

# **Automated Capacitor Bank Health Analysis Using Waveform Event Data from PQMs and DFRs**

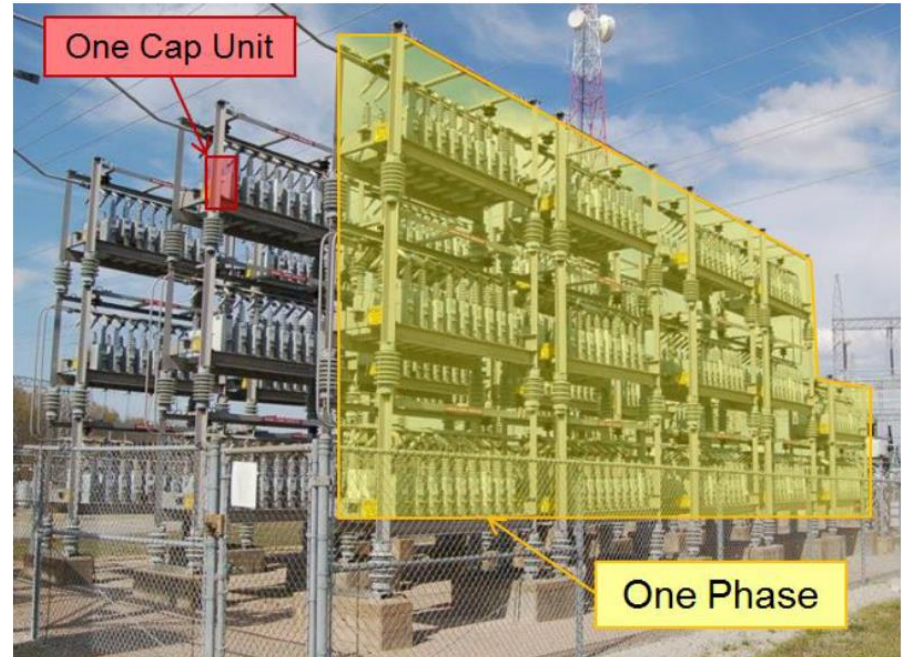
# Cap Bank Monitoring

Tony Murphy, TVA

# PQ Monitoring of Capacitor Banks

## Why Cap Bank Monitoring?

- An Aging Fleet
- Nuisance Trips
- Excessive CMs
- Catastrophic Failures
- Reportable Mis-ops
- Out of Service when Needed
- Tens of Thousands of Cap Units and Fuses



