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

Zhihan Xu, Ilia Voloh

GE Digital Energy

Texas A&M Relay Conference 2014

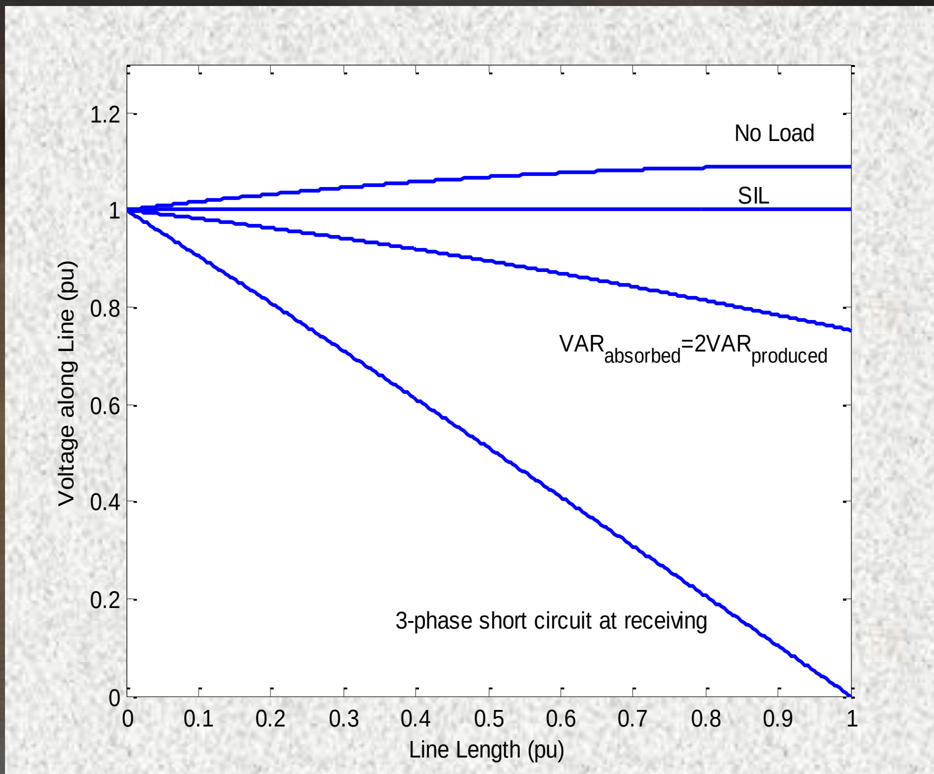
Outline

- 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

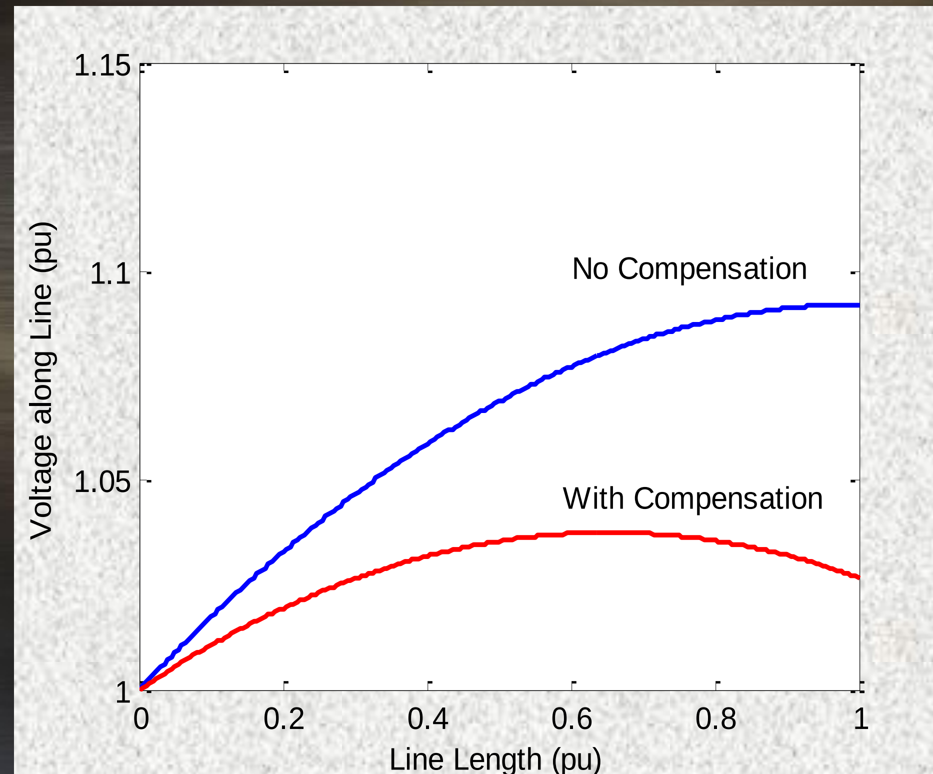
Shunt Reactors – Applications

- 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

Shunt Reactors - Voltage Profile



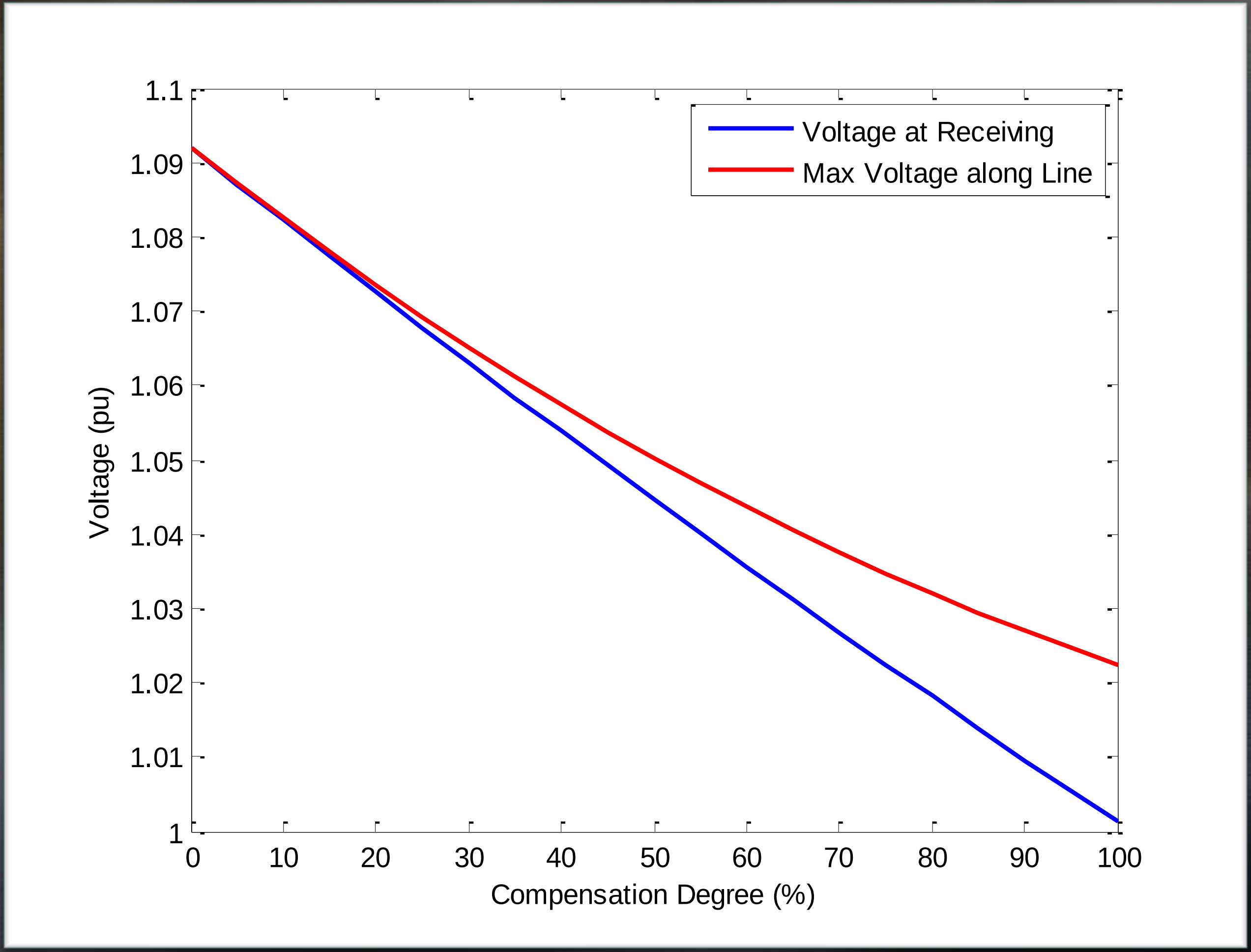
Voltage Profile w/o compensation



Comparison if compensation applied

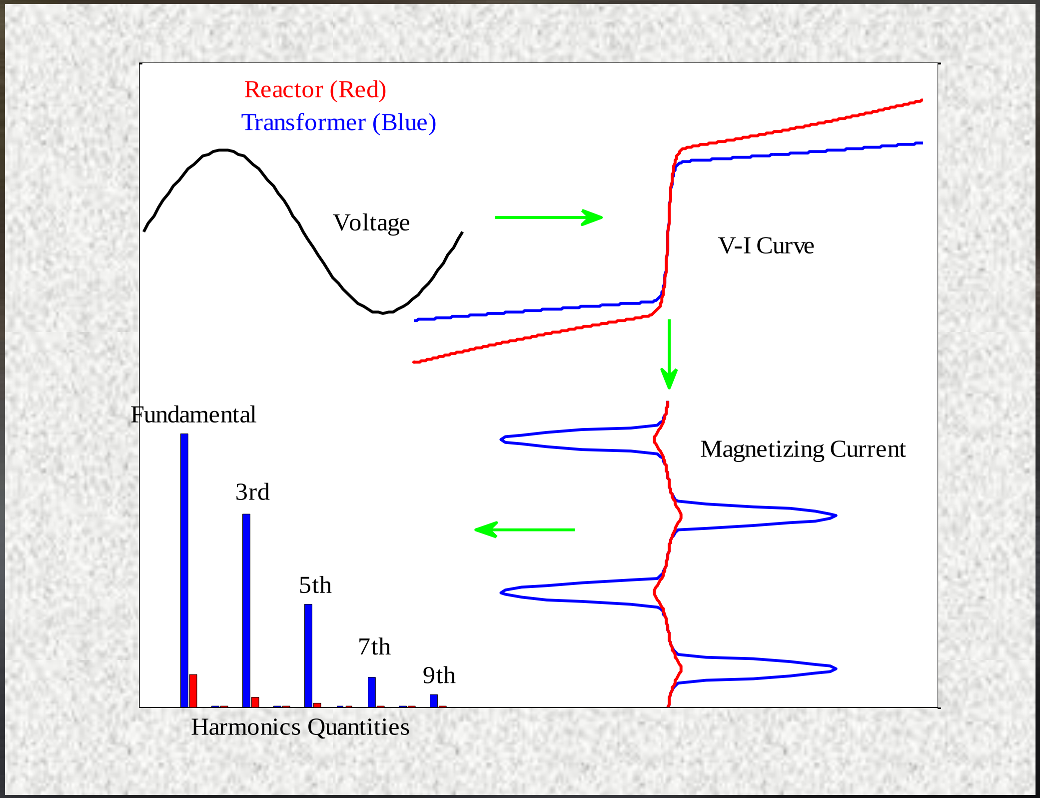
Shunt Reactors - Voltage Profile

Receiving voltage when changing the compensation degree of reactor from 0% to 100%



