Waveform Characterization of Animal Contact, Tree Contact, and Lightning Induced Faults

Waveform Characteristics of Underground Cable Failures

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Objective

Determine or estimate the root cause of a fault based on the voltage and current waveforms captured by power quality monitors.

Approach: Perform waveform characterization and identify unique features.

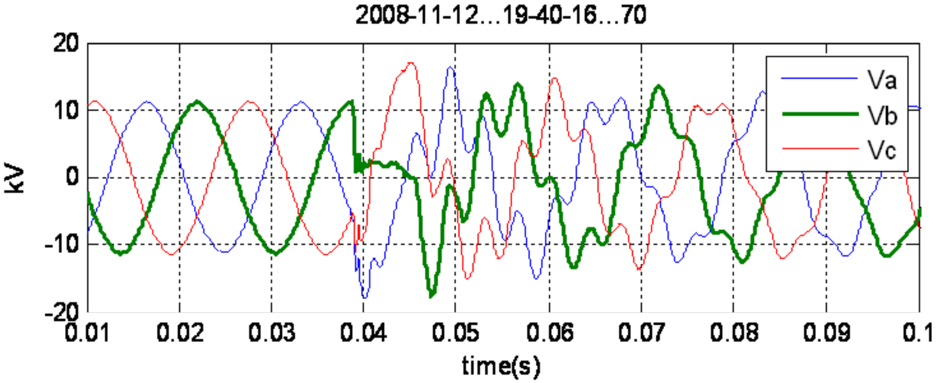
- Underground cable faults: cable, joint or splice, and termination failures
- Animal contacts
- Tree contacts
- Lightning induced

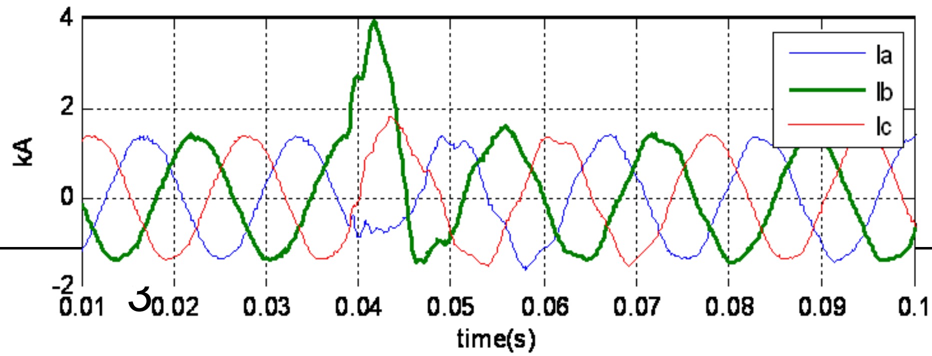
Introduction: Incipient Faults

Cable faults can be self-clearing vs sustained.

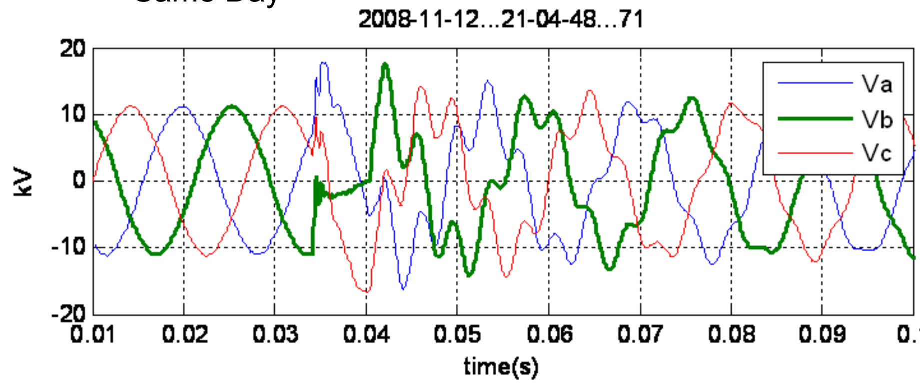
- Fault duration less than one cycle, ¼ to ½ cycles, no overcurrent device operates
- Single phase, start near peak of voltage waveform
- Common in failing cable splices following moisture penetration, insulation failure

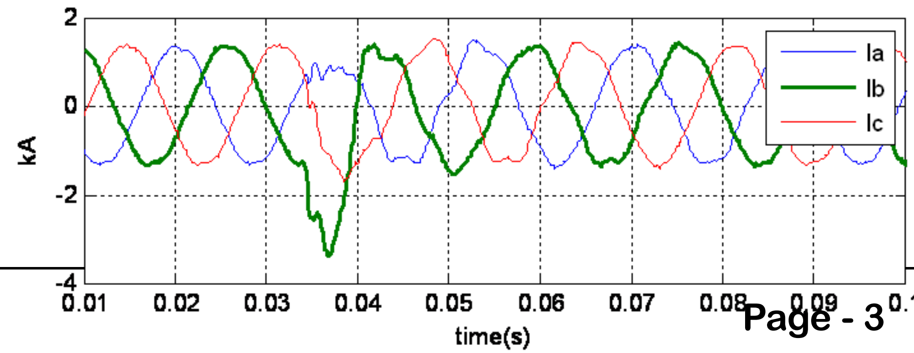
Self Clearing Cable Fault at 19:40:16 PM on 12th Nov. 2008





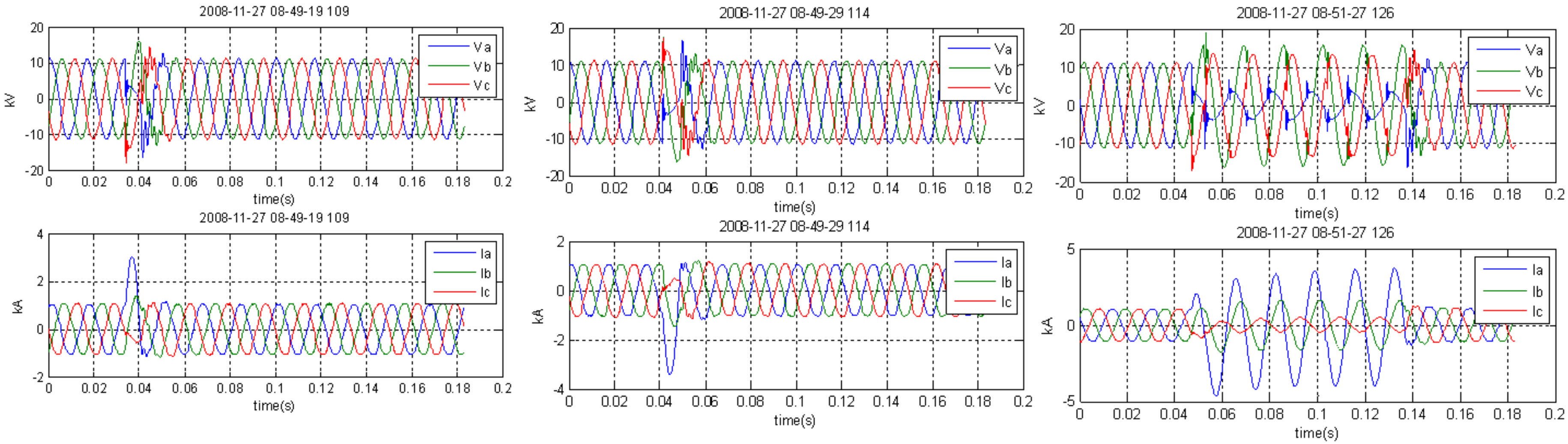
Self Clearing Cable Fault at 21:04:48 PM on Same Day





Introduction: Incipient Faults

- Frequency increases over time and finally turn permanent
- Generally single phase events

