Investigation on Generator Loss of Excitation Protection in Generator Protection Coordination

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Abstract

This thesis analyzes the generator loss of excitation fault and describes an investigation on existing loss of excitation protection schemes. In addition, a simulation model is established in PSCAD to simulate the loss of excitation fault and external faults.

According to the simulation results, this thesis compares the speed of different protection schemes on loss of excitation fault detection and finds the drawbacks of some protection schemes on fault detection during special operation condition. What's more, this thesis also compares the stabilities of different loss of excitation protection schemes during generator external faults.

Finally, this thesis summarizes the advantages and disadvantages of different schemes and serves as a reference for selecting the loss of excitation protection scheme.

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Contents

1. Introduction

1.1. Background

Loss Of excitation (LOE) is a very common fault in synchronous machine operating and can be caused by short circuit of the field winding, unexpected field breaker open or LOE relay mal-operation. According to the statistic in China, the generator failure due to LOE accounts for 69.5% of all generator failures [1]. LOE may cause severe damages to both generator and system.

Damage to the generator:

a) When LOE happens, a slip occurs. This may cause rotor over heating due to the slip frequency in rotor circuits.

b) As the machine operates as an induction machine after loss of excitation, large amount of reactive power supplied by stator current is required and the stator may suffer over heating because of this large current.

c) Under heavy load condition, the generator, especially for salient pole generator, may suffer from severe mechanical stress because of the power swing after loss of excitation.

Damage to the system:

a) The system voltage declines after the generator loses its excitation, because the generator operates as an induction machine and absorbs reactive power from the system. For some weak system, the system voltage may collapse due to the loss of excitation of an important generator.

b) When a generator loses its excitation, other generators in the system increase the reactive power output. This may cause the overloading in some transmission lines or transformers and the over-current relay may consider this overloading as a fault and isolate the non-fault equipments.

c) The power swing and voltage drop caused by loss of excitation may affect the normal operating generators and lead to loss of synchronism of some normal operating generators in the system.

However, a LOE on a hydro unit at light load may not result in a loss of synchronism. Normally salient pole machines can carry 15%-25% [2] rated load without loss of synchronism after LOE. But for cylindrical pole generator, the generator will lose synchronism after LOE even carrying very small active load, in other words, it is not allowed to operate at leading power factor.

1.2. Objective

The main objective of the thesis is to compare the existing LOE protection schemes and find the advantages and disadvantages of these schemes.

1.3. Scope

This thesis describes a review of generator loss of excitation and presents the principles and behaviors of existing hydro generator loss of excitation protection schemes. It summarizes the advantages and disadvantages of different schemes and serves as a reference for selecting the loss of excitation protection scheme. The thesis is concerned with hydro generator loss of excitation protection during normal operation and condenser operation. In addition, it also tests stability of the loss of excitation scheme during external symmetrical and unsymmetrical faults.

This thesis does not describe the loss of excitation schemes for cylindrical pole generator and special operation situation of hydro generator, e.g. standby, start-up.

1.4. Definitions

R-X scheme	LOE protection scheme which is based on generator terminal impedance measurement in R-X plane.
G-B scheme	LOE protection scheme which is based on generator terminal admittance measurement in G-B plane.
P-Q scheme	LOE protection scheme which is based on generator active- and reactive power output measurement in P-Q plane.
U-I scheme	LOE protection scheme which is based on the measurement of phase angle difference between phase voltage and current.

1.5. Outline

Chapter 2 gives the overview of LOE and analyzes the generator characteristics during LOE.

Chapter 3 describes the existing protection schemes for LOE and gives an example setting criterion for P-Q scheme.

Chapter 4 introduces the simulation model used in PSCAD.

Chapter 5 describes the simulation results of different schemes during LOE and makes the comparison on fault detection time among these schemes.

Chapter 6 describes the simulation results of different schemes during external faults and compares the stabilities of different schemes.

Chapter 7 summarizes the simulation results and makes the conclusions.

2. Overview of Loss of excitation

A common excitation system consists of an exciter and an Automatic Voltage Regulator (AVR) The DC field current supplied by the excitation system excites the field winding to establish the rotor flux and internal voltage in synchronous generator. In addition, the excitation system also provides the control functions for the field voltage which controls the generator voltage and reactive power indirectly and enhances the system stability [3].

Generally, there are two types of excitation systems, rotating and static. Rotating system uses dc or ac generator as the sources and static system applies the rectifiers as sources which are directly fed from the generator terminals via a step-down transformer. Today, most excitation systems are ac or static types because of the fast response ability.

When a generator loses its excitation, the rotor current gradually decreases and the field voltage decays by the field time constant as well. In this case, the generator operates as an induction generator and draws reactive power from the power system instead of generating reactive power.

Considering the generator active power output equation:

$$Pe = \frac{E_q U_s}{X_d + X_s} \sin \delta \qquad (2.1)$$

where P_e is termed active power output to the system, E_q is termed generator internal voltage behind the d-axis synchronous reactance, Us is termed equivalent system voltage, X_d is termed d-axis synchronous reactance, X_d is termed system impedance and δ is termed angle between E_q and U.

The active power output is proportional to the system voltage and generator internal voltage and the sine of δ. As the generator internal voltage E_q is a function of field voltage, the generator active power output is a function of field voltage as well.

In steady state, the operation point is the point where the mechanical power input equals the electrical power output. When the mechanical power increases, the load angle δ will increase as well. The maximum mechanical power can increase until the load angle reaches δ=90°, after then the mechanical power will be greater than the electrical power and the generator will loss synchronism as there is no equilibrium point between mechanical power input and electrical power output.

For the same reason, when the mechanical power input is fixed and maximum electrical power output decreases due to the field voltage reduction, the load angle δ will increase as the intersection of mechanical power and electrical power moves up to the peak. The generator electric power output versus load angle is shown in Figure 2.1:

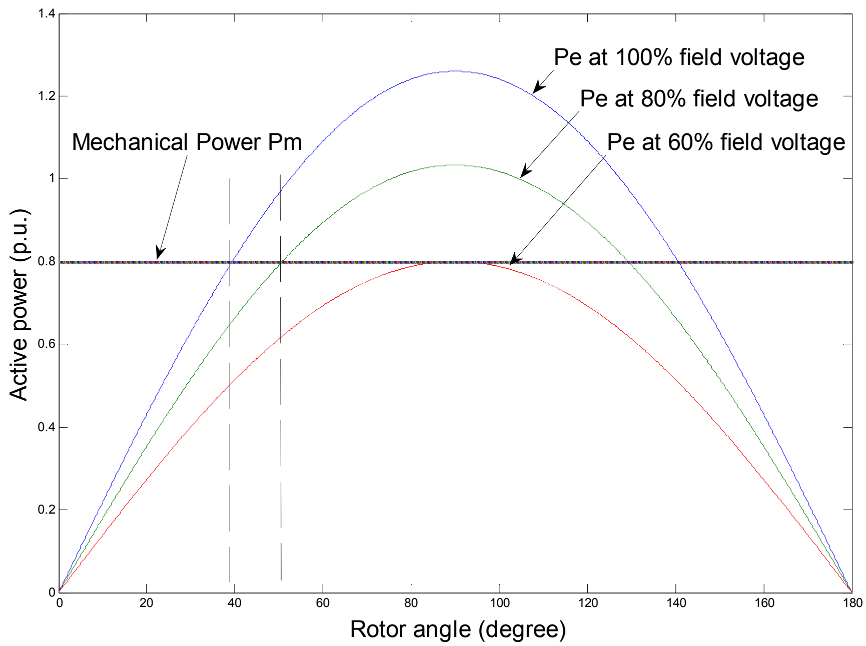


Figure 2.1: Generator active power versus load angle

When the generator operates at $\delta = 90^{\circ}$, any increase of mechanical power or decrease of electrical power will lead to generator loss of synchronism. As a result, the generator will operate asynchronously as an induction machine, typically with 2% to 5% slip, and draws the reactive power from the system for the excitation instead of generating reactive power to the system [4].

3. Protection schemes survey

This chapter describes the existing protection schemes for LOE and gives an example setting criterion for P-Q scheme.

3.1. Introduction

Normally, the generator field voltage cannot be measured directly, in order to detect the LOE, the protection scheme applies the generator terminal voltage, current, active power or reactive power output as the input value and calculates the generator characteristic values to determine the LOE fault.

Generally, there are four LOE protection schemes, which are P-Q scheme, U-I scheme, R-X scheme and G-B scheme. R-X scheme is widely used in the industry, but P-Q scheme has not been used in the industry yet.

3.2. P-Q measurement scheme

The synchronous generator delivering active and reactive power is related to the generator capability. The generator capability is limited by the capability curve given by the generator manufactory, System Steady-State Stability Limit and Under Excitation Limit.

3.2.1. Generator Capability limitation

Generator capability curve
First of all, the generator capability is limited by the rated MVA which represents the generator maximum continuous output in steady state without overheating. However, concerning the voltage stability and long term stability, it is essential to consider the reactive power capability which is limited by field current limit, armature current limit and stator end region heating limit [5].

The generator thermal limits are shown in Figure 3.1:

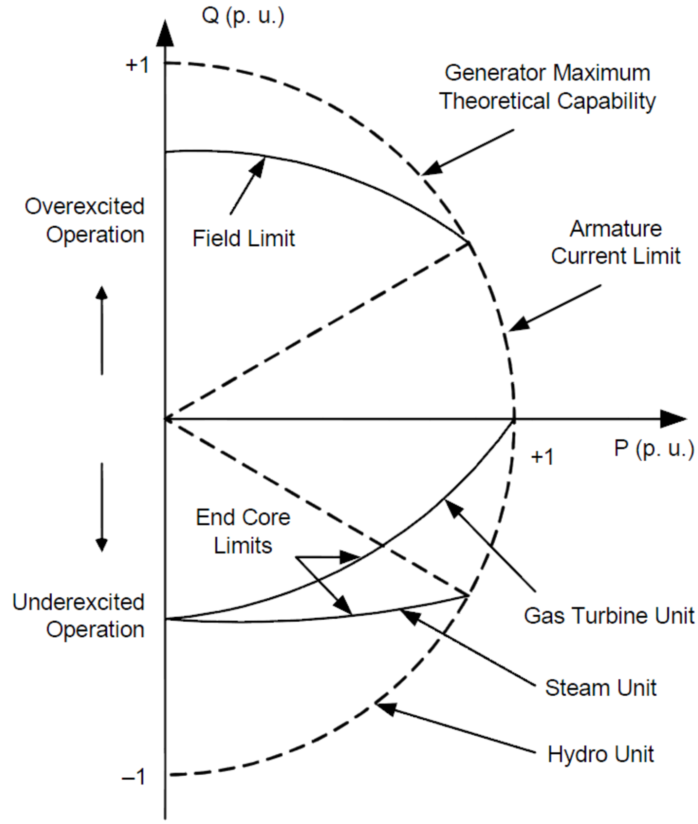


Figure 3.1: Generator operation thermal limits [7]

- Field current limit

Due to the copper loss in the field winding, the heat resulting from the field winding loss imposes the limit of generator capability. The active and reactive power of a cylindrical pole generator ($X_d = X_q$) under constant field current is given in the equations below:

$$P = E_t I_t \cos\phi = \frac{E_q E_t}{X_d}\cos\delta \tag{3.1}$$

$$Q = E_t I_t \sin\phi = \frac{E_q E_t}{X_d}\cos\delta - \frac{E_t^2}{X_d} \tag{3.2}$$

where E_q is steady state q-axis internal voltage and E_t is generator terminal voltage.

P and Q equations give a circle in the P-Q plane which is centered at $(0, -\frac{E_t^2}{X_d})$ and with a radius $\frac{E_q E_t}{X_d}$.

- Armature current limit

The stator winding copper loss increases the temperature of stator winding and imposes the armature current limit. The maximum current that the generator stator can carry is the armature current limitation which is shown as a circle centered at (0,0) and with a radius Rated MVA in P-Q plane.

- Stator end region heating limit

The stator end turn leakage flux is perpendicular to the stator laminations. When the generator operates at overexcitation condition, the retaining ring the saturated as the field current is high. However, in underexcitation condition, the field current is low and the leakage flux is high as the retaining ring is not saturated. In this case, the eddy current caused by the leakage flux is high enough to cause the overheating in the end region [6].

The stator end region heating limit is determined by the rotor type of generator and could be more severe for a cylindrical pole generator. But for a salient pole generator, this limitation may be nonexistent [7].

For the active power output, the input mechanical torque from the turbine takes the dominant responsibility and the generator generates the rated power at rated power factor under rated mechanical torque input. In the capability curve, it is represented by the vertical dashed line. The generator capability curve is shown in Figure 3.2:

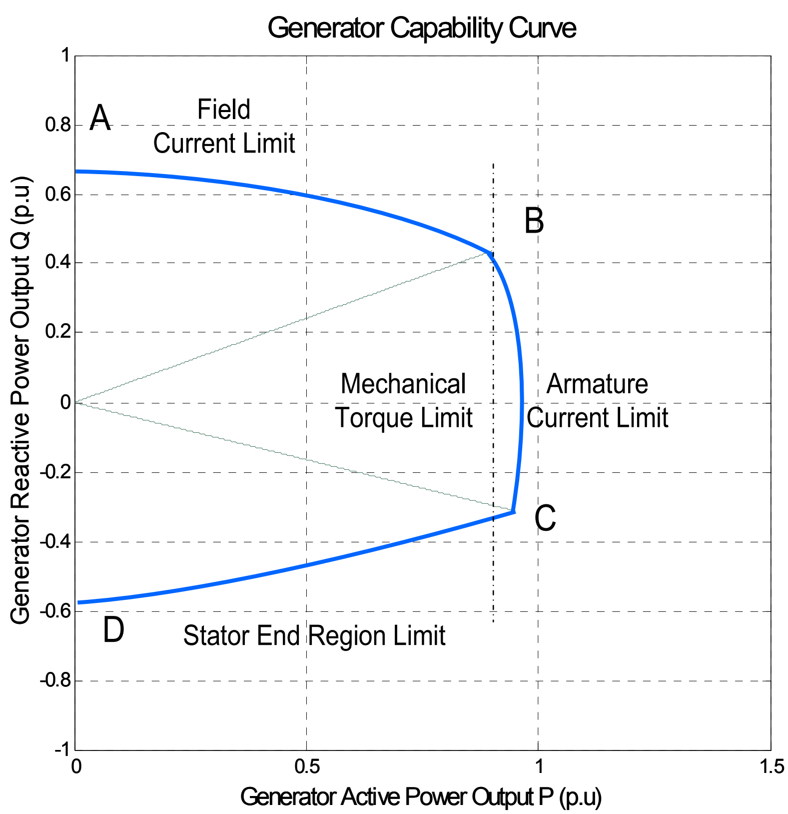


Figure 3.2: Generator capability curve

The field current limit in the generator capability curve is represented by arc AB [6] in Figure 3.2 and the armature current limit in the generator capability curve is represented by arc BC in Figure 3.2 and intersected by field current limit at point B [6].

Steady-state stability limit (SSSL)

When the generator operates at leading power factor, the field current will decrease. As the internal voltage is a function of field current, the internal voltage will decrease as well. This case is already described in Chapter 2 above and the maximum operation load angle in steady state is 90 degree. If the field voltage keeps decreasing, there will be no intersection point between mechanical power and electrical power and the generator will lose synchronism.

- SSSL of cylindrical pole generator ($X_d = X_q$)

From the figure below, the active power P and reactive power Q can be obtained:

$$P = U_t I_r \tag{3.3}$$

$$Q = U_t I_x \tag{3.4}$$

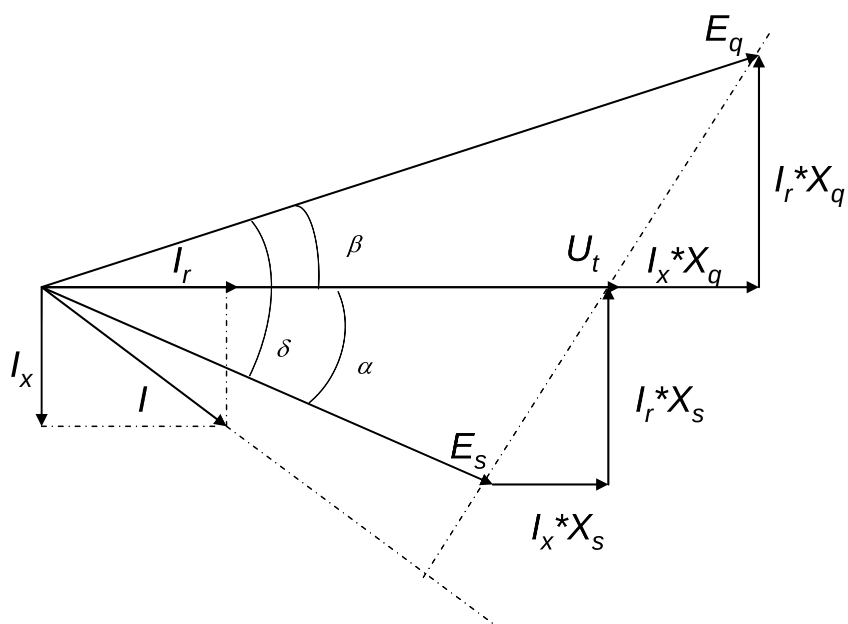


Figure 3.3: Generator current and voltage [4]

where E_q is termed generator internal voltage, U_t is termed generator terminal voltage and E_s is termed system voltage.

The stability limit occurs at $\delta = 90°$

$$\tan(\alpha + \beta) = \frac{\tan\alpha + \tan\beta}{1 - \tan\alpha\tan\beta} = \propto \tag{3.5}$$

´where $1 - \tan\alpha\tan\beta = 0$

From the figure, $\tan\alpha$ and $\tan\beta$ can be defined as:

$$\tan\alpha = \frac{I_r X_s}{U_t - I_x X_s} \quad (3.6)$$

$$\tan\beta = \frac{I_r X_q}{U_t + I_x X_q} \quad (3.7)$$

where Xs is the system reactance

Substituting these two equations to $1 - \tan\alpha\tan\beta = 0$

$$\left[\frac{U_t^2}{2}\left(\frac{1}{X_d} + \frac{1}{X_s}\right)\right]^2 = \left[\frac{U_t^2}{2}\left(\frac{1}{X_s} - \frac{1}{X_d}\right) + Q\right]^2 + P^2 \quad (3.8)$$

From the equation, the SSSL circle in P-Q plane is obtained

Center: $(0, \frac{U_t^2}{2}(\frac{1}{X_s} - \frac{1}{X_d}))$; Radius: $\frac{U_t^2}{2}(\frac{1}{X_d} + \frac{1}{X_s})$

- SSSL of salient pole generator ($X_d \neq X_q$)

The salient pole generator output active power and reactive power is shown in the equations [1] below:

$$P = \frac{E_q U_s}{X_d + X_s}\sin\delta + \frac{U_s^2}{2}\left(\frac{1}{X_q + X_s} - \frac{1}{X_d + X_s}\right)\sin 2\delta \quad (3.9)$$

$$Q = \frac{E_q U_s}{X_d + X_s}\cos\delta - \frac{U_s^2}{2}\left(\frac{1}{X_q + X_s} - \frac{1}{X_d + X_s}\right)\sin^2\delta - \frac{U_s^2}{X_d + X_s} \quad (3.10)$$

Taking the derivative of P and making $dP/d\delta = 0$, the limit point is obtained at certain load angle δ_s. The relationship between P and Q at SSSL point in P-Q plane is:

$$P_s = \frac{X_d - X_q}{(X_d + X_s)(X_q + X_s)} U_s^2 \tan\delta_s \sin^2\delta_s \quad (3.11)$$

$$Q_s = -\frac{X_d - X_q}{(X_d + X_s)(X_q + X_s)} U_s^2 \cos^2\delta_s - \frac{U_s^2}{X_d + X_s} \quad (3.12)$$

This is only available when the generator connects to the infinite bus and terminal voltage remains constant.

when $\delta_s = 0$, $P_s = 0$ and $Q_s = -\frac{U_s^2}{X_q + X_s}$; $\delta_s = 90°$, $P_s = \propto$ and $Q_s = -\frac{U_s^2}{X_d + X_s}$

Figure 3.4 depicts the plot of P and Q at SSSL point in P-Q plane:

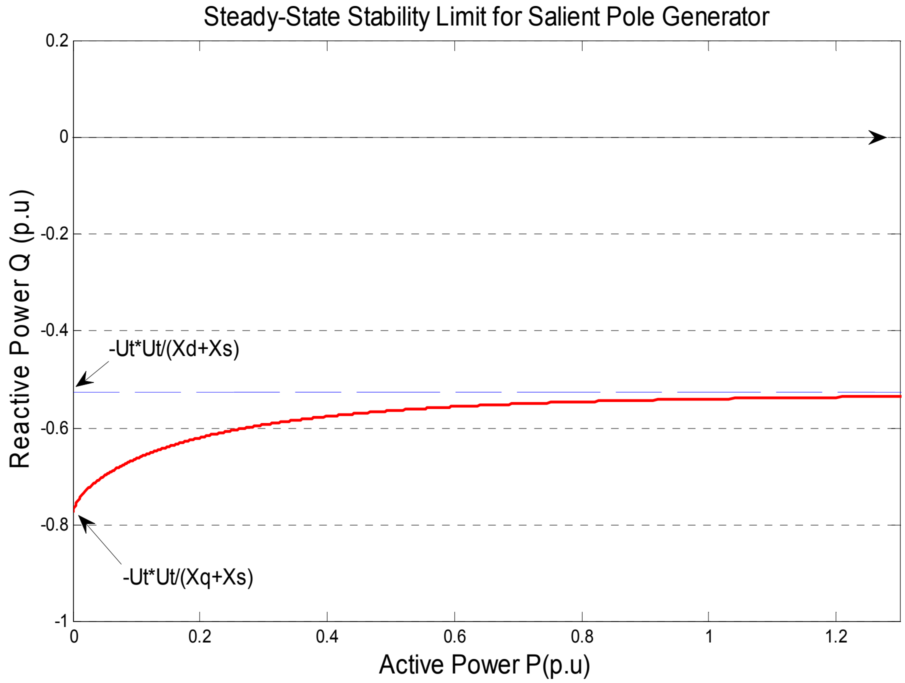


Figure 3.4: SSSL for salient pole generator in P-Q plane

From the Figure 3.4, the SSSL curve is an asymptotic curve for salient pole generator.