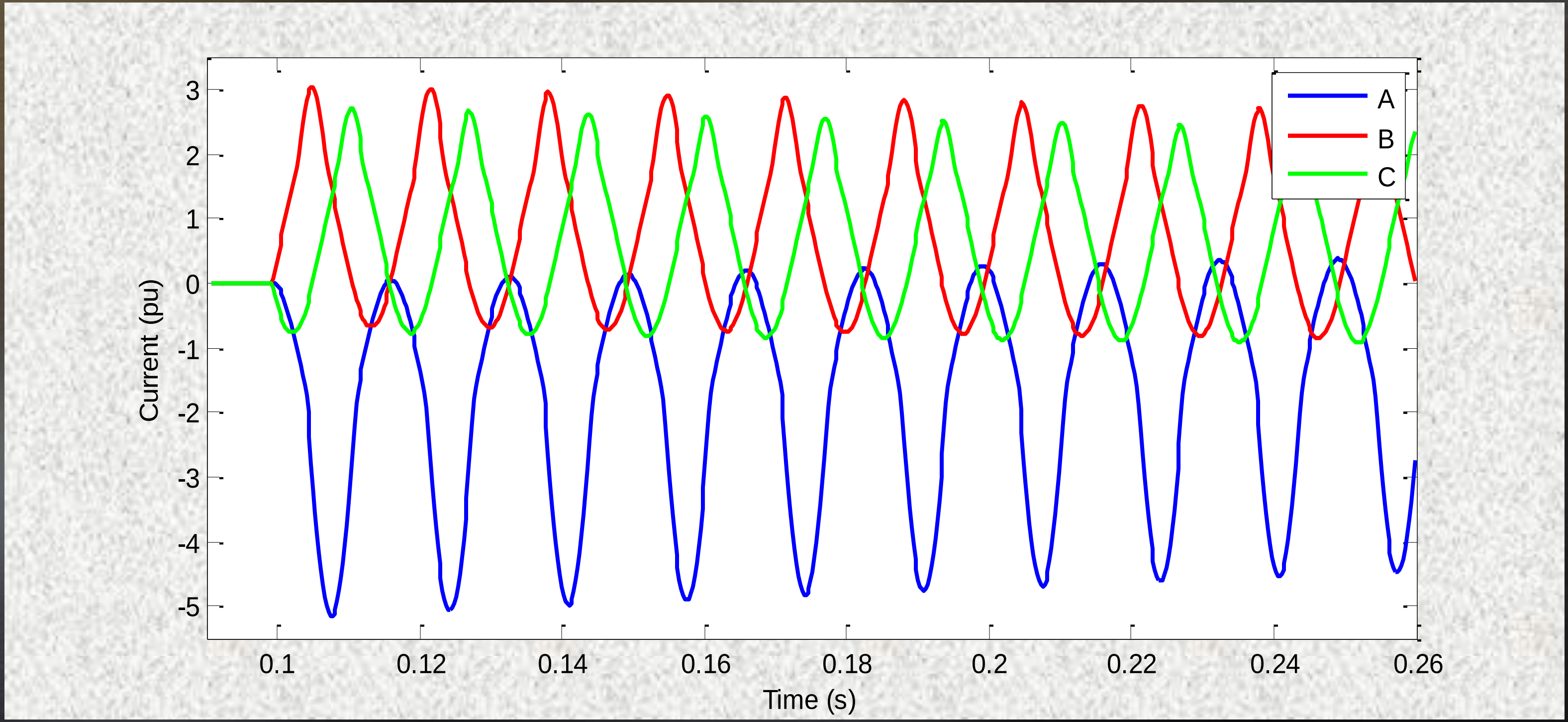
Reactors – Overvoltage

- 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



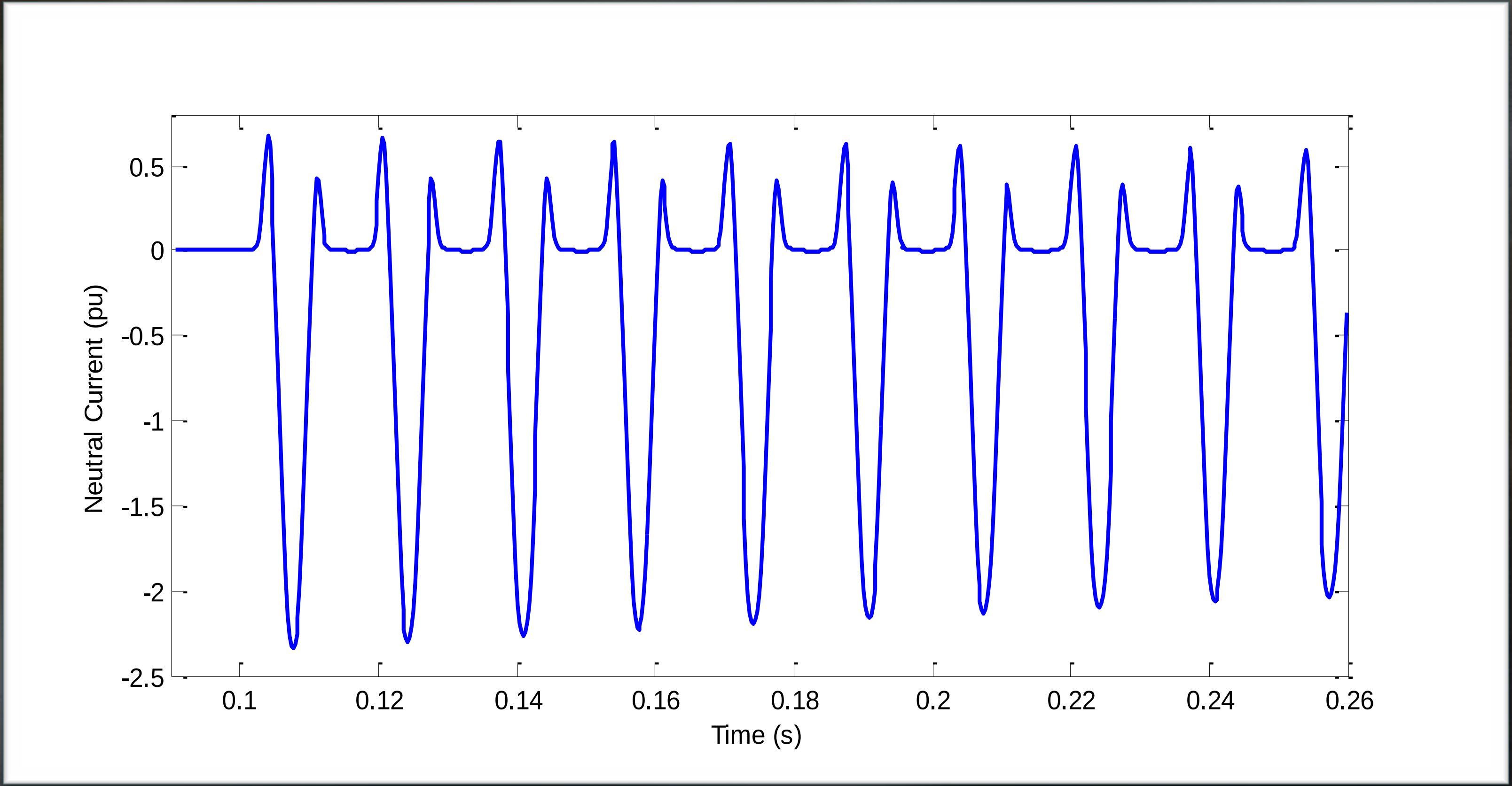
Reactors – Switch-in

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



Reactors – Switch-in

- **Neutral current of shunt reactor during a 3-pole simultaneous switching-in**

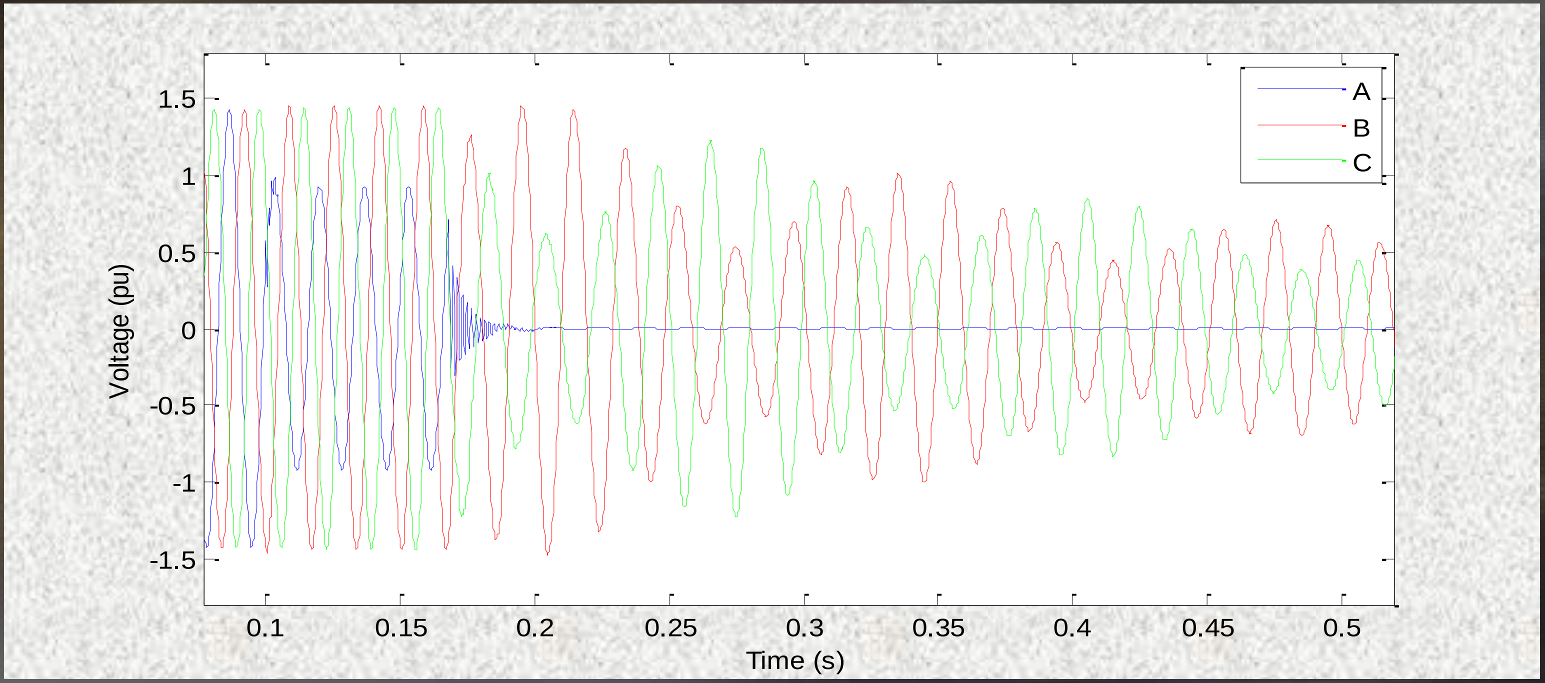


Reactors – Switch-in

- DC offset takes several seconds to decay because of the quite large time constant (higher X/R ratio);
