Charging current: basics, compensation, approximations, errors, and remediation

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2024 Texas A&M Protective Relay Conference

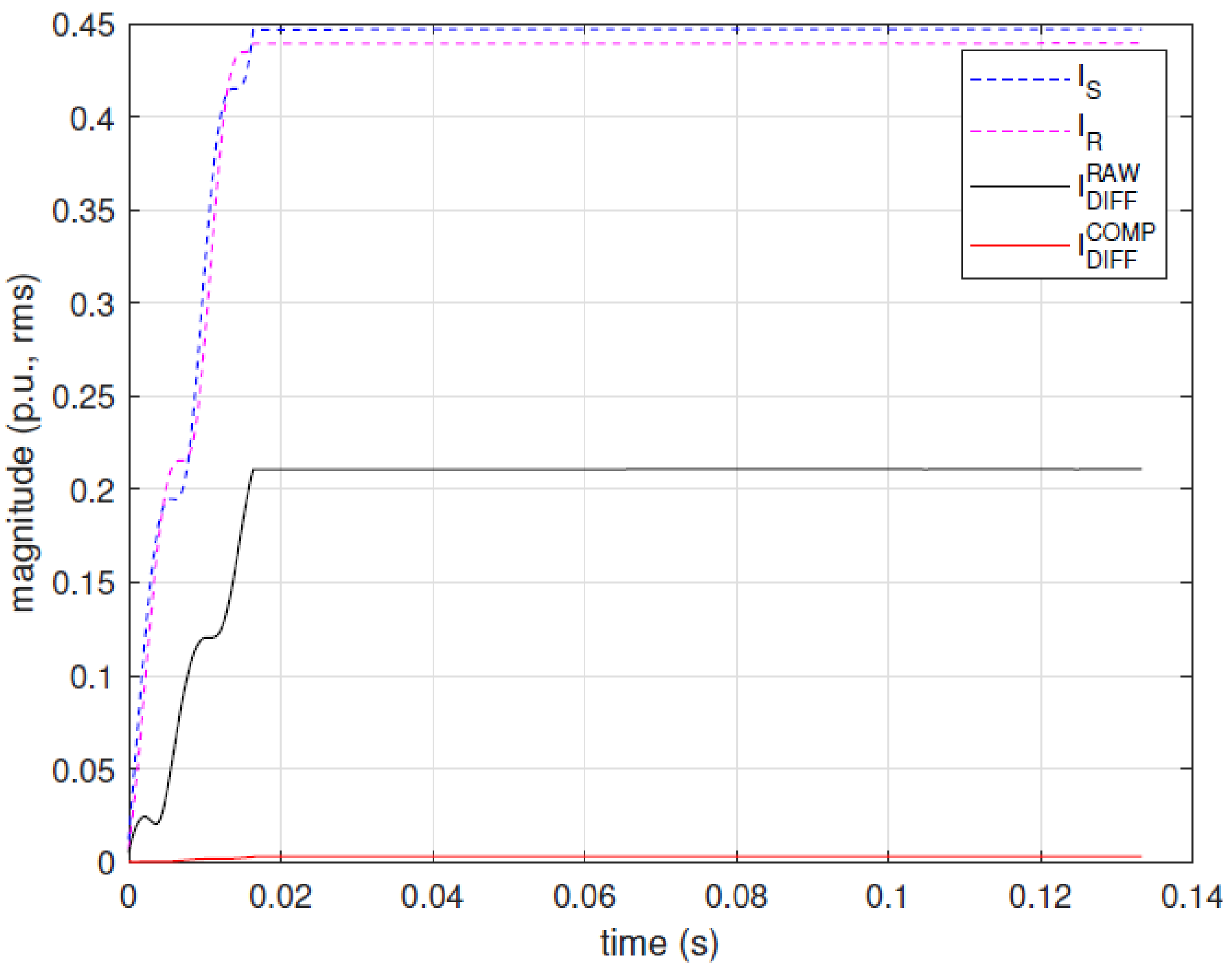
Agenda

- Introduction
- Shunt Capacitance estimation
  - Analytical method
  - From recorded waveforms
- Charging current estimation
- Methods of charging current compensation for 87L
- Shunt reactors and charging current compensation
- Field case: Improper compensation and mal-operation
- Recommendations and conclusion

Charging Current

Charging Current:

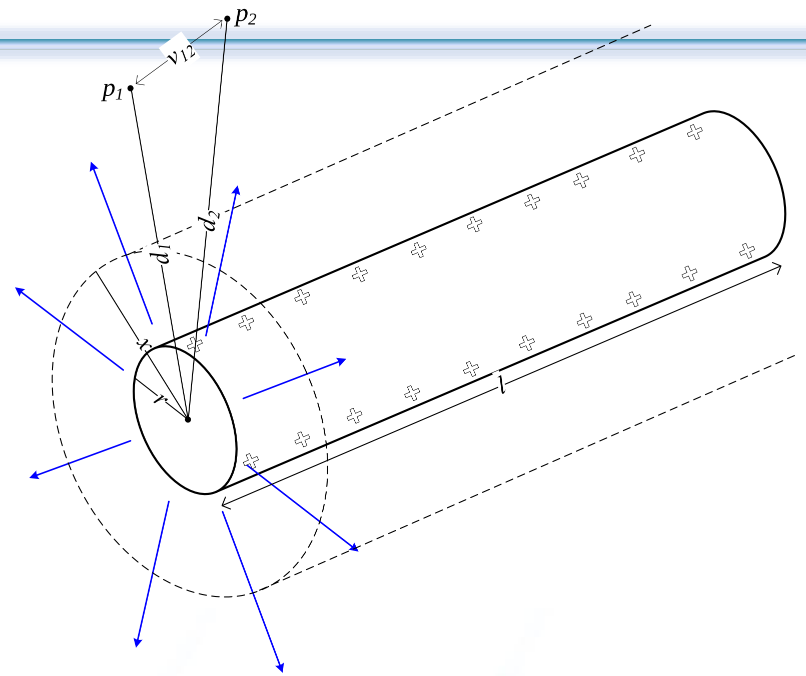
- caused by shunt capacitance.
- appears as fictitious differential current.
- reduces the security margin of 87L
- increases with line length and system voltage



