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ECE 476 Power System Analysis
Lecture 25 Fault Analysis

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Material courtesy of Prof. Tom Overbye.

Generalized System Solution

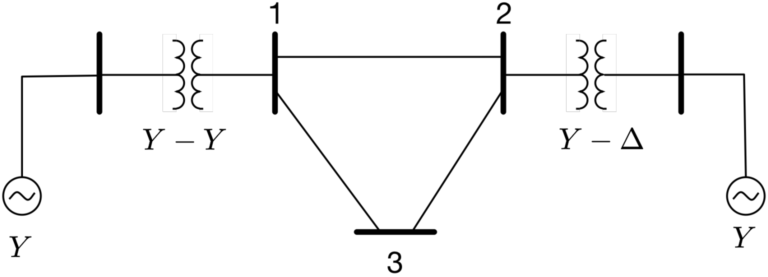
Assume we know the pre-fault voltages. The general procedure is then

- Calculate $\boldsymbol{Z}_{\text{bus}}$ for each sequence
- For a fault at bus i, the Z_{ii} values are the thevenin equivalent impedances; the pre-fault voltage is the positive sequence thevenin voltage
- Connect and solve the thevenin equivalent sequence networks to determine the fault current
- Sequence voltages throughout the system are given by

$$\boldsymbol{V} = \boldsymbol{V}^{\text{pre-fault}} + \boldsymbol{Z} \begin{bmatrix} 0 \\ \vdots \\ 0 \\ -I_f \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

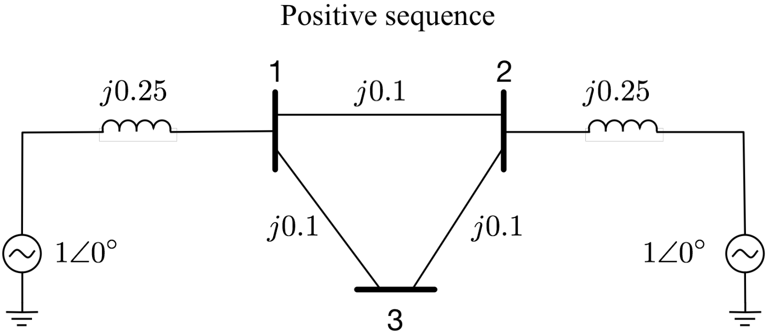
- Phase values are determined from the sequence values

Unbalanced System Example



- For the generators assume $Z^+ = Z^- = j0.2$, $Z^0 = j0.05$
- For the transformers assume $Z^+ = Z^- = Z^0 = j0.05$
- For the lines assume $Z^+ = Z^- = j0.1$, $Z^0 = j0.3$
- Assume unloaded pre-fault, with voltages equal to 1.0 p.u.

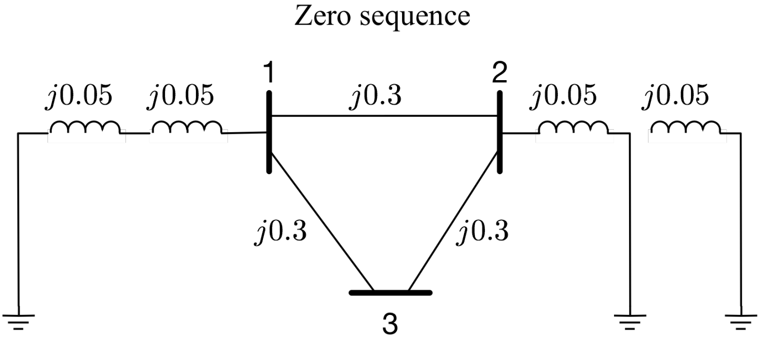
Positive/Negative Sequence Network



$$\boldsymbol{Y}_{\text{bus}}^{+} = j\begin{bmatrix} -24 & 10 & 10 \\ 10 & -24 & 10 \\ 10 & 10 & -20 \end{bmatrix}, \boldsymbol{Z}_{\text{bus}}^{+} = j\begin{bmatrix} 0.1397 & 0.1103 & 0.1250 \\ 0.1103 & 0.1397 & 0.1250 \\ 0.1250 & 0.1250 & 0.1750 \end{bmatrix}$$