- Magnitude of decaying dc component is most influenced by the phase of the voltage when the reactor is energized;
- Unbalanced three-phase currents result in the zero sequence current in the neutral;
- Transient can be avoided if three circuit breaker poles are precisely closed at three consecutive phase voltage peaks.

Reactors – Resonance

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

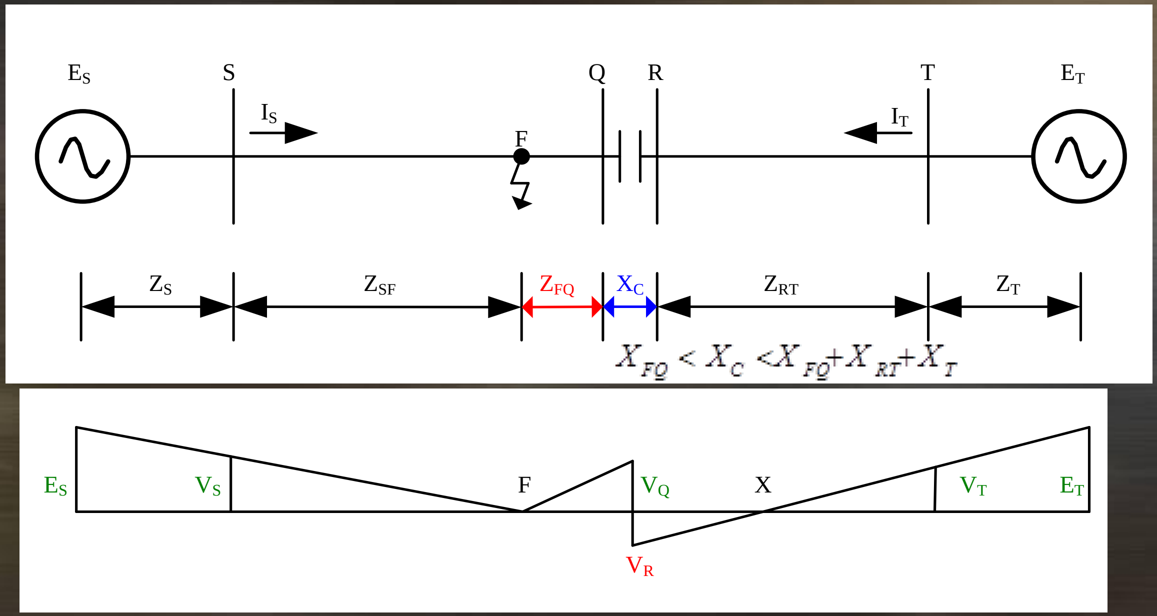


- Resonance frequency is less than the system frequency, can be approximated by $f_R = f_0\sqrt{\frac{\eta}{100}}$

