Comparative Analysis of Distribution Lines
Falling Conductor Protection Methods

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Our discussion today

Challenges for distribution systems

Falling-conductor detection methods

Current based

Voltage based

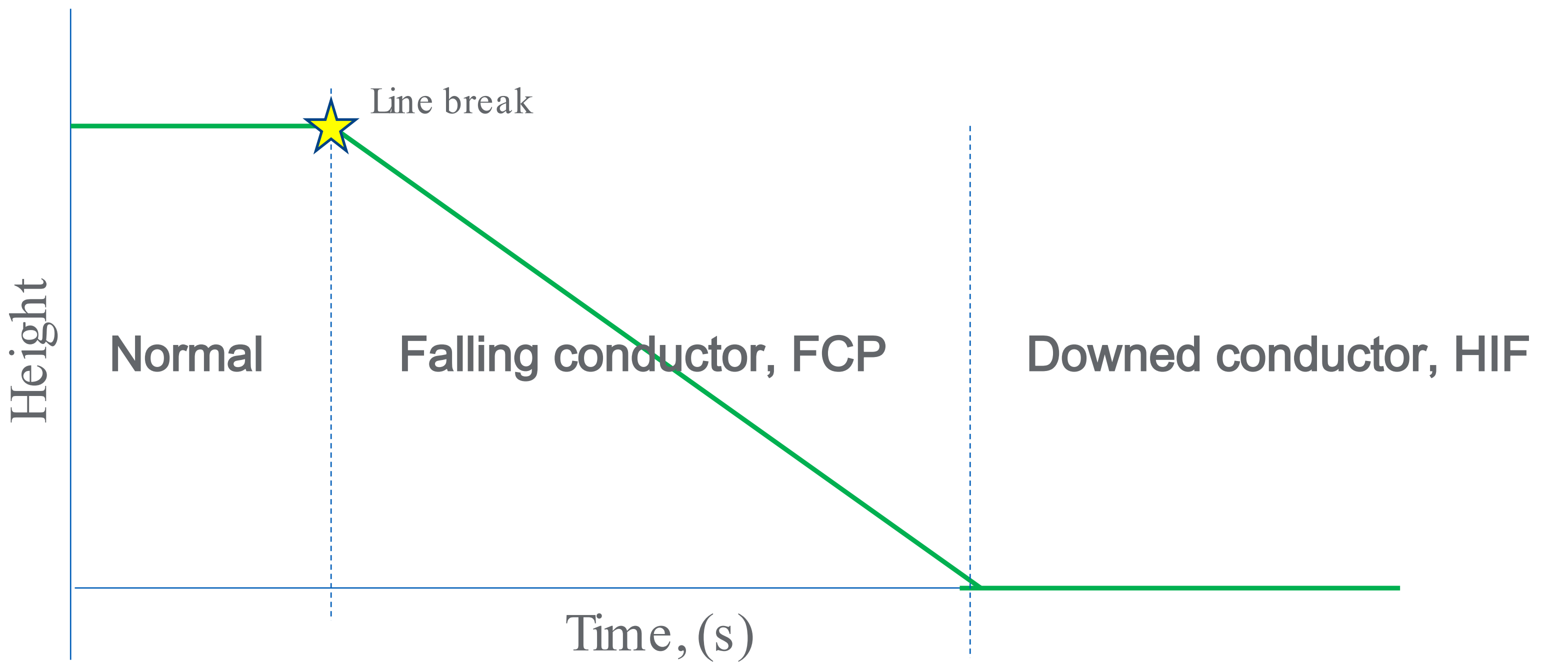
Impedance based

Challenges for distribution systems

Broken-conductor detection schemes for transmission systems might not work effectively for complex distribution systems

- Large DER penetration
- Advanced distribution automation
- Feeder reconfiguration
- Varying load profiles
- Single-phase switching and fusing
- Mixed, overhead lines and underground cables

Falling-conductor and arcing-fault detection time



Broken, falling-conductor protection, FCP

Trip before line becomes downed conductor

Current-based; I2/I1 ratio

Voltage-based (loss of voltage, rate-of-change of voltage)

Impedance-based (V and I measurements)

Scalable to multiple relays per line / feeder

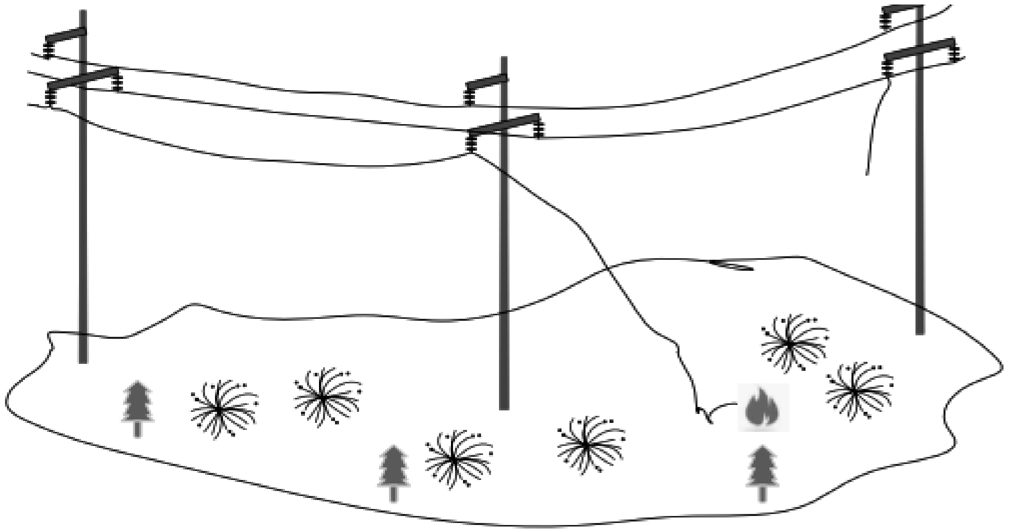
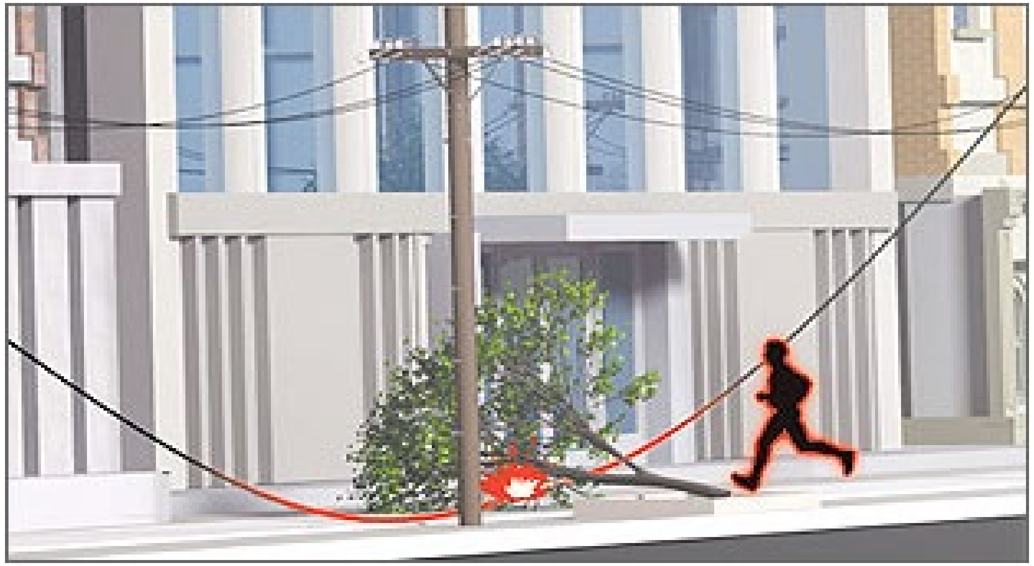


Image reference: https://resources.gegridsolutions.com/services/white-paper-high-speed-falling-conductor-protection-in-distribution-systems-using-synchrophasor-data

Downed-conductor methods

HIF—single relay / feeder based

Transient ground-fault detection—TGFD



Arcing, high-impedance fault (HIF)

Energized conductor contacts
quasi-insulating object

- Tree, pole
- Structure or ground

Hi-Z fault produces current levels of mA to 100 A

Not detected by fuses and conventional overcurrent

Little threat of damage to power system equipment, but is safety and fire hazard

Current-based FCP

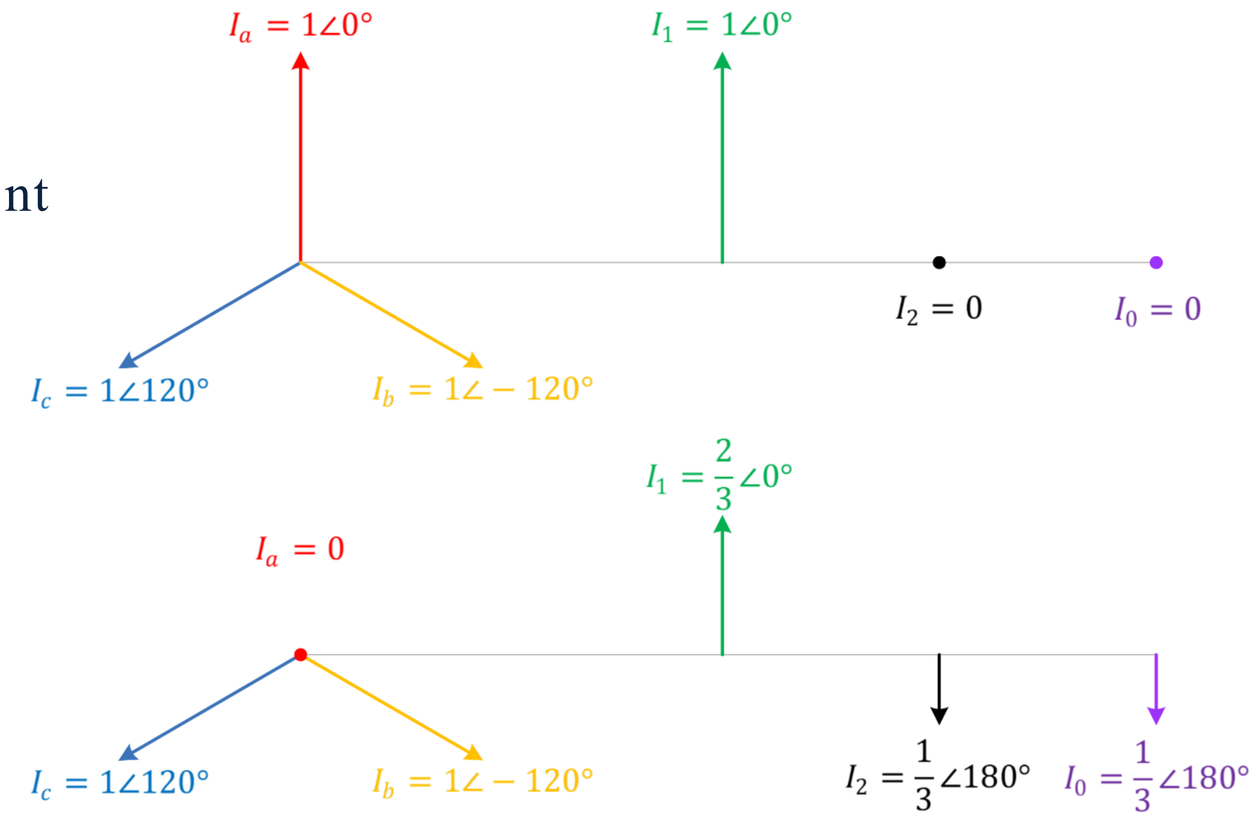
I2 / I1 broken-conductor detection method