Under Excitation Limiter (UEL)
The under excitation limiter is equipped to avoid the excitation decreasing over the stator end region heating limit. The UEL and LOE relay setting should not overlap each other and when LOE happens, the leading reactive power should reach UEL ahead of LOE relay. The typical UEL characteristic is a straight line in P-Q plane and setting criteria is limited by SSSL and generator under excited capability limit, normally 80%-85% of generator leading reactive power capability [4] in generator capability curve. However, when the generator equipped with AVR and PSS, the AVR stability limit is far beyond the leading reactive power capability which should not be the limit of UEL.

In this case, the UEL is set in parallel with P axis and starts from the p.f. 0.95 leading point in armature limit line.

3.2.2. Protection scheme setting criterion

Using this method, the protection region can be directly obtained from the generator capability curve, SSSL and UEL. P-Q plane based LOE protection scheme includes four elements, a UEL element, a LOE element and an undervoltage element. The protection characteristic is shown in Figure 3.5:

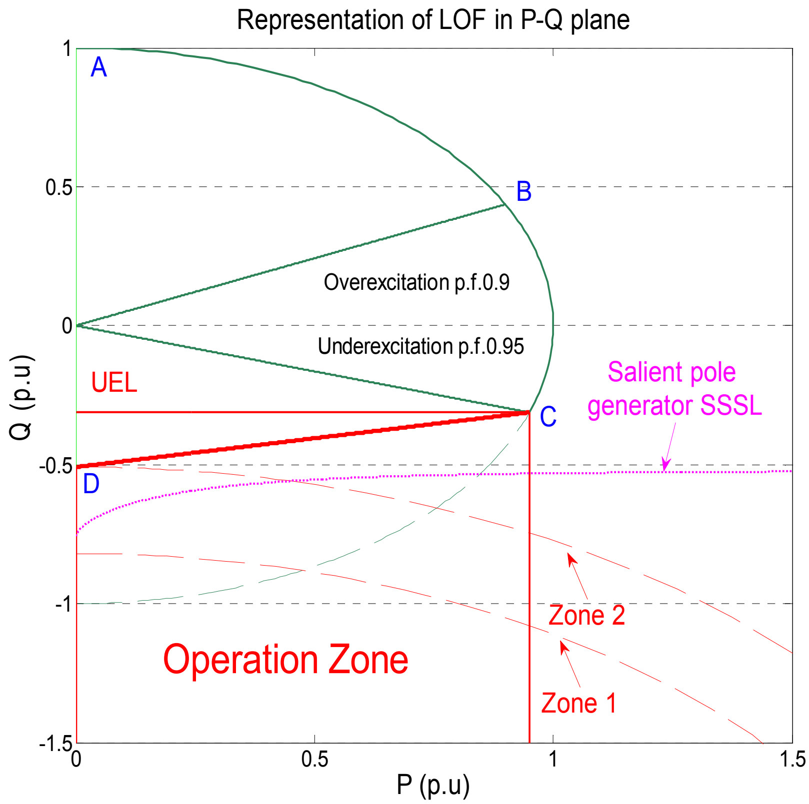


Figure 3.5: LOE protection scheme representation in P-Q plane

Protection setting:

For salient pole generator, there is no stator end region heating problem, so the SSSL will limit the LOE element and the LOE element characteristic lies just inside the SSSL curve. The upper limit point C is the intersection point of the generator MVA rating and UEL, which is the generator maximum leading power factor in normal operation; the lower limit point D is the crossover point of Q axis and Zone 2 which is transformed from R-X plane.

Operation principle:

Alarming:

When the generator reactive power output exceeds UEL, the alarm element will pick up after 0.5s time delay.

Tripping:

When the operating point falls into the operating region, LOE protection element will pick up and sent a trip signal after 0.75s time delay. If the operating point exceeds the UEL but stays outside the protection zone, the tripping signal will be initiated by UEL after long time delay, e.g. 1 minute; meanwhile an undervoltage element will be implemented to accelerate the tripping process, if the voltage reduction exceeds the relay setting.

Logic diagram:

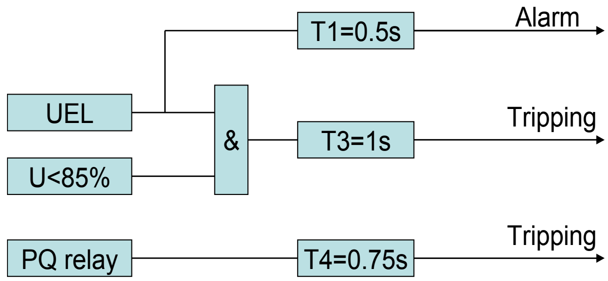


Figure 3.6: Logic diagram of P-Q scheme

3.3. U-I measurement scheme

When the LOE occurs, the generator reactive power output falls down and generator starts to import reactive power from the system. Meanwhile, the current phase angle becomes leading the voltage phase angle. In order to detect the LOE, a direction overcurrent relay is implemented by comparing the phase angle difference between voltage and current.

Characteristics of directional relay

The directional overcurrent relay compares the phase angle between the current and reference voltage. It operates only when the current flow in one direction and will be insensitive for the opposite direction. The maximum positive torque of the relay is developed by a wattmeter when the current and voltage are in phase [8]. The phasor diagram is shown in the figure below:

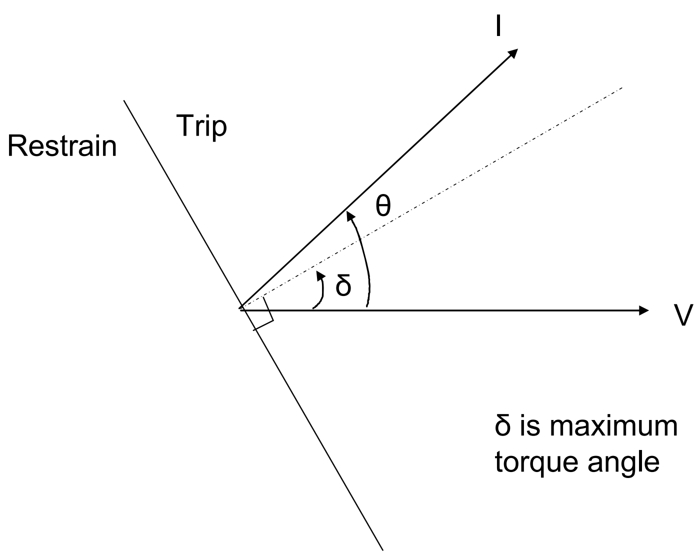


Figure 3.7: Phasor diagram for a directional relay

The directional overcurrent relay comprises a directional current stage (I_{α}), with a characteristic angle $-120°$ to $+120°$ and a nondirectional current stage (I>) [9] [10].

The typical setting is shown in Figure 3.8:

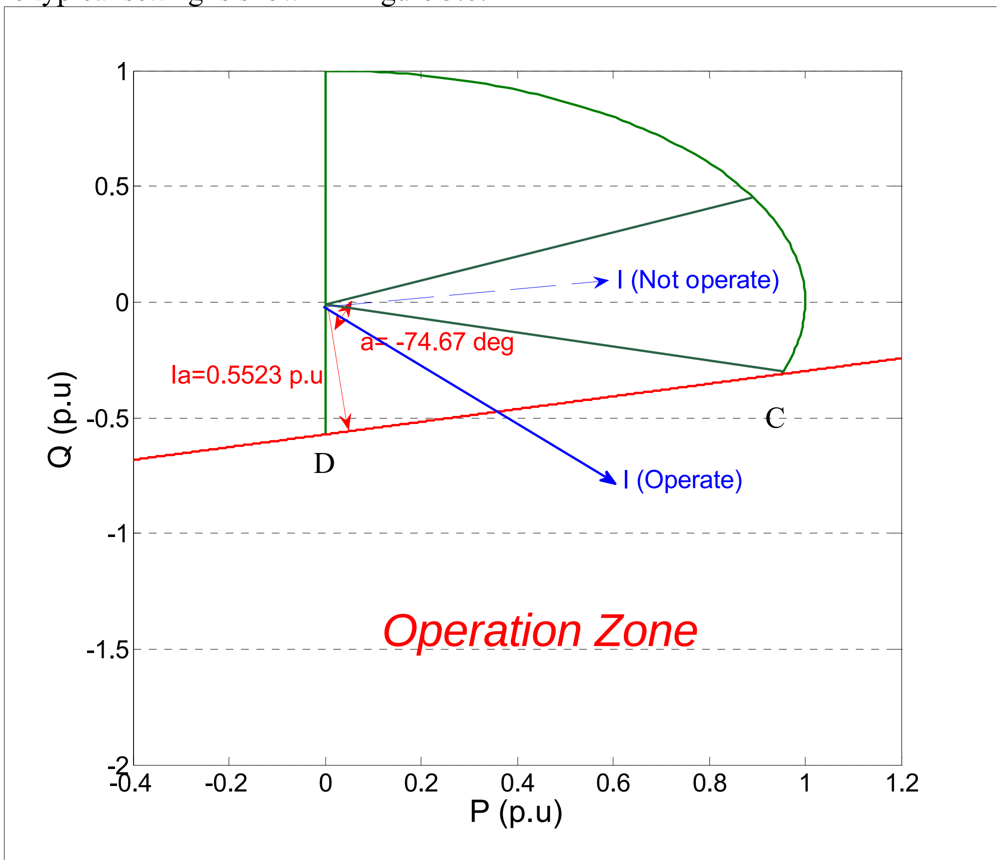


Figure 3.8: LOE protection scheme based on U-I measurement

The directional overcurrent operating characteristic is set to coinside to the generator thermal capability or the stability limit curve with 2s time delay. If the generator is with UEL, the operating characteristic is set as the back-up of UEL [9].

To initiate a tripping signal, the directional overcurrent relay operates together with an undervoltage element which is set to 90% of rated voltage and an overcurrent element which is set to 110% of rated current. The tripping circuit is shown in Figure 3.9 [9]:

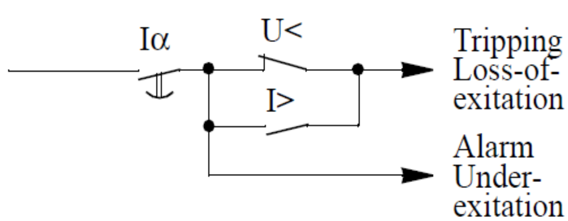


Figure 3.9: Logic diagram of U-I scheme

3.4. Impedance measurement scheme

The impedance measurement is widely used for LOE protection. The protection scheme applies an offset mho relay, which receive the terminal voltage and current as input signals to calculate the terminal impedance.

3.4.1 Mho distance relay

The distance relay is a kind of relay that measures the circuit impedance compared with the pre-defined value to determine whether the fault occurs or not [4].The distance relay will operate, when the measured impedance falls into the relay operation zone. Mho relay is the most common type of distance relay [4] and the characteristic of mho relay is shown in the figure below:

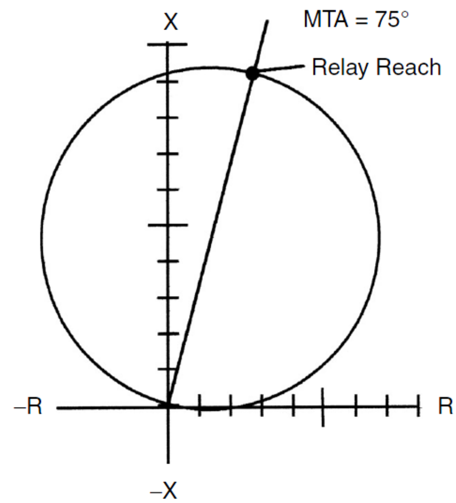


Figure 3.10: Mho relay characteristic [4]

The origin of mho relay is determined by the relay PT and the angle between R axis and the line which extends through origin and center of characteristic circle, so called maximum torque angle (MTA) [4].

The distance relay used in R-X scheme is offset-mho relay which has an offset along the –X axis, as the endpoint of generator LOE characteristic stays around the –X axis. The offset-mho relay characteristic is shown in the figure below:

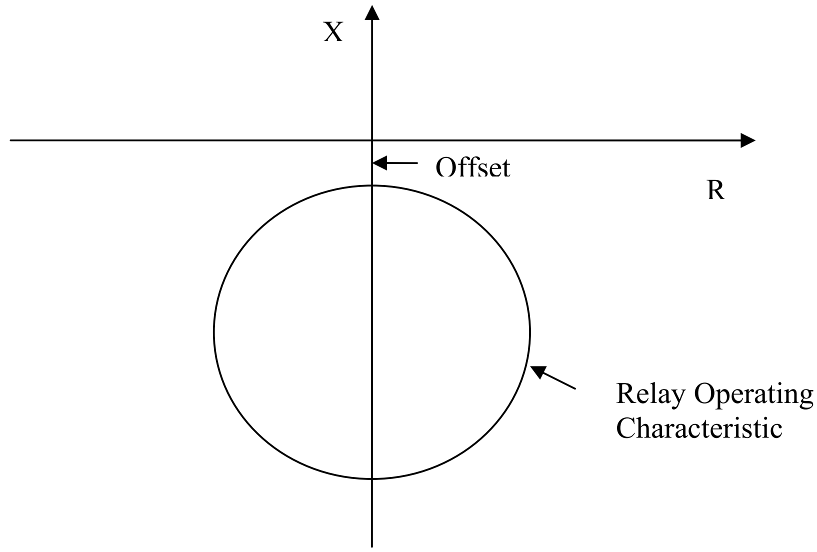


Figure 3.11: Offset mho relay characteristic

3.4.2 Impedance measurement scheme

The generator terminal impedance is calculated as:

$$\overline{Z} = \frac{\overline{U}}{\overline{I}} = \frac{U^2}{\overline{S}^*} = \frac{U^2}{P - jQ} = \frac{U^2 * (P + jQ)}{P^2 + Q^2} = \frac{U^2 * P}{P^2 + Q^2} + j\frac{U^2 * Q}{P^2 + Q^2} = R + jX \qquad (3.13)$$

where U is positive sequence voltage and I is positive sequence current.

In normal operation condition, the generator generates active and reactive power to the system which means both R and X are positive in Equation 3.13 and the terminal impedance is located in the first quadrant in R-X plane.

When the excitation is lost, the generator starts to draws reactive power from the system and X becomes negative from the LOE relay point of view. As a result, the terminal impedance loci in R-X plane moves to the forth quadrant and the endpoint of terminal impedance ranges between the subtransient reactance and synchronous d axis reactance. The endpoints depend on the initial load and the trajectories of endpoints are shown in the figure below:

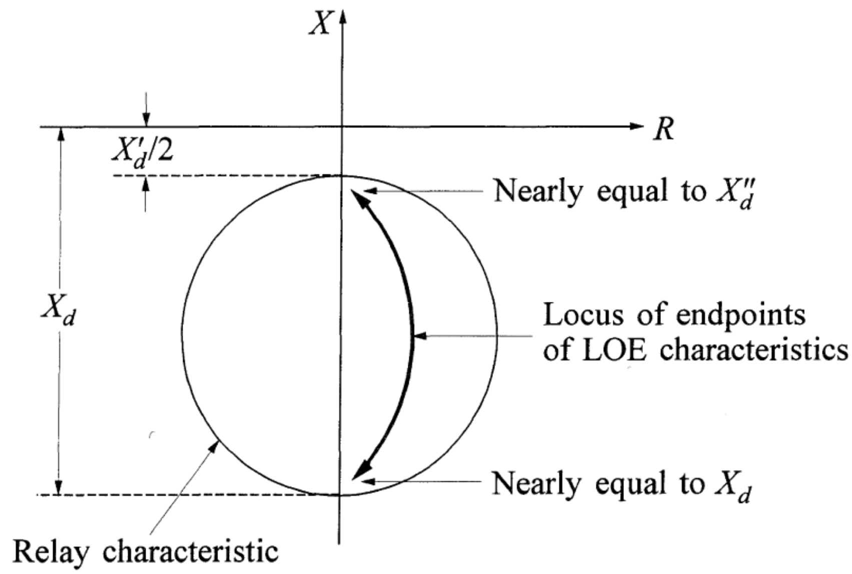


Figure 3.12: Terminal impedance characteristics after LOE [6]

Normally, there are two approaches to detect the loss of excitation based on impedance measurement. One is using two negative-offset mho elements and the other is using a positive-offset mho and a directional element.

Negative-offset mho elements

The normal setting for the offset-mho in the impedance plane is a circle with the diameter X_d and a negative offset $-X'_d/2$ shown in Figure 3.13:

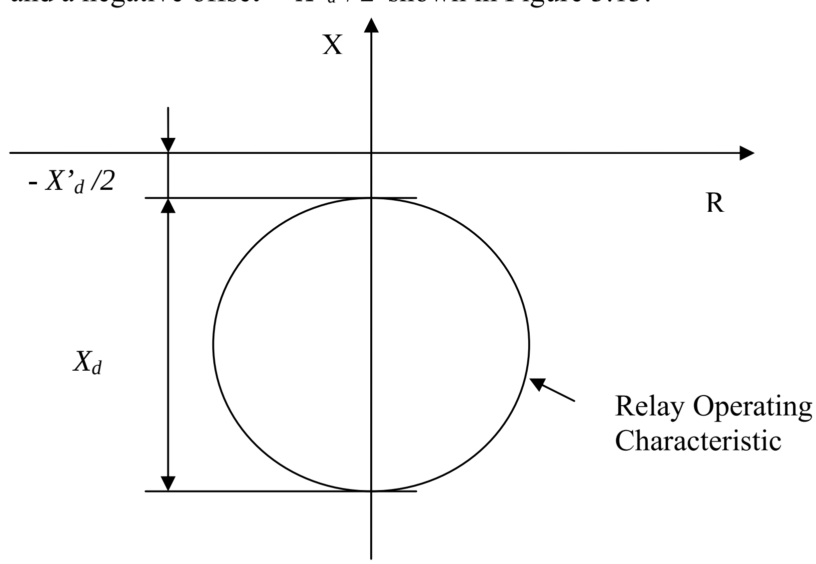


Figure 3.13: LOE protection scheme using a negative-offset mho element [11]

When the measured impedance falls into the operating region, the relay function will be picked up and after a certain time delay to enhance the security for power swing, a trip signal will be sent to the generator main breaker.

