Protection of Bus Bars (Unit-3)

→ Basic principle remains same as differential protection scheme.

Unit-3

- Distance protection
- Differential protection

[Different segment]

Transmission Line
Generator
Motor
Lines
Feeders

Feeder, xmr, Paut of winding

→ Protective zone is defined by CT’s second

Normal operating condition

\[ I_{CT1} = I_{CT2} \]

\[ I_{R} = I_{CT1} - I_{CT2} \]

\[ I_{CT1} \neq I_{CT2} \]
Differential Protection

\[ I_R = \frac{3}{2} I - I = \frac{I}{2} \]

when both currents are equal.

\[ I_R = I_1 - I_2 = 0 \]

magnitude and well as vector

Secondary Linear Coupler Connection

Fault Condition

Protection scheme with linear couplers

Normal Condition

\[ I_1 + I_2 + I_3 = I_f \]

\[ V_s \propto I_p \]
Distance Protection

CAB Segment of Transmission Line

1. Protection of Transmission Line (CAB)

2. Constant magnitude of V and I

3. Both connections of CT's, PI's

4. Fault Location

Basic operation of impedance relay

Comparison between Zref and Zf

\[ \text{Zref} = \frac{V}{I} \]

\[ \text{Zdesign} = \frac{V}{I} \]

Impedance Relay Expression

\[ (\text{Actual voltage}) \rightarrow I \leftarrow (\text{Actual current}) \]

1. Actual voltage \((V, I)\)

2. net torque on the relay

depends upon

\[ T_{\text{net}} = K_1 I^2 - K_2 V^2 - K_3 \]

\( K_1, K_2 \) and \( K_3 \) are constants

\( I, \) current, \( V, \) voltage

\[ K_1 I^2 - K_2 V^2 - K_3 = 0 \]

\( K_3 = 0 \)

\[ \frac{V}{I} = \sqrt{\frac{K_1}{K_2}} \]

\[ Z = Z_{\text{ref}} \]

\[ Z < Z_{\text{design}} \]
\[ Z = K \]
\[ |Z| = K = \sqrt{R^2 + x^2} = K \]
\[ R^2 + x^2 = K^2 \]

1. Plain Impedance Relay
2. Non directional (\( V + iVc, I + iVc \))
3. Arc resistance Relay operated also affect the performance (over reach)
4. Power swing Can affect this Relay.

Transmission line (Distance Protection)

1. Length of transmission line and it exposure to atmosphere. (Special Care)
2. Segment of transmission line (ab)
3. \( Z_{se} = \frac{V}{I} \) (Design parameter of Relay)

\[ Z_{se} \geq Z_{Ef} \] Operate Condition
The operation of the relay depends upon the distance both the point where the relay is connected to the location of fault.

1. Continuous measurement of I, and voltage.

\[ Z_f_1 = \frac{V_1}{I_1}, \quad Z_f_2 = \frac{V_2}{I_2}, \quad Z_f_3 = \frac{V_3}{I_3} \]

\[ Z_{set} > Z_f_1 \quad Z_{set} = Z_f_2 \quad Z_{set} < Z_f_3 \]

Relay operate Relay operate Relay will not operate

2. Double active tripping quantity relay.

\[ Z_t < K \]

\[ K = 3 + 1/4 \]

\[ K = 5 \]

Relay will not operate

\[ Z_t > K \]

\[ \sqrt{4^2 + 3^2} = 5 \]
Impedance Relay Expression
\[ I \]
\[ V \]

1. Actual input quantity \((V, I)\)
2. Net torque of this relay depends upon
   - Torque
   \[ T_{net} = k_1I^2 - k_2V^2 - k_3 \]
   - \(k_1, k_2, k_3\) are constants
   - \(I, \text{ current}\), \(V, \text{ voltage}\)
   - \(k_1I^2 - k_2V^2 - k_3 = 0\)
   - \(k_3 = 0\)
   - \(k_3 \text{ spring constant}\)

