Power Quality Data Analytics

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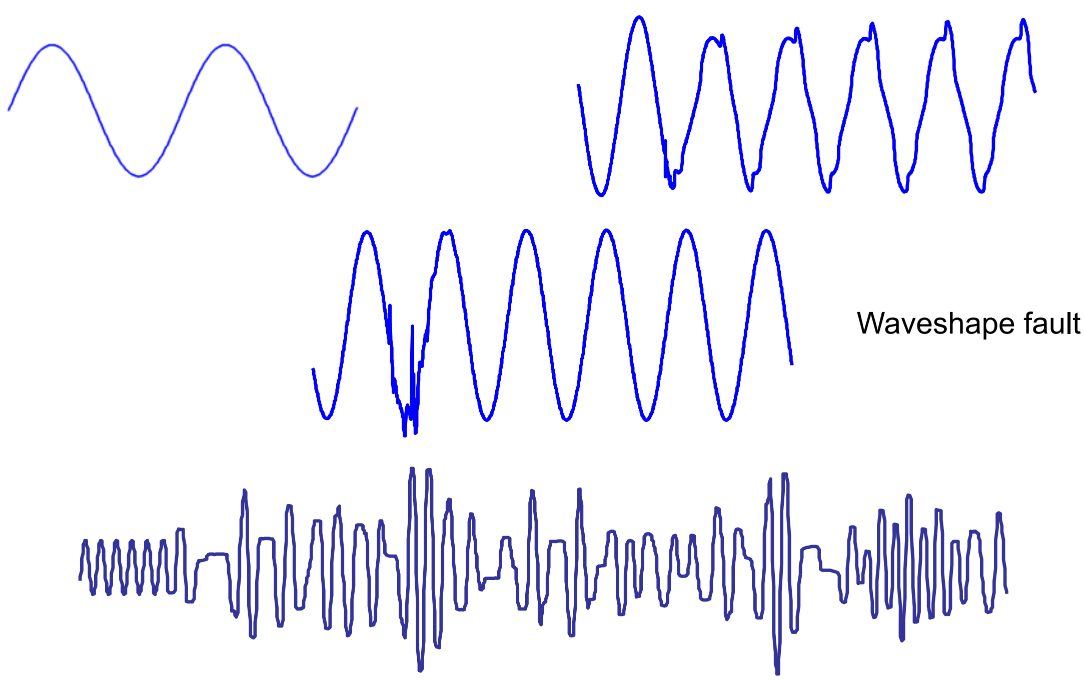
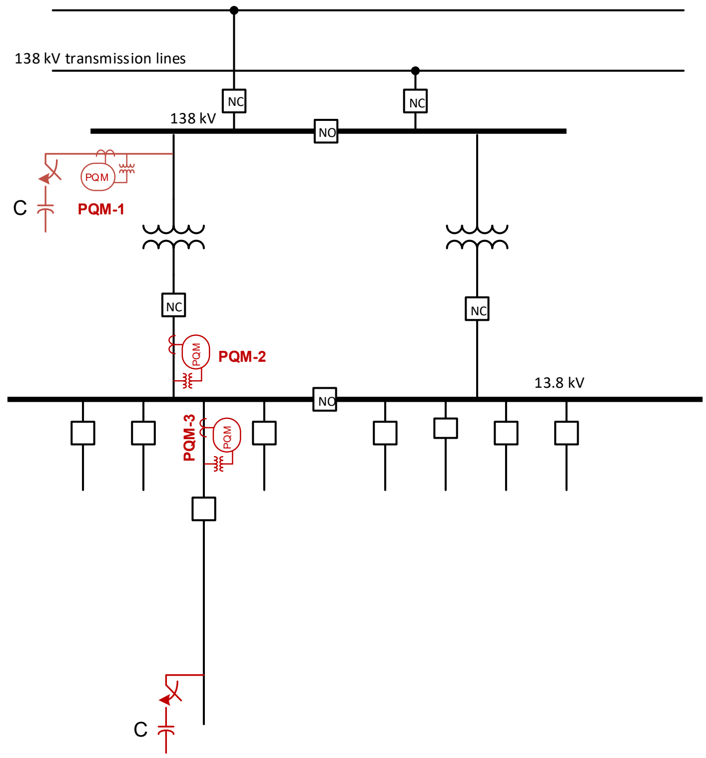
September 5, 2019

- PQ disturbance waveforms
- Instrumentation, location, and data size
- General approach
- Application: Capacitor health condition monitoring
- Application: Incipient cable fault detection and location

Power Quality Disturbance Waveforms



PQ Monitor Locations



Instruments for Power Quality Monitoring

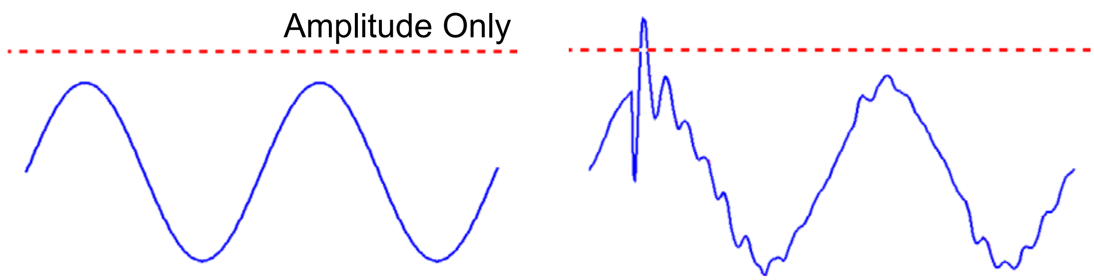
Continuous Data Recorder

Records waveform data continuously
No worries about missing data due to incorrect trigger settings.

Disturbance Monitor (Triggers Recording)

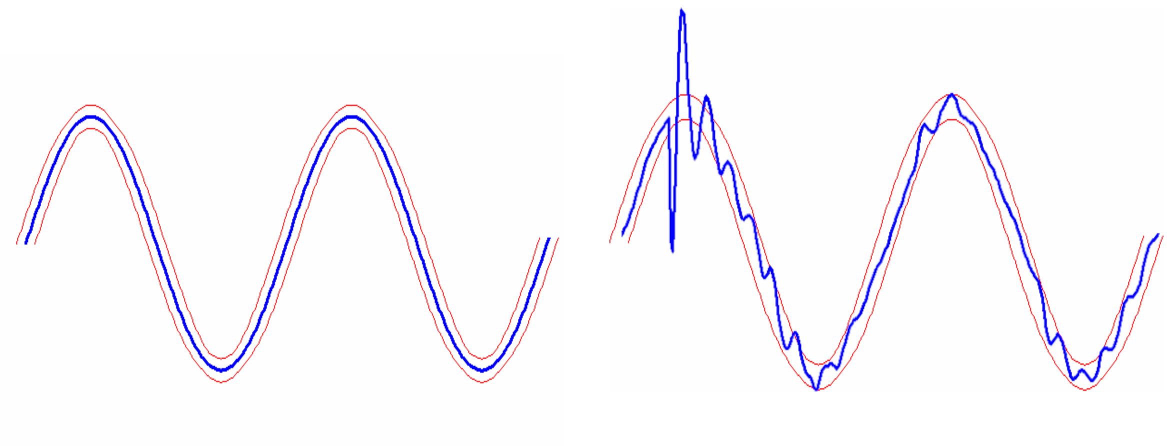
Smaller sets of data
Need appropriate trigger settings

Triggering on Instantaneous Level Threshold

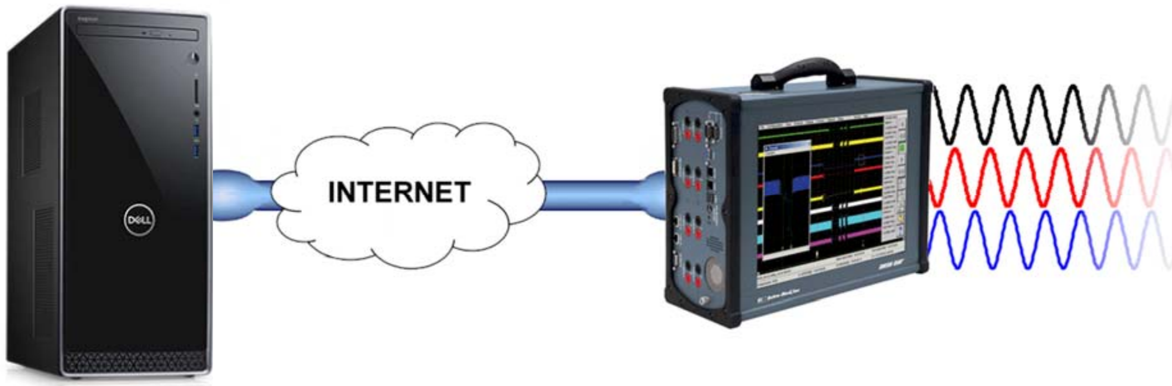


Triggering on Waveshape Change

Amplitude: Unit Value or Percent
Time: % of Cycle Sensitivity



Data Size: One Hour



(2 bytes/sample) X (512 samples/cycle) X (60 cycles/sec) X
(60 sec/min) X (60 min/hr)

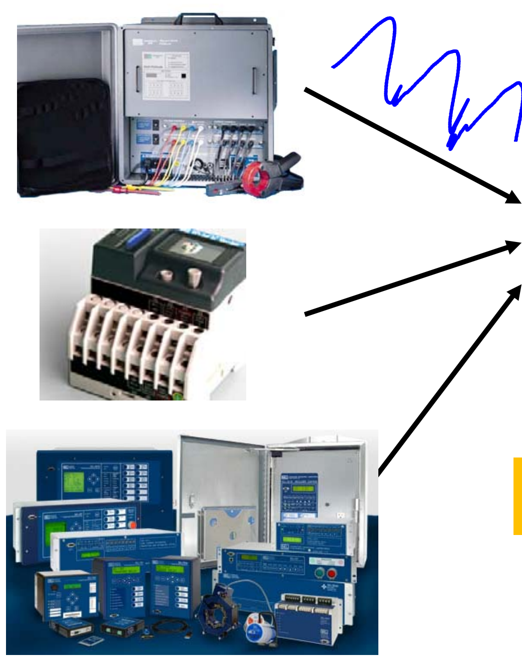
221,184,000 bytes or 221 MB

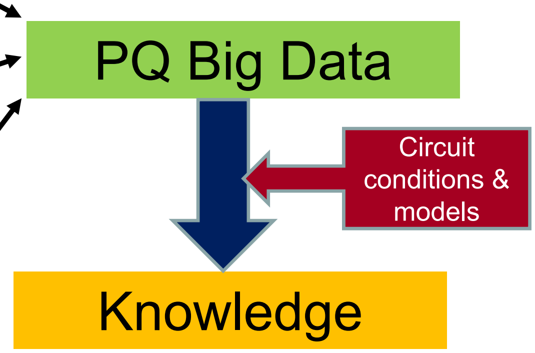
X (8 channels of Voltage and Current data)