For modern large generators, X_d is typically about 1.5-2 p.u. [5] and the diameter of the LOE relay characteristic must be larger than X_d. As a result, the larger relay characteristic may affect the protection capability. In order to avoid this problem, the characteristic diameter is reduced to 1 p.u., which limits the detection region for the high load condition [12]. For salient pole generator, the diameter of Zone 1 may be set with diameter of 0.75*Xd [12]. The two zone protection characteristic is shown in Figure 3.14:

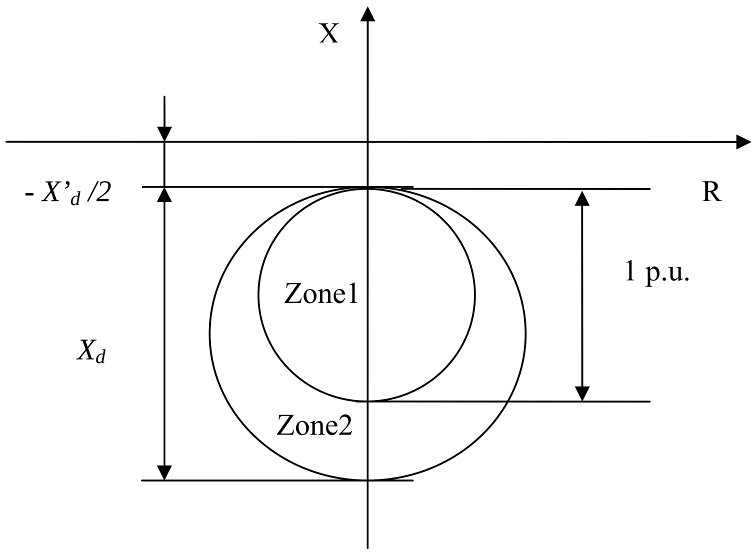


Figure 3.14: LOE protection scheme using two negative-offset mho elements

Zone 1 and Zone 2 are for detecting loss of excitation with full load and light load respectively. The typical time delay for Zone 1 and Zone 2 are about 0.1s and 0.5-0.6s [5].

Offset mho combined with directional element

This scheme applies two offset mho elements and a directional element to detect the loss of excitation. The first offset mho Zone 1 is set equal to a negative offset X'd/2 and long interception 1.1 times X_d. The second offset mho Zone 2 setting is identical to the steady-state stability limit in impedance plane which is a circle centered at $(0, -j\frac{(X_d - X_s)}{2})$ with the radius $\frac{(X_d + X_s)}{2}$ [11].

The directional element is set to coordinated with the generator maximum reactive power output (normally set to p.f. 0.95 leading) and the operation zone is set to ''look into'' the generator which avoids the mal-operation of external faults [8]. Figure 3.15 shows the example of LOE protection scheme with negative-offset mho and directional elements.

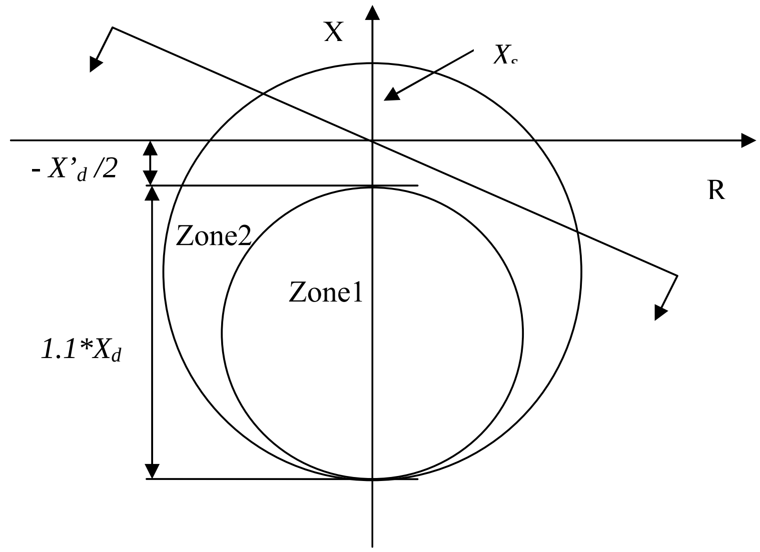


Figure 3.15: LOE protection with negative-offset mho and directional elements

The directional element always issues an alarm signal and a time-delay tripping typical within the range from 10s to 1 minute [5]. Zone 1 and Zone 2 initiate a trip signal with certain time delay respectively, normally, 0.2 to 0.3s time delay for Zone 1 to override the power swings and approximately 0.75s for Zone 2 [13].

Besides, the additional elements can be introduced to implement the protection function such as directional element, under voltage element, over current element, minimum excitation limit, steady-state stability limit and etc.

3.5. Admittance measurement scheme

The main principle of underexcitation protection based on admittance measurement is to transform the generator stability limitation in admittance plan [14]. The generator terminal measurement admittance can be derived from the following equations:

$$\overline{Y} = \frac{\overline{I}}{\overline{U}} = \frac{\overline{I}}{\overline{U}} * \frac{\overline{U}^*}{\overline{U}^*} = \frac{\overline{S}^*}{U^2} = \frac{P - jQ}{U^2} = G + jB \qquad (3.14)$$

In normal operation condition, generator generates active power and reactive power to the system, so B shall be negative and G shall be positive according to the Equation 3.14.

When simplifying the equation where the terminal voltage equals to the reference voltage ($U = U_N = 1$), the value in admittance plane is identical to the capability curve in P-Q plane. Therefore, the protection value in admittance plane can be directly read from the generator capability diagram. The figure below shows an example of the generator capability curve:

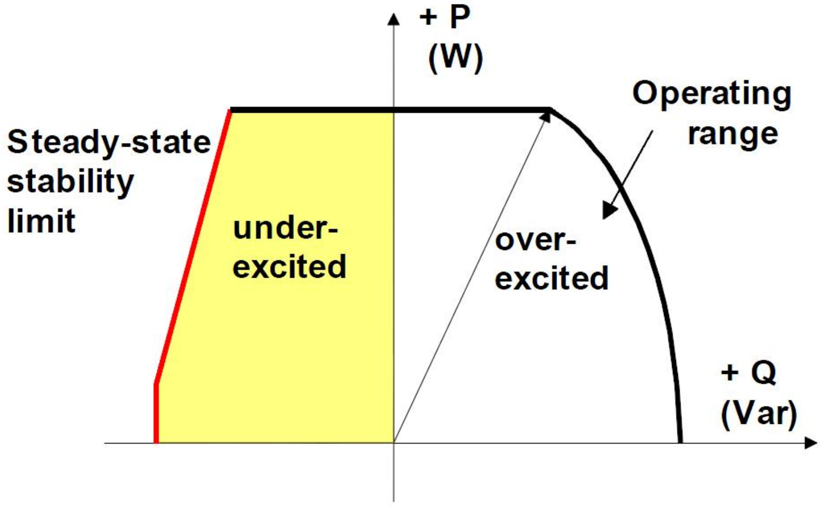


Figure 3.16: Example of generator capability curve [14]

The region outside the capability limit is the same as the protection relay operation region. Normally, the generator capability limit is provided by the generator manufacturer.

Figure 3.17 describes the characteristic of admittance scheme.

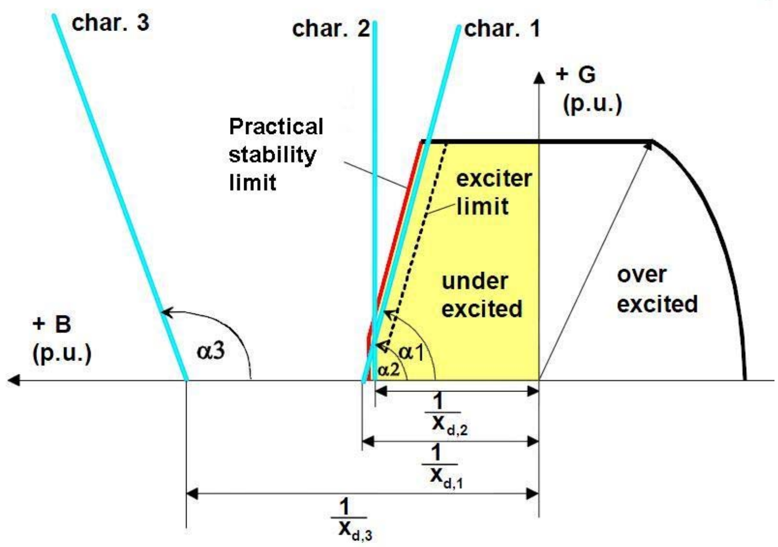


Figure 3.17: LOE protection scheme based on admittance measurement [14]

Protection setting for cylindrical pole generator:

Char1: $\dfrac{1}{X_1} = \dfrac{1}{X_d} \quad \alpha 1 \approx 80^\circ$

Char2: $\dfrac{1}{X_2} = 0.9\dfrac{1}{X_d} \quad \alpha 2 = 90^\circ$

Char3: $\dfrac{1}{X_3} = \dfrac{2}{X_d} \quad \alpha 3 \approx 110^\circ$

Protection setting for salient pole generator:

Char1: $\frac{1}{X_1} = \frac{1}{X_d} + \frac{1}{2}(\frac{1}{X_q} - \frac{1}{X_d}) \quad \alpha 1 \approx 80^\circ$

Char2: $\frac{1}{X_2} = \frac{1}{X_d} \quad \alpha 2 = 100^\circ$

Char3: $\frac{1}{X_3} = \frac{2}{X_d} \quad \alpha 3 \approx 110^\circ$

The inclination of the char in admittance plane is to gain a better match to the generator capability curve. If the generators direct axis reactance is given, the setting values can be calculated by the IEEE recommendation equations which are represented above.

4. Model establishment in PSCAD

4.1. PSCAD introduction

PSCAD (Power System CAD) is graphical user interface software which enables users to construct a circuit, run a simulation and analyze the results schematically [15]. It helps users to study the transient behavior of power system network in time domain. The commercial version of PSCAD was available since 1993 and it becomes a very popular simulation tool for both academic researchers and engineers.

4.2. Model description

The model established in PSCAD is to simulate the LOE of a pumped-storage generator-motor machine operating as generator mode.

4.2.1. System model

The model configuration is shown in the Figure 4.1 below:

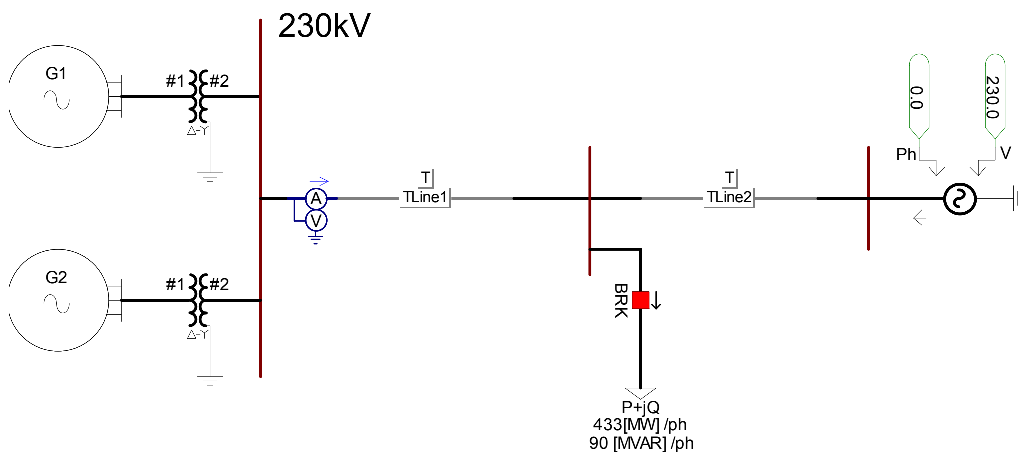


Figure 4.1: One-line diagram of the simulation model in PSCAD

The simulation model includes two salient pole generators which are connected to a common bus via a $\Delta - Y$ connection step-up transformer respectively. The common bus connects to the infinite bus via 100km transmission line. The transformer primary side voltage is 20kV and secondary side voltage is 230kV. The system data is shown in Appendix A.

4.2.2. Generator model

The generator model comprises a synchronous generator, hydro turbine with governor, automatic voltage regulator (AVR) and power system stabilizer (PSS). The block diagram of generator unit with control loop is shown in the Figure 4.2 below:

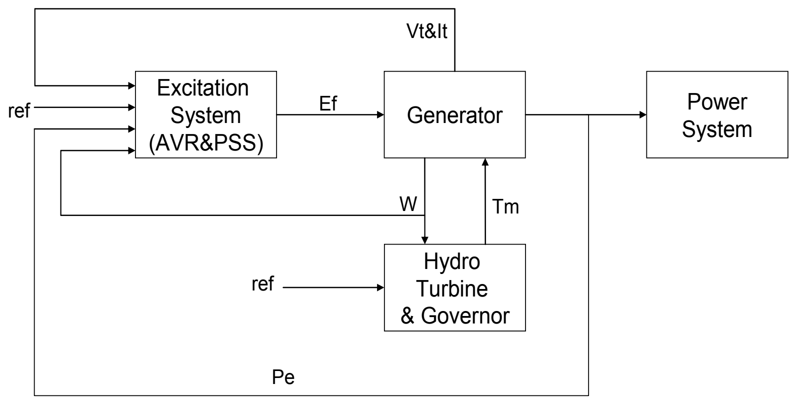


Figure 4.2: Block diagram of generator unit with control system

The exciter used in the model is a static exciter which is standard IEEE type ST1A. The transfer function is shown in Appendix B.

The power supply for the exciter is obtained from the generator terminal voltage via a step-down transformer and controlled rectifier. In this type if exciter, the inherent time constant is very small and it can operate without a stabilizer [16]. But in this model, PSS is implemented to accelerate the stabilization.

For the excitation system with high gain, PSS is introduced to enhance the damping through excitation control. The PSS used in the model is also standard IEEE type PSS2B which transfer function is shown in Appendix C.

The inputs of PSS are generator active power output and deviation of rotor speed $\Delta\omega$. The generator data and control system data are listed in Appendix A.

5. Simulation results comparison of LOE

In this chapter, three cases of LOE are simulated and compared, which are:
Case 1: One generator complete loss of excitation.
Case 2: One generator partial loss of excitation.
Case 3: One generator loss of excitation during condenser operation mode.

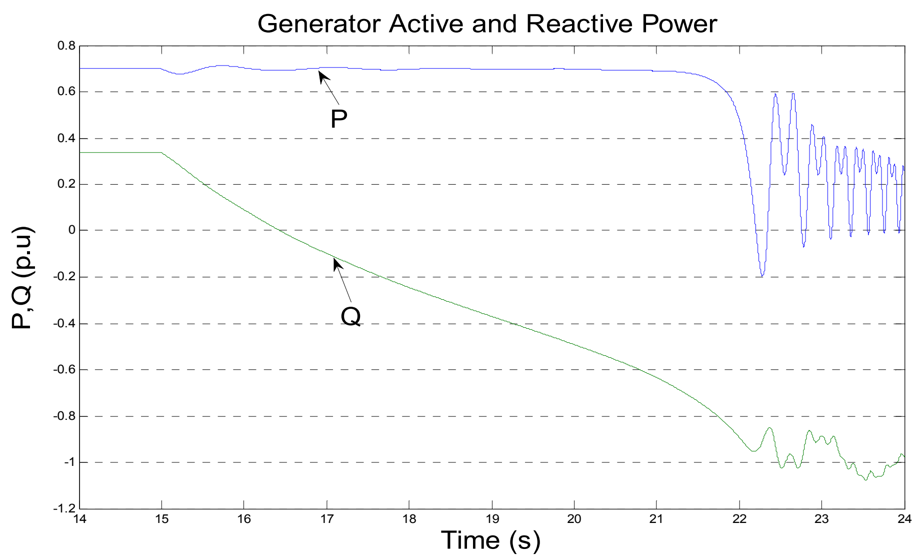
5.1. Complete loss of excitation

5.1.1. Description

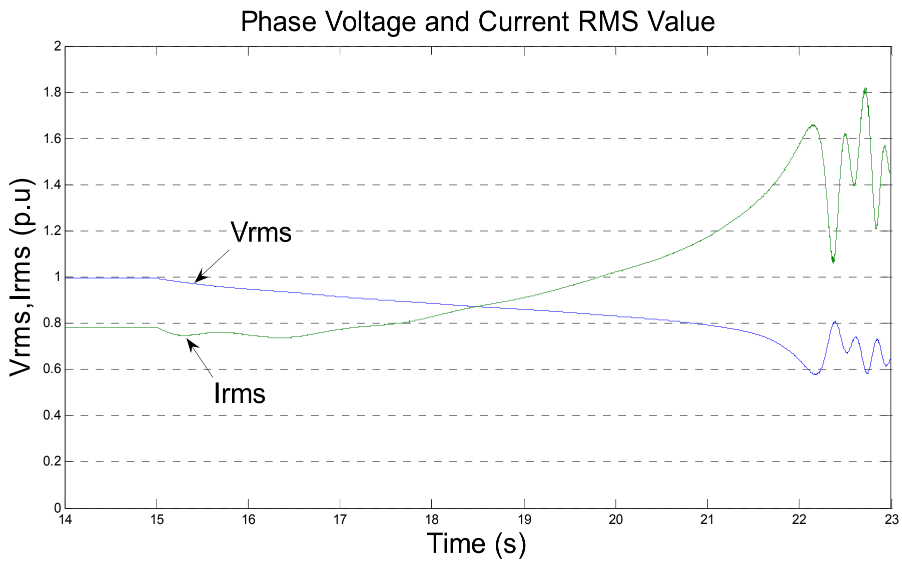
Scenario 1: The generator 1 and 2 operate at 80% load p.f. 0.9. The LOE happens on Generator 1 at 15s. The field voltage of Generator 1 falls to zero due to the fault.
Scenario 2: The generator 1 and 2 operate at 40% load p.f. 0.9. The LOE happens on Generator 1 at 15s. The field voltage of Generator 1 falls to zero due to the fault.

5.1.2. Simulation results analysis

Figures 5.1 shows the Generator 1 active power, reactive power, phase RMS voltage and phase RMS current during the fault with 80% load and p.f. 0.9.



(a)



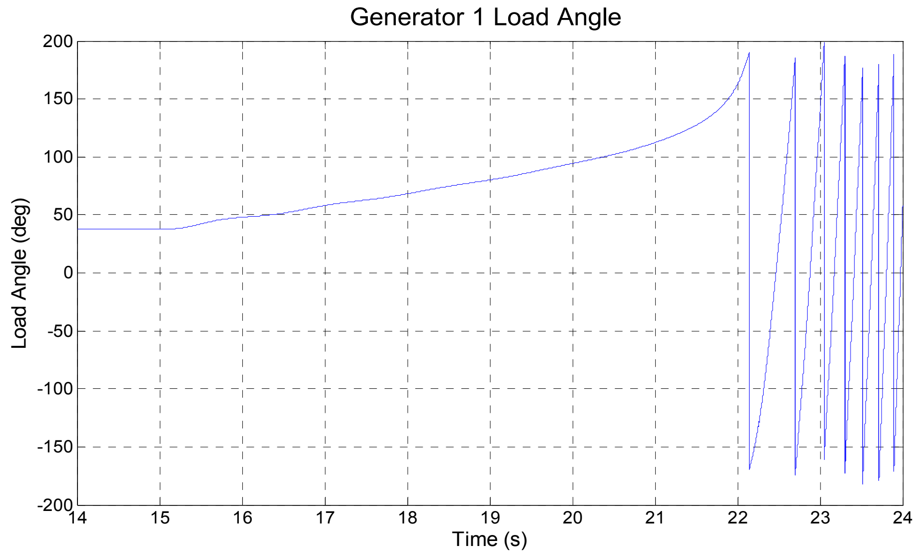
(b)

Figure 5.1: Generator 1 characteristic curves during complete LOE
(a) active and reactive power output (b) phase voltage and current R.M.S. value

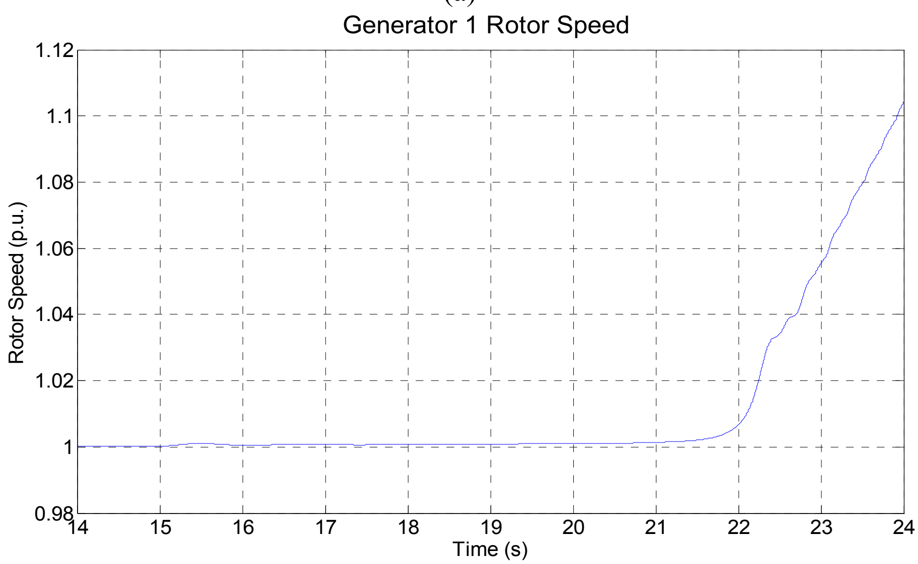
When LOE occurs, due to the mechanical inertia, the mechanical input and load angle keeps constant temporarily. The reactive power output decreases to zero quickly and generator starts to import the reactive power from the system. The generator internal voltage decays because of field voltage reduction and phase current goes up due to large amount of reactive power imported.