- Negative sequence is identical to positive sequence

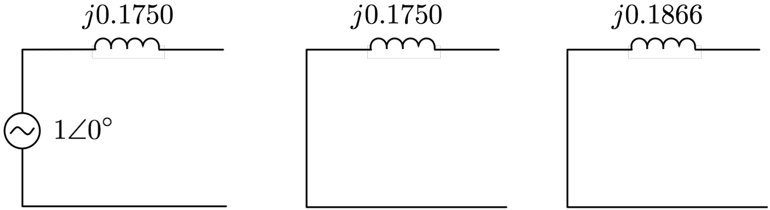
Zero Sequence Network



$$\boldsymbol{Y}^0_{\text{bus}} = j\begin{bmatrix} -16.66 & 3.33 & 3.33 \\ 3.33 & -26.66 & 3.33 \\ 3.33 & 3.33 & -6.66 \end{bmatrix}, \boldsymbol{Z}^0_{\text{bus}} = j\begin{bmatrix} 0.0732 & 0.0148 & 0.0440 \\ 0.0148 & 0.0435 & 0.0292 \\ 0.0440 & 0.0292 & 0.1866 \end{bmatrix}$$

For a SLG Fault at Bus 3

- The sequence networks are created using the pre-fault voltage for the positive sequence thevenin voltage, and the Z_{bus} diagonals for the thevenin impedances



- The fault type then determines how the networks are interconnected

Bus 3 SLG Fault, cont'd

$$I_f^+ = \frac{1.0\angle 0^\circ}{j(0.1750 + 0.1750 + 0.1866)} = -j1.863$$

$$I_f^+ = I_f^- = I_f^0 = -j1.863$$

$$\boldsymbol{V}^+ = \begin{bmatrix} 1.0\angle 0^\circ \\ 1.0\angle 0^\circ \\ 1.0\angle 0^\circ \end{bmatrix} + \boldsymbol{Z}_{\text{bus}}^+ \begin{bmatrix} 0 \\ 0 \\ j1.863 \end{bmatrix} = \begin{bmatrix} 0.7671 \\ 0.7671 \\ 0.6740 \end{bmatrix}$$

$$\boldsymbol{V}^- = \boldsymbol{Z}_{\text{bus}}^- \begin{bmatrix} 0 \\ 0 \\ j1.863 \end{bmatrix} = \begin{bmatrix} -0.2329 \\ -0.2329 \\ -0.3260 \end{bmatrix}$$

Bus 3 SLG Fault, cont'd

$$\boldsymbol{V}^0 = \boldsymbol{Z}^0_{\text{bus}} \begin{bmatrix} 0 \\ 0 \\ j1.863 \end{bmatrix} = \begin{bmatrix} -0.0820 \\ -0.0544 \\ -0.3479 \end{bmatrix}$$

We can then calculate the phase voltages at any bus

$$\boldsymbol{V}_3 = \boldsymbol{A} \begin{bmatrix} -0.3479 \\ 0.6740 \\ -0.3260 \end{bmatrix} = \begin{bmatrix} 0 \\ -0.5220 - j0.8660 \\ -0.5220 + j0.8660 \end{bmatrix}$$

$$\boldsymbol{V}_1 = \boldsymbol{A} \begin{bmatrix} -0.0820 \\ 0.7671 \\ -0.2329 \end{bmatrix} = \begin{bmatrix} 0.4522 \\ -0.3491 - j0.8660 \\ -0.3491 + j0.8660 \end{bmatrix}$$

