End-to-End Testing Transmission Line Protection Schemes and Double-Ended Fault Locators

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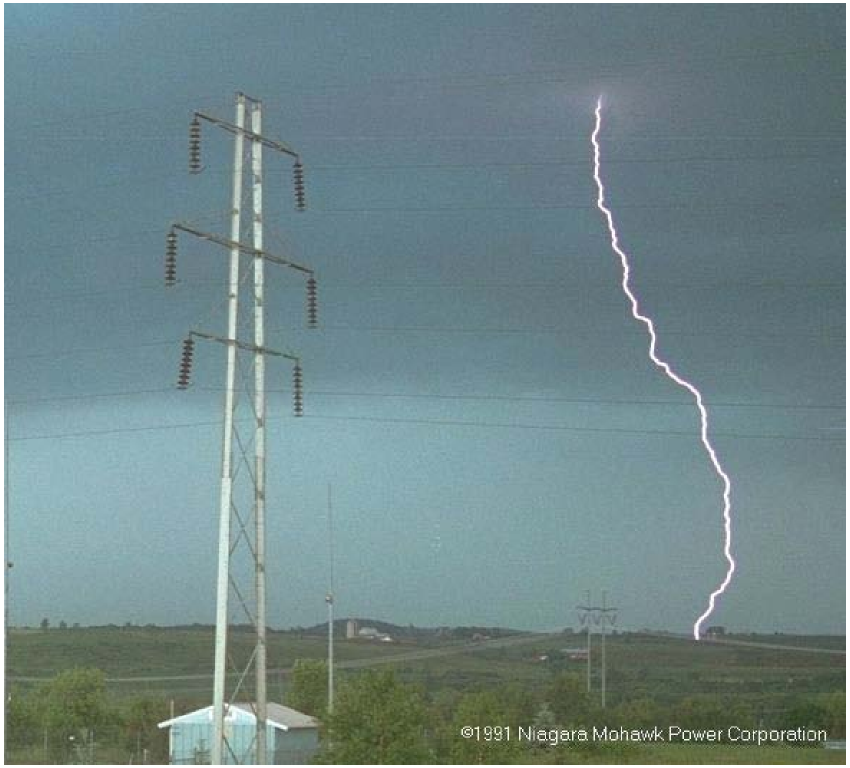
Transmission Line Faults

Overhead high-voltage line faults result in high magnitude current flows through the conductor and connected equipment.

Line faults occur due to:

- Lightning
- Tree limb or tree branch contact
- Other inadvertent ground contact (e.g. wind-blown debris, agricultural spraying, etc.)

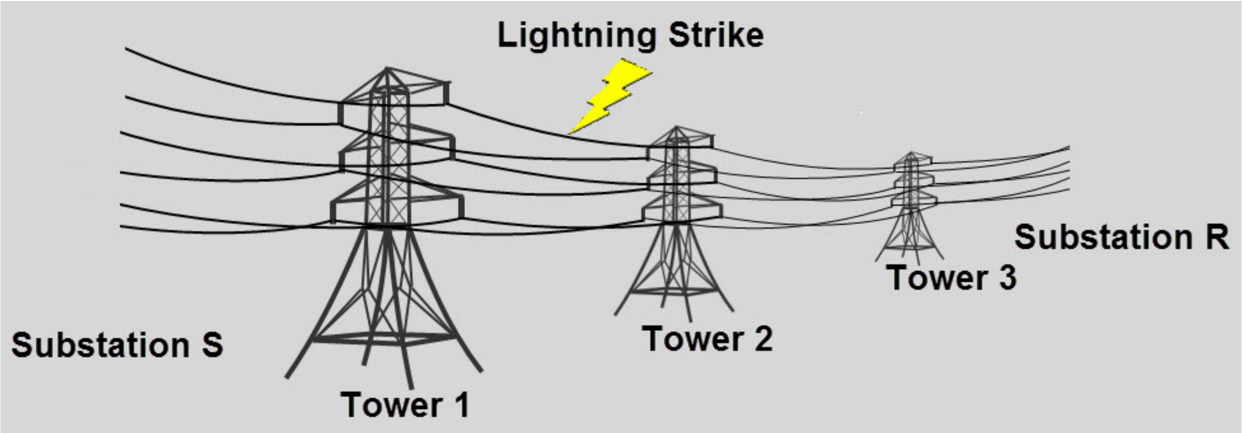


Protecting the System from Faults

- Protective relays detect disturbances on overhead transmission lines.
- The relays send commands to open the circuit breakers, protecting the system from damage.
- Accurate fault location helps utility personnel expedite service restoration.
- If the utility knows the distance to the fault, line crews can be dispatched quickly to make repairs.
- Otherwise, *a lot of time and expense is required to patrol the overhead line for possible damage*.

When lightning strikes:

- Voltage at the strike builds rapidly until it flashes over to ground.
- High magnitude current flows on the faulted phase.



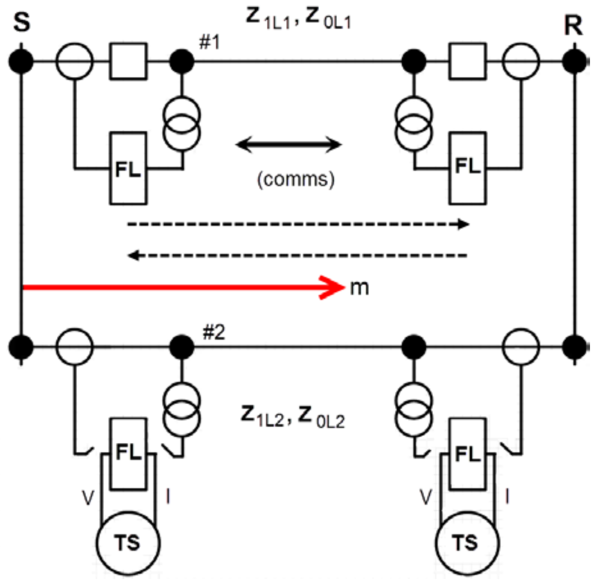
Protective relays at Substation S and Substation R monitor the transmission line.