Before loss of synchronism, the active power keeps almost constant at around 0.7 p.u.. At 6.5 s after loss of excitation, the active power decreases sharply from 0.7 p.u. to -0.2 p.u. and oscillates around 0.2 p.u. with 0.4 p.u. deviation. Meanwhile, the reactive power output decreases steadily from 0.34 p.u. to zero after 1.5 s and the generator starts to absorb the reactive power from the system. Finally, the imported reactive power goes up to almost 0.9 p.u. and starts to oscillate around 0.9 p.u. with 0.2 p.u. deviation. Due to this large amount of imported reactive power, the phase current goes up to 1.3 p.u. before loss of synchronism and phase voltage goes down to 0.75 p.u. .

Figure 5.2 depicts the load angle and rotor speed characteristic curves during loss of excitation.



(a)



(b)

Figure 5.2: Generator 1 load angle and rotor speed variation during LOE
(a) load angle (b) rotor speed

When load angle rises close to 180 degree, the import reactive power Q and slip goes up sharply and the active power goes down quickly. After then, the active power, reactive power, terminal voltage and phase current start oscillation and come into a new cycle.

R-X scheme

Figure 5.3 describes the Generator 1 terminal impedance characteristic trajectory in RX plane.

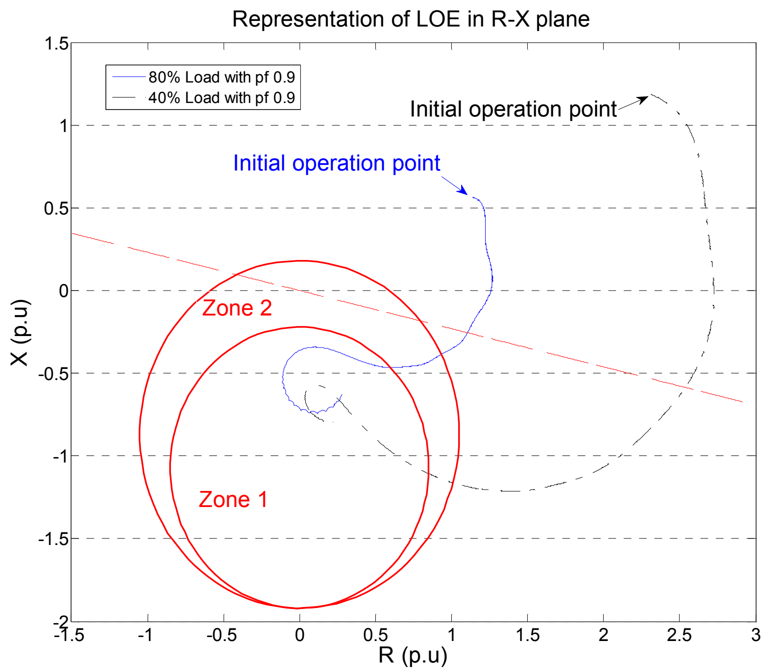


Figure 5.3: Complete LOE representation in R-X scheme

In order to simplify the operation time, the simulation time is subtracted by 15 s, which means the loss of excitation occurs at 0 second, and terminates just after loss of synchronism. The simulation results are listed in Table 5.1:

Table 5.1: Complete LOE simulation results of R-X scheme

Protection Scheme: RX	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 lagging	
Enter relay operation region time	Zone 2	5.306s	Zone 2	7.391s
	Alarm time delay	0.5 s	Alarm time delay	0.5 s
	Tripping time delay	1 s	Tripping time delay	1 s
	Zone 1	6.415s	Zone 1	14.08s
	Time delay	0.3s	Time delay	0.3 s
U<90% pick up time	2.515s		5.361s	
I>110% pick up time	5.61s		17.4s	
Alarm signal	5.806s		7.891s	
Tripping signal	6.306s		8.391s	

For 80% load condition, the terminal impedance curve enters the protection Zone 2 at 5.306 s and Zone 2 issues an alarm signal after 0.5 second. Although it also enters Zone 1 at 6.415 s, the tripping signal will be initiated by Zone 2 after 1 second at 6.306 s.

For 40 % load condition, the terminal impedance curve enters the protection Zone 2 at 7.391 s and Zone 2 gives an alarm signal after 0.5 second. The tripping signal also is given by Zone 2 after 1 second at 8.391 s.

The protection scheme can be combined with undervoltage and overcurrent elements. The undervoltage element (U<90%) picks up at 2.515 s and 5.361s for 80% and 40% load respectively. The overcurrent element (I>110%) picks up at 5.61 s and 17.4 s.

R-X with directional element scheme

Figure 5.4 shows the Generator 1 terminal impedance characteristic trajectory in R-X plane with directional element.

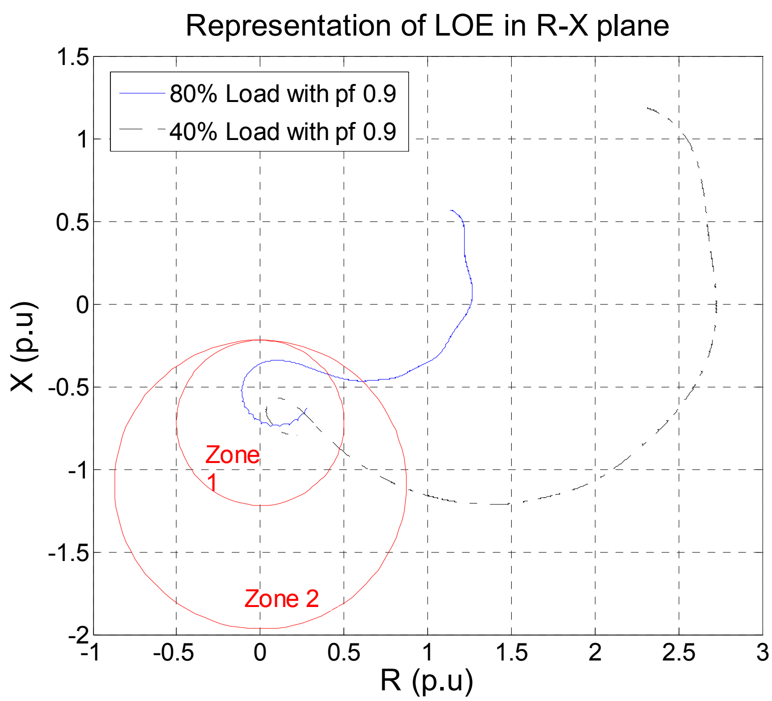


Figure 5.4: Complete LOE representation in R-X scheme with directional element

The simulation results are listed in Table 5.2:

Table 5.2: Complete LOE simulation results of R-X scheme with directional element

Protection Scheme: RX	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 lagging	
Enter relay operation region time	Direction relay	2.46s	Direction relay	1.6s
	Alarm Time delay	0.5s	Alarm Time delay	0.5s
	Zone 2	3.421s	Zone 2	6.181s
	Time delay	2 s	Time delay	2 s
	Zone 1	5.436s	Zone 1	7.63s
	Time delay	0.3s	Time delay	0.3 s
Alarm signal	2.96s		2.1s	
Tripping signal	5.421s		7.93s	

The directional element can issue an alarm signal faster comparing to RX scheme. In this case, it gives an alarm signal at 2.9 s for 80% load and 2.1 s for 40% load respectively. The tripping signal is initiated by Zone 2 at 5.421 s for 80% load and 7.93 s for 40% load.

G-B scheme

Figure 5.5 describes the Generator 1 terminal admittance locus in G-B plane.

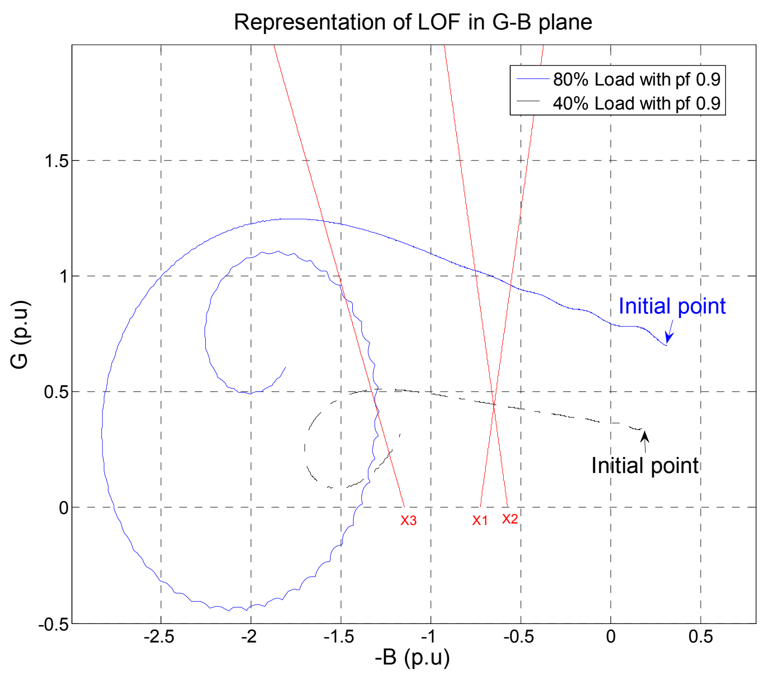


Figure 5.5: Complete LOE representation in G-B scheme

The simulation results are listed in Table 5.3:

Table 5.3: Complete LOE simulation results of G-B scheme

Protection Scheme: GB	80% load, p.f. 0.9		40% load, p.f. 0.9	
Enter relay operation region time	Char1	4.264s	Char1	9.231s
	Alarm time delay	0.5 s	Alarm time delay	0.5 s
	Tripping time delay	10 s	Tripping time delay	10 s
	Char2	5.215s	Char2	9.231s
	Time delay	1.5s	Time delay	1.5s
	Char3	6.789s	Char3	17.51s
	Time delay	0.3s	Time delay	0.3s
Alarm signal	4.764s		9.731s	
Tripping signal	6.715s		10.731s	

In admittance measurement scheme, the alarm signals are issued by Char 1 at 4.764 s for 80% load and 5.361 s for 40 % load. The tripping signals are initiated by Char 2 at 6.715 s for 80% load and 10.731 s for 40% load. Normally, Char 1 only gives an alarm and a long time delay tripping signal. Char 2 initiates a tripping signal after 1.5 second to 2 second and Char 3 should generates a tripping signal very quickly but with very short time delay just to override the power swing from the system, as Char 3 is very close to the loss of synchronism point.

PQ measurement based scheme

Figure 5.6 describes the Generator 1 characteristic curve in P-Q plane for Case 1. The protection scheme setting is introduced in the previous chapter. UEL only issues an alarm signal and the tripping signal is initiated by the P-Q relay.

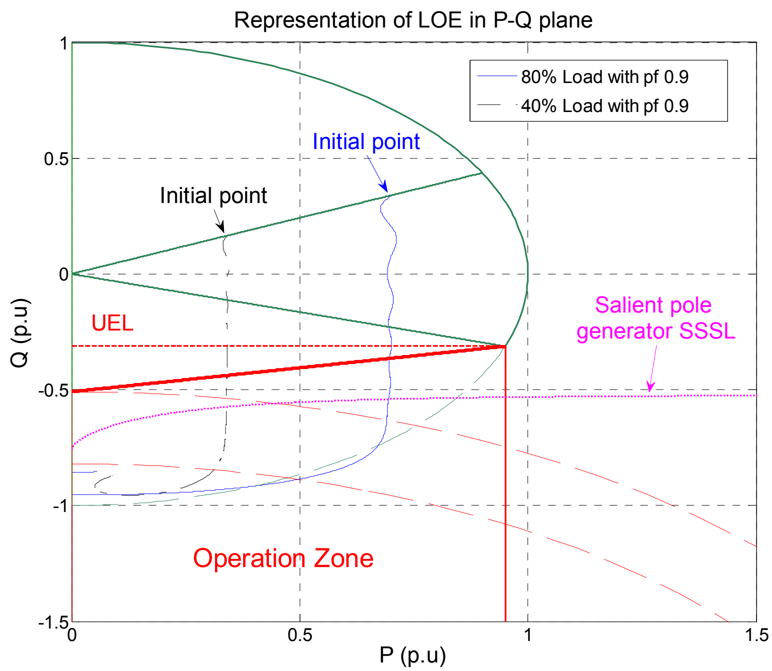


Figure 5.6: Complete LOE representation in P-Q scheme

The blue solid P-Q locus represents the 80% load and black dashed locus represents the 40% load. The P-Q trajectories start from the rated power factor 0.9 and after loss of excitation occurs, they fall into the UEL and finally enter the operation zone.

For cylindrical pole generator, underexcitated operation is not allowed. However, for salient pole generator, it could operate at underexcitation mode or even asynchronously for short time [1]. The simulation results are shown in Table 5.4:

Table 5.4: Complete LOE simulation results of P-Q scheme

Protection Scheme: PQ	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 leading	
Enter relay operation region time	UEL	3.534s	UEL	4.312s
	Issue alarm time delay	0.5 s	Issue alarm time delay	0.5 s
	Operation Zone	3.98s	Operation Zone	7.3s
	Time delay	0.75s	Time delay	0.75s
U<85% pick up time	4.37s		12.97s	
I>110% pick up time	5.61s		17.4s	
Alarm signal	4.03s		4.8s	
Tripping signal	4.73 s		8.05 s	

The tripping signals are initiated more quickly by this scheme as well as the alarm signal comparing to R-X and G-B based schemes. For this scheme, undervoltage (U<85%) supervision element can be implemented to accelerate the protection zone tripping, typically 0.25 s-1 s. With undervoltage element, UEL shall be able to initiate a tripping signal after long time delay.

U-I based scheme

The setting of directional current relay coincide the generator capability limit and stability limit. In this case, the setting is identical to the operation zone in P-Q scheme where the characteristic angle of direction current relay is 78.32 deg and non-directional current stage is 49.8% rated current. Besides the directional relay, the undervoltage relay (U< 90% rated voltage) and the overcurrent relay (I>110% rated current) are also implemented in the protection scheme. The tripping signal is initiated by the directional relay combined with an undervoltage element or overcurrent element [12].

Figure 5.7 describes the Generator 1 directional current characteristic curve in P-Q plane.

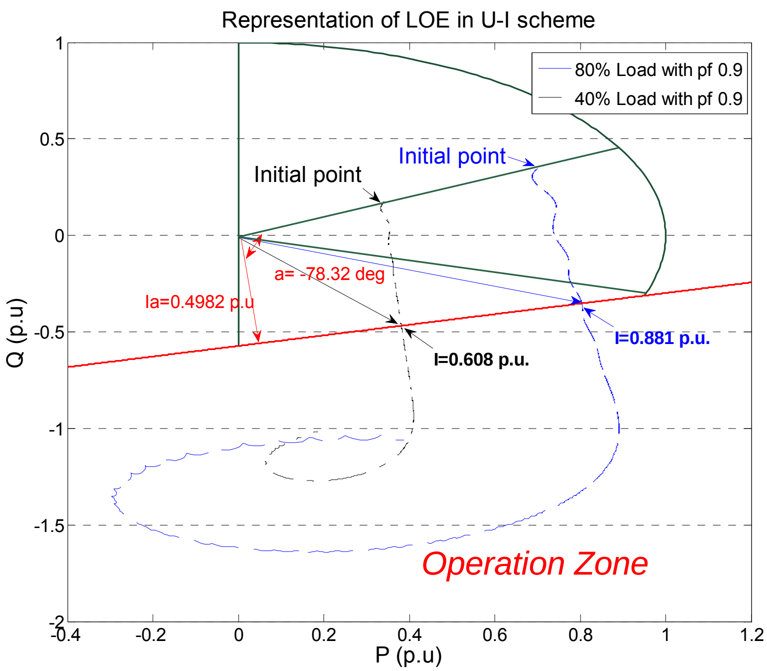


Figure 5.7: Complete LOE representation in U-I scheme

The simulation results are shown in Table 5.5:

Table 5.5: Complete LOE simulation results of U-I scheme

Protection Scheme: Directional Current Relay	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 leading	
Relay setting	Characteristic Angle	-78.32deg	Non-directional current stage	49.8%
Enter relay operation region time	Operation region	3.47s	Operation region	5.93s
	Alarm time delay	0.5 s	Alarm time delay	0.5 s
	Tripping time delay	2 s	Tripping time delay	2 s
U<90% pick up time	2.515s		5.361s	
I>110% pick up time	5.61s		17.4s	
Alarm signal	3.97s		6.43s	
Tripping signal	5.47s		7.93s	

This scheme can generate a tripping very quickly, at 5.47 second after loss of excitation. If the current locus falls into the directional current relay protection region but the undervoltage element is not picked up, the directional current relay will only issue an alarm signal after 0.5 second time delay.

5.2. Partial loss of excitation

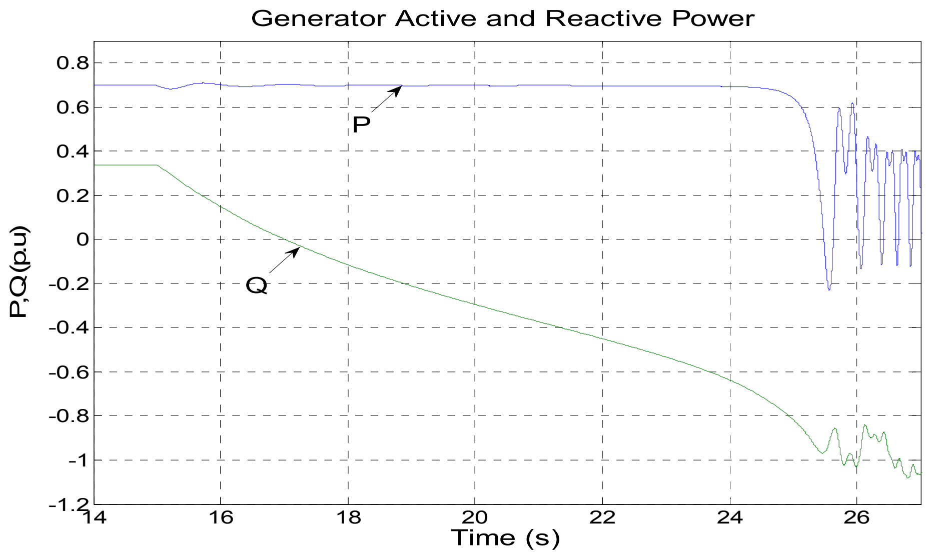
5.2.1. Description

The partial LOE happens on Generator 1 at 15s. The field voltage of Generator 1 falls down to 0.5 p.u..
Scenario 1: Generator 1 and 2 operate at 80% load p.f. 0.9.
Scenario 2: Generator 1 and 2 operate at 40% load p.f. 0.9.