Plain Impedance Relay
Impedance = Constant
\[ V = I \frac{k_1}{k_2} \]
\[ \frac{V}{I} = \frac{k_1}{k_2} \]
\[ Z < Z_{\text{design}} \]

Non-Operational Zone
\[ R^2 + x^2 = k^2 \]
\[ Z_f < k \]
\[ R^2 + y^2 < k^2 \]
\[ Z_f < k \]

Positive torque points
\[ \begin{align*}
Z_f > k & \quad \text{Impedance relay will operate} \\
Z_f < k & \quad \text{Impedance relay will not operate}
\end{align*} \]
Disadvantages of Impedance Relay

1. Non directional Relay (less discrimination between internal and external fault)

\[ E_R - E_Z - X_R Z \]

2. When there is a fault arc exists, arc resistance of line fault affects the performance of relay.

3. Effects of power swing are prominent due to value of large area on Rx diagram.

Directional Impedance Relay

- Rx diagram area is reduced to half.
- we added a directional element by which the relay will respond only a particular direction of current (flow/ power flow)

\[ T = K_1 I^2 - K_2 (V + K_3 I)^2 \]
Reactance Relay
\[ T = K_1 I^2 - K_2 V I \sin(\theta - \beta) \]
0 = K_1 I^2 - K_2 V I \sin(\theta - \beta)
\[ K_1 = K_2 Z \sin(\theta - \beta) \]
\[ Z \sin(\theta) = \frac{K_1}{K_2} \]
X = constant

Reactance Relay
\[ T_{\text{net}} = \text{Topering } - \text{Restraining Torque} \]
\[ T_{\text{net}} \geq 0 \]

Reactor relay is an overcurrent relay with directional element.

Restaining \( \Phi \) coil
Polarizing \( \Phi \) coil
Current voltage direct and rela.
**Diagonal Element**

Conditions:
1. Direction of the current in the cir. should be reversed to operate this element.
2. The value of current should be greater than the current setting.
3. The high value of current for a time that is greater than the setting of the relay.

**Let us study a phasor diagram**

\[
\begin{align*}
V & \rightarrow \phi_V \\
I & \rightarrow \phi_I \\
\phi_V, \phi_I & = \phi
\end{align*}
\]

Relay operation depends upon voltage and current.

\[
\begin{align*}
T = k \left( \phi_V \phi_I \sin(\phi + \theta) \right) \\
\phi_V = \Delta \\
\phi_I = \theta + \phi = 90° \\
\theta + \phi + \gamma - \theta = 90° \\
\phi = 90° - \gamma \\
T = k \sqrt{V}\sqrt{I} \cos(\theta - \gamma - \phi) - (\Delta)
\end{align*}
\]
Let us design a relay logic

\[ T = k_1 I^2 - k_2 V I \cos(\theta - \beta) \]

Relay operation \( T_{net} = 0 \)

\[ k_1 I^2 = k_2 V I \cos(\theta - \beta) = 0 \]
\[ k_1 = \frac{k_2 V}{I} \cos(\theta - \beta) \]

\[ \frac{k_1}{k_2} = \frac{Z \sin \theta}{\sqrt{3}} \]

\[ X = \frac{k_1}{k_2} \]

Let us design another relay

\[ T = k_3 V^2 - k_2 V I \cos(\theta - \beta) \]

For operation of the relay

\[ k_3 V^2 = k_2 V I \cos(\theta - \beta) \]

\[ \frac{k_3}{k_2} = \frac{1}{Z} \sin(\theta - \beta) \]

\[ \frac{k_3}{k_2} = \frac{1}{Z} \sin \theta \]

Another type of relay
Mho Relay Realization with Universal Torque Equation

\[ T = k_1 V I \cos(\theta - \phi) - k_2 V^2 - k_3 \]

\[ Z = \frac{k_1}{k_2} \frac{V^2}{\cos(\theta - \phi)} \]

ks \approx 0 (assume)

k1 and k2 are important design parameters which decide the characteristic diagram.