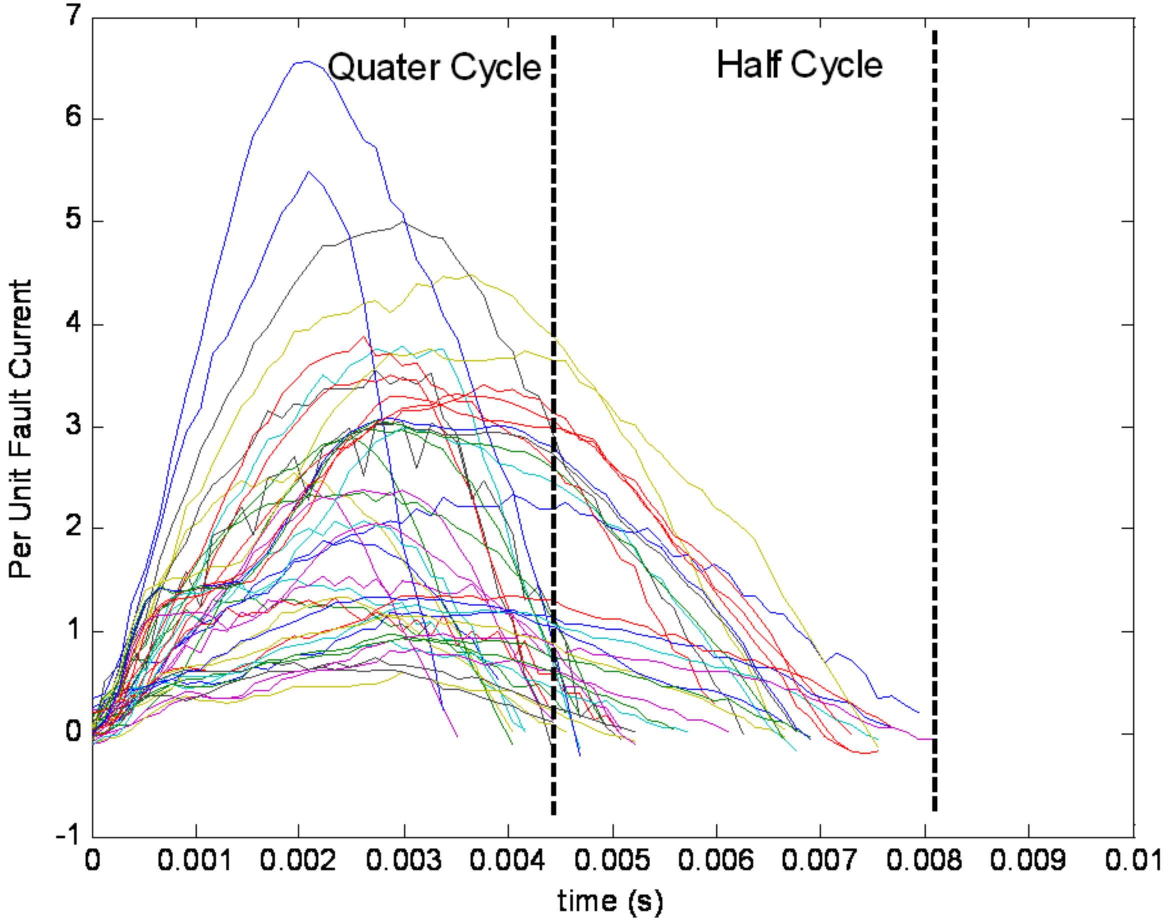


Incipient faults in cables

- Moisture penetrates and builds up in the insulation, reduces the electrical breakdown voltage.
- Arc is produced, heats up the moisture, creates high pressure vapors
- Vapors in turn extinguish the arc, clearing the fault.

Sub-cycle Fault Current Characteristics

- 70 self-clearing cable faults are plotted and analyzed for characterizations.
- Sub-cycle blips identified based on duration and peak magnitude of fault current



Sub-cycle Fault Current Blips- Generic Equations

- Quarter cycle blip of high magnitude (a)
  - Duration ≈ 32 samples
  - Magnitude >> 5 p.u.

$$a = 6.17 * \sin(695.4 * t - 0.126) \; ; 0 <= t < 0.05$$

- Half cycle blip of high magnitude (b)
  - Duration ≈ 64 samples
  - Magnitude >> 2-3 p.u.

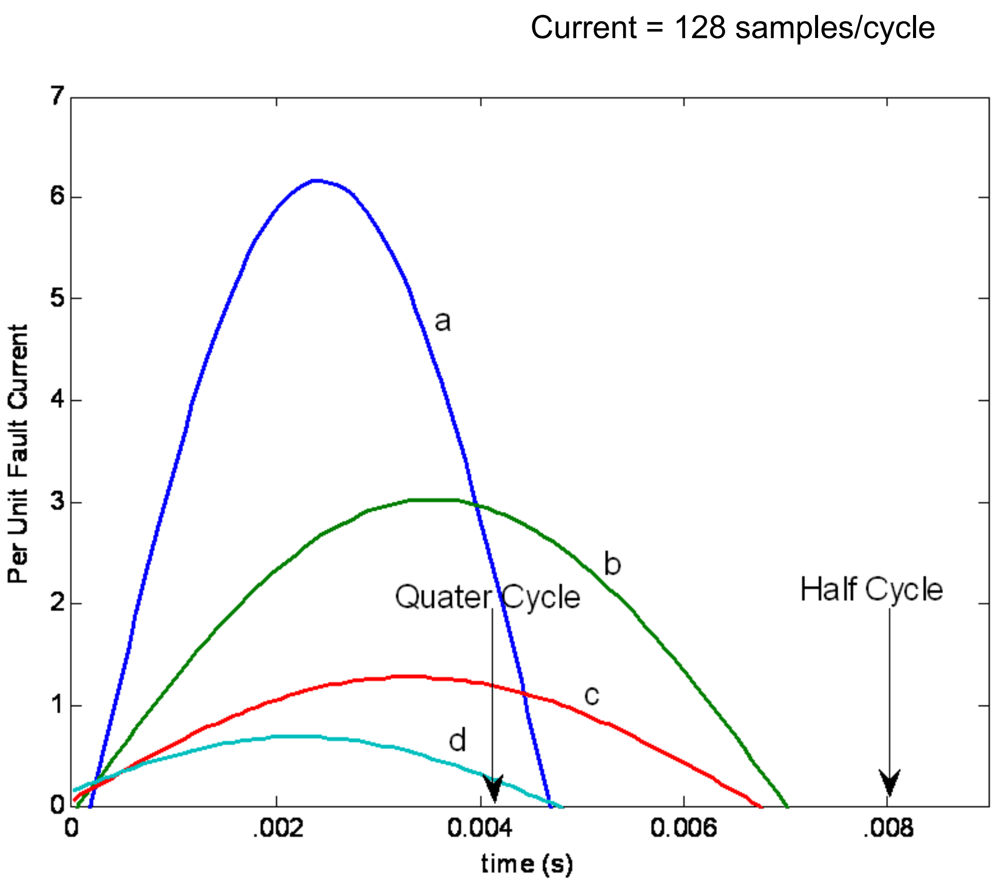
$$b = 3.029 * \sin(451.37 * t - 0.02726) \; ; 0 <= t < 0.08$$

- Quarter cycle blip of small magnitude (c)
  - Duration ≈ 32 samples
  - Magnitude < 1 p.u.

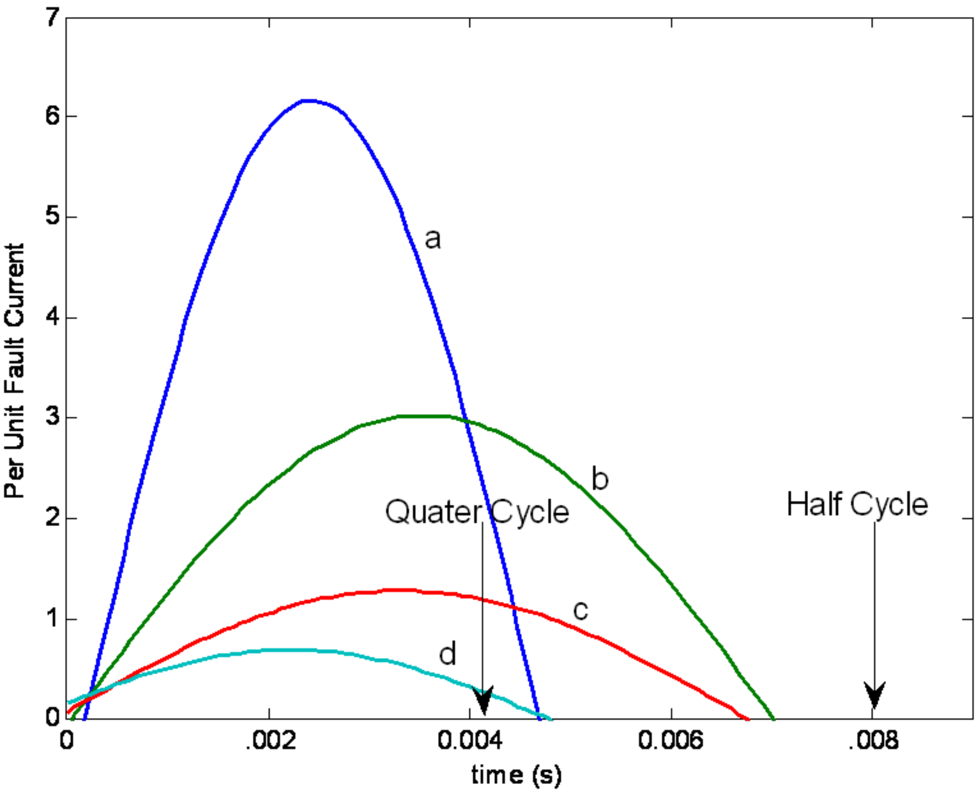
$$c = 1.275 * \sin(458.036 * t + 0.04495) \; ; 0 <= t < 0.05$$

- Half cycle blip of small magnitude (d)
  - Duration ≈ 64 samples
  - Magnitude ≈ 1 p.u.

$$d = 0.6846 * \sin(612.708 * t + 0.213) \; ; 0 <= t < 0.08$$



Sub-cycle Fault Current Blips- Generic Equations



Magnitude and duration give clues about the nature of the fault type:

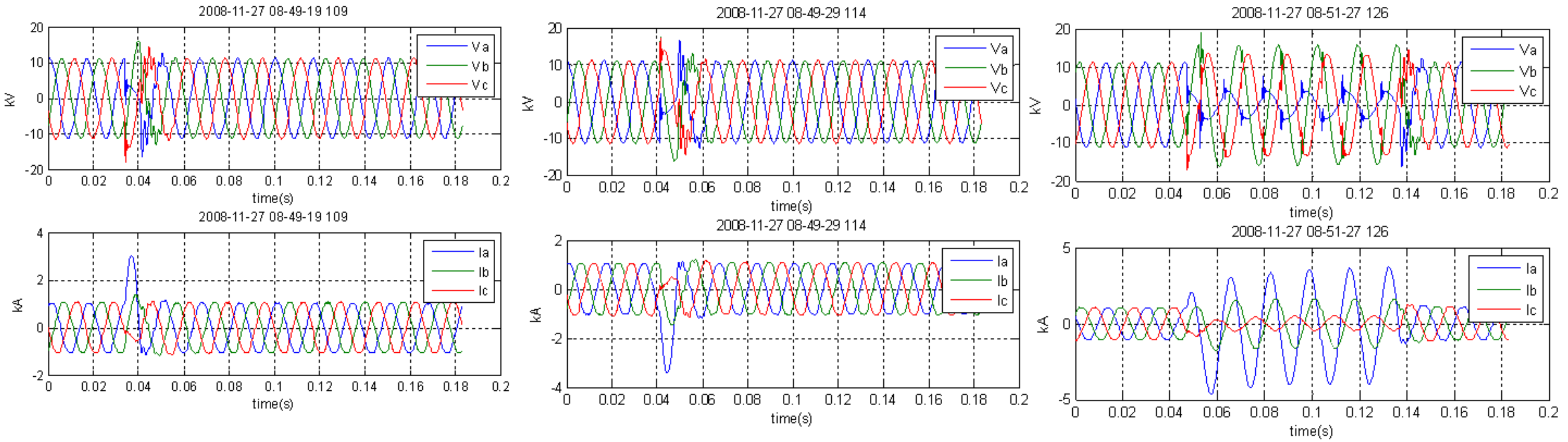
High magnitude, short duration

- Perhaps, moisture or water in the splice.
- Cable failure is in the early stage.