1,769,472,000 bytes or 1.8 Gb/hour

PQ Data Analytics: Concepts

Rigorous applications and exploitations of
PQ Big Data, so as to turn them into knowledge

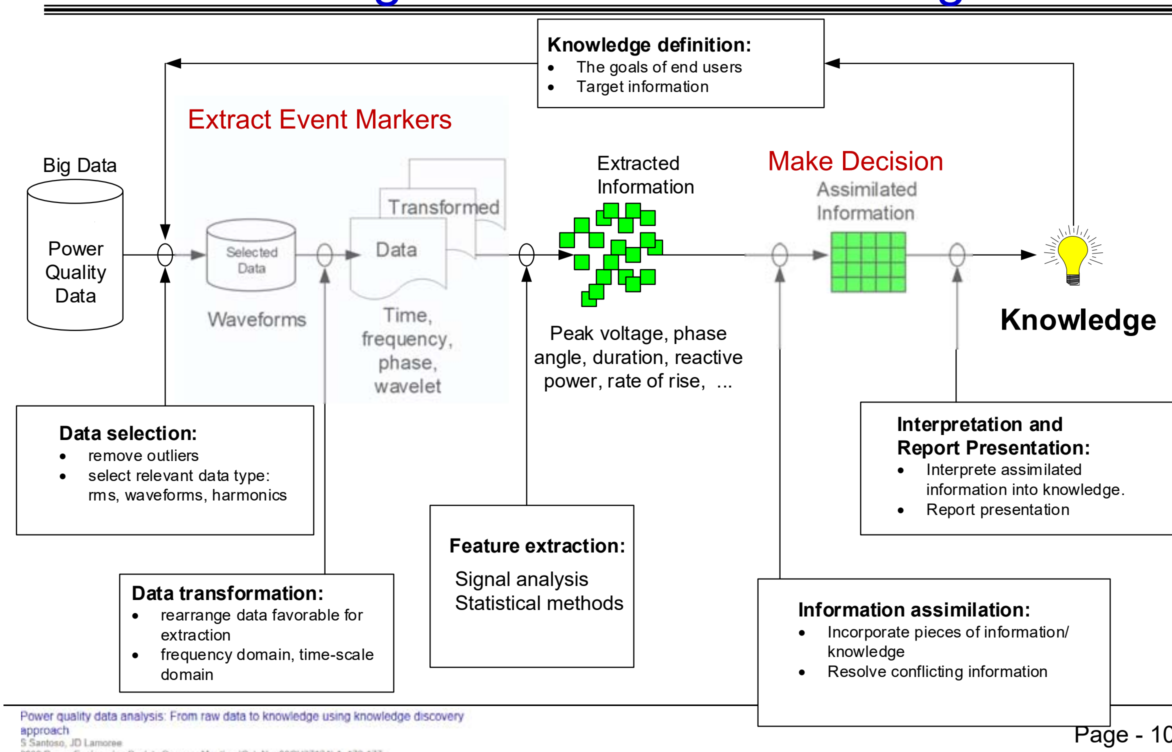




Applications of PQ Data

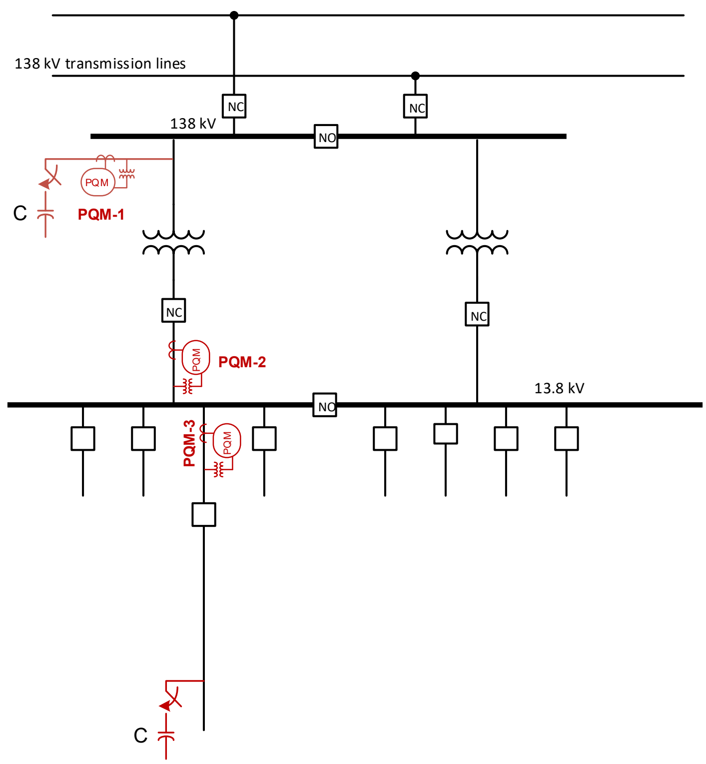
- Health monitoring of capacitor banks
- Detecting incipient cable faults and estimating their locations
- Identifying operations of protective devices

General Approach: Turning raw data into knowledge



Power quality data analysis: From raw data to knowledge using knowledge discovery approach
S Santoso, JD Lamoree
2000 Power Engineering Society Summer Meeting (Cat. No. 00CH37134) 1, 172-177

PQ Monitor Locations



Distribution Feeder Capacitor Banks

Monitoring purposes:
** Impacts of capacitors on the system: overvoltage, transients, reactive power, resonance, harmonics

**Health condition of capacitor units

**Health condition of circuit switchers

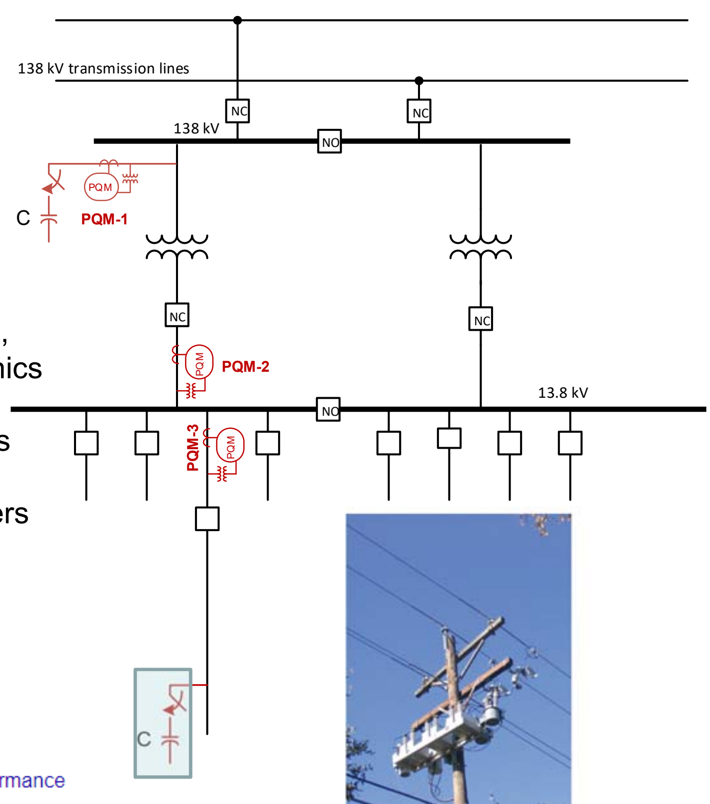


Figure 1.11 Pole-mounted three-phase distribution capacitor bank.

Signature analysis to track capacitor switching performance
S Santoso, JD Lamoree, MF McGranaghan
2001 IEEE/PES Transmission and Distribution Conference and Exposition ...

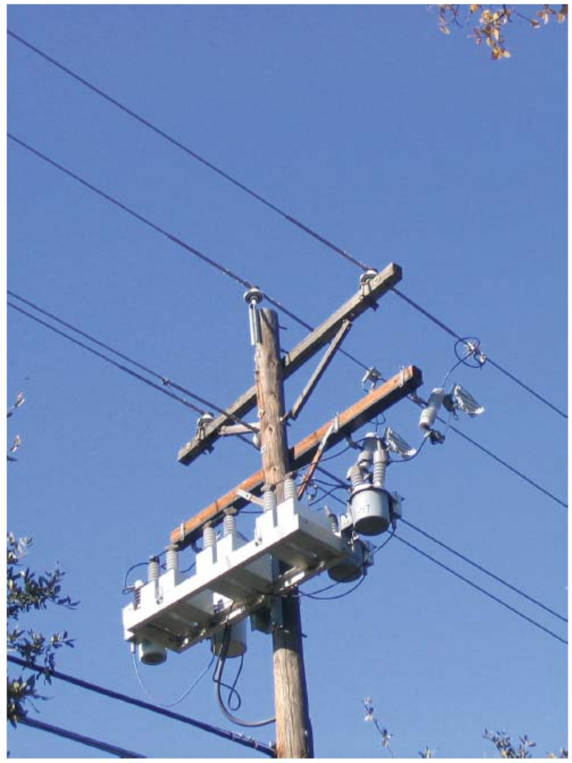
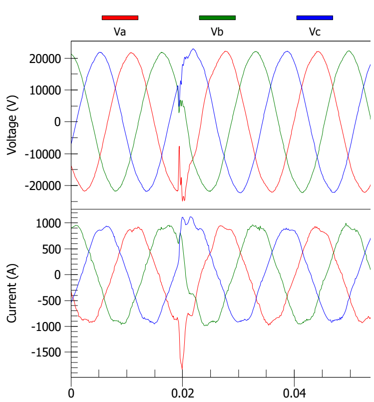


Figure 1.11 Pole-mounted three-phase distribution capacitor bank.