In the past, numerical line relays calculated the distance to the fault by using current and voltage data.

- This is referred to as the single-ended method.
- Fault resistance can cause significant errors in these calculations.
- Double-ended methods are far superior.

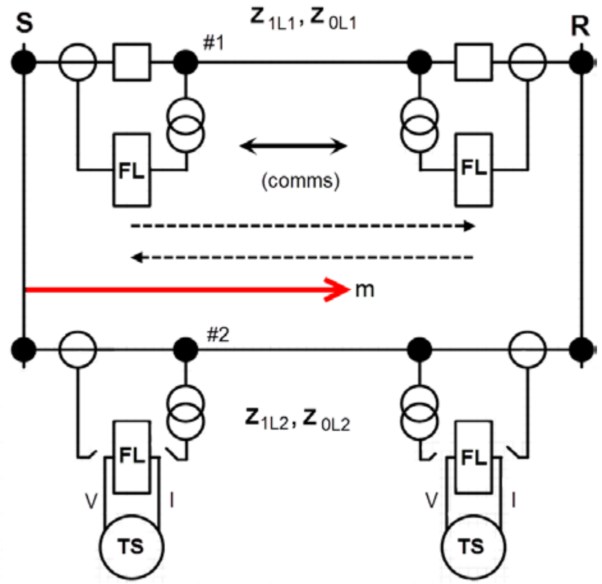
Testing Double-Ended Fault Locators for High Voltage Overhead Lines

- Many similarities to testing high speed communication tripping schemes (HSCATS)
- Can be performed while testing the HSCATS



- The diagram shows a typical test setup on line #2

Legend:
- TS – Test Set
- FL – Fault Locator
- m – Distance to fault with respect to substation "S"



Test Requirements and Parameters:
- Short circuit studies determine the fault voltage and current measured by each fault locator for faults internal to the protected line.
- Zero-sequence mutual coupling of the parallel lines and high fault resistance during heavy load are considered as power system parameters.

These signals are played back to the fault locators via the synchronized test sets.

Fault Location

Utility companies have been researching fault location methods since early 1950s in order to:

- Expedite service restoration
- Reduce operating costs
- Reduce outage time
- Reduce customer complaints

Most numerical line relays use single-ended fault location algorithms

Uses data from only one end of line to calculate the distance to fault

Single-ended fault location method pros:

- Fast
- Easy

Single-ended fault location method cons:

- Commonly encountered factors can severely degrade accuracy
  - ➢ High fault resistance
  - ➢ Zero-sequence mutual coupling
  - ➢ Non-homogenious power systems

This presentation describes one double-ended fault location technique.

Single phase-to-ground faults are the most common type of fault and typically the most rigorous for distance-to-fault calculations.

The double-ended method also applies to three-phase, phase-to-phase, and phase-to-phase-to-ground faults.

The double-ended method is immune to the most common problems associated with fault location:

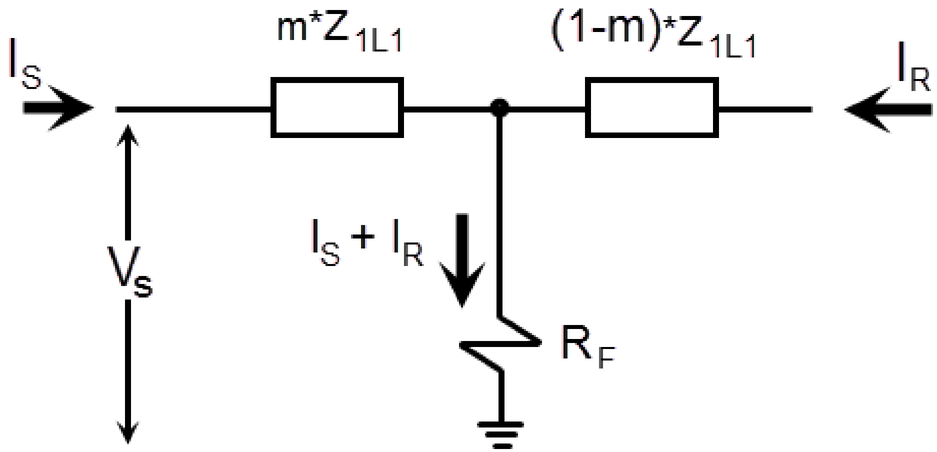
- Remote infeed
- Zero-sequence mutual coupling

Double-ended method algorithm requirements:

- Negative-sequence voltage and current from both terminals
- Positive-sequence line impedance

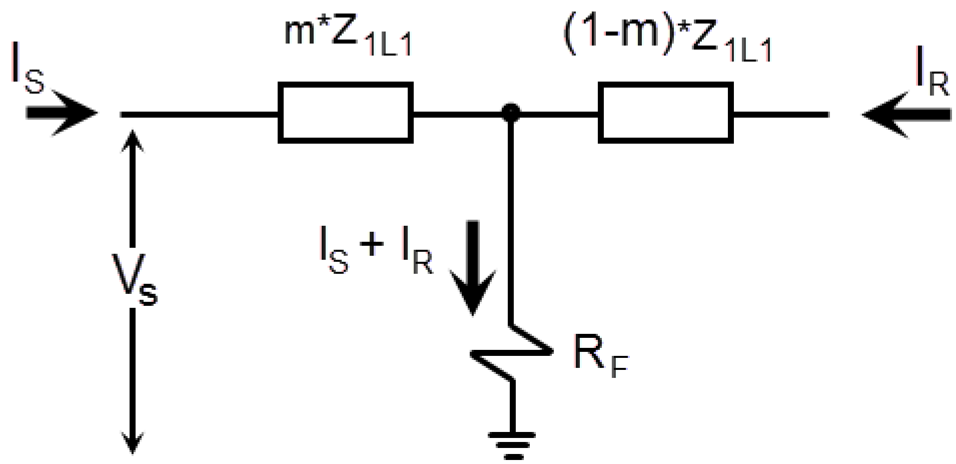
Most significant sources of error:

- Fault resistance
- Zero-sequence mutual coupling



The diagram shows the fault voltage and current measured from the two ends of a faulted overhead transmission line during a single-phase fault ground.