Low magnitude, longer duration

- Arc/discharge over cracks in the solid insulation (electrical treeing)
- Cable failure is perhaps in the mid stage → moving to a more 'sustained' fault

Incipient to Sustained Cable Faults



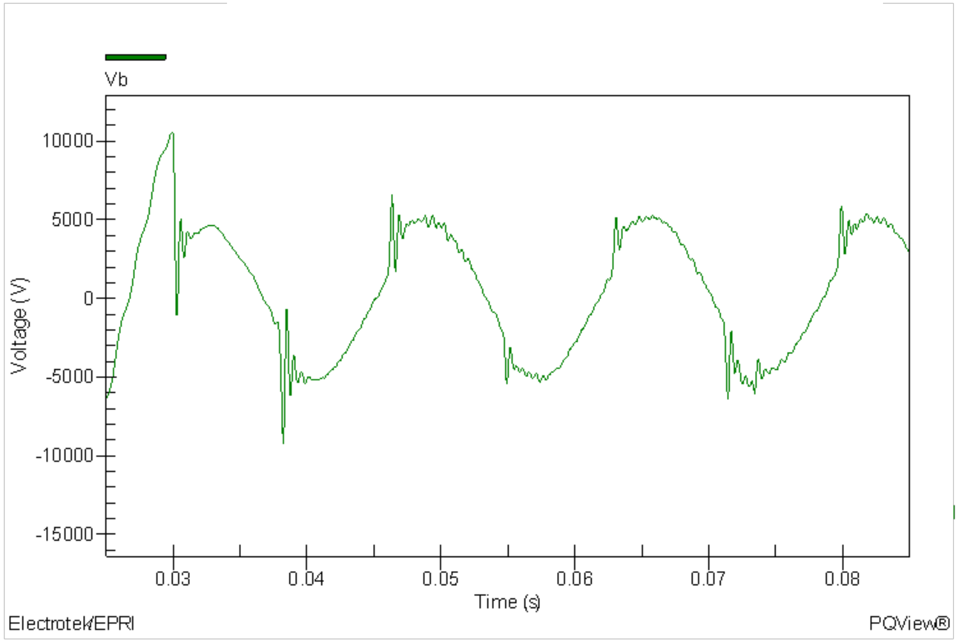
Root Causes of Cable Failures

- Cable fault classification by part
  - Cable body: Insulation failure
  - Splice/ Joint : Part connecting separate pieces of conductor
  - Termination: Part where underground cable is terminated

- Treeing is main cause of cable faults
  - Treeing: general term used to describe type of electrical breakdown that occurs in solid dielectric insulation of cable
  - Treeing may not necessarily cause a fault but it often precedes faults.

Cable Joint Failures

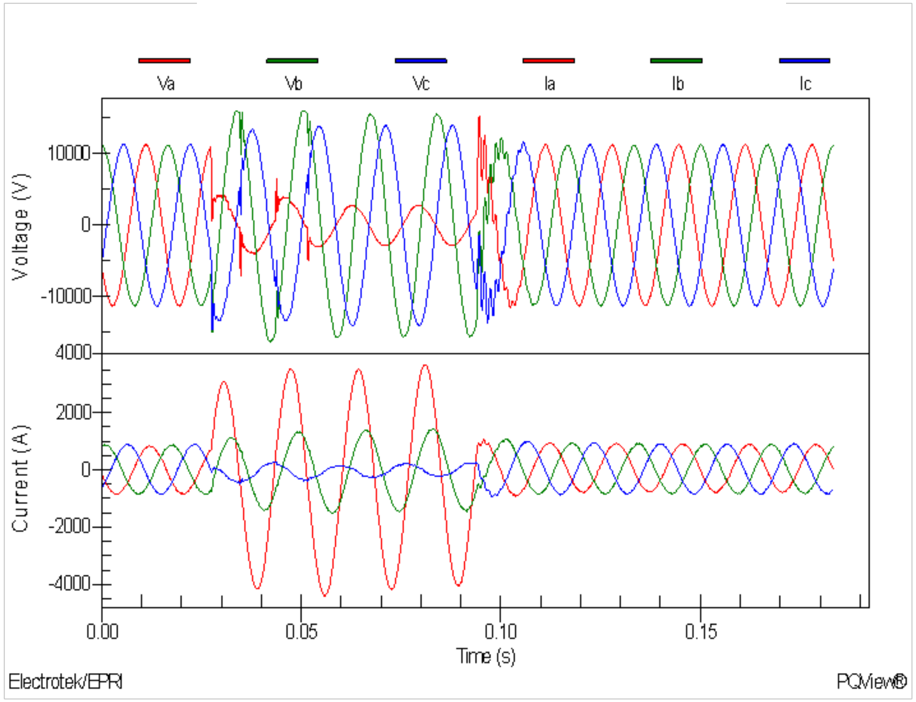
- Short duration impulses/ high frequency oscillations occur once each half cycle
- Impulses occur at same instant as faulted phase current zero crossing
- For all cable faults, oscillation frequency is from 0.9 to 4.0 kHz
- Cable faults in joints with tracking, oscillation frequency is from 1.3 to 1.9 kHz
- Oscillations or impulses may appear at different instants of event
- Impulses can continue throughout duration of even or appear near middle or end of event



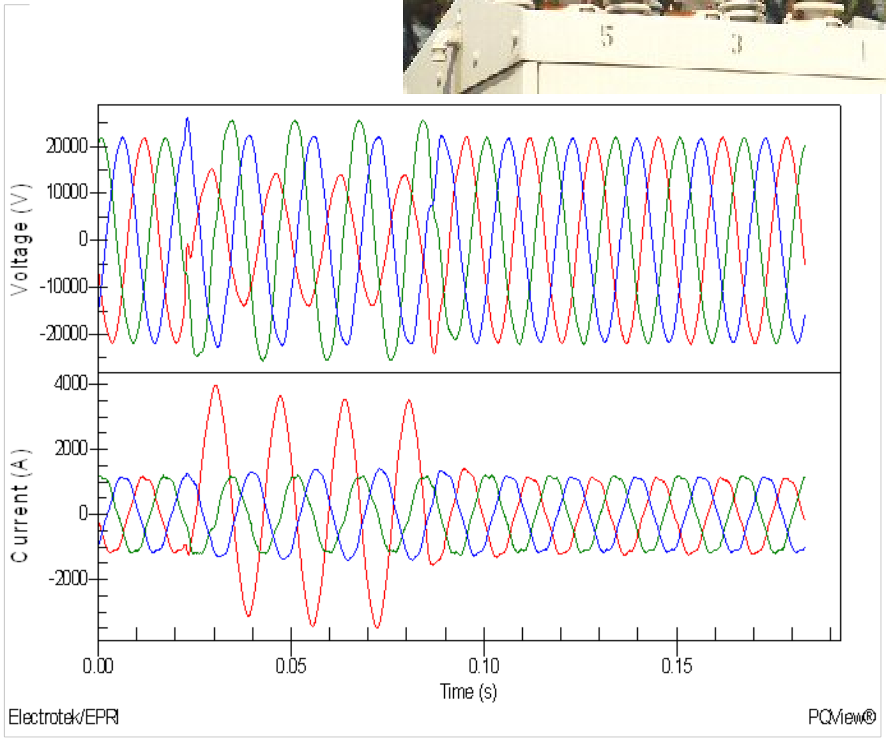
Oscillation of 1.9 kHz in the Voltage Waveform during a Cable Fault in Joint with Tracking

Cable Termination Failures

- Cable faults at termination may or may not have impulses in faulted phase voltage waveforms



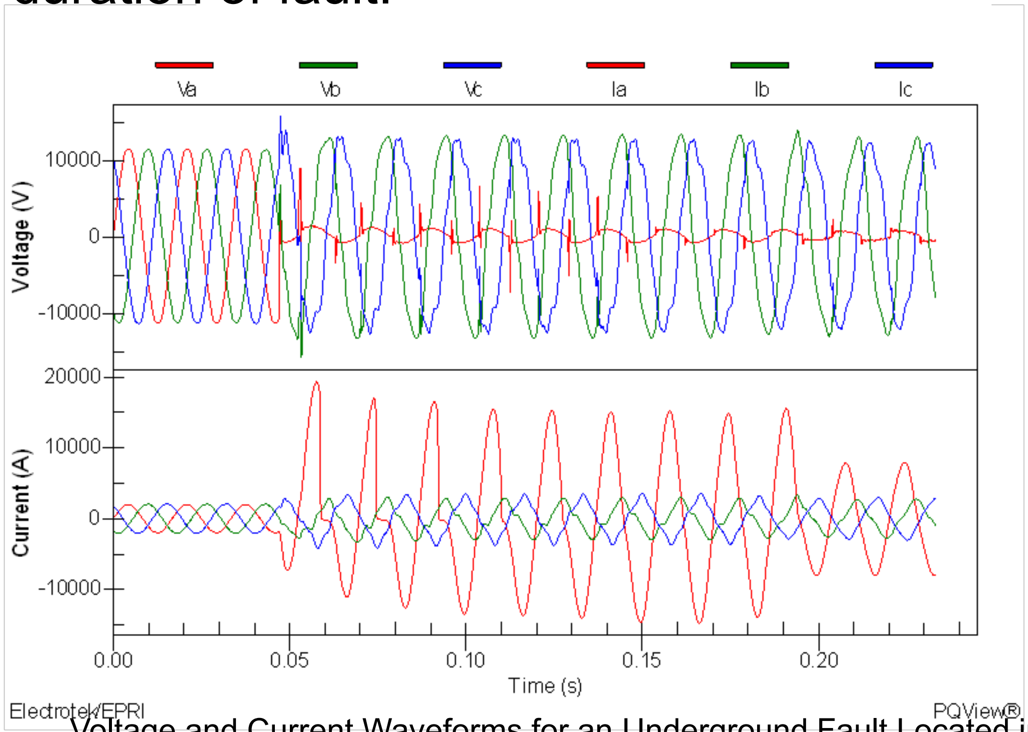
Fault Located at Cable Termination with Impulses in Voltage