Cap. Swit

```
Cap. switching event is [normal energizing] OR [successful de-energizing]
OR [restrike-on-opening]
Cap. switching event is normal energizing
Cap bank is down-line from PQ monitor
High confidence
----------------- Resonant Frequency ------------------------------
Resonant frequency [Hz] = 280
No resonance

---Capacitor unit health: Unbalance switching/kvar change ---------
kvar change: balance, either in energizing (closing) or
de-energizing (opening)
Cap banks are energized [kvar] = 6472.26
kvar change for each phase [kvar] = 2209.95 ; 2109.05 ; 2153.26

---Performance of Circuit Switchers: Restrike Analysis ---------
No Restrike during closing in any phase
No Restrike during closing on Phase A
Ph. A Time instants of the two restrikes: 0 s; 0 s;
Ph. A Voltage at time instants: 0 pu, 0 pu;
No Restrike during closing on Phase B
Ph. B Time instants of the two restrikes: 0 s; 0 s;
Ph. B Voltage at time instants: 0 pu, 0 pu;
No Restrike during closing on Phase C
Ph. C Time instants of the two restrikes: 0 s; 0 s;
Ph. C Voltage at time instants: 0 pu, 0 pu;
--------- Synchronous Closing Control ---------------------------
Phase A closing time = 0.0188802 s
Phase A closing is premature by -89.5955 degrees
Phase B closing time = 0.0191406 s
Phase B closing is premature by -23.9238 degrees
Phase C closing time = 0.0191406 s
Phase C closing is delayed by 37.22 degrees
-------- Estimate of Cap Bank Distance -
Estimate of cap. bank distance is 2.94699 to 3.73134
```



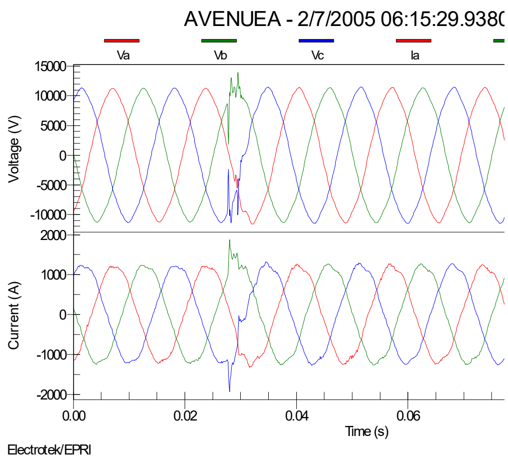
Electrotek/EPRI

On determining the relative location of switched ca
S Santoso
IEEE Transactions on power delivery 22 (2), 1108-1116

On two fundamental signatures for determining the relative location of switched capacitor banks
K Hur, S Santoso
IEEE Transactions on Power Delivery 23 (2), 1105-1112

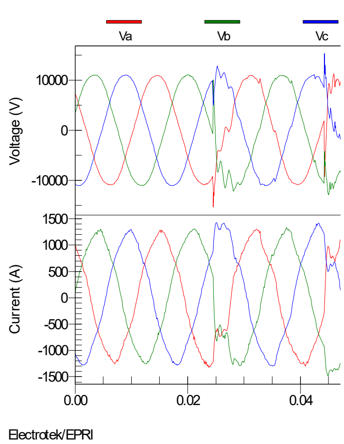
Distance estimation of switched capacitor banks in utility distribution feeders
K Hur, S Santoso
IEEE transactions on power delivery 22 (4), 2419-2427

Cap. Switching Data Analytics: Event 2



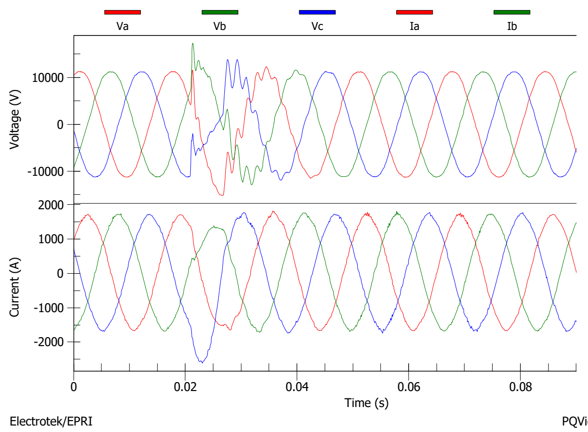

```
Cap. switching event is [normal energizing] OR [successful de-energizing]
OR [restrike-on-opening]
Cap. switching event is normal energizing
Cap bank is down-line from PQ monitor
High confidence

------------------ Resonant Frequency -----------------------------
Resonant frequency [Hz] = 520

------------------ Unbalance switching/kvar change ----------------
kvar change: balance, either in energizing (closing) or de-energizing (opening)
Cap banks are energized [kvar] = 2254.87
kvar change for each phase [kvar] = 775.597 ; 723.353 ; 755.922

------------------ Restrike Analysis -----------------------------
No Restrike during closing in any phase
No Restrike during closing on Phase A
Ph. A Time instants of the two restrikes: 0 s; 0 s;
Ph. A Voltage at time instants: 0 pu, 0 pu;

No Restrike during closing on Phase B
Ph. B Time instants of the two restrikes: 0 s; 0 s;
Ph. B Voltage at time instants: 0 pu, 0 pu;

No Restrike during closing on Phase C
Ph. C Time instants of the two restrikes: 0 s; 0 s;
Ph. C Voltage at time instants: 0 pu, 0 pu;

------------------ Synchronous Closing Control ------------------------------
Phase A closing time = 0.0291667 s
Phase A closing is delayed by 31.0457 degrees
Phase B closing time = 0.0276042 s
Phase B closing is delayed by 58.3861 degrees
Phase C closing time = 0.0276042 s
Phase C closing is premature by -60.957 degrees

------------------ Estimate of Cap Bank Distance ------------------------
Estimate of cap. bank distance is 1.57638 to 1.81085
```


Cap. Sw



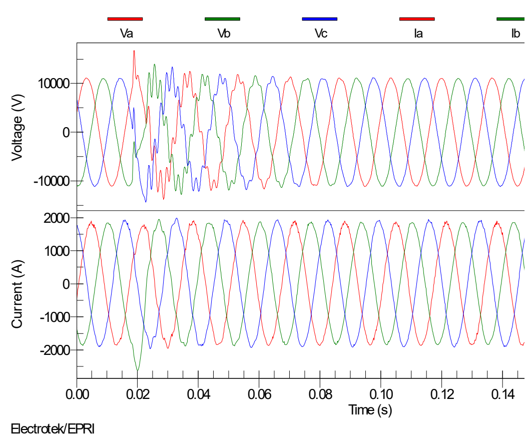

```
Cap. switching event is [normal energizing] OR [successful de-energizing]
OR [restrike-on-opening]
Cap. switching event is restrike-on-opening
Cap bank is down-line from PQ monitor
High confidence
-------------- Resonant Frequency ------------------------------
Resonant frequency [Hz] = 340
No resonance

---Capacitor unit health: Unbalance switching/kvar change ---------
kvar change: balance, either in energizing (closing) or de-energizing
(opening)
Cap banks are de-energized [kvar] = -3091.17
kvar change for each phase [kvar] = -1043.1 ; -1016.04 ; -1032.04

---Performance of Circuit Switchers: Restrike Analysis ---------
Restrike during opening on one or more phases
Restrike during opening on Phase A: two or more restrikes
Ph. A Time instants of the two restrikes: 0.0242187 s; 0.0438802 s;
Ph. A Voltage at time instants: 1.39684 pu, 0 pu;
Restrike during opening on Phase B: two or more restrikes
Ph. B Time instants of the two restrikes: 0.0242187 s; 0.0438802 s;
Ph. B Voltage at time instants: 1.10608 pu, 0 pu;
Restrike during opening on Phase C: two or more restrikes
Ph. C Time instants of the two restrikes: 0.0240885 s; 0.0438802 s;
Ph. C Voltage at time instants: 1.1617 pu, 1.39517 pu;
-------- Synchronous Closing Control ------------------------------
Phase A closing time = 0 s
No closing operation, Phase A is de-energized
Phase B closing time = 0 s
No closing operation, Phase B is de-energized
Phase C closing time = 0 s
No closing operation, Phase C is de-energized
-------- Estimate of Cap Bank Distance ------------------------
Estimate of cap. bank distance is undetermined.
```

Cap. Switching Data Analytics: Event 4




```
----Capacitor Switching Transient Evaluation --------

Not a capacitor switching event
Moderate confidence

-------- Resonant Frequency -------------
Resonant frequency [Hz] = 0

-------- Unbalance switching/kvar change

-------- Restrike Analysis ---------------

-------- Synchronous Closing Control -----

-------- Estimate of Cap Bank Distance ---
```

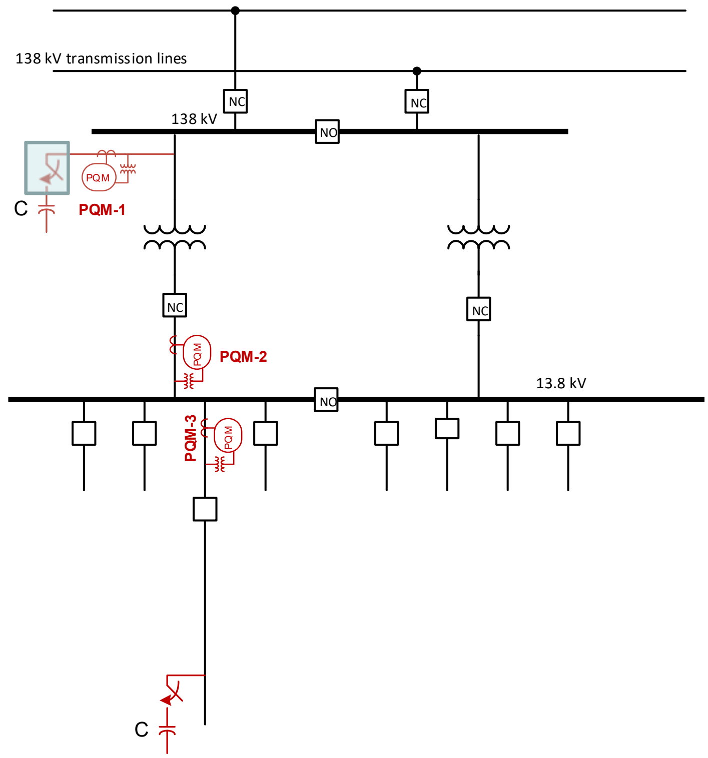

Cap. Switching Data Analytics: Event 5



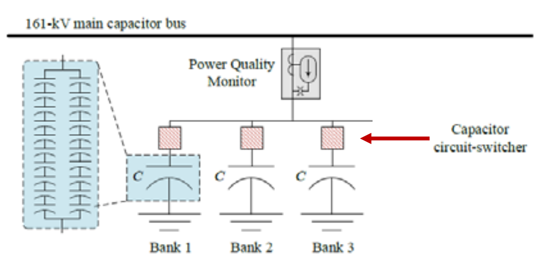

```
----Capacitor Switching Transient Evaluation ------------

Not a capacitor switching event
Moderate confidence

------------------ Resonant Frequency -----------------
Resonant frequency [Hz] = 0

------------- Unbalance switching/kvar change -----

------------- Restrike Analysis ------------------

------------- Synchronous Closing Control ---------

------------- Estimate of Cap Bank Distance -------
```

