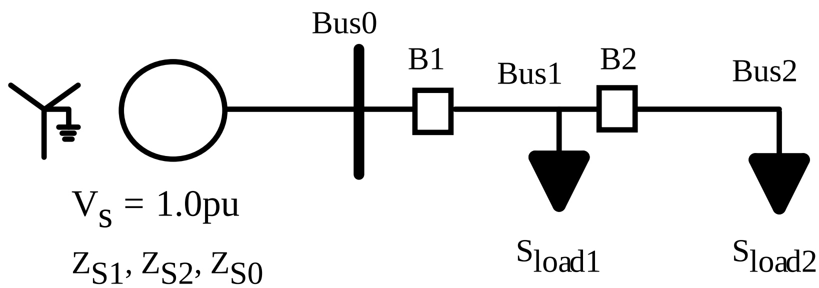
ECE 525: Setting inverse time overcurrent relays



$MVA := 1000kW$ $\quad pu := 1$

$V_{LL} := 24kV$ $\quad S_B := 100MVA$ $\quad I_b := \frac{S_B}{\sqrt{3} \cdot V_{LL}}$ $\quad I_b = 2405.63\,A$

- Source impedance

$Z_{S1} := j \cdot 0.5pu$ $\quad Z_{S0} := j \cdot 0.2pu$

- Feeder section from Bus 0 to Bus 1

$Z_{fd11} := j \cdot 1.0pu$ $\quad Z_{fd10} := j \cdot 1.5pu$

- Feeder section from Bus 0 to Bus 1

$Z_{fd21} := j \cdot 3.0pu$ $\quad Z_{fd20} := j \cdot 4.5pu$

- Complex power drawn at each load

$S_{load2} := 3MVA$ at unity power factor

$S_{load1} := 3.5MVA$ at unity power factor

- Desired coordinating time interval set to 18 cycles

$CTI := \frac{18}{60Hz}$ $\quad CTI = 0.3\,s$

- Fault current calculations (note that these shortcut equations must be applied with care)

$I_{f3phB1} := \frac{1}{Z_{S1} + Z_{fd11}}$ $\quad I_{f3phB1} = -0.67i$ $\quad I_{3ph\_bus1} := \left| I_{f3phB1} \right| \cdot I_b$

$I_{f3phB2} := \frac{1}{Z_{S1} + Z_{fd11} + Z_{fd21}}$ $I_{f3phB2} = -0.22i$ $I_{3ph\_bus2} := \left|I_{f3phB2}\right| \cdot I_b$

$I_{1LLB1} := \frac{1}{2\left(Z_{S1} + Z_{fd11}\right)}$ $I_{BCLLB1} := -j\sqrt{3} \cdot I_{1LLB1}$ $I_{LL\_bus1} := \left|I_{BCLLB1}\right| \cdot I_b$

$I_{1LLB2} := \frac{1}{2\left(Z_{S1} + Z_{fd11} + Z_{fd21}\right)}$ $I_{BCLLB2} := -j\sqrt{3} \cdot I_{1LLB2}$ $I_{LL\_bus2} := \left|I_{BCLLB2}\right| \cdot I_b$

- A more precise approach would be:

$a := 1 \cdot e^{j \cdot 120deg}$

$$A_{012} := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$$

$I_{2LLB1} := -I_{1LLB1}$

$$I_{ABC\_LL\_B1} := A_{012} \cdot \begin{pmatrix} 10^{-15} \\ I_{1LLB1} \\ I_{2LLB1} \end{pmatrix} \quad \overrightarrow{\left|I_{ABC\_LL\_B1}\right|} = \begin{pmatrix} 0 \\ 0.58 \\ 0.58 \end{pmatrix} \cdot pu \quad \overrightarrow{\arg\left(I_{ABC\_LL\_B1}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

$I_{BCLLB1} = -0.58 \cdot pu$ so these give the same result for phase B

$I_{2LLB2} := -I_{1LLB2}$

$$I_{ABC\_LL\_B2} := A_{012} \cdot \begin{pmatrix} 10^{-15} \\ I_{1LLB2} \\ I_{2LLB2} \end{pmatrix} \quad \overrightarrow{\left|I_{ABC\_LL\_B2}\right|} = \begin{pmatrix} 0 \\ 0.19 \\ 0.19 \end{pmatrix} \cdot pu \quad \overrightarrow{\arg\left(I_{ABC\_LL\_B2}\right)} = \begin{pmatrix} 0 \\ 180 \\ 0 \end{pmatrix} \cdot deg$$

$I_{ASLGB1} := \frac{3 \cdot 1}{\left[2\left(Z_{S1} + Z_{fd11}\right) + Z_{S0} + Z_{fd10}\right]}$ $I_{SLG\_bus1} := \left|I_{ASLGB1}\right| \cdot I_b$

$I_{ASLGB2} := \frac{3 \cdot 1}{\left[2\left(Z_{S1} + Z_{fd11} + Z_{fd21}\right) + Z_{S0} + Z_{fd10} + Z_{fd20}\right]}$ $I_{SLG\_bus2} := \left|I_{ASLGB2}\right| \cdot I_b$