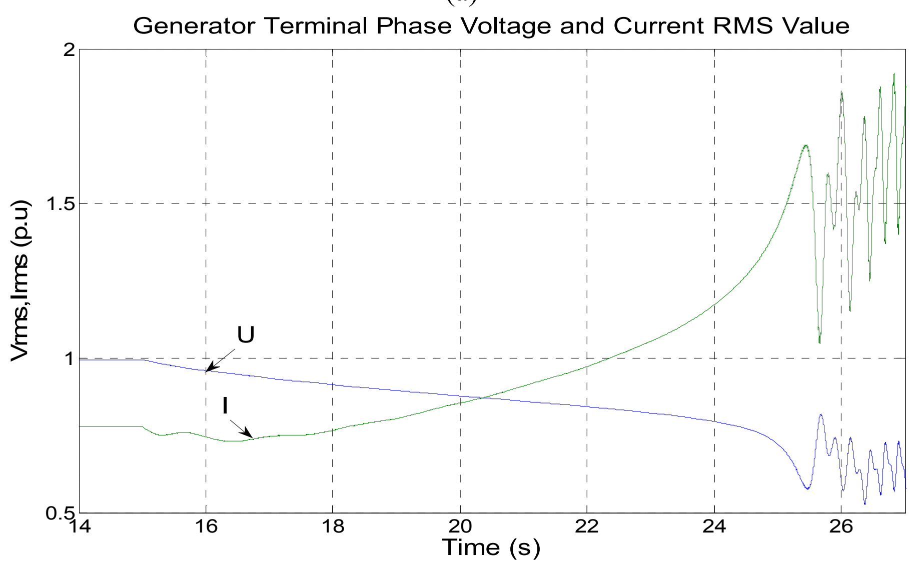
5.2.2. Simulation results analysis

The initial operation condition is the same as Case 1. The generator carried 80 % and 40% rated load respectively with rated power factor 0.9 leading. At 15 s, a partial loss of excitation fault happened at Generator 1.

Figure 5.8 describe the Generator 1 active power, reactive power, terminal voltage RMS value and terminal current RMS value with 80% load and p.f. 0.9.



(a)



(b)

Figure 5.8: Generator 1 characteristic curves during partial LOE
(a) active and reactive power output (b) phase voltage and current R.M.S. value

During partial loss of excitation, the generator can operate for longer time without synchronism compared to the complete loss of excitation fault case. The active-, reactive power, terminal voltage and terminal current reach the same level as Case 1 after loss of synchronism which means the generator output during loss of excitation is only determined by the generator initial condition. The field voltage reduction only affects the duration time and variables changing rate.

In this case, the generator loses synchronism at around 25 s which is 10 second after LOE fault.

R-X scheme

Figure 5.9 describes the Generator 1 terminal impedance characteristic trajectory in RX plane.

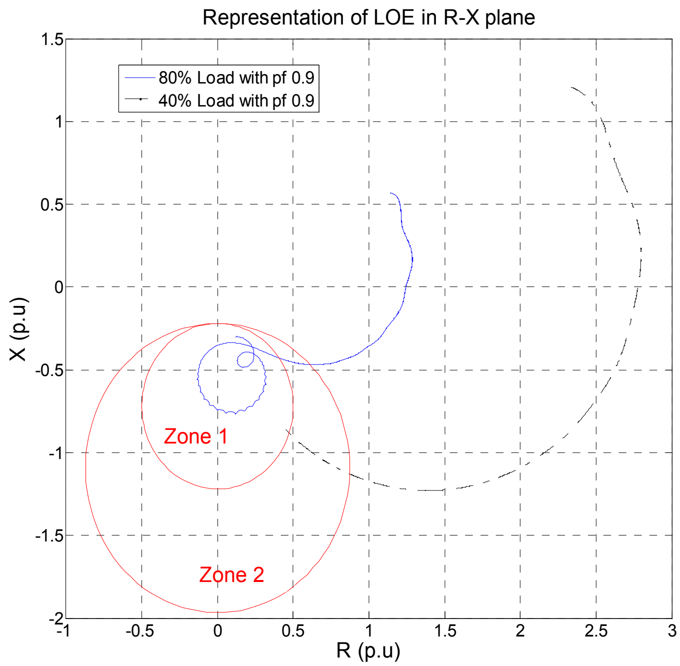


Figure 5.9: Partial LOE representation in R-X scheme

The simulation results of R-X scheme are listed in the table below:

Table 5.6: Partial LOE simulation results of R-X scheme

Protection Scheme: RX	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 lagging	
Enter relay operation region time	Zone 2	8.072s	Zone 2	33.28s
	Alarm time delay	0.5 s	Alarm time delay	0.5 s
	Tripping time delay	1 s	Tripping time delay	1 s
	Zone 1	9.586s	Zone 1	81.41s
	Time delay	0.3 s	Time delay	0.3 s
U<90% pick up time	3.72s		16.865s	
I>110% pick up time	8.462s		88s	
Alarm signal	8.572s		33.775s	
Trip signal	9.072s		34.28s	

The terminal impedance locus start at the same point in R-X plane as Case 1 and the alarm signals are issued by Zone at 8.572 s and 33.775 s for 80% load and 40% load respectively. The tripping signals are also initiated by Zone 2 at 9.072 s for 80% load and 34.28 s for 40% load. In this case, the undervoltage element picks up at 3.72 s. However, the overcurrent element takes 88 second to pick up at light load condition.

R-X with directional unit scheme

Figure 5.10 shows the Generator 1 terminal impedance characteristic trajectory in R-X plane with directional element.

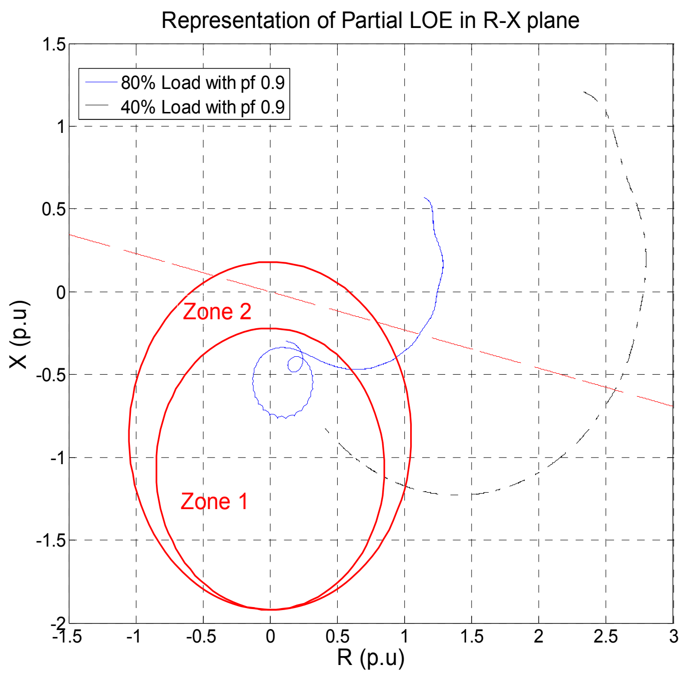


Figure 5.10: Partial LOE representation in R-X scheme with directional element

The simulation results are listed in the below table:

Table 5.7: Partial LOE simulation results of R-X scheme with directional element

Protection Scheme: RX	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 lagging	
Enter relay operation region time	Direction relay	3.59s	Direction relay	2.85s
	Alarm Time delay	0.5s	Alarm Time delay	0.5s
	Zone 2	5.12s	Zone 2	22.5s
	Time delay	2 s	Time delay	2 s
	Zone 1	8.2s	Zone 1	35.83s

	Time delay	0.3 s	Time delay	0.3 s
U<90% pick up time	3.72s		16.865s	
I>110% pick up time	8.462s		88s	
Alarm signal	4.09s		3.35s	
Trip signal	7.12s		24.5s	

The direction unit issues alarm signals at 4.09 s for 80% load and 3.35 s for 40% load. Comparing to R-X scheme, it can detect abnormal condition in very short time and gives an alarm to the system operator. The tripping signals are generated by Zone 2 at 5.421 s for 80% load and 7.93 s for 40% load which are more quickly than R-X scheme. The reason is that the protection zone of this scheme is larger than R-X scheme protection zone. The advantage of this setting criterion is that it can detect the loss of excitation fault faster compared to other schemes.

G-B scheme

Figure 5.11 describes the Generator 1 terminal admittance locus in G-B plane.

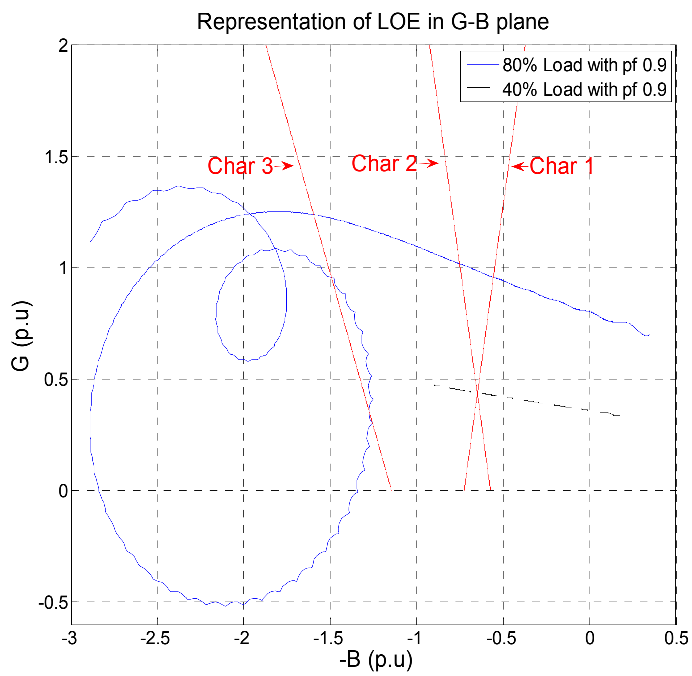


Figure 5.11: Partial LOE representation in G-B scheme

The simulation results are listed in Table 5.8:

Table 5.8: Partial LOE simulation results of G-B scheme

Protection Scheme: GB	80% load, p.f. 0.9		40% load, p.f. 0.9	
Enter relay operation region time	Char1	6.532s	Char1	54.51s
	Alarm time delay	0.5 s	Alarm time delay	0.5 s
	Tripping time delay	10 s	Tripping time delay	10 s
	Char2	7.883s	Char2	54.51s
	Time delay	1.5s	Time delay	1.5s
	Char3	10.04s	Char3	-
	Time delay	0.3s	Time delay	0.3s
U<90% pick up time	3.72s		16.865s	
I>110% pick up time	8.462s		88s	
Alarm signal	7.032s		55s	
Trip signal	9.383s		56.01s	

In this case, the alarm signals are generated by Char 1 at 7.032 s for 80% load and 55 s for 40% load. The tripping signals are initiated by Char 2 at 9.383 s for 80% load 56.01 s for 40% load. In some setting examples, Char 2 only issues an alarm and Char 3 initiates a tripping. During partial loss of excitation, the generator terminal admittance locus only enters Char 1 and Char 2 at light load condition, so Char 2 should be able to initiate tipping after certain time delay.

PQ measurement based scheme

Figure 5.12 describes the Generator 1 characteristic curve in P-Q plane.

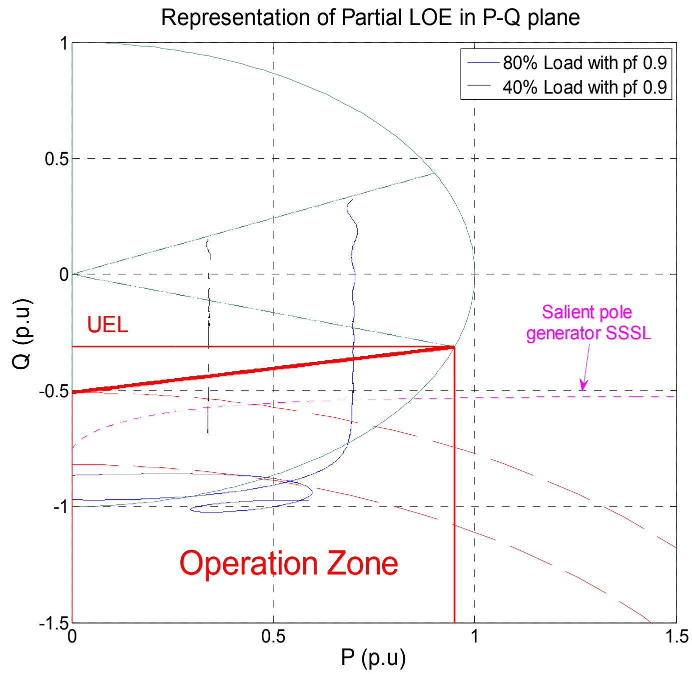


Figure 5.12: Partial LOE representation in P-Q scheme

The blue solid P-Q locus represents the 80% load and black dashed locus represents the 40% load. The P-Q trajectories start from the rated power factor 0.9.

The simulation results are shown in Table 5.9:

Table 5.9: Partial LOE simulation results of P-Q scheme

Protection Scheme: PQ	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 leading	
Enter relay operation region time	UEL	5.179s	UEL	10.58s
	Alarm delay	0.5s	Alarm delay	0.5s
	Operation Zone	5.85 s	Operation Zone	30.13s
	Time delay	0.5s	Time delay	0.5s
U<85% pick up time	6.61s		77.5s	
I>110% pick up time	8.462s		88s	
Alarm signal	5.679s		11.8s	
Trip signal	6.35s		30.63s	

U-I scheme

The setting criterion of this case is the same as Case 1. Figure 5.13 describes the Generator 1 directional current characteristic curve in P-Q plane.

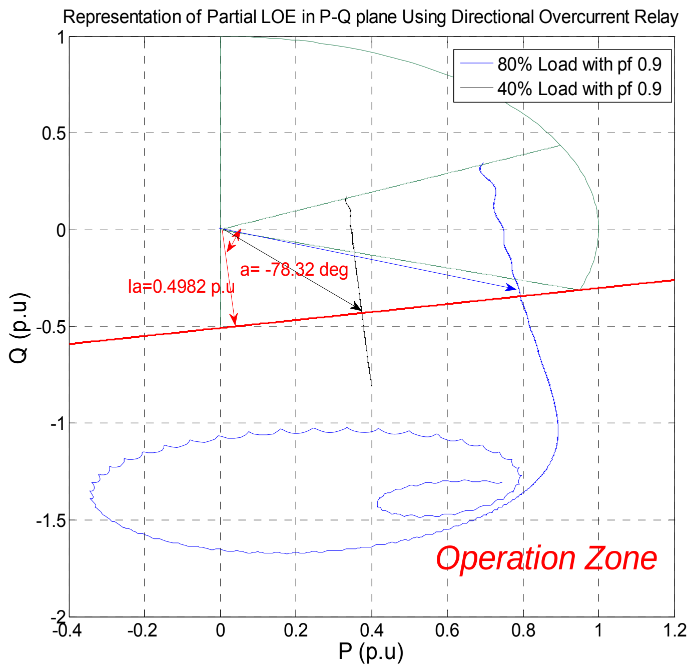


Figure 5.13: Partial LOE representation in U-I scheme

The simulation results are shown in the table below:

Table 5.10: Partial LOE simulation results of U-I scheme

Protection Scheme: Directional Current Relay	80% load, p.f. 0.9 lagging		40% load, p.f. 0.9 leading	
Relay setting	Characteristic Angle	-78.32deg	Nondirectional current stage	49.8%
Enter relay operation region time	Operation area	5.242s	Operation area	21.1s
	Alarm time delay	0.5 s	Alarm time delay	0.5 s
	Tripping time delay	2 s	Tripping time delay	2 s
U<90% pick up time	3.72s		16.865s	
I>110% pick up time	8.462s		88s	
Alarm signal	5.742s		21.6s	
Trip signal	7.242s		23.1s	

The directional current relay issues the alarm signals at 5.742 s for 80% load and 21.6 s for 40% load. The tripping signals are initiated at 7.242 s and 23.1 s respectively. From the simulation results, this scheme responds very fast for partial loss of excitation at light load condition comparing to other schemes.

5.3. Loss of excitation in condenser operation situation

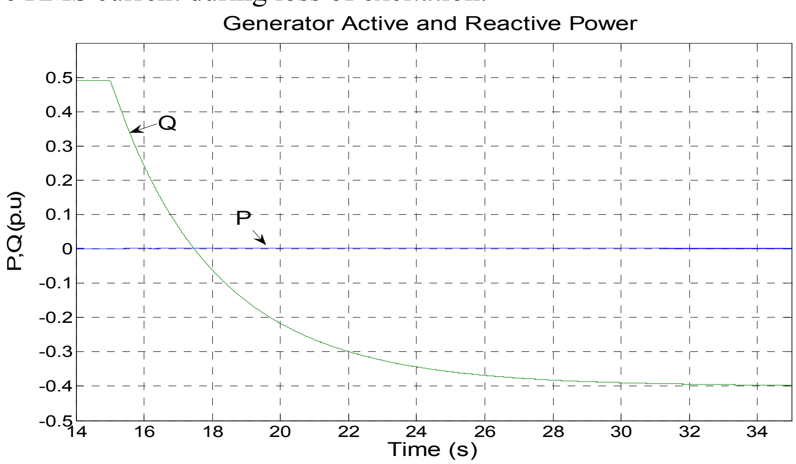
5.3.1. Description

The generator 1 and 2 operate as condenser with zero active power and 0.5 p.u. reactive power output. The complete LOE happens on Generator 1 at 15s.

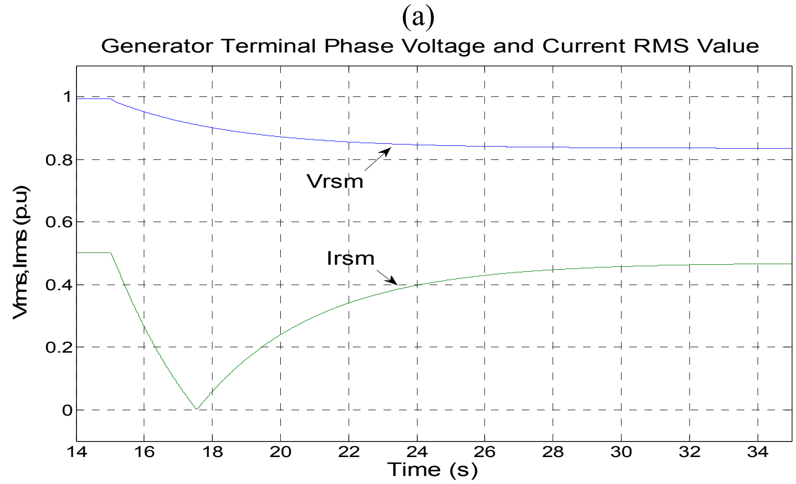
5.3.2. Simulation results analysis

Sometimes, the generator may operate as a synchronous condenser to adjust the system voltage or maintain the power factor. In this case, the generator generates zero active power (P=0) and 0.5 p.u. reactive power (Q=0.5 p.u.) before loss of excitation.

Figure 5.14 shows the Generator 1 active power, reactive power, phase RMS voltage and phase RMS current during loss of excitation.



(a)



(b)

Figure 5.14: Generator 1 LOE characteristic curves during condenser operation
(a) active and reactive power output (b) phase voltage and current R.M.S. value

In this case, the active power output is zero and reactive power output decreases from 0.5 p.u. to -0.4 p.u. after loss of excitation. From the simulation, the Generator 1 operates as an induction generator without loss of synchronism after transient period, although the generator starts to draw reactive power from the system. The terminal voltage decays steadily and finally keep the value of 84% rated voltage. The terminal current decreases down to zero at the beginning due to the reactive power falls down to zero and then increase to 46.6% rated current.

R-X scheme

Figure 5.14 describes the Generator 1 terminal impedance characteristic trajectory in RX plane.