Ideally, negative sequence current is zero in distribution line

When conductor breaks negative-sequence current increases to 50% of positive-sequence current

pX W W
pW Y X [US
X X
Y

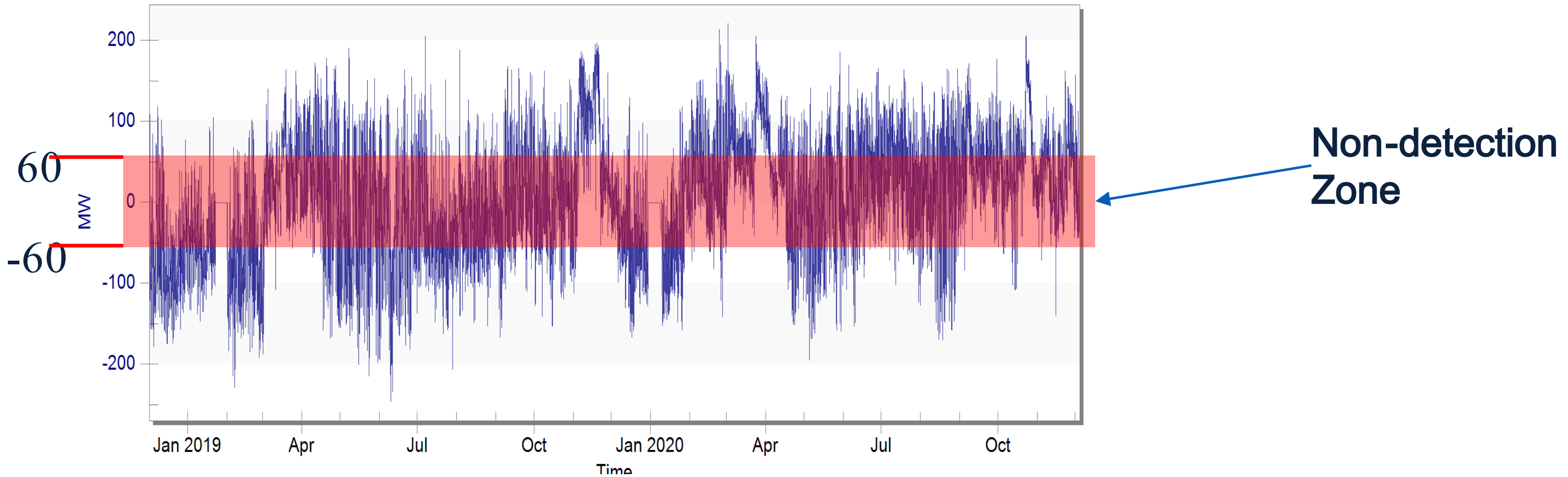
Pickup level is 20–30%—trip



I2 / I1 broken-conductor not dependable

Not dependable detection

- Large CTR
- Lightly loaded lines



I2 / I1 broken-conductor detection challenges

Specific to two-terminal lines

Overreaches in series lines

Misoperates for distant faults because of line mutual coupling

Needs coordination with existing primary and backup protection system—increases operating time

Voltage-based FCP

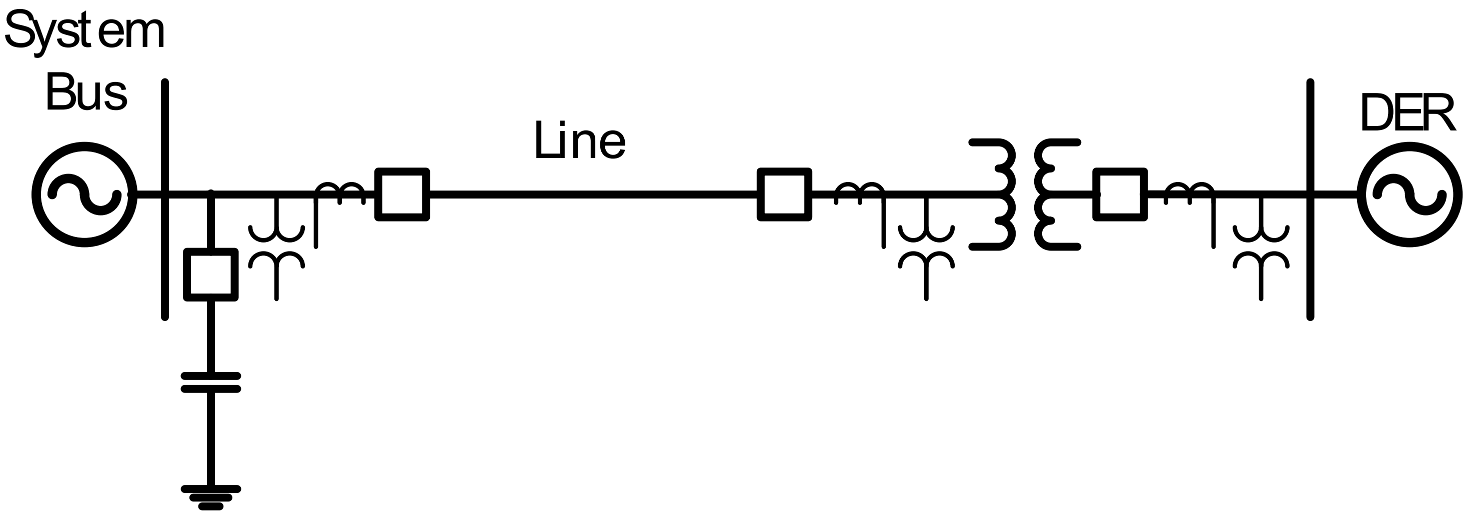
Voltage-based FCP

Loss of voltage / rate of change

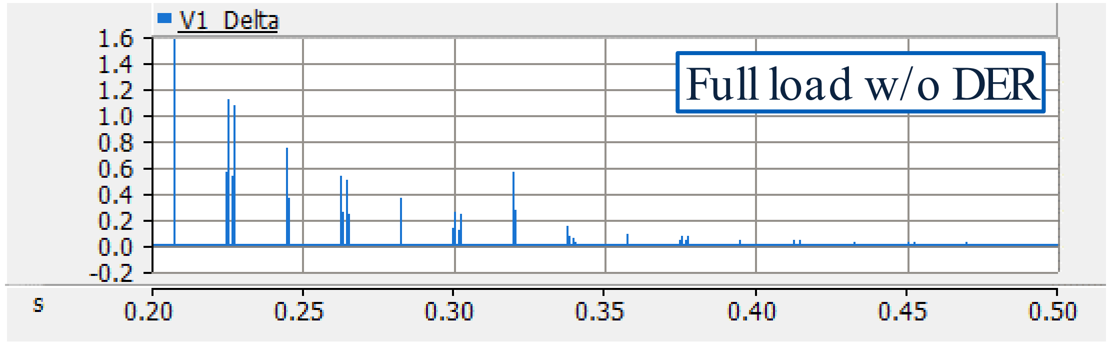
Sequence voltages

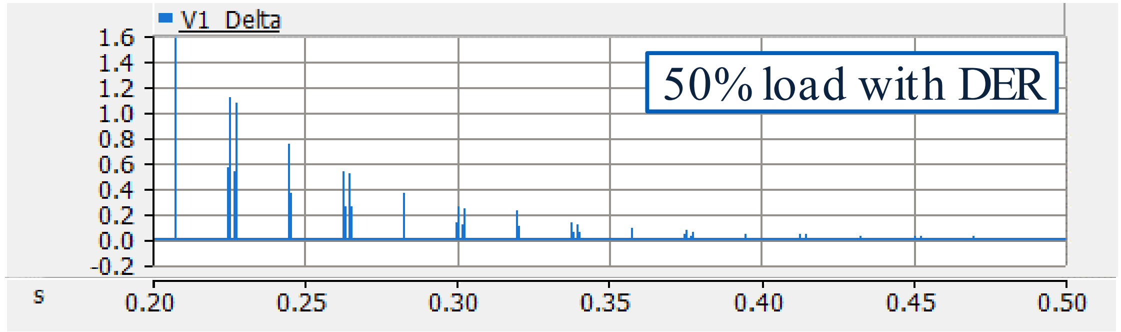
Voltage measurements at multiple locations