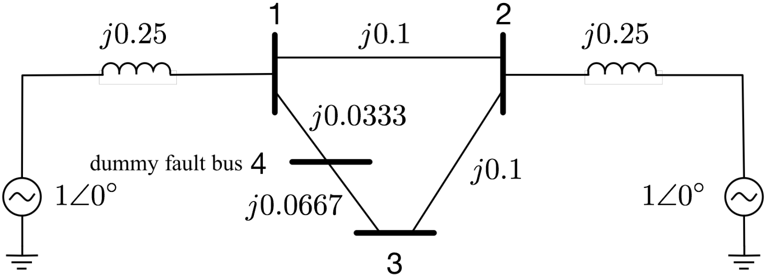
Faults on Lines

- The previous analysis has assumed that the fault is at a bus. Most faults occur on transmission lines, not at the buses

- For analysis these faults are treated by including a dummy bus at the fault location. How the impedance of the transmission line is then split depends upon the fault location

Line Fault Example

Assume a SLG fault occurs on the previous system on the line from bus 1 to bus 3, one third of the way from bus 1 to bus 3. To solve the system we add a dummy bus, bus 4, at the fault location



Line Fault Example, cont'd

- The $\boldsymbol{Y}_{\text{bus}}$ now has 4 buses : $\boldsymbol{Y}_{\text{bus}}^{+} = j \begin{bmatrix} -44 & 10 & 0 & 30 \\ 10 & -24 & 10 & 0 \\ 0 & 10 & -25 & 15 \\ 30 & 0 & 15 & -45 \end{bmatrix}$
- Adding the dummy bus only changes the new row/column entries associated with the dummy bus
- $\boldsymbol{Z}_{\text{bus}}^{+} = j \begin{bmatrix} 0.1397 & 0.1103 & 0.1250 & 0.1348 \\ 0.1103 & 0.1397 & 0.1250 & 0.1152 \\ 0.1250 & 0.1250 & 0.1750 & 0.1417 \\ 0.1348 & 0.1152 & 0.1417 & 0.1593 \end{bmatrix}$

Power System Protection

- Main idea is to remove faults as quickly as possible while leaving as much of the system intact as possible

- Fault sequence of events

  1. Fault occurs somewhere on the system, changing the system currents and voltages

  2. Current transformers (CTs) and potential transformers (PTs) sensors detect the change in currents/voltages

  3. Relays use sensor input to determine whether a fault has occurred

  4. When a fault occurs the relays open the circuit breakers to isolate fault

Power System Protection, cont'd

- Protection systems must be designed with both primary protection and backup protection in case primary protection devices fail

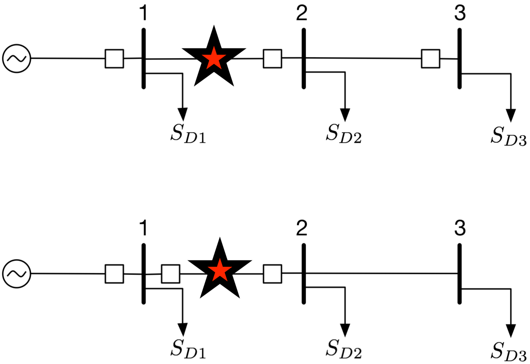
- In designing power system protection systems there are two main types of systems that need to be considered:

  – Radial: there is a single source of power, so power always flows in a single direction; this is the easiest from a protection point of view

  – Network: power can flow in either direction: protection is much more involved

Radial Power System Protection

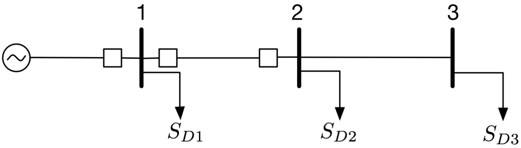
- Radial systems are primarily used in the lower voltage distribution systems. Protection actions usually result in loss of customer load, but the outages are usually quite local



The figure shows potential protection schemes for a radial system. The bottom scheme is preferred since it results in less lost load

