Transmission Lines and Feeders Protection

- Pilot wire differential relays (Device 87L)
- Distance protection
1. **Pilot wire differential relays (Device 87L)**

The pilot wire differential relay is a high-speed relay designed for protection of transmission and distribution lines. They are generally applied on short lines, normally less than 40 km long.

The scheme requires communication channel (link) to carry system voltage and current information to the control location. The main objective of using pilot relaying is to remote control of the circuit breakers.

Four basic communication channels are used:

1. Separate telephone circuit (telephone wire or cable) this is called pilot wire carrier.
2. Microwave system using directional dishes.
3. Fibre optic cable.
4. Power line carrier.

(a) Operating principles of a current pilot wire relay

Pilot wire differential relaying is a relay system consisting of two identical relays located at each end of a line (see Figure 1). The relays are connected together with a two-conductor pilot wire. The output from three individual phase CTs is applied to a summing transformer that produces a composite current which is proportional to the line current and has a polarity related to line current flow direction.

The circuit is basically that of the percentage (restraint) differential relay with the operating circuit broken into parallel circuits separated by pilot wires. This relay is available in both electromechanical and static designs.

- When the fault is external to the relay’s protective zone, current flows in the pilot wire through each relay’s restraint coils, but not through the relay’s operating coil.
- If the fault is within the relay’s protective zone and current is flowing into the fault from both directions, the direction of pilot wire current $I_{PA}$ remains the same; but the direction of current $I_{PB}$ reverses and forces current to flow into each relay’s operating coil. If the fault current flows through circuit breaker $A$ only, the relay at $A$ still passes sufficient current through the pilot wire to operate the relay at circuit breaker $B$. 

- Summing transformer is used to convert current signal to voltage signal.
- For faults outside the line from both sides at F\textsubscript{1} and F\textsubscript{3}, VA = VB, relay will not operate.
- For fault inside the line at F\textsubscript{2}, relay will operate, since VA ≠ VB.
- The pilot wire signal is about 30V ac at 50 Hz or 20V ac at 60 Hz.

![Diagram of pilot relaying of short transmission line](image)

**Fig.1 Pilot relaying of short transmission line. R=voltage restrain coil; O= current operating coil.**

**(b) Power Line Carrier (PLC)**

In power line carrier protection scheme, a high frequency signal in the band of 80-500 kHz and of low power lever is transmitted via the power line conductors from each end of the transmission to the other.

Signal is received by either end of the line by a receiver R to give tripping or blocking orders to the circuit breaker. The system is shown in Fig.2.

- The high frequency is injected to the power line by a coupling capacitor.
- The signals are confined to the line by an LC blocking filter at each end. This is called a line trap. Line trap is shown in Fig.3.
- This means that the power transmission line is used as the communication channel (circuit).
Fig. 2 Power line carrier system.

Fig. 3 A 500kV Line Trap.
2. Transmission Line Protection: Distance Relay

Transmission line protection by pilot wires (pilot relaying) is limited to 30 to 40 km in route length. For longer transmission lines and subtransmission lines or even distribution feeders, distance protection is used.

Principle of Distance Protection

The term *distance* is used for a family of relays that respond to a ratio of voltage to current and therefore to impedance or component of impedance. Distance relay may have the following features:

- A distance relay has the ability to detect a fault within a pre-set distance along a transmission line from its location.

- Every power line has a resistance and reactive per kilometer related to its design and construction so its total impedance will be a function of its length or distance.

- A distance relay therefore looks at current and voltage and compares these two quantities on the basis of Ohm’s law (see Figure 1).

Consider the simple radial line with distance protection system installed at the end A (the local end) while end B is called the remote end. These relays sense local voltage and current and calculate the effective impedance at that point. This means that the relay requires voltage and current information.

![Fig.1](image-url)
When the protected line becomes faulted, the effective impedance becomes the impedance from that point to the fault.

Assume balanced three-phase fault at distance d:

- For internal fault at point $p$ :
  \[ Z_p = \frac{V_p}{I} < Z_L \quad \text{Relay will operate} \]

- For external fault at point $k$ :
  \[ Z_p = \frac{V_k}{I} > Z_L \quad \text{Relay will not operate} \]

In general the relay will trip when $Z_f = \frac{V}{I} < Z_L$ where $Z_f$ is the impedance at the fault point which is \( \propto \) line length. For example at point $p$: $Z_{fp} = \frac{d}{L} Z_L$.

Hence the distance relay action is to compare the local voltage with the local current, i.e. the secondary values of $V$ and $I$ in the voltage and current transformers so as the quantity \( \frac{V}{I} \) …is the measured impedance $Z_m$ where,

\[
Z_m = \frac{V}{I} = \frac{V}{I} \times \frac{CT \text{ ratio}}{VT \text{ ratio}} = Z_f \times \frac{CT \text{ ratio}}{VT \text{ ratio}}
\]

Where $Z_m$ is the measured impedance (appears at the relay terminal) also called the secondary impedance.

and $Z_f$ is the also called the primary impedance.