Shunt capacitance: Analytical Estimation

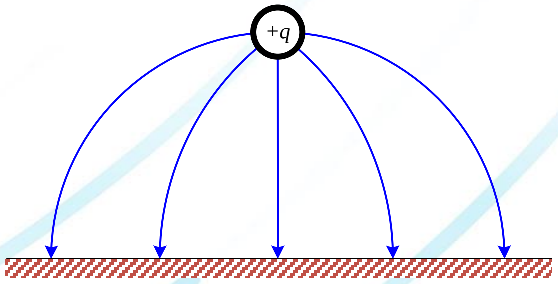
Potential difference between two points *p1* and *p2* located at distance *d1* and *d2* given by:

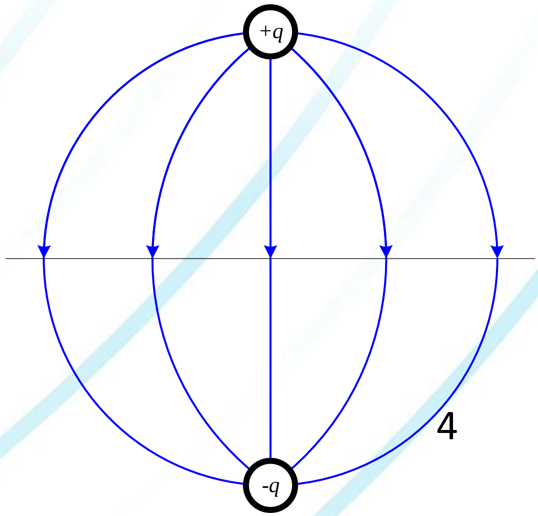
$$V_{12} = \int_{d1}^{d2} \frac{q}{2\pi\epsilon_0 x} dx = \frac{q}{2\pi\epsilon_0} \ln\frac{d2}{d1}$$



Effect of earth:

- Earth is approximated as a perfect conducting surface.
- A mirror image of the conductor but with opposite polarity accounts for the presence of the earth





Shunt capacitance: Analytical Estimation

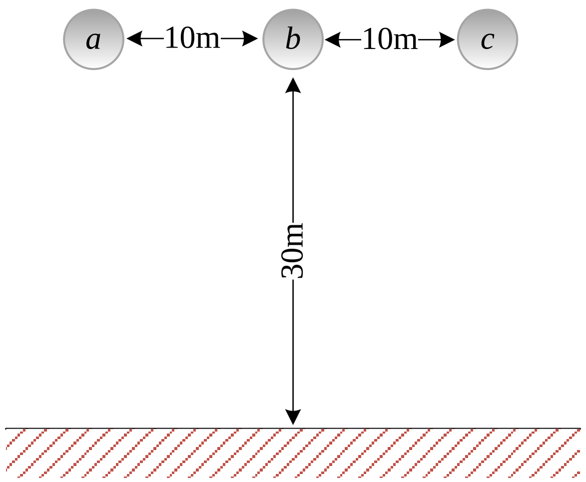
Based on formula $V_{12} = \frac{q}{2\pi\varepsilon_0 x} ln\frac{d2}{d1}$,

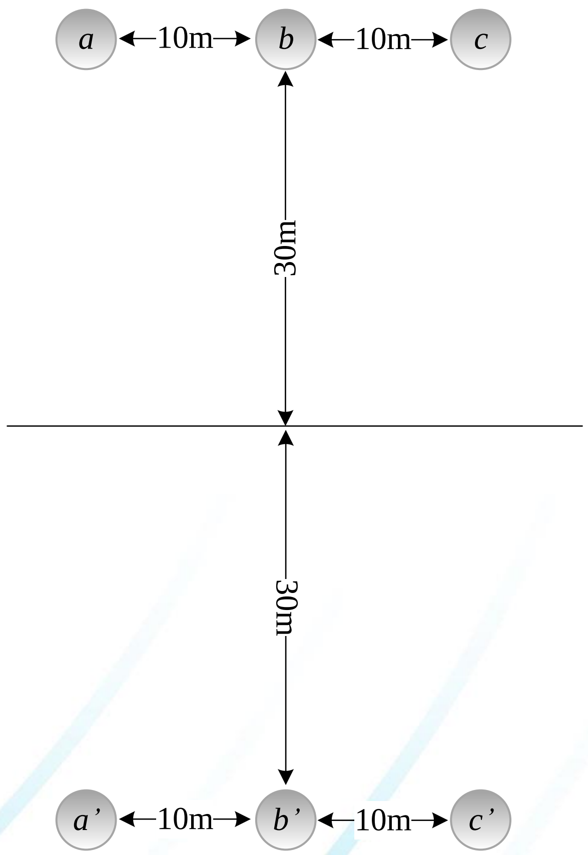
the equation for $V_{aa'}$ becomes:

$$V_{aa'} = \frac{2}{2\pi\epsilon_0}[q_a \ln\frac{D_{aa'}}{r} + q_b \ln\frac{D_{a'b}}{D_{ab}} + q_c \ln\frac{D_{a'c}}{D_{ac}}]V$$