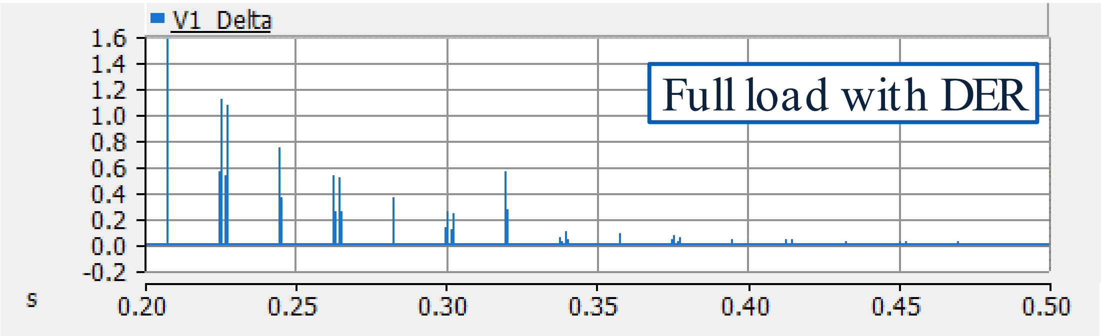
Voltage study system

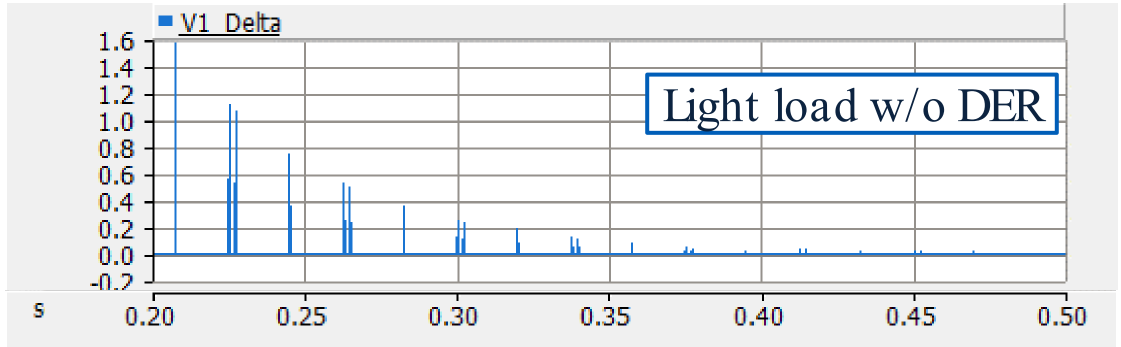


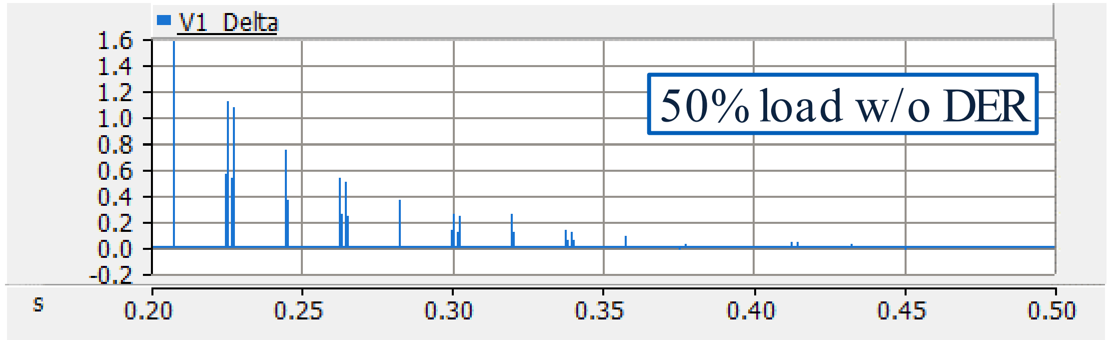
Positive-sequence voltage rate of change

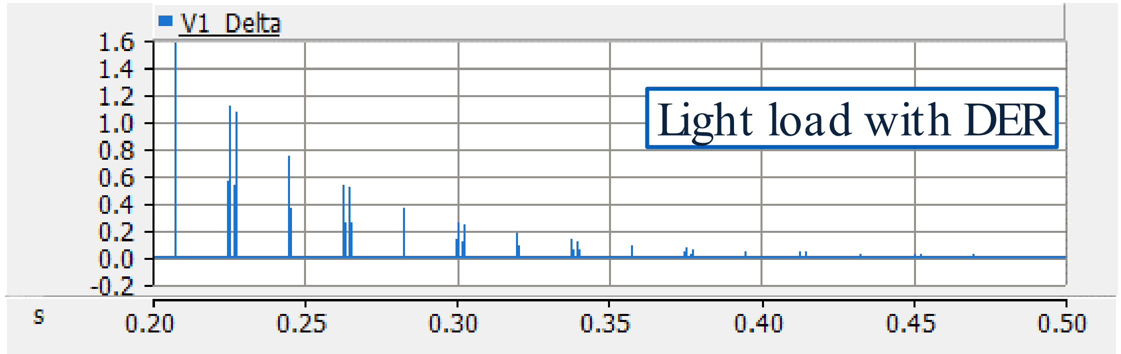












Results—positive-sequence voltage rate of change

Performance does not deteriorate in presence of DER and light loading

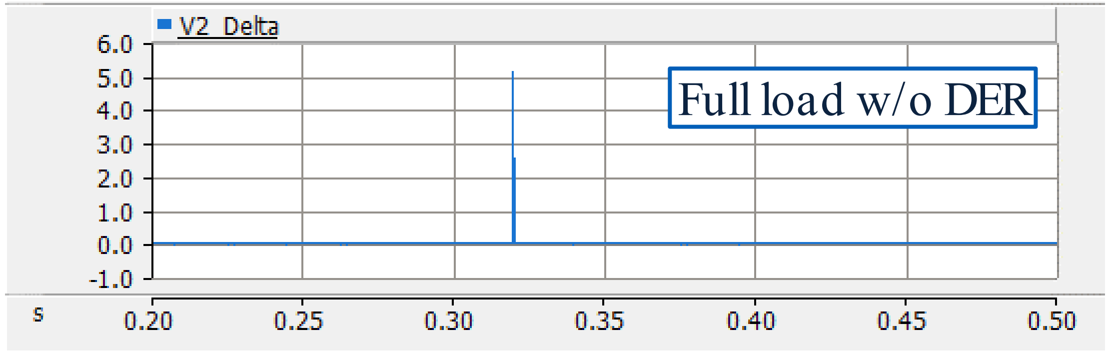
Must have measurements at both ends

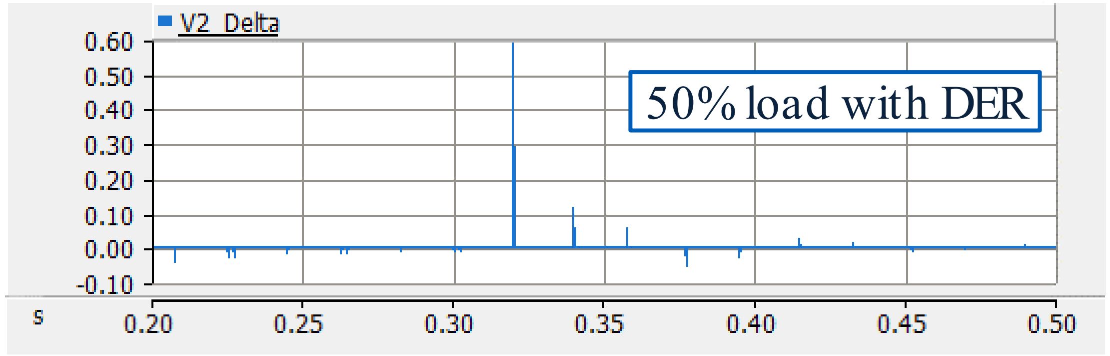
- Large cost
- Impractical in distribution systems

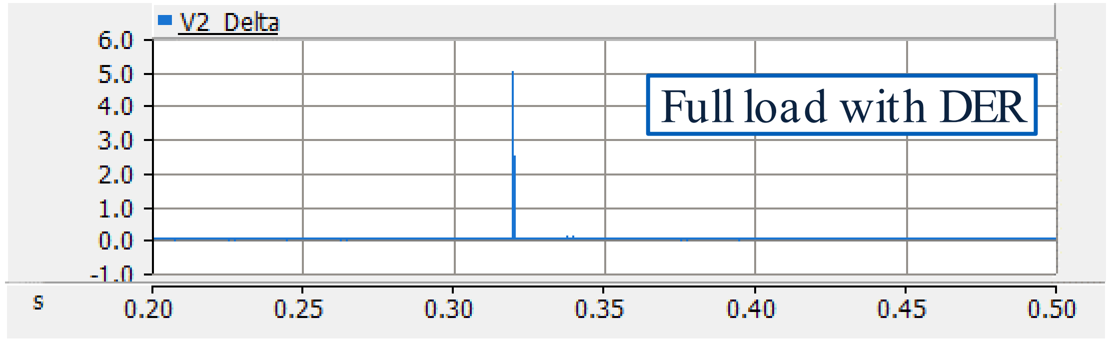
Further testing needed (voltage variations)

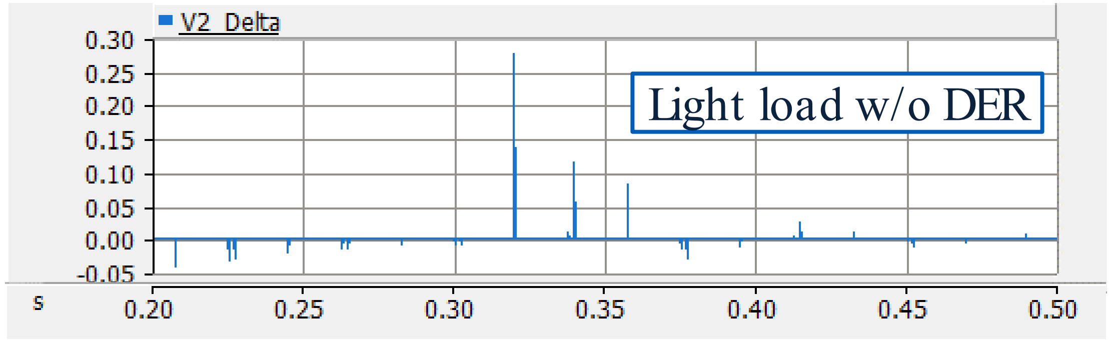
- VAr compensation (FACTS)
- Voltage regulators
- Tap-changing transformers