Series Capacitor Banks – Applications

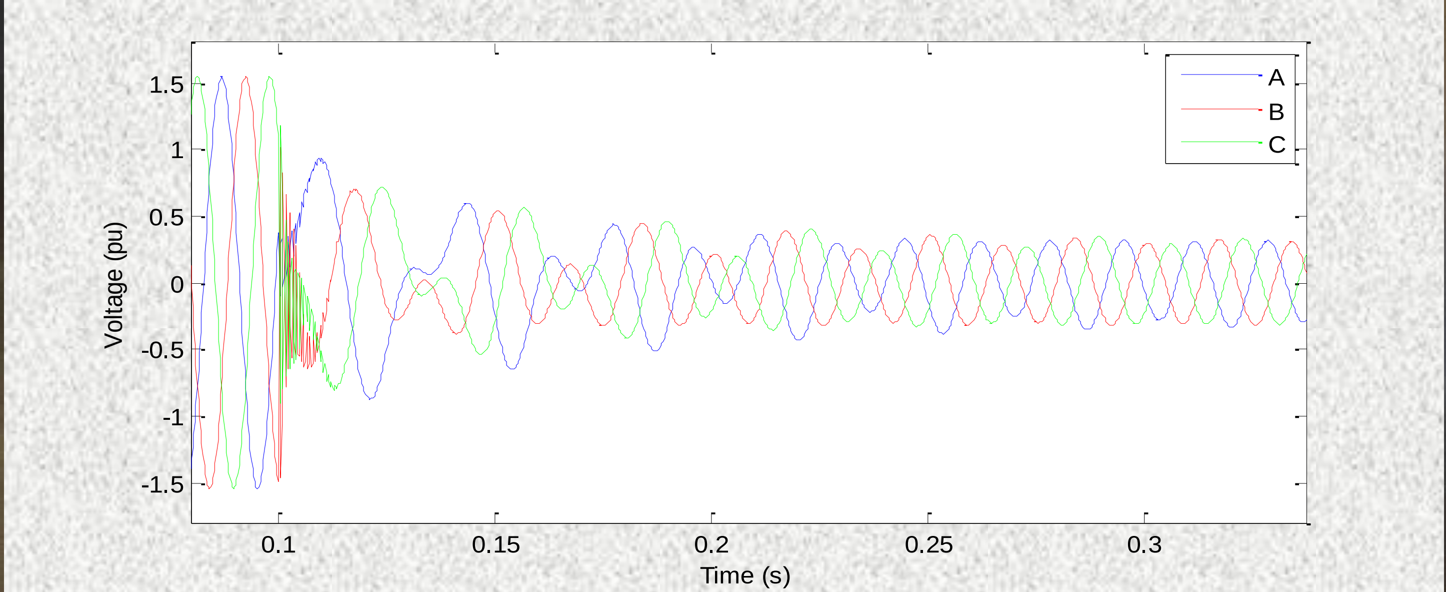
- Improve power transfer capacity
- Improve angular stability
- Dynamically adjust voltage profile, depending on the load current

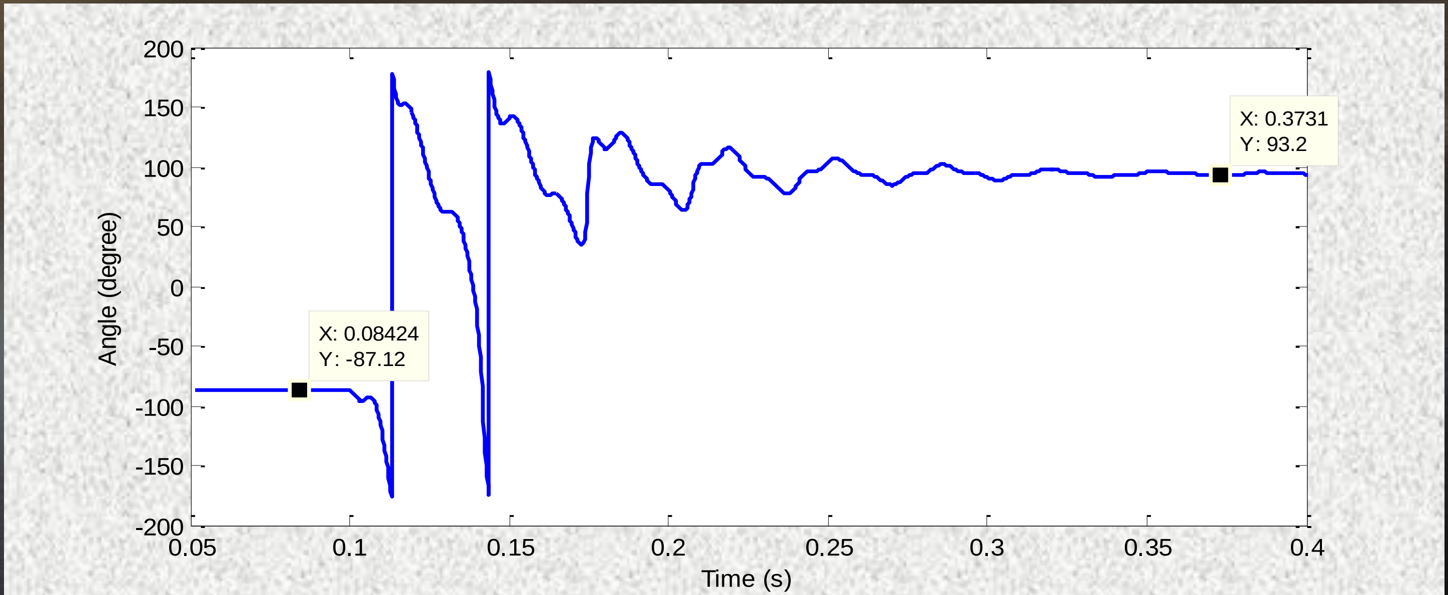
Capacitors – Voltage Inversion



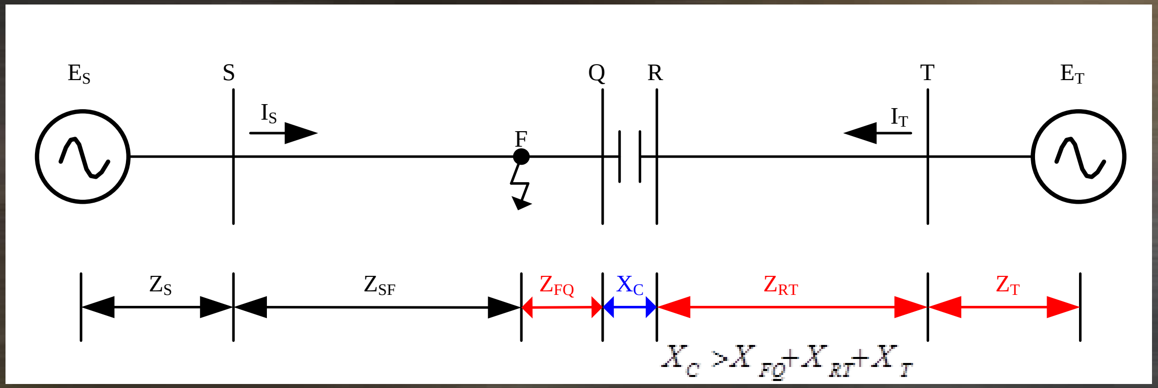
- The occurrence of voltage inversion depends on the fault location; if the fault point is far away from the capacitor, there may not be a voltage inversion
- If there is a voltage inversion, the bus side voltage (VR) has 180 degree angle difference from the source voltage (ET)
- If there is a voltage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