Single-ended Distance to Fault Calculation



"m" is the per unit distance to fault with respect to Substation S

Therefore:

$m{*}Z_{1L1}$ = total impedance of the faulted phase to the point of the fault from Station S

$(1-m){*}Z_{1L1}$ = total impedance of the faulted phase to the point of the fault from Station R

R_F = total fault resistance

V_S = faulted phase voltage measured at Station S

I_S = faulted phase current measured at Station S

I_R = faulted phase current measured at Station R

Single-ended Distance to Fault Calculation

Simple explanation of a popular single-ended method:

$$\frac{\text{Local Fault Voltage}}{\text{Local Fault Current}} = \text{Faulted phase loop impedance, } Z_{LOOP}\text{,}$$

from the substation to the fault

$Z_{LOOP} =$ V_S/I_S *Equation 1*

$X_F =$ $\mathrm{Im}\{Z_{LOOP}\}$ *Equation 2*

Where

$\mathrm{Im}\{\ldots\} =$ Imaginary part of …

The fault reactance (X_F) is then divided by the total reactance of the transmission line (X_L) to estimate the per-unit distance to fault with respect to Station S.

$m = X_F/X_L$ *Equation 3*

Remote Infeed:
The fault current, $I_{R,}$ into the fault resistance from the opposite end of the overhead transmission line.

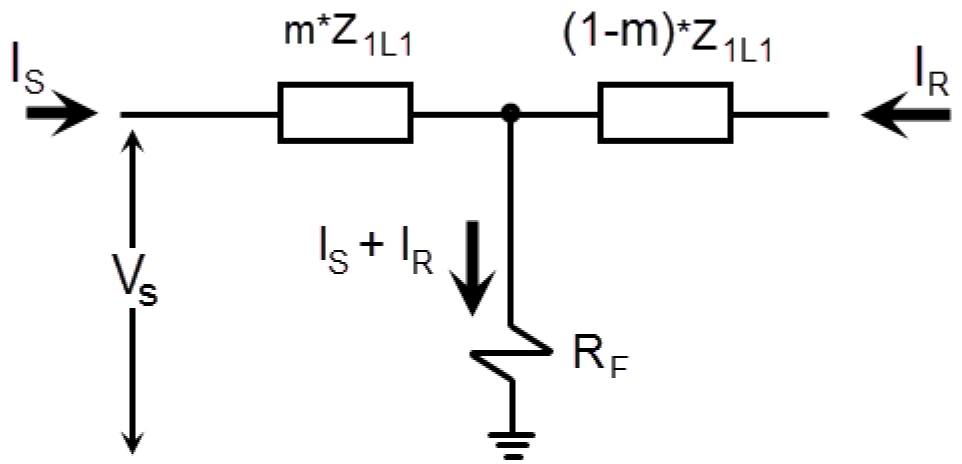
The main problem with single-ended fault location methods:

- The assumption that the faulted current from both ends of the transmission line are in phase
- If there is load flow this is typically not the case
- As the angular distance between I_S and I_R increases, so does the error

The cause of the error:

- The faulted voltage measured at Station S (V_S) is dependent on the faulted phase current flowing from Station R (I_R)

The faulted phase voltage measured at Station S is derived via ***Kirchhoff's Voltage Law*** (that is, the sum of the voltages measured around any loop equals zero).



$V_S = I_S \bullet m \bullet Z_{1L1} + (I_S + I_R) \bullet R_F$ *Equation 4a*

- Angular displacement between I_S and I_R introduces a reactance component due to voltage drop across the fault resistance when calculating the imaginary part of the faulted phase loop impedance.

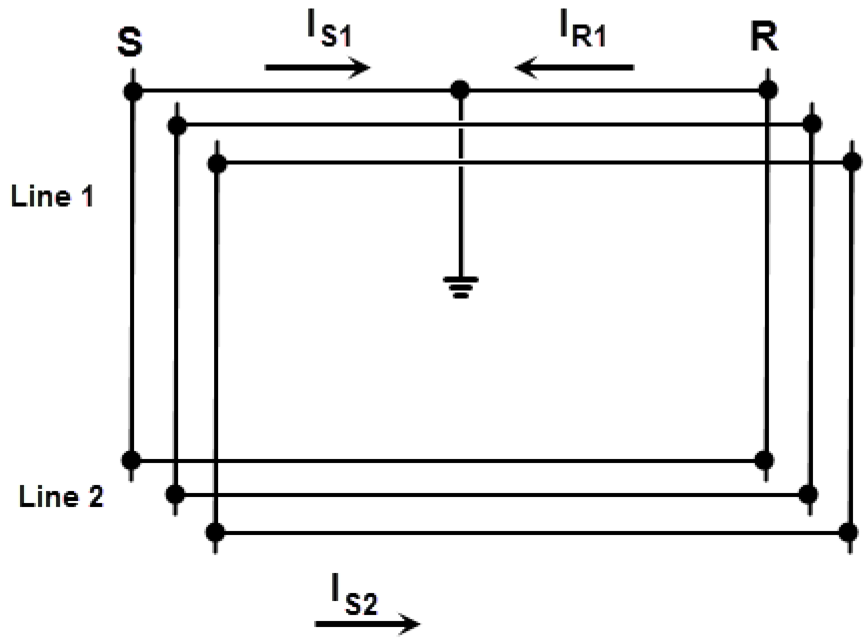
$V_S/I_S = m \bullet Z_{1L1} + \bullet R_F$ *Equation 4b*

