

Ground Protection Methods for Transmission Lines using Segmented Static Wires

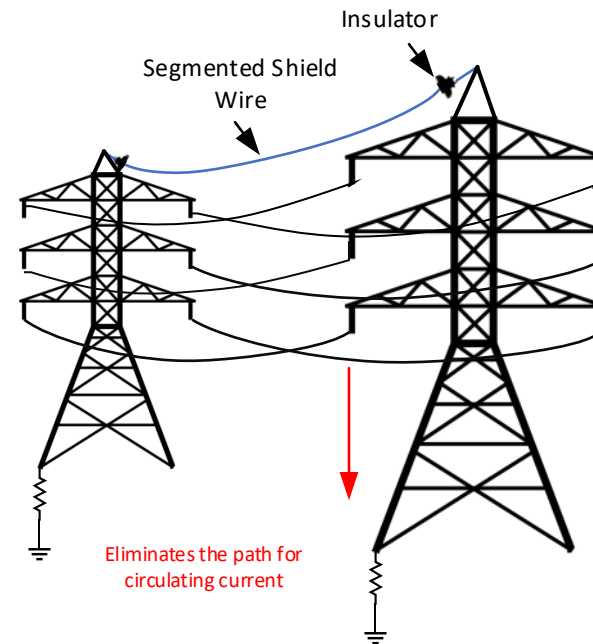
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Background

- Static wires on EHV lines are often segmented to improve efficiency

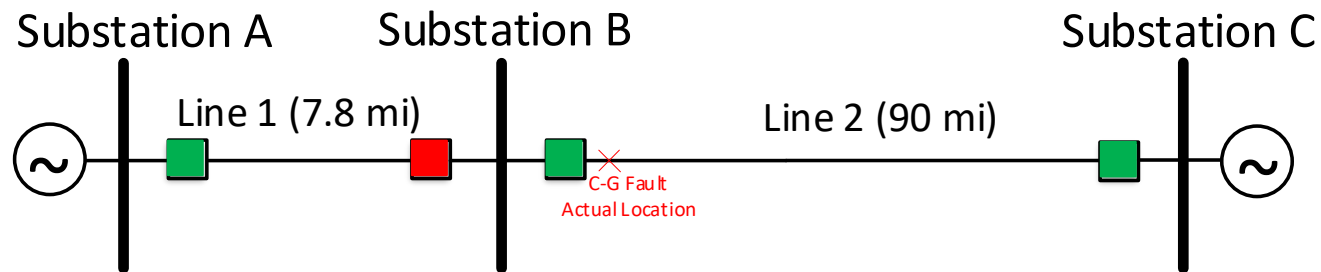
$$V_{ind} = \oint \vec{E} * d\vec{l}$$

- Lightning produces sufficient voltage to flash over the insulation points, as well as fault currents of sizeable magnitude



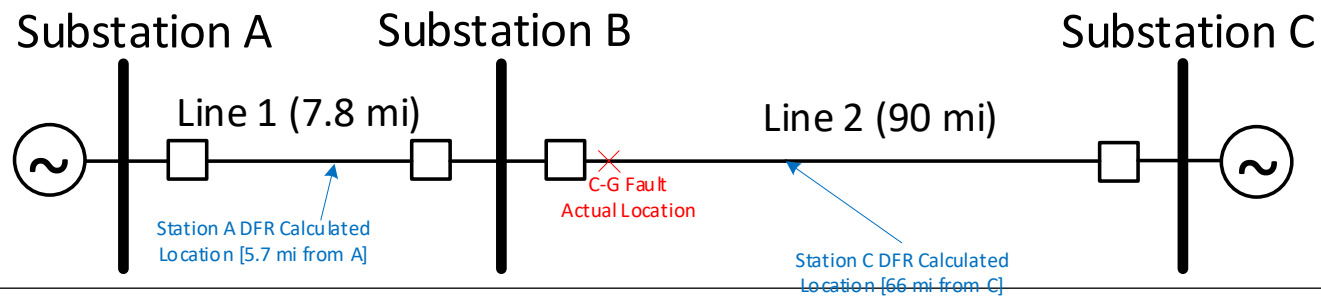
Ground Protection Mis-Operation Event

- A Close-In C-G fault on 500kV Line 2 inside Substation B.
- Line 2 tripped as expected. Goes through reclose cycle to lockout.
- Simultaneously, Substation A, Line 1 CBs trip.
- Substation B, Line 1 CBs did not trip