Fault Located at Cable Termination without Impulses in Voltage

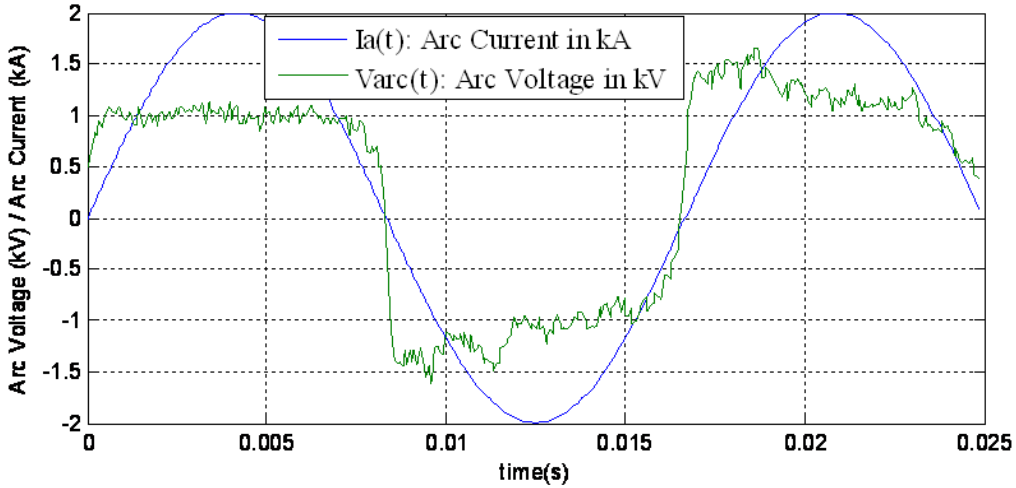
Cable Insulation Failures

- Fault located in body of underground cable is due to insulation failure
- Typically SLG and may evolve into other phases due to proximity
- Impulses in faulted phase voltage are very high and occur throughout duration of fault.



Voltage and Current Waveforms for an Underground Fault Located in Cable

Representation and Modeling of Arc Voltage

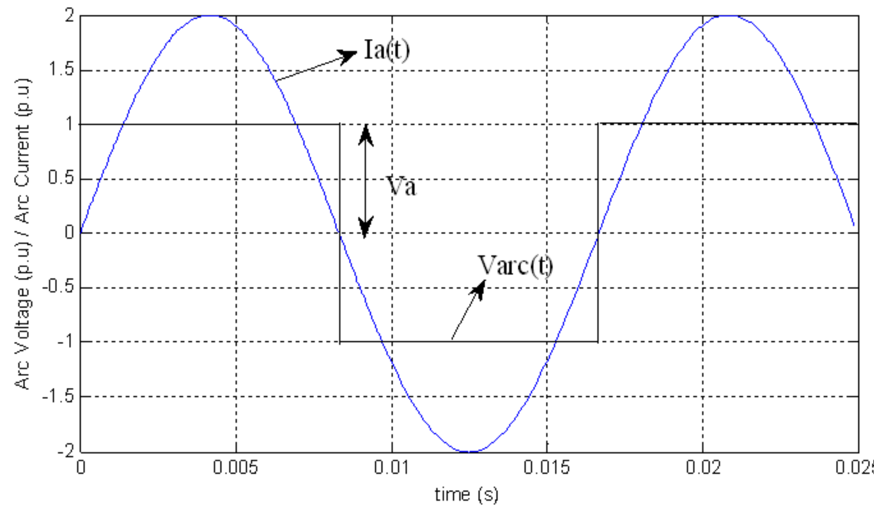


- Preferred to measure in terms of voltage rather than resistance
- Difficult to obtain an analytical expression for the arc voltage
- Presence of high odd harmonics
- Distorted square wave shape

- Arc voltage has an ideal square wave shape
- Arc voltage is constant irrespective of the arc current.
- Arc current and voltage are in phase
- Normalized arc voltage model used with $|V_{arc}| = 1$ per unit

$$V_{arc}(t) = \sum_{r=1}^{\infty} a_r V_a \sin(r \omega t)$$

$$V_{arc}(t) = V_a \times sign\,[I_a(t)] + £(t)$$



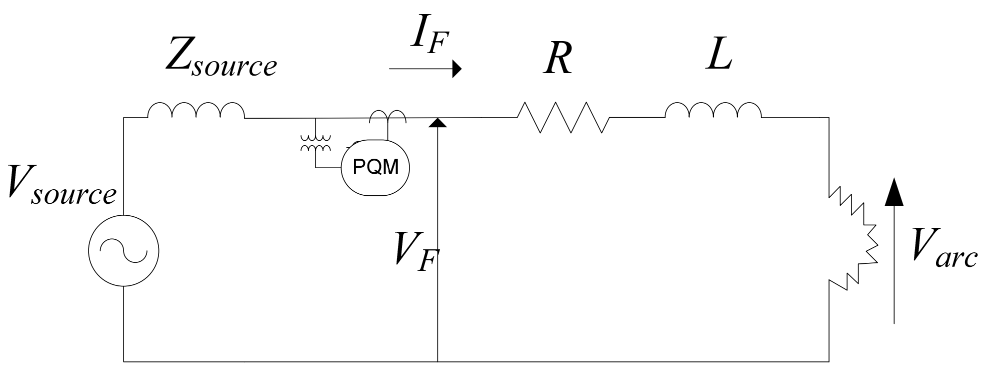
Characteristic Signatures - Arc Voltage

- Method proposed by Radojevic et al.
- Looking from the PQ monitoring site

$$V_F = R.I_F + L.\frac{dI_F}{dt} + V_{arc}.sign(I_F)$$

- Applicable to SLG fault

V_F is the fault phase voltage measured at PQ monitoring site
I_F is the fault current
L is the line inductance
R is the line resistance
V_{arc} is the peak arc voltage at the fault location
$sign(I_F) = 1$, if $I_F > 0$ and -1 if $I_F \leq 0$



Implementation

$$[\mathbf{V}_F] = [\mathbf{I}_F \quad \frac{\mathbf{dI_F}}{\mathbf{dt}} \quad sign(\mathbf{I}_F)] \begin{bmatrix} \mathbf{R} \\ \mathbf{L} \\ \mathbf{V_{arc}} \end{bmatrix}$$

$$a_1 = I_F$$

$$a_2 = \frac{dI_F}{dt}$$

$$a_3 = sign(I)$$

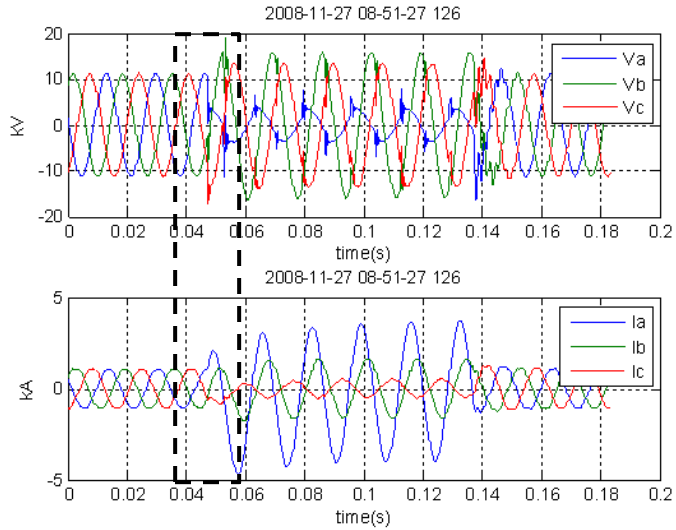
$$A = [a_1 a_2 a_3]$$

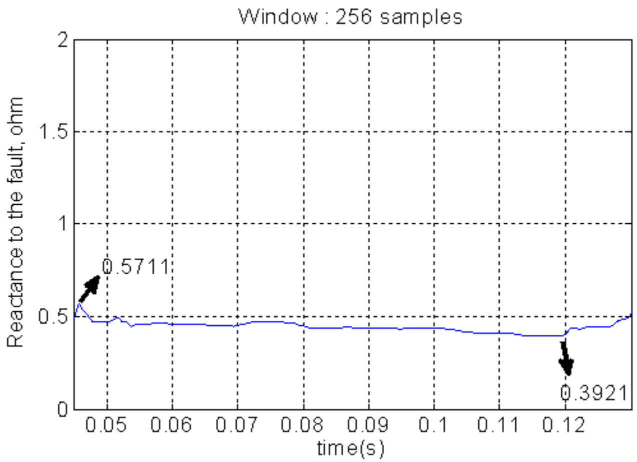
$$x = [R \quad L \quad V_{arc}]^T$$

$$b = V$$

$$\boldsymbol{Ax} = \boldsymbol{b}$$

- Smoothing splines based curve fitting differentiation technique used for finding the derivatives
- Each cycle will give 128/256 equations, 3 unknowns
- Overdetermined system solved by **non-negative least square error method**
- Only positive values accepted for V_{arc}, L and R
- **Neutral current** is used as the fault current