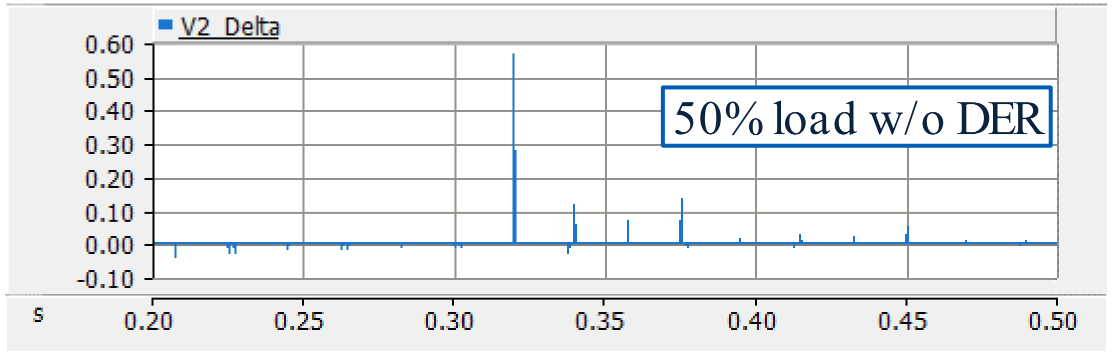
Negative-sequence voltage rate of change

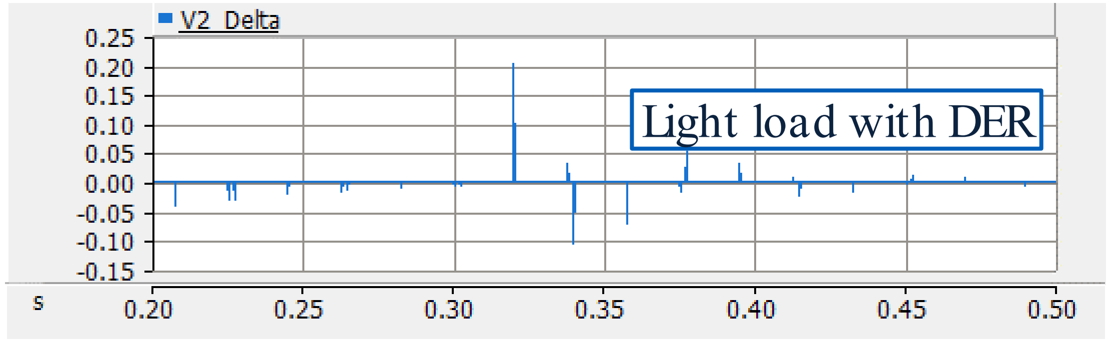












Results—negative-sequence voltage rate of change

Performance deteriorates in presence of system loading

Difficult to determine pick-up setting for dependable assertion

Must have measurements at both ends

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Further testing needed (voltage variations)

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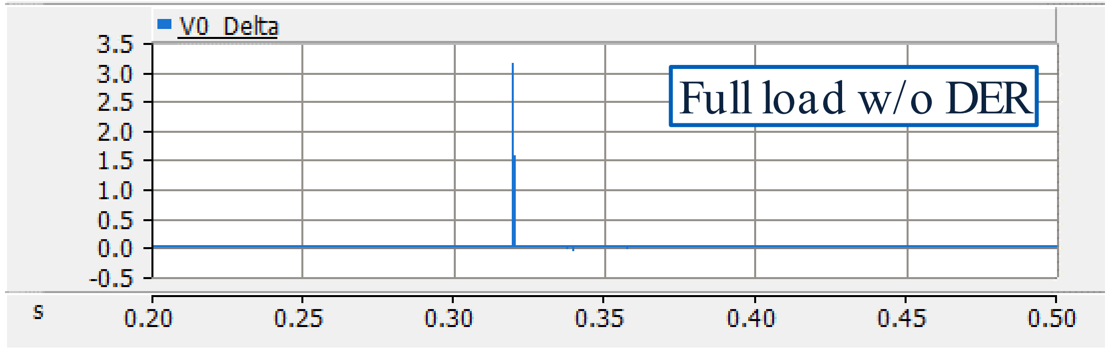
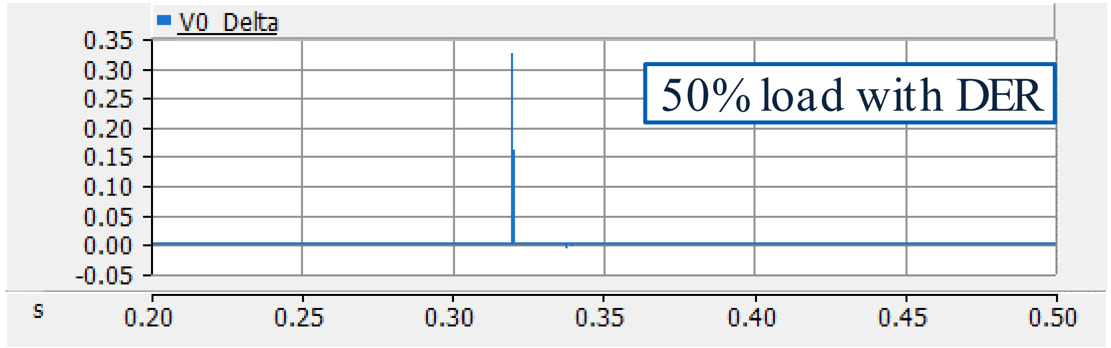
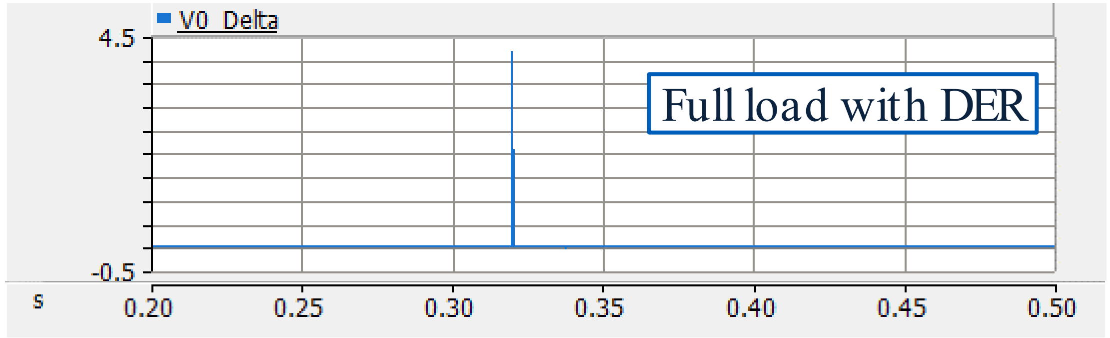
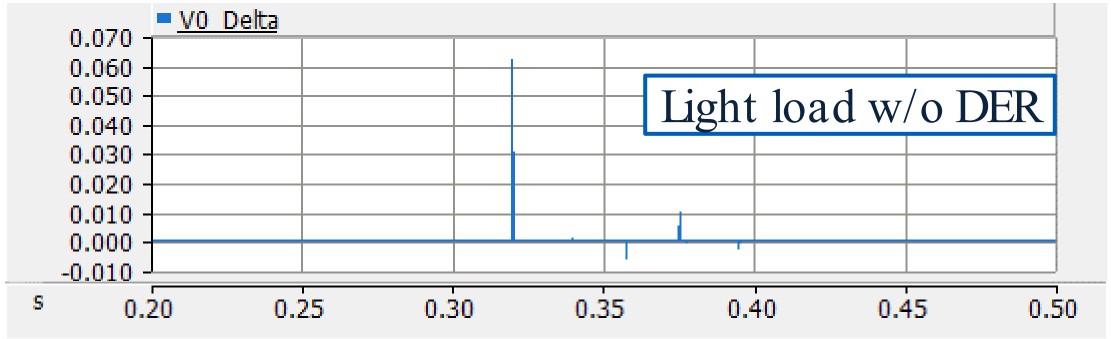
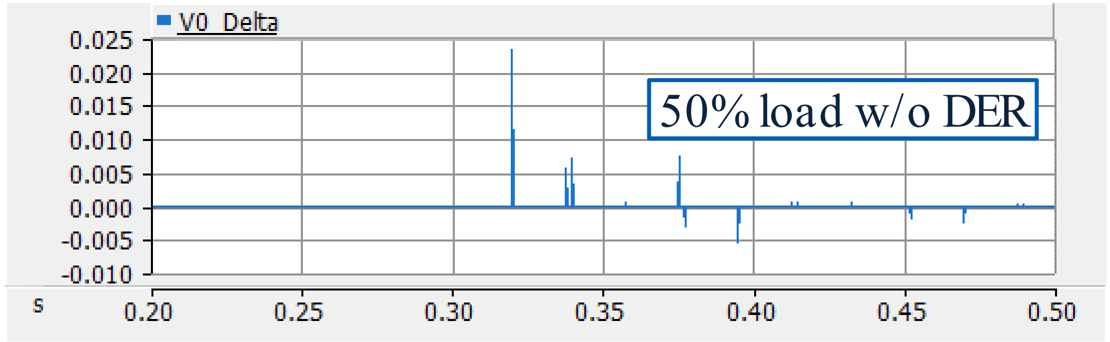
Zero-sequence voltage rate of change