Since $V_{an} = \frac{1}{2}V_{aa'}$

$$V_{an} = \frac{1}{2\pi\epsilon_0}[q_a \ln\frac{D_{a'a}}{r} + q_b \ln\frac{D_{a'b}}{D_{ab}} + q_c \ln\frac{D_{a'c}}{D_{ac}}]V$$



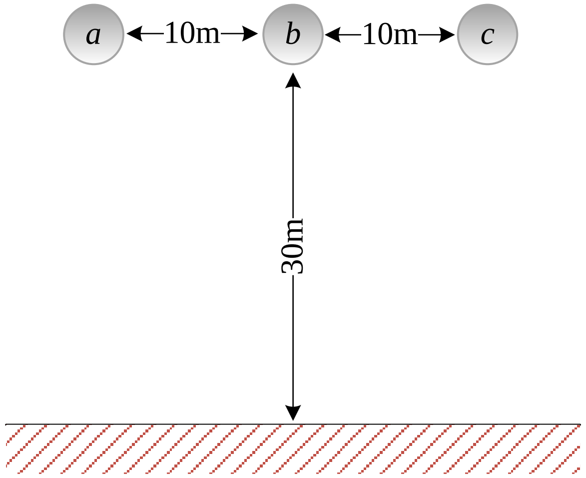


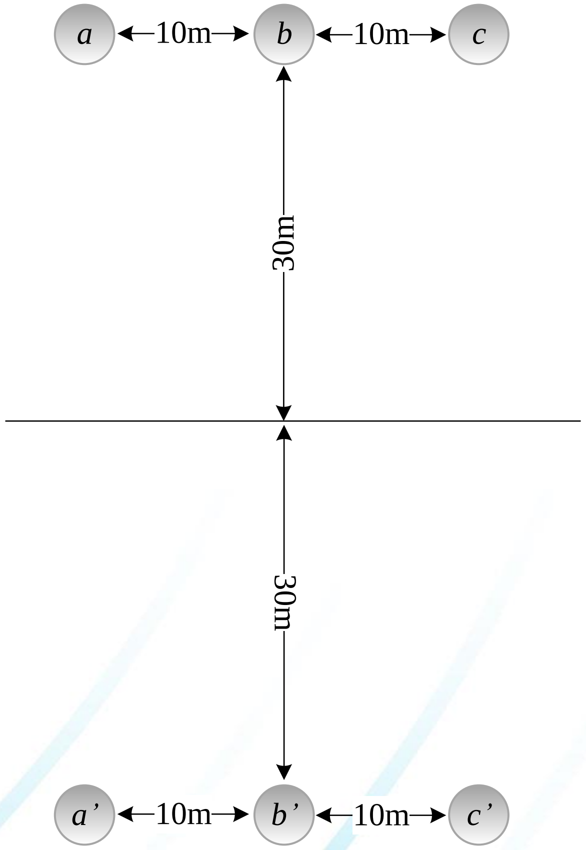
Shunt capacitance: Analytical Estimation

Similarly, writing equations for V_{bn}, V_{cn}

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{2\pi\epsilon_0} \begin{bmatrix} \ln\frac{D_{a'a}}{r} & \ln\frac{D_{a'b}}{D_{ab}} & \ln\frac{D_{a'c}}{D_{ac}} \\ \ln\frac{D_{b'a}}{D_{ba}} & \ln\frac{D_{b'b}}{r} & \ln\frac{D_{b'c}}{D_{bc}} \\ \ln\frac{D_{c'a}}{D_{ca}} & \ln\frac{D_{c'b}}{D_{cb}} & \ln\frac{D_{c'c}}{r} \end{bmatrix} \begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix}$$

$[C]^{-1}$





The above equation provides shunt capacitance values just by entering dimensions of the conductors and its geometrical arrangement.

Shunt capacitance: Estimation from waveforms

The shunt reactance (or capacitance) values could also be obtained from recorded waveforms.

Known fact: if charging current is not enabled then differential current observed for an external fault is the charging current, i.e.,

$$I_{kS} + I_{kR} = \frac{V_{kS}}{2X_{Ck}} + \frac{V_{kR}}{2X_{Ck}}$$

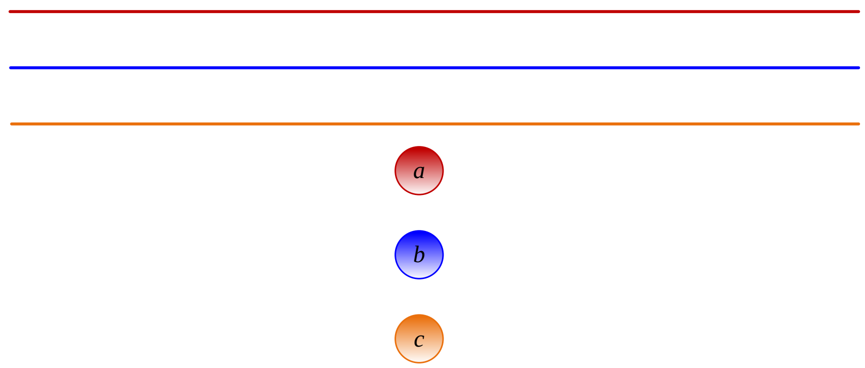
OR

$$X_{Ck} = \frac{V_{kS} + V_{kR}}{2(I_{kS} + I_{kR})}$$

where k= 0 for zero-sequence; 1 for positive sequence domains.