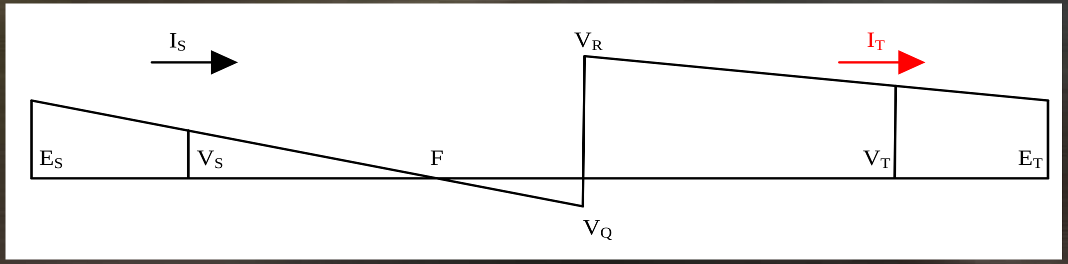
Capacitors – Voltage Inversion





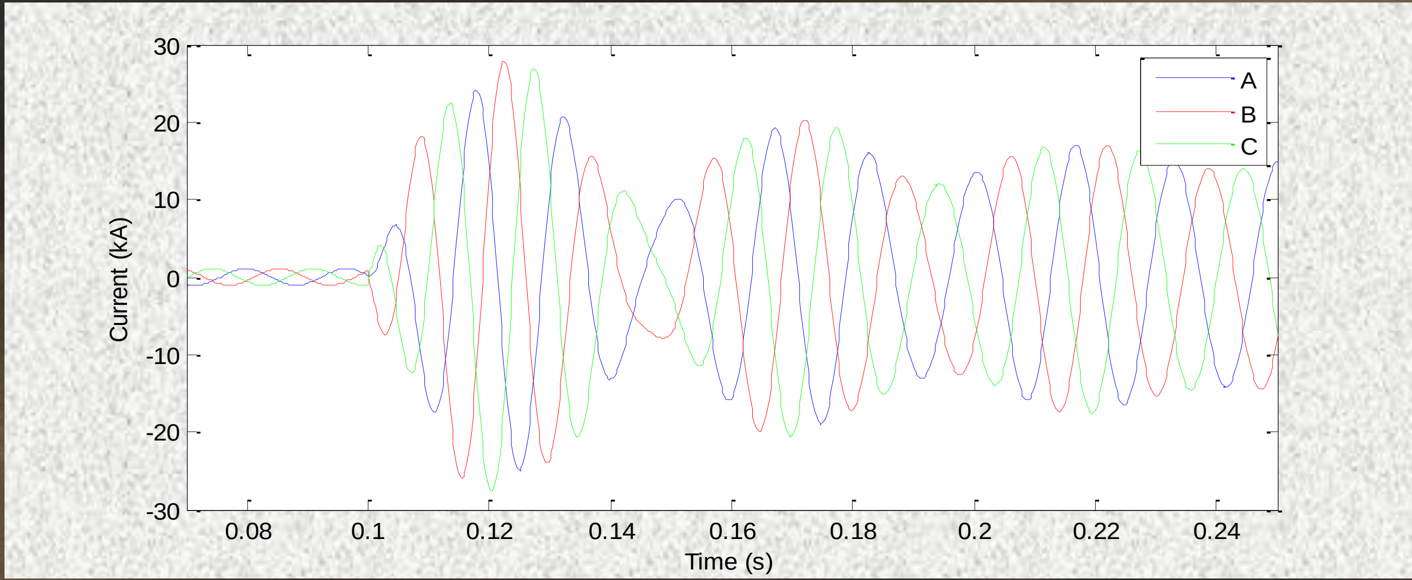
Capacitors – Current Inversion

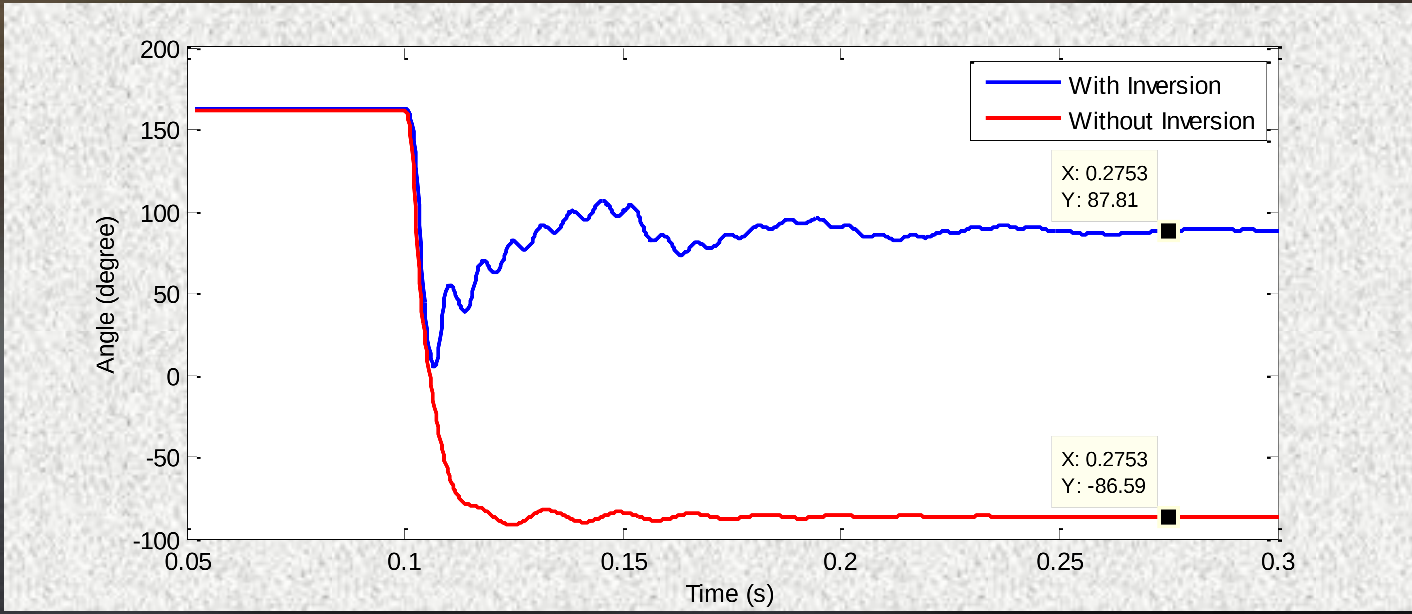




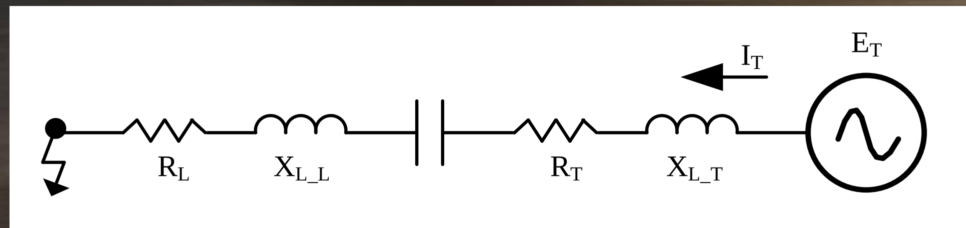
- The occurrence of current inversion depends on the fault location and the total backward reactance
- Current inversion is rare for most system configurations
- If there is a current inversion, the line side voltage (VQ) would have voltage inversion as well

Capacitors – Current Inversion





Capacitors – Sub-harmonic transients



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

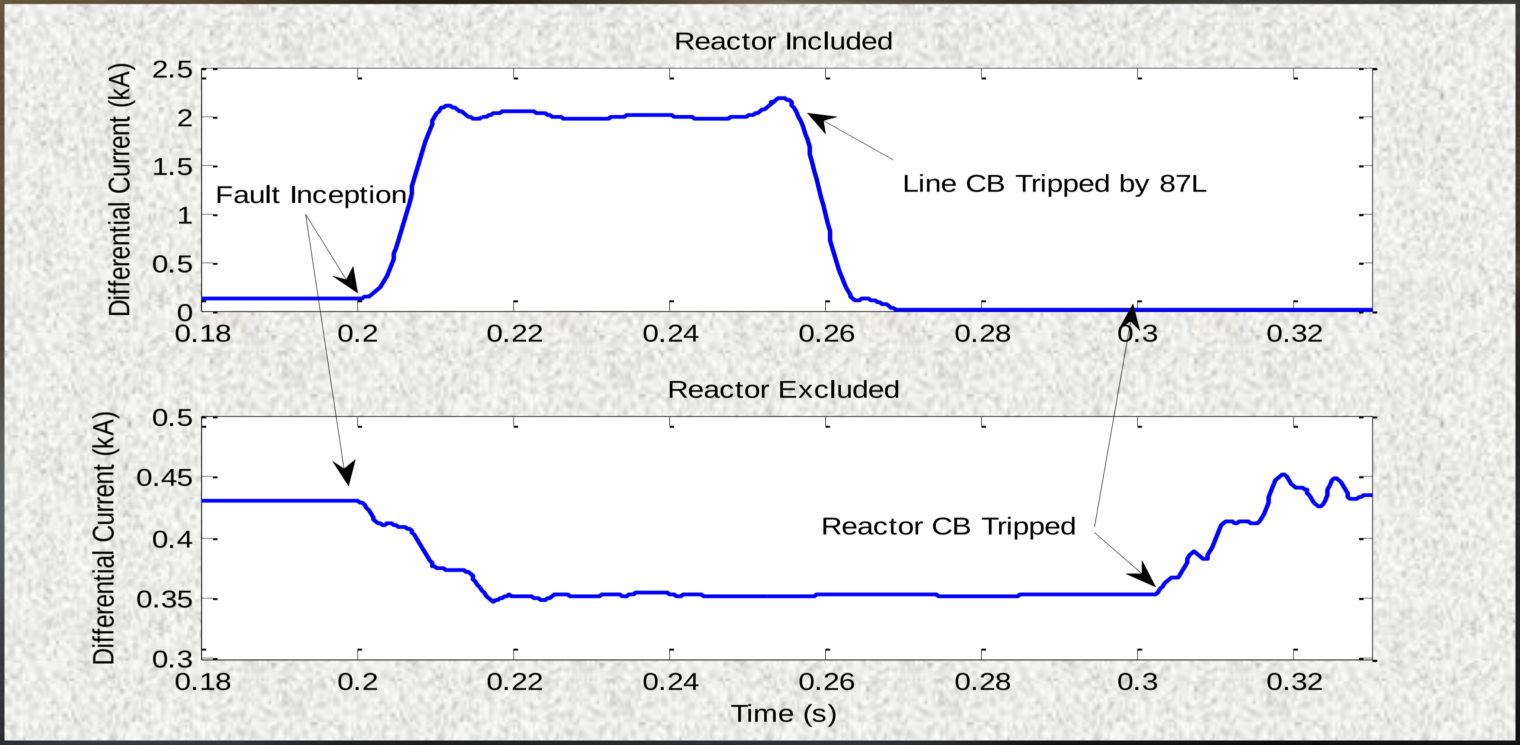
- The frequency of sub-harmonic frequency transient current is normally less than the power frequency
- The decaying time constant τ is two times the time constant of fundamental component
- The magnitude depends on the source parameters, line parameters, capacitor compensation degree and fault inception 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
  - Charging current compensation has to be variable
- 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.