**Types of Distance Relays**

In general there are four main types of distance relays

- Impedance relay (Ohms relay)
- Admittance relay (Mho relay)
- Reactance relay
- Offset Mho relay

- Impedance relay can also be of two types: a plain relay or directional type. It can be constructed as electromagnetic like the balanced beam relay or static type like the bridge comparator relay. Also digital impedance relay is available.

- Admittance relay can be either static or digital types.
Plain impedance relays:

1 - Balanced beam relay

- The concept can best be appreciated by looking at the pioneer-type balanced beam relay (see Figure 2). The voltage is fed onto one coil to provide restraining torque $T_r$, whilst the current is fed to the other coil to provide the operating torque $T_o$.
- Under healthy conditions, the voltage will be high (i.e. at full-rated level), whilst the current will be low (at normal load value), thereby balancing the beam, and restraining it so that the contacts remain open.
- Under fault conditions, the voltage collapses and the current increase dramatically, causing the beam to unbalance and close the contacts.

![Fig.2 Balanced beam relay used as a distance relay.](image)

For voltage coil : $T_r = K_1 V^2$

For current coil : $T_o = K_2 I^2$

Where $K_1$ and $K_2$ are constants.

For balance case: $T_r = T_o$ or $K_1 V^2 = K_2 I^2$

For the contact of relay to close: $T_r < T_o$ or $K_1 V^2 < K_2 I^2$

$$\frac{V^2}{I^2} = \frac{K_2}{K_1} \quad \frac{V}{I} < \sqrt[2]{\frac{K_2}{K_1}} \quad \text{or} \quad Z < \sqrt[2]{\frac{K_2}{K_1}}$$

Hence, the relay will operate when the impedance it ‘sees’ is less than a predetermined value.
Tripping characteristics of distance relay

If the relay’s operating boundary is plotted, on an $R$-$X$ diagram, its impedance characteristic is a circle with its center at the origin of the coordinates and its radius will be the setting in ohms (Figure 3).

The relay will operate for all values less than its setting i.e. is for all points within the circle. This is known as a plain impedance relay and it will be noted that it is non-directional, in that it can operate for faults behind the relaying point. It takes no account of the phase angle between voltage and current.

![Fig.3 Plain impedance characteristic.](image)

2. Bridge comparator static impedance type distance relay

A more modern technique for achieving the same result is to use a bridge comparator distance relay (see Figure 4).

Referring to Fig.4:

- VT output is converted to a current $I_R$ which is the restrain current due to $Z_R$.
- CT provide the operating current $I_o$.
- $I_R$ and $I_o$ are converted to scalar values by two rectifiers, and the relay current is the numerical difference of the two currents.
- If the current through the relay is greater than the setting current, it will cause the relay to close the contacts (operates).
- If at the remote point B, the restrain current is approximately equal to the operating current, the relay will not operate.
- During an internal fault (0 – 80% in Zone 1), the relay current should be several times the setting current to ensure its fast operation, the operation should be within 60 ms time.

**Fig.4** Bridge comparator in modern distance relay.

**Notes:**
- The impedance relay does not consider the phase angle between the voltage and current applied to it.
- The relay operates for all impedance values that are less than its setting (all the values inside the circle shown in Fig.3).
- It restrain for all values (points) outside the circle.
**Relay Reach, underreach and overreach**

The reach of the distance relay is that distance from the relaying point to the point of fault. The reach is usually referred to as the relay setting and can be as a distance (m), or as a primary or secondary impedance.

**Relay reach adjustment**

Referred to Fig.2, by changing the ampere-turns relationship of the current coil to the voltage coil, the ohmic reach of the balanced - beam relay can be adjusted. A more modern technique for achieving the same result is to use a bridge comparator (see Figure 4).

**Advantage of distance relay:**

1. Provide backup protection easily.
2. Eliminates the pilot channel.

**Features**

- Distance protection is available for both phase and ground faults.
- Step distance protection combines instantaneous and time delay tripping.

**Zones of protection**

- Due to the tolerance in the circuit components, the measuring accuracy cannot be perfect so it is usual to set the relay at the local point A at 80% of the secondary impedance of AB. This is referred as zone 1 or stage A1 setting (see figure 5).
- The remaining 20% of AB is protected by changing the setting of the relay to reach 50% into zone BC (zone 2 or stage A2). Stage A2 is usually set at 0.3 s time.
- For system reliability (failure of relay A will cause failure of stage A1 and stage A2), another distance relay is added for backup protection. This separate relay should have a reach of 20% into CD and called zone 3 or stage A3 which has a time delay of 0.6 s.
Fig. 5 A three-sage distance protection system.

**Notes:**

- Zone 1 is an underreaching element, any fault within Zone 1 is known to be on the protected line. When Zone 1 operates, the line is tripped instantaneously.
- Zone 2, however, will operate for some external faults.