Implementation

- The algorithm is applied only in faulted phase of circuit

$$[\mathbf{V}_F] = [\mathbf{I}_F \quad \frac{\mathbf{dI_F}}{\mathbf{dt}} \quad sign(\mathbf{I}_F)] \begin{bmatrix} \mathbf{R} \\ \mathbf{L} \\ \mathbf{V_{arc}} \end{bmatrix}$$

- Residual/ Neutral current (I_n) is used instead of fault current for term I_F

$$I_n = I_a + I_b + I_c$$

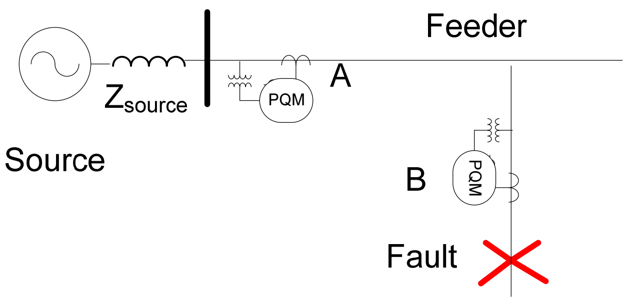
- For single line to ground faults- from sequence networks
  - I_1, I_2, and I_0 are +ve, -ve and zero sequence currents measured at monitoring site
  - V_f is faulted phase voltage

- Reactance to fault location is given in terms of loop impedance

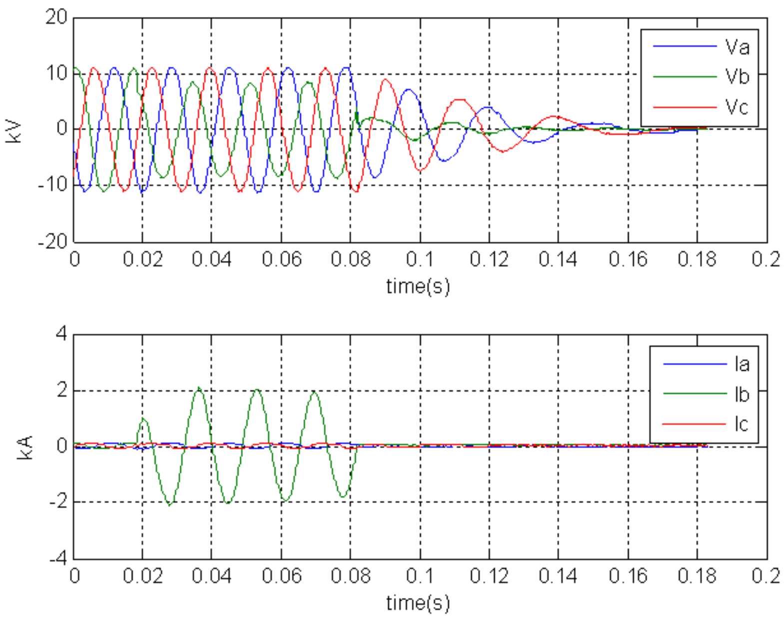
$$I_0 = I_1 = I_2 = \frac{I_n}{3} = \frac{V_f}{z_1 + z_2 + z_0} \longrightarrow \frac{V_f}{I_n} = \hat{z}_s$$

$$\hat{z}_s = \frac{z_1 + z_2 + z_0}{3} = \frac{2z_1 + z_0}{3}$$

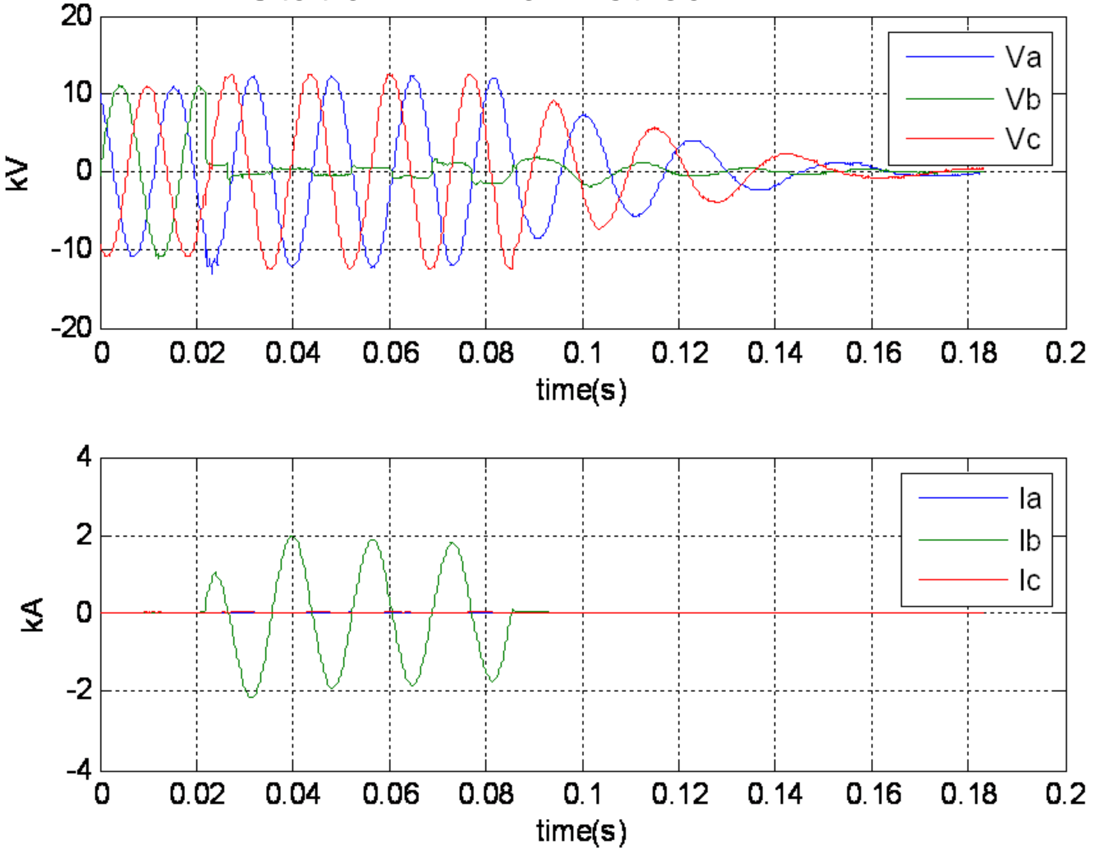
Validation of Algorithm: Arc Voltage Waveshapes (actual data)