Mho Relay or Admittance Relay

Impedance Relay + Directional Unit

Operating

Topoperating = V, I element

Toprestrain = Voltage element

Top = 1, 2, 3

Top (1, 2, 3)

Tres = 1, 3, 4

Gadhusn Cup

Series<br>

Unit Coil

Dr. Akash Saxena, Power System Protection
On RX diagram \( Z = 3 + j4 \)

**Realize**. Impedance, mho, Reactance

\( R_{ac} = 1 + j0 \) (max. portion of the line that can be protected)

Characteristics of reactance

\( OD = 1 \text{m} \)

1. RX diagram area is less for mho relay

2. Part of line protected by mho relay is less as compared to impedance relay

\[ mho = \frac{ON}{OA} \times 100 \approx 80\% \]

\[ Imped = \frac{ON}{OA} = 85\% \approx 6 \]

3. mho relay is robust relay that can be used for long transmission line.
Three stepped characteristics (Distance Relays)

All three distance relays are installed:

1. Definite Impedance relay elements used to operate instantaneously within nearest 75% section
2. Time lag is also provided

Diagram showing distance and time relationships.
Transmission Line (3 step protection)

1. Relay Back up: Same breaker is used for tripping the ckt. Component zones are different and separate trip coils may be used.

2. Breaker Back up: Different breakers are provided for main and back up.

3. Remote Back up: Completely independent from each other and at different stations.

---

Long Transmission Line

X = Pair of Distance Relay and CB

For fault F1 the relay and CB that is located nearest to the fault location should be operated.

* Relay Band CB fails to operate
  = Back up protection relay A after some time.
  Relay A will trip CB at B (Relay back up)

a. RA will trip for fault near B and will enable CB at Substation B (Relay back up)

b. Further if RA won’t be able to trip CB at Substation B then RA will trip CB at A.
Let us draw characteristic of distance relay RA.

- If \( t_3 > t_2 > t_1 \) (operating time), RA will operate.
- If \( l_1 \leq t_2 < l_3 \) (time at station), CB at station B.
- If \( l_1 < l_2 < l_3 \), RA will operate (RB and RC fail).
- CB at station A.

At time \( t_a \), RA operates.

- 85% AB segment
- 25-50% BC segment

With delay time (moderate speed):

- Zone 1
- \( Z = \sqrt{R^2 + X^2} \)
- 75-80%: AB
- \( t_a \)
- \( t_a' \)
- \( t_a'' \)

Characteristics of RA for different zones.
Differential Protection

Normal Condition:
\[ I_1 = I_2 \]

1. \[ |I_1| = |I_2| \]
2. \[ |I_1| = \frac{|I_2|}{\sqrt{3}} \]

During Internal Fault:
\[ I_2 = -I_2 \]
\[ I_1 - I_2 = (I_1 + I_2) \neq 0 \]

For external fault:
\[ I_1 - I_2 = 0 \]
So the relay will operate only for Internal Faults.

Applications of Differential Protection

Most protection schemes are Current differential Schemes in which vector difference between the current entering the winding and current leaving the winding is used for sensing and relay operation.

Differential Protection principle is used in the following applications:
A. Protection of Generator, Protection of Generator and Transformer Unit
B. Protection of Transformer
C. Protection of Feeder
D. Protection of Transmission line by Phase comparison Carrier Current Protection
E. Protection of Large MOTORS
F. Protection of Bus Bars

Difficulties in Differential Protection

Pilot wire length is not equal then there will be a difference both CT currcnts. => a mis-operation of relay.

For solution: we connect adjustable resistors.
To connect CT's on equipotential points.

\[ (R_w + R_{L1}) \]
\[ (R_w + R_{L2}) \]

\[ R_w + R_{L1} \neq R_w + R_{L2} \]
\[ I_1 \neq I_2 \]
\[ (I_1, -I_2) \]

L_1 
L_2 

Equipotential

No Fault

Difference in length of Pilot wire
2. Derive short circuit condition CT ratio errors