Shunt capacitance: Transposition

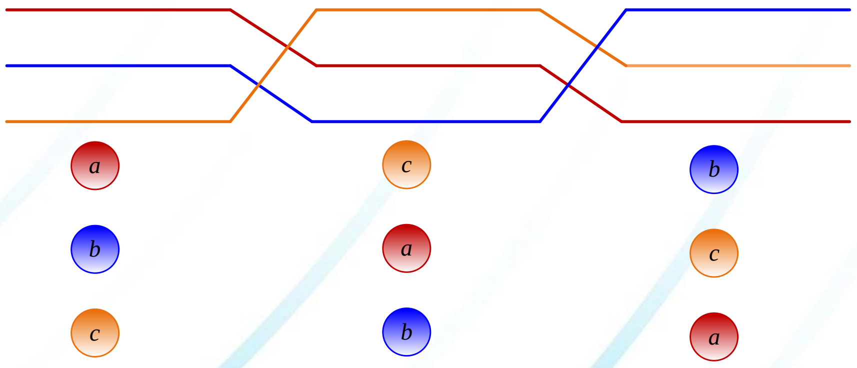
Untransposed line:



- Phase domain

$$\begin{bmatrix} C_{aa} & C_{ab} & C_{ac} \\ C_{ab} & C_{bb} & C_{bc} \\ C_{ac} & C_{bc} & C_{cc} \end{bmatrix} = \begin{bmatrix} 1.0490 & -0.2840 & -0.1173 \\ -0.2840 & 1.1128 & -0.2840 \\ -0.1173 & -0.2840 & 1.0490 \end{bmatrix} \times 10^{-8} \frac{F}{km}$$

Fully transposed line:



- Phase domain

$$\begin{bmatrix} C_{aa} & C_{ab} & C_{ac} \\ C_{ab} & C_{bb} & C_{bc} \\ C_{ac} & C_{bc} & C_{cc} \end{bmatrix} = \begin{bmatrix} 1.0596 & -0.2240 & -0.2240 \\ -0.2240 & 1.0596 & -0.2240 \\ -0.2240 & -0.2240 & 1.0596 \end{bmatrix} \times 10^{-8} \frac{F}{km}$$

- Sequence domain

$$\begin{bmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} 0.6116 & 0 & 0 \\ 0 & 1.2837 & 0 \\ 0 & 0 & 1.2837 \end{bmatrix} \times 10^{-8} \frac{F}{km}$$

Charging current Estimation

The charging current in each phase can be estimating through following equations using:

- Phase shunt capacitances:

$$\begin{bmatrix} i_{aC} \\ i_{bC} \\ i_{cC} \end{bmatrix} = \begin{bmatrix} C_s & C_m & C_m \\ C_m & C_s & C_m \\ C_m & C_m & C_s \end{bmatrix} \frac{\partial}{\partial t} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

- Sequence shunt capacitances:

$$\begin{bmatrix} i_{aC} \\ i_{bC} \\ i_{cC} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} C_0 + 2C_1 & C_0 - C_1 & C_0 - C_1 \\ C_0 - C_1 & C_0 + 2C_1 & C_0 - C_1 \\ C_0 - C_1 & C_0 - C_1 & C_0 + 2C_1 \end{bmatrix} \frac{\partial}{\partial t} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

- Sequence shunt reactances:

$$\begin{bmatrix} i_{aC} \\ i_{bC} \\ i_{cC} \end{bmatrix} = \frac{1}{3\omega} \begin{bmatrix} \frac{1}{X_{C0}} + \frac{2}{X_{C1}} & \frac{1}{X_{C0}} - \frac{1}{X_{C1}} & \frac{1}{X_{C0}} - \frac{1}{X_{C1}} \\ \frac{1}{X_{C0}} - \frac{1}{X_{C1}} & \frac{1}{X_{C0}} + \frac{2}{X_{C1}} & \frac{1}{X_{C0}} - \frac{1}{X_{C1}} \\ \frac{1}{X_{C0}} - \frac{1}{X_{C1}} & \frac{1}{X_{C0}} - \frac{1}{X_{C1}} & \frac{1}{X_{C0}} + \frac{2}{X_{C1}} \end{bmatrix} \frac{\partial}{\partial t} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Charging current compensation

Methods of mitigating the effects of charging current on 87L:

- Higher Cut-off for 87L
  - ❑ Straightforward but desensitizes the 87L element.