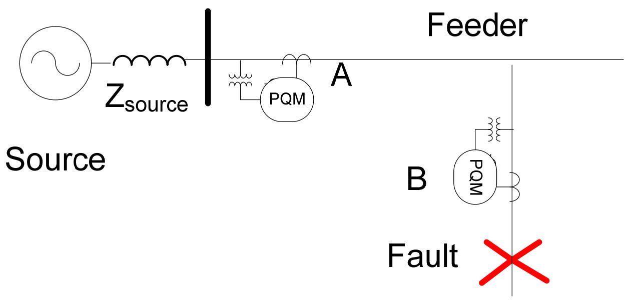
Station A - Upstream

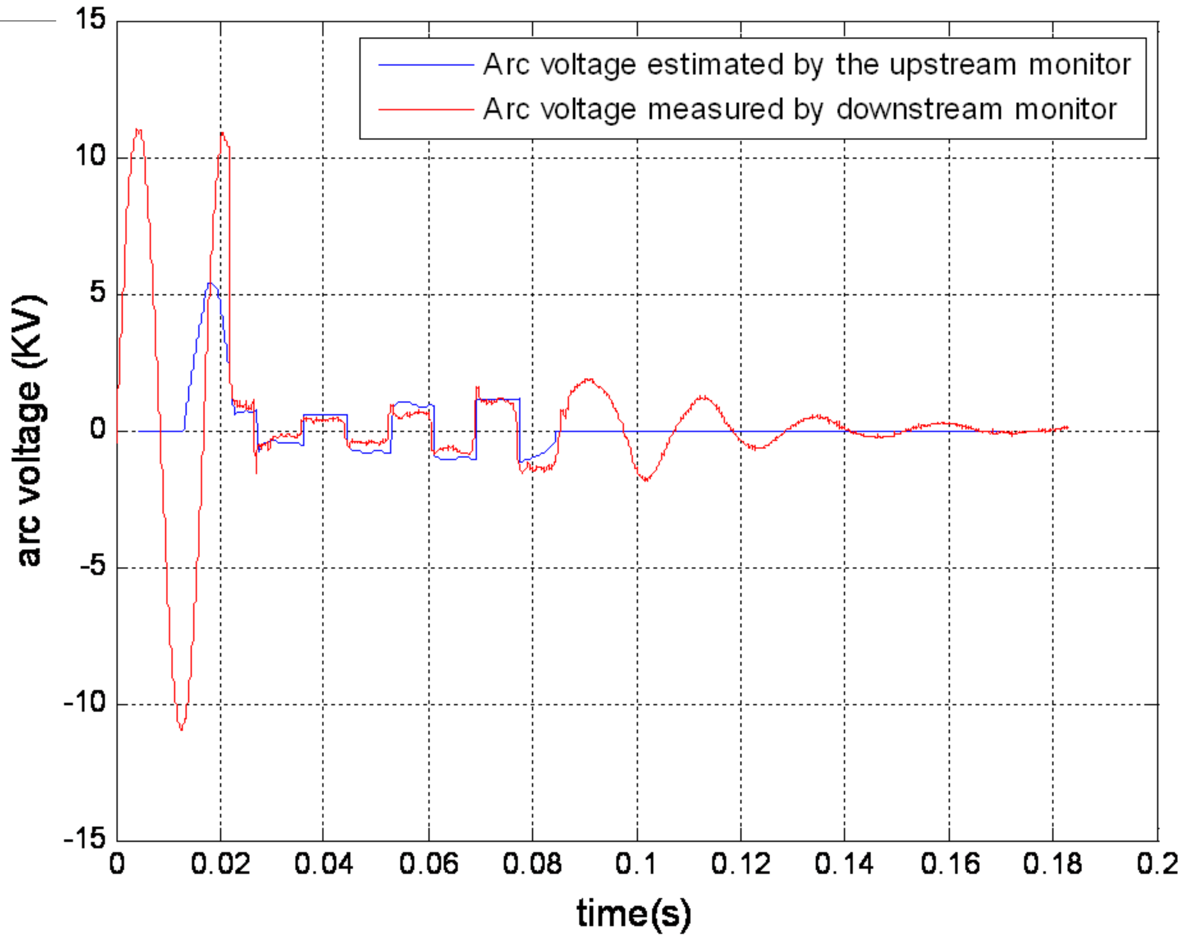


Station B - Downstream



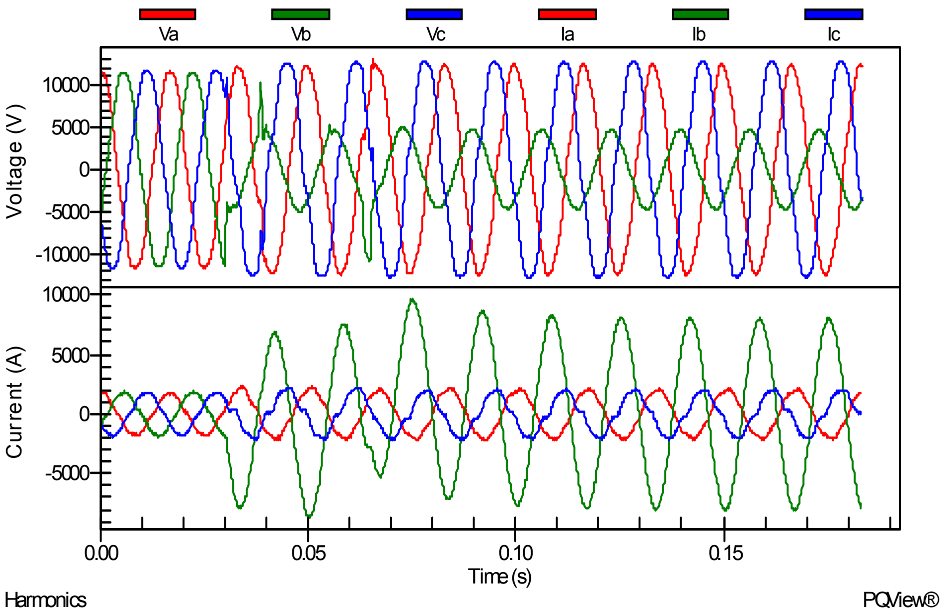
Validation of Algorithm: Arc Voltage Waveshape



