

87L Application on Long Transmission Line with Series Capacitor Banks and Shunt Reactors

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Outline

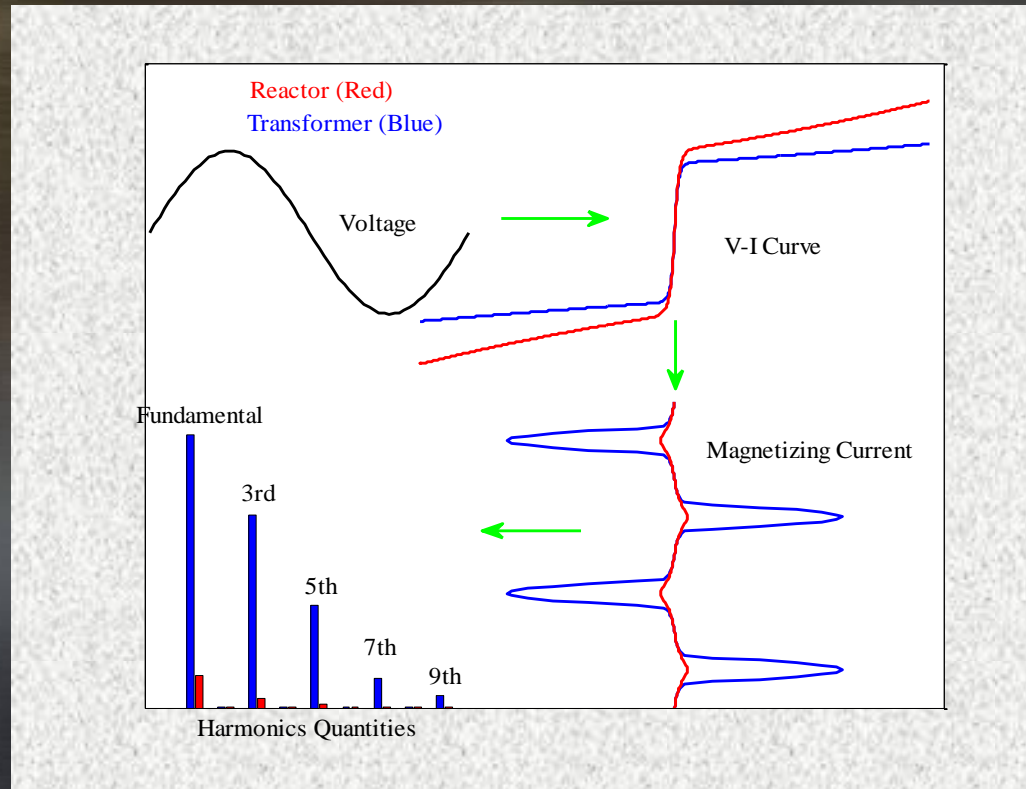
- Principles and applications of series capacitor banks and shunt reactors.
- Effects of shunt reactors on power systems under normal and fault conditions.
- Effects of series capacitor banks on power systems – Voltage/current inversion, sub-harmonic transient.
- Line differential relay application, solution, configuration, communication, and setting recommendation.

Shunt Reactors – Applications

- Reduce voltage rise during light load;
- Reduce overvoltage on healthy phases during SLG fault;
- Absorb reactive power;
- Prevent overvoltage caused by generator self-excitation on capacitive loads;
- Prevent over-excitation of power transformers caused by overvoltage;
- Suppress secondary arc with a neutral reactor.

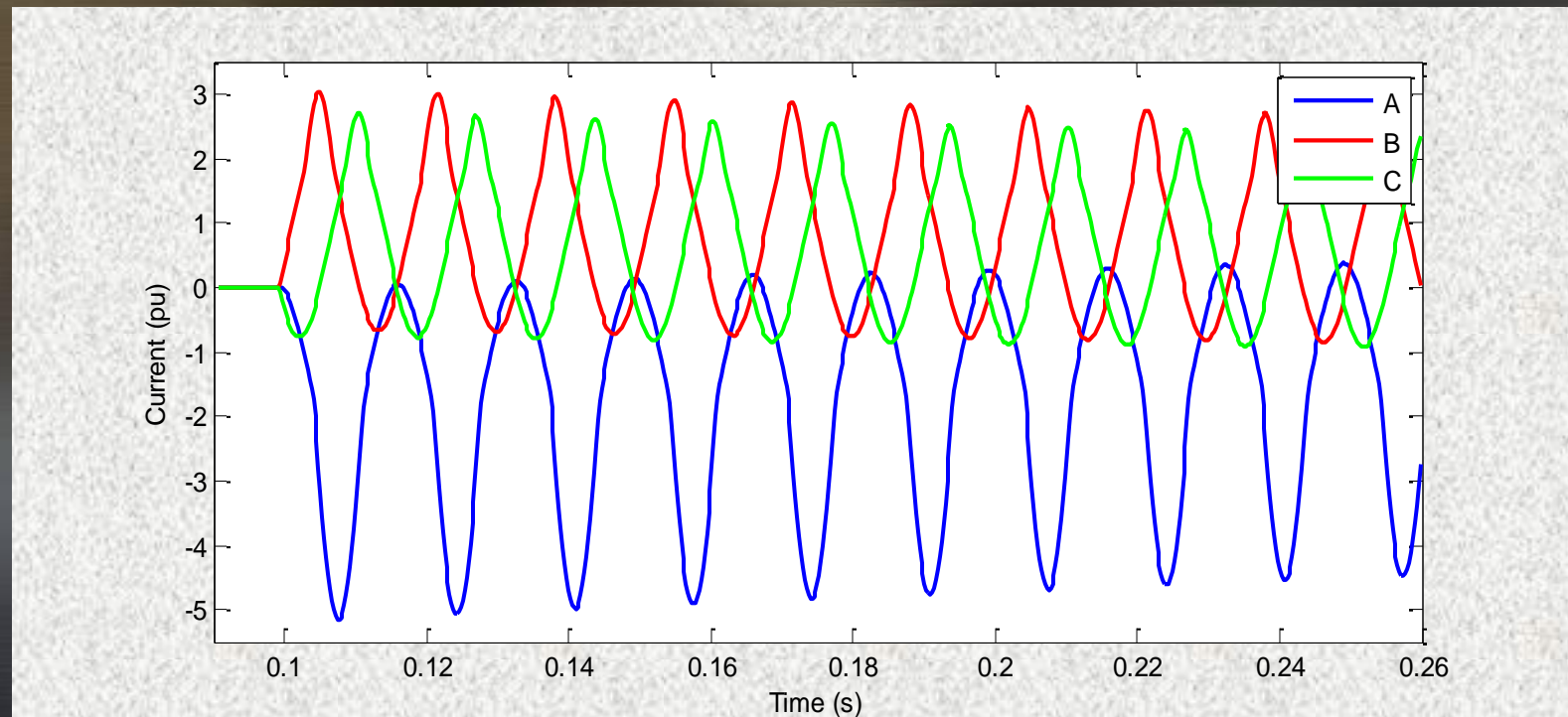
Reactors – Overvoltage

- Unlikely to experience core saturation compared with transformers under the same overvoltage;
- Under saturation, the third and fifth harmonics are dominant, but have very small effects and no practical impairment on the performance of protection.