Radial Power System Protection, cont'd

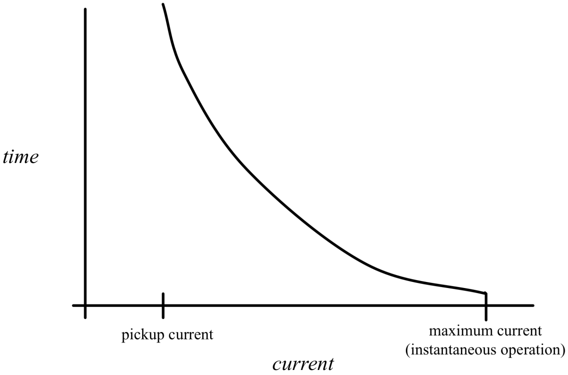
- In radial power systems the amount of fault current is limited by the fault distance from the power source: faults further down the feeder have less fault current since the current is limited by feeder impedance
- Radial power system protection systems usually use inverse-time overcurrent relays
- Coordination of relay current settings is needed to open the correct breakers



Inverse Time Overcurrent Relays

- Inverse time overcurrent relays respond instantaneously to a current above their maximum setting

- They respond slower to currents below this value but above the pickup current value



Inverse Time Overcurrent Relays, cont'd

- The inverse time characteristic provides backup protection since relays further upstream (closer to power source) should eventually trip if relays closer to the fault fail

- Challenge is to make sure the minimum pickup current is set low enough to pick up all likely faults, but high enough not to trip on load current

- When outaged feeders are returned to service there can be a large in-rush current as all the motors try to simultaneously start; this in-rush current may re-trip the feeder

Inverse Time Overcurrent Relays, cont'd

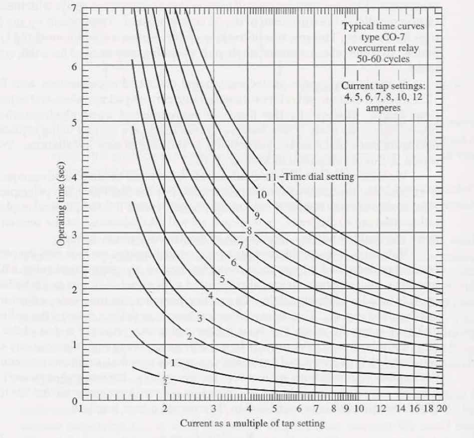


Figure 13.3 CO-7 time-delay overcurrent relay characteristics.
(Courtesy of Westinghouse Electric Corporation.)

Current and time settings are adjusted using dials on the relay Relays have traditionally been electromechanical devices, but are gradually being replaced by digital relays

Protection of Network Systems

- In a networked system there are a number of difference sources of power. Power flows are bidirectional
- Networked system offer greater reliability, since the failure of a single device does not result in a loss of load
- Networked systems are usually used with the transmission system, and are sometimes used with the distribution systems, particularly in urban areas

Network System Protection

- Removing networked elements require the opening of circuit breakers at both ends of the device
- There are several common protection schemes; multiple overlapping schemes are usually used
  - Directional relays with communication between the device terminals
  - Impedance (distance) relays
  - Differential protection

Directional Relays

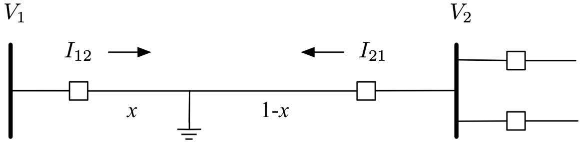
- Directional relays are commonly used to protect high voltage transmission lines
- Voltage and current measurements are used to determine direction of current flow (into or out of line)
- Relays on both ends of line communicate and will only trip the line if excessive current is flowing into the line from both ends

  – line carrier communication is popular in which a high frequency signal (30 kHz to 300 kHz) is used