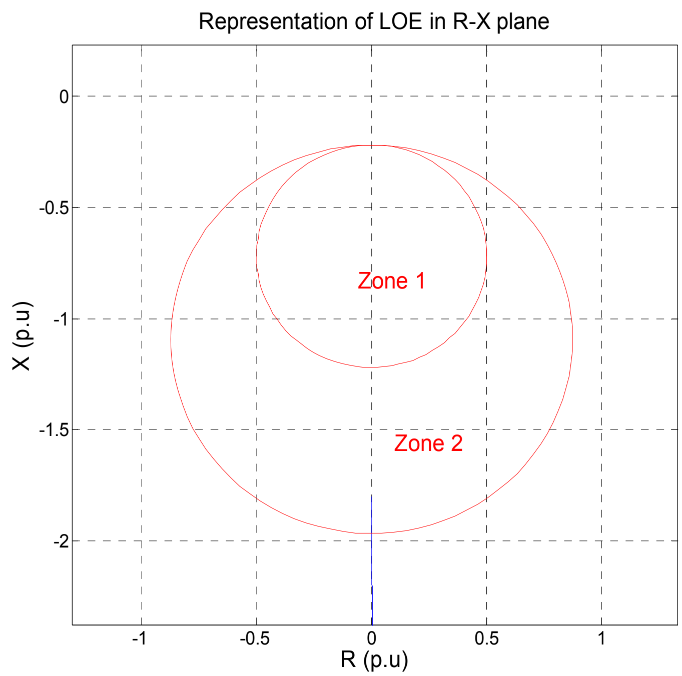


Figure 5.15: LOE representation in R-X scheme during condenser operation

In this case, the generator terminal impedance trajectory only enters the protection Zone 2 and stays in Zone 2 [2]. The results are listed in Table 5.11:

Table 5.11: LOE simulation results of R-X scheme during condenser operation

Protection Scheme: RX	P=0, Q=0.5p.u.	
Enter relay operation region time	Zone 2	10.88s
	Alarm time delay	0.5 s
	Tripping time delay	1 s
	Zone 1	-
	Time delay	0.3 s

U<90% pick up time	3.08s
I>110% pick up time	-
Alarm signal	11.38s
Tripping signal	11.88s

The protection Zone 2 issues an alarm signal at 11.38 s and initiates a tripping signal at 11.88 s. The undervoltage element picks up at 3.08 s.

R-X with directional element scheme
Figure 5.16 shows the Generator 1 terminal impedance characteristic trajectory in R-X plane with directional element.

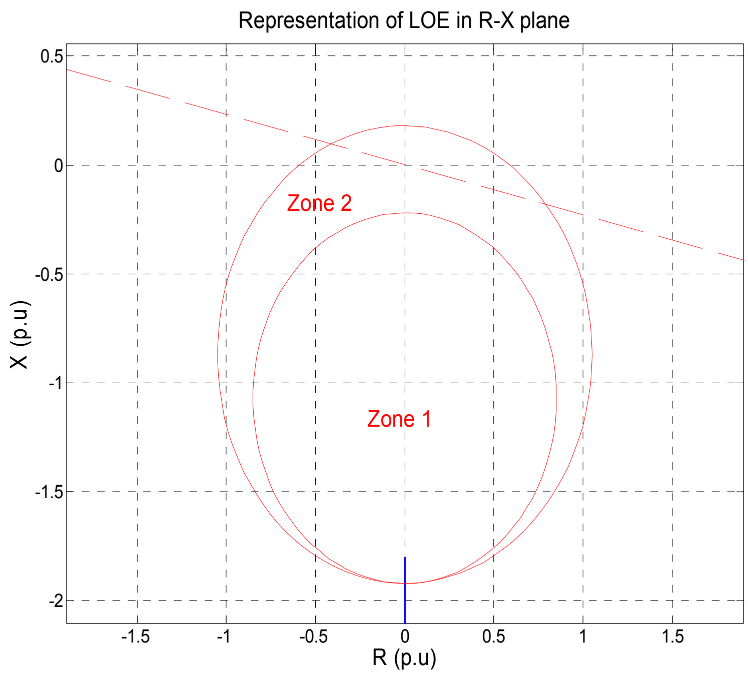


Figure 5.16: LOE in R-X scheme with directional element during condenser operation

In this case, the terminal impedance trajectory enters protection Zone 2 and Zone 1 at same time and stays in Zone 1.

The results are listed in the table below:

Table 5.12: LOE results of R-X scheme with directional element as condenser

Protection Scheme: RX with directional element	P=0, Q=0.5p.u.	
Enter relay operation region time	Direction relay	2.55s
	Alarm time delay	0.5s
	Zone 2	11.12s
	Time delay	1 s
	Zone 1	11.12s
	Time delay	0.3 s
Alarm signal	3.05s	
Tripping signal	11.42s	

The directional element issues an alarm signal very fast at 3.08 s which provides more time for the system operator adjusting the generator operation mode. The impedance locus enters both Zone 2 and Zone 1, but the tripping signal is generated by Zone 1 at 11.42 s, as the time delay of Zone 1 is less than Zone 2.

G-B scheme

Figure 5.17 describes the Generator 1 terminal admittance locus in G-B plane.

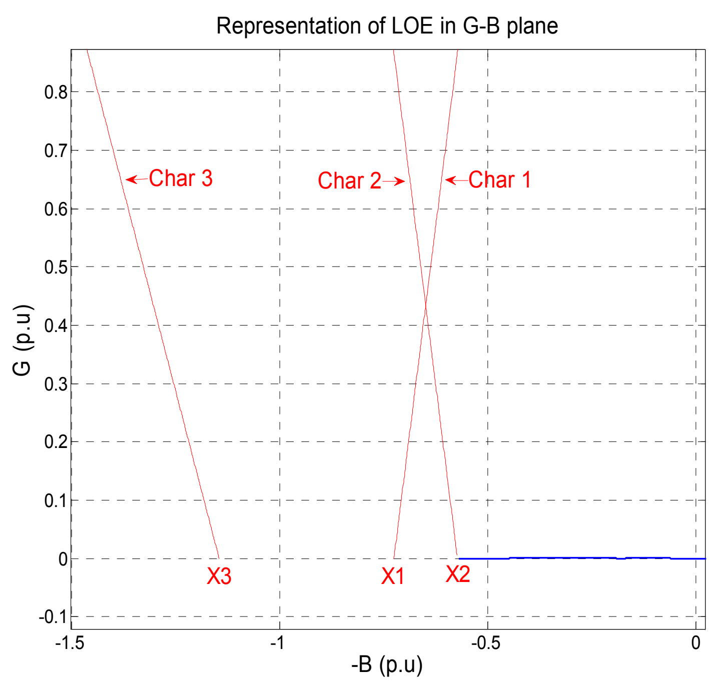


Figure 5.17: LOE in G-B scheme during condenser operation

The generator terminal admittance curve enters none of three protection zones and stays outside the protection zone. In this case, G-B scheme cannot detect the loss of excitation fault.

PQ measurement based scheme

Figure 5.18 describes the Generator 1 characteristic curve in P-Q plane.

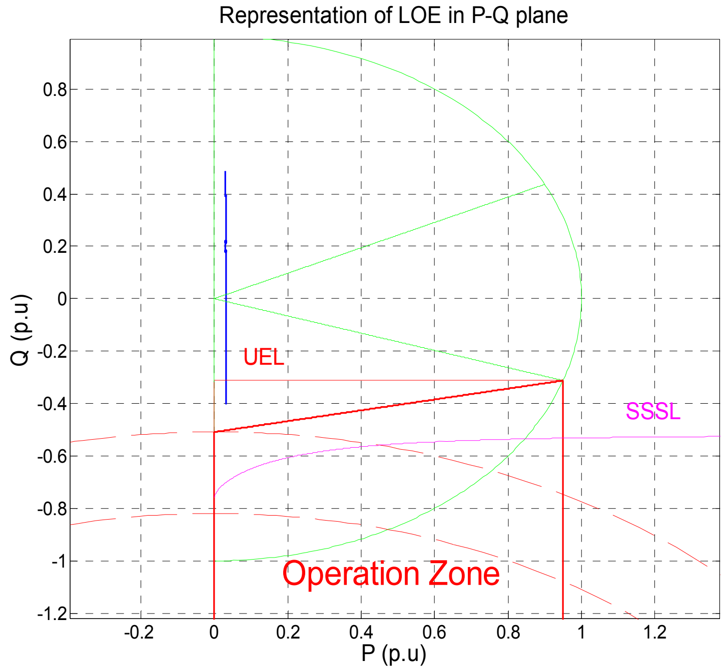


Figure 5.18: LOE in P-Q scheme during condenser operation

The P-Q trajectory exceeds UEL at 2.44 s but does not enter protection zone just stays between UEL and relay operation zone. In this case, UEL combined with undervoltage element shall initiate a tripping signal after long time delay. The undervoltage element picks up at 8.2 s and UEL picks up at 2.44 s. So the alarm signal is issued at 2.94 s and tripping signal is initiated 1 second time delay after the undervoltage element picking up at 9.2 s.

U-I scheme

Figure 5.19 describes the Generator 1 directional current characteristic curve in P-Q plane.

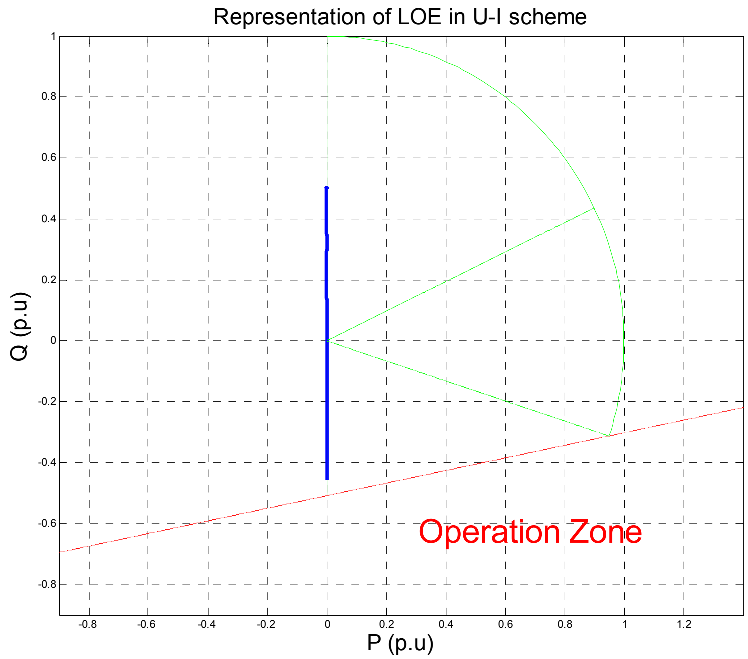


Figure 5.19: LOE in U-I scheme during condenser operation

From the figure, the generator terminal characteristic curve does not falls into the operation, so this scheme cannot detect loss of excitation during condenser operation.

6. Simulation results comparison of external faults

This section describes four cases of external fault, including symmetrical faults and unsymmetrical faults.
Case 1: Busbar three phase short circuit fault.
Case 2: Generator terminal three phase to ground fault
Case 3: Busbar phase to phase short circuit fault.
Case 4: Busbar single phase to ground fault

6.1. Busbar three phase short circuit fault

6.1.1 Description

A three phase short circuit fault occurs at busbar and the fault resistance is 0.1 ohm. The initial condition and fault duration is described below:
Scenario 1: P=0.7 p.u.; Q=-0.24 p.u.; p.f.=0.95 leading; Fault duration: 150ms
Scenario 2: P=0.7 p.u.; Q=-0.24 p.u.; p.f.=0.95 leading; Fault duration: 100ms
Scenario 3: P=0.7 p.u.; Q=0.34 p.u.; p.f.=0.9 lagging; Fault duration: 150ms
Scenario 4: P=0.7 p.u.; Q=0.34 p.u.; p.f.=0.9 lagging; Fault duration: 100ms

The fault location is shown in Figure 6.1:

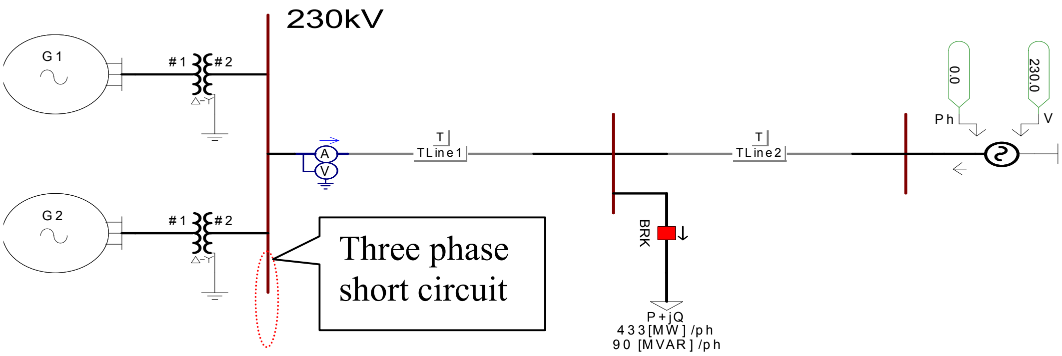
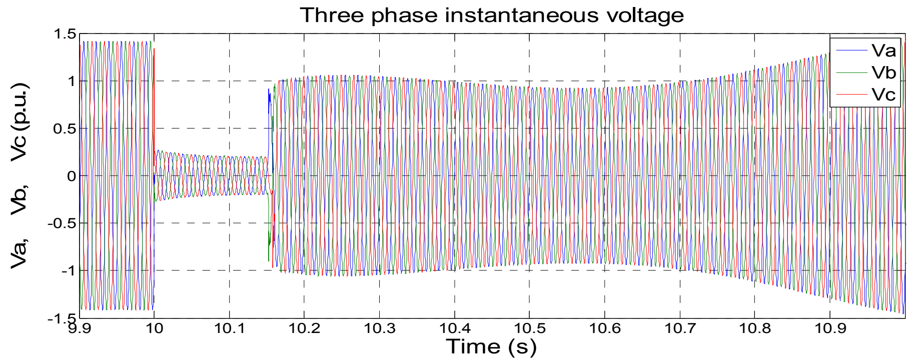


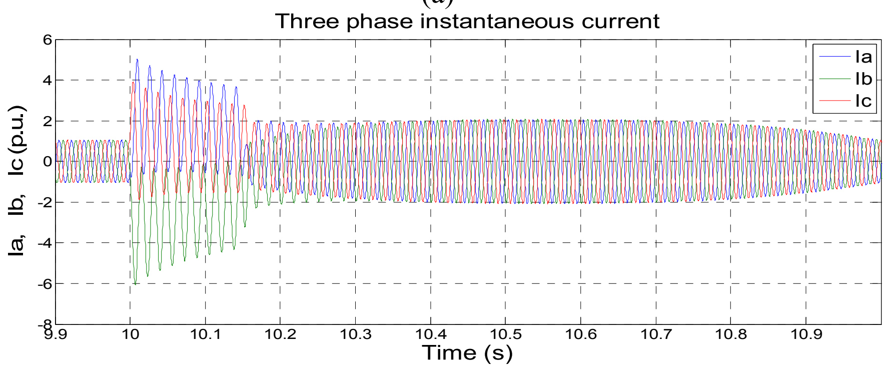
Figure 6.1: Busbar fault location in simulation model

6.2.2 Simulation results analysis

Simulation results of Scenario 1
Figure 6.2 shows the simulation results of Scenario 1:



(a)



(b)

Figure 6.2: Generator 1 three phase voltage and current during the fault
(a) three phase voltage (b) three phase current

During the fault, the three phase voltage decrease and the phase voltage during the fault depend on the fault resistance. If the fault resistance is zero, the phase voltage will decreases to zero. Otherwise, the phase voltage will goes down to certain value and recover after the fault if the generator still keeps synchronism.
The short-circuit current is influenced by the value of the armature-windings and armature-reaction. The initial short-circuit current is calculated as:

$$I_t = \frac{E}{X_t} \tag{6.1}$$

where I_t is the R.M.S. value of initial short-circuit current and E is the R.M.S. value of the open-circuit voltage and X_t is the transient reactance. If the damping winding is considered, the transient reactance is substituted by the sub-transient reactance. Due to the inductive characteristic of the circuit, current cannot change magnitude and phase immediately and displaces from the zero-axis. This phenomenon is shown as the blue curve Ia in Figure 6.2 b. In this case, the current is considered as containing an AC component and a DC component.

The load angle is depicted in the figure below:

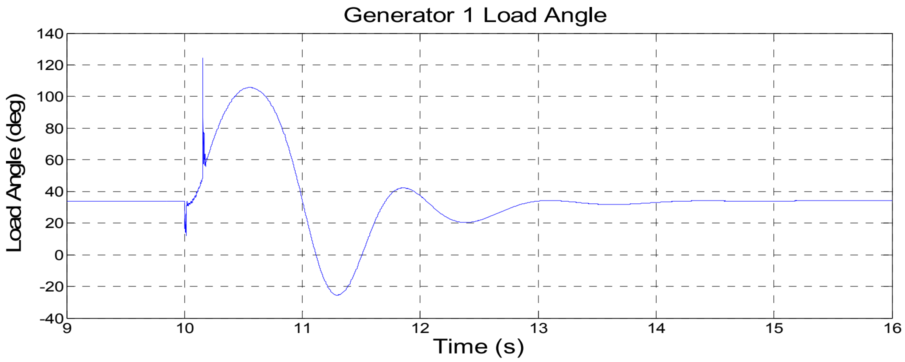
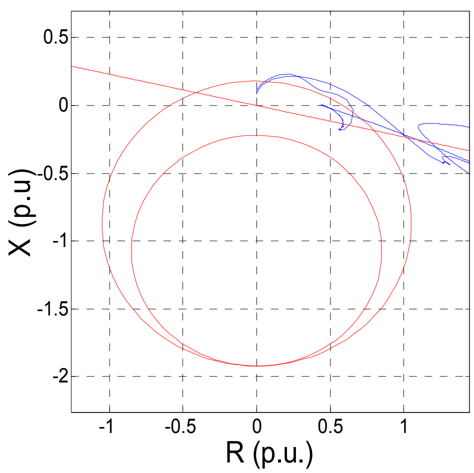


Figure 6.3: Generator 1 load angle variation during fault

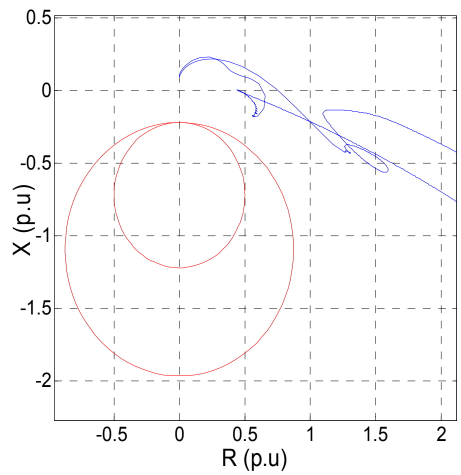
From the figure, the peak value of load angle reached 105 degree and then decreases, which means the generator still operates without loss of synchronism. Figure 6.4 shows the behaviors of R-X, G-B, P-Q and U-I schemes during busbar three-phase short circuit fault.

R-X (directional)



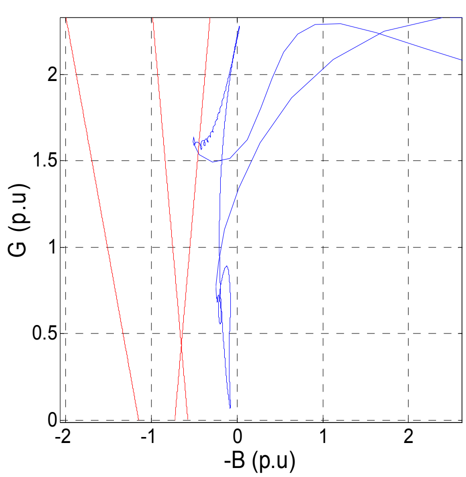
(a)

R-X



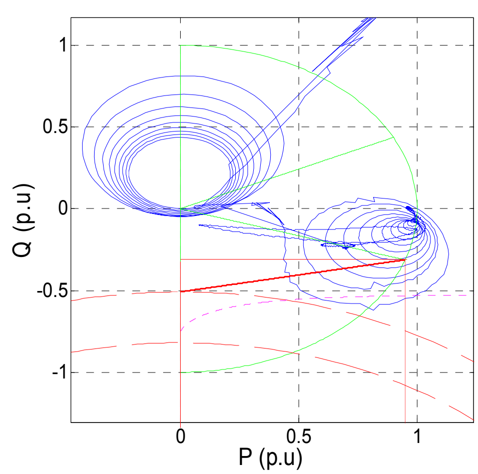
(b)

G-B



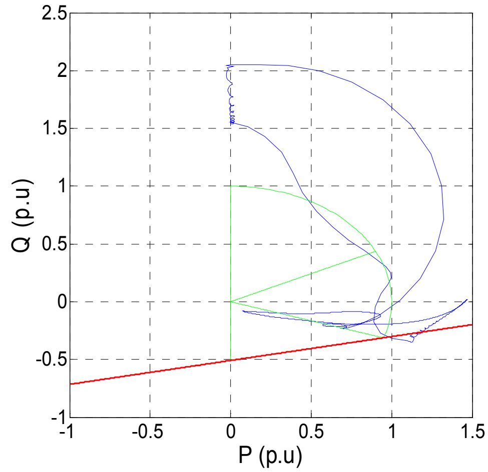
(c)

P-Q



(d)

UI



(e)

Figure 6.4: Generator terminal characteristic curve in LOE protection schemes
(a) R-X with directional element scheme (b) R-X scheme (c) G-B scheme
(d) P-Q scheme (e) U-I scheme

From the simulation results, the characteristic curves will enter the LOE protection zones of R-X directional element, G-B, P-Q and U-I schemes during busbar three-phase short circuit fault. For P-Q scheme, it enters and exits the protection zone several times during the fault. However, the LOE relay can override the external faults with enough time delay.