Ground Protection Mis-Operation Event

- Fault location confirmed at Substation B
- The Digital Fault Recorders at Substations A and C short of true location



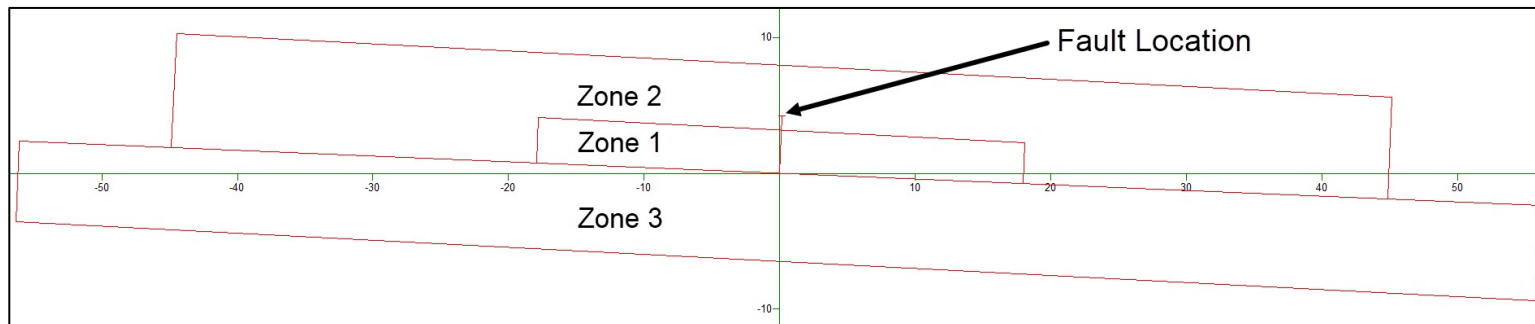
Ground Protection Mis-Operation Event

Line 1 (Line Differential & Impedance)

- Line 1 differential relays did not trip as expected
- Line 1 (A) impedance relays tripped on Zone 1 Ground Quadrilateral

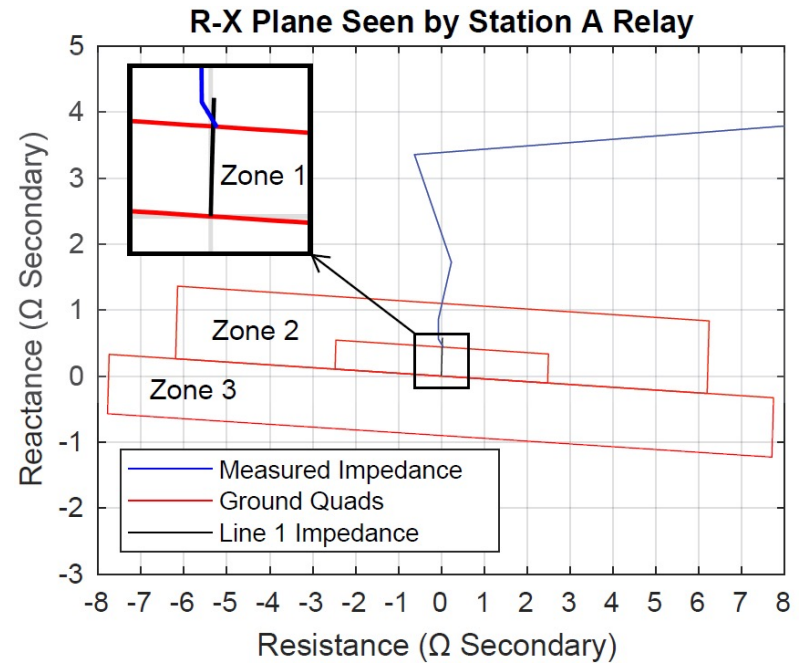
Line 1 Impedance Protection Settings

- Zone 1 set to cover 80% of total line impedance (underreach)
- Zone 1 not blocked since it is an unconditional trip