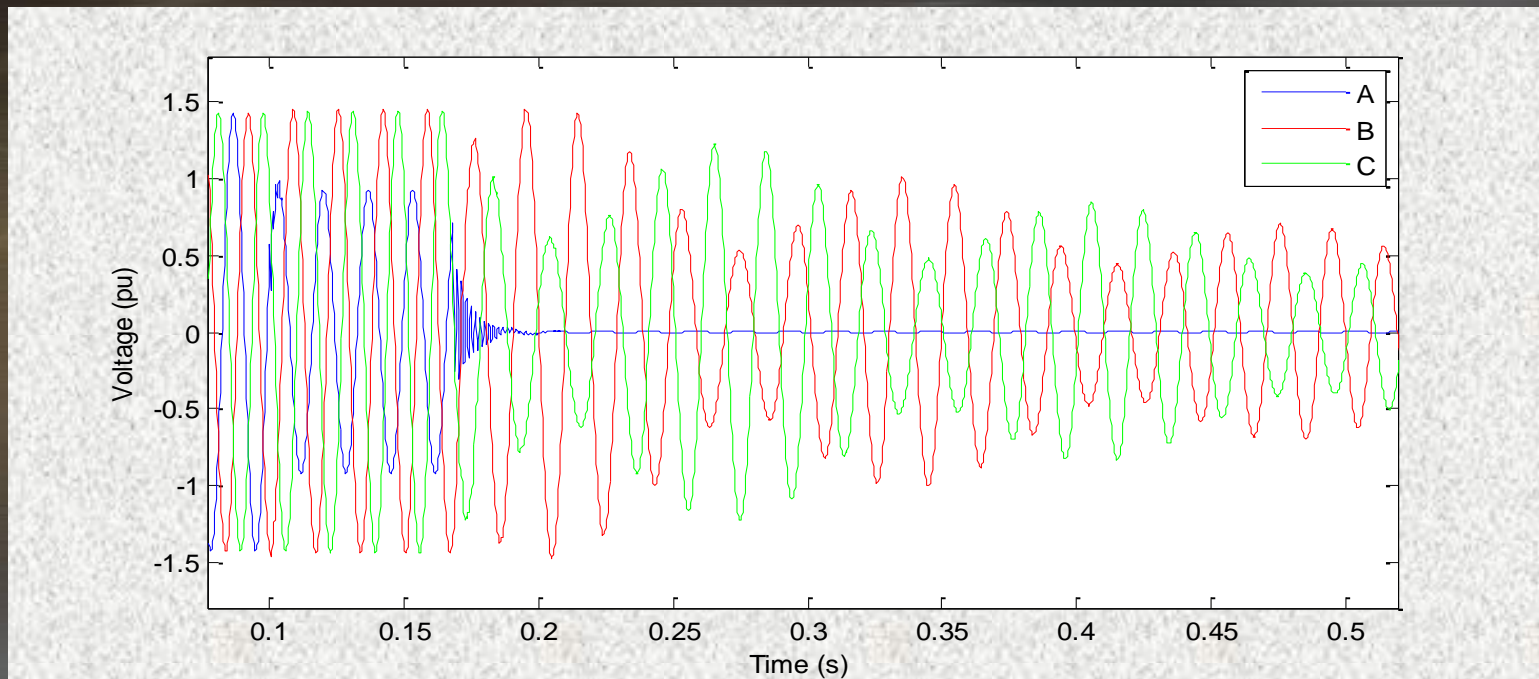
Reactors – Switch-in

- Magnetic core reactors is prone to inrush currents during switching-in;
- Experience core saturation;
- Generate slightly distorted current, but with a significant dc component.



Reactors – Resonance

- After a three-pole tripping, healthy phase(s) of shunt reactor starts resonance with the line capacitance.



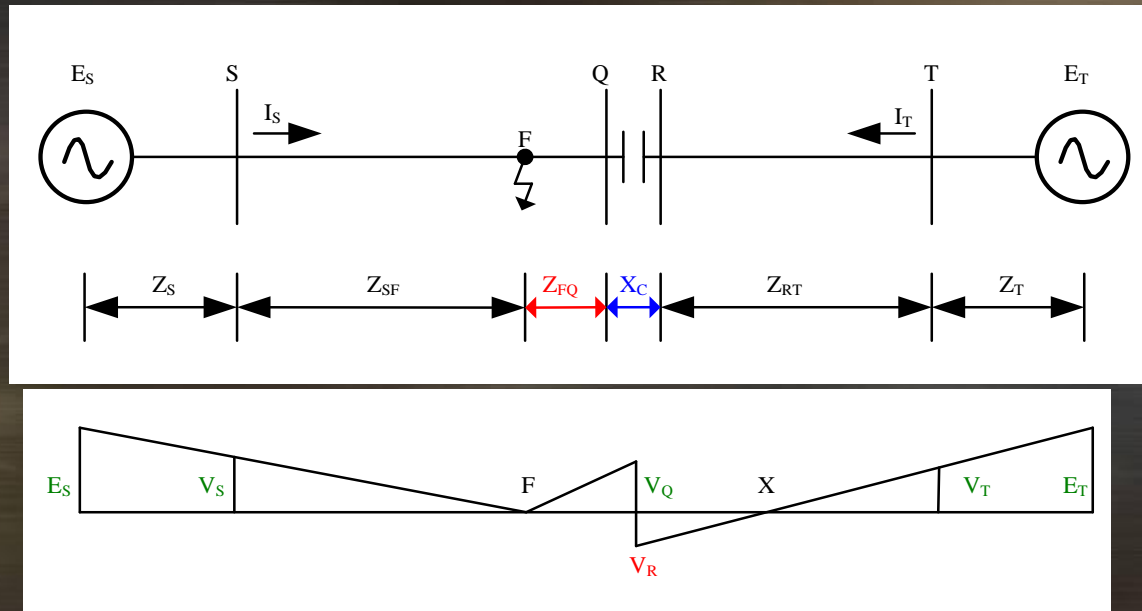
- Resonance frequency is less than the system frequency, can be approximated by