- Again, a more precise approach is:

$$I_{0SLGB1} := \frac{1}{\left(Z_{S1} + Z_{fd11}\right) + \left(Z_{S1} + Z_{fd11}\right) + Z_{S0} + Z_{fd10}}$$

$$I_{1SLGB1} := I_{0SLGB1}$$

$$I_{2SLGB1} := I_{0SLGB1}$$

$$I_{ABC\_SLGB1} := A_{012} \cdot \begin{pmatrix} I_{0SLGB1} \\ I_{1SLGB1} \\ I_{2SLGB1} \end{pmatrix} \qquad \overrightarrow{\left|I_{ABC\_SLGB1}\right|} = \begin{pmatrix} 0.64 \\ 0 \\ 0 \end{pmatrix} \cdot pu \qquad \overrightarrow{\arg\left(I_{ABC\_SLGB1}\right)} = \begin{pmatrix} -90 \\ 18.43 \\ 18.43 \end{pmatrix} \cdot deg$$

From above:

$$I_{ASLGB1} = -0.64i$$

- Load current calculaitons

$$I_{ld1} := \frac{S_{load1}}{\sqrt{3} \cdot V_{LL}} \qquad I_{ld1\_0} := 0.175 \cdot I_{ld1}$$

$$I_{ld2} := \frac{S_{load2}}{\sqrt{3} \cdot V_{LL}} \qquad I_{ld2\_0} := 0.175 \cdot I_{ld2}$$

- Load currents:

$$I_{ld1} = 84.2\,A \qquad I_{ld1\_0} = 14.73\,A$$

$$I_{ld2} = 72.17\,A \qquad I_{ld2\_0} = 12.63\,A$$

- Fault Currents (on phase with biggest current)

$$I_{3ph\_bus1} = 1603.75\,A \qquad I_{3ph\_bus2} = 534.58\,A$$

$$I_{LL\_bus1} = 1388.89\,A \qquad I_{LL\_bus2} = 462.96\,A$$

$$I_{SLG\_bus1} = 1535.51\,A \qquad I_{SLG\_bus2} = 474.79\,A$$

- Choose to use a very inverse characteristic

$$t_{VI}(TD, M) := TD \cdot \left(\frac{3.88}{M^2 - 1} + 0.0963\right) \cdot sec$$

- Set CT Ratio for each relay location

- Total load current relay 1 (controls B1):

$I_{load\_R1} := I_{ld1} + I_{ld2}$ $\qquad$ $I_{load\_R1} = 156.37\,A$

- Set current transformer turns ratio at:

$$CTR_{R1} := \frac{160}{5}$$

- Total load current at relay 2 (controls B2)

$I_{load\_R2} := I_{ld2}$ $\qquad$ $I_{load\_R2} = 72.17\,A$

- Set current transformer turns ratio at:

$$CTR_{R2} := \frac{75}{5}$$

- Now set relay pick up for relay 2:

- First determine load current on CT secondary:

$I_{ldR2\_sec} := \dfrac{I_{load\_R2}}{CTR_{R2}}$ $\qquad$ $I_{ldR2\_sec} = 4.81\,A$

- Minimum phase fault current seen by the relay

$I_{ph\_f\_minR2\_sec} := \dfrac{I_{LL\_bus2}}{CTR_{R2}}$ $\qquad$ $I_{ph\_f\_minR2\_sec} = 30.86\,A$

- Set pick up to be appoximately between twice maximum load current and one half of minimum fault current

$2I_{ldR2\_sec} = 9.62\,A$ $\qquad$ $0.5 \cdot I_{ph\_f\_minR2\_sec} = 15.43\,A$

$I_{pu\_R2} := 10A$ $\qquad$ - This is a little under 1/3 of minimum fault current

Set time dial for relay 2 at the minimum

$TD_{R2} := 0.5$

- Calculate pick-up time for faults at the far end of the feeder

$$I_{ph\_f\_maxR2\_sec} := \frac{I_{3ph\_bus2}}{CTR_{R2}} \qquad I_{ph\_f\_maxR2\_sec} = 35.64\,A$$

$$M_{R2\_ph\_f\_bus2max} := \frac{I_{ph\_f\_maxR2\_sec}}{I_{pu\_R2}} \qquad M_{R2\_ph\_f\_bus2max} = 3.56$$

$$t_{pu\_R2\_bus2max} := t_{VI}\left(TD_{R2}, M_{R2\_ph\_f\_bus2max}\right) \qquad t_{pu\_R2\_bus2max} = 0.21\,s$$

- Now we need to set relay 1 (controls B1)

- First determine load current on relay secondary:

$$I_{ldR1\_sec} := \frac{I_{load\_R1}}{CTR_{R1}} \qquad I_{ldR1\_sec} = 4.89\,A$$

- Minimum phase fault current seen by the relay (fault at bus 2)

$$I_{ph\_f\_minR1\_sec} := \frac{I_{LL\_bus2}}{CTR_{R1}} \qquad I_{ph\_f\_minR1\_sec} = 14.47\,A$$