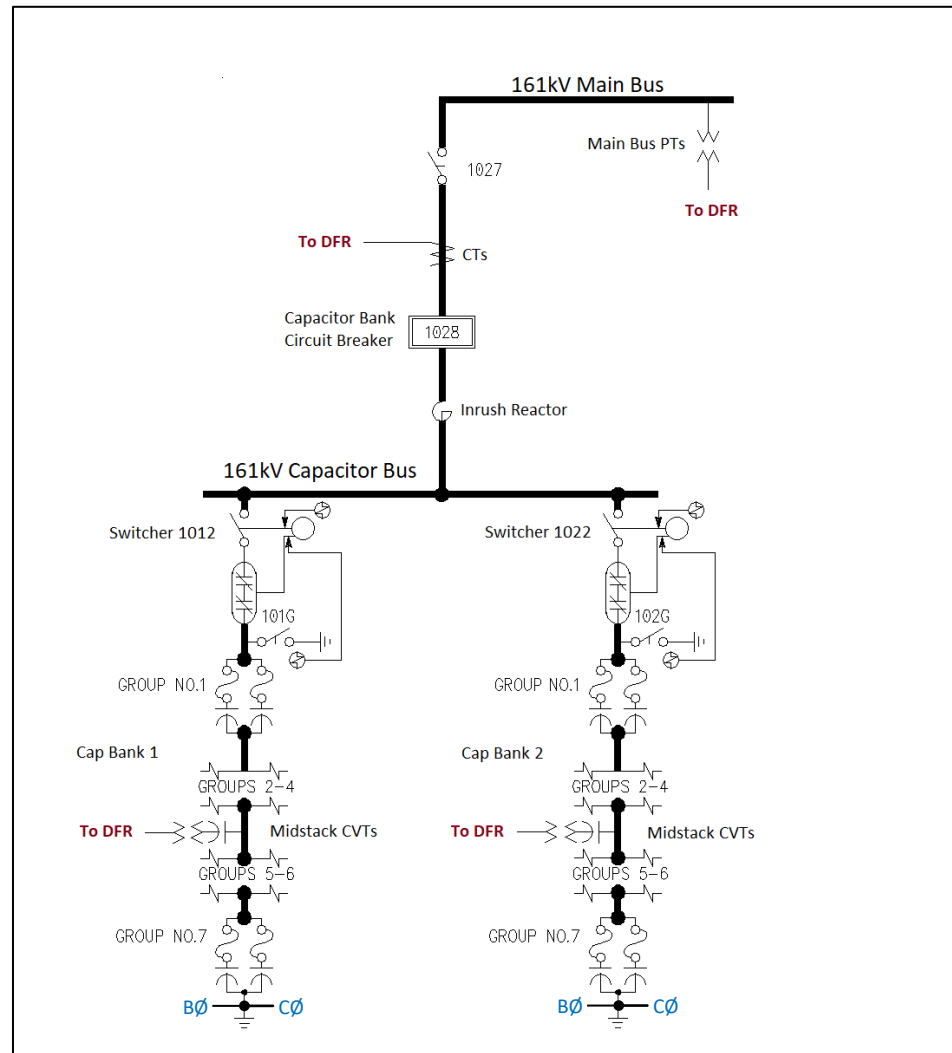
# Data Analytics

Analytic	Equipment				
	Circuit Breaker	Circuit Switcher	Bus PTs	Capacitor Bank	Protection System
Timing	X	X			
$i^2t$	X	X			
Restrike	X	X			
Transient Overvoltage	X	X			
Missing Pole	X	X			
Voltage Closing Control	X	X			
Preinsertion Type	X	X			
Alignment		X			
Loss of Signal			X		
Incipient Failure			X		
Loose Fuses			X		
Chattering Relays			X		
Voltage Step Change				X	
Voltage Regulation				X	
Harmonic Resonance				X	
Current Exceedance				X	
Switching Frequency				X	
Blown Fuses				X	
Shorted Elements				X	
Voltage Unbalance					X
Control Voltage Integrity					X
Disabled Protection					X
Relay Configuration / Readings					X

# Cap Design 1: Externally Fused (Pre 1990)

PQM / DFR Inputs:

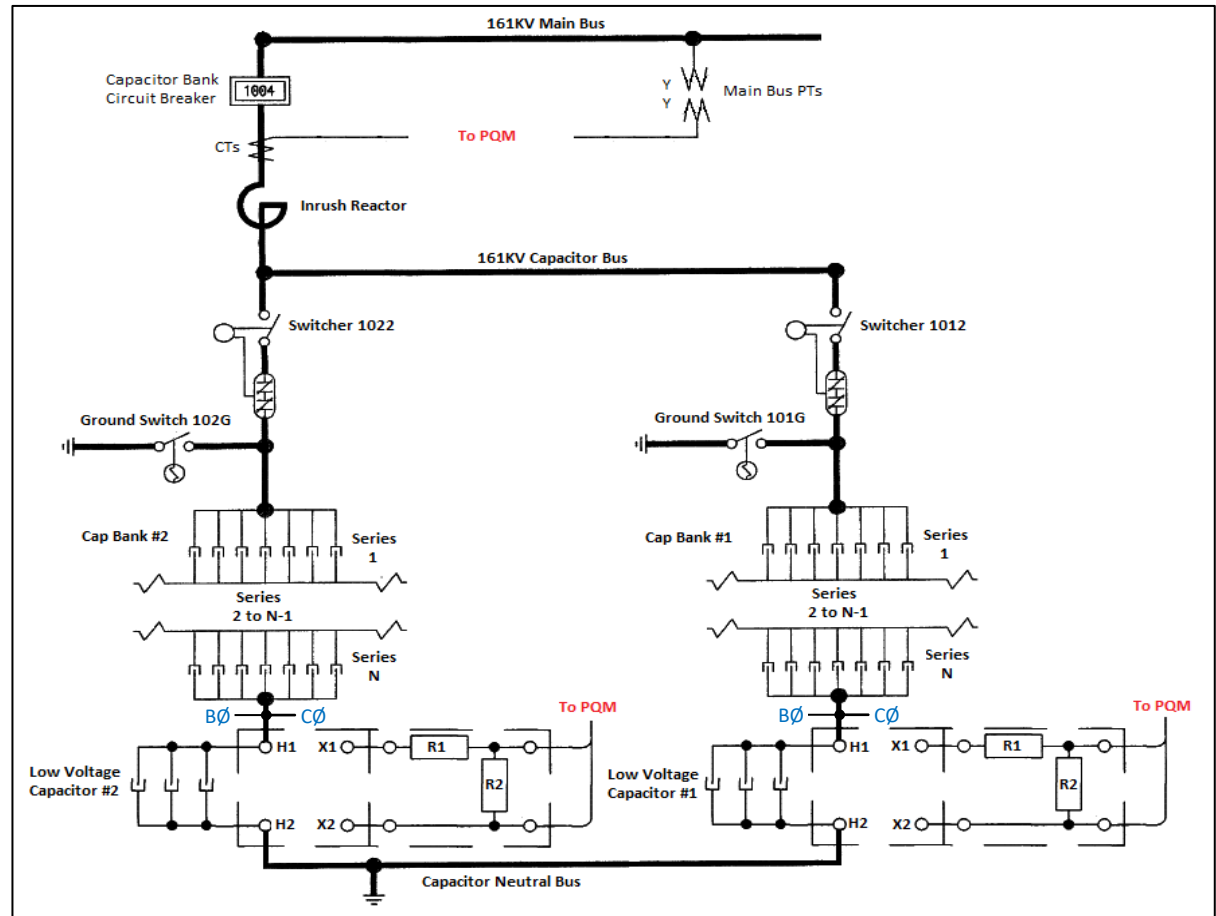
- Main Bus Voltages
- Cap Bank Breaker Currents
- Mid-stack Voltages
- Digital Status of Cap Circuit Switchers



# Cap Design 2: Fuseless Uncompensated (1990 – 2000)

PQM / DFR Inputs:

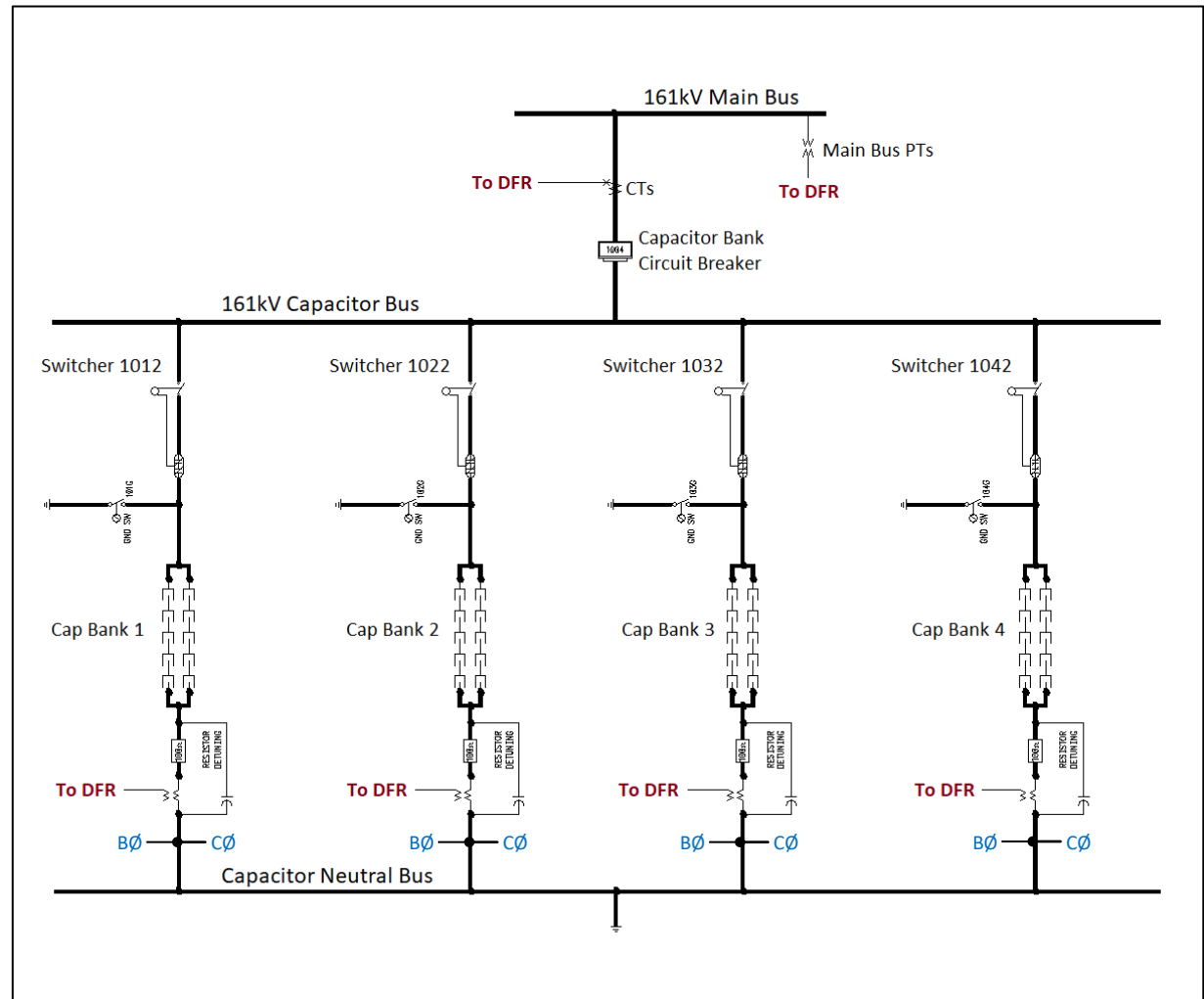
- Main Bus Voltages
- Cap Bank Breaker Currents
- Cap Bank Relay Control Voltages
- Digital Status of Cap Circuit Switchers



# Cap Design 3: Fuseless Compensated (Post 2000)

PQM / DFR Inputs:

- Main Bus Voltages
- Cap Bank Breaker Currents
- Cap Bank Relay Control Voltages
- Digital Status of Cap Circuit Switchers

