POWER SYSTEMS PROTECTION
COURSE

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2016-2017
Part 7
Transmission and distribution
Lines protection
Introduction:

- Transmission lines are exposed to short circuits between phases or from phase to ground.
- Transmission and distribution lines protection problem concern’s to the fault current range, effect of load, directionality, and system configuration impact.
- Line Classification:
  - Distribution: 33 kV and lower
  - Sub transmission: 33 - 132 kV
  - Transmission: 132 kV and higher
  - HV: 132 - 220 kV
  - EHV: 400 - 750 kV
  - UHV: 1000 kV and higher
Transmission Line Protection Principles:
For distribution and transmission lines. There are four types of protection principles used:-

1. **Overcurrent** (instantaneous overcurrent and inverse, time delay, overcurrent) (50, 51, 50N, 51N)

2. **Directional Overcurrent** (67, 67N)

3. **Distance** (21, 21N)

4. **Differential** (pilot) (87)

1- **Overcurrent protection:**
- Its simplest and chipper principle.
- Is used in radial lines.
- In looped lines (ring) may be used with addition of directionality overcurrent.
- Widely use in distribution and industrial systems.
- Distance protection also is added In order to increase the speed operation of OC pilot protection is used.
Finally, we may apply the differential principle to transmission lines over a communications channel.

- **Protection of Radial System by Overcurrent Relay:**

Consider a case of a radial line supplying three substation as shown in Fig.1:

Fig.1

a. Under fault conditions only the breakers closest to the fault are tripped.

b. If the closest breaker fails to operate, the next breaker closer trip (backup relay).
The relay operations must be coordinated with respect to each other in order to provide the desired selectivity. This is called "relay coordination".

There are three methods to relay coordination:

1. Discrimination by time (Time-grading).
2. Discrimination by current (Current-grading).
3. Discrimination by both time and current (Time-Current grading).

All three methods are to give correct discrimination by isolate faulty section only, leaving the rest in operation.

- **Time-grading** (Discrimination by time)

  In this method, time setting is given to each of the relays to ensure that the breaker nearest to the fault opens first. Overcurrent relay with definite time characteristic are used.
Consider the following radial power system shown in Figure 1

![Radial Power System Diagram]

Fig. 1

if the time considered to be:
R1 = 1.0 sec.
R2 = 0.50 sec.
R3 = 0.25 sec

Then the relay settings are shown graphically in Figs. 2

![Graphical Representation]

Fig 2
The fault current can be calculated as:

a) Three-Phase Fault on a Radial Line

Not that for a perfect three-phase fault, **only the positive-sequence impedance is involved in the calculations**, the positive-sequence of voltage and current are equal (since $Z^+$) to the phase voltage and current "a".

Consider the following three phase faulted system in figure at distance (d)

The Impedance Diagram of positive-sequence for a three-phase fault of this system is shown in the net slide
Where:

- $I_1 =$ positive sequences current.
- $V_1 =$ positive sequences voltage.
- $L =$ total length of feeder.
- $d =$ fault location to protection location.
- $Z_L =$ line impedances.
- $Z_{s1} =$ System’s Thevenin Equivalent Impedance.

The fault current in each phase is balanced and is equal to the phase current measured by the relays at the substation. This current depends on the parameters shown above ($I^+, V^+, L, d, Z_L, Z_{s1}$).

The Thevenin impedance depends on the conditions of the system such as, the topology and system loading.
- **Current-grading** (Discrimination by current).
  - This method is used only in LV systems due to its disadvantages in HV systems.
  - Since the impedance values differing between the source and fault location then the fault current value also varies from point to point.
  - The relays controlled with various current settings, in order to operate only nearest to the fault location and trips its breaker.

- **Time-Current grading** (Discrimination by both time and current).
  - In this case the **Inverse, time-delay overcurrent relays** is used.

For protection of transmission line with multiple sections as shown in Fig.
The coordination between the relays for fault at F graphical is shown.

Relay coordination principle.

1. American school of coordination:

**Coordination delay time (CDT) between 2 relay in American standard. is 0.4 seconds.**

(This comes from interruption time of the circuit breaker = 0.1 s, or 6 cycles in 60 Hz system) and error margin of 0.3 s.)
The **current tap setting** CTS from experience are:

\[
\begin{align*}
\text{CTS} & \leq \frac{1}{3} \times \text{Minimum fault current} \\
\text{CTS} & \geq 2 \times \text{Maximum load current}
\end{align*}
\]

This tells us for minim. we multiply by 1/3 and for max. multiply by 2.