Transmission Capacitor Banks

** Health condition of circuit switchers

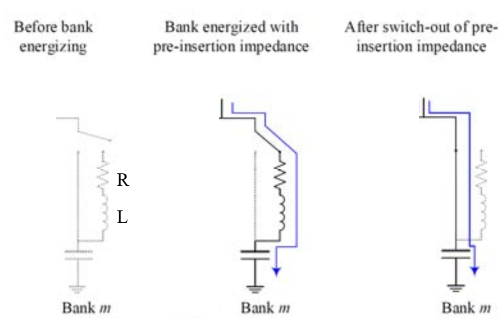


Transmission Capacitor Banks

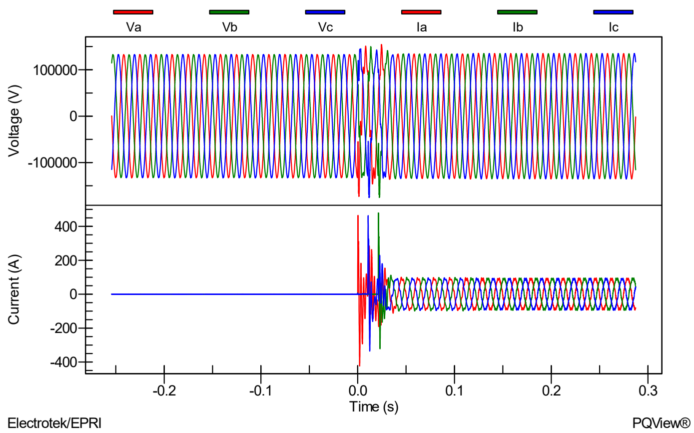


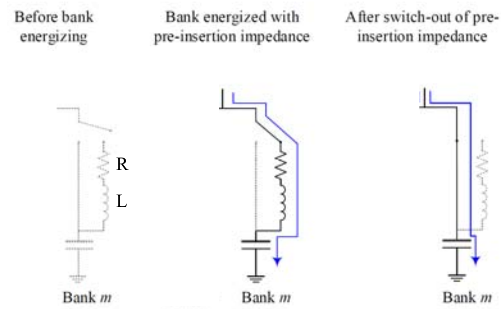
(a) (b) (c)

Fig. 2. Normal sequence of operations for energizing a capacitor bank through a pre-insertion impedance [19]. (a) Capacitor energizing with pre-insertion impedance through an open-air arc. (b) Physical contact between moving and stationary rods. (c) Pre-insertion impedance switched-out.



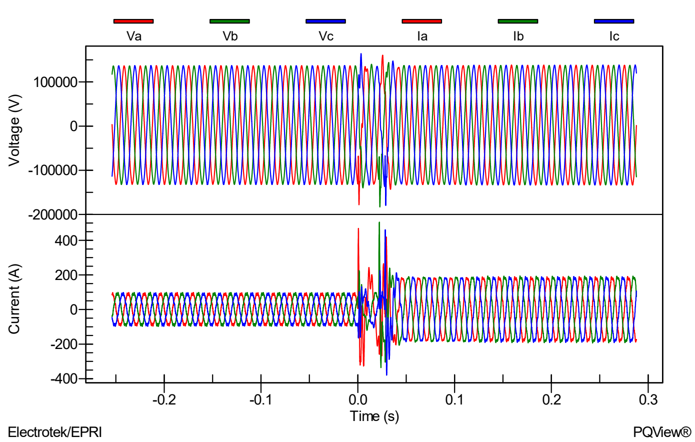
C.ville MDB

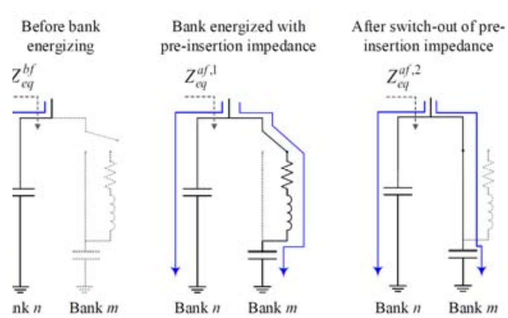




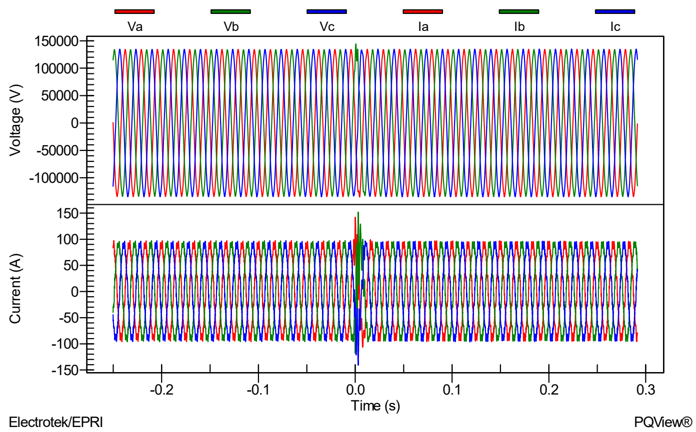
Determine pre-insertion R & L
Determine the switched-out duration

C.ville MDB





C.ville MDB



Approach:
**Make sure it is an energizing, not a de-energizing or sympathetic transient

**Flag abnormal energizing: missing pre-insertion elements (blades mis-alignment) And failed switch-out

**Detect switch-in and out times

**Estimate pre-insertion impedance; must decoupled energized capacitors

C.Ville MDB – Event 12

```
Capacitor Switching Analysis Module
Event filename: C.ville MS 161-B1004-Caps-20170717T201612-12.csv
Analysis Outcomes:
**Pre-insertion Closing on Phase A
**Pre-insertion Closing on Phase B
**Per-Insertion Closing on Phase C

Type of operation = 31, 31, 31
isResonance, Res Freq, Vpeak, Vrms_bf, Vrms_af, dVrms, Ipeak, Irms_bf, Irms_af, dIrms, Freq, dQ,
PFinit, PFend, THDI_bf, THDI_af, dTHDI, THDV_bf, THDV_af, dTHDv, nstep_bf, nstep_af, X_bf, X_af
0, 0.00 Hz, 1.31 pu, 1.01 pu, 1.02 pu, 0.97 pct, 464.57 Apk, 0.00 Arms, 64.22 Arms, 64.14 Arms, 660.00 Hz, -6062.68 kvar,
0.00, -0.02, 0.00 pct, 7.46 pct, 7.46 pct, 0.59 pct, 0.77 pct, 0.17 pct, 0, 1, 1000000.00 ohms, -1471.45 ohms
0, 0.00 Hz, 1.32 pu, 1.01 pu, 1.02 pu, 0.97 pct, 479.33 Apk, 0.00 Arms, 65.02 Arms, 65.48 Arms, 660.00 Hz, -6141.10 kvar,
0.00, -0.01, 0.00 pct, 7.22 pct, 7.22 pct, 0.61 pct, 0.72 pct, 0.11 pct, 0, 1, 1000000.00 ohms, -1453.99 ohms
0, 0.00 Hz, 1.32 pu, 1.01 pu, 1.02 pu, 0.98 pct, 463.63 Apk, 0.00 Arms, 64.52 Arms, 65.14 Arms, 660.00 Hz, -6110.09 kvar,
0.00, -0.02, 0.00 pct, 7.11 pct, 7.11 pct, 0.59 pct, 0.70 pct, 0.10 pct, 0, 1, 1000000.00 ohms, -1468.72 ohms
Time instant of the first sample point = -0.2543 s
Phase ABC First Closing Operation Time = 0.2541, 0.2545, 0.2651 s
Phase ABC Second Closing Operation Time = 0.3612, 0.3671, 0.3619 s
Phase Diff at the first closing = 111.4520, 89.0766, 10.6431 deg
Energy during the first closing = 17.2724, 7.7258, 8.0622 million A^2s
Phase ABC Switched-out duration = 7.23 8.15 6.87 cycles
Phase ABC Step Change in R = -9999.00, -9999.00, -9999.00 ohms
Phase ABC R before Switched Out = -9999.00, -9999.00, -9999.00 ohms
Phase ABC R after Switched Out = -9999.00, -9999.00, -9999.00 ohms
Phase ABC Step Change in X = -13.36, -13.41, -13.62 ohms
Phase ABC X before Switched Out = -1458.31, -1440.52, -1455.10 ohms
Phase ABC X after Switched Out = -1471.68, -1453.93, -1468.72 ohms
```

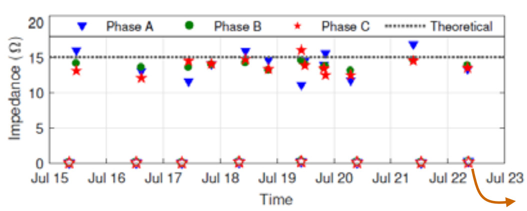
Capacitor Circuit Switchers			
Switch #	Pre-Insertion Inductor		
	Inductance (mH)	Reactance (Ohms)	Resistance (Ohms)
1012	40	15.08	5.50
1022	40	15.08	5.50
1032	40	15.08	5.50
1042	40	15.08	81.00