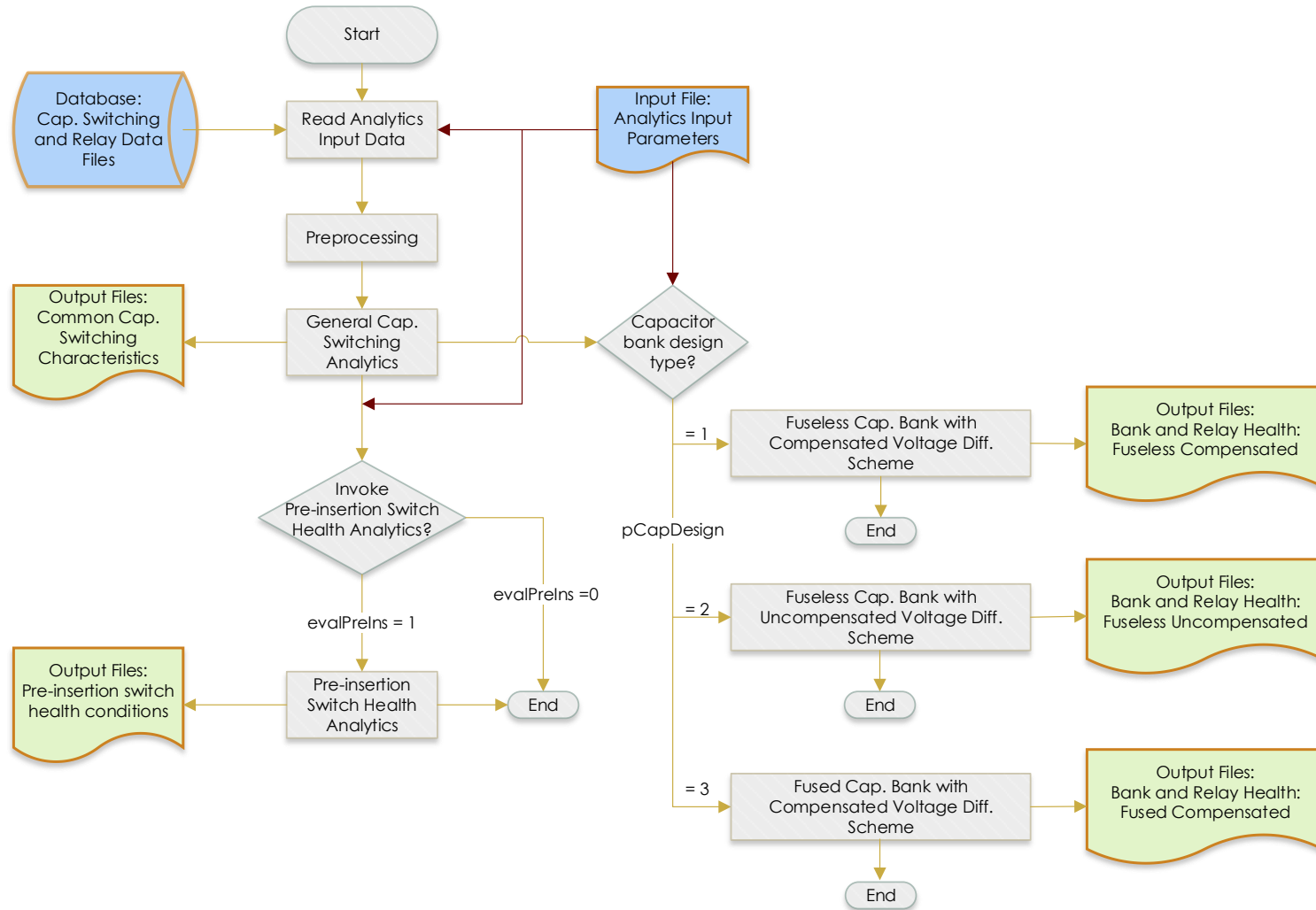


# Matlab Analytic Development

Dr. Surya Santoso, University of Texas



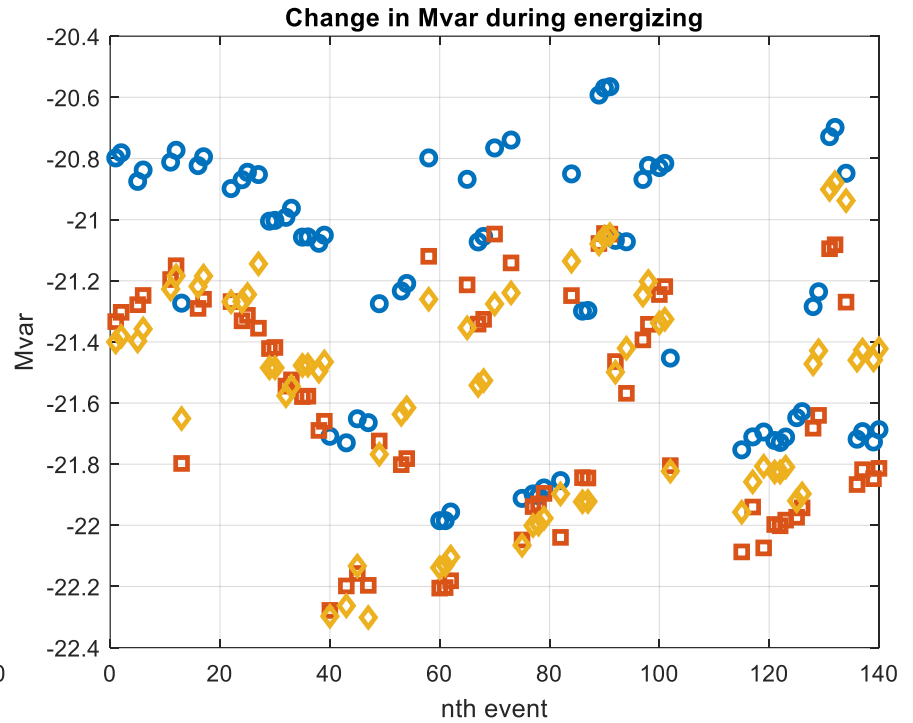
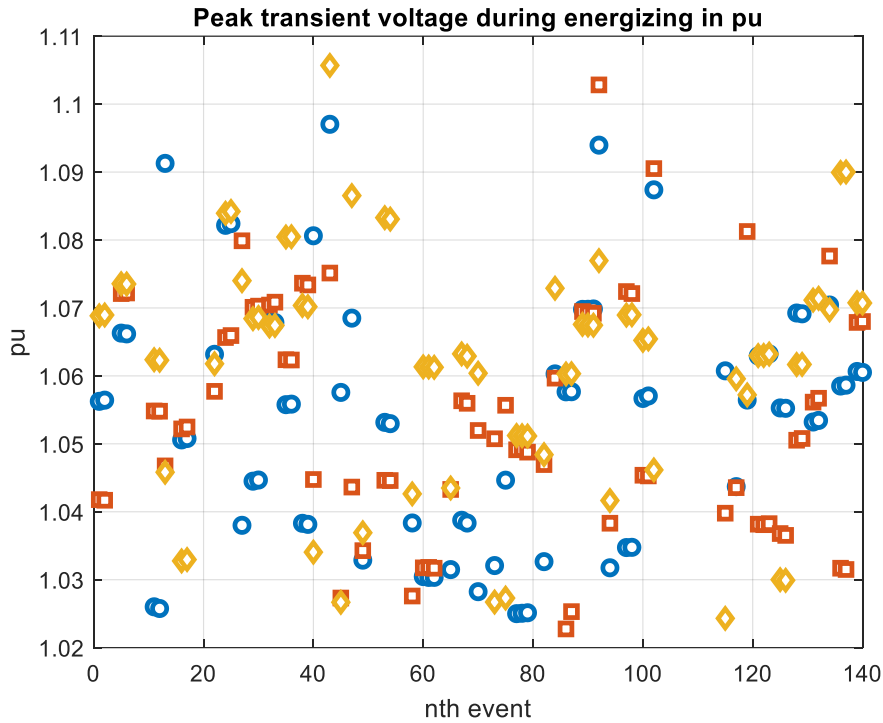
# Capacitor Bank and Relay Health Analytics: Flow Diagram