- Magnetic saturation characteristic of CT's are different
- Unequal DC component

\[ % \text{biased Differential Protection Scheme} \]

\[ CT^1 \quad CT^2 \rightarrow I_2 \]

\[ N_0 = N_0 \cdot \frac{N_1}{N_2} \quad \text{turns in} \]

\[ N_r = N_0 \cdot \frac{N_1}{N_2} \quad \text{turns in} \]

\[ T_{operating} > T_{returning} \]

\[ T_{op} = (I_1 - I_2) \cdot N_0 \]

\[ T_{res} = (I_1 + I_2) \cdot N_r \]

\[ \frac{I_1 - I_2}{2} \cdot N_0 = \frac{(I_1 + I_2) \cdot K \cdot N_0}{2} \]

\[ \text{For limiting case} \]

\[ T_{op} = T_{res} \]

\[ N_r = K \cdot N_0 \]

\[ K = 10 - 40 \text{V} \]

\[ \text{Reducing the area of positive torque zone} \]

\[ 2I_1 - 2I_2 = KI_1 + KI_2 \]

\[ I_1 \left( 2 - K \right) = I_a \left( 2 + K \right) \]

\[ \frac{I_1}{I_a} = \frac{2 + K}{2 - K} \]
Energize a large Xmer (2nd Harmonic Current Flow)

\[ f = 50\text{Hz} \]
\[ f_2 = 100\text{Hz} \]

Harmonic Restraint Relay

The 2nd order harmonic is rich when transformer draws magnetizing current at the time of switching of transformer. The differential relay has a 100 Hz filter circuit which measures the frequency and the magnitude of the 2nd order harmonic current in the differential current. If the relay senses the current of 100 Hz frequency and if the current is more than the differential current setting of the relay, the relay will observe that the transformer is taking the inrush magnetizing current and the relay blocks its main tripping mechanism.

Therefore, the 2nd order harmonic current needs to be blocked in the differential relay because 2nd order harmonic current will operate under no fault within the transformer. The magnitude of 2nd order harmonic current in inrush current depends on transformer material and construction. Therefore, the setting of the 2nd order harmonic blocking current can not be calculated in a straightforward way.

The relay measures the ratio of 2nd order harmonic current and the fundamental current and the setting of the 2nd order harmonic blocking current can be done accordingly.

Harmonic Restrain Relay Contd.

- The harmonic restraining elements of the relay measure the magnitude of the harmonic current and tripping of the relay is restrained if the harmonic current is well below the specified current.
- The setting of the 2nd order harmonic restraining is generally kept between 20-25% of the differential relay setting. If the current is below the differential relay setting, the relay does not trip because the relay will observe it as a transformer charging phenomenon.
- If the harmonic restraining current is more than the differential relay setting, the relay will trip with differential protection fault.

Provide high impedance path for 2nd Harmonic Current.
Transformer Protection

### Transformer Protection

#### Power Transformer Connections

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>Delta</td>
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<tr>
<td>Delta</td>
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<tr>
<td>Delta</td>
<td>Star</td>
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<tr>
<td>Star</td>
<td>Star</td>
</tr>
</tbody>
</table>

#### CT Connections

<table>
<thead>
<tr>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star</td>
<td>Delta</td>
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<tr>
<td>Delta</td>
<td>Star</td>
</tr>
<tr>
<td>Star</td>
<td>Delta</td>
</tr>
</tbody>
</table>

#### Differential Protection

\[
I_{S1} = I_{S2}
\]

\[
\angle I_{S1} = \angle I_{S2}
\]

\[
I_{S1} = \left| I_{S2} \right|
\]

\[
\text{Power CT Primary}
\]
Simple example of connection of CT's

\[ \begin{align*}
\text{Star side of power transformer} & \quad \text{Delta side of power transformer} \\
\text{C.T. Secondaries in delta} & \quad \text{C.T. Secondaries in star} \\
\text{Pilot wires} & \quad \text{Closed loop} \\
\end{align*} \]

Relays

\[ \begin{align*}
I_R & \quad I_Y \\
I^L & \quad I_B \\
\end{align*} \]

Merm-Price Protection (3 phase x mem)