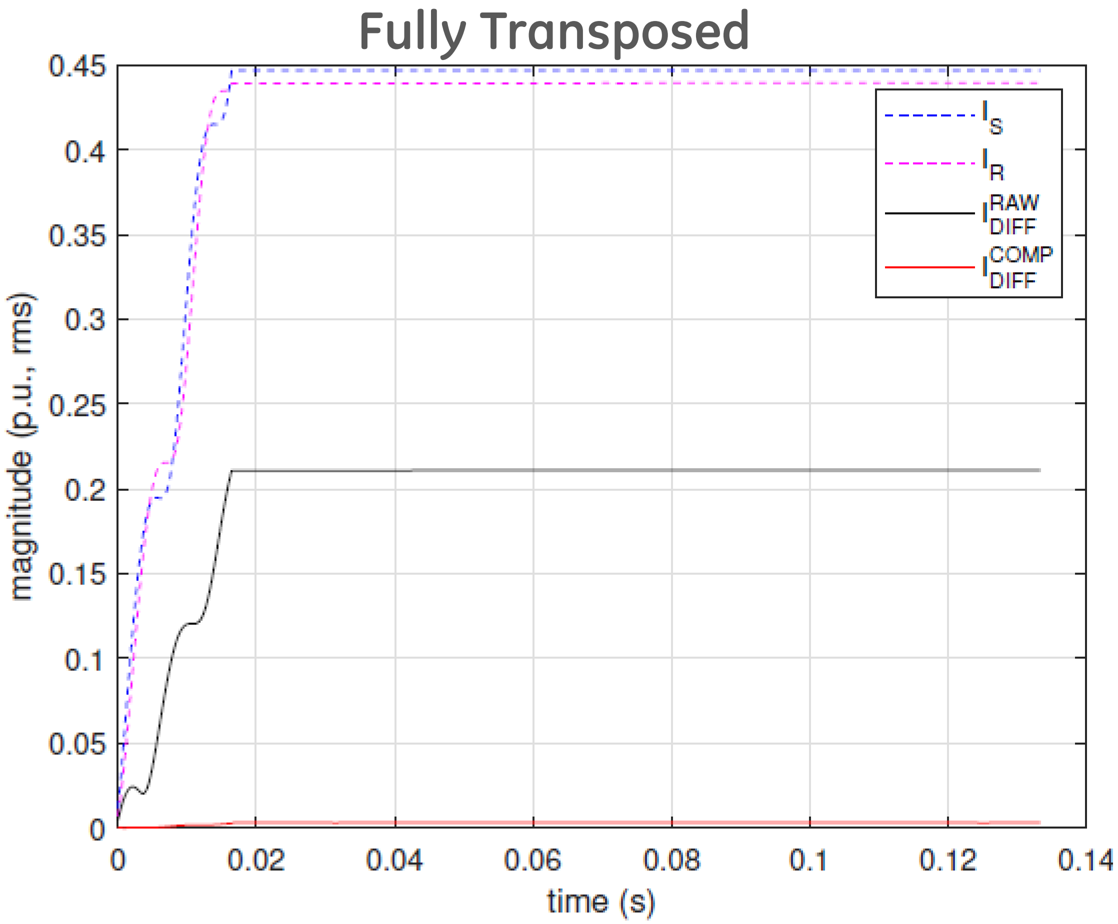
- Fixed charging current compensation
  - ❑ Involves subtracting the fixed current (pre-calculated).
  - ❑ Loses accuracy during external faults or due to change in voltage of the system.

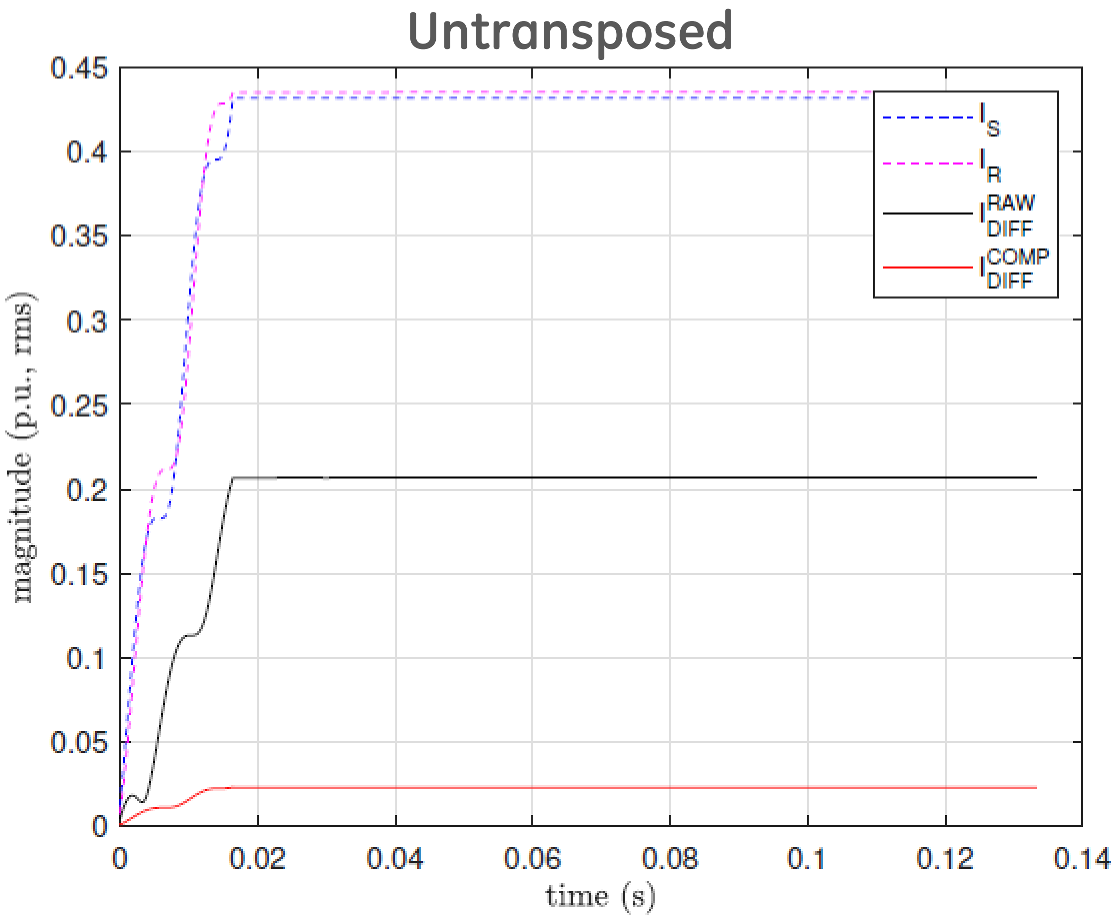
- Voltage measurement-based charging current compensation
  - ❑ Adaptive compensation depending upon voltage level.
  - ❑ Maintains accuracy during external faults and other disturbances.
  - ❑ Can be generalized for multi-ended transmission lines