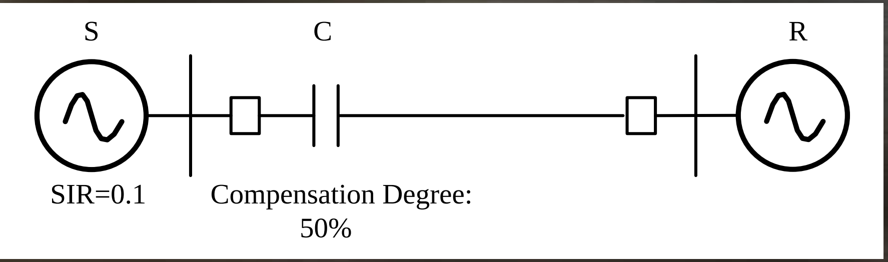
87L with Reactors – Reactor Fault

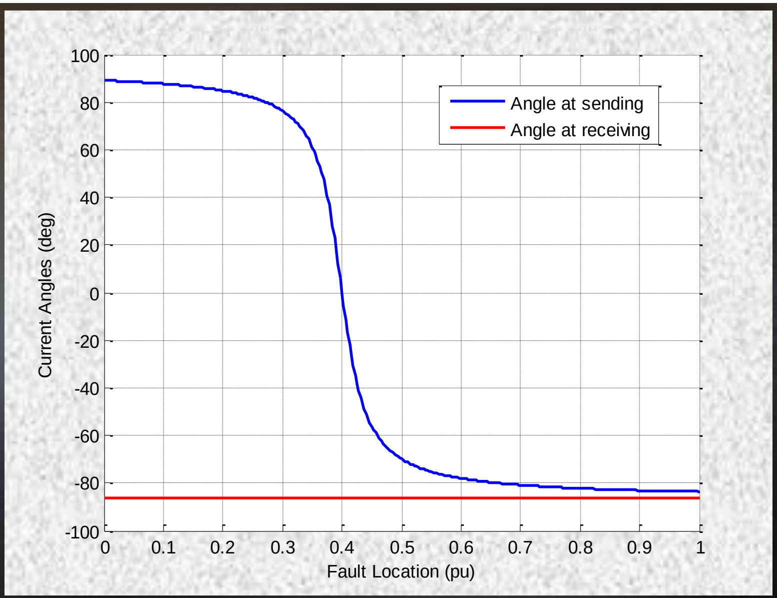
- Include reactor in the protection zone:
  - A fault in the reactor, especially closed to the line side of the reactor, may result in 87L operation
- Exclude reactor in the protection zone:
  - 87L cannot see any increase of differential current
  - Reactor protection would trip its breaker only



87L with Series Caps – Inversion

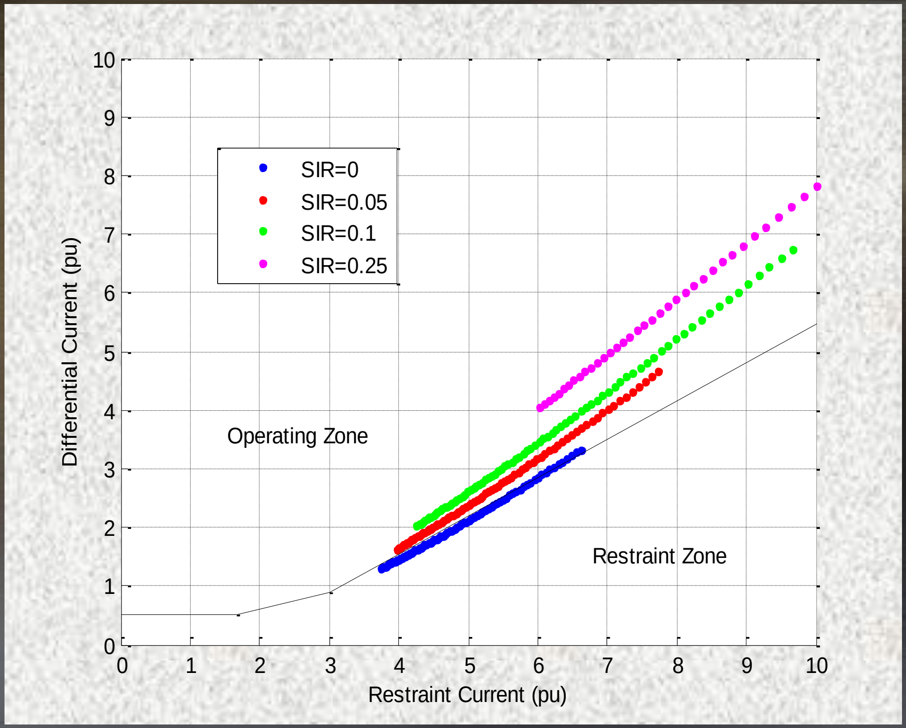
- Voltage inversion slightly affects current charging compensation
- Occurrence of current inversion depends on the fault location





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**



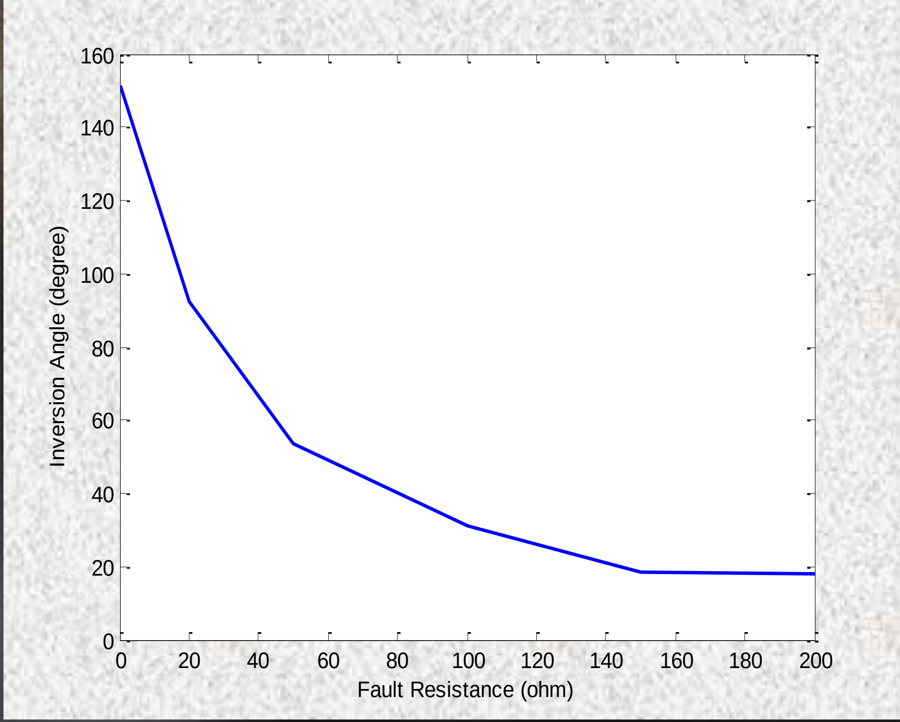
- Adjust the boundary settings in the percentage plane to avoid failure to operate during the current inversion

