Module 6 : Distance Protection

Lecture 21 : Introduction to Distance Relaying

Objectives

In this lecture we will

- Introduce distance protection.
- Discuss advantages of distance protection.
- Fault modeling of balanced transmission line for 3 phase faults, L-L fault.
- Show that ground fault relays require different configuration.

21.1 Introduction

Overcurrent protection scheme is essentially a simple protection scheme. Consequently, its accuracy is not very high. It is comparatively cheap as non-directional protection does not require VT. However, it is not suitable for protection of meshed transmission systems where selectivity and sensitivity requirements are more stringent. Overcurrent protection is also not a feasible option, if fault current and load currents are comparable. We now discuss about distance protection scheme which provides both 'higher' sensitivity and selectivity.

Distance protection provides the following features:

- More accurate as more information is used for taking decision.
- Directional, i.e. it responds to the phase angle of current with respect to voltage phasor.
- Fast and accurate.
- Back-up protection.
- Primarily used in transmission line protection. Also it can be applied to generator backup, loss of field and transformer

  backup protection.

21.2 Phase Fault Protection

21.2.1 Three Phase Fault Protection

Consider a balanced (transposed) transmission line (fig 21.1)

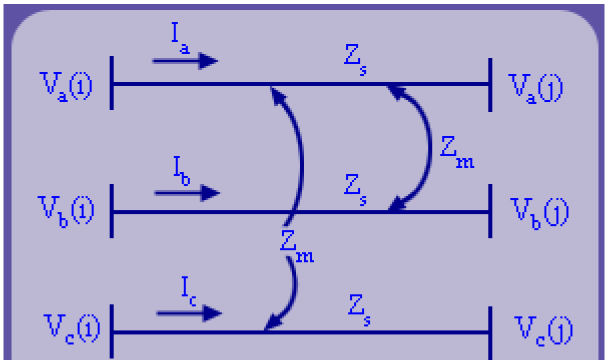

Fig 21.1 A Balanced Transmission System

$$\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (1)$$

Let T = $\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$ (sequence transformation matrix) (2)

Then, $\left[\Delta V^{abc}\right] = [T]\left[\Delta V^{012}\right]$ (3)

Similarly, $\left[I^{abc}\right] = [T]\left[I^{012}\right]$ (4)

Applying sequence transformation matrix,

$$\left[\Delta V^{012}\right] = T^{-1}\left[Z^{abc}\right]T\left[I^{012}\right]$$

$$\left[\Delta V^{012}\right] = diag\left(Z_0, Z_1, Z_2\right)\left[I^{012}\right]$$

21.2 Phase Fault Protection (contd..)

21.2.1 Three Phase Fault Protection (contd..)

Where $Z_0 = Z_s + 2Z_m$; [zero sequence impedance]
$Z_1 = Z_s - Z_m$; [positive sequence impedance]
$Z_2 = Z_s - Z_m$; [negative sequence impedance]

Thus, $\Delta V_0 = Z_0 I_0$;

$\Delta V_1 = Z_1 I_1$;

$\Delta V_2 = Z_2 I_2$;

Now let a $3-\phi$ bolted fault occur at percentage (%) distance, x of the line (fig 21.2)

Then the fault model is given by

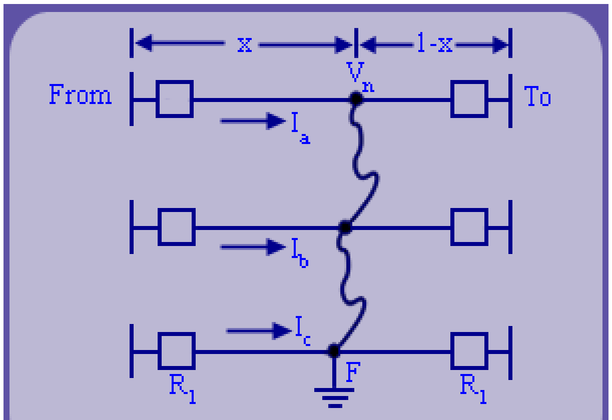

Fig 21.2 Three Phase Fault

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} V_n = x \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

For a solid $3-\phi$ fault, $V_n = 0$. Thus,

$$\left[V^{abc}\right] = x\left[Z^{abc}\right]\left[I^{abc}\right]$$

21.2 Phase Fault Protection (contd..)

21.2.1Three Phase Fault Protection (contd..)