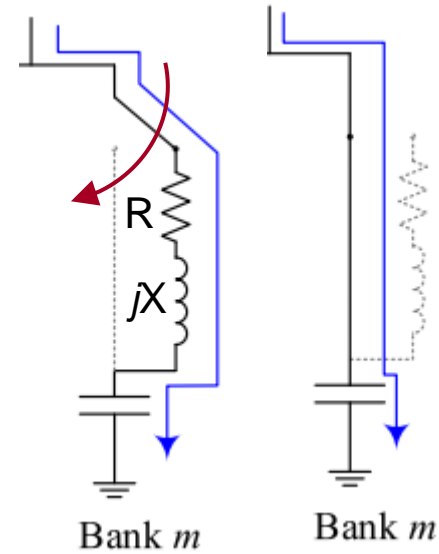
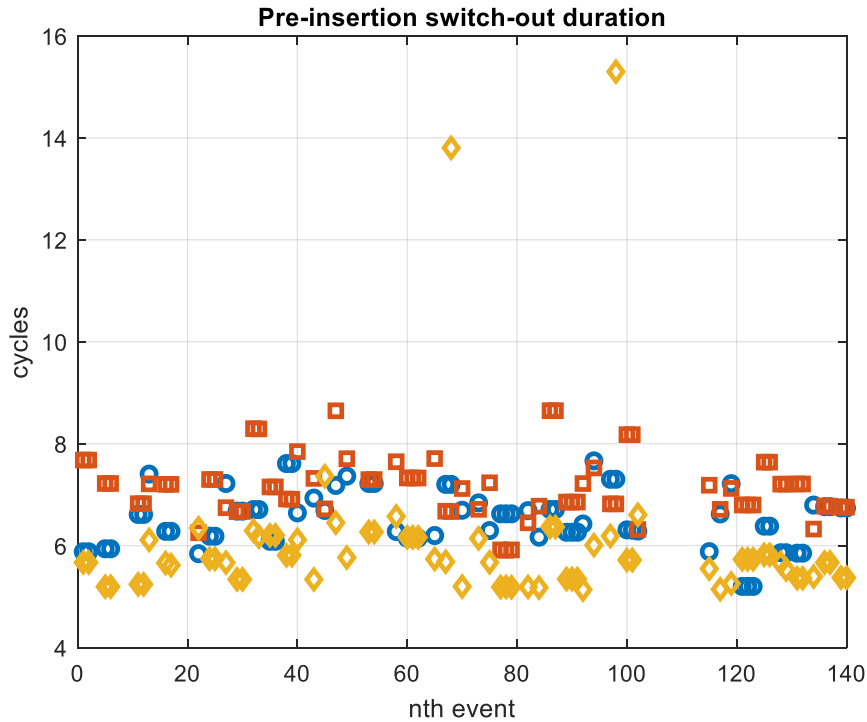
# Module data input formats and other requirements: Input parameters must be prepared in a separate txt file

```
6 Specify the directory where cap bank events are stored
7 1 dataDir = G:\My Drive\aaHome\Active Projects\CapAnalyticsTVA\Data_TVA\Compensated\
8 Specify the directory where cap. health analysis results will be stored. It cannot be in dataDir
9 3 resultDirName = G:\My Drive\aaHome\Active Projects\CapAnalyticsTVA\AppDev\UnBalProt
10 Specify the capacitor bank keyword used in the cap bank file names
11 5 fileKeyCapEvents = Tazewell TN 161-B1004-Caps
12
13 Specify the analysis period
14 7 start date; fDateStartInputStr = 2019-08-01
15 8 end date; fDateEndInputStr = 2019-08-07
16
17 Specify cap bank data
18 10 number of banks; numBanks = 3
19 11 nominal bus voltage in kV line-to-line; nominalBuskVLL = 161
20 12 capacitor step size; StepSizeQ3kvar = 18e3
21 13 type of the circuit switcher (0 for no control, 1 for pre-ins, 2 for sync closing); capSwitcherTypeMultBanks = [1 0 1]
22
23 Specify cap bank measurement requirements
24 15 fundamental frequency; fundf = 60
25 16 sampling rate for voltage; svNSPC = 512
26 17 sampling rate for current; siNSPC = 512
27 18 no-voltage threshold for voltage waveforms in V; noBusVoltage = 500
28 19 no-current threshold for current waveforms in A; noBusCurrent = 4.0
29 20 the upper limit (in percent) to detect harmonic resonance; iTHDLimit = 5.5
30
31 Specify capacitor configuration data
32 22 bank max operating voltage in kV; bankMCOV = 166
33 23 rated kvar of a capacitor unit; capUnitRatedkvar = 600
34 24 rated kV of a capacitor unit; capUnitRatedkV = 19.1
35 25 the number of parallel strings of capacitor units connected in series; Nps = 2
36 26 the number of capacitor units connected in series in each parallel string; Nus = 5
37 27 the number of series groups of capacitor elements connected in parallel in each capacitor unit; Nesg = 10
38 28 the number of capacitor elements connected in parallel in each series group in each capacitor unit; Negp = 3
39
40 Specify relay data inputs and requirements
41 30 Offset time between cap bank and relay time stamps; dTOffset = 1
42 31 Rated relay voltage in V; ratedRelayVoltage = 251
43 32 No voltage for relay; noRelayVoltage = 1.0
44 33 Bus VT ratio; busVT = 1400
45
46 Specify relay capacitor configuration
47 35 the number of relay capacitor; NLVcapUnit = 1
48 36 the number of elements; NLVcapE = 28
49 37 low-voltage capacitor size for capacitor bank relaying; LVcapUnitRatedkvar = 167
50 38 rated voltage of the low-voltage capacitor; LVcapUnitRatedV = 825
51 39 relay PT ratio, high to low; relayPTR = [800 250]
52
53 Specify relay keywords
54 41 fileKeyRelay4Cap{1} = Tazewell TN 161-Cap 1 Relay
55 42 fileKeyRelay4Cap{2} = Tazewell TN 161-Cap 2 Relay
56 43 fileKeyRelay4Cap{3} = Tazewell TN 161-Cap 3 Relay
57
```