  – microwave communication is sometimes used

Impedance Relays

- Impedance (distance) relays measure ratio of voltage to current to determine if a fault exists on a particular line



- Assume Z is the line impedance and x is the normalized fault location ($x = 0$ at bus 1, $x = 1$ at bus 2). Normally, $\frac{V_1}{I_{12}}$ is high; during fault $\frac{V_1}{I_{12}} \approx xZ$

Impedance Relays Protection Zones

- To avoid inadvertent tripping for faults on other transmission lines, impedance relays usually have several zones of protection:

  – zone 1 may be 80% of line for a three-phase fault; trip is instantaneous

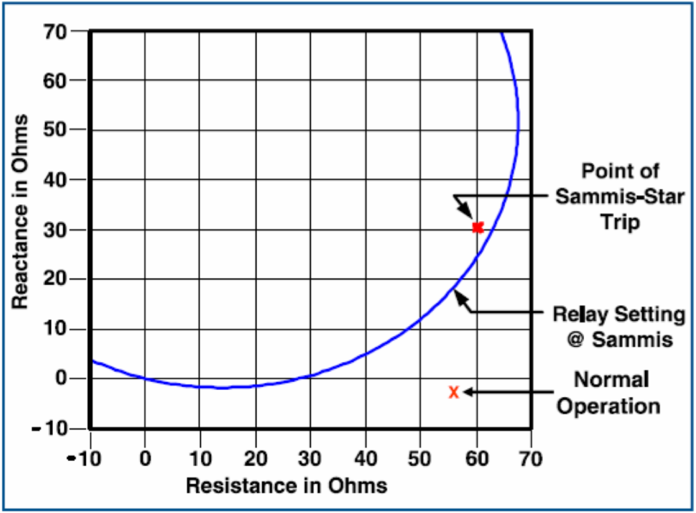
  – zone 2 may cover 120% of line but with a delay to prevent tripping for faults on adjacent lines

  – zone 3 went further; most removed due to 8/14/03 events

- The key problem is that different fault types will present the relays with different apparent impedances; adequate protection for a three-phase fault gives very limited protection for LL faults

Impedance Relay Trip Characteristics

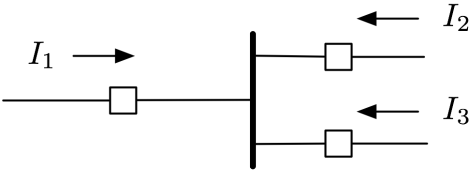
Figure 6.4. Sammis-Star 345-kV Line Trip



Source: August 14th 2003 Blackout Final Report, p. 78

Differential Relays

- Main idea behind differential protection is that during normal operation the net current into a device should sum to zero for each phase
  - transformer turns ratios must, of course, be considered
- Differential protection is used with geographically local devices
  - buses, transformers, generators



$I_1 + I_2 + I_3 = 0$ for each phase except during a fault

Other Types of Relays

- In addition to providing fault protection, relays are used to protect the system against operational problems as well
- Being automatic devices, relays can respond much quicker than a human operator and therefore have an advantage when time is of the essence
- Other common types of relays include

  – under-frequency for load: e.g., 10% of system load must be shed if system frequency falls to 59.3 Hz

  – over-frequency on generators

  – under-voltage on loads (less common)

Sequence of Events Recording

- During major system disturbances numerous relays at a number of substations may operate
- Event reconstruction requires time synchronization between substations to figure out the sequence of events
- Most utilities now have sequence of events recording that provide time synchronization of at least 1 microsecond

Use of GPS for Fault Location

- Since power system lines may span hundreds of miles, a key difficulty in power system restoration is determining the location of the fault
- One newer technique is the use of the global positioning system (GPS)
- GPS can provide time synchronization of about 1 microsecond
- Since the traveling electromagnetic waves propagate at about the speed of light (300m per microsecond), the fault location can be found by comparing arrival times of the waves at each substation