- Set pick up to be appoximately between twice maximum load current and one half of minimum fault current

$2I_{ldR1\_sec} = 9.77\,A$ $\qquad$ $0.5 \cdot I_{ph\_f\_minR1\_sec} = 7.23\,A$

Need to use 1.5 time load: $\quad 1.5I_{ldR1\_sec} = 7.33\,A$

$I_{pu\_R1} := 7.33A$ $\qquad$ This change will impact time dial for R1

- Now we need to choose a time dial setting based on the coordinating time interval
  - We need to use the largest fault current seen by relay 2
  - This is for a fault on the feeder side of the relay
  - The fault current is the same as the largest Bus 1 fault current
  - The fault current will be essentially the same
    * at the bus as
    * at the breaker (on either side of the breaker

- Determine the relay R2 response time

$$M_{R2\_If\_max} := \frac{\left(\frac{I_{3ph\_bus1}}{CTR_{R2}}\right)}{I_{pu\_R2}} \qquad M_{R2\_If\_max} = 10.69$$

$$t_{pu\_R2\_If\_max} := t_{VI}\left(TD_{R2}, M_{R2\_If\_max}\right) \qquad t_{pu\_R2\_If\_max} = 0.065\,s$$

- Desired minimum pick up time relay 1 for a bus 1 fault:

$$t_{pu\_R1\_desired} := t_{pu\_R2\_If\_max} + CTI \qquad t_{pu\_R1\_desired} = 0.365\,s$$

- Now find M for relay 1 for this fault

$$M_{R1\_If\_max} := \frac{\left(\frac{I_{3ph\_bus1}}{CTR_{R1}}\right)}{I_{pu\_R1}} \qquad M_{R1\_If\_max} = 6.84$$

- Now rewrite the response time equation so we can solve for time dial setting
- Note that we could also do this step graphically

$$TD_{VI}\left(t_{req}, M\right) := \frac{\frac{t_{req}}{sec}}{\left(\frac{3.88}{M^2 - 1} + 0.0963\right)}$$

$$TD_{R1} := TD_{VI}\left(t_{pu\_R1\_desired}, M_{R1\_If\_max}\right)$$

$$TD_{R1} = 2.02$$

Set TD to nearest 0.1:

$$TD_{R1\_set} := 2.1$$

$$t_{VI}\left(TD_{R1\_set}, M_{R1\_If\_max}\right) = 0.38\,s$$

So we see a time interval of:

$$t_{VI}\left(TD_{R1\_set}, M_{R1\_If\_max}\right) - t_{VI}\left(TD_{R2}, M_{R2\_If\_max}\right) = 0.315\,s \quad \text{Meets criteria}$$

- Now check the coordination with the other extreme:

$$M_{R1\_If\_min} := \frac{\left(\frac{I_{LL\_bus2}}{CTR_{R1}}\right)}{I_{pu\_R1}} \qquad M_{R1\_If\_min} = 1.97$$

$$M_{R2\_If\_min} := \frac{\left(\frac{I_{LL\_bus2}}{CTR_{R2}}\right)}{I_{pu\_R2}} \qquad M_{R2\_If\_min} = 3.09$$

$$t_{VI}\left(TD_{R1\_set}, M_{R1\_If\_min}\right) - t_{VI}\left(TD_{R2}, M_{R2\_If\_min}\right) = 2.74\,s$$

Other types of elements:

- Ground elements: set Ipu based on the worst case zero sequence load current
  - Make sure you are clear on whether you are using I0 or IR = 3I0 (residual current)
- Negative sequence elements use a similar criteria.

Adding an instantaneous element at B1 to increase response time for a close-in, high current faults.

- Calculate 3 phase fault current 60% of the length of the feeder.

$$I_{f3phpu60\%} := \frac{1}{Z_{S1} + 0.6 \cdot Z_{fd11}} \qquad I_{f3phpu60\%} = -0.91i \qquad I_{f3ph60\%} := \left|I_{f3phpu60\%}\right| \cdot I_b$$

$$I_{f3ph60\%} = 2186.93\,A$$

- Convert secondary amps

$$I_{f3ph60\%\_sec} := \frac{I_{f3ph60\%}}{CTR_{R1}} \qquad I_{f3ph60\%\_sec} = 68.34\,A$$

- Round this value up and use this as the pick up setting for the 50P (instantaneous) element

$$I_{R1\_50\_set} := 70A$$

- Combine this with the output for the 51 element for R1 using a Mathcad If-Then-Else element
- Also convert the response of the 50 element to be functions of M (not generally done otherwise)

$$t_{R1}(M) := \begin{cases} \dfrac{t_{VI}\left(TD_{R1\_set}, M\right)}{sec} & \text{if } 0 \le M \le \dfrac{I_{R1\_50\_set}}{I_{pu\_R1}} \\ 0.00001 & \text{otherwise} \end{cases}$$

$$M := 1, 1.1 .. 100$$