In the sequence domain

$$\left[V^{012}\right] = x\,diag\left(Z_0, Z_1, Z_2\right)\left[I^{012}\right]$$

For a 3-phase fault,
$I_b = a^2 I_a$
$I_c = aI_a$
From equation (4), we get
$I_0 = 0$; $I_1 = I_a$; $I_2 = 0$;
So only positive sequence network is excited. Hence,

$$\frac{V_1}{I_1} = xZ_1 \qquad (5)$$

By using equation (5), we can locate the $3-\phi$ fault on a transmission line. Also, for the case of $3-\phi$ fault, it can be easily verified that,

$$\frac{V_a}{I_a} = \frac{V_b}{I_b} = \frac{V_c}{I_c} = \frac{V_1}{I_1} = xZ_1 \qquad (6)$$

It then follows that, a relay which monitor line current and phase voltages can locate $3-\phi$ fault by using equation (6). In the absence of fault currents I_a, I_b and I_c are smaller in magnitude. Consequently, apparent impedance seen by the relay is much higher. Hence, a simple logic to locate $3-\phi$ fault is provided by equation (6).

It can be easily seen that for a $3-\phi$ fault, equation (6) is equivalent to the following equation.

$$\frac{V_a - V_b}{I_a - I_b} = \frac{V_b - V_c}{I_b - I_c} = \frac{V_c - V_a}{I_c - I_a} = xZ_1 \qquad (7)$$

[Hint: Substitute $I_b = a^2 I_a$, $V_b = a^2 V_a$, $I_c = aI_a$, $V_c = a V_a$]

Notice that, if equation (7) is used for locating fault, then the relay input voltage is the line voltage and not the phase voltage. Similarly, current input is the difference of line currents and not actual line currents. Thus, equation (7) provides an alternate way of locating $3-\phi$ fault. Note that per unit distance to fault is given by ratio of apparent impedance seen by the relay to the positive sequence impedance of the line.

21.2 Phase Fault Protection (contd..)

21.2.2Line to Line Fault Protection

Consider a bolted L-L fault on the phase b-c of the system (fig 21.3).

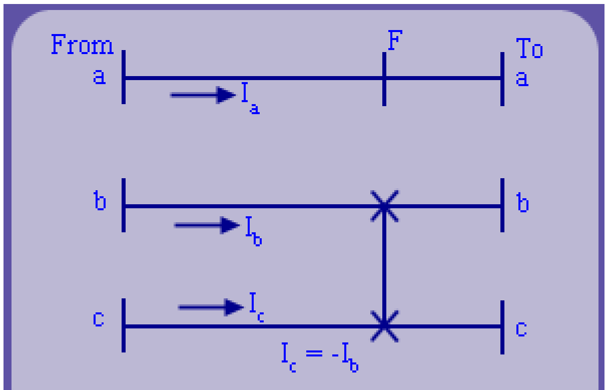

Fig 21.3 Bolted b - c Phase Fault

Again, system is considered unloaded for simplicity. Then the governing equations in 3-phase coordinates given by

$$\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = x \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} \qquad (8)$$

where

$$\Delta V_a = V_a - V_f^a$$

$$\Delta V_b = V_b - V_f^b$$

$$\Delta V_c = V_c - V_f^c$$

Further

$$V_f^b = V_f^c = V$$

21.2 Phase Fault Protection (contd..)

21.2.2Line to Line Fault Protection (contd..)