And the time delay sitting (TDS) is selected at least 0.4 second as coordination time delay (CDT) in American standard.

**Example**

For the 13.8 kV feeding system shown in Fig.1, with reactances are given in pu.
And the system data is given in Table 1 for 3 relays:

<table>
<thead>
<tr>
<th>Bus</th>
<th>S in MVA</th>
<th>P.F (lag)</th>
<th>Breaker</th>
<th>CT ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.5</td>
<td>0.8</td>
<td>B1</td>
<td>800/5</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.8</td>
<td>B2</td>
<td>400/5</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0.8</td>
<td>B3</td>
<td>400/5</td>
</tr>
</tbody>
</table>

Consider 3-phase faults with short circuit 10 MVA. Use the overcurrent relay CO7 whose characteristic is given in Fig.2. to determine the satisfactory relay settings.
Fig 2

Typical time curves
Type CO-7
over current relay
50–60 cycles

Current tap settings:
4, 5, 6, 7, 8, 10, 12 amperes

Operating time in seconds

Current as a multiple or tap setting

Dr. Audih
Solution
The relays are CO-7 then two setting are to be determine for each relay.

**CTS and TDS**, we starting with relay B3.

**For B3**

\[ I_{\text{full load}} = \frac{S}{\sqrt{3}V} = \frac{5 \text{MVA}}{\sqrt{3} \times 13.8 \text{kV}} = 209 \text{A} , \]

\[ I_{\text{relay}} = \frac{I_{\text{Load}} (I_p)}{CT \text{ ratio (a)}} = \frac{209 \text{A}}{\frac{400}{5}} = 2.61 \text{A} (\text{Which is the current at max. load the relay.}) \]

Now since X is given in pu, we chose \( V_{pu} = 1 \) on base of 13.8kV

and 209 A base of current, Then

\[ I_{3\text{p}u(I_{\text{max} \text{ or I}_{\text{fault}}})} = \frac{V_{pu}}{X_{pu}} = \frac{1}{0.05+0.05+0.1} = \frac{1}{0.2} = 5 \text{pu} \]

The actual \( I_{\text{max}} \) of the line \( I_3 \) is

\[ I_{\text{pu base (fault)}} \times I_{\text{base (fault)}} = 5 \times \left( \frac{10 \text{MVA}}{\sqrt{3} \times 13.8 \text{kV}} \right) = 2092 \text{ A (is } I_{\text{fault}} \text{)} \]
\[ I_{\text{relay (max or fault conditions)}} = \frac{I_{\text{(primary)}}}{\text{ratio}} = \frac{2092}{(400/5)} = 26.1 \text{ A (This is min. fault current)} \]

**CTS \leq \frac{1}{3} \times \text{Minimum fault current}**

**CTS \geq 2 \times \text{Maximum load current}**

Thus; \[ 2 \times I_{\text{relay (min.)}} \leq CTS \leq \frac{I_{\text{relay (max.)}}}{3} \Rightarrow 2 \times 2.61 \leq CTS \leq \frac{1}{3} \times 26.1 \]

\[ 5.22 \leq CTS \leq 8.7 \text{ the CTS}_3 \text{ is chose as 6A to be fast as possible} \]

**For TDS =1/2 for 6A we have \( t=0.18 \text{ sec} \) (note we can selected any TDS but gradually since its setting)**
Now for relay $B_2$

$$I_{\text{min}} = I_{\text{load}} = \frac{(3+5) \times 10^6}{\sqrt{3} \times 13.8 \times 10^3} = 335 \text{A}$$

$$I_{\text{relay(min)}} = \frac{335}{400} \times 5 = 4.188 \text{A}$$

$$I_{\text{max}} = I_{\text{fault}} = \left( \frac{10 \text{MVA}}{\sqrt{3} \times 13.8 \text{kV}} \right) = 418.4 \text{A}$$

$I_{\text{pu}}$ at relay in resent of impedances in pu

$$I_{2(\text{pu})} = \frac{V_{\text{pu}}}{X_{\text{pu}}} = \frac{1}{0.05+0.1} = \frac{1}{0.15} = 6.67 \text{ pu}$$