$$f_R = f_0 \sqrt{\frac{\eta}{100}}$$

Series Capacitor Banks – Applications

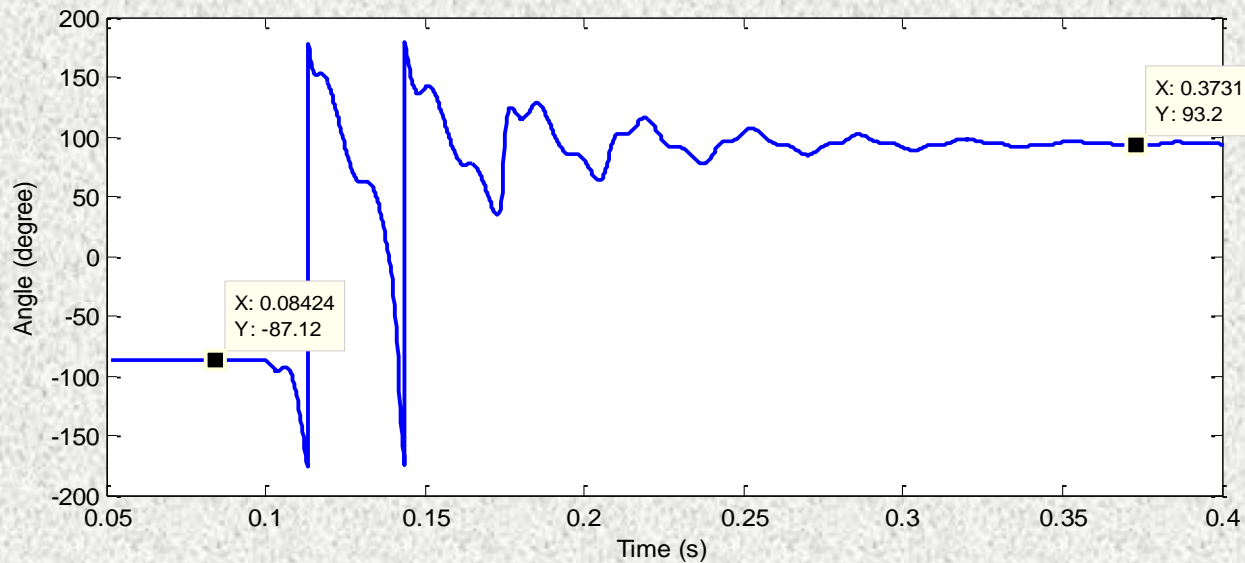
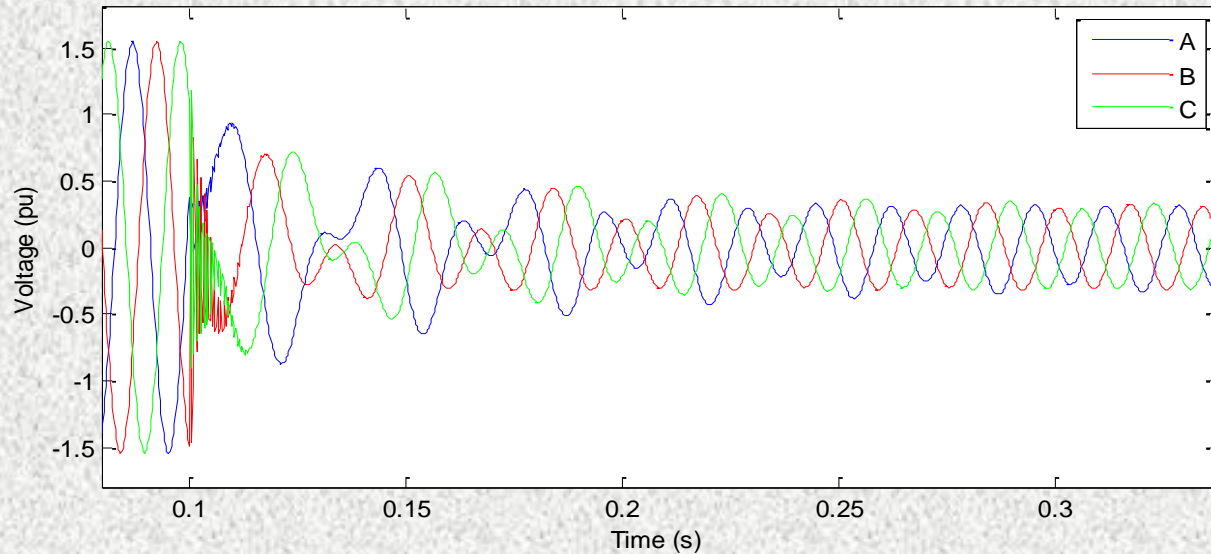
- Improve power transfer capacity;
- Improve angular stability;
- Dynamically adjust voltage profile, depending on the load current.

Capacitors – Voltage Inversion

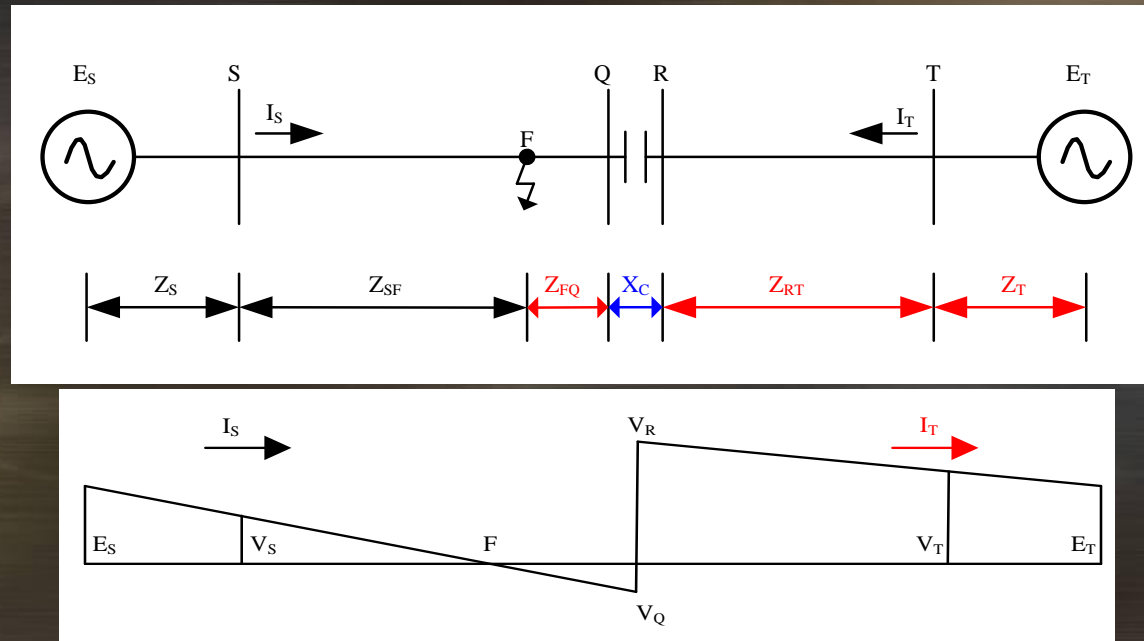


- The occurrence of voltage inversion depends on the fault location; if the fault point is far away from the capacitor, there may not be a voltage inversion.
- If there is a voltage inversion, the bus side voltage (V_R) has 180 degree angle difference from the source voltage (E_T).
- If there is a voltage inversion, the line side voltage (V_Q) has no inversion.