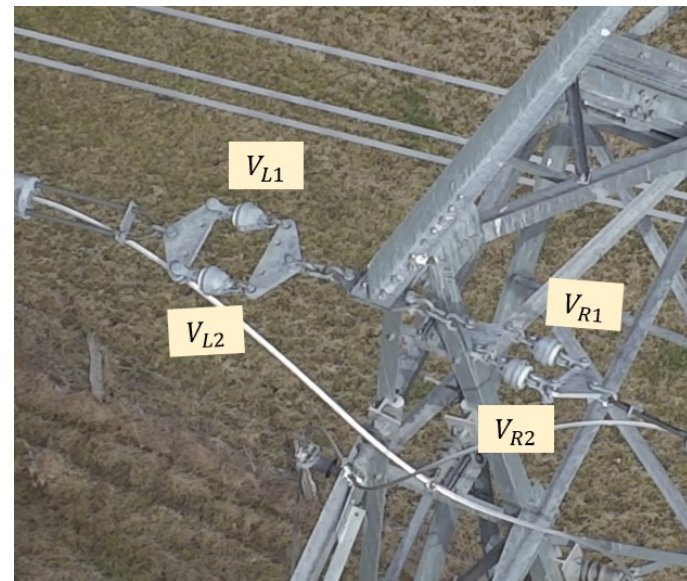
Ground Protection Mis-Operation Event

- Records from the line relays at Substation A show the measured impedance trajectory during the event
- The apparent impedance settles out in the Zone 1 Ground Quadrilateral, causing an instantaneous trip