Simplifying equation (8), we get

$$\Delta V_a = 0 \qquad (9)$$

$$\Delta V_b = x(Z_s - Z_m)(I_b) = xZ_1 I_b \qquad (10)$$

$$\Delta V_c = -x(Z_s - Z_m)(I_b) = -xZ_1 I_b = xZ_1 I_c \qquad (11)$$

Now, subtract equation (11) from equation (10)

$$V_b - V_c = \Delta V_b - \Delta V_c = xZ_1(I_b - I_c)$$

$$\frac{V_b - V_c}{I_b - I_c} = xZ_1 \qquad (12)$$

From equation (7) and (12) we conclude that a relay input configured as per equation (7) can measure both 3-phase fault and L-L fault.

Similarly, for a-c L-L fault

$$\frac{V_c - V_a}{I_c - I_a} = xZ_1$$

And for a-b L-L fault

$$\frac{V_a - V_b}{I_a - I_b} = xZ_1$$

Therefore, traditionally the distance relays are configured as per equation (7) to detect and locate both L-L and 3-phase faults. Therefore, distance to fault is given by $x = \frac{Z_{app}}{Z_1} \times l$

where, l is length of line and Z_{app} is the impedance seen by the relay.
This is the fundamental principle of distance relaying.

21.3 Earth Fault Protection

21.3.1 Single Line to Ground Fault

We now derive the governing equation for S-L-G fault case. Consider a single line to ground fault in phase 'a' on a unloaded transmission line at a per unit distance x. (fig 21.4)

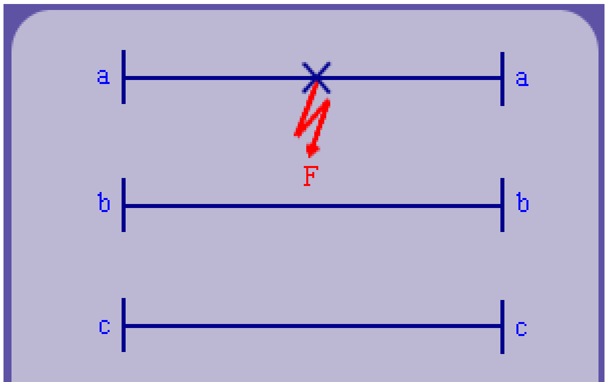

Fig 21.4 Bolted S-L-G Fault

Then 3-phase model is given by

$$\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = x \begin{bmatrix} Z_s\, Z_m\, Z_m \\ Z_m\, Z_s\, Z_m \\ Z_m\, Z_m\, Z_s \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix}$$

Then governing equation is given by

$$\Delta V_a = V_a - V_f = V_a - 0 = V_a$$

$$V_a = xZ_s I_a \qquad (13)$$

Thus, ratio $\frac{V_a}{I_a}$ equals xZ_s and not xZ_1. A fundamental requirement of distance relaying is that the relay input voltages and currents have to be configured in such a way that for any type of bolted fault (Z_f = 0), the apparent impedance seen by relay is given by xZ_1. Therefore, it follows that we should modify equation (13) suitably.

$$V_a = xZ_s I_a$$

$$V_a = x\left(Z_s - Z_m + Z_m\right) I_a$$

$$V_a = x\left[Z_1 + Z_m\right] I_a \qquad (14)$$

$$= xZ_1\left[1+\left(\frac{Z_m}{Z_1}\right)\right]I_a$$

21.3 Earth Fault Protection (contd..)

21.3.1 Single Line to Ground Fault (contd..)

$$\frac{V_a}{I_a+\left(\frac{Z_m}{Z_1}\right)I_a} = xZ_1 \qquad (15)$$

Now, $Z_0 = Z_s + 2Z_m$

$Z_1 = Z_s - Z_m$

Hence, $Z_m = \left(\frac{Z_0 - Z_1}{3}\right)$ (16)

Substituting in equation (15) we get,

$$\left(\frac{V_a}{I_a+\left(\frac{Z_0-Z_1}{Z_1}\right)\times\frac{I_a}{3}}\right) = xZ_1 \qquad (17)$$

Since $I_0 = \frac{I_a}{3}$, let $m = \frac{Z_0 - Z_1}{Z_1}$

equation (17) can be written as

$$\frac{V_a}{I_a + mI_0} = xZ_1 \qquad (18)$$

21.3 Earth Fault Protection (contd..)

21.3.1 Single Line to Ground Fault (contd..)

where *m* is called compensation factor for zero sequence current. Similarly, it can be shown for b-g and c-g faults.