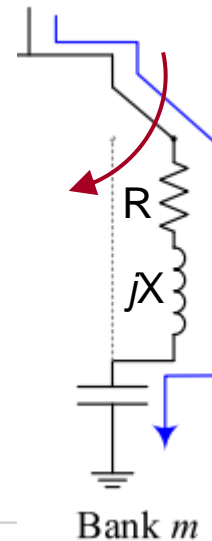
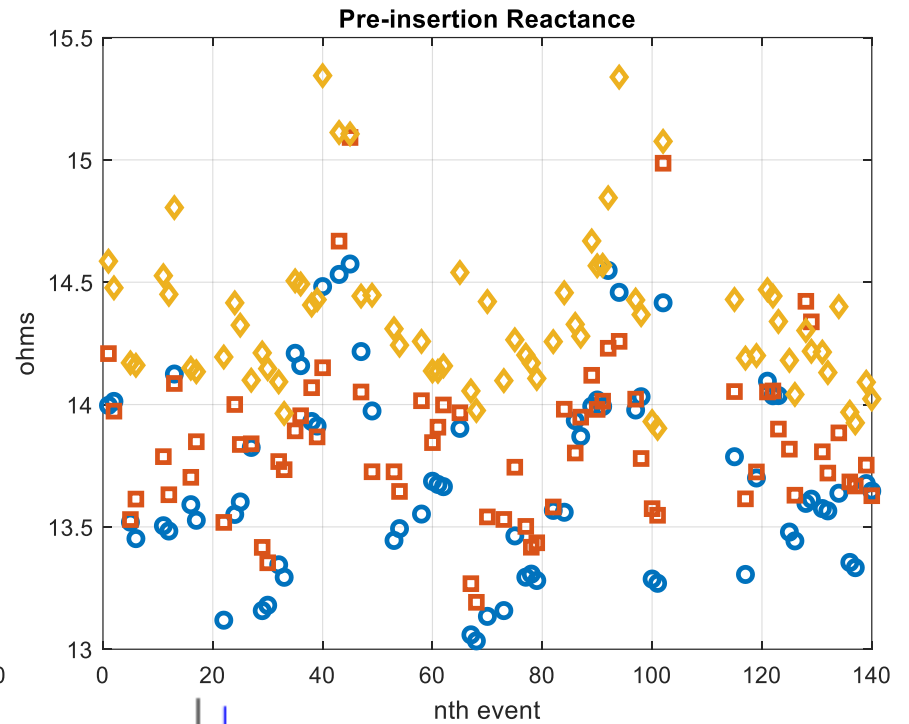
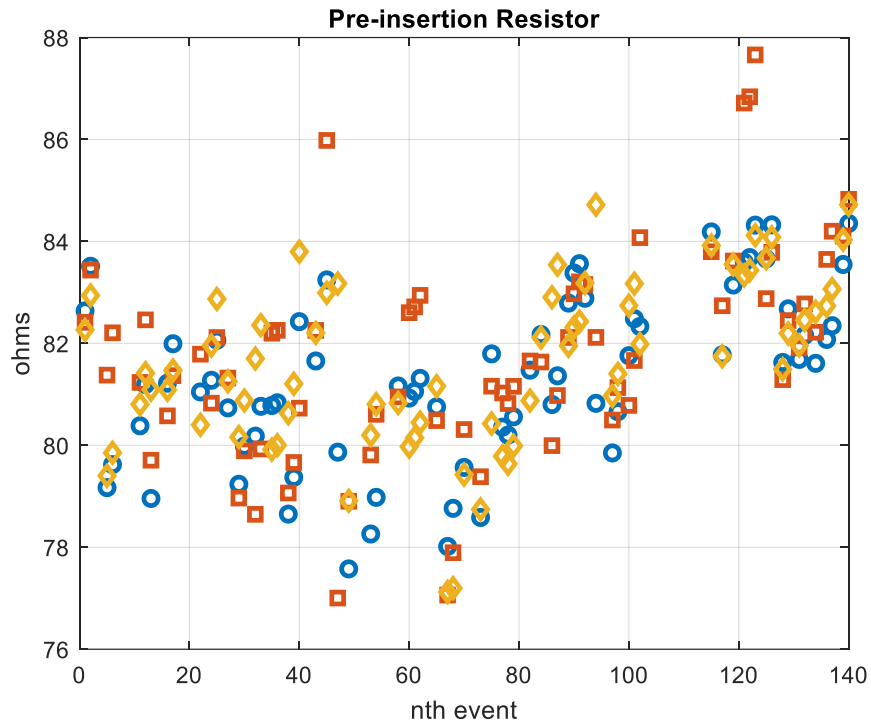
# General Cap Energizing Characteristics: Peak Voltage and Mvar Change