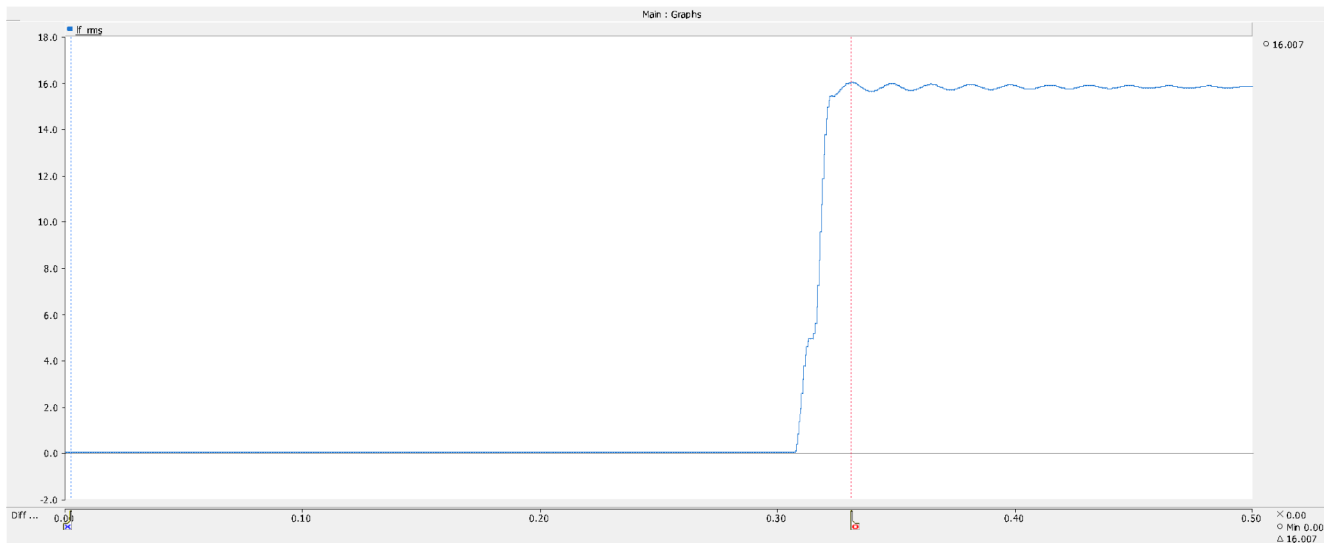
Segmentation Point Flashover

- Porcelain insulators on the 500 kV static wires are rated for 10 kV in wet conditions and 20 kV in dry
- A flashover occurs across these insulators if the voltage threshold is exceeded
- The flashover at the segmentation points caused the static conductors to be continuous from Substation A to Substation B



Segmentation Point Flashover Simulations

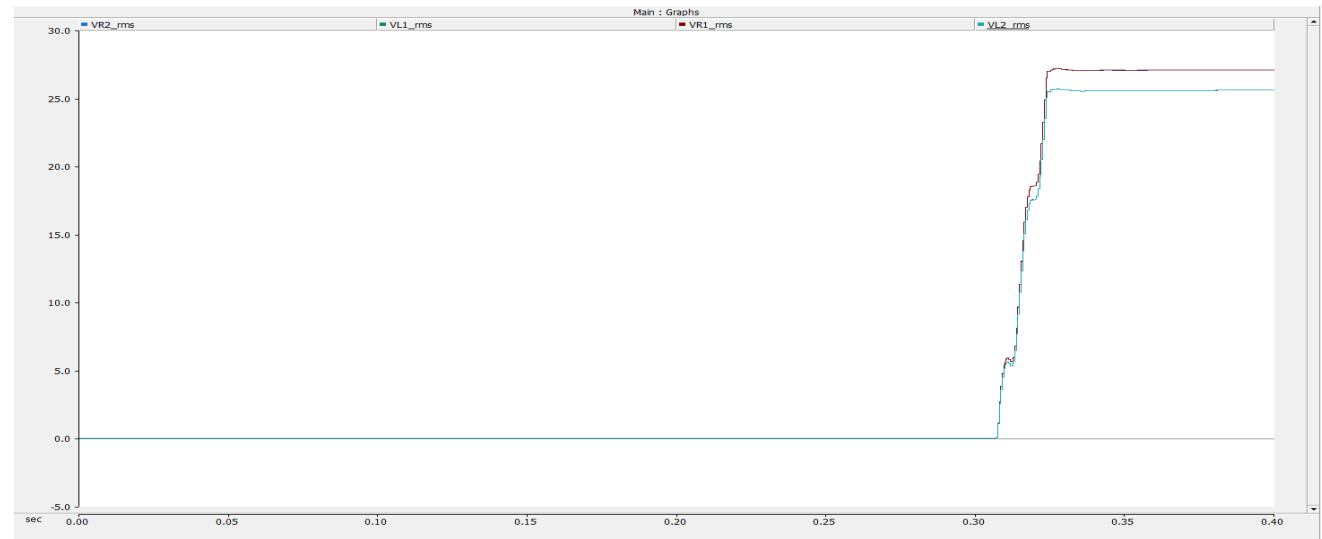
- The DFR at Substation A recorded a fault current of 16,350 A.