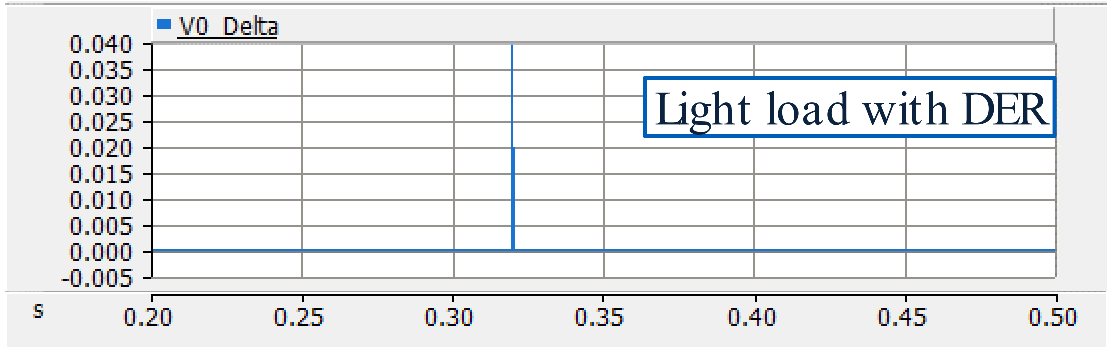












Results—zero-sequence voltage rate of change

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Impedance-based FCP

Impedance-based FCP calculations

1. Calculate the load impedances

$$Z_{ag} = \frac{V_a}{I_a} \qquad Z_{bg} = \frac{V_b}{I_b} \qquad Z_{cg} = \frac{V_c}{I_c} \qquad (1)$$

$$Z_{ab} = \frac{V_a - V_b}{I_a - I_b} \qquad Z_{bc} = \frac{V_b - V_c}{I_b - I_c} \qquad Z_{ca} = \frac{V_c - V_a}{I_c - I_a} \qquad (2)$$

2. Calculate Impedance Change Ratio (ICR) δZ for phase-to-ground and phase-to-phase

δÇ, $\frac{|Ç| \quad Ç'}{Ç'}$

$$\delta_Z = \frac{|Z|}{|Z'|} - 1 \qquad (3)$$

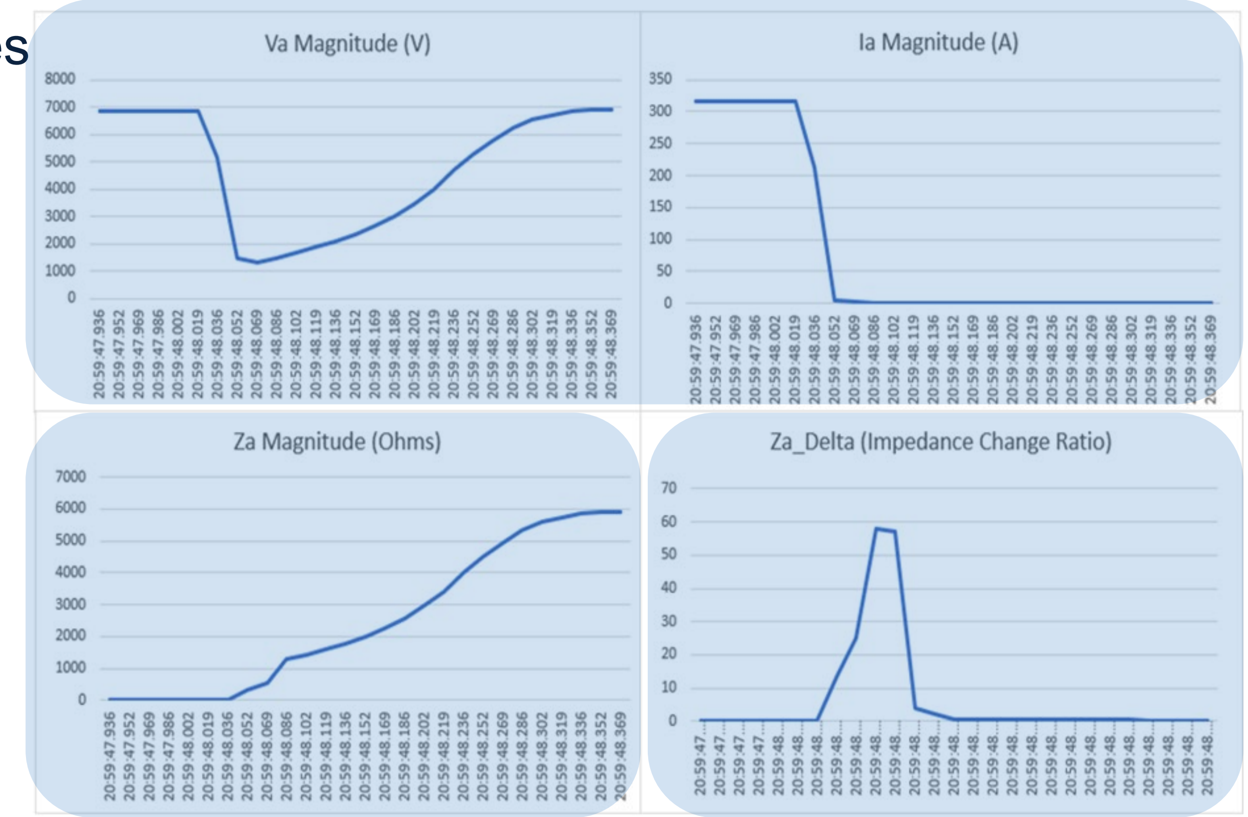
$$\begin{bmatrix} \delta_{Zag} \\ \delta_{Zbg} \\ \delta_{Zcg} \end{bmatrix} = \begin{bmatrix} \frac{|Z_{ag}|}{|Z'_{ag}|} - 1 \\ \frac{|Z_{bg}|}{|Z'_{bg}|} - 1 \\ \frac{|Z_{cg}|}{|Z'_{cg}|} - 1 \end{bmatrix} \qquad \begin{bmatrix} \delta_{Zab} \\ \delta_{Zbc} \\ \delta_{Zca} \end{bmatrix} = \begin{bmatrix} \frac{|Z_{ab}|}{|Z'_{ab}|} - 1 \\ \frac{|Z_{bc}|}{|Z'_{bc}|} - 1 \\ \frac{|Z_{ca}|}{|Z'_{ca}|} - 1 \end{bmatrix}$$