During external faults, the generator characteristic curve may enter LOE protection region and stay in the region for some time. The maximum duration time, which is the maximum time that the characteristic curve stays in the protection region, is listed in Table 6.1:

Table 6.1: Maximum duration time in LOE protection scheme of Scenario 1

Busbar 3 phase short circuit	Scenario 1: p.f. 0.95 leading; 150ms	
	Enter LOE protection zone (Y/N)	Maximum duration time
RX (directional)	Y	Zone2:0.04 s
RX	N	-
GB	Y	0.01 s
PQ	Y	0.004 s
UI	Y	0.03 s

Simulation results of Scenario 2, 3, 4

For Scenario 2, 3, 4, the simulation results are described in Table 6.2:

Table 6.2: Maximum duration time in LOE protection scheme of Scenario 2, 3, 4

Busbar 3 phase short circuit	Scenario 2 p.f. 0.95 leading; 100ms		Scenario 3 p.f. 0.9 lagging; 150ms		Scenario 4 p.f. 0.9 lagging; 100ms	
	Enter LOE protection zone (Y/N)	Maximum duration time	Enter LOE protection zone (Y/N)	Maximum duration time	Enter LOE protection zone (Y/N)	Maximum duration time
RX (directional)	Y	Zone2:0.09 s	N	-	N	-
RX	N	-	N	-	N	-
GB	N	-	N	-	N	-
PQ	Y	0.004 s	N	-	N	-
UI	Y	0.029 s	N	-	N	-

During busbar three-phase short circuit fault, the generator characteristic curves may enter the LOE protection zone and stays in the protection for short time. From the simulation result, R-X scheme is the most stable one, as the protection zone of R-X scheme is the smallest one. Normally there is short time delay for LOE relay and if the maximum duration time exceeds this time delay, LOE relay will mal-operate.

6.2. Generator terminal three phase to ground fault

6.2.1. Description

A three phase to ground fault occurs at Generator 1 terminal. The fault resistance is 0.1 ohm.
Scenario 1: P=0.7 p.u.; Q=-0.24 p.u.; p.f.=0.95 leading; Fault duration: 150ms
Scenario 2: P=0.7 p.u.; Q=-0.24 p.u.; p.f.=0.95 leading; Fault duration: 100ms
Scenario 3: P=0.7 p.u.; Q=0.34 p.u.; p.f.=0.9 lagging; Fault duration: 150ms
Scenario 4: P=0.7 p.u.; Q=0.34 p.u.; p.f.=0.9 lagging; Fault duration: 100ms

The fault location is shown in Figure 6.5:

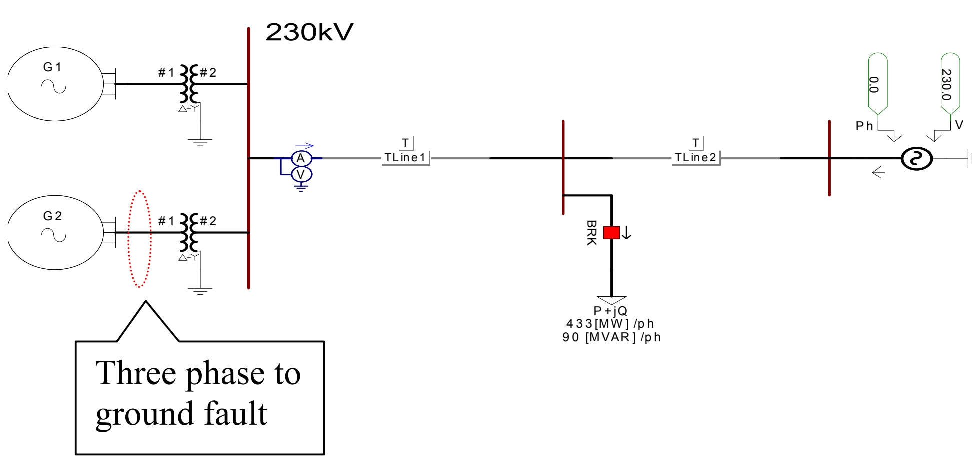


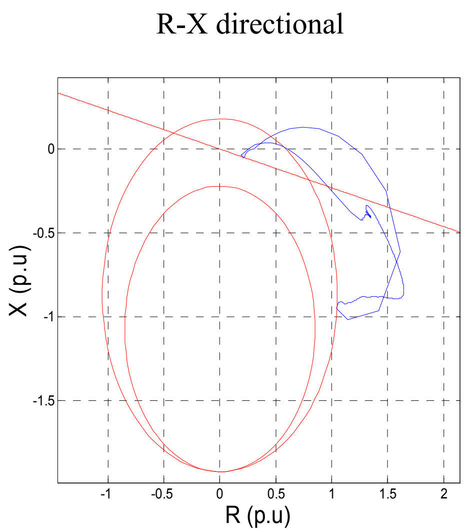
Figure 6.5: Generator terminal fault location in simulation model

6.2.2. Simulation results analysis

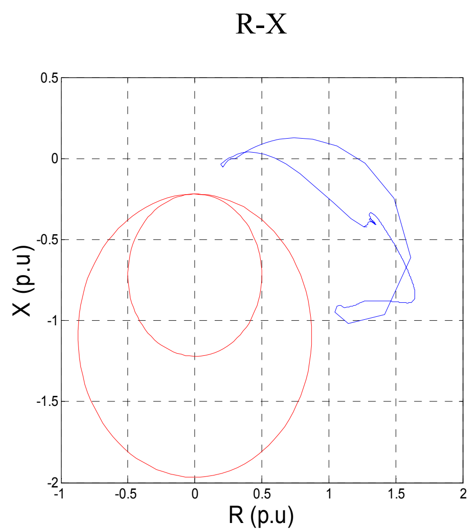
During three-phase-to-ground fault, the simulation result is almost the similar to three phase short circuit fault. The phase voltage during the fault is also determined by the fault impedance and phase current is influenced by the value of the armature-windings and armature-reaction.

Simulation results of Scenario 1

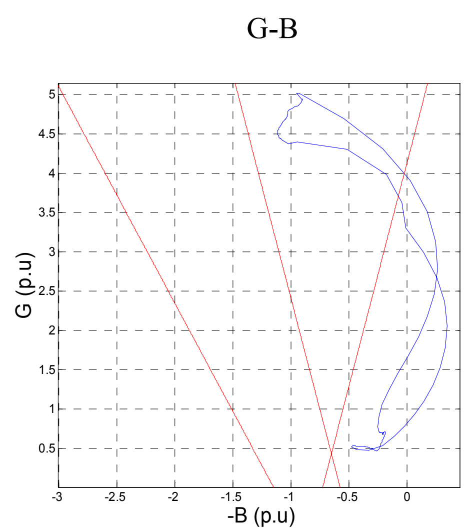
Figure 6.6 shows the behaviors of R-X, G-B, P-Q and U-I schemes during generator terminal three-phase-to-ground fault.



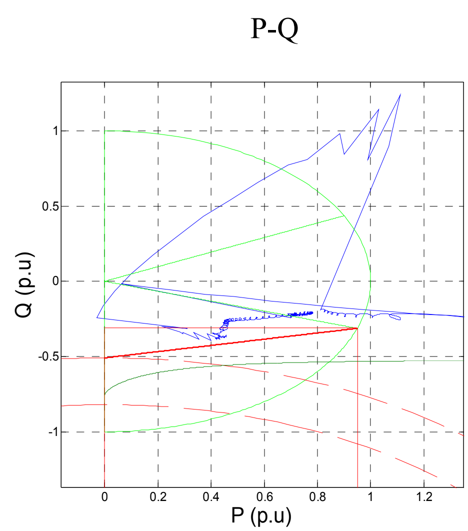
(a)



(b)



(c)



(d)

U-I

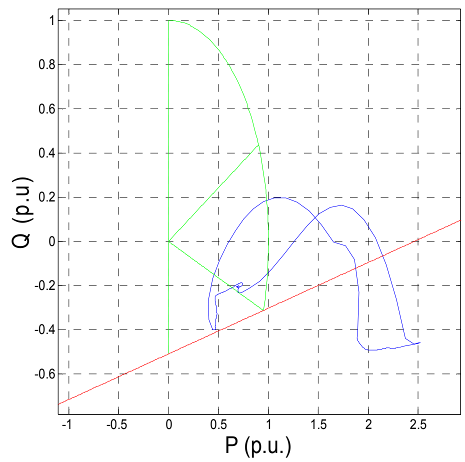


Figure 6.6: Generator terminal characteristic curve in LOE protection schemes
(a) R-X with directional element scheme (b) R-X scheme (c) G-B scheme
(d) P-Q scheme (e) U-I scheme

In this case, the characteristic curve enters the G-B and U-I schemes and stay in the protection zones for long time, which will cause LOE relay mal-operation.

Maximum duration time

The maximum duration time in the protection zone is listed in Table 6.3:

Table 6.3: Maximum duration time in LOE protection scheme during the fault

Generator terminal 3 phase to ground fault	Scenario 1 p.f. 0.95 leading; 150ms	Scenario 2 p.f. 0.95 leading; 100ms	Scenario 3 p.f. 0.9 lagging; 150ms	Scenario 4 p.f. 0.9 lagging; 100ms
	Maximum duration time	Maximum duration time	Maximum duration time	Maximum duration time
RX (directional)	-	-	-	-
RX	-	-	-	-
GB	Char1: 0.1425s	Char1: 0.093s	Char1: 0.1363 s	Char1: 0.0865 s
PQ	-	-	-	-
UI	0.1392 s	0.0905 s	0.1363 s	0.0853 s

From the simulation results, the maximum duration time in the protection zone lasts more than 0.1 second for G-B and U-I scheme. This is very dangerous for the LOE relay and causes LOE relay mal-operation during three-phase-to-ground fault if the time delay is smaller than 0.1 second. In order to prevent this risk, the enough time delay should be set for LOE relay to override this fault, e.g. 0.3s-0.5s.

6.3. Busbar phase to phase short circuit fault

6.3.1. Description

A phase-to-phase fault occurs on Busbar at 10 s . The fault resistance is 0.1 ohm.
Scenario 1: Phase to phase fault (A-B). P=0.7 p.u.; Q=0.34 p.u.; p.f. 0.95 leading; Fault duration: 100ms
Scenario 2: Phase to phase fault (A-B). P=0.7 p.u.; Q=0.34 p.u.; p.f. 0.9 lagging; Fault duration: 100ms
The fault location is shown in Figure 6.7:

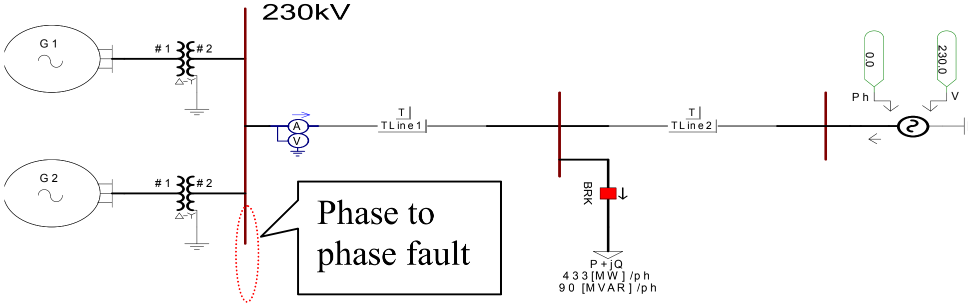
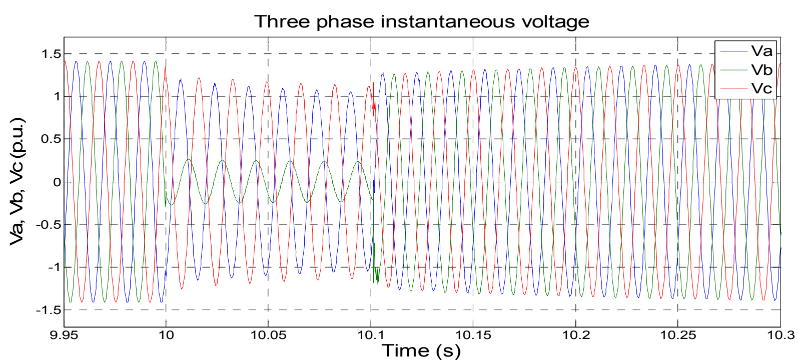


Figure 6.7: Busbar phase to phase fault location in simulation model

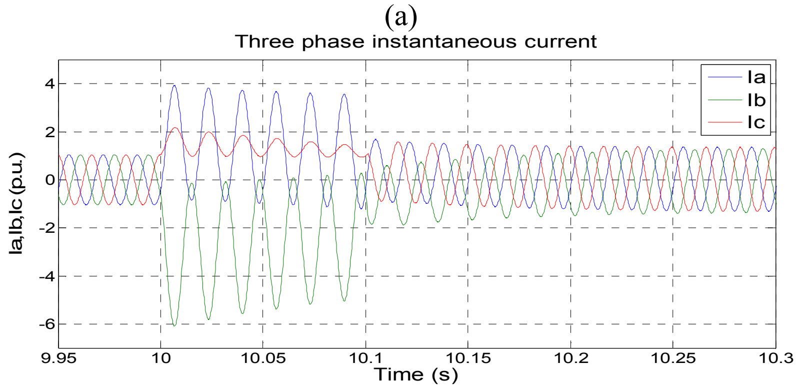
6.3.2. Simulation results analysis

Simulation results of Scenario 1

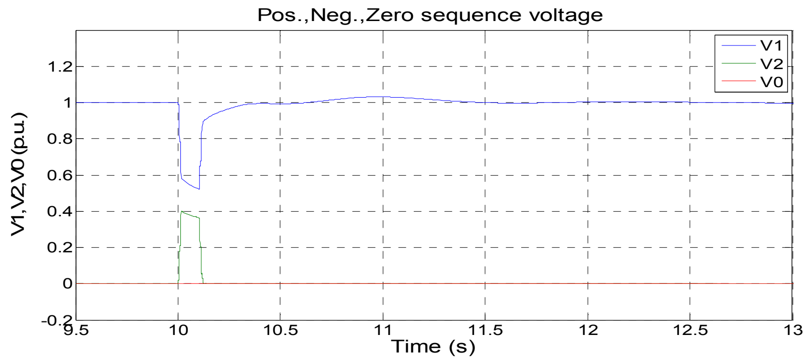
The phase voltage and current during the fault is shown in Figure 6.8:



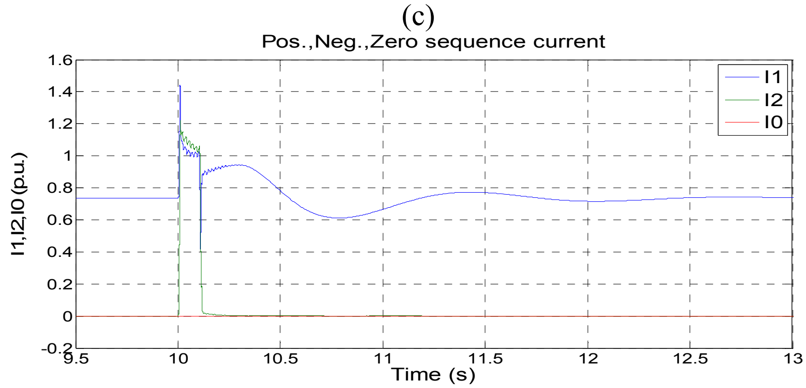
(a)



(b)



(c)



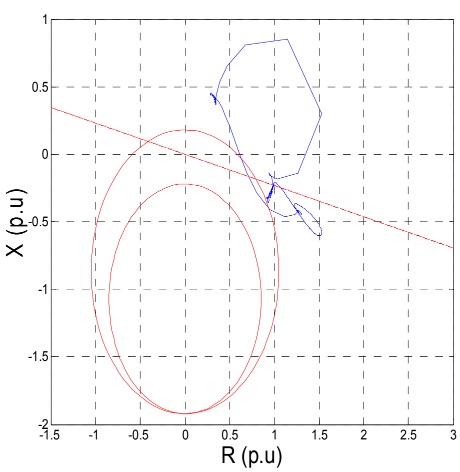
(d)

Figure 6.8: Generator three phase voltage, current and sequence component
(a) three phase voltage (b) three phase current
(c) voltage sequence component (d) current sequence component

From Figure 6.8, we can see the current of fault phases (AB) rises up and has a displacement from the zero-axis with opposite directions. In addition, during the fault, large amount of negative sequence component occurs in phase current.

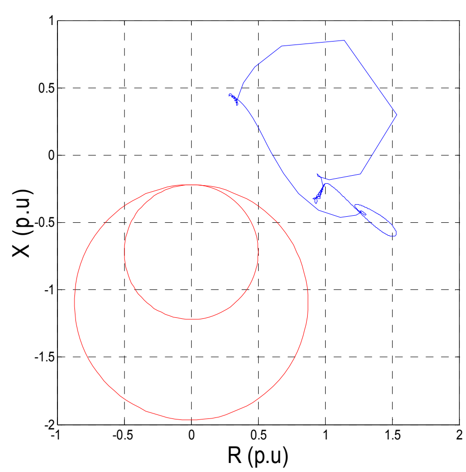
Figure 6.9 depicts the characteristic curves in R-X, G-B, P-Q and U-I schemes during busbar phase-to-phase fault.

R-X directional



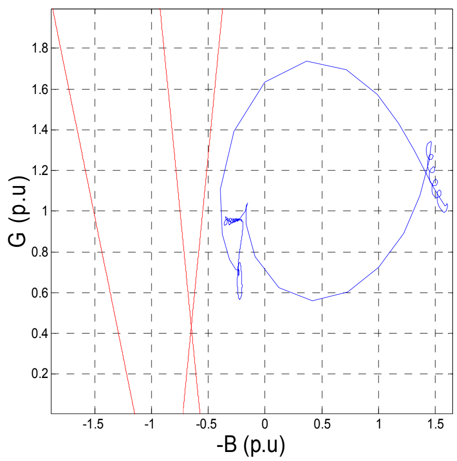
(a)

R-X



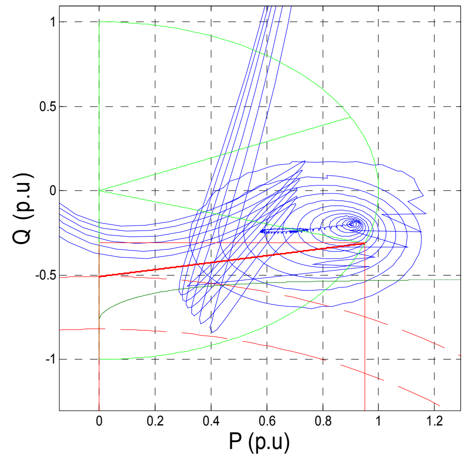
(b)

G-B



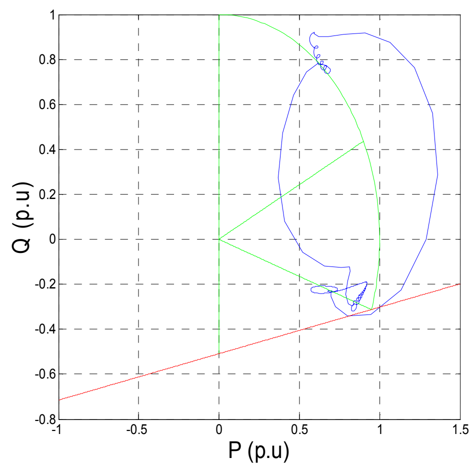
(c)

P-Q



(d)

U-I



(e)

Figure 6.9: Generator terminal characteristic curve in LOE protection schemes
(a) R-X with directional element scheme (b) R-X scheme (c) G-B scheme
(d) P-Q scheme (e) U-I scheme

In this case, the generator characteristic curves enter R-X with directional, P-Q and U-I scheme protection zones and pass through P-Q protection zone many times.