Tty AL 161 MDB

```
Capacitor Switching Analysis Module
Event filename: Tty AL 161-B1018-Caps-20170726T052713-18.csv
Analysis Outcomes:
**Pre-insertion Closing on Phase A
**Pre-insertion Closing on Phase B
**Per-Insertion Closing on Phase C

Type of operation = 31, 31, 31
isResonance, Res Freq, Vpeak, Vrms_bf, Vrms_af, dVrms, Ipeak, Irms_bf, Irms_af, dIrms, Freq, dQ,
PFinit, PFend, THDI_bf, THDI_af, dTHDI, THDV_bf, THDV_af, dTHDv, nstep_bf, nstep_af, X_bf, X_af
0, 0.00 Hz, 1.06 pu, 1.00 pu, 1.01 pu, 0.75 pct, 1553.80 Apk, 0.00 Arms, 322.05 Arms, 323.91 Arms, 720.00 Hz, -30089.62
kvar, 0.00, 0.01, 0.00 pct, 4.63 pct, 4.63 pct, 0.81 pct, 0.94 pct, 0.12 pct, 0, 1, 1000000.00 ohms, -290.12 ohms
0, 0.00 Hz, 1.05 pu, 1.01 pu, 1.02 pu, 0.75 pct, 1294.85 Apk, 0.00 Arms, 322.26 Arms, 324.10 Arms, 780.00 Hz, -30406.16
kvar, 0.00, 0.02, 0.00 pct, 4.55 pct, 4.55 pct, 0.66 pct, 0.79 pct, 0.13 pct, 0, 1, 1000000.00 ohms, -292.93 ohms
0, 0.00 Hz, 1.06 pu, 1.00 pu, 1.01 pu, 0.78 pct, 975.24 Apk, 0.00 Arms, 321.01 Arms, 321.94 Arms, 600.00 Hz, -30116.41
kvar, 0.00, 0.01, 0.00 pct, 4.90 pct, 4.90 pct, 0.75 pct, 0.85 pct, 0.11 pct, 0, 1, 1000000.00 ohms, -292.13 ohms
Time instant of the first sample point = -0.2499 s
Phase ABC First Closing Operation Time = 0.2548, 0.2579, 0.2806 s
Phase ABC Second Closing Operation Time = 0.3704, 0.3738, 0.3938 s
Phase Diff at the first closing = 21.2051, 22.5975, 331.4885 deg
Energy during the first closing = 47.9864, 44.3163, 45.3196 million A^2s
Phase ABC Switched-out duration = 6.43 6.45 6.39 cycles
Phase ABC Step Change in R = -80.64, -81.17, -84.36 ohms
Phase ABC R before Switched Out = 83.24, 85.43, 87.73 ohms
Phase ABC R after Switched Out = 2.60, 4.26, 3.38 ohms
Phase ABC Step Change in X = -15.94, -15.34, -14.69 ohms
Phase ABC X before Switched Out = -274.23, -277.66, -277.34 ohms
Phase ABC X after Switched Out = -290.17, -293.00, -292.03 ohms
```

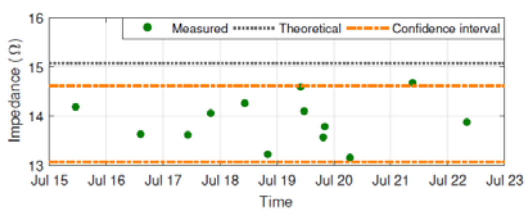
Capacitor Circuit Switchers			
	Pre-Insertion Inductor		
Switch #	Inductance (mH)	Reactance (Ohms)	Resistance (Ohms)
1012	40	15.08	5.50
1022	40	15.08	5.50
1032	40	15.08	5.50
1042	40	15.08	81.00

Measurements of Pre-insertion Impedance



(a)

Does not employ pre-insertion elements



(b)

Fig. 11. Trend of the downstream impedance variation for performance assessment of the circuit-switchers. (a) Impedance variation at the switch-out instant for normal (filled) and abnormal (hollow) switching operations. (b) Baseline for the expected impedance variation.

TABLE III
BASELINE FOR DETECTION OF ABNORMAL IMPEDANCE VARIATION VALUES AT THE SWITCH-OUT INSTANT

Phase	Average (Ω)	Confidence interval limits	
		Lower (Ω)	Upper (Ω)
A	14.096	11.095	17.091
B	13.839	13.064	14.615
C	13.477	11.695	15.260

Measurements of Pre-insertion Impedance

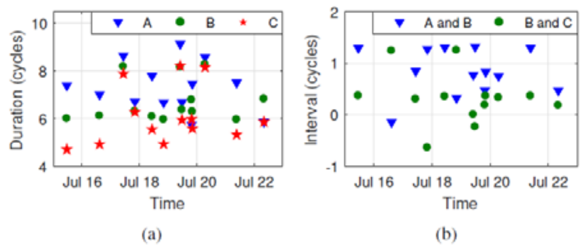


Fig. 12. Trend of selected parameters during normal capacitor switching operations. (a) Interval between the capacitor energizing and pre-insertion switch-out instants. (b) Time difference between the energizing instants in each phase.

Incipient Cable Faults

Background and Data Source:

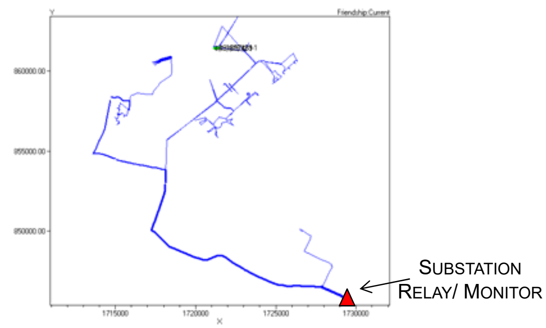
- Data are collected from protective relays and PQ monitors

Target knowledge:

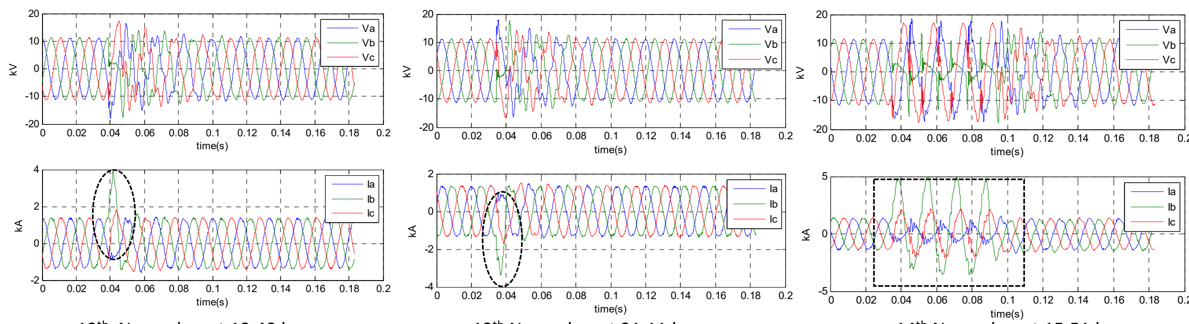
•Detect incipient cable faults
•Determine root cause of cable failure: insulation, termination, and joint/splice
•Distance to incipient faults

Incipient fault location algorithm for underground cables
S Kulkarni, S Santoso, TA Short
IEEE Transactions on Smart Grid 5 (3), 1165-1174

Incipient Cable Faults

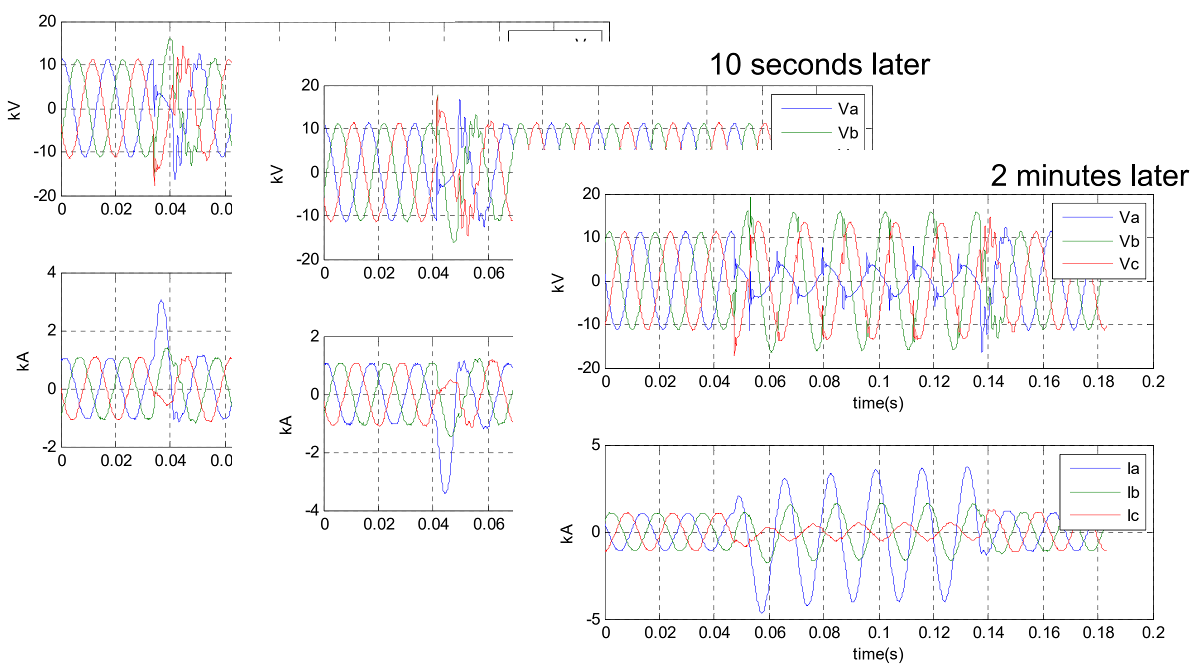


- Fault duration less than one cycle, a few are 1½ cycles
- Single-phase faults at current peak
- No overcurrent protection device operates, difficult to detect
- Frequency increases over time and finally turn permanent