- Faults located in 0-25% of line section
- Assume MOV is not conducted

87L with Series Caps – Current Inversion

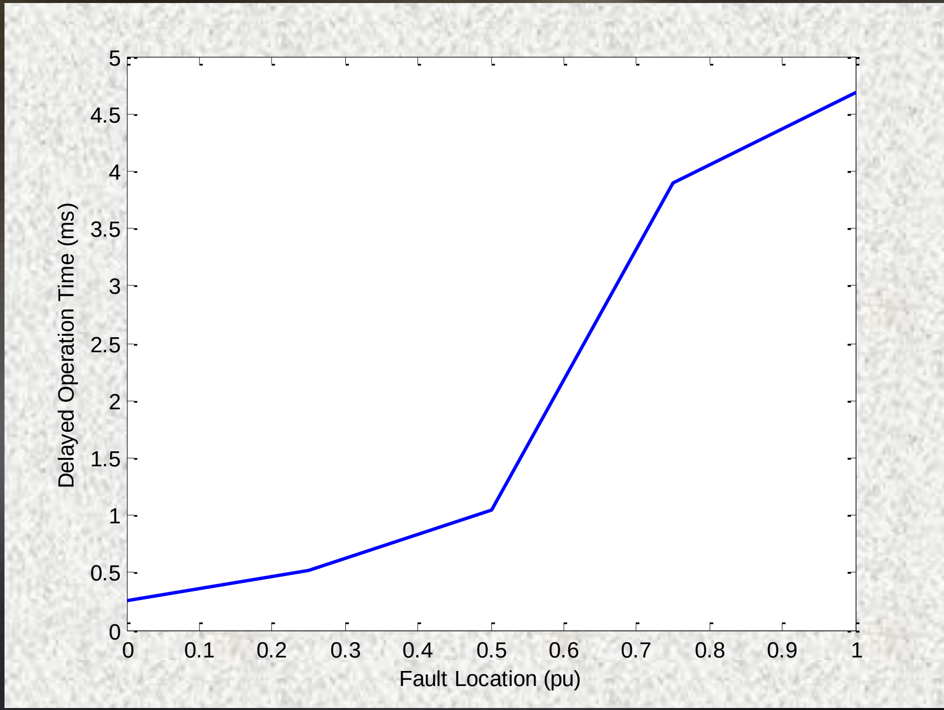
- 87LG is more complicated to be analyzed
- 87LG is designed to detect high-resistive (low fault current) ground faults

High fault resistance increases the resistive part of fault loop impedance, which decreases the inversion angle significantly

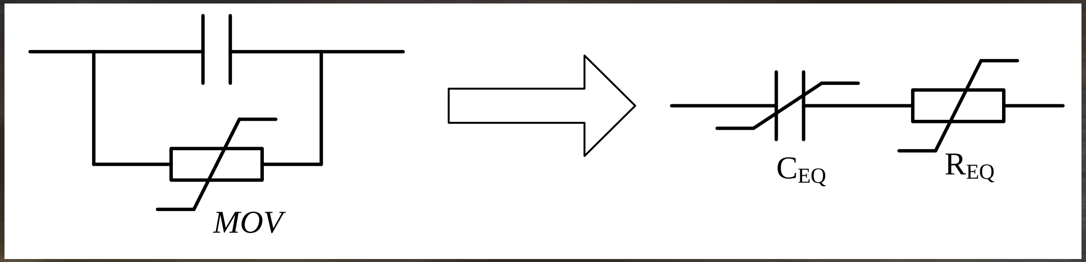


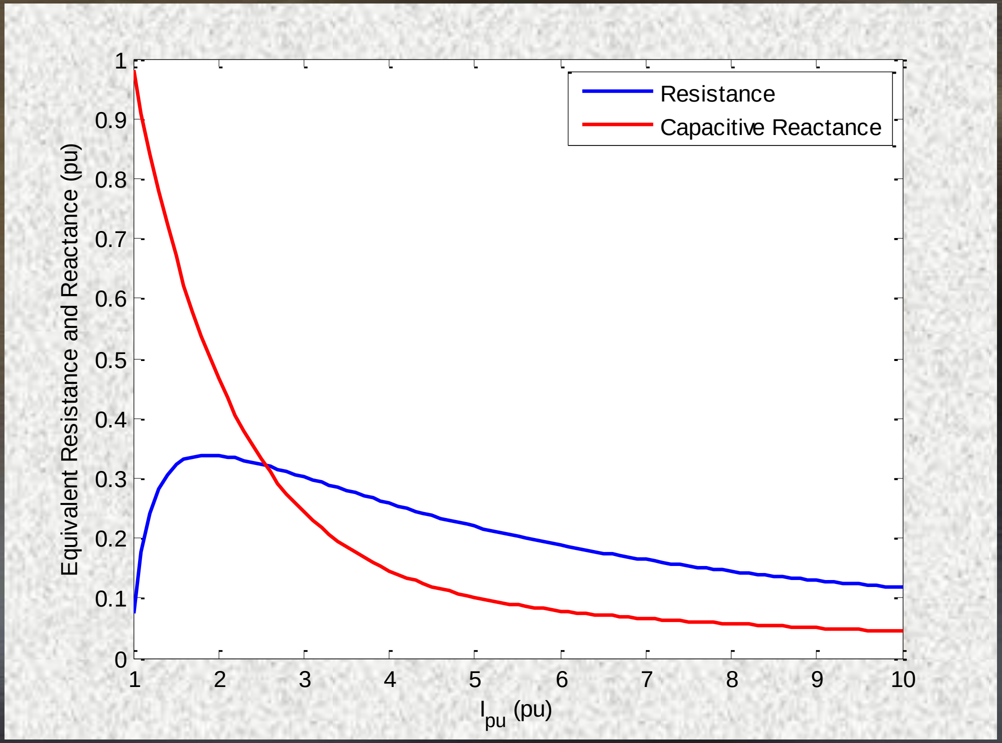
87L with Series Caps – Sub-harmonic Transients

- 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





- When fault current increases, both equivalent resistance and capacitive reactance decrease, but not to zero before bypassing.

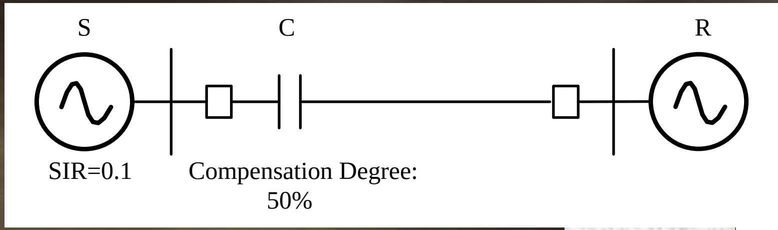
Ipu=2.5~3 Irated

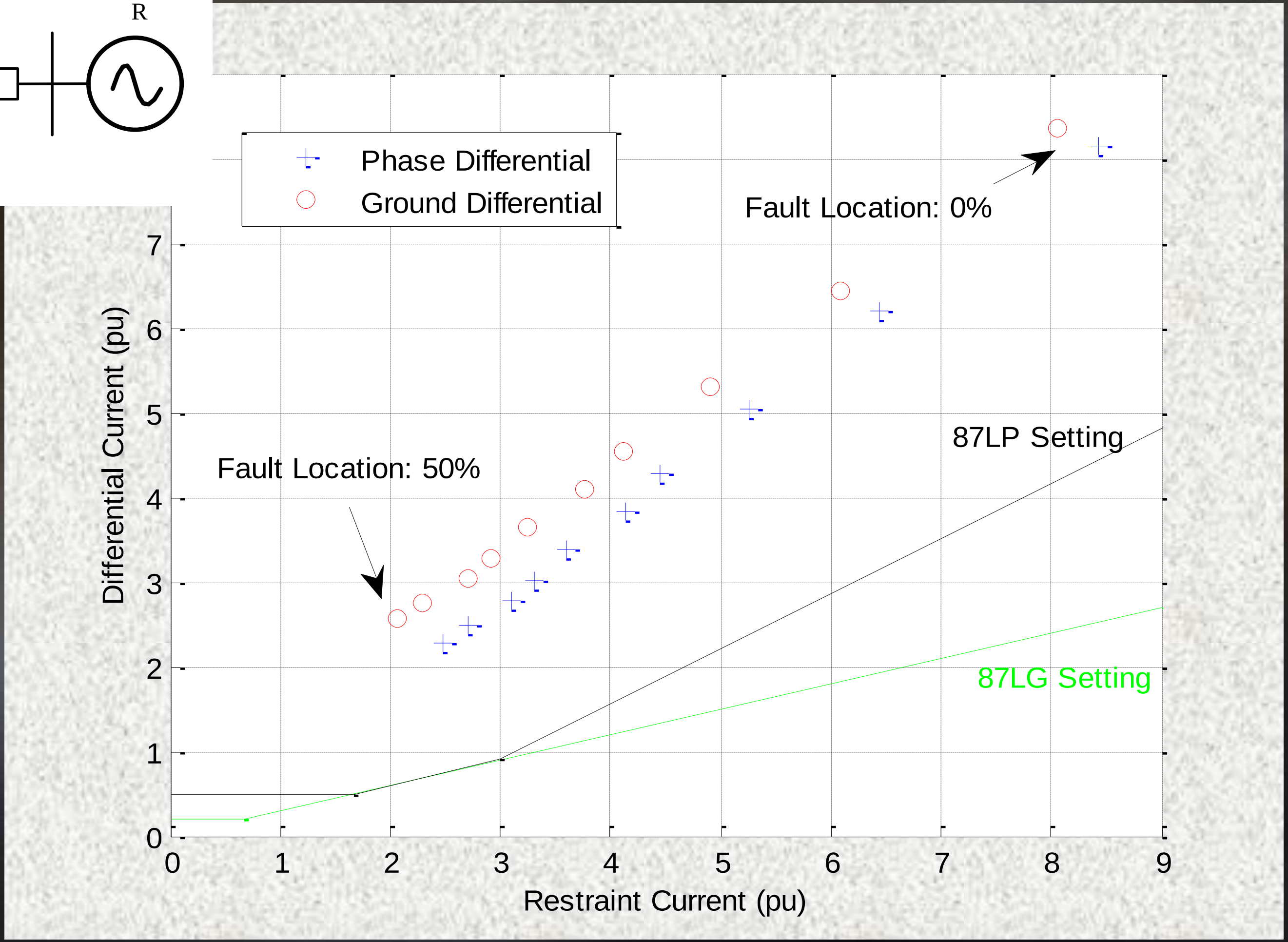
87L with Series Caps – MOV Conducting

- MOV conducting would reduce the possibility of current inversion
- MOV conducting has no effect on 87LP
- 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