The actual $I_{\text{max}}$ at $B_3$ is $= I_{\text{pu}} \times I_{(\text{base fault})} = 6.67 \times 418.4 = 2790 \text{A}$

$$I_{\text{relay}} = \frac{I_{(\text{primery})}}{\text{ratio}} = 2790 \times \frac{5}{400} = 34.87 \text{ A}$$

Thus;

$$2 \times I_{\text{relay (min.)}} \leq CTS \leq \frac{1}{3} \times I_{\text{relay (max.)}} \Rightarrow 2 \times 4.18 \leq CTS \leq \frac{1}{3} \times 34.87$$

$$8.37 \leq CTS_2 \leq 11.6 \text{ we select } CTS_2 = 10 \text{A}$$

thus from curve is 0.4sec

From curve for TDS $2=0.4s$ this setting in case of the fault is at bus 2
Noting the following for delays time:

1- circuit breaker delay = 0.1 s, or 6 cycles in 60 Hz system).
2- Error margin of 0.3 s
3- Relay operation time delay is 0.18.

If we considered the fault at bus 3 then the desired (high value) operating relay is \((0.4+0.18=0.58\text{sec})\)

margin: Is the time interval that must be allowed between the operation of two adjacent relays in order to achieve correct discrimination between them (its just for check the multifunction and not included the relay setting).

And since relay B2 setting is 10 CTS, then the max current is changed as:

\[
\frac{I_{2\text{(relay)}}}{CTS_2} = \frac{26.1}{10} = 2.61
\]

From curve for TDS2=1.1 sec.
This see that the second relay will operate at 1.1 second if the first relay not operate B3 but at 10 CTS.

**Now for B1**

\[
I_1 = \frac{16.5}{0.0138\sqrt{3}} = 690A
\]

\[
I_{\text{relay (min.)}} = 690 \times \frac{5}{800} = 4.31A
\]

\[
I_{\text{(max)}} = 418.4A
\]

\[
I_{\text{pu at realy in resent of impedances in pu}}
\]

\[
I_{2(\text{pu})} = \frac{V_{\text{pu}}}{X_{\text{pu}}} = \frac{1}{0.1} = 10 \text{ pu}
\]

\[
I_{\text{(max.)}} = 418.4 \times 10 = 4184A
\]

\[
I_{\text{(max relay)}} = 4184 \times \frac{5}{800} = 26.15A
\]

\[
8.62 \leq \text{CTS} \leq 8.7
\]

For 8A and TDS 2=0.45sec

Select CTS1=8A which cheats a little on the lower bound ,but is the best we can do.
To determine TDS1, consider a fault at bus 2. The desired operation time for relay 1 is

- Relay 1 operation time = 0.45s
- Operating time = 0.1s
- Margin = 0.3s
- **Total** = 0.85s

Note: Since we consider the fault at bus 2 then we calculate the current become from bus 2 to bus 1 then:

\[ I_{B1} = \frac{I_{B2}}{a} \quad \text{or} \quad I_{CTS} = 2789 \times \frac{5}{800} = 2.18 \]

*then TDS_1 = 1.3*
2. English school of coordination:

Same as American school but taking CDT = 0.5 s instead of 0.4 as coordination delay time between two adjacent relays.

Example: It's required to provide time–curve grading using 2.2 sec. IDMTL overcurrent relay for the following:

<table>
<thead>
<tr>
<th>Relay point</th>
<th>CT rating</th>
<th>PS of relay</th>
<th>Fault current</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>400/5</td>
<td>125%</td>
<td>6000Amps</td>
</tr>
<tr>
<td>B</td>
<td>200/5</td>
<td>125%</td>
<td>5000Amps</td>
</tr>
<tr>
<td>C</td>
<td>200/5</td>
<td>100%</td>
<td>4000Amps</td>
</tr>
</tbody>
</table>

Delay time = 0.5 s
PS% = 25, 50, 75, 100, 125, 150, 175, 200
The relay has to settings primary and backup settings.
Solution:
Starting from Relay C primary and no backup setting. For maximum current in fault condition is:

\[
I_{\text{relay (max.current)}} = \frac{I_{\text{fault}}}{CT_{\text{ratio}}} = \frac{4000}{\left(\frac{200}{5}\right)} = 100A
\]