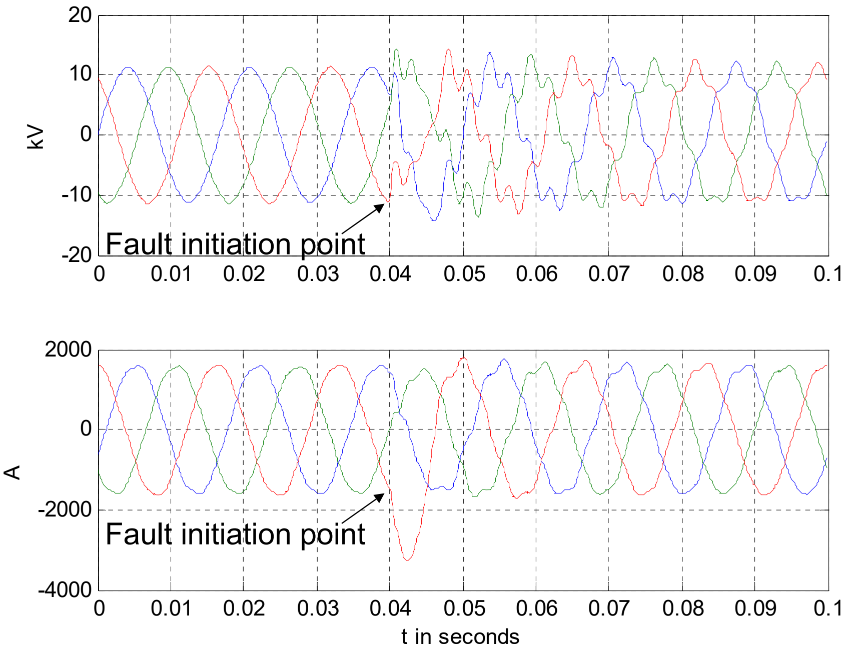


12th November at 19:40 hrs | 12th November at 21:11 hrs | 14th November at 15:51 hrs

Incipient Cable Faults: Examples

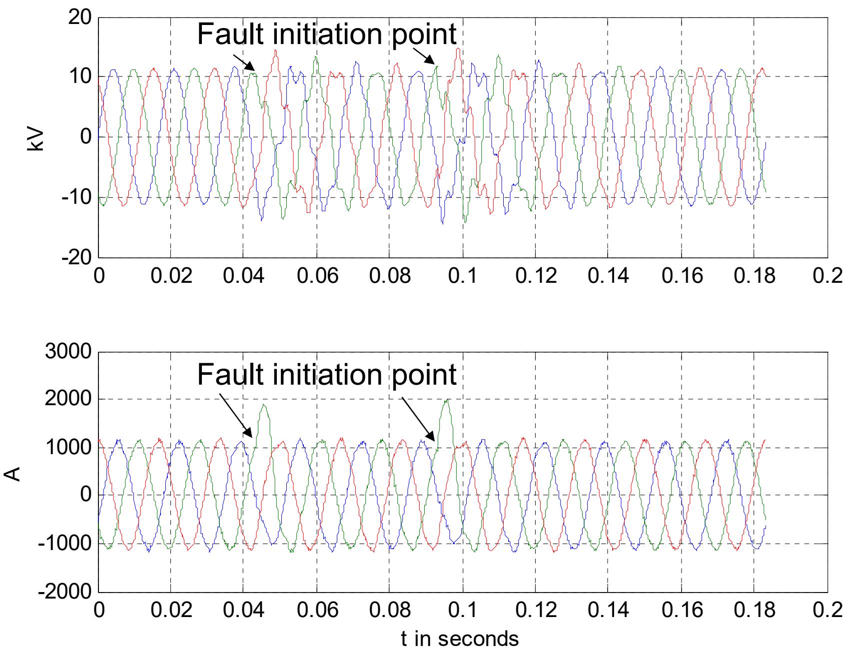


Samples of Incipient Cable Fault Waveforms (1)



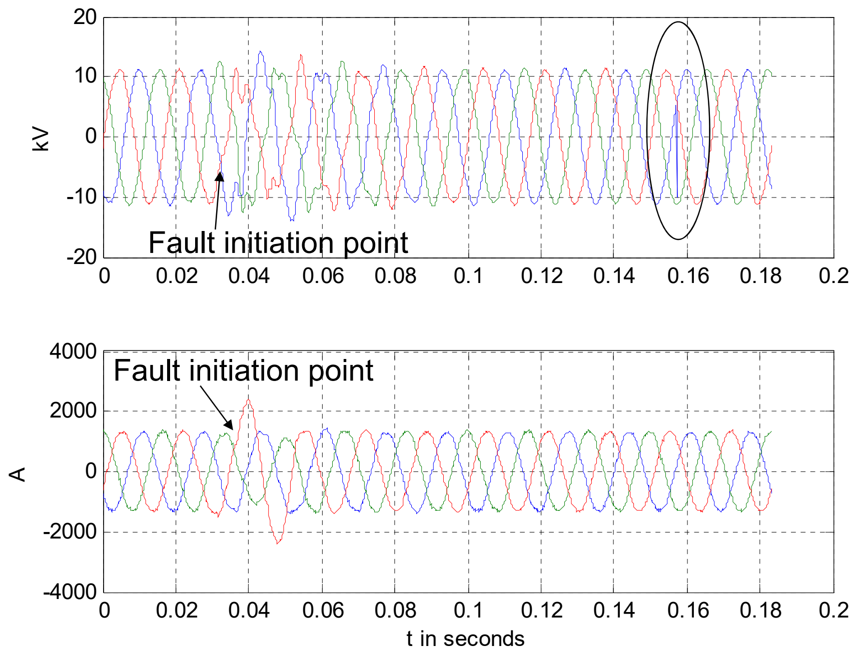
One ½-cycle fault

Samples of Incipient Cable Fault Waveforms (2)



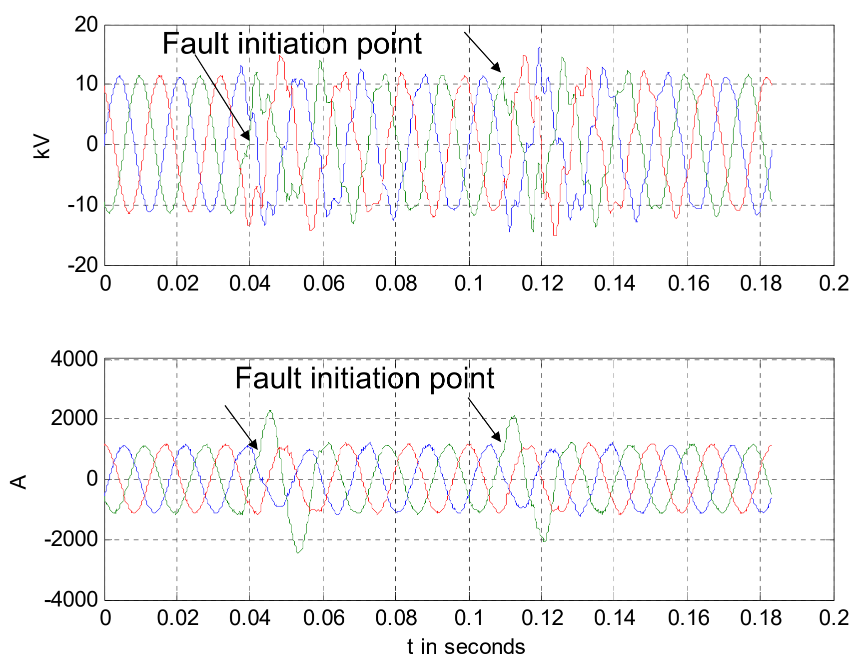
Two ½-cycle faults

Samples of Incipient Cable Fault Waveforms (3)



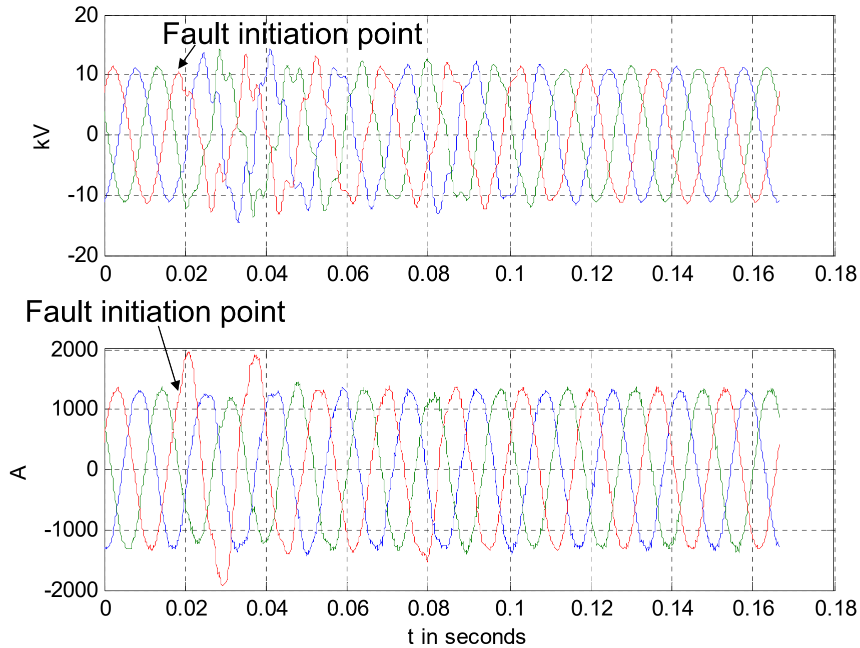
One 1-cycle fault

Samples of Incipient Cable Fault Waveforms (4)



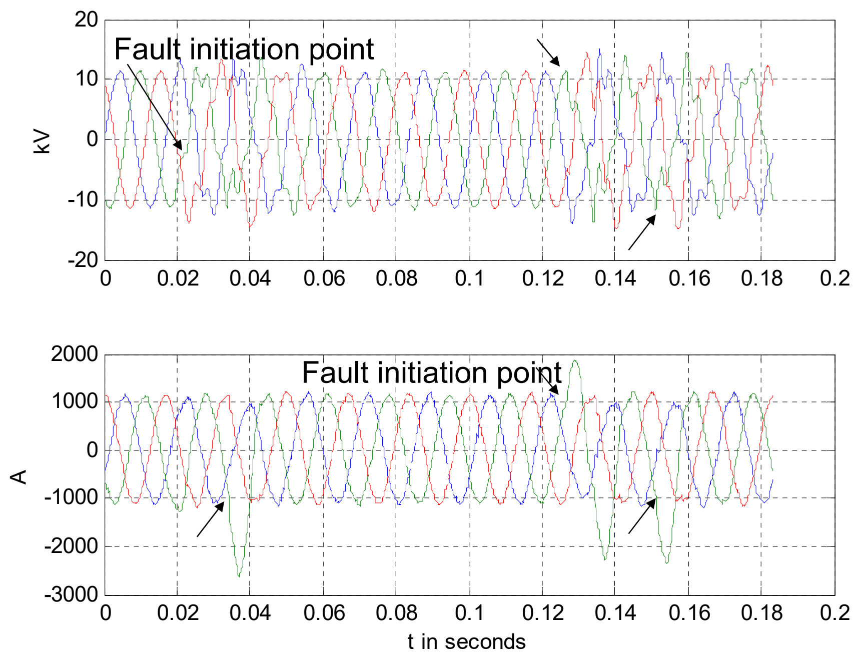
Two 1-cycle faults

Samples of Incipient Cable Fault Waveforms (5)