Charging current compensation: Example

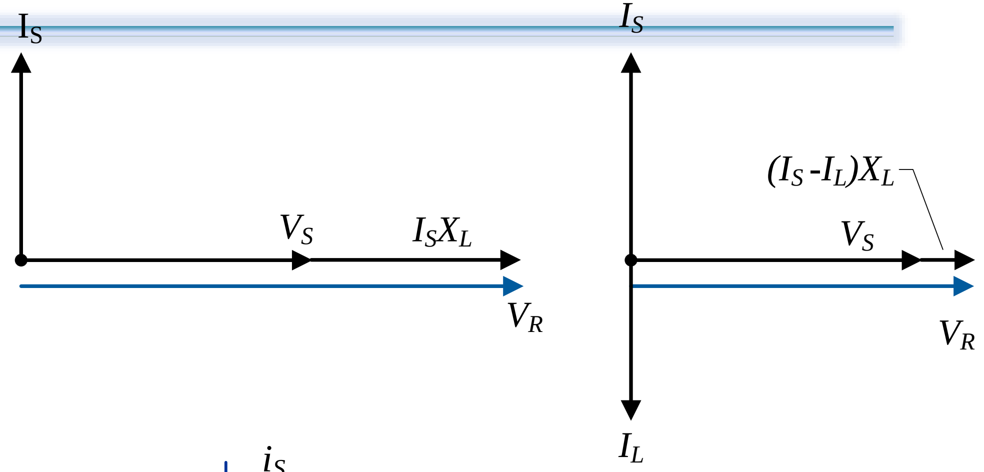
Line Length: 300km System Voltage:500kV CT ratio 2000:5

$C_1 = 1.2858\times10^{-8}$ F/km $C_0 = 0.6120 \times 10^{-8}$ F/km

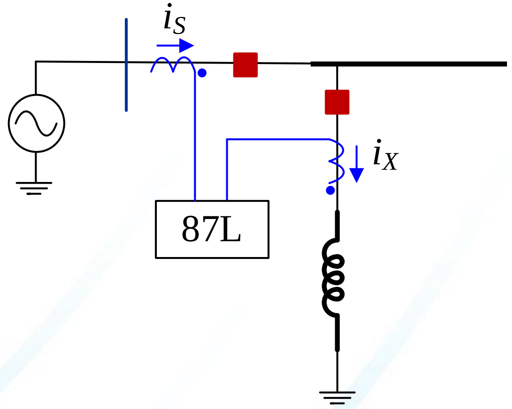




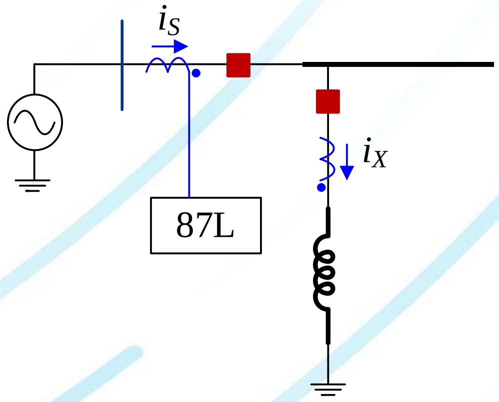
Charging current compensation: Shunt Reactors



- Shunt reactors are added to compensate the Ferranti Effect (elevated receiving end voltage during light or no load conditions)



- If the reactor is excluded from the protected zone, the compensated is applied using line shunt reactance values only.



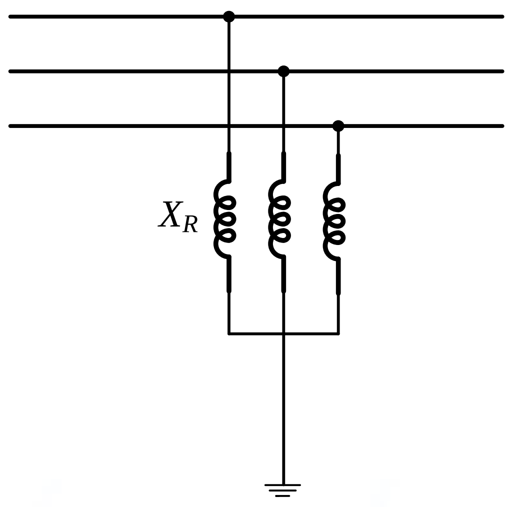
- If reactor is included in the protection zone, the compensation is applied by using the reactance of the parallel combination of line reactance and reactance of the shunt reactors.