$V_S/I_S = m \bullet Z_{1L1} + (1 + \alpha) \bullet R_F$ *Equation 4c*

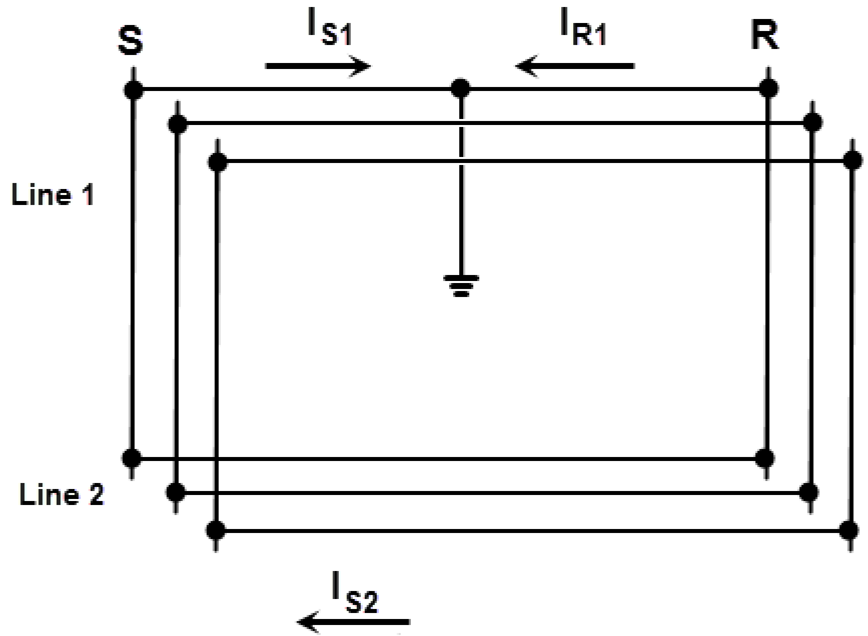
$\alpha = I_R/I_S$ *Equation 4d*

Zero-sequence mutual coupling occurs when:

- Two or more overhead transmissions lines share the same right-of-way
- The components are in-phase

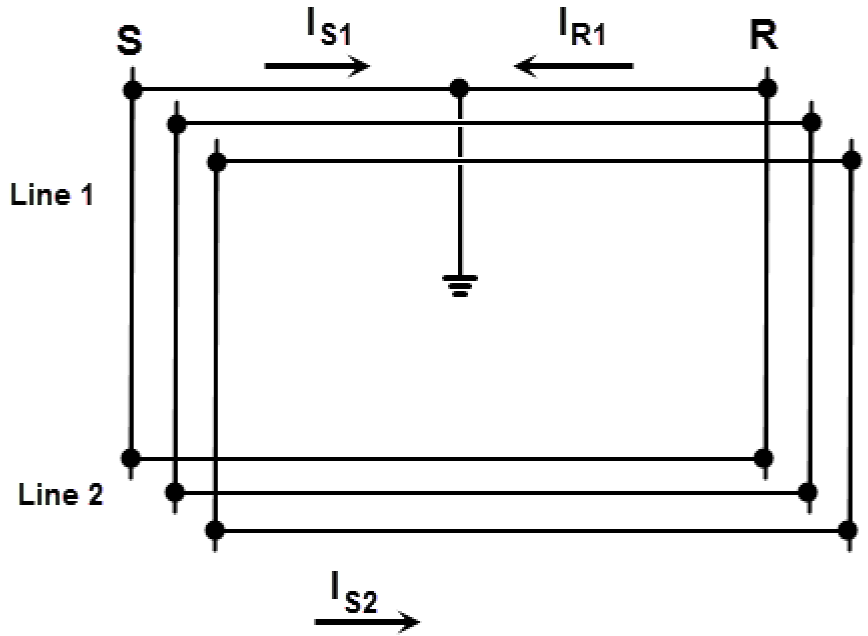


- The faulted phase current flowing in Line #2 (I_{S2}) affects the faulted phase voltage measured on Line #1 at Station S



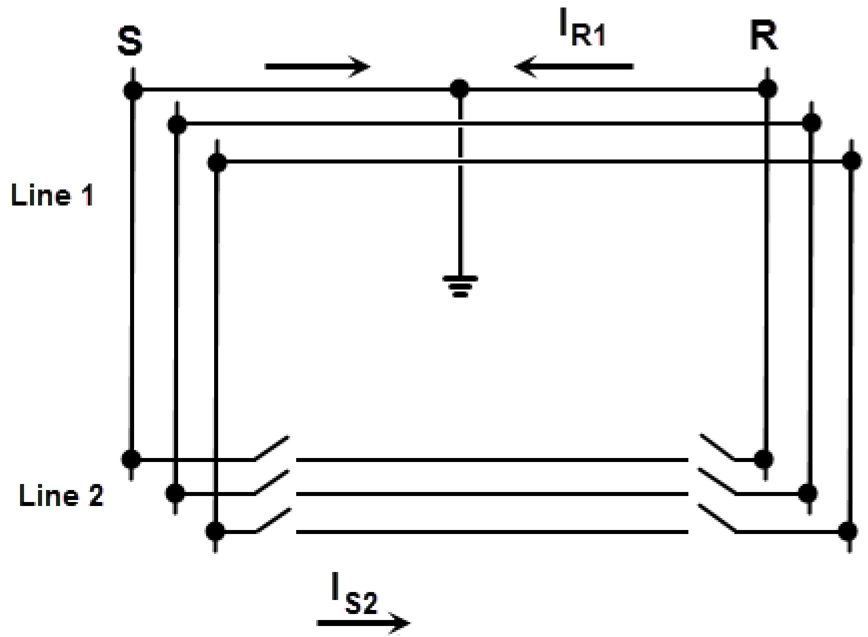
Zero-sequence mutual coupling overreaching:

- If I_{S1} and I_{S2} flow in opposite directions, the faulted phase voltage measured on Line number 1 at Station S decreases.
- This reduces the faulted phase loop impedance measured at Station S for Line number 1 ($Z_{LOOP} = V^{-}/I$).
- The distance-to-fault calculation is closer to Station S than the actual location of the fault.