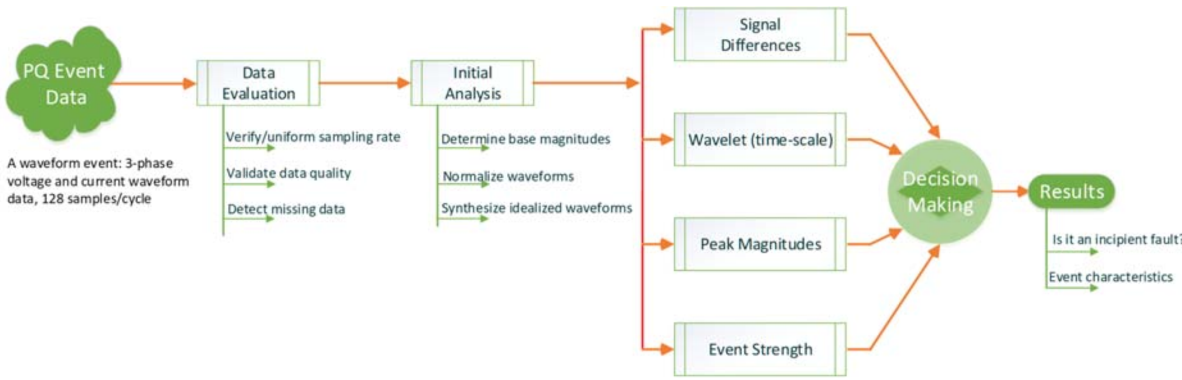
One 1½-cycle fault

Samples of Incipient Cable Fault Waveforms (6)

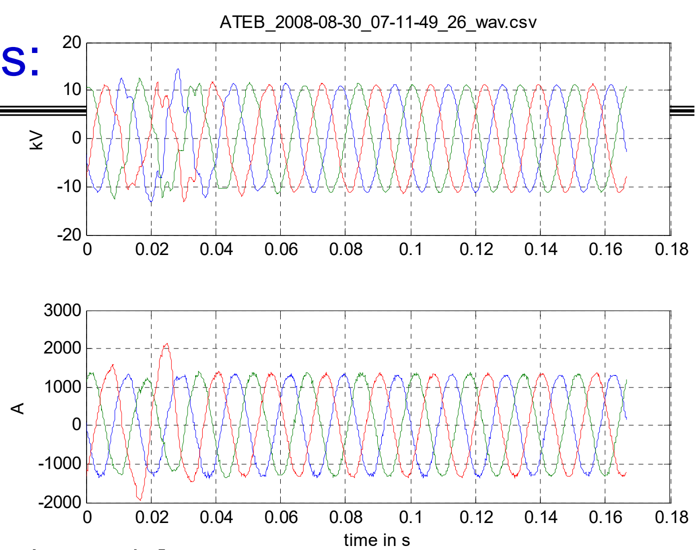


Multiple faults

Detection Algorithms

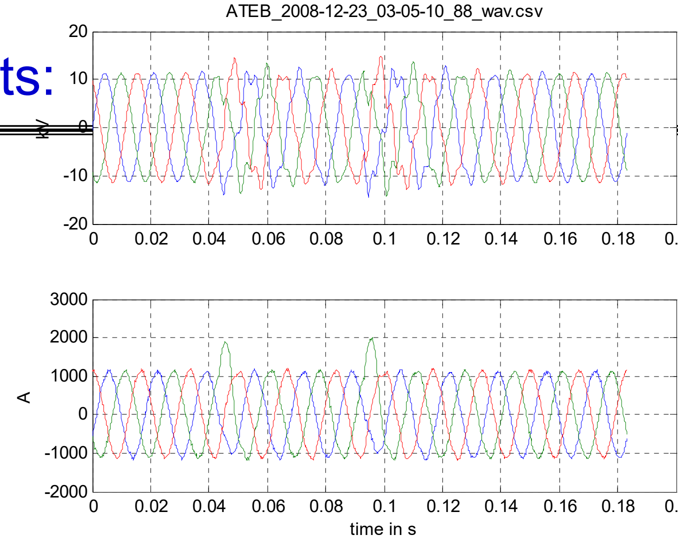


Detection Outputs:



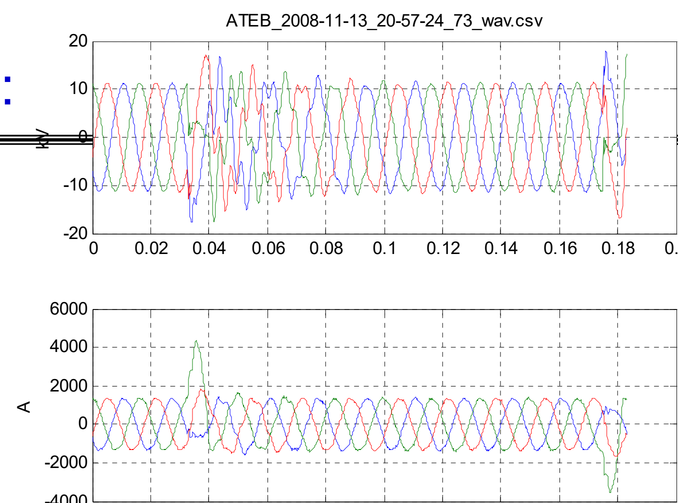

```
Incipient Cable Fault Detection Module
Event filename: ATEB_2008-08-30_07-11-49_26_wav.csv
The event is an incipient cable fault - with high confidence
Incipient fault is on Phase C
Number of incipient faults = 1
Time of Event #1 = 0.017318 s, duration is 0.8125 cycle
Peak fault current = 2147.8271 A
Increase in current during fault = 993.2048 A
```

Detection Outputs:



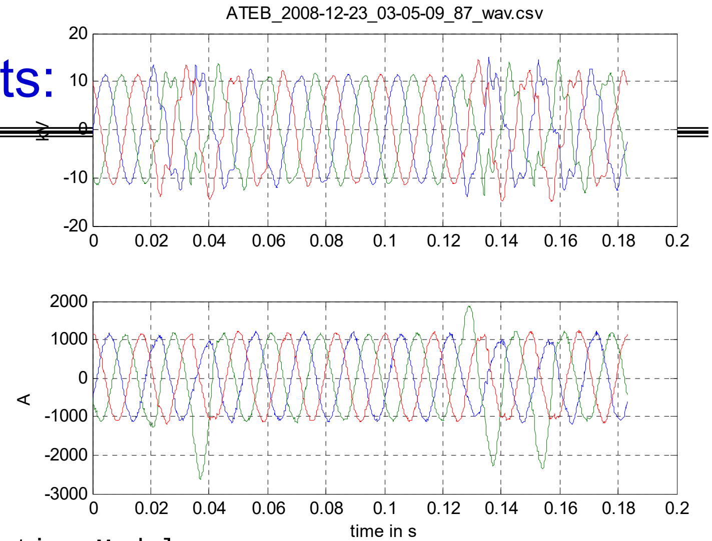

```
Incipient Cable Fault Detection Module
Event filename: ATEB_2008-12-23_03-05-10_88_wav.csv
The event is an incipient cable fault - with high confidence
Incipient fault is on Phase B
Number of incipient faults is 2 or more
Time of Event #1 = 0.096484 s, duration is 0.3125 cycle
Peak fault current = 2003.1738 A
Increase in current during fault = 1079.509 A
Time of event #2 = 0.046745 s, duration is 0.29688 cycle
Peak fault current = 1895.1416 A
Increase in current during fault = 1001.9745 A
```


Detection Outputs:



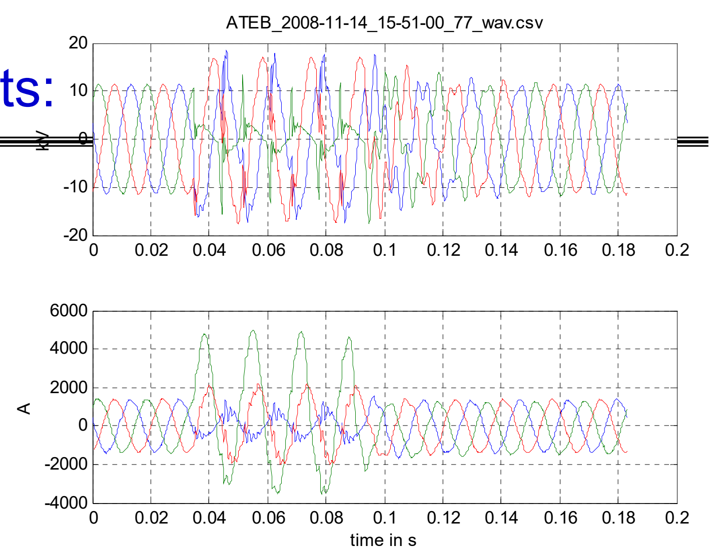

```
Incipient Cable Fault Detection Module
Event filename: ATEB_2008-11-13_20-57-24_73_wav.csv
The event is an incipient cable fault - with moderate confidence
Incipient fault is on Phase B
Number of incipient faults is 2 or more
Time of Event #1 = 0.036068 s, duration is 0.45313 cycle
Peak fault current = 4374.3896 A
Increase in current during fault = 3577.142 A
Time of event #2 = 0.17786 s, duration is 0.48438 cycle
Peak fault current = 3570.5566 A
Increase in current during fault = 2899.3777 A
```

Detection Outputs:




```
Incipient Cable Fault Detection Module
Event filename: ATEB_2008-12-23_03-05-09_87_wav.csv
The event may be an incipient cable fault
Incipient fault is on Phase B
Number of incipient faults is 2 or more
Time of Event #1 = 0.037109 s, duration is 0.5 cycle
Peak fault current = 2647.7051 A
Increase in current during fault = 1575.8072 A
Time of event #2 = 0.15443 s, duration is 0.44531 cycle
Peak fault current = 2349.2432 A
Increase in current during fault = 1380.9309 A
```