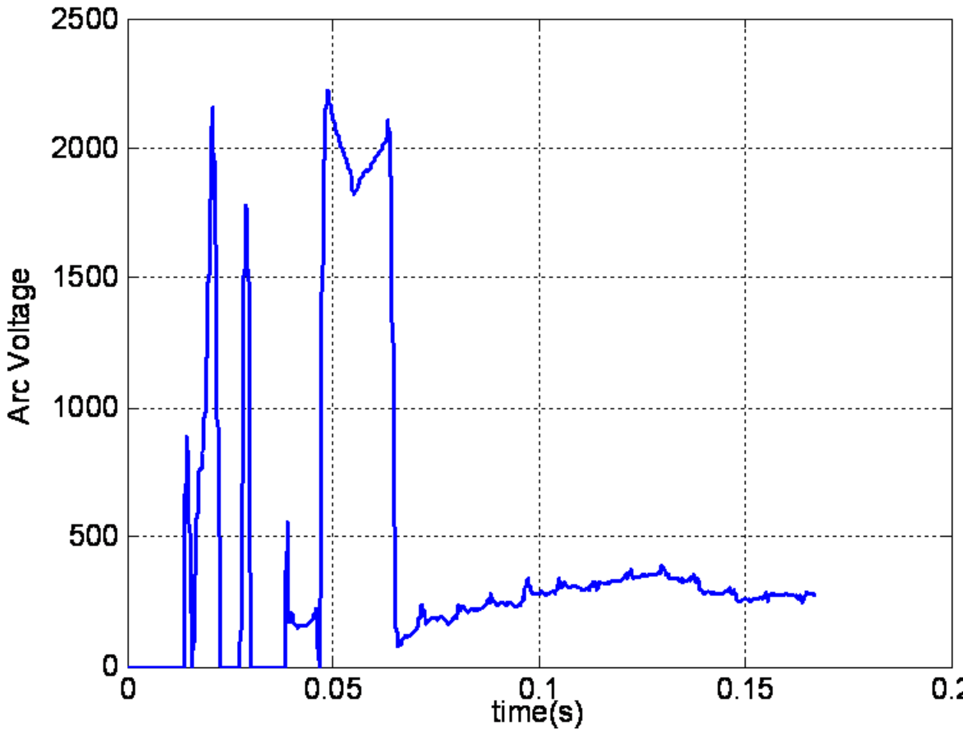


Arc Voltage in Cable Faults

Underground Cable Fault

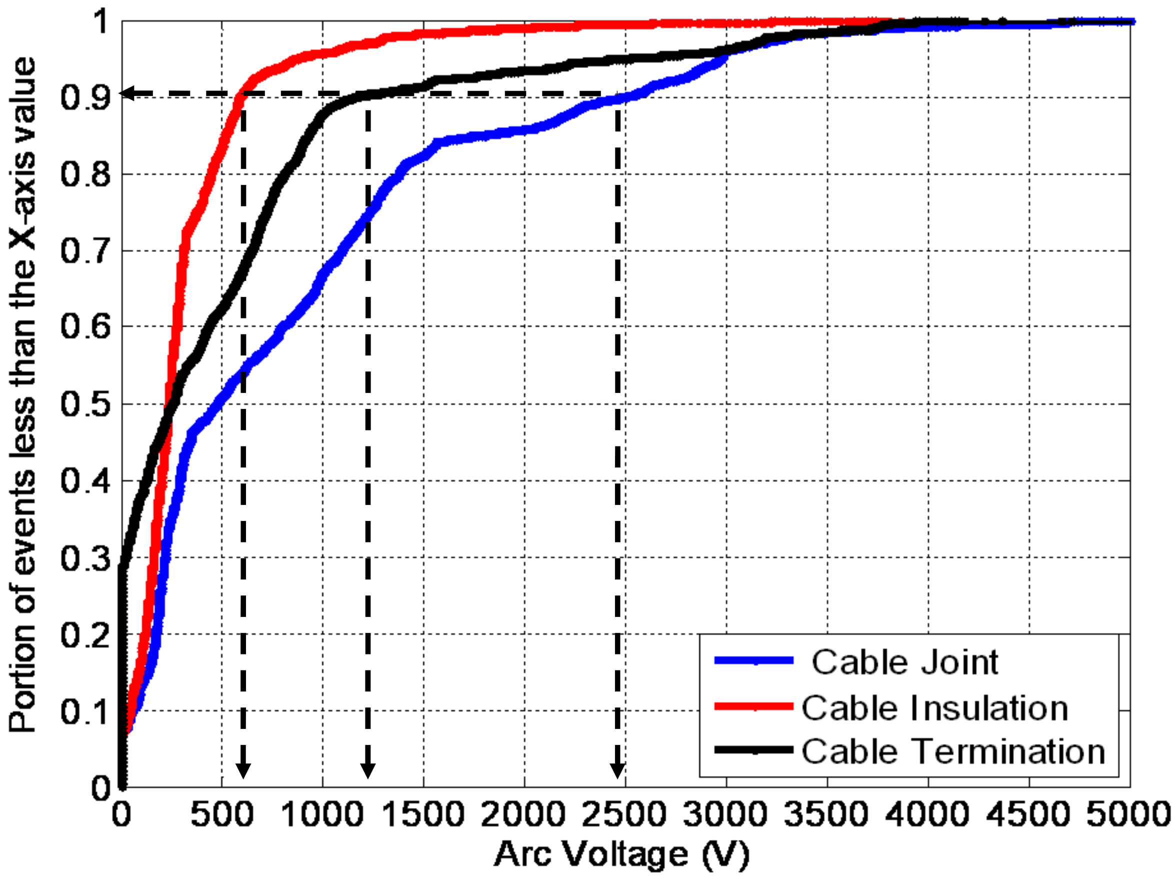


Arc Voltage magnitude in Phase B



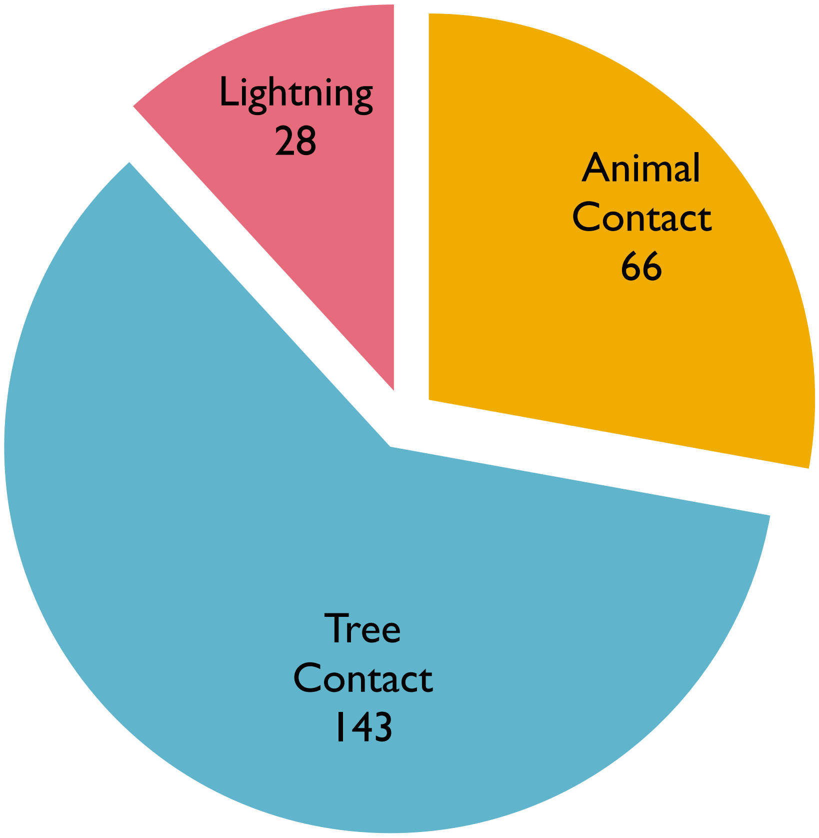
Normalized Arc Voltage

- Cable joint failure: 25 Cases
- Cable insulation failure: 22 cases
- Cable termination failure: 16 cases
- Cable insulation failure has lowest arc voltage
- Cable joint failure has highest arc voltage

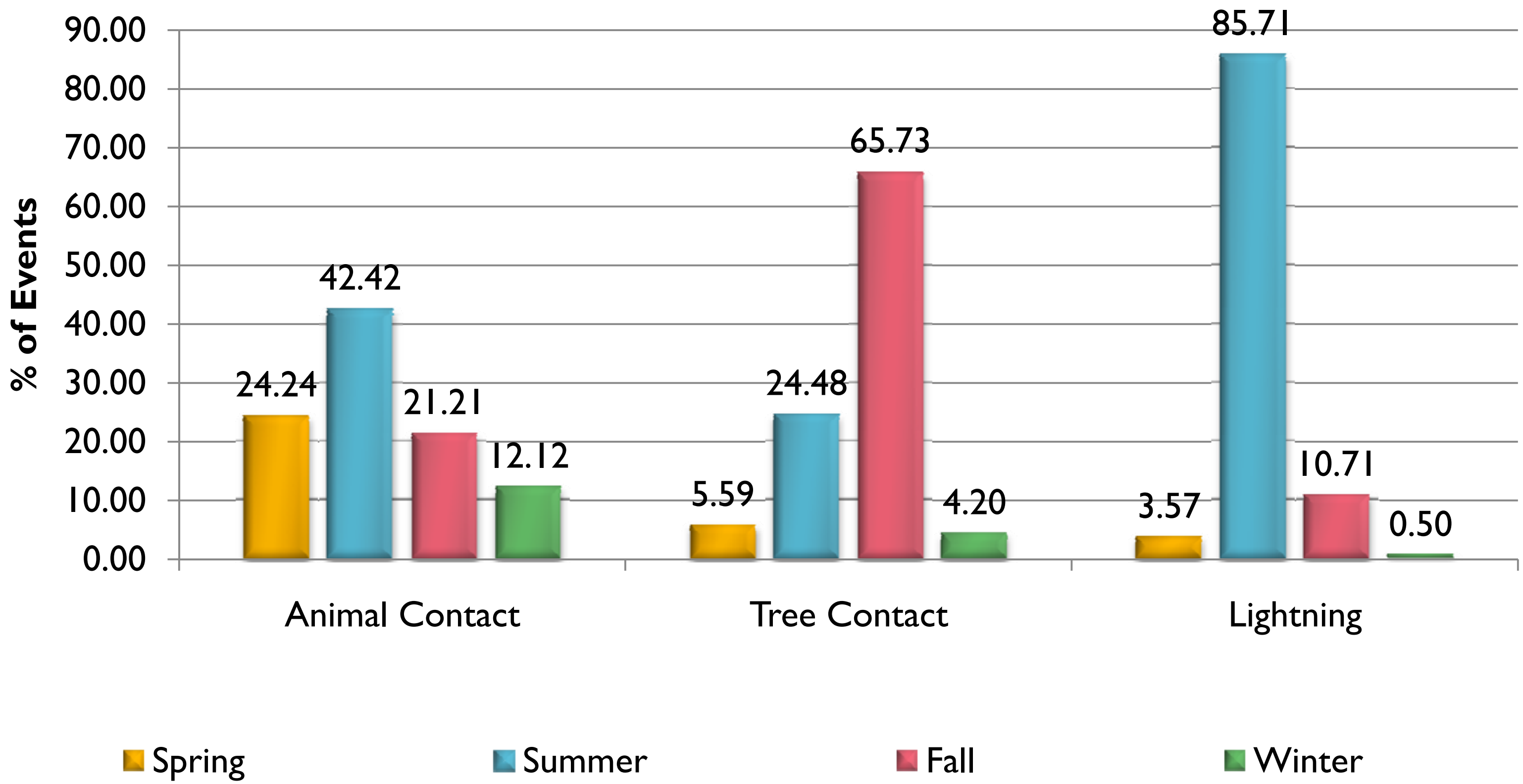


Waveform Characterization of Animal Contact, Tree Contact, and Lightning Induced Faults

- Utility located in Northeastern part of United States
- Voltage level generally 12.47 kV
- Sample Window: 10 cycles
- Sampling Rate
  - Voltage: 256 samples/ cycle
  - Current: 128 samples/cycle