Capacitors – Voltage Inversion

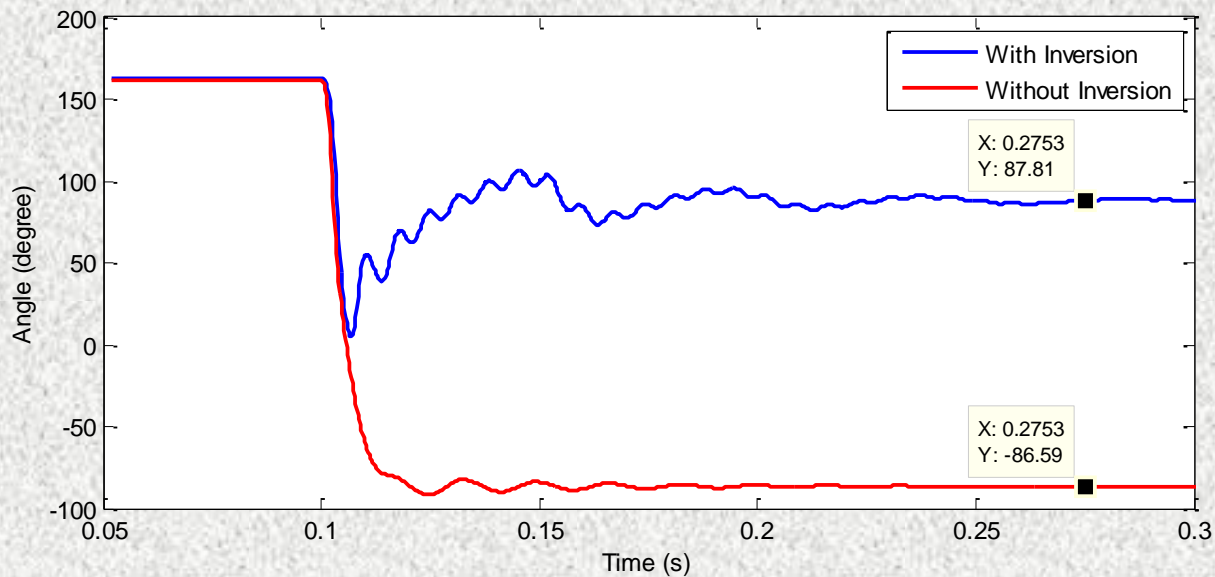
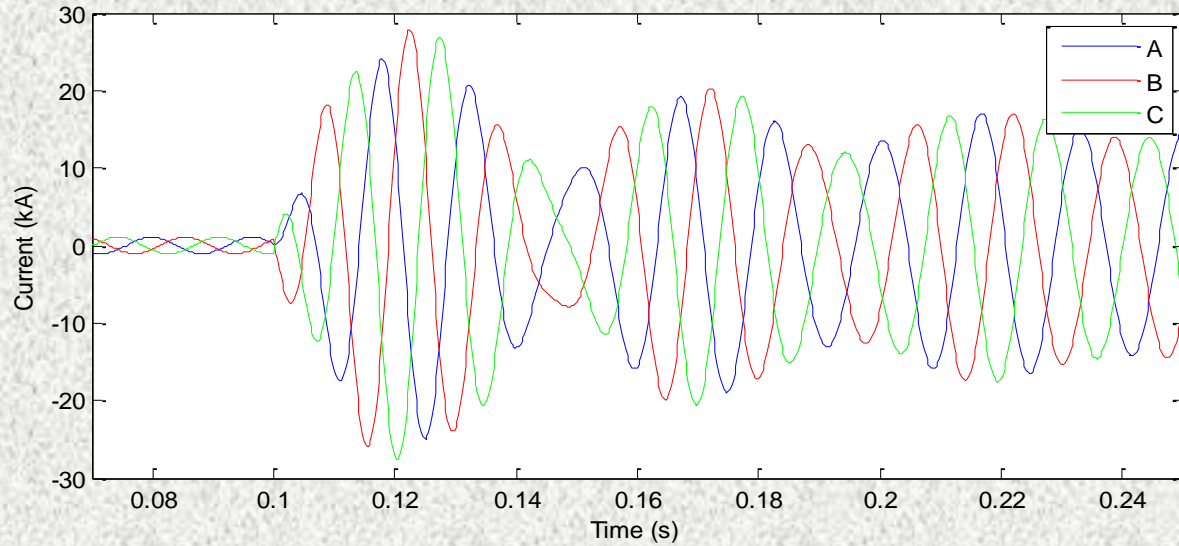


Capacitors – Current Inversion

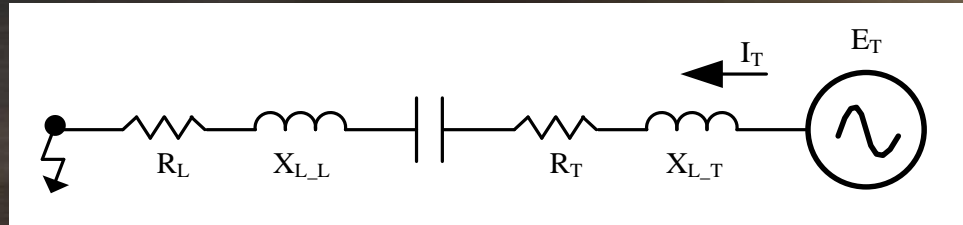


- The occurrence of current inversion depends on the fault location and the total backward reactance.
- Current inversion is rare for most system configurations.
- If there is a current inversion, the line side voltage (V_Q) would have voltage inversion as well.

