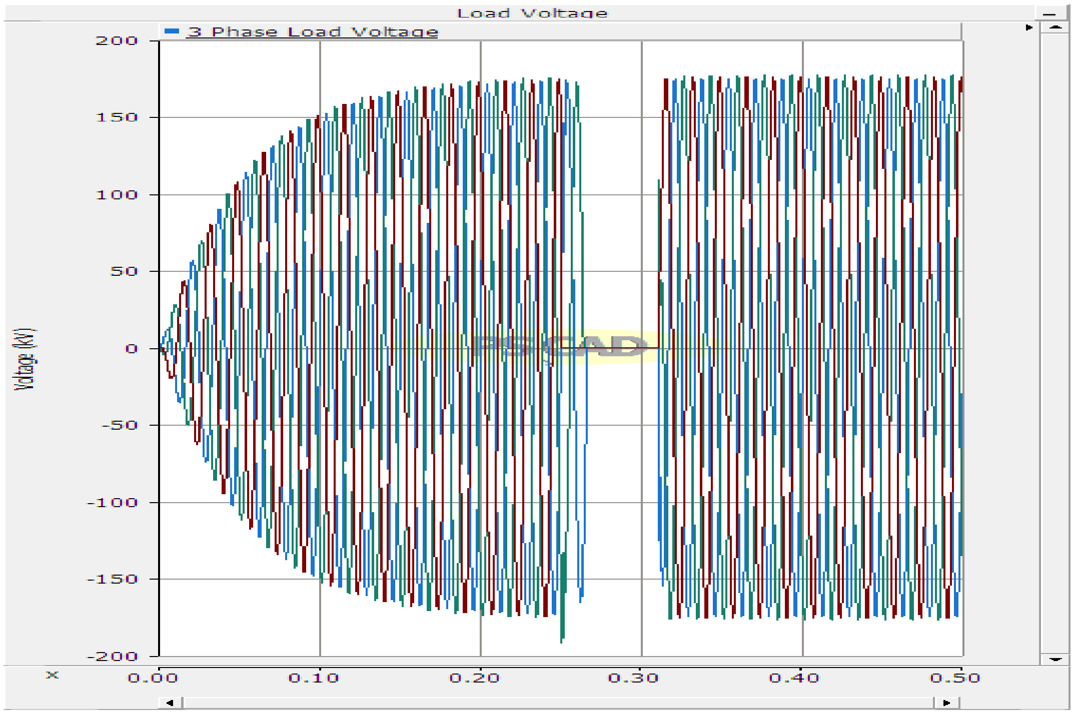


Figure 5.13 3 Phase Voltage w.r.t time

CHAPTER 6

Conclusion & Discussion

6.1 Conclusions

To decrease the risk of shut-down of the whole power system, suitable control method may be taken on when major disturbance occurs. In this research work, develop a modify technique of control of power swing using out-of-step method. In this thesis used the power area technique in which not only calculate power with respect to time, also calculate phase angle and also the phase angle difference with respect to time and then calculate the power. If the area **A** is smaller than or equal to area **B**, system will be stable. If the area **A** is larger than **B**, system will be unstable (out-of-step).

The result of all measurements of this research work show that algorithm works properly. Algorithm is designed to detect power swing, differentiate the unstable and stable power swing correctly. Therefore it is possible to use this method in an algorithm to find out Out-Of-Step conditions.

Result after the simulation in simple circuit performed in PSCAD shows that if you set a time of fault duration and time in which fault occur properly work to clear fault and stable power swing. Result of power swing curve shows that criteria in which defined three conditions easily determine the pre-fault, during fault and post fault condition on different values of power angles.

6.2 Discussion

This research work presents an alternative method to detect power swings and oscillations in a power system. The results of the simulation show that methodology to detect unstable power swing using modified out-of- step method is a useful method to predict loss-of-synchronism in power system network.

6.3 Future work

In this research work stability and fault analysis have been considered. Out-Of- Step methods and power swings in the power system has been the main focus. Presented protection for these conditions and new approaches to protect the power networks from these actions has been evaluated.

More robust and proficient methods for identification of the unstable power swing fault in an electrical power system network should be adopted as a future work.

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