Zero-sequence mutual coupling under-reaching:

- If I_{S1} and I_{S2} flow in the same direction, the faulted phase voltage measured on Line number 1 at Station S increases.
- This increases the faulted phase loop impedance measured at Station S for Line number 1 ($Z_{LOOP} = V^{+}/I$).
- The distance-to-fault calculation is further from Station S than the actual location of the fault.



Lines out-of-service and grounded at Station S and Station R:

- Loop current flows in the grounded line for faults involving ground on the parallel in-service line.
- The loop current cannot be measured since the current transformers are outside of the loop flow.
- The distance-to-fault calculation on the parallel in-service line is too close at one station, and too far at the other.

Double-Ended Fault Location

This section introduces a double-ended fault location algorithm for high voltage overhead transmission lines that uses synchronized voltage and current measurements from both ends of the line.

Advantages:

- Does not have any problems with fault resistance or zero-sequence mutual coupling
  - ➢ Use time-synchronized voltage and current measurements from both ends of the overhead transmission line
  - ➢ Uses only the negative-sequence voltage and current to calculate the fault location
- Uses commonly available time-synchronization via GPS receivers
- Substation instrumentation records fault voltage and current from each end of the overhead transmission line

Double-Ended Fault Location

Voltage and Current Measurements:

- Calculations use fundamental quantities (60 Hz in the United States)
- Modern protective relays filter voltage and current measurements to provide the fundamental quantities

Derivation:

- Transform voltage and current measured during fault conditions to their respective positive-, negative-, and zero-sequence quantities
- Negative-sequence quantities are present for single phase-to-ground, phase-to-phase, and phase-to-phase-to-ground faults
- Negative-sequence quantities are very reliable

Derivation, cont'd

- Calculating negative-sequence voltage and current from the three-phase voltage and current measurements:

$V_2 = 0.333 \bullet (V_a + a^2 \bullet V_b + a \bullet V_c)$ *Equation 5a*

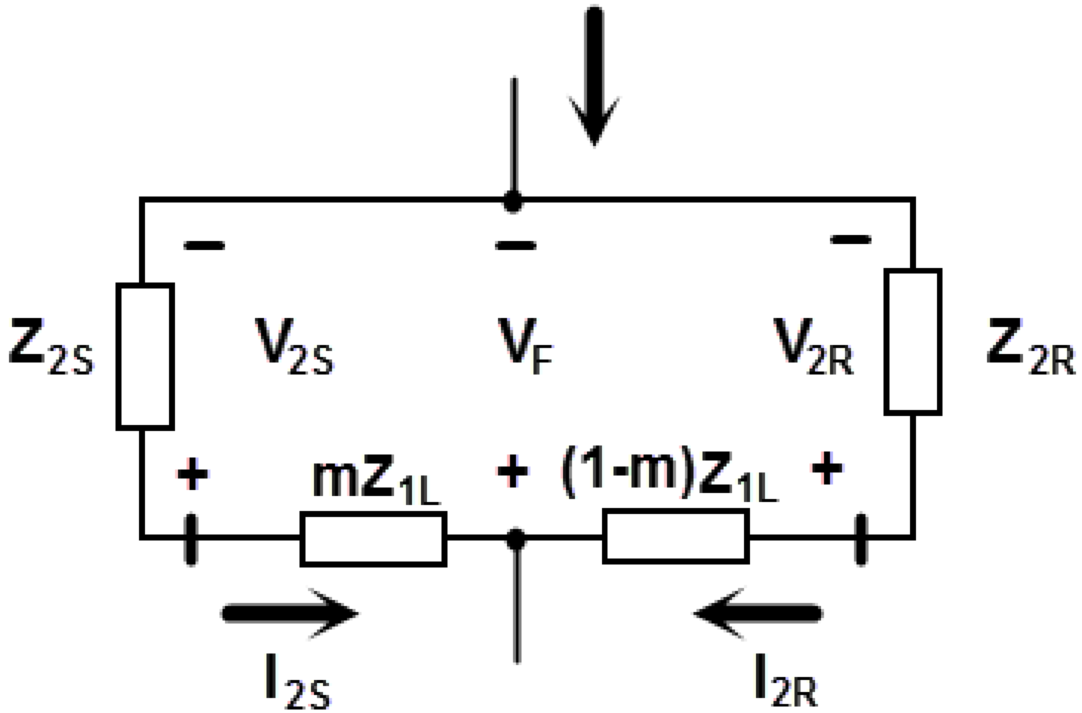
$I_2 = 0.333 \bullet (I_a + a^2 \bullet I_b + a \bullet I_c)$ *Equation 5b*

Where:

$a = 1 \angle 120°$

$a^2 = 1 \angle -120°$

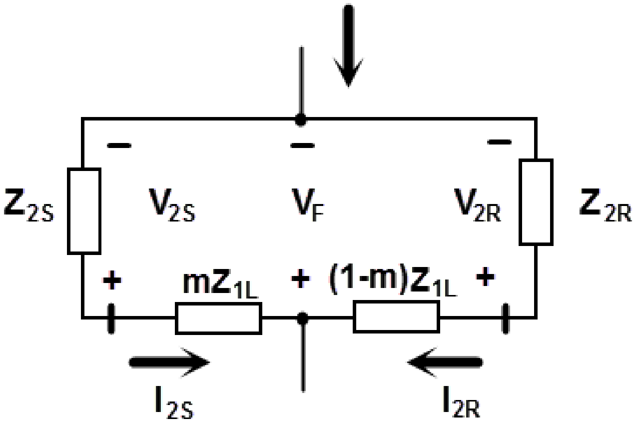
Faulted Overhead Transmission Line Negative-Sequence Example