Capacitors – Current Inversion



Capacitors – Sub-harmonic transients



$$i_T(t) = I_T \sin(\omega t + \alpha - \varphi) + (A \sin \omega_0 t + B \cos \omega_0 t) e^{-t/\tau}$$

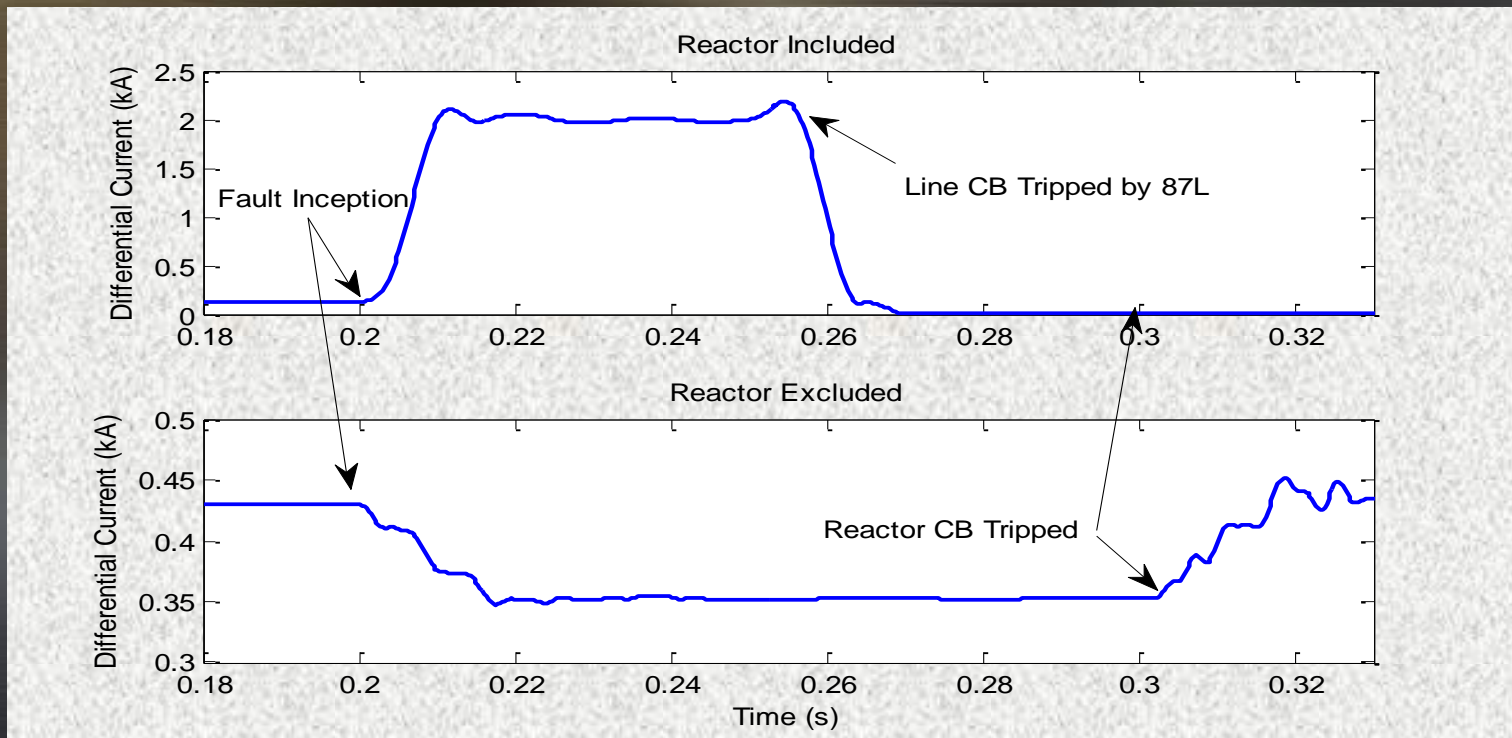
- The frequency of sub-harmonic frequency transient current is normally less than the power frequency.
- The decaying time constant is two times the time constant of fundamental component.
- The magnitude depends on the source parameters, line parameters, capacitor compensation degree and fault inception angle.
- The zero fault inception angle would result in the largest transient current.

87L with Reactors – Charging Current

- Differential current is equal to the charging current in the normal operating condition.
- Include reactor in the protection zone:
 - differential current decreases to the uncompensated charging current when switching reactor in;
 - differential current is the full charging current when switching reactor out.
- Exclude reactor from the protection zone:
 - differential current in the normal condition is always the charging current.
 - A charging current compensation method can be always applied.

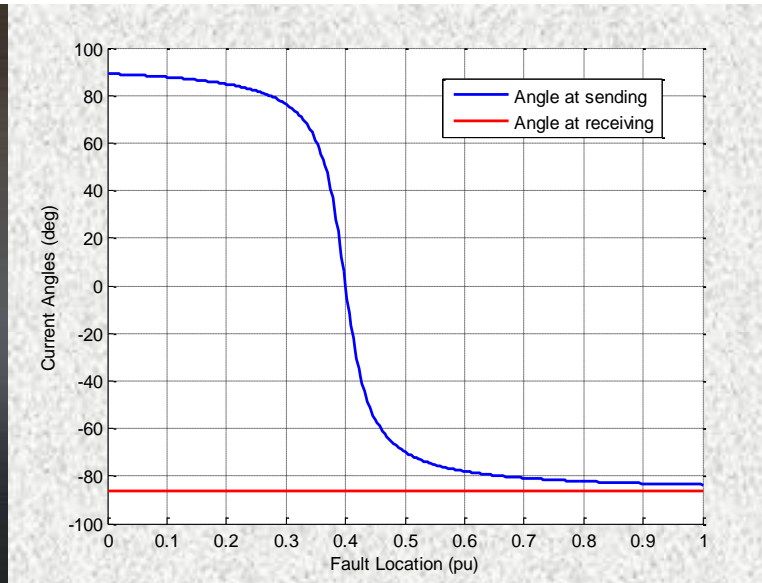
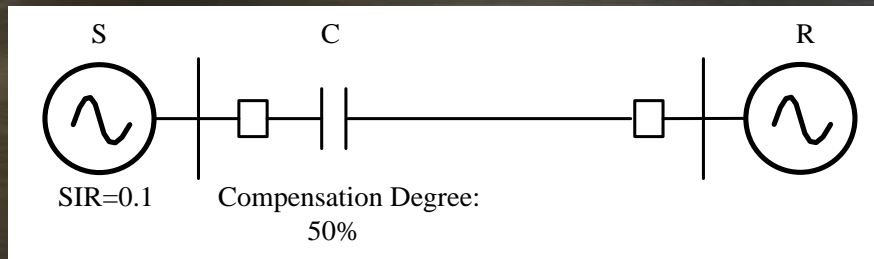
87L with Reactors – Reactor Fault

- Include reactor in the protection zone:
 - A fault in the reactor, especially closed to the line side of the reactor, may result in 87L operation.
- Exclude reactor in the protection zone:
 - 87L cannot see any increase of differential current.
 - Reactor protection would trip its breaker only.