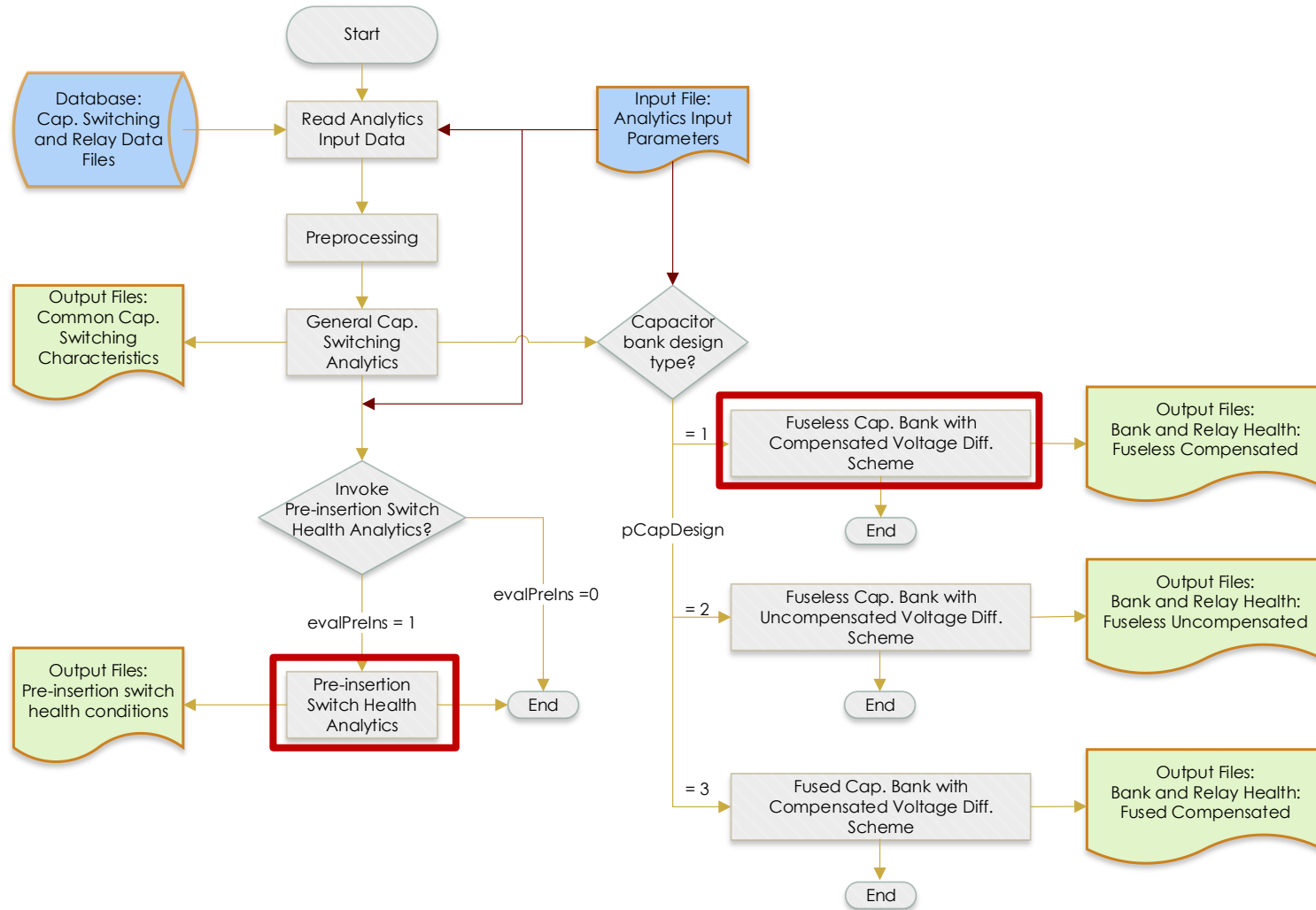
# Pre-insertion Circuit Switcher Health Analytics