Impedance change ratio, ICR

Line break causes voltage and current changes

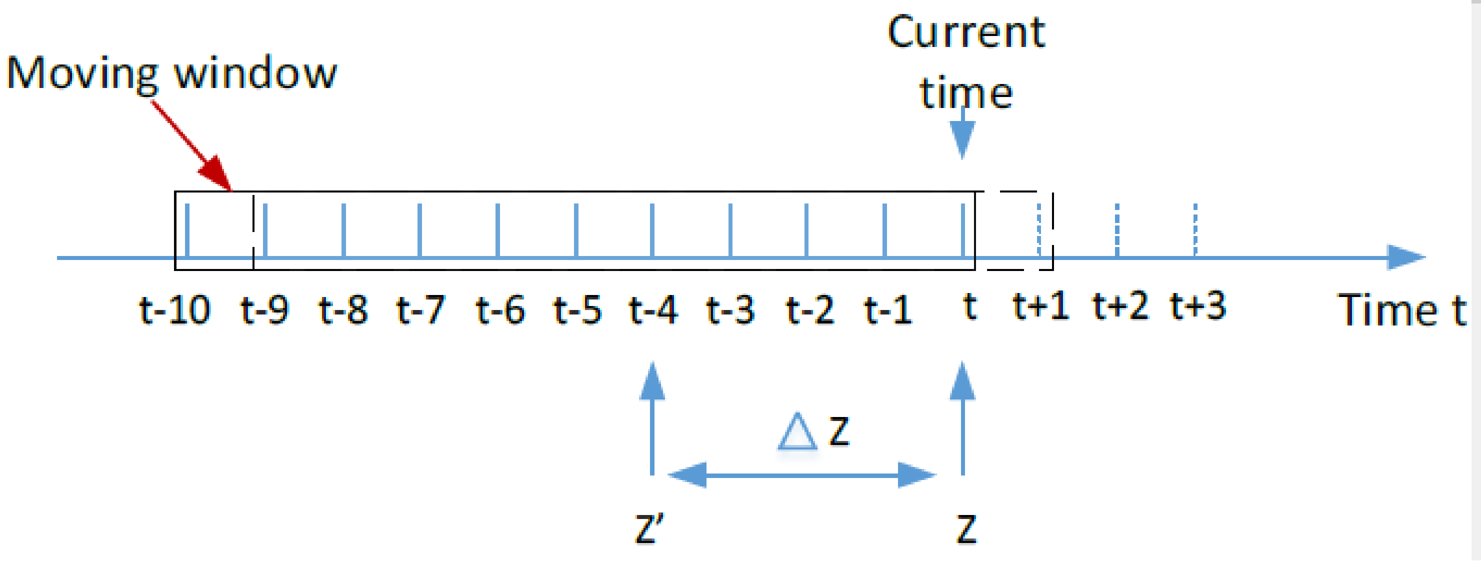
Impedance rises

Impedance change ratio, ICR, gives definite indication of line break

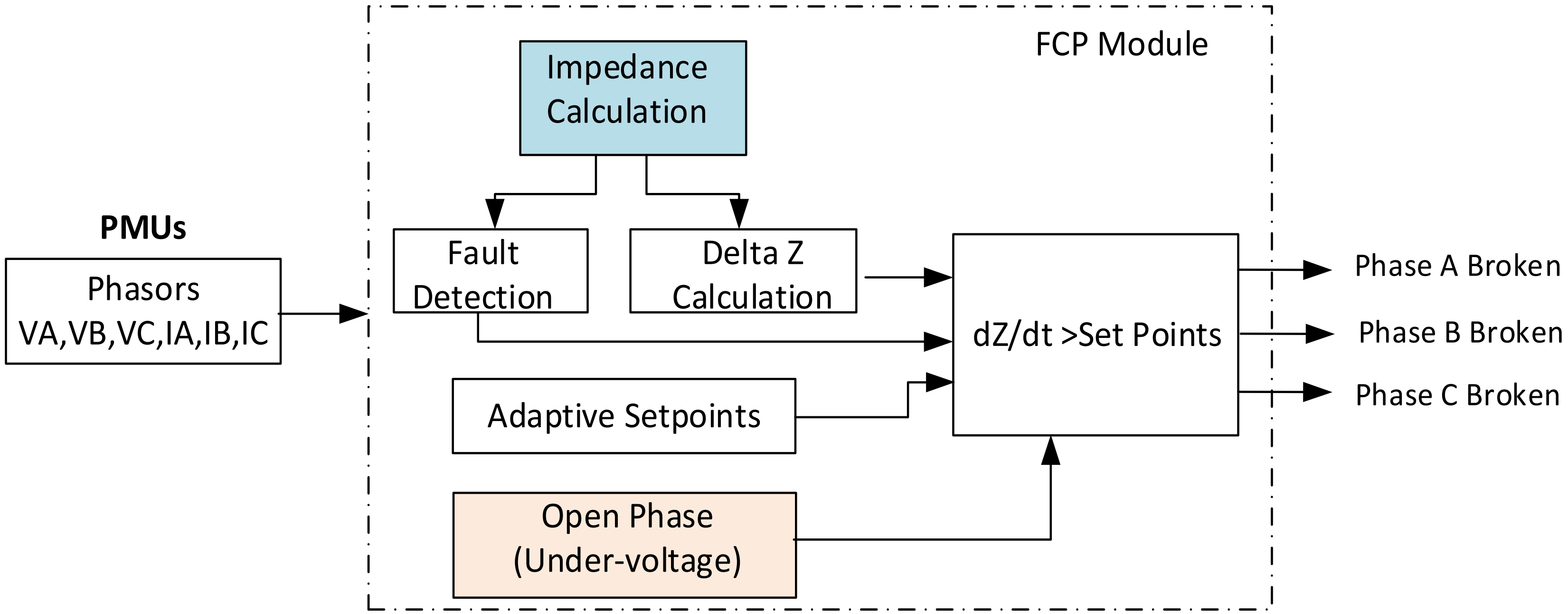


Phase-A broken conductor

Impedance-based sliding window



Block diagram of impedance calculation / setpoints



FCP logic blocked

Any phase current is less than or greater than threshold

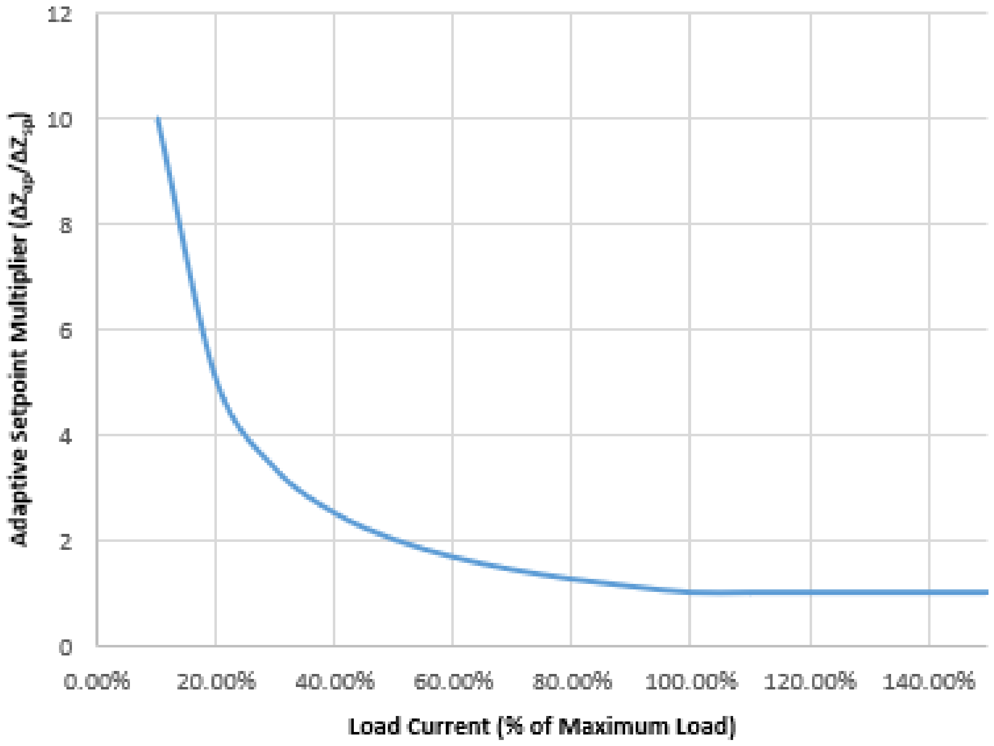
Any phase voltage is beyond defined healthy level