Segmentation Point Flashover Simulations

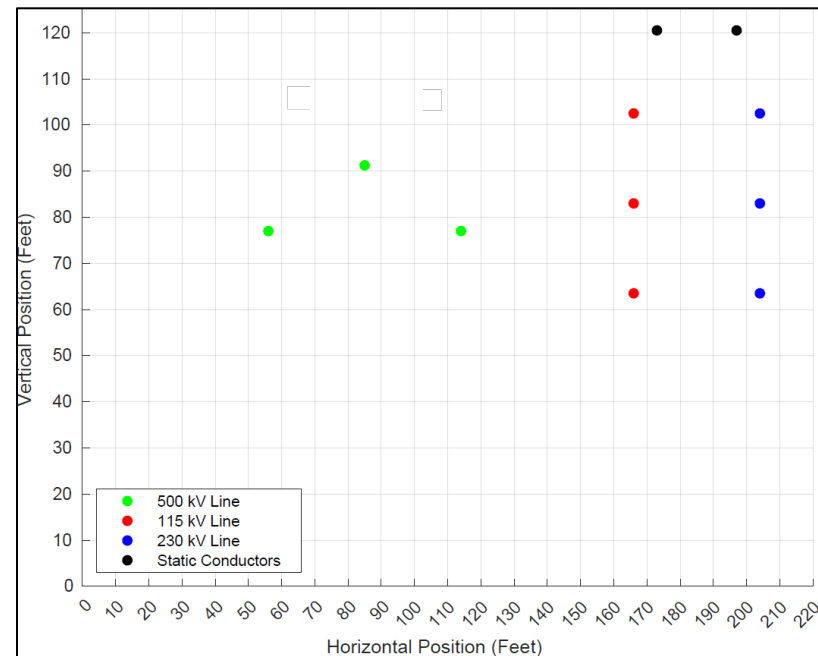
Computer simulation showed maximum induced voltage across the 4 insulators is:

- 25.67 kV (V_{L_1})
- 27.15 kV (V_{R_1})
- 25.69 kV (V_{L_2})
- 27.17 kV (V_{R_2})



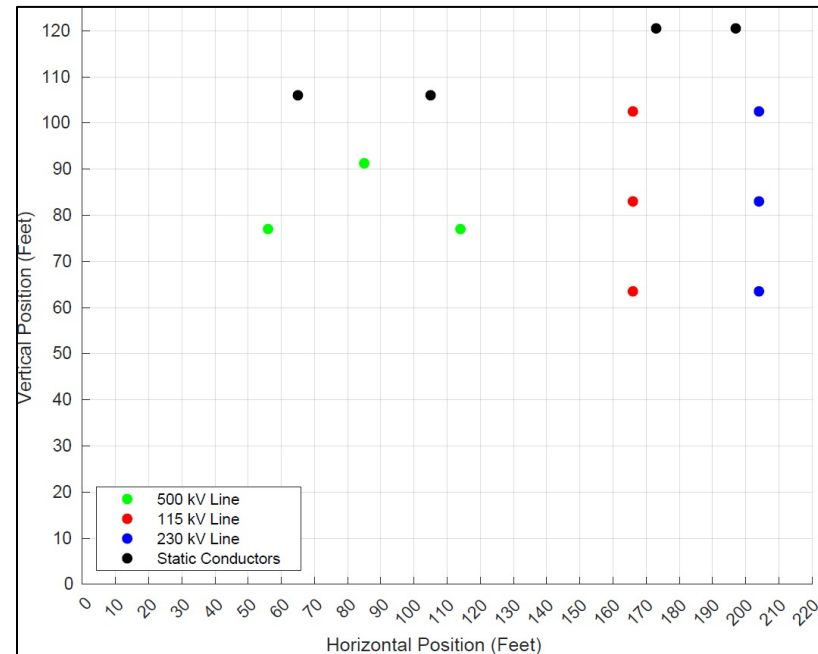
Process of Transmission Line Impedance Calculation

- Transmission lines are modeled in cross-sectional views of the Right Of Way
- Historically segmented shield wires modeled by removing them from the cross-section
- Assumed the segmented shield wires were not paths for zero-sequence current



Process of Transmission Line Impedance Calculation

- A new impedance calculation process is needed
- New process requires the line impedance to be calculated twice
 - A segmented static impedance model (historical method)
 - A continuous static impedance model retaining the shield wires



Apparent Impedance Seen By Line Relays

An important consideration is the zero-sequence compensation factor

$$k_0 = \frac{Z_{0L} - Z_{1L}}{3 \cdot Z_{1L}}$$

Z_{0L} = Zero-Sequence Line Impedance

Z_{1L} = Positive-Sequence Line Impedance

Apparent Impedance Seen By Line Relays

The relay then uses k_0 to calculate the apparent impedance, Z_{App} , seen by the relay during a fault.