Detection Outputs:

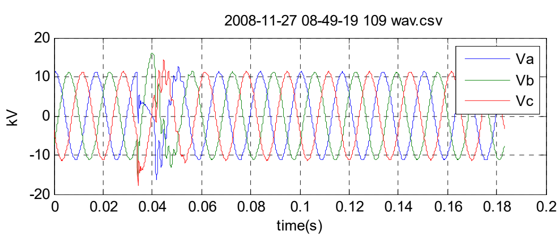


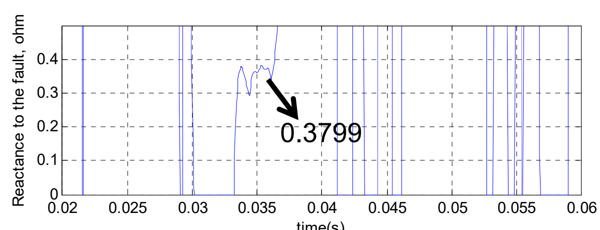

```
Incipient Cable Fault Detection Module
Event filename: ATEB_2008-11-14_15-51-00_77_wav.csv
The event is not an incipient cable fault
```

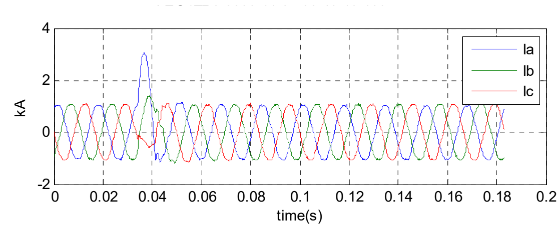
Pre-locating Self-clearing Faults

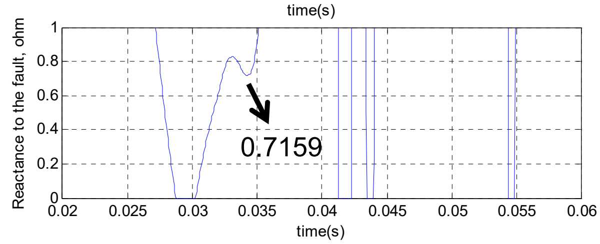
- Develop an algorithm to estimate locations of temporary ¼-to-½ cycle self-clearing faults in cables.
  - The algorithm attempts to “pre-locate” self-clearing faults before an actual fault occurs – hence a term “pre-locating self-clearing faults.”
- Typical fault location methods are not effective as they require longer fault duration.
- Try arc voltage methods

Application to Pre-Locating Cable Faults: Failing Cable - Precursor Event #1



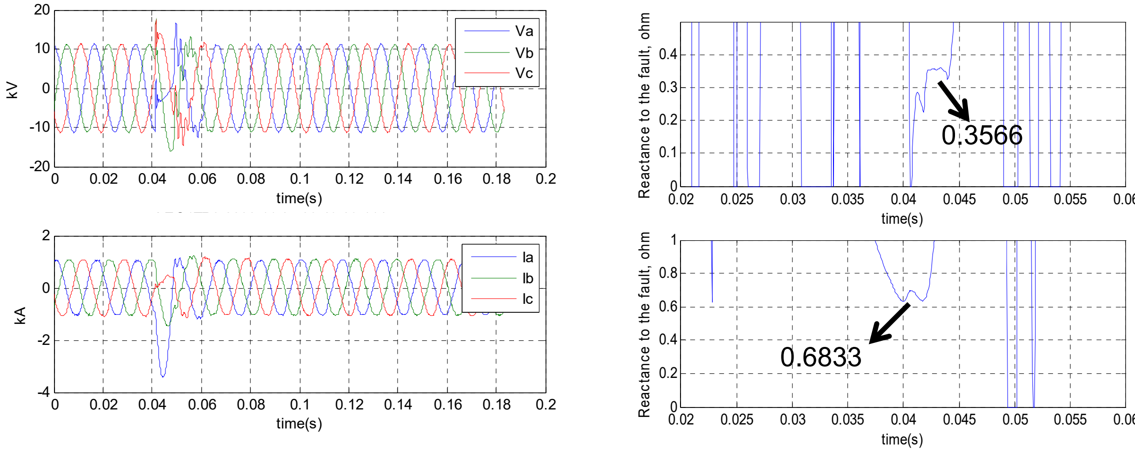






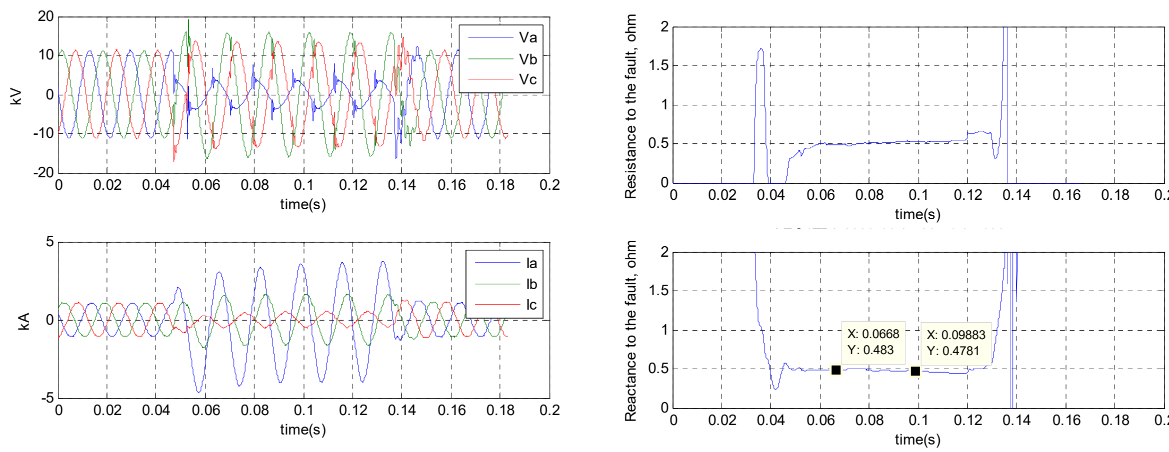
Low estimate is 0.3799 ohm
High estimate is 0.7159 ohm

Application to Pre-Locating: Failing Cable - Precursor Event #2



Low estimate is 0.3566 ohm
High estimate is 0.6833 ohm

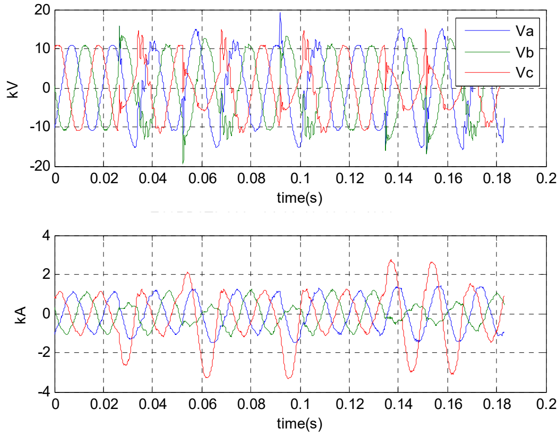
Application to Pre-Locating: Failing Cable – Resulted in an actual fault following Precursor #2

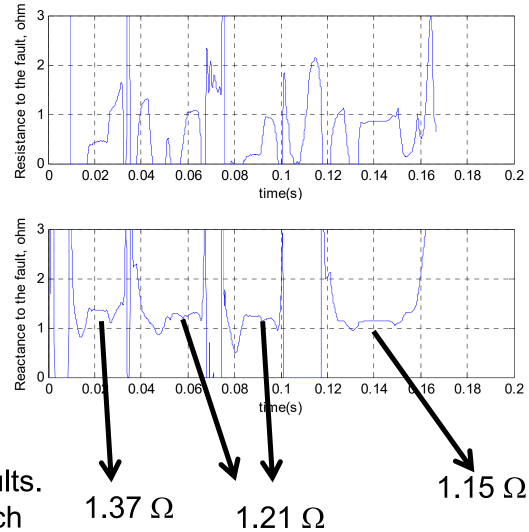


Actual cable fault – cleared by an overcurrent protective device.
Reactance to fault is 0.483 ohms

Incipient fault location algorithm for underground cables
S Kulkarni, S Santoso, TA Short
IEEE Transactions on Smart Grid 5 (3), 1165-1174

Estimating Location of Incipient Faults





There are multiple ½-cycle self-clearing faults. Reactance estimates are consistent for each self-clearing and 'sustained' fault.

Error Estimates

TABLE IV
REACTANCE TO FAULT ESTIMATES FOR EVENTS SHOWN IN FIG. 14

Event	*Mean Reactance Estimate(Ω)*	*Absolute Error(Ω)*	*Absolute Error(%)*
Self-Clearing Fault 1	0.954	0.092	8.80
Self-Clearing Fault 2	1.004	0.042	4.02
Self-Clearing Fault 3	1.033	0.013	1.24
Average		0.049	4.69
Permanent Fault	1.046	N/A	N/A

TABLE V
REACTANCE TO FAULT ESTIMATES FOR EVENTS CAPTURED BY PQ MONITOR

Event	*Mean Reactance Estimate(Ω)*	*Absolute Error(Ω)*	*Absolute Error(%)*
Self-Clearing Fault 1	0.6460	0.0064	11.05
Self-Clearing Fault 2	0.5740	0.0077	1.32
Self-Clearing Fault 3	0.5775	0.0042	0.72
Self-Clearing Fault 4	0.5888	0.0071	1.21
Average		0.0208	3.58
Permanent Fault	0.6125	0.0308	5.29

D. A Note on Error in Incipient Fault Location

The algorithm developed in this paper is specifically intended for application with underground cables. The objective is to detect incipient faults and repair the cable before a full-blown permanent fault occurs. The only access the utility crew has to underground cables is through manholes. The typical distance between two manholes is a maximum of 500 ft [26]. In urban areas, which predominantly have underground power cable networks; manholes are located at every street intersection. Hence, the job of the algorithm is to predict the cable fault location such that it lies between two adjacent manholes. In other words, the fault location error percentage value is not the direct representation of the accuracy and effectiveness of the proposed method. Even if the error value is slightly higher in some cases, as long as the algorithm is able to pinpoint the location of an incipient fault between two adjacent manholes, the necessary repairs can be carried out to prevent a permanent cable fault.