**Summary:**

**Discrimination zone (or setting zone) by:**

\[
\begin{align*}
Z_1^\text{protection} & : (0.80\% - 0.85\%) \\
Z_2^\text{protection} & : (120\% - 150\%) \\
Z_3^\text{protection} & : (200\% - 250\%)
\end{align*}
\]
Example 1: For the 66kV radial feeder shown in Fig.6, Calculate zone 1 setting for the distance relay in primary ohms.

![Diagram of 66kV Line](image)

\[ z_L = 0.24 + j0.80 \text{ Ohms/km} \]
\[ L = 15 \text{ km} \]
\[ Z_L = (0.24 + j0.8) \cdot 15 = 3.6 + j12 \text{ Ohms (primary)} \]

Zone 1
Relay setting: \[ Zr1 = (0.8) \cdot |3.6 + j12| = 10.02 \text{ Ohms} \]

Fig.6

Example 2:

Figure 7 shows a simple two radial lines. We will consider the settings for line \( AB \) at bus \( B \). The impedance angle for each line is 75°. The line length is 80 km, the distance relay at bus \( A \) is fed by current transformers rated at 2000 A: 5 A and voltage transformers rated at 345 kV/200 kV Y: 120 V/69 V Y. Find the settings of zone 1 and zone 2 of the relays.

Solution

Set Zone 1 for 85%:

Zone 1 setting = 0.85 \times 80 = 68 \text{ ohm, primary ohm setting (} Z_{fp} \text{)}

CT ratio = 2000/5 = 400

VT ratio = 200,000/69 = 2900

Relay setting for zone 1 = \( Z_{fp} \cdot \frac{\text{CT ratio}}{\text{VT ratio}} \)

= 68 \times \frac{400}{2900}

= 9.38 \text{ relay ohms}
Fig. 7

Zone 2 setting: 120% - 150%. Choose 140%.

Zone 2 setting = 1.40 \times 80 = 112 \ \text{ohm}, \text{primary ohm setting} (Z_{fp})

Relay setting for zone 2 = Z_{fp} \cdot \text{CT ratio/VT ratio}

= 112 \ (400)/(2900)

= 15.44 \text{ relay ohms}

Example-3 Consider the 230-kV transmission system shown in Fig.8. Assume that the positive-sequence impedances of the lines L1 and L2 are \(2 + j \ 20 \ \Omega\) and \(2.5 + j \ 25 \ \Omega\), respectively. If the maximum peak load supplied by the line L1 is 100 MVA with a lagging power factor of 0.9, design a three-zone distance-relaying system for the R12 impedance relay by determining the following:

(a) Maximum load current

(b) CT ratio and VT ratio

(c) Impedances measured by relay

(d) Zone 1 setting of relay R12

(e) Zone 2 setting of relay R12

(f) Zone 3 setting of relay R12

(g) Draw the zones of protection for R12 and suggest time settings for the three zones.
Solution:

(a) Max. load current \( = \frac{S}{\sqrt{3}} = \frac{100 \times 10^6}{230 \times 10^3 \sqrt{3}} = 251.02 \text{ A} \)

(b) Choose: CT ratio = \( \frac{250}{5} \)  

VT ratio = \( \frac{230 \times 10^2}{120} = \frac{1916.7}{1} \)

(c) Impedances measured by relay is  

\[ Z_{sec} = Z_{prim} \times \frac{CT \text{ ratio}}{VT \text{ ratio}} = \frac{250/5}{1916.7/1} \]

\[ Z_{prim} = 0.026 Z_{line} \]

Impedance of line L1 and line L2 as seen by the relay (Line impedances based on secondary ohms) are:

\[ Z_{sec - L1} = 0.026 \times (2+j20) = 0.52 + j 0.5196 \Omega \]

\[ Z_{sec - L2} = 0.026 \times (2.5+j25) = 0.65 + j 0.6495 \Omega \]

(d) Zone 1 setting of relay \( R_{12} \) is

\[ Z1 = 0.8 \times (0.52 + j 0.5196) = 0.416 + j 0.4157 \text{ sec. } \Omega \]

(e) Zone 2 setting of relay \( R_{12} \) is

Z2 setting is = 120% - 150% , Choose 140%  

\[ Z2 = 1.4 \times (0.52 + j 0.5196) = 0.728 + j 0.727 \text{ sec. } \Omega \]

(f) Zone 3 setting of relay \( R_{12} \): Since the zone 3 setting must reach beyond the longest line connected to bus 2, thus

\[ Z3 = 120\% \times (Z_{sec - L1} + Z_{sec - L2}) = 1.20 \times (0.52 + j 0.5196 + 0.65 + j 0.6495) = 0.1400 + j 1.402 \text{ sec. } \Omega \]
(g) Draw the zones of protection for R12 and suggest time settings for the three zones.

Is the distance relay of plain impedance type is directional?

The impedance relay is non-directional that is, it operates for all faults along the vector AB in Fig.10 such as point p and also for all faults behind the bus A up to impedance AC such as point k.

A directional unit may be added to the plain impedance distance relay to make it operate in one direction only as depicted in Fig.11.
Fig. 11 Typical per-phase arrangement for a three – zone distance relay with directional unit. The directional unit may be a wattmetric relay.