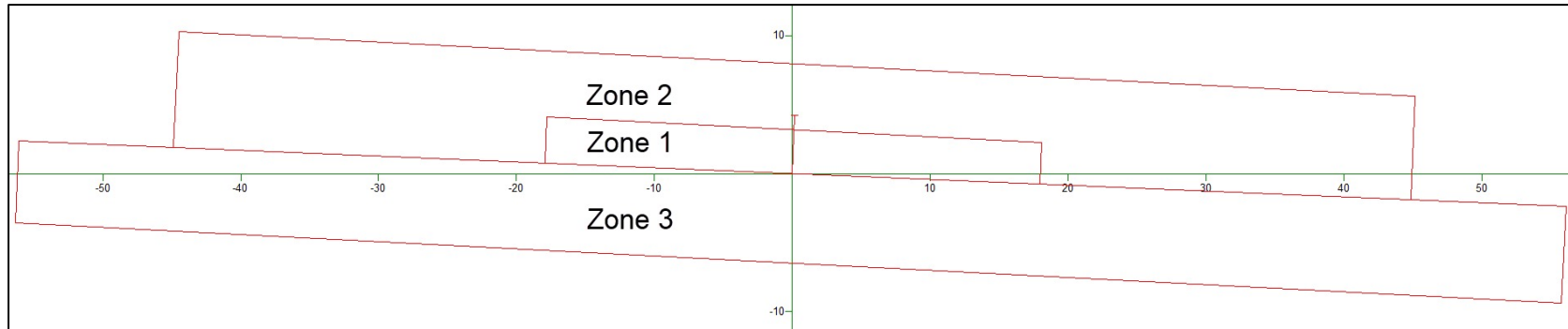
$$Z_{App} = \frac{V_a}{(I_a + k_0 \cdot 3I_0)}$$

What are the impacts to ground protection?

Impacts to Ground Protection

Impedance-Based Schemes

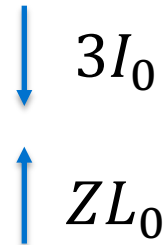
- Zone 1 Ground must consider a continuous static so it does not overreach
- In Short Circuit Analysis, k_0 needs to be adjusted so Z_{app} is calculated correctly



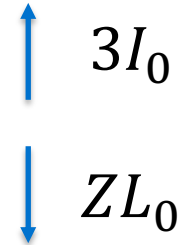
Impacts to Ground Protection

Historically was set based on remote bus faults on the transmission system with a line impedance using segmented static conductors

No Flashover Occurs (Segmented Static)



All Segmentation Points Flash Over (Continuous Static)



Impacts to Ground Protection (Underreaching Distance Protection – Zone 1)

No Flashover Occurs

Consider the following line parameters:

$$ZL_1 = 9.76 \angle 87.5^\circ \Omega_{Primary}$$

$$ZL_{0,Segmented} = 39.41 \angle 82.4^\circ \Omega_{Primary}$$

$$k_{0,Segmented} = 1.014 \angle -6.82^\circ$$

Voltage/Current seen by Line Relays:

(No flashover)

$$V_a = 100.29 \angle 29.5^\circ \text{ kV}$$

$$3I_0 = 4240 \angle -55.0^\circ A_{Primary}$$

$$I_a = 5640 \angle -54.8^\circ A_{Primary}$$

All Segmentation Points Flash Over

Consider the following line parameters:

$$ZL_1 = 9.76 \angle 87.5^\circ \Omega_{Primary}$$

$$ZL_{0,Segmented} = 23.58 \angle 74.01^\circ \Omega_{Primary}$$

$$k_{0,Continuous} = 0.487 \angle -22.67^\circ$$

Voltage/Current seen by Line Relays:

(All segmentation points flash over)

$$V_a = 85.06 \angle 27.3^\circ \text{ kV}$$

$$3I_0 = 5122 \angle -52.2^\circ A_{Primary}$$

$$I_a = 6036 \angle -53.8^\circ A_{Primary}$$

Impacts to Ground Protection (Underreaching Distance Protection – Zone 1)