- V_{2S} and I_{2S} are the negative-sequence quantities measured at Station S
- V_{2R} and I_{2R} are the negative-sequence quantities measured at Station R

Faulted Overhead Transmission Line Negative-Sequence Example

"m" is the per-unit distance to the fault with respect to Station S, therefore:



$m \bullet Z_L$ = Total conductor impedance to the point of the fault from Station S

$(1\text{-}m) \bullet Z_L$ = Total conductor impedance to the point of the fault from Station R

V_F = Fault voltage at the point of the fault

V_{2S} = Negative-sequence voltage measured at Station S

I_{2S} = Negative-sequence current measured at Station S

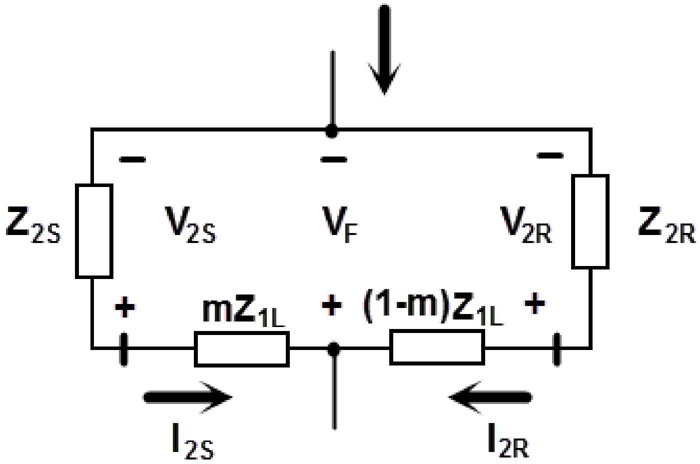
V_{2R} = Negative-sequence voltage measured at Station R

I_{2R} = Negative-sequence current measured at Station R

I_2 = Total negative-sequence fault current ($I_{2S} + I_{2R}$)

Faulted Overhead Transmission Line Negative-Sequence Example

Determine the apparent negative-sequence source impedances at Stations S and R as follows:



$Z_{2S} = -V_{2S}/I_{2S}$ *Equation 6a*

$Z_{2R} = -V_{2R}/I_{2R}$ *Equation 6b*

Derive two loop voltage equations in terms of the fault voltage:

@ Station S

$$-V_{2S} + I_{2S} \bullet m \bullet Z_L + V_F = 0$$

$$V_F = V_{2S} - m \bullet I_{2S} \bullet Z_L \qquad \text{(Equation 7)}$$

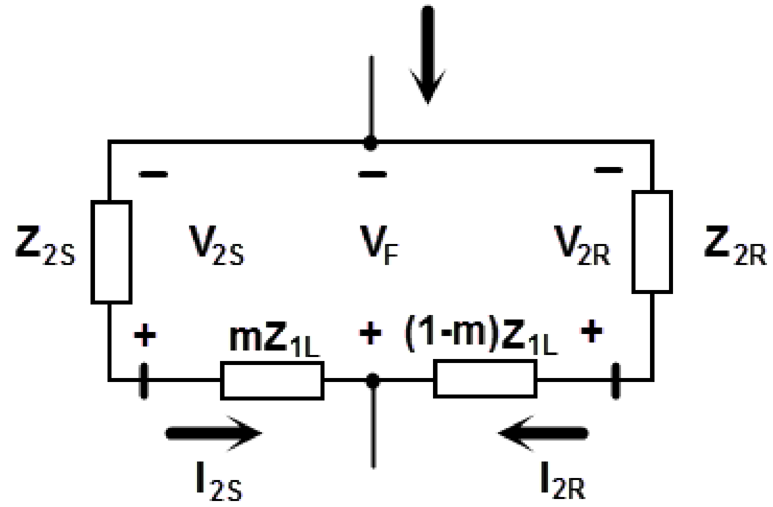
@ Station R

$$-V_{2R} + I_{2R} \bullet (1 - m) \bullet Z_L + V_F = 0$$

$$V_F = V_{2R} + m \bullet I_{2R} \bullet Z_L - I_{2R} \bullet Z \qquad \text{(Equation 8)}$$

Faulted Overhead Transmission Line Negative-Sequence Example

Set the two equations (Equations 7 and 8) equal to each other and solve for “m” with respect to Station S.



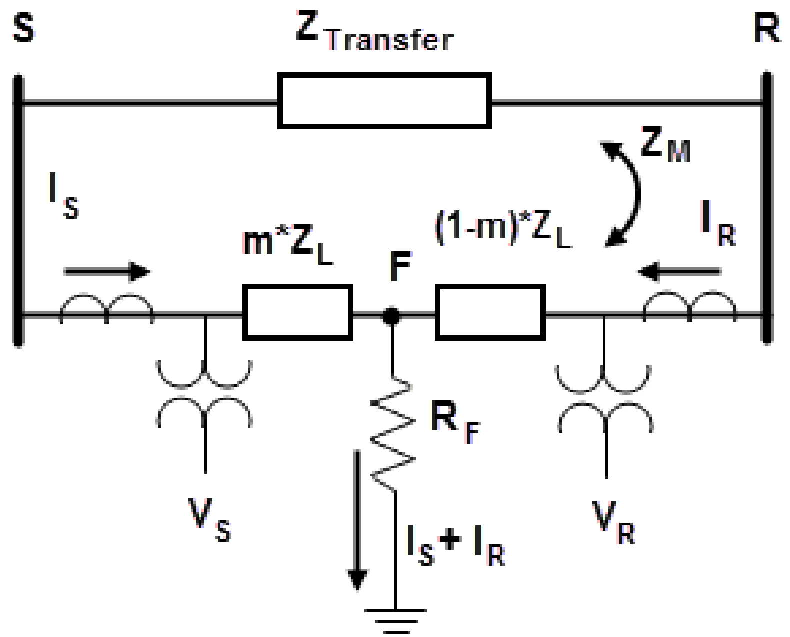
$$V_{2S} - m \bullet I_{2S} \bullet Z_L = V_{2R} + m \bullet I_{2R} \bullet Z_L - I_{2R} \bullet Z_L$$

$$V_{2S} - V_{2R} + I_{2R} \bullet Z_L = m \bullet I_2 \bullet Z_L$$ *Equation 9*

$$m_{(s)} = \frac{V_{2S} - V_{2R} + I_{2R} \bullet Z_L}{I_{2R} \bullet Z_L}$$ *Equation 10*