1. Primary wdg of power x mem
2. CB is attached
3. Delta connected CT's
4. Control CT's

\[ \begin{align*}
N_0 & = K_0 N_D \\
I_{12} & = \frac{I_1 + I_2}{2} \\
T_{03} & = (I_1 - I_2) N_0 \\
T_{10} & = (I_1 + I_2) N_Y \\
\end{align*} \]
Bucholz Relay ** (CRTU + GATE)

1. ** Actually Quantity = GAS
2. Alarm + Trip CRT
3. Mercury operated system
4. Internal fault (Incipient faults)
5. Both Conservator and oil tank

Decomposition of oil → \( 70\% \text{ H}_2 \)

Operation based on mercury switch 1st switch

- Oil Level

1. Insulation fault
2. Core heating
3. Faulty joints
4. Contact switch

Limitations
- a. Oil immersed tank Xmer
- b. Oil level
- c. Mercury switch settling (Vibration, Earthquake, mechanical shocks)
- d. Slow relay (0-2s)
Earth Fault Protection for XmuR

Earth Fault Current Depends Upon

1. Method of Neutral Grounding
2. The Point Where the Fault Occurs in the Wye
3. Winding Connection

Earth is involved in XmuR at normal conditions

\[ I_R + I_Y + I_B = 0 \]

\[ I_R' + I_Y' + I_B' = 0 \]

Relaying

\[ \sum I_I = 0 \]
Generator Protection

**GENERATOR PROTECTION**

**GENERATOR Protection Importance**

a. Very large m/c's. Connected to the bus bar, produce very high voltage.

b. Association of various equipments
   - Prime mover
   - Excitation system
   - Voltage regulators

c. Generators are expensive (costly), it shouldn't shut off as soon as possible.

**GENERATOR Faults**

a. Stator faults
b. Rotor faults

c. Abnormal running conditions

**Faults:**
- Phase to earth
- Phase to phase
- Stator inter turn faults
- Sc of field winding
- Phase to ground / turn faults

**Abnormal Conditions**
- Overloading
- Over speeding
- Unbalanced loading
- Over voltage

Failure of
- Cooling system
- Prime mover
- Loss of excitation
**Stator Faults**

1. **Phase to Earth Faults**
   - Armature coils (Most Common)
   - Burning of the core
   - We need to change laminated stator core.
   - South sensitive earth fault protection

2. **Phase to Phase Fault** (Uncommon)
   - At the end of connection of armature winding
   - Over heating / Arcing
   - Fire hazards

3. **Stator Inter Turn Fault**
   - This fault occurs due to current surge like short circuit between turns.
   - Multi turn coils
   - Short circuit in the coil
   - > 500mV & single turn coils are used.

**Rotor Faults** (Most Past)

- Field winding
- Inter turn fault or ground fault
- Reason for these faults (mechanical and thermal stress)
- Unbalance windings of the generator
  - Negative sequence
  - Torque reverse
- Rotor earth fault indicator direction
  - Rotor temperature indicator
  - $\text{emf}$ induced
  - Over heating of the rotor
Abnormal Condition

a. Overloading → Rise in temperature ↑

b. Overspeeding (Hydraulic) → Sudden loss of load
   → Precaution measured → Turbo governor

c. Unbalanced loading → Occurrence of Unsymmetrical Fault
   → Failure of CB near the Generator, clearing three phase fault

   → Atmospheric surge (Lightning)

d. Over voltage → Overspeeding of the generator
   → Faulty operating voltage regulator
   → Atmospheric surge (Lightning)

e. Prime mover failure
   → Dangerous mechanical Condition
   → Reverse power directed voltage fed into the abnormal condition

f. Loss of excitation (Field winding)
   → Rotor + DC voltage x
   → Loss of synchronism
   → Syn generator became
   → Inducing generator
   → Draw on reactive power from bus
   → Overheat per stator only

f. Cooling system → Thermal Couple
Generator Protection

Also named as 

\[ T_0 = N_0 (I_1 - I_2) \]

\[ T_r = N_r \left( \frac{I_1 + I_2}{2} \right) \]

\[ N_r = K N_0 \]