$$\frac{V_b}{I_b + mI_0} = xZ_1 \qquad (19)$$

and

$$\frac{V_c}{I_c + mI_0} = xZ_1 \qquad (20)$$

It is clear that traditionally the ground fault relays require a different input configuration from phase fault relays (3-phase and L-L)

21.4 Overall Distance Protection Scheme

A L-L-G fault can also be detected by the S-L-G relay equations. There are 10 types of shunt faults against which a system has to be protected. They are:

1.	3-phase fault	1
2.	L-L faults	3
3.	S-L-G faults	3
4.	L-L-G faults	3

The relaying units configured by equation (7) and (18,19,20) do this job satisfactorily.

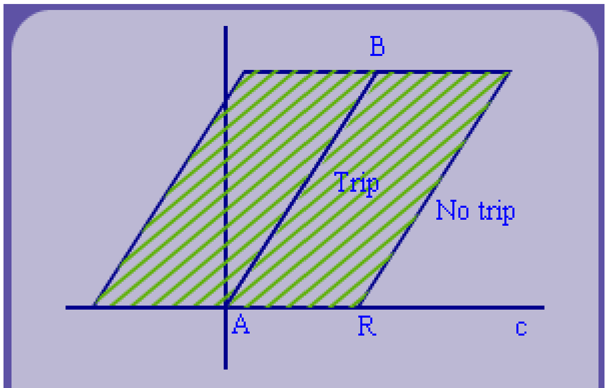

Fig 21.5 Quadrilateral Characteristic

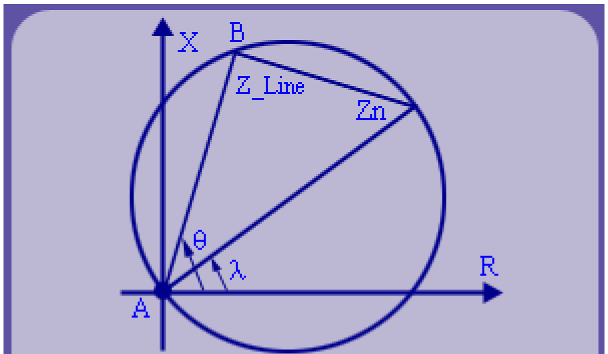

Fig 21.6 Mho Relay

We had so far assumed bolted and unloaded faults. Therefore, there would be errors introduced when the fault has some impedance Z_f. Hence, the apparent impedance seen by the relay will not exactly lie on transmission line impedance AB. Rather it would lie in a region shown by trapezoid in fig 21.5. Also, note that arcing faults are primarily resistive in nature.

Usually, distance relay characteristics are visualized by drawing the relay characteristics in R-X plane. If the apparent impedance seen by the relay falls inside the trip region (enclosed region), then relay declares a fault and issues a trip decision. This decision making can be done in about 1/2 - 1 cycle time, if no intentional time delays are introduced, e.g, for backup protection.

While trapezoid or quadrilateral characteristics are quite popular with the numerical relays, previous generation of electromechanical and solid state relays used other characteristics like 'mho' characteristics (see fig 21.6), which were easier to derive. Mho relay circles usually enclosed a larger area than the quadrilateral characteristics for identical line impedance and arcing impedance parameters. Thus, they are more susceptible to nuisance tripping. Hence, these characteristics have been superceded by the trapezoidal characteristics.

Review Questions

1. What are the advantages of distance relays over overcurrent relays?
2. Show that for a bolted fault per unit distance to a fault in a transmission is the ratio of apparent impedance seen by the relay to the positive sequence impedance of line.
3. Derive an equation for locating a-b fault in a transmission line.
4. Why does the distance ground fault relay require a different configuration?

Recap

In this lecture we have learnt the following:

- The advantages of distance protection.
- To derive an equation to locate 3ϕ and L-L fault in a transmission line.
- Distance relays can be used for protecting the system from all kinds of fault.