Charging current compensation: Shunt Reactors

- Three reactor arrangement:

$$X'_{C1} = \frac{X_R X_{C1}}{X_R - X_{C1}}$$

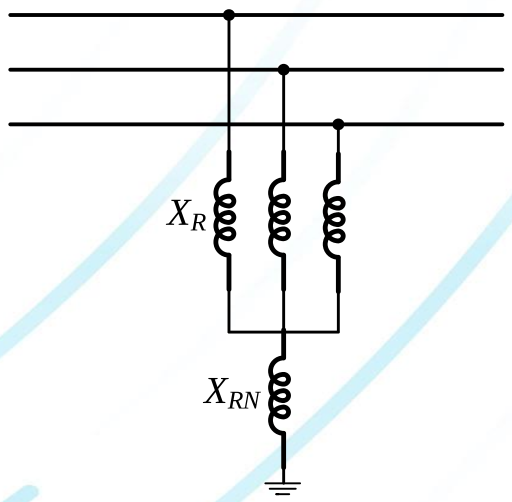
$$X'_{C0} = \frac{X_R X_{C0}}{X_R - X_{C0}}$$



- Four reactor arrangement:

$$X'_{C1} = \frac{X_R X_{C1}}{X_R - X_{C1}}$$

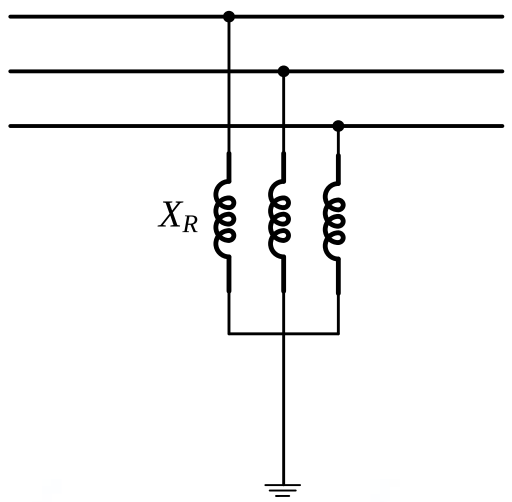
$$X'_{C0} = \frac{(X_R + 3X_{RN}) X_{C0}}{X_R + 3X_{RN} - X_{C0}}$$



Charging current compensation: Field Case

System description:

- Transmission line: 230kV 256km long
- CT ratio: 1250:1 (1A secondary)
- Line shunt reactances: X_{C1} = 810.0Ω, X_{C0} = 1322.5Ω
- Reactor bank (3-reactor arrangement): 1322.5Ω/ph (included in zone)
- Effective line shu



$$X'_{C1} = \frac{1322.5 \times 810.0}{1322.5 - 810.0} = 2090.2\Omega$$

$$X'_{C0} = \frac{1322.5 \times 1422.3}{1322.5 - 1422.3} = -18847.6\Omega$$

- The negative value of X'_{C0} signifies that the effective zero-sequence reactance is inductive in nature.
- High value of X'_{C0} is signifies the charging current for worst case external fault will be very small (less than 5A primary).

Charging current compensation: Field Case

87L element

- Minimum PKP: 0.2pu.
- Charging current based on (X'_{C1}=2090.2): 0.05pu
- Security margin: 0.2 - 0.05 = 0.15pu