Now we select PS(25%, 50%, 75%, 100%, ....... 200%)
The PS must be equal or greater scale from the relay current.
In this case we select PS=100% (since its first relay) for quick response then;

\[
PSM = \frac{I_{\text{relay}}}{CT_{\text{secondary}} \times PS} = \frac{100}{5 \times 100\%} = 20
\]

From TMS curve for 1.0 TMS the operation time corresponding to 20 PSM is 2.2 sec.
Since is the first relay and not is a backup relay then we select the operation to be faster as possible, then we select TMS=0.1 this result the operation will be

\[ t_{op}^{RC} = \frac{0.1}{1.0} \times 2.2 = 0.22 \text{sec.} \]

Faster as possible

Hence for relay C TMS=0.1 and Time of operation=0.22sec and PS=100%

Now in relay B working as Backup response of Relay C (taking in consideration that the CT is changed) in case the fault is on C

To discriminate between relay C and B we introduce the time margin which is 0.5 for British school then the operation time of relay B

\[ t_{op}^{RB} = 0.5 + 0.22 = 0.72 \text{sec.} \]

(Note delay time for relay B to detected fault in C only in case of backup)
Now if the fault occur at C and B as backup

\[ I_{\text{relay (max. current)}} = \frac{I_{\text{fault}}}{CT_{\text{ratio}}} = \frac{4000}{200/5} = 100A \]

For this relay we select PS=125\%( note 100\% also valid).

\[ PSM = \frac{100}{5 \times 125\%} = \frac{100}{6.25} = 16 \]

PSM= the current interring in relay =100A but the plug changed it to 6.25 depending on plug setting(like transformer into relay)

From the TMS curve for 16 the time is 2.5 and from relay calculated before time is 0.72 second and to find TMS then \( \frac{0.72}{2.5} = 0.29 \) .

TMS =0.29

Important note: the relay B is backup for C and A is backup for B but in our case we consider the fault occur at C the relay A is not function a backup relay.
Now if the fault is near B (Like setting of A)

\[ I_{\text{relay (B)}} = \frac{I_{\text{fault}}}{CT_{\text{ratio}}} = \frac{5000}{\left(\frac{200}{5}\right)} = \frac{5000}{40} \]

\[ PS \] was sett to 125% then

\[ PSM = \frac{\left(\frac{5000}{40}\right)}{(5 \times 125\%)} = 20 \]

From the curve the time corresponding is 2.2 sec.

The actual operation time of relay A is

\[ t_{\text{op}} \bigg|_{RA} = 2.2 \times \left(\frac{TMS = 0.29}{TMS = 1.0}\right) = 0.638 \text{sec}. \]

Note if the fault accrue at C only B is backup
| Relay C |   |   |
|---------|---------|
| TMS    | Time of relay (sec) | PSM | PS |
| 0.1    | 0.22    | 20  | 100% |

| Relay B |   |   |
|---------|---------|
| TMS    | Time of relay | PSM | PS |
| 0.29   | 0.22    | 20  | 120% |

| Relay B backup for C fault |   |   |
|---------------------------|---------|
| TMS          | Time of relay | PSM | PS |
| 0.29         | 0.72     | 16  | 125% |

| Relay B3 |   |   |
|----------|---------|
| TDS      | Time of relay | PSM | PS |
| 1        | 0.638    | 20  | 125% |
**Instantaneous Overcurrent Relay Setting and Reach**

- The load is not usually considered for the instantaneous relay setting.
- Is commonly set to reach faults up to 80% of total line length. (detected the fault by 20% reduction of the line length L)

\[ I_{SETTING} \approx \frac{E}{Z_{S1} + (0.8)Z_{L1}} \]

\( Z_{S1} \) generator impedance

Since we decreased the line length is means the TL impedance is also decreased.
4. Directional overcurrent relays
- Directional relays are usually of wattmetric induction type (need VT and CT).
- Used in complex power system such as ring systems.
Directional Overcurrent Protection

The arrows shown in the figure are used to represent the protection direction.

The relays are into two independent groups: the relays “looking” to the right and those “looking” to the left.