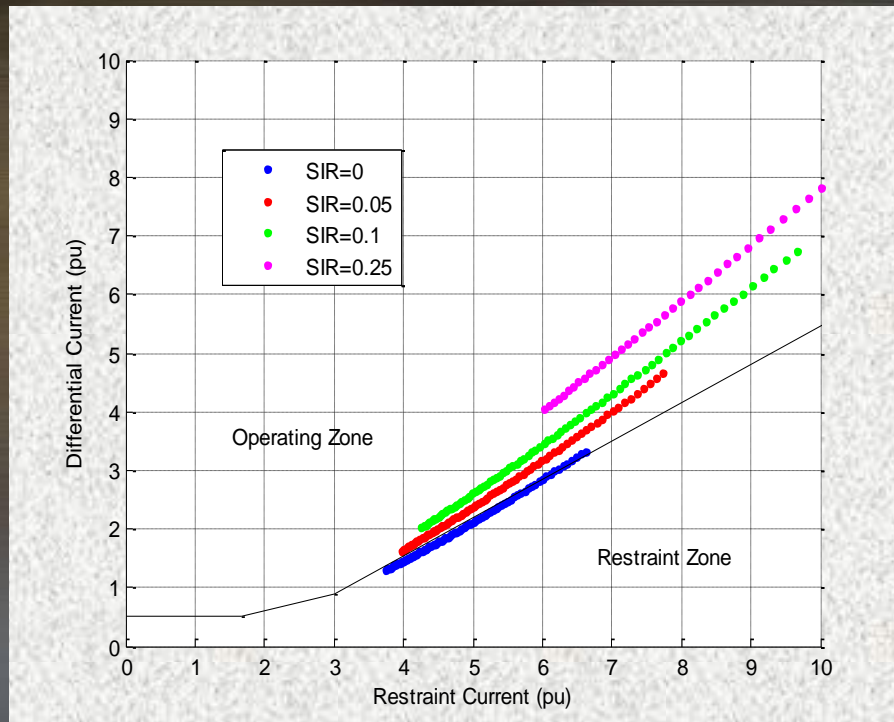
87L with Series Caps – Inversion

- Voltage inversion slightly affects current charging compensation.
- Occurrence of current inversion depends on the fault location.



87L with Series Caps – Current Inversion

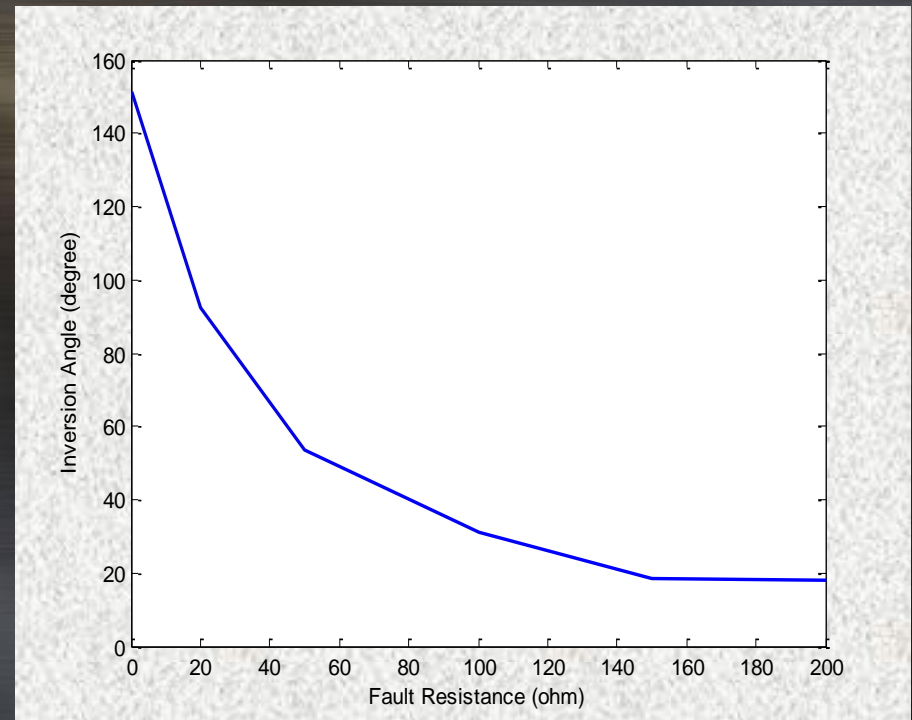
- Current inversion may cause 87LP fail to trip for an internal fault because the inversed current appears to be through current.



- Adjust the boundary settings in the percentage plane to avoid failure to operate during the current inversion
- Faults located in 0-25% of line section
- Assume MOV is not conducted

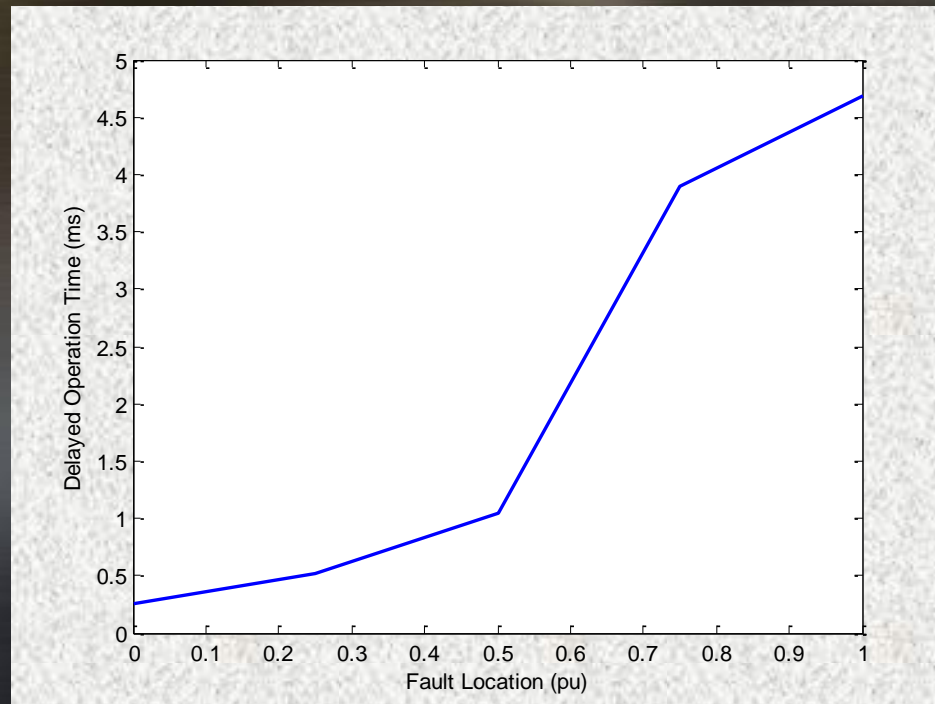
87L with Series Caps – Current Inversion

- 87LG is more complicated to be analyzed.
- 87LG is designed to detect high-resistive (low fault current) ground faults.
- High fault resistance increases the resistive part of fault loop impedance, which decreases the inversion angle significantly.



87L with Series Caps – Sub-harmonic Transients

- May result in the slower operation of 87L.
 - Transients are not eliminated in the DFT calculation.
 - Introduce more oscillation in the current magnitude.
 - Longer time constant increases the settling time of the calculated phasor.