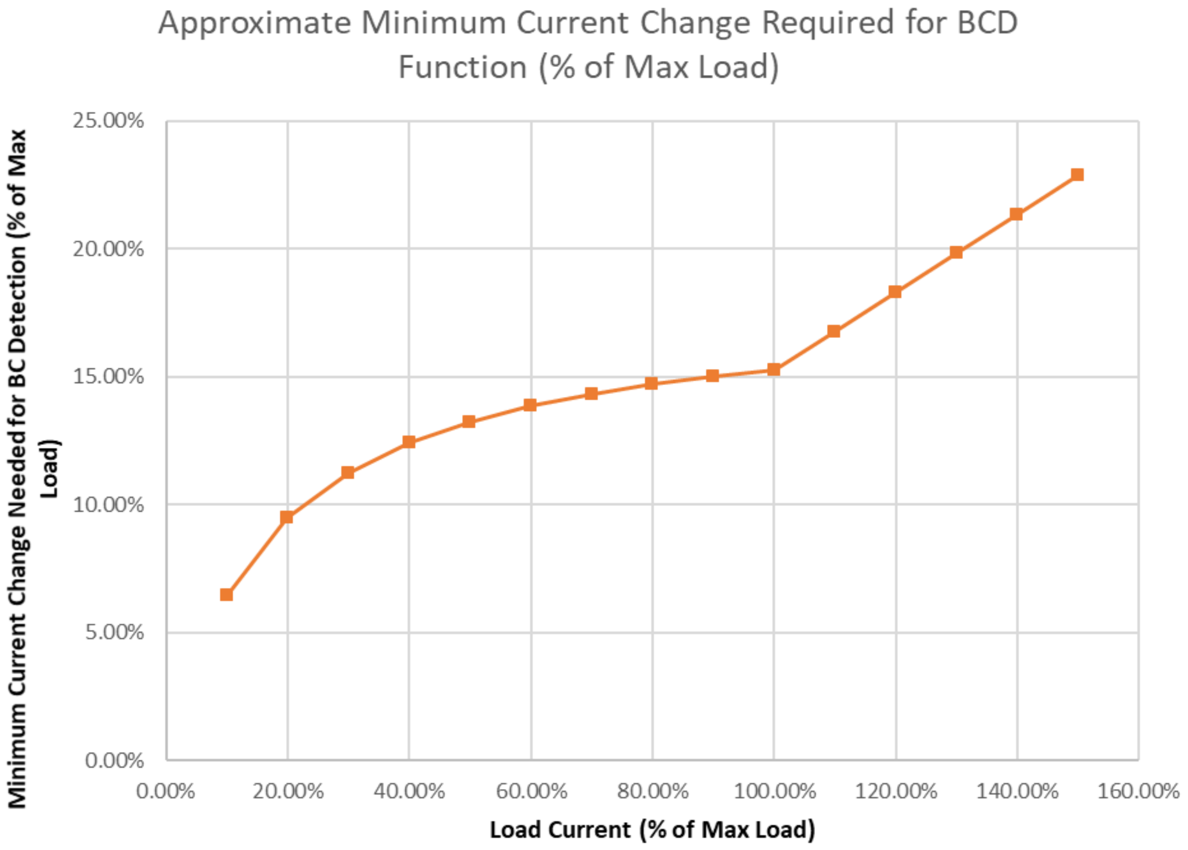
Single-phase fault condition identified

PT secondary fuse blown

Feeder power fuse blown because of short-circuit fault

Loading effects on setpoint threshold and minimum current change





PMU architecture

HFCP is substation solution

Real-time controller

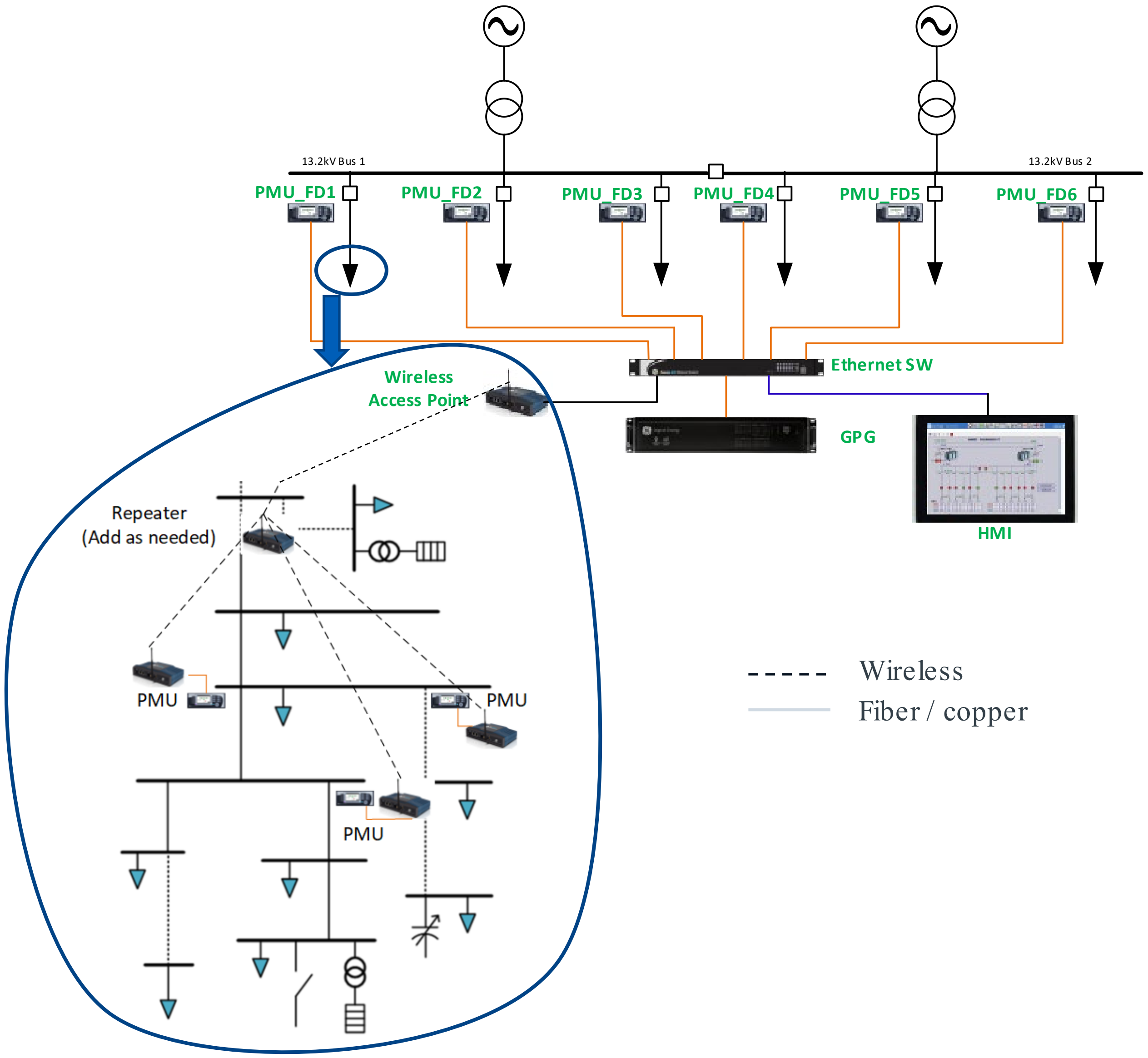
Covers multiple distribution feeders

PMUs installed at selected locations along feeder and at substation

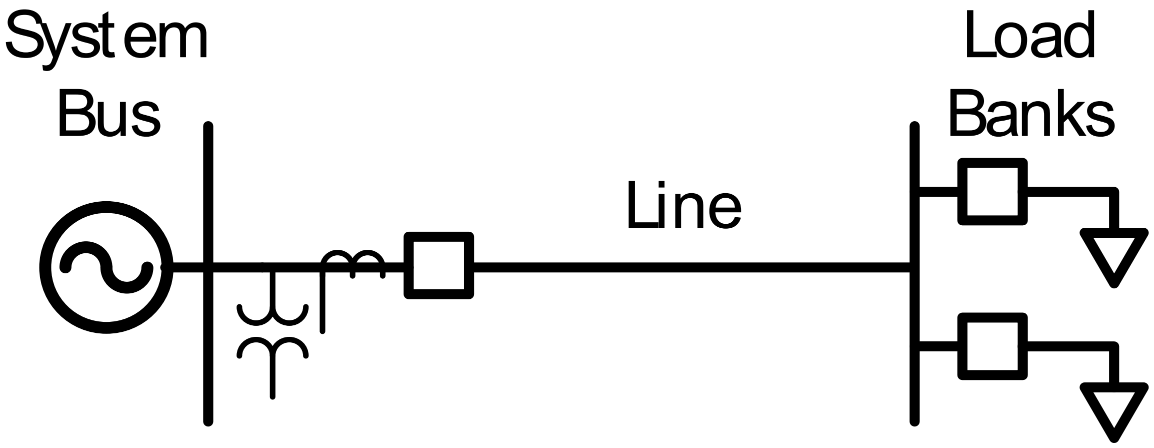
PMUs at each location operate independently

Coordination implemented between substation PMU and downstream PMUs

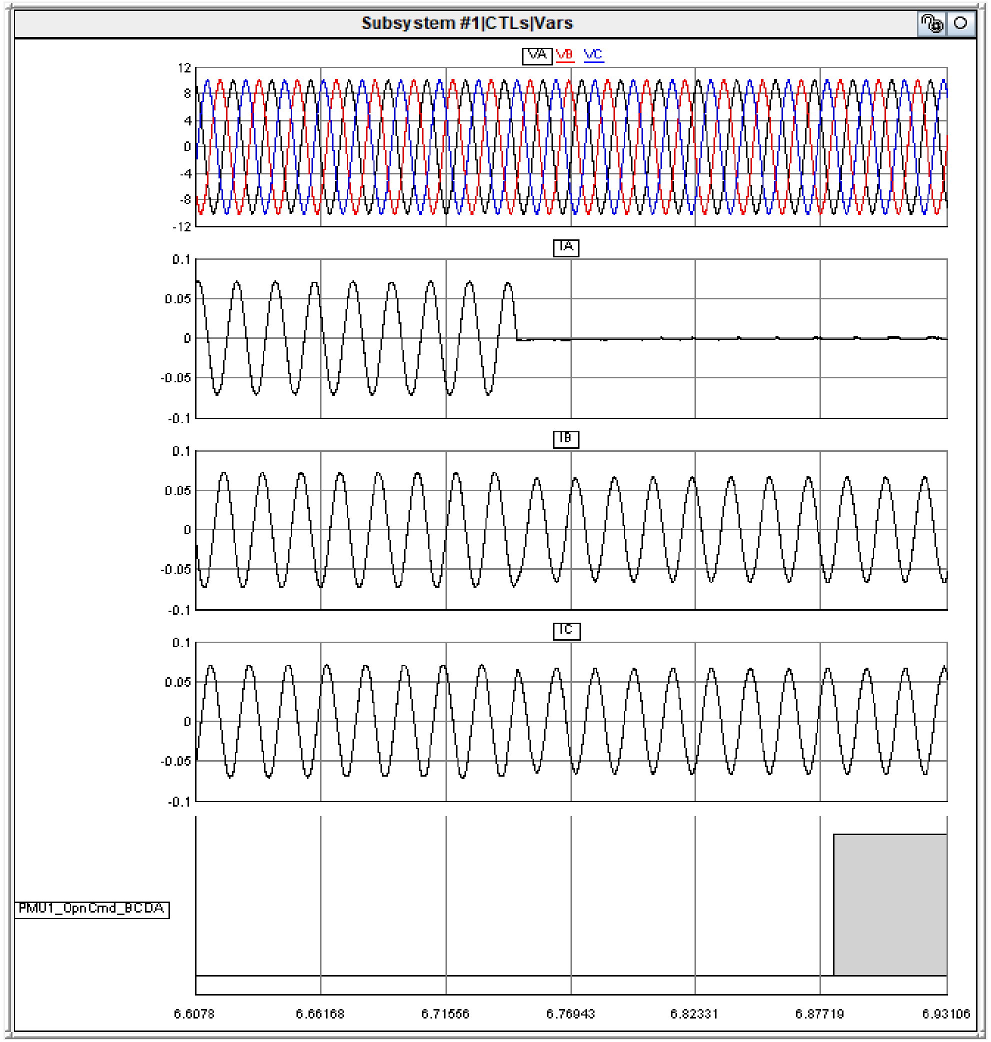
IP-based communication between PMUs and GPG over fiber, radio, and cellular