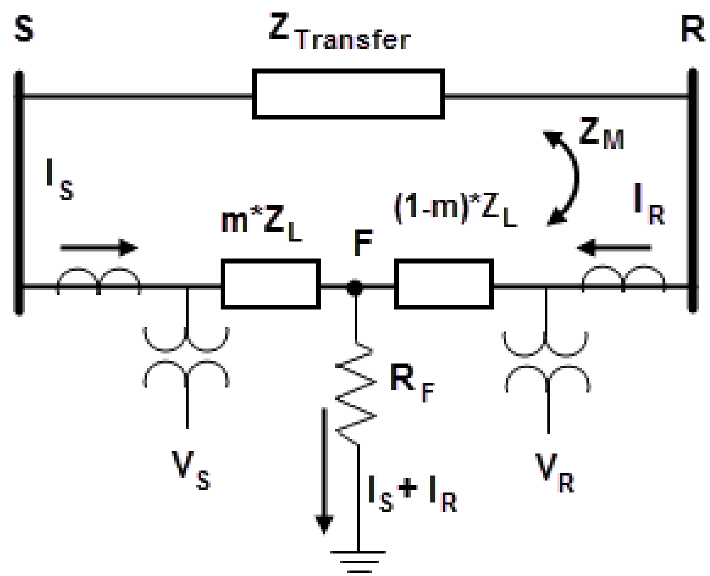
How to Test the Fault Locator

Use time-synchronized test signals to verify that the double-ended fault locator works properly.



Test requirements:

- Fault locating equipment enabled at both terminals
- Communication channel available



Z_L	=	Line impedance
$Z_{Transfer}$	=	Transfer impedance
Z_M	=	Mutual coupling
F	=	Fault location
V_S	=	Fault location at Substation S
V_R	=	Fault location at Substation R
I_S	=	Fault current from Substation S
I_R	=	Fault current from Substation R

How to Test the Fault Locator

- The diagram represents a simple model of a faulted transmission line.
- Substation S is the reference bus with respect to the distance-to-fault (m).

Use this equation to calculate the per unit distance to fault with respect to Substation S:

$$m = \frac{V_{2S} - V_{2R} + I_{2R} \bullet Z_L}{I_{2R} \bullet Z_L}$$

(Equation 11)

Example 1 Scenario

- Resistive "A" phase-to-ground fault located at 75 percent of the line (15 miles) from substation S
- Simulated using Mathcad (simulation could also be accomplished using short circuit software such as ASPEN or CAPE)
- Modeled with mild load prior to fault occurrence
- Line is mutually coupled to another transmission line

Calculate fault voltage and current at each end of the line:

$V_{AS} =$	$53.4 \angle -32.1°$ volts	$V_{AR} =$	$55.6 \angle -18.1°$ volts
$V_{BS} =$	$68.6 \angle -128.5°$ volts	$V_{BR} =$	$63.2 \angle -123.0°$ volts
$V_{CS} =$	$63.9 \angle 115.2°$ volts	$V_{CR} =$	$66.3 \angle 114.6°$ volts

Example 1 Scenario, cont'd

Negative-sequence voltage and negative-sequence current are shown below:

$V_{2S} =$ 7.86 $\angle$-133.8° volts $V_{2R} =$ 6.90 $\angle$-133.6° volts

$I_{2S} =$ 0.58 $\angle$-13.9° amps $I_{2R} =$ 2.82 $\angle$-36.4° amps

- Equation 11 yields a result of 75 percent that matches the actual fault location.
- Equation 11 is immune to problems associated with fault resistance and zero-sequence mutual coupling since it only uses negative-sequence quantities.

Example 2 Scenario

- “A” phase-to-ground fault occurred on a 230 kV overhead transmission line
- Event captured by digital fault recorders at both ends
- Conventional methods proved futile in locating the fault
- The fault turned out to be caused by transmission lines contacting tree branches
- Tree branches represented an extremely high level of fault resistance

Example 2 Scenario, cont'd

- The double-ended distance-to-fault equation correctly calculated the distance-to-fault with an error less than 5 percent
- Time synchronized negative-sequence quantities measured at each end of the line:

$V_{2S} = 8.454 \angle 238.6^\circ$ kV

$I_{2S} = 456.69 \angle 368.4^\circ$ A

$V_{2R} = 6.697 \angle 239.4^\circ$ kV

$I_{2R} = 345.82 \angle 350.4^\circ$ A

$I_2 = I_{2S} + I_{2R} = 792.82 \angle 0.7^\circ$ A

$Z_{1L} = 24.899 \angle 82.7^\circ\ \Omega$ primary

$$m = \frac{V_{2S} - V_{2R} + I_{2R} \bullet Z_{1L}}{I_{2R} \bullet Z_L}$$

$V_{2S} - V_{2R} + I_{2R} \bullet Z_{1L} = 6.952 \angle 77.5^\circ$ kV

$I_2 \bullet Z_{1L} = 19.7 \angle 83.4^\circ$ kV

$|m| = 0.352$ per-unit

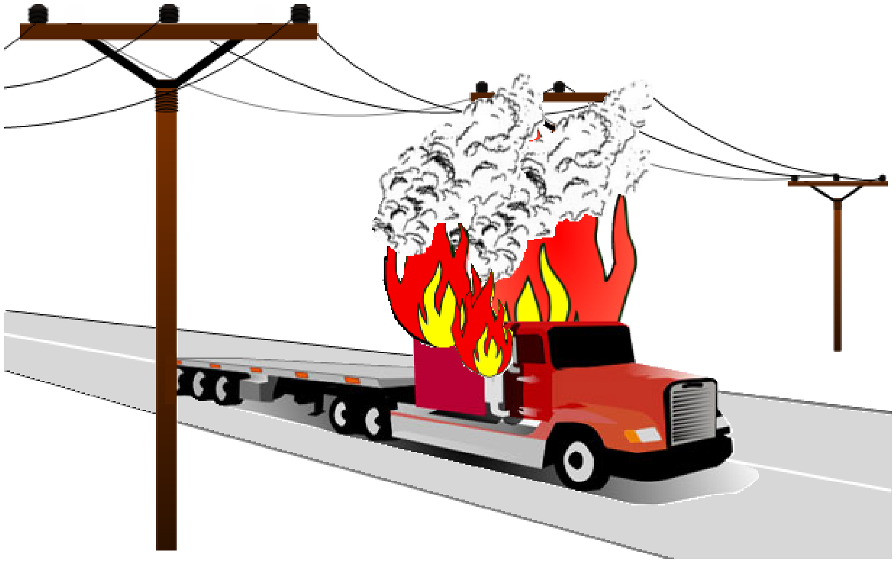
Example 2 Scenario, cont'd

Calculation Results:

- The actual line length was 35.43 miles.
- The calculated distance-to-fault with respect to Substation S was 12.5 miles (35.43 * 0.352).
- The actual distance-to-fault was 13 miles.

Example 3 Scenario

- “B”-phase-to-“C”-phase fault occurred on a 230 kV overhead transmission line between Substation S and Substation R.
- The fault was due to a truck that caught fire under the line.
- The resulting smoke created a path for electrical current to flow between “B”- and “C”-phase conductors.
- Negative-sequence voltage and current recorded by instrumentation at the two ends of the line.



Example 3 Scenario, cont'd

- The double-ended distance-to-fault equation was applied using the negative-sequence voltage and current recorded by instrumentation at the two ends of the line.
- The actual calculations show that this method produced results with an error of less than 2 percent.

$V_{2S} = 51.7 \angle 1.9° \text{ kV}$ $V_{2R} = 37.9 \angle 1.3° \text{ kV}$

$I_{2S} = 11{,}900 \angle 96.5° \text{ A}$ $I_{2R} = 2{,}470 \angle 94° \text{ A}$

$I_2 = I_{2S} + I_{2R} = 14{,}370 \angle 96° \text{ A}$

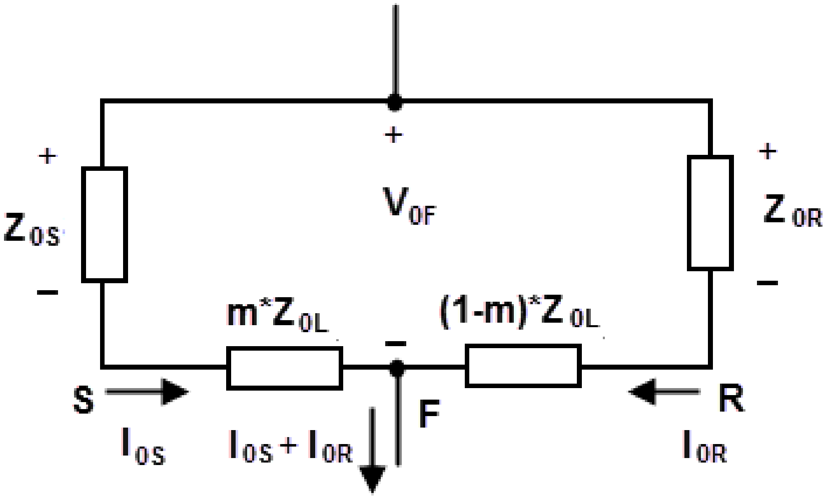
$Z_{1L} = 11.96 \angle 85.8° \ \Omega \text{ primary}$

$|m| = 0.092 \text{ per-unit}$

- The actual line length was 21 miles.
- The calculated distance-to-fault with respect to Substation S was 1.93 miles (21*0.092).
- The actual distance was 1.97 miles

Zero-sequence overhead transmission line impedance verification

The diagram shows a zero-sequence network for faults involving ground.



- Use equation 12 to calculate the zero-sequence impedance of the transmission line.
- The components required for the calculation are the synchronized zero-sequence voltage and current measured at each end of the line.

$$Z_{0L} = \frac{I_{0S}Z_{0S} - I_{0R}Z_{0R}}{mI_{0S} - (m-1)I_{0R}}$$

(*Equation 12*)

- Equation 12 does not account for zero-sequence mutual coupling.

Double-Ended Fault Location for Transmission Line Protection:

- Implementation of Equation 11 provides high-speed protection of overhead transmission lines.
- Calculate terminal voltage and current phasors in real time and then pass them from end-to-end via a digital communication channel.
- The double-ended fault locator is immune to many problems associated with conventional distance based schemes such as overreach and under-reach.

Conclusions

- Double-ended fault locator testing contains many similarities to testing high-speed communication assisted tripping schemes (HSCATS).
- Modern protective relays use single-ended methods to determine distance to fault, but this method is prone to error when there is fault resistance and power flow through the line.
- Double-ended testing methods can determine fault location on high voltage overhead lines quickly and accurately, sparing the utility from a great deal of time and expense patrolling the lines for damage.

Conclusions, cont’d

- The double-ended method uses time-synchronized filtered data from both ends of the overhead transmission line to determine the exact fault distance from the reference point.
- Unlike the single-ended method, the double-ended method is immune from problems due to fault resistance or zero-sequence mutual coupling.

Questions?

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