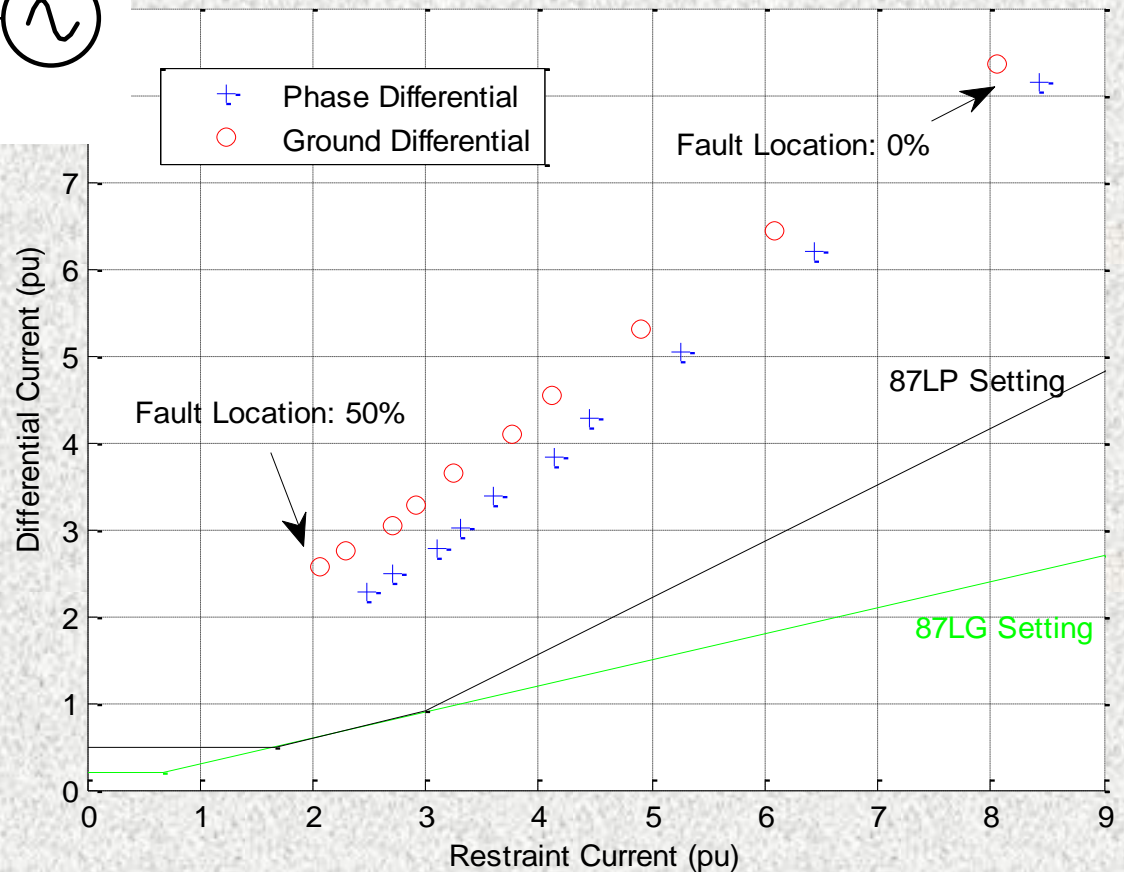
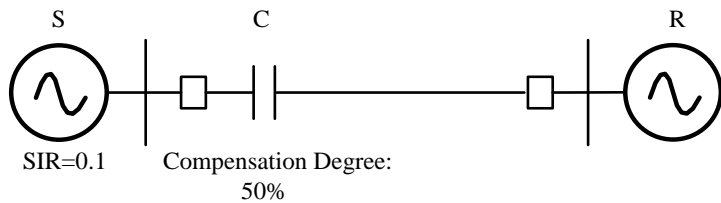


87L with Series Caps – MOV Conducting

- MOV conducting would reduce the possibility of current inversion.
- MOV conducting has no effect on 87LP.
- Basically, MOV conducting has limited effect on 87LG.
 - 87LG is mostly used to detect low current level ground faults and MOV may not conduct under such condition;
 - high current faults would decrease the capacitive reactance significantly and the 87LP element should operate for such faults.

87L with Series Caps – MOV Conducting

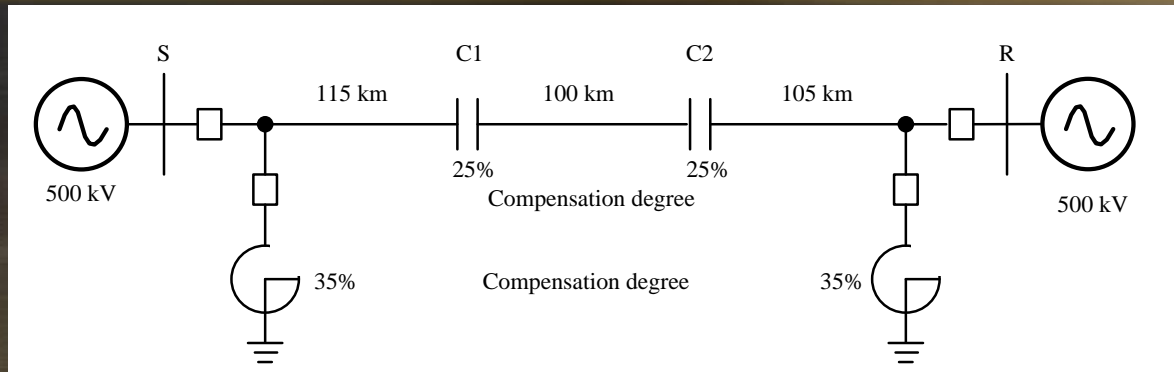
- No misoperation during MOV conducting in the studied system.