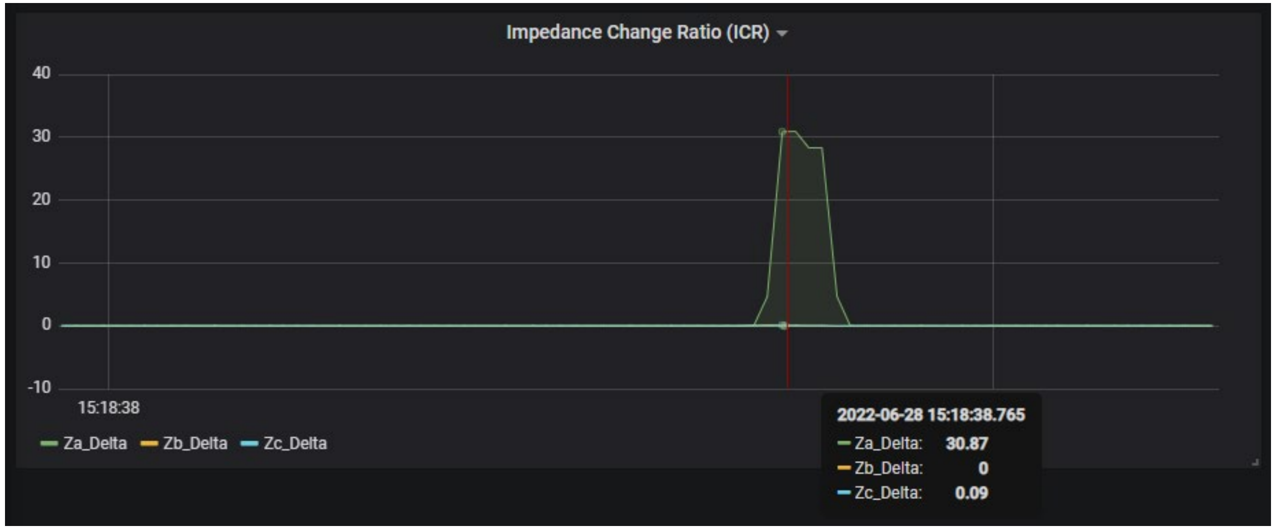


Impedance-based FCP study system

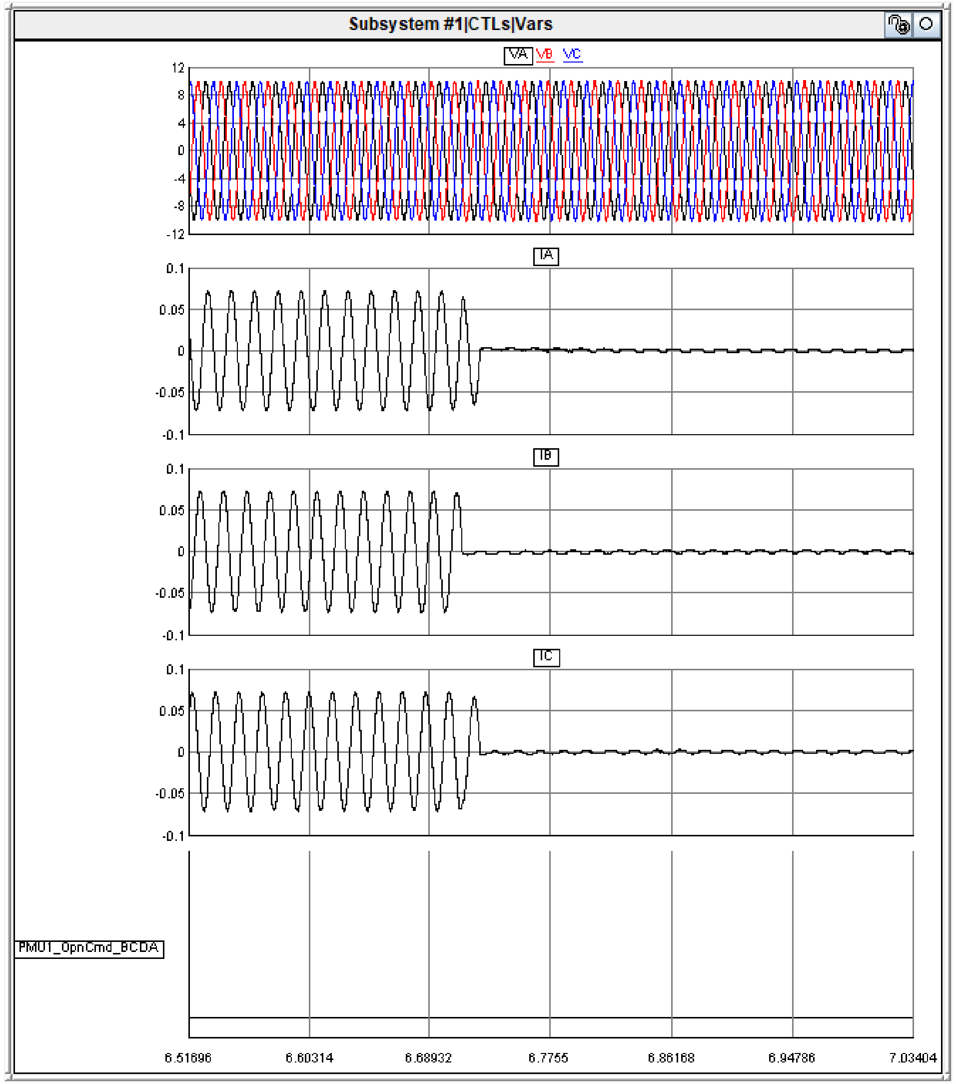


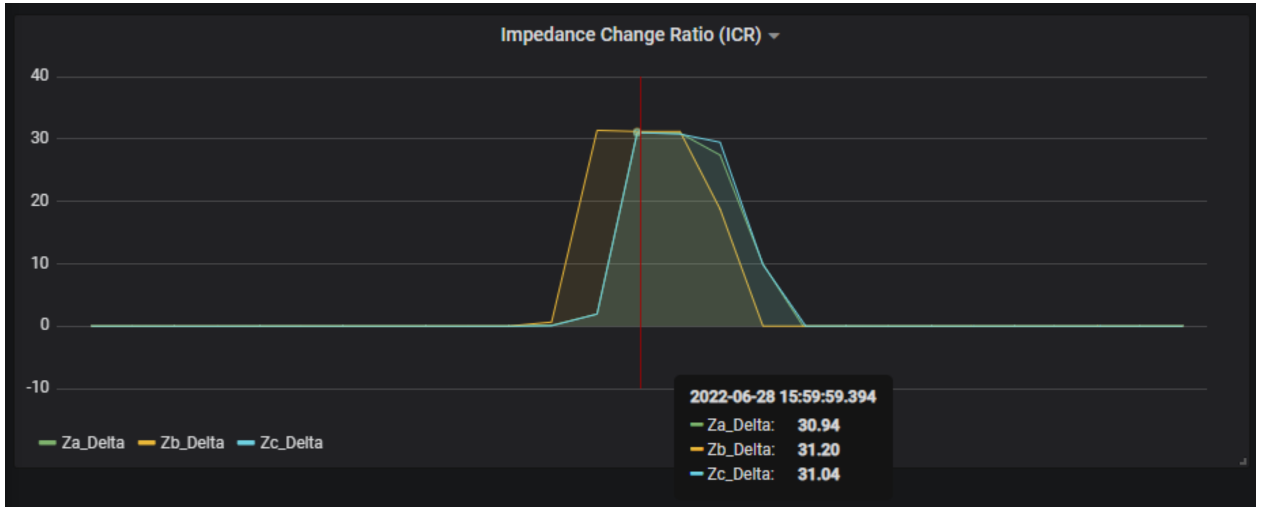
Case 1: small current Phase-A line open



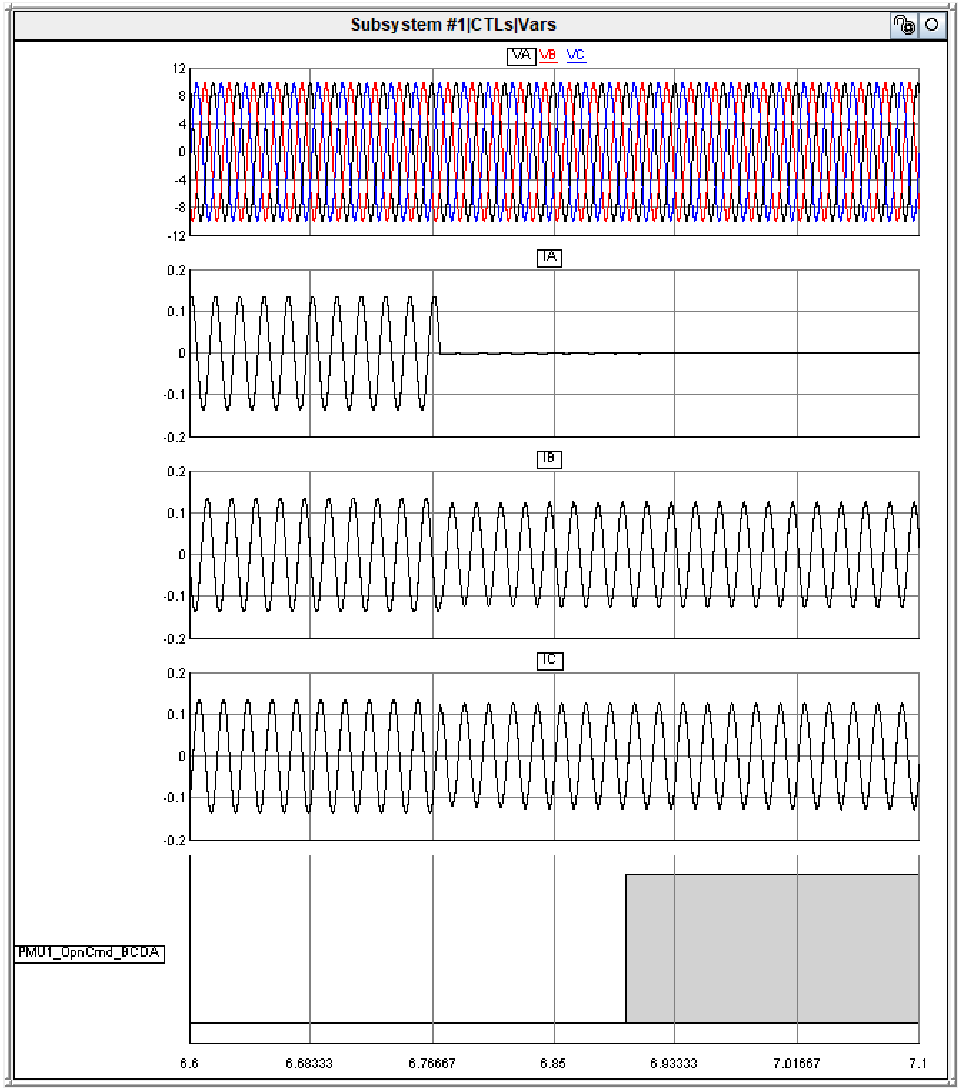


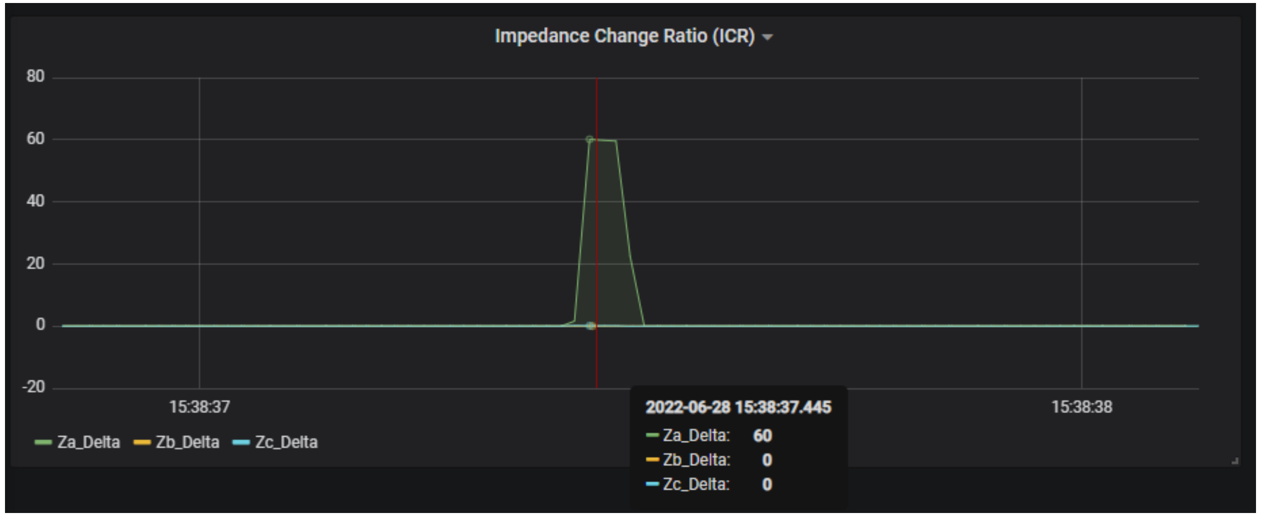
Case 2: three-phase load drop





Case 3: larger load current on Phase A open





Conclusions

Detect broken conductor quickly to avoid wildfires and improve safety

Current-based I2/I1 detection performs poorly because of feeder loading

Positive-sequence voltage detection performs well with DER and light loading

Voltage methods depend on measurements at both line ends; impractical for distribution systems

Impedance-based FCP are effective with light loading and DERs

Questions?