1. **Biased Differential Protection**

\[ T_0 = T_r - \]  

\[ N_0 (I_1 - I_2) = K N_0 (I_1 + I_2) \]

\[ (2-K)I_1 = (2+K)I_2 \]

Let us draw Herz Price Protection for Star Connected Alternator

Total no. of CT's = 6  No. of coil per phase = 2

For any phase relay will operate

\[ I_R = I_R - (Normal) \]

\[ Tap > TCS \]

**Steps:**

1. Protected 30 \[\frac{kV}{A}\] should be drawn
2. Connect CT's (Relay + CB)
3. Connect CT's (Neutral should be designated)
4. Connect RC in phase with CT  O.C. with CT Neutral ad phase

For Internal Fault (Unit type)
Some Important Points on Merz Price Protection

1. CT's ratios should be equal
2. High speed protection (15 ms/sec)
3. It allows low fault setting that ensures max. protection
4. Complete stability (most severe through and external)
5. No requirement of linear couplers
When fault occurs near to neutral, Y. relay will not operate.

\[
V_{Bx_1} < V_{Bx_2} < V_{Bx_3}
\]
\[
I_{x_1} < I_{x_2} < I_{x_3}
\]

Fault occurs near to neutral.

Terminal is connected to neutral.

Windings at a generator.
EFFECT OF EARTH RESISTANCE ON Y. WDG.

1. Value of this earth's resistance limit earth fault current
   \[ R = \frac{V}{I_e} \]
   \[ I_e = \text{Minimum Operating Current in Primary} \]

2. \[ V = \text{Full line to neutral voltage} \]
   \[ I = \text{Full load current} \]
   \[ R = \text{Earth Resistance} \]

Unrestricted Earth Fault Protection

Voltage to be protected

Generator

Normal operation

Case

\[ I_R + I_Y + I_B = 0 \]
\[ I_R = 0 \]
\[ a. \text{Fault remains in operation} \]

Fault Condition

\[ I_R + I_Y + I_B = I_{RS} \]
\[ I_{RS} > \text{Pick up} \]
Balanced Earth Fault Relay

Restricted Earth Fault
- If the fault is outside the relay zone, the relay does not operate.

Unrestricted Protection → I_{RA} (Residual Current) for Earth Fault

Balanced Earth Fault (Small ratio generator)

Balanced Earth Fault Relay

1. Small ratio generator

Earth's Resistance

N

R

F_1

F_2

IN = Neutral Term

R = Earth Fault

I_{RA} = Earth Fault

N = Neutral Term

Relay

Unit Protection

Internal Fault

Neutral CT

Phase CT
STATOR Protection against Inter-turn fault

Large Ratio - One Turn

Hydro-generator

→ Cross Central Protection

→ Sensitive Protection

Rotor Protection of Field Winding

Exciter - DC Generator

Loss of Excitation (Distance Relay)

Generators are induction generators

Exciter - DC generator

Reactive power

Z = 3 + j4

Z = 2 - j4

Normal operation

R+ve (Power)

R-ve

Locus of equivalent generator

Impedance during loss of excitation

First example where we use distance relay.

Economic
Negative Sequence Protection

1. These relays are called phase unbalance relay as they provide protection against negative sequence component.

\[ I^+ \rightarrow I^- \rightarrow \text{Torque} \]

Unsymmetrical fault

Load Unbalanced

Rotor stability got disturbed due to negative sequence current and torque generated by that

\[ Z_1 \text{ and } Z_2 \text{ are pure resistive} \]

\[ Z_3 \text{ and } Z_4 \text{ are reactive} \]

\[ I_1 = I_2 = \frac{I_A}{\sqrt{3}} \]

\[ I_3 \times I_4 = \frac{I_B}{\sqrt{3}} \]

\[ I_{RELAY} = I_1 + I_2 + I_4 \]

\[ I_4 = \frac{I_A}{\sqrt{3}} + \frac{I_B}{\sqrt{3}} \]