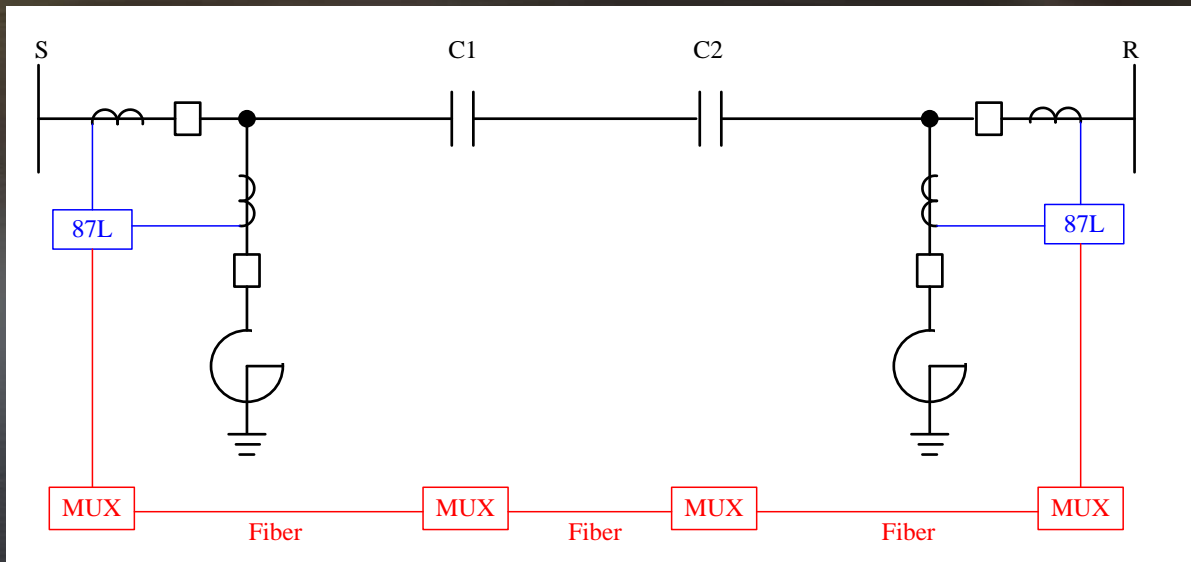
87L Application – Recommendations

- Exclude the shunt reactors from the 87L protection zone;
- Implement charging current compensation technique;
- Study system carefully and adjust settings to accommodate current inversion if exists and to avoid possible failure to operate;
- Apply both 87LP and 87LG since these elements may respond to the different fault conditions, such that the relay dependability can be increased.

87L Configuration and Communication

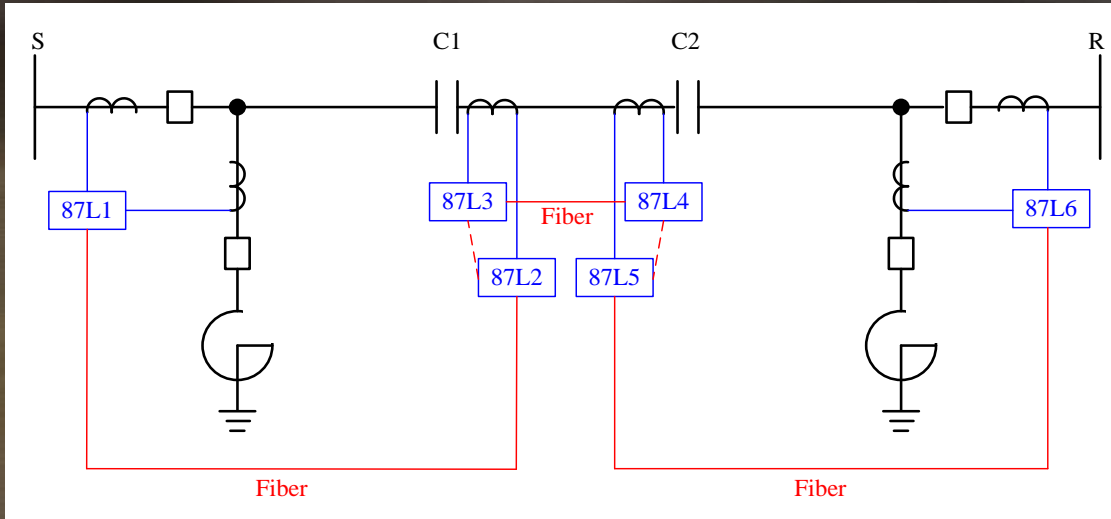


- Configuration 1: protect the whole line using two 87L relays over fiber optic communications.
 - multiplexers may be required for the long line.



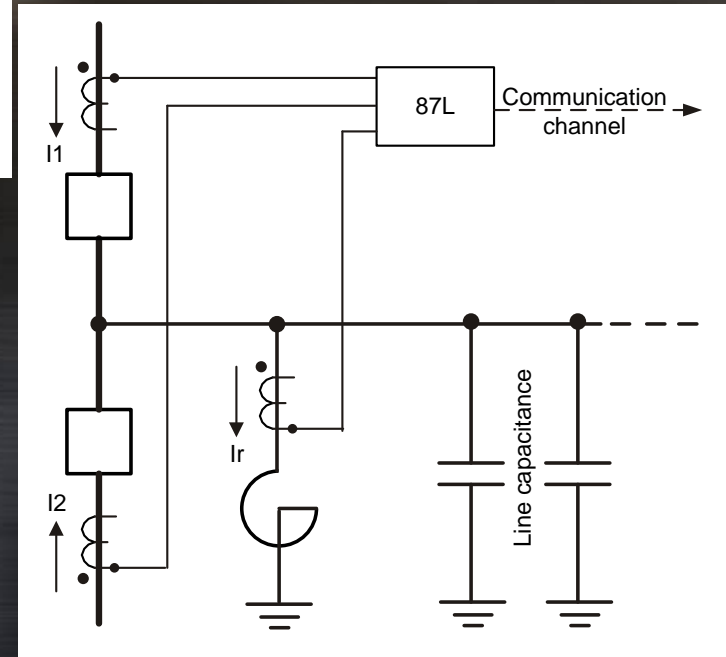
87L Configuration and Communication

- Configuration 2: protect each line section using three sets of 87L relays.



- Two separate channels can be configured to work in parallel to achieve maximum security and dependability.

Breaker-and-a-half Configuration



87L Settings

- Four settings in the dual slope percentage differential principle.
- **Pickup Level** establishes the sensitivity of the element to high impedance faults
- **Restraint Slope 1** controls the element characteristic when current is below the breakpoint, where CT errors and saturation effects are not expected to be significant
- **Restraint Slope 2** controls the element characteristic when current is above the breakpoint, where CT errors and saturation effects are expected to be significant
- **Break Point** controls the threshold where the relay changes from using the restraint 1 to the restraint 2.

Estimation of Line Capacitive Reactance

- Used for charging current compensation.
- Utilizing the synchronized phasors from both terminals in the line differential relay.
 - Positive sequence capacitive reactance: using the positive sequence voltages and differential current under the normal operating condition.
 - Zero sequence capacitive reactance: using the zero sequence voltages and currents during an external ground fault.

Estimation Error	X_{c1}	X_{c0}
Lumped Method	1.4%	2.65%
Distributed Method	0.0054%	0.037%

Conclusion

- Principles and applications of shunt reactors and series capacitor banks;
- Effects of these apparatus on power systems;
- Impact on 87L performance under steady and transient conditions;
- Recommendations for 87L applications.
- Configurations of the 87L scheme;
- Arrangement of communication channels;
- 87L settings in the dual-slope percentage differential plane;
- Simple methods to estimate positive and zero sequence capacitive reactance for CCC setting.

Thank You

Questions?