All the relays are directional except the relays near the generation.
- Pilot wire differential relays (Device 87L)
- Distance protection
1. **Pilot wire differential relays (Device 87L)**

- The main objective is to remote control of the circuit breakers.
- 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.
- **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 are connected together with a two-conductor pilot wire.

\[ L \quad \bar{I}_L \quad \text{Relays} \quad \text{Communications Channel} \quad \bar{I}_R \quad R \]

Exchange of logic information on relay status

T: transmit data
R: received data
If the fault current flows through circuit breaker (A) only, the relay passes sufficient current through the pilot wire to operate the relay at circuit breaker B.
- Transformers are used to convert current signal to voltage signal.
- For faults outside since, $V_A = V_B$, relay will not operate and if the fault inside the line $V_A \neq V_B$, relay will operate.
- The pilot wire signal is about 30V ac at 50 Hz or 20V ac at 60 Hz.

(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 to give tripping 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 limited to the line by an LC blocking filter at each end. This is called a line trap.
2. Transmission Line Protection by Distance Relay

- Since protection by pilot wires (pilot relaying) is limited to 30 to 40 km in route length of TL then for longer distance of transmission lines and distribution feeders, distance protection is used.

**Principle of Distance Protection:**

- Every power line has a resistance and reactance 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.
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.

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): \( Z_p = \frac{V_p}{I} < Z_L \)  
  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 \( Z_f = \frac{V}{I} < Z_L \) here \( Z_f \) is the impedance at the fault point which is line length. For example at point p:

\[ Z_{fp} = \frac{a}{L} Z_L \]

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

**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 3).
- 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. 3 A three-sage distance protection system

Notes:
- Zone 1 is an under reaching 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:

- $Z_1\text{ protection} (0.80\% - 0.85\%)$
- $Z_2\text{ protection} (120\% - 150\%)$
- $Z_3\text{ protection} (200\% - 250\%)$

Example 1:
For the 66kV radial feeder shown in Fig., Calculate **zone 1** setting for the distance relay in primary ohms.

$$Z_{r1} = 0.8 \left| Z_L \right| = 0.8 \times (\sqrt{3.6^2 + 12^2}) = 10.02 \ \Omega$$
Example 2:

Figure shows a simple two radial lines. We will consider the settings for line AB at bus B. The line length is 80 km.

The distance relay at bus A is fed by current transformers rated at 2000/5A and voltage transformers rated at 345 kV/200 kVY, and 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 _ = \(0.85 \times 80 = 68\) ohm, primary ohm setting \((Z_{fp})\)

CT ratio = \(2000/5 = 400\)

VT ratio _ = \(200,000/69 = 2900\)

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

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

= 9.38 relay ohms

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

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

Relay setting for zone 2 = \(Z_{fp} \times \frac{CT\ ratio}{VT\ ratio}\)

= \(112 \times \frac{400}{2900}\)

= 15.44 relay ohms
Relay reach adjustment
Referred to Fig.3, 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).
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 (reach) in ohms (Figure 5).

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.
This limitation can be overcome by a technique known as self-polarization. Additional voltages are fed into the comparator in order to compare the relative phase angles of voltage and current, so providing a directional feature. This has the effect of moving the circle such that the circumference of the circle now passes through the origin. Angle $\theta$ is known as the relay’s characteristic angle (see Figure 6 (a)).

![Diagram of MHO relay characteristic](image)

(a) Mho characteristics  
(b) offset mho characteristic

Fig.6  MHO relay characteristic
This is known as the MHO relay, so called as it appears as a straight line on an admittance diagram. By the use of a further technique of feeding in voltages from the healthy phases into the comparator (known as cross polarization) a reverse movement or offset of the characteristic can be obtained (see Figure 6 (b)). This is called the offset MHO characteristic.

**Types of Distance Relay**

Distance relays are classified according to their characteristics in the R-X diagram and there are numerous differences in relay characteristics. The relays are set according to the positive and zero-sequence impedance of the transmission line. Fig.7 shows the R-X diagrams of common types of distance relays.
Fig. 7 Basic Distance Relay Types.

(a) Impedance Characteristic

(b) Mho Characteristic

(c) Offset Mho Characteristic

(d) Mho and Reactance Characteristic

(e) Quadrilateral Characteristic

(f) Lenticular Characteristic
Thank You