$$X'_{C1} = \frac{1322.5 \times 810.0}{1322.5 - 810.0} = 2090.2\Omega$$

$$X'_{C0} = \frac{1322.5 \times 1422.3}{1322.5 - 1422.3} = -18847.6\Omega$$

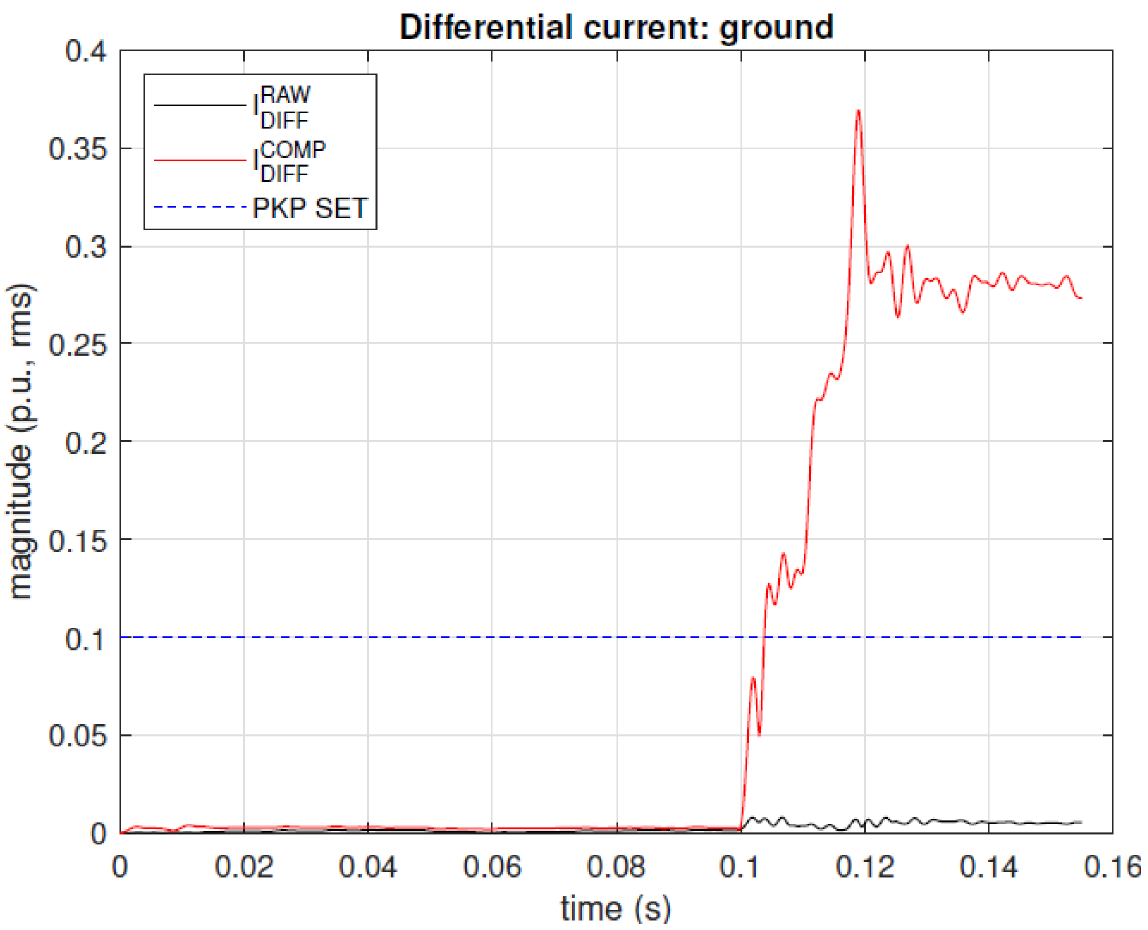
87LG element

- minimum PKP: 0.10pu
- Charging current based on (X'_{C0}=-18847.6) ≈ 0pu
- Security margin: 0.1 – 0 = 0.10pu

The charging current compensation was not necessary as significant security margin existed for 87L and 87LG elements

Charging current compensation: Field Case

- The charging current compensation was applied 87L to further increase security margin but mistake was made element
- The relay did not allow negative value setting for X'_{C0}.
- User entered the lowest positive setting value for X'_{C0}. (leading to erroneous and large charging current compensation in zero-sequence domain).



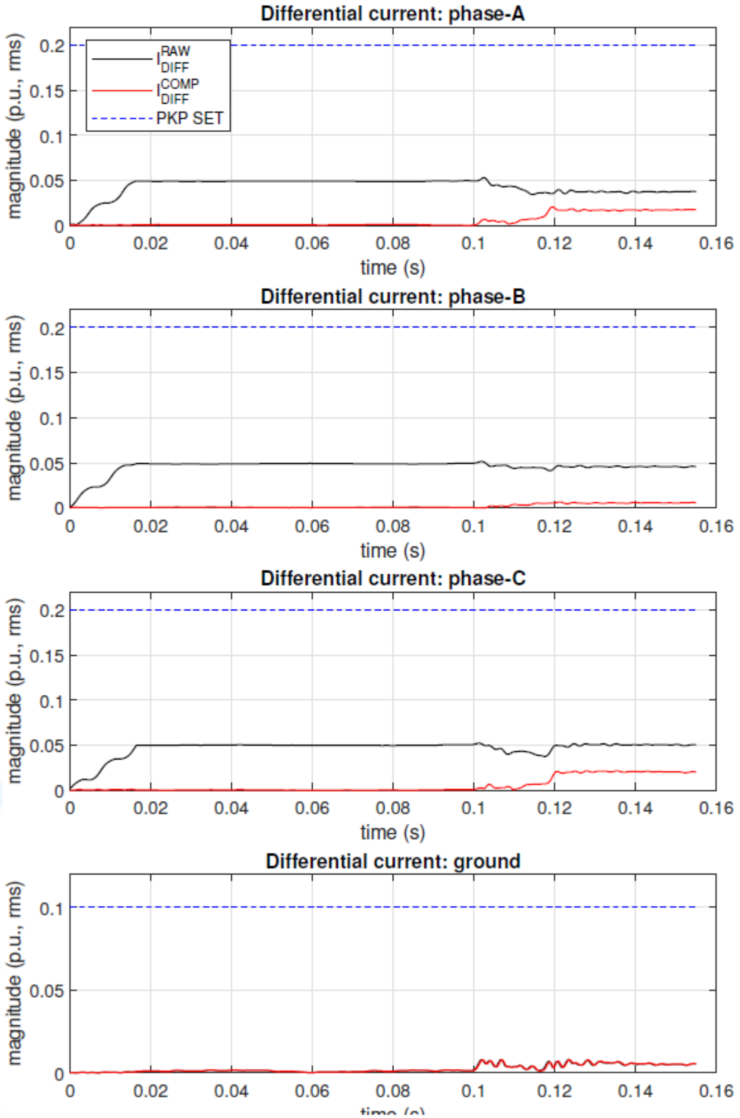
Field Case of an external ACG fault: Raw and compensated ground differential current.

Charging current compensation: Field Case

Correct way to apply charging current compensation for such case (though not necessary):

- Enter the correct value for X'_{C1} (=2090.2).
- Enter the largest positive setting for X'_{C0}.

This ensures that correct charging current compensation is applied to positive and negative sequence domains while not affecting zero-sequence domain considerably.



Field Case of an external ACG fault: Raw and compensatec differential current in phases-A, B, C and ground channel.

Charging current compensation: recommendations

- Line zero-sequence capacitive reactance XC0 should always be higher than line positive-sequence capacitive reactance XC1.
- If reactors are present and can be switched in or out, charging current needs to be estimated for both conditions to make a decision as to whether you should apply compensation or not.
- If the pu charging current of the CT nominal in the worst configuration (when reactors are switched) is less than half of the 87L pickup setting, then charging current compensation is not needed, as there is enough security margin.

Charging current compensation: recommendations

- Typically, the 87L (or 87LG) pickup setting should be at least 1.5 times higher than the worst-case charging current when charging current compensation is enabled.
- When charging current compensation is disabled it has to be set to at least 2.5 times the worst-case charging current or higher.
- The charging current compensation should not be aimed at completely eradicating the 'fictitious' differential.

Thank You

Questions?