No Flashover Occurs

$$Z_{App,Segmented} = 10.11 \angle 87.3^\circ \Omega_{Primary}$$

$$\begin{aligned} Z1G_{segmented} &= 80\% \cdot |Z_{App,Segmented}| \angle (ZL_1) \\ &= 8.08 \angle 87.5^\circ \Omega_{Primary} \end{aligned}$$

All Segmentation Points Flash Over

If $k_{0,segmented}$ is used, the resulting Z_{app} is

$$Z_{App,Continuous,k0segmented} = 7.58 \angle 87.5^\circ \Omega_{Primary}$$

$$\begin{aligned} Z1G_{continuous} &= 80\% \cdot |Z_{App,Continuous,k0segmented}| \angle (ZL_1) \\ &= 6.06 \angle 87.5^\circ \Omega_{Primary} \end{aligned}$$

Out of curiosity, what if $k_{0,continuous}$ is used?

$$Z_{App,Continuous,k0continuous} = 10.11 \angle 87.3^\circ \Omega_{Primary}$$

Zone 1 Ground Setting	Reach with Z_{app} & Segmented Static	Reach with Z_{app} & Continuous Static
8.08	80%	107%
6.06	60%	80%

Impacts to Ground Protection (Overreaching Distance Protection – Zone 2)

Consider the same line used for the previous Zone 1 example:

No Flashover Occurs

$$\begin{aligned} Z_{2G_{Segmented}} &= 150\% \cdot |Z_{App,Segmented}| \angle(ZL_1) \\ &= 15.17 \angle 87.5^\circ \Omega_{Primary} \end{aligned}$$

All Segmentation Points Flash Over

$$\begin{aligned} Z_{2G_{Continuous}} &= 150\% \cdot |Z_{App,Continuous,k0Segmented}| \angle(ZL_1) \\ &= 11.37 \angle 87.5^\circ \Omega_{Primary} \end{aligned}$$

Zone 2 Ground Setting	Reach with Z_{app} & Segmented Static	Reach with Z_{app} & Continuous Static
15.17	150%	200%
11.37	112%	150%

Impacts to Ground Protection (Inverse Time Overcurrent Protection)

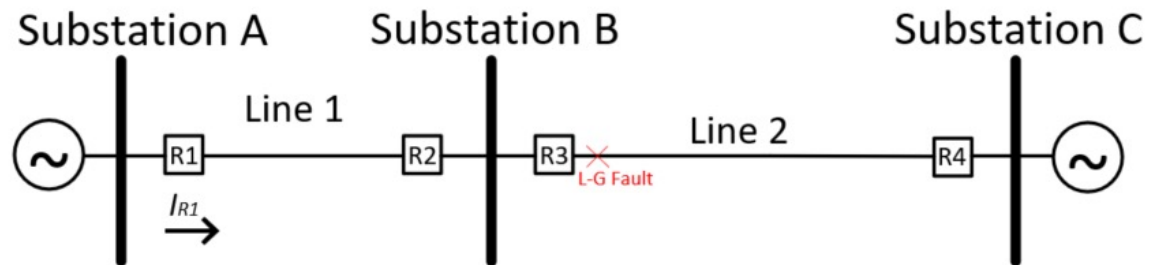
- Traditionally, the overcurrent settings are determined using the minimum reach for L-G faults at the remote bus
- Since minimum reach is concerned with the lowest possible flow of fault current, a segmented static should be used
- Any flashover at the segmentation points will cause the zero-sequence impedance to decrease (and zero sequence current to rise), this results in
 - **Improved Reach**
 - **Faster Relay Operating Time**

$$\text{Overcurrent Reach} = \frac{\text{Fault Current (A)}}{\text{Pickup (A)}}$$

Impacts to Ground Protection (Inverse Time Overcurrent Protection)

Consider the power system topology below

A close-in bolted L-G fault occurs on Line 2 inside Substation B



Impacts to Ground Protection (Inverse Time Overcurrent Protection)