The maximum duration time in the protection zone is listed in the table below:

Table 6.4: Maximum duration time in LOE protection scheme during the fault

Busbar phase to phase short circuit	Scenario 1: p.f. 0.95 leading; 100ms	
	Enter LOE protection zone (Y/N)	Maximum duration time
RX (directional)	Y	Zone2: 0.001 s
RX	N	-
GB	N	-
PQ	Y	0.0035 s
UI	Y	0.003 s

In this case, the maximum duration in protection zone is very small which cannot cause LOE relay operation if the time delay of LOE relay is long enough.

Simulation results of Scenario 2

The simulation results of Scenario 2 are listed in the table below:

Table 6.5: Simulation results of Scenario 2

Busbar phase to phase short circuit	Scenario 2: p.f. 0.9 lagging; 100ms	
	Enter LOE protection zone (Y/N)	Maximum duration time
RX (directional)	N	-
RX	N	-
GB	N	-
PQ	N	-
UI	N	-

For busbar phase-to-phase fault, it is not as severe as three phase fault. But the characteristic curve also enters the LOE protection zone when the generator operates at leading power factor. In order to prevent the LOE relay mal-operation during external phase-to-phase fault, a negative sequence supervision element can be implemented to initiate a block signal for LOE relay during external phase-to-phase fault.

6.4. Busbar single-phase-to-ground fault

6.4.1. Description

A single phase-to-ground fault occurs at Busbar. The fault resistance is 0.1 ohm.

Scenario 1: Single phase-to-ground fault (A-G). P=0.7 p.u.; Q=0.34 p.u.; p.f. 0.95 leading; Fault duration: 100ms
Scenario 2: Single phase-to-ground fault (A-G). P=0.7 p.u.; Q=0.34 p.u.; p.f. 0.9 lagging; Fault duration: 100ms

The fault location is shown in Figure 6.10:

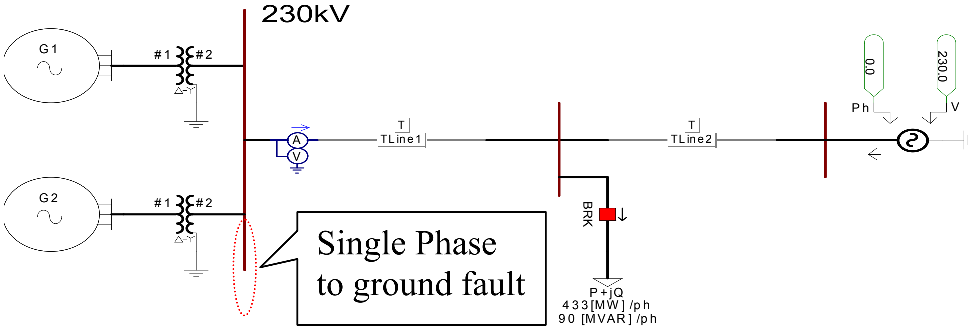
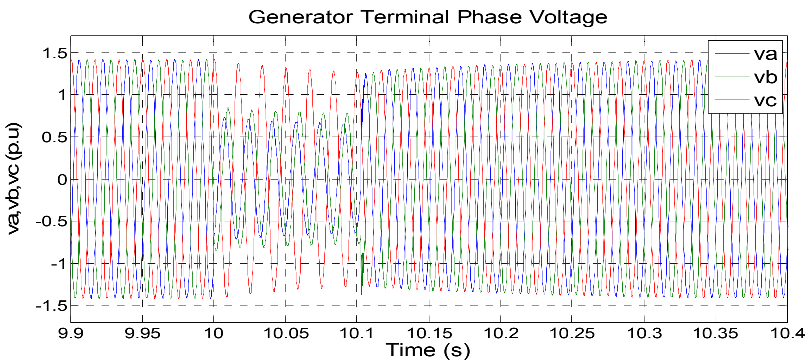


Figure 6.10: Busbar single phase-to-ground fault location in simulation model

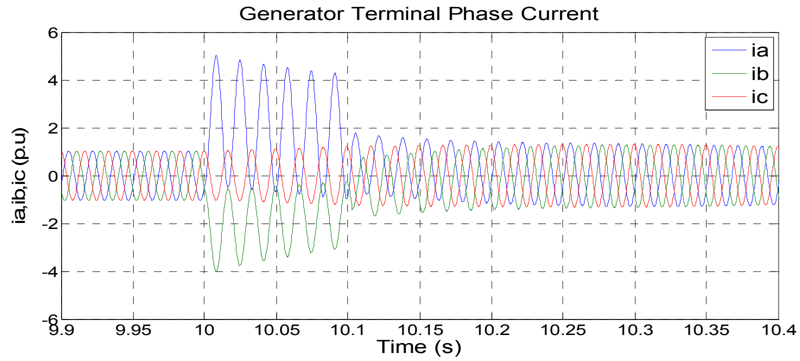
6.4.2. Simulation results analysis

Simulation results of Scenario 1

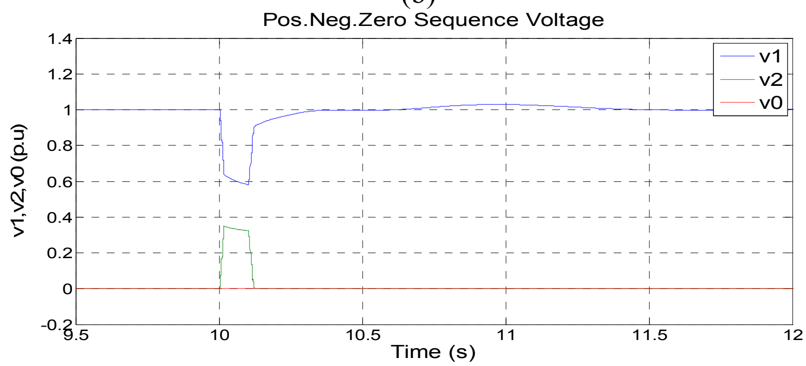
The phase voltage and current during the fault is shown in Figure 6.11:



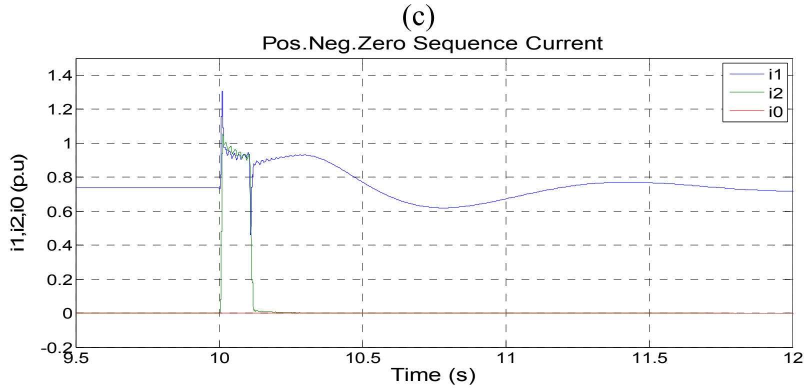
(a)



(b)



(c)



(d)

Figure 6.11: Generator phase voltage, current and sequence component during fault
(a) three phase voltage (b) three phase current
(c) voltage sequence component (d) current sequence component

In this case, the step-up transformer blocks the zero-sequence component caused by external fault, so the terminal voltage and phase current behave like the phase-to-ground fault. During single-phase-to-ground fault, the phase current also contains large amount of negative sequence component, which can be used to discriminate the LOE and external unsymmetrical fault.

Figure 6.12 depicts the characteristic curves in R-X, G-B, P-Q and U-I schemes during busbar single phase-to-ground fault of Scenario 1.

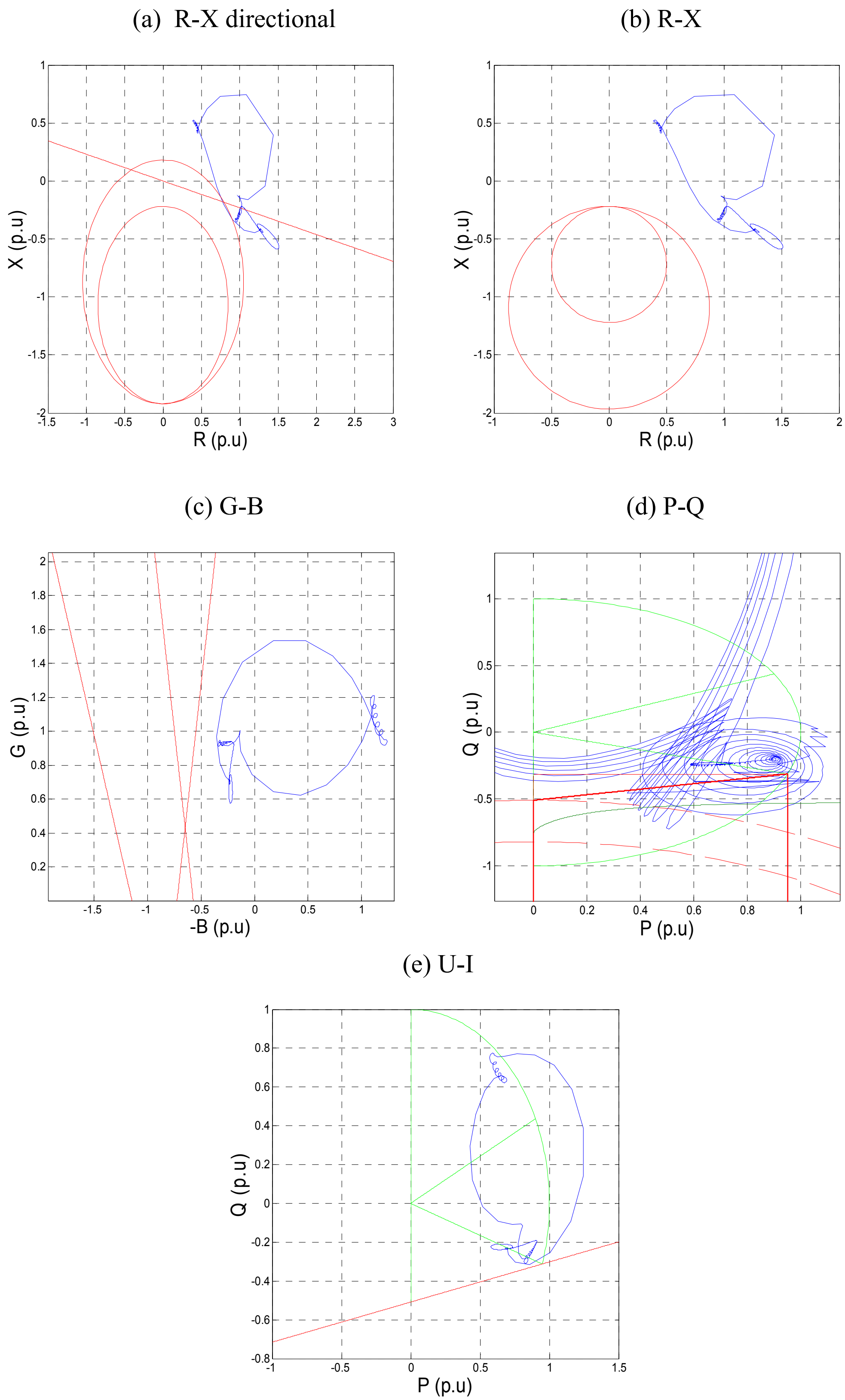


Figure 6.12: Generator characteristic curve in LOE protection schemes during fault
(a) R-X with directional element scheme (b) R-X scheme (c) G-B scheme
(d) P-Q scheme (e) U-I scheme

In this case, the characteristic curve only enters the P-Q scheme during the fault. The maximum duration time in the protection zone is listed in Table 6.6:

Table 6.6: Simulation results of Scenario 1

Busbar phase-to-ground fault	Scenario 1: p.f. 0.95 leading; 100ms	
	Enter LOE protection zone (Y/N)	Maximum duration time
RX (directional)	N	-
RX	N	-
GB	N	-
PQ	Y	0.0045 s
UI	N	-

Simulation results of Scenario 2

For Scenario 2, the generator operates at lagging power factor before the fault and no characteristic curve enters the LOE protection zone during single phase-to-ground fault.

7. Closure

7.1. Discussion

7.1.1 LOE results comparison

The simulation results of loss of excitation are listed in Table 7.1:

Legend
Slow
Medium
Fast

Table 7.1: LOE simulation results comparison

Case		RX	RX directional	GB	PQ	UI	Out of step
Case 1: 80% load	Alarm signal	5.81s	2.9s	4.76s	4.03s	3.97s	7.13 s
	Trip signal	6.31s	5.42s	6.72s	4.73s	5.47s	
Case 1: 40% load	Alarm signal	7.89s	2.1s	9.73s	4.8s	6.43s	18.08 s
	Trip signal	8.39s	7.93s	10.73s	8.05s	7.93s	
Case 2: 80% load	Alarm signal	8.57s	4.19s	7.03s	5.68s	5.74s	10.43 s
	Trip signal	9.07s	7.12s	9.38s	6. 35s	7.24s	
Case 2: 40% load	Alarm signal	33.78s	3.35s	55.01s	11.8s	21.6s	-
	Trip signal	34.28s	24.5s	56.01s	30.63s	23.1s	
Case 3: Condenser	Alarm signal	11.38s	3.05s	-	2.94s	-	-
	Trip signal	11.88s	11.42s	-	9.2s	-	

From the simulation results, we can see that R-X scheme and G-B schemes need longer time than to send the trip signals than other schemes. In addition, during condenser operation, G-B and U-I schemes cannot detect loss of excitation fault. Considering the detection speed and reliability, R-X with directional element scheme and P-Q scheme are recommended for loss of excitation protection.

7.1.2 External faults results comparison

The simulation results of external faults are listed in Table 7.2:

Stable
Not stable

Table 7.2: LOE protection schemes comparison during external faults

External fault	Case 1: Busbar ABC fault				Case 2:Generator terminal ABC-G fault				Case 3 :Busbar AB fault		Case 4: Busbar A-G fault	
	p.f. 0.95 leading		p.f. 0.9 lagging		p.f. 0.95 leading		p.f. 0.9 lagging		p.f. 0.95 leading	p.f. 0.9 lagging	p.f. 0.95 leading	p.f. 0.9 lagging
	100ms	150ms	100ms	150ms	100ms	150ms	100ms	150ms	100ms	100ms	100ms	100ms
RX(directional)	Y	Y	N	N	N	N	N	N	Y	N	N	N
RX	N	N	N	N	N	N	N	N	N	N	N	N
GB	N	Y	N	N	Y	Y	Y	Y	N	N	N	N
PQ	Y	Y	N	N	N	N	N	N	Y	N	Y	N
UI	Y	Y	N	N	Y	Y	Y	Y	Y	N	N	N

During external faults, R-X scheme, R-X with directional element scheme and P-Q scheme are more stable than G-B scheme and U-I scheme. R-X scheme is the most stable one in all external fault cases, as the protection zone of R-X scheme is the smallest one and it takes longer time to detect the LOE.

From the simulation results, the characteristic curve may enter the LOE protection zone and cause LOE relay mal-operation during external faults. So the LOE protection relay should have enough time delay to override the external faults, e.g. 0.3s-0.5s.

7.2. Conclusion

For LOE fault, all schemes can detect it and initiate a tripping signal to the main breaker. However, G-B scheme and U-I scheme cannot detect LOE during condenser operation mode. During external faults, R-X scheme and R-X with directional element scheme behave more stable than other schemes.

Considering all the cases, R-X with directional element scheme is recommended for the LOE protection, as it can detect the LOE much faster and behaves more stable during external faults. Although during some cases, the characteristic curve may enter the protection zone. But with enough time delay, the LOE protection shall be able to override external faults without mal-operation.

8. Reference

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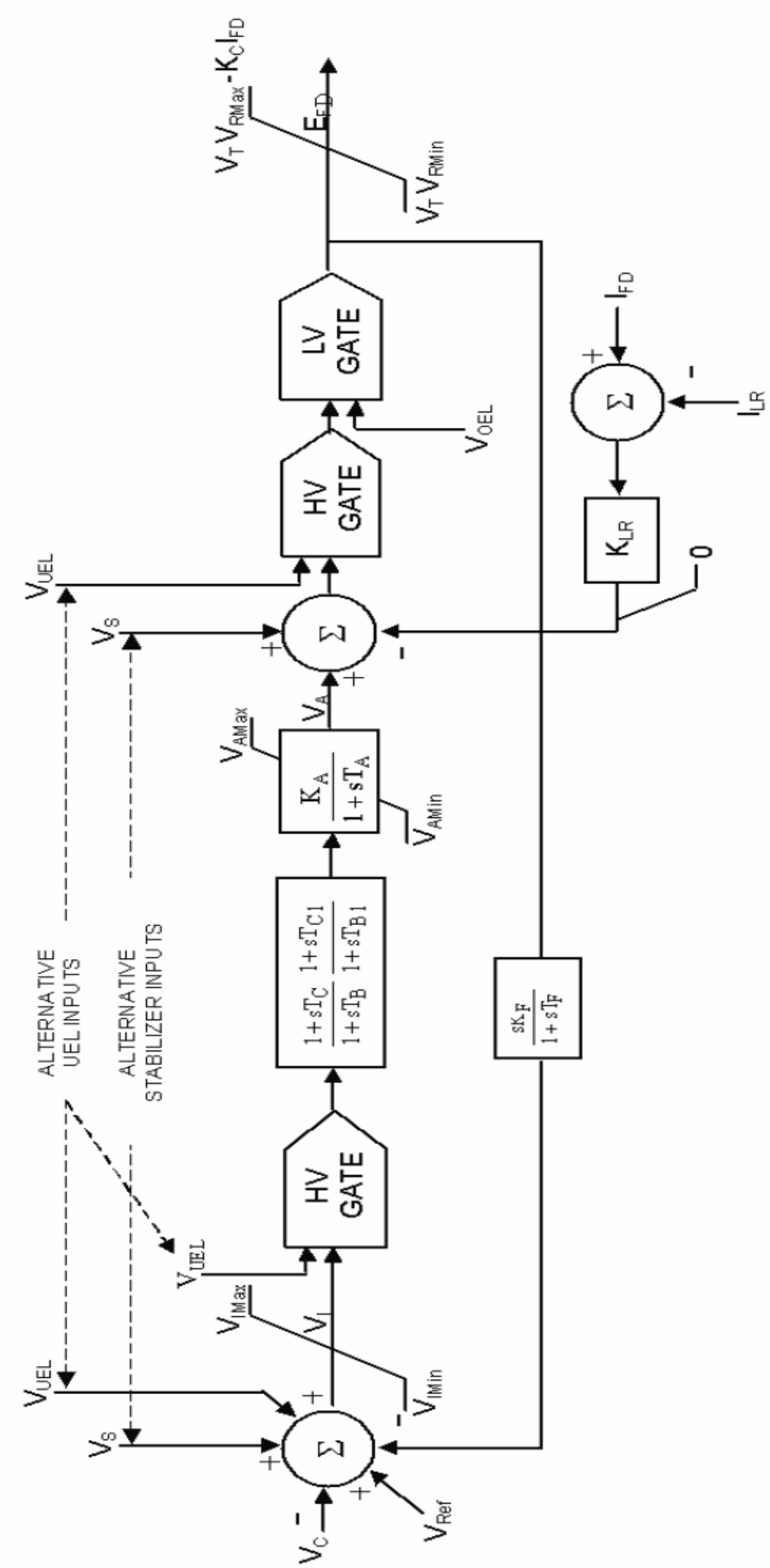
Appendix A

System data	
Positive sequence equivalent impedance	**0.0068+j0.096 p.u. (230kV, 100 MVA)**
System voltage	**230 kV, L-L, RMS**
System frequency	**60 Hz**
Generator data	
Rated MVA	**406 MVA**
Rated voltage	**20 kV**
Rated power factor	**0.9 lagging**
Rated speed	**225 r.p.m.**
Xd	**1.746 p.u.**
Xq	**1.138 p.u.**
X’d	**0.44 p.u.**
X’q	**0.35 p.u.**
T’do	**11 second**
Inertia H	**4.226 p.u.**
Transformer data	
Rated MVA	**450 MVA**
Rated voltage	**20/230 kV**
Z%	**10%**
Connection mode	**DY11**
ST1A Exciter	
AVR gain	**360 p.u.**
AVR time constant	**0.01s**
PSS2B	
Stabilizer gain	**6**
Phase lead time constant	**0.1s**
Phase lag time constant	**0.02s**

Appendix B

Type ST1A—Potential-source, controlled-rectifier exciter [15]



Appendix C

Type PSS2B—Dual Input [15]