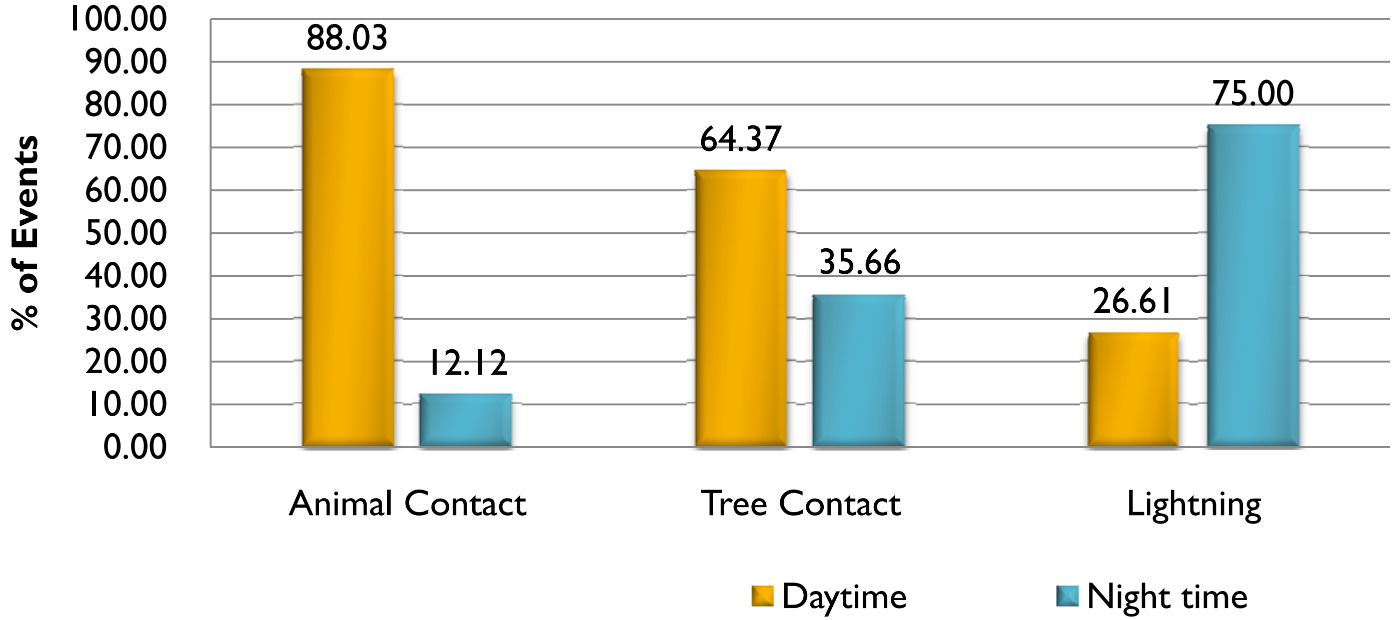


Characteristic Signatures - Time Stamp



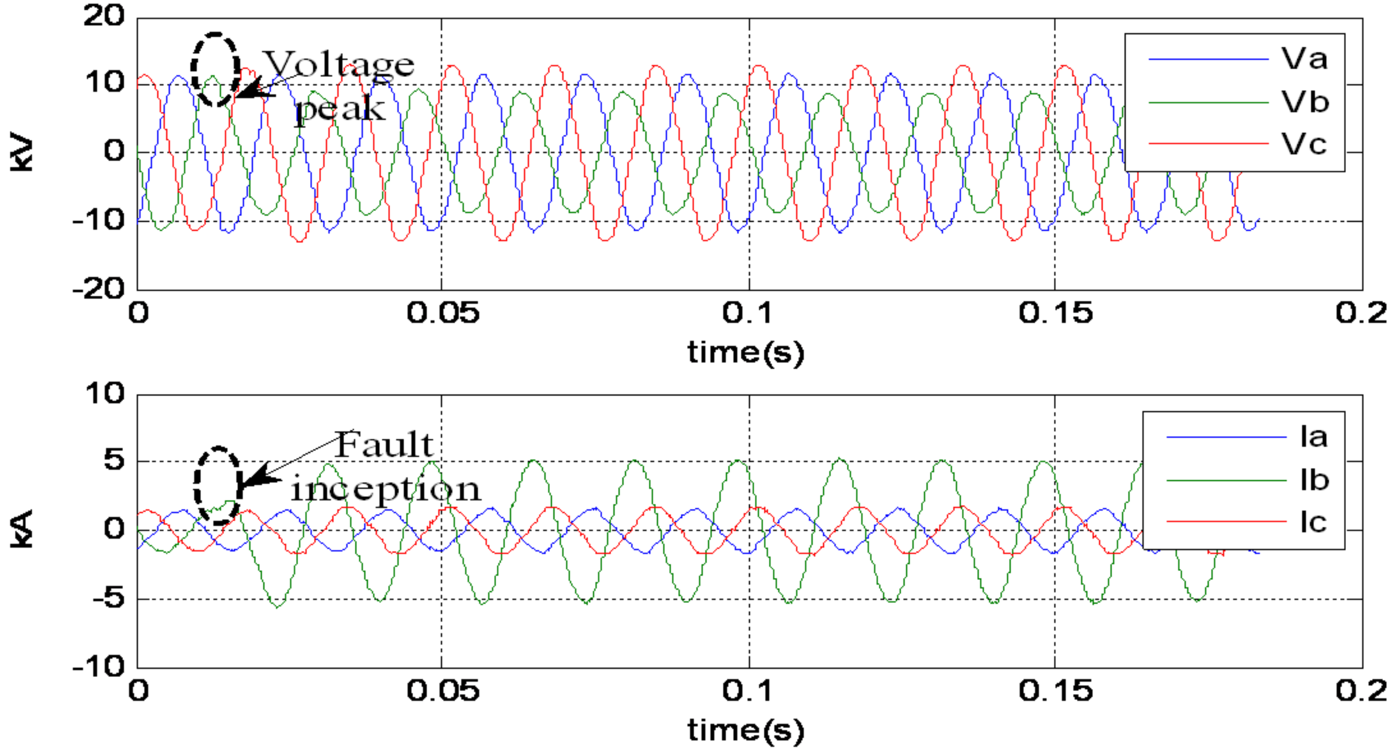
- Faults are influenced by weather conditions and seasons
- Lightning: mostly in summer; Tree contact: mostly in fall

Characteristic Signatures - Time Stamp

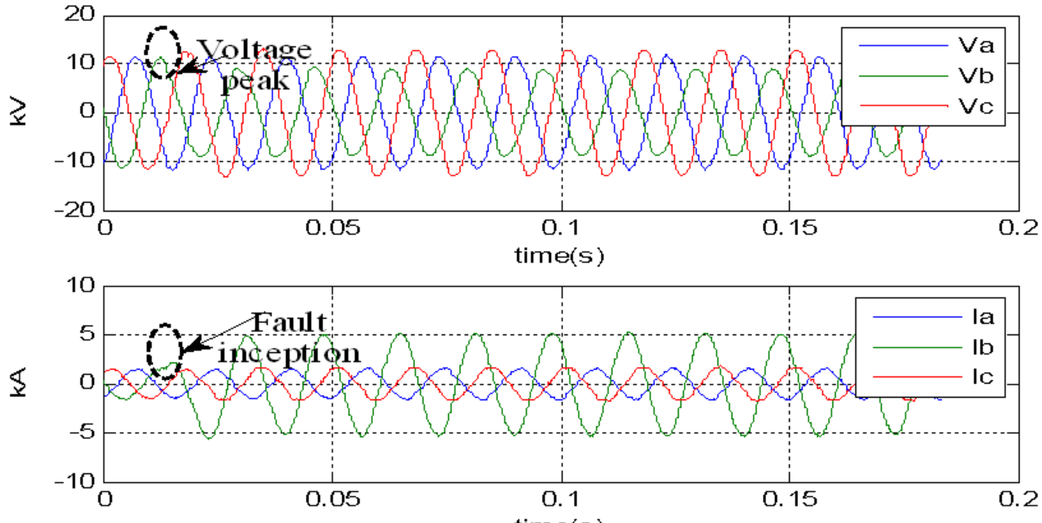


- Distribution depends on geographical location of utility
- Lightning : Mainly during night hours (!?)
- Animal Contacts: Mostly during daytime, depends on type of animals

Characteristic Signatures - Fault Insertion Angle



Characteristic Signatures - Fault Insertion Angle



Event	*Insertion angle around peak 15° of (±90°)*	*Off-peak Insertion angle*	*Total cases*
Animal Contact	43 (70.5%)	18 (29.5%)	61
Tree Contact	66 (73.33%)	24 (26.67%)	90
Lightning Induced	16 (84.21%)	3 (15.79%)	19

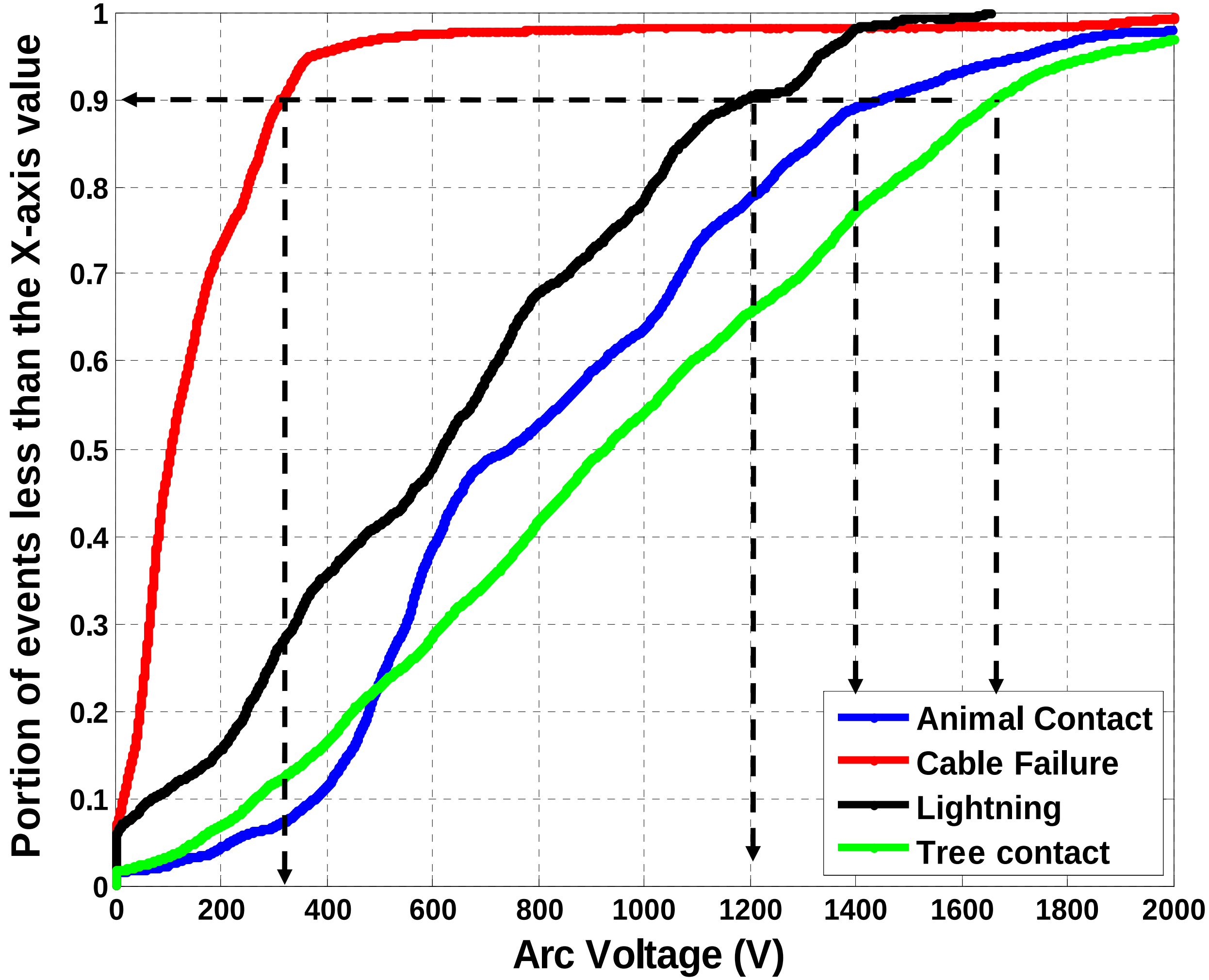
Animal Contact Event

Characteristic Signatures - Number of Phases

- Single phase fault
  - Voltage sag in one phase accompanied by rise in current in same phase
- Multiphase fault
  - Voltage sag in two or three phases accompanied by rise in current
- Animal and tree contact events generally single phase
  - Foreign object comes in contact with one phase
- Lightning strike tends to affect all three phases simultaneously

Event	*Single phase faults*	*Multiphase faults*	*Total cases*
Animal Contact	53 (86.88%)	8 (13.12%)	61
Tree Contact	66 (73.33%)	24 (26.67%)	90
Lightning Induced	8 (42.10%)	11 (57.90%)	19

Normalized Arc Voltage



Concluding Remarks

- A fault cannot be completely described by a single characteristics.
- Combining common and unique characteristics are necessary to determine the root cause of the fault.