No Flashover Occurs

$$Z_{L0,Segmented} = 59.98 \angle 81.9^\circ$$

$$I_{R1,Segmented} = 4422 A_{Primary}$$

$$51G_{Pickup,Segmented} = \frac{I_{R1,Segmented}}{2.0} = \frac{4422}{2.0}$$

$$= 2211 A_{Primary}$$

All Segmentation Points Flashover

$$Z_{L0,Continuous} = 46.37 \angle 70.7^\circ$$

$$I_{R1,Continuous} = 5214 A_{Primary}$$

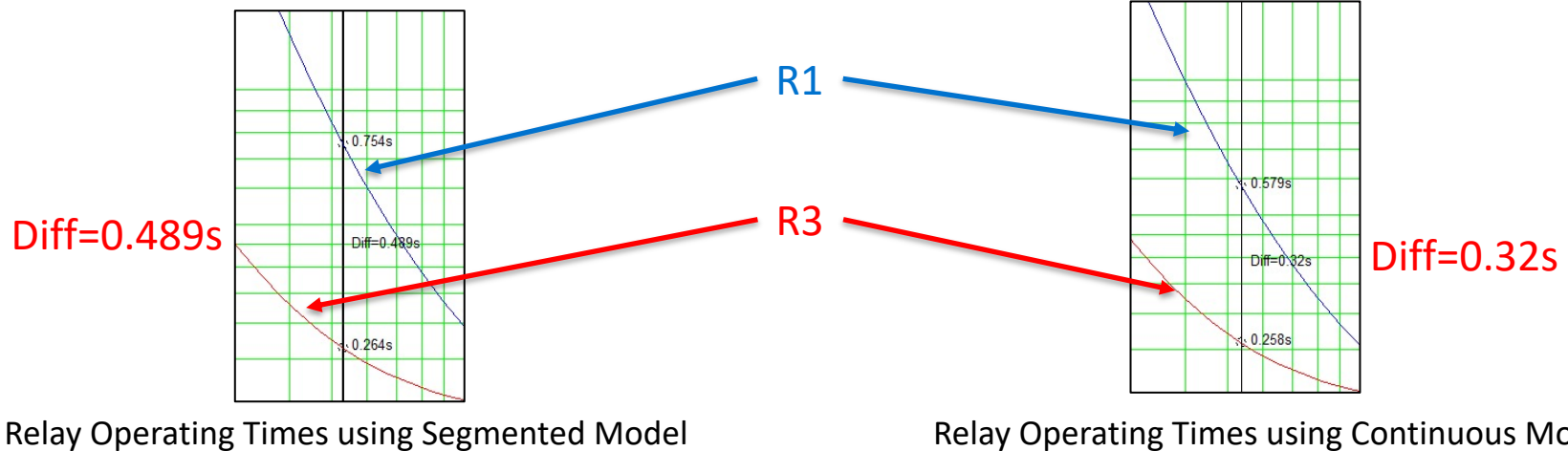
$$51G_{Pickup,Continuous} = \frac{I_{R1,Continuous}}{2.0} = \frac{5214}{2.0}$$

$$= 2607 A_{Primary}$$

51G Pickup Setting	Reach under Segmented Static Conditions	Reach under Continuous Static Condition
2211	2.0	2.4
2607	1.7	2.0

Impacts to Ground Protection (Inverse Time Overcurrent Protection)

Considering the Time Dial for R1 and R3 have already been determined, the time separation is shown in the operating curves below



CONCLUSION

- Systems where segmented static conductors are used and the BIL is low enough to allow for fault current induced flashovers can cause **Underreaching Protection to inadvertently trip for a remote bus fault**
 - Fault modeling using a continuous static needs to be used to adequately set the underreaching ground protection.
- Pilot overreaching elements need to be sensitive enough to ensure the protection reaches beyond the remote terminal
 - Fault modeling using a segmented static needs to be used to adequately set the overreaching ground protection

The background of the slide features three parallel, light blue diagonal stripes that run from the top-left towards the bottom-right. The stripes are evenly spaced and have a consistent width.

Questions?