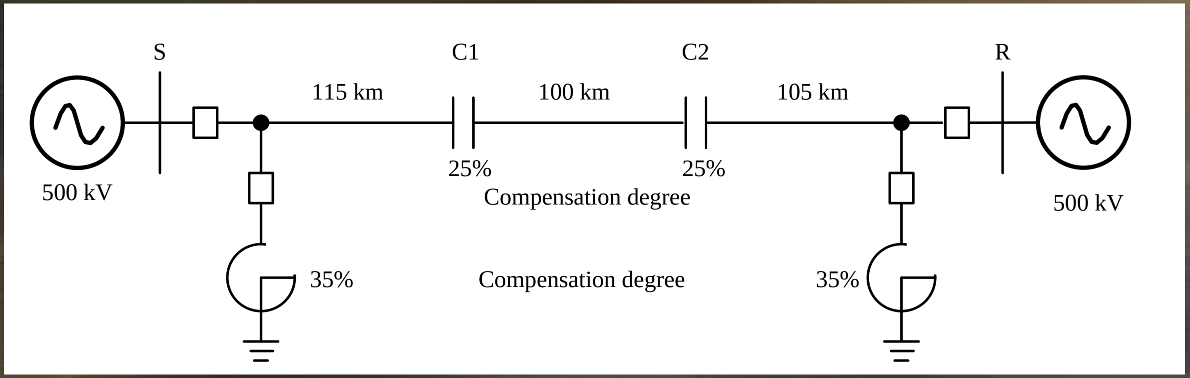




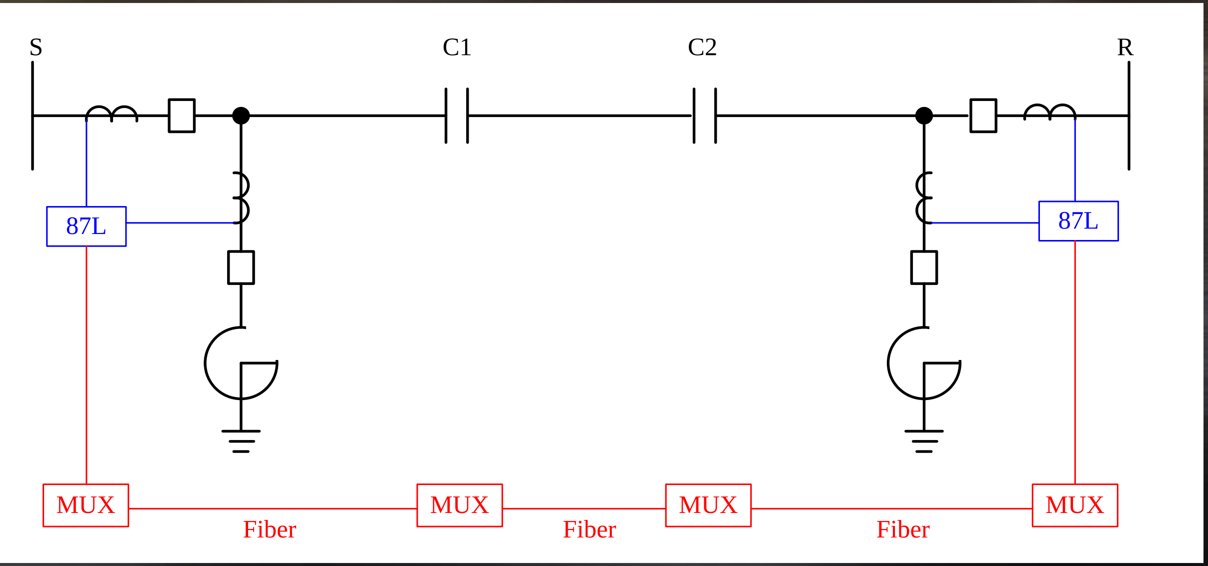
87L Application – Recommendations

- 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

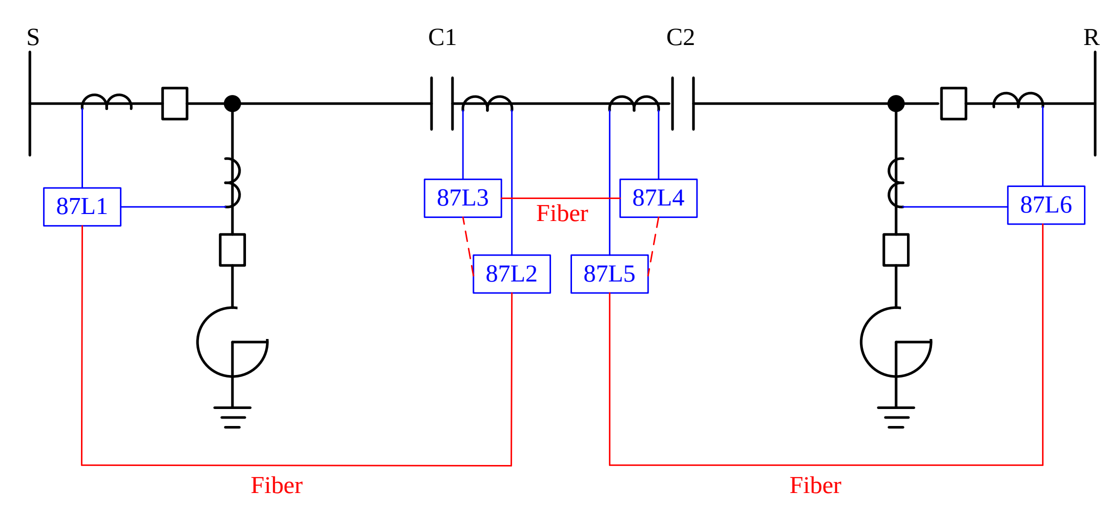


- Configuration 1: protect the whole line using two 87L relays over fiber optic communications
  - Multiplexers may be required for the long line

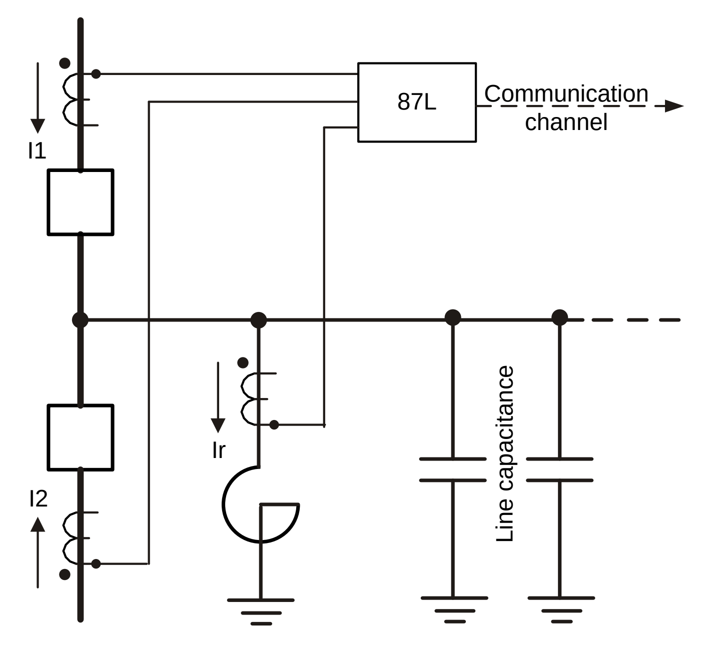


87L Configuration and Communication

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



Breaker-and-a-half Configuration



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

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%

Conclusions

- 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?