# Pre-insertion Circuit Switcher



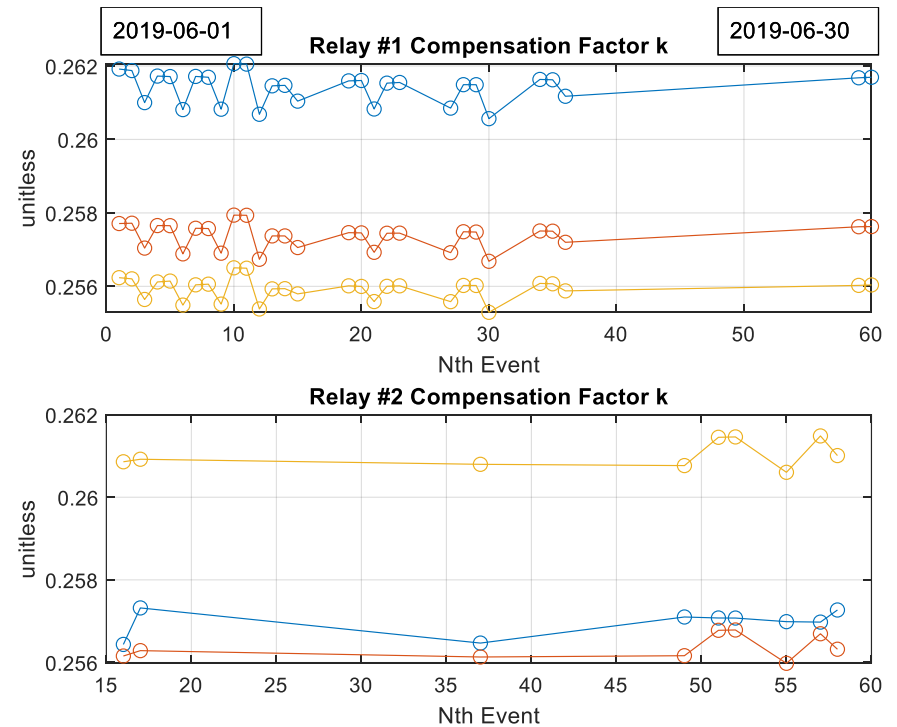
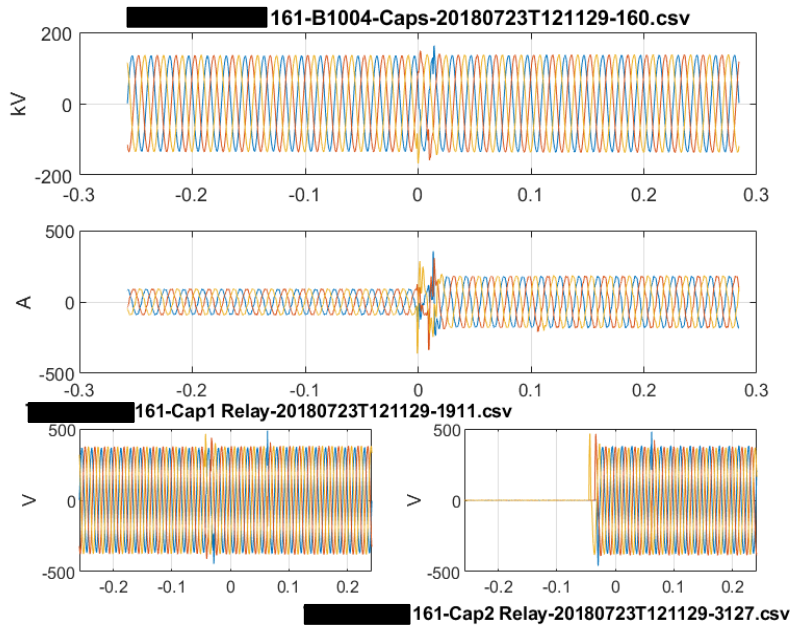
# Capacitor Bank and Relay Health Analytics: Flow Diagram



# Cap. Health Analytics: Compensated Voltage Differential Scheme (Fuseless Cap Design); $dV = VX - k VY$

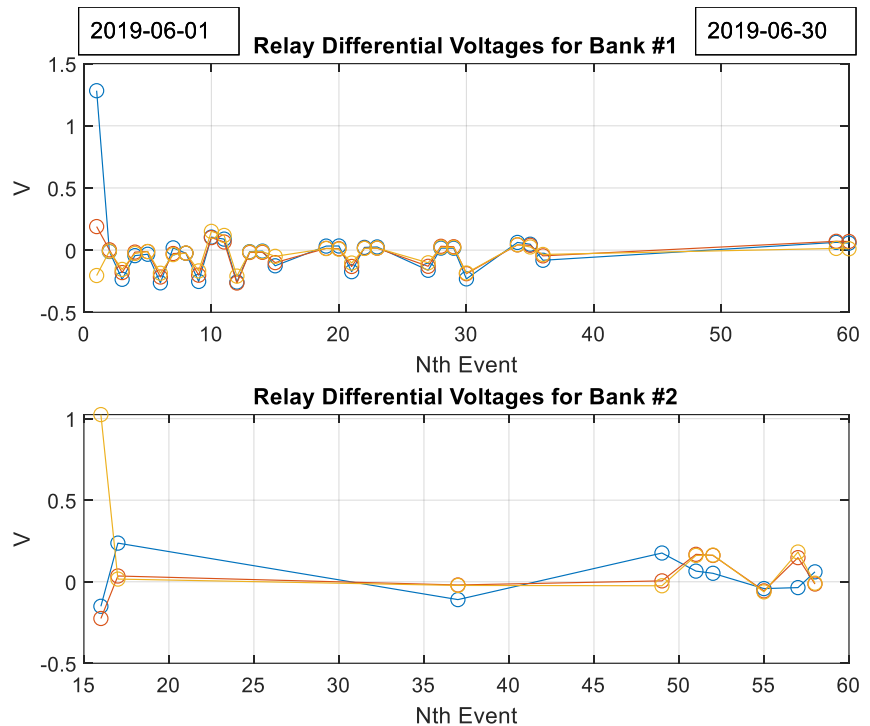
- Differential protection analysis:
  - k factor = the scaled-down bus voltage over relay voltage (in rms) =  $(VX/VY)$ .
  - Compute differential voltage: scaled-down bus voltage – k historical \* relay voltage

- k historical: mean with outliers removed
- Polarity of diff. voltage is preserved



# Differential Voltage

- Initial  $k$  from a relay calculation sheet is only used once.
- Differential voltage fluctuated about zero but less than 0.5 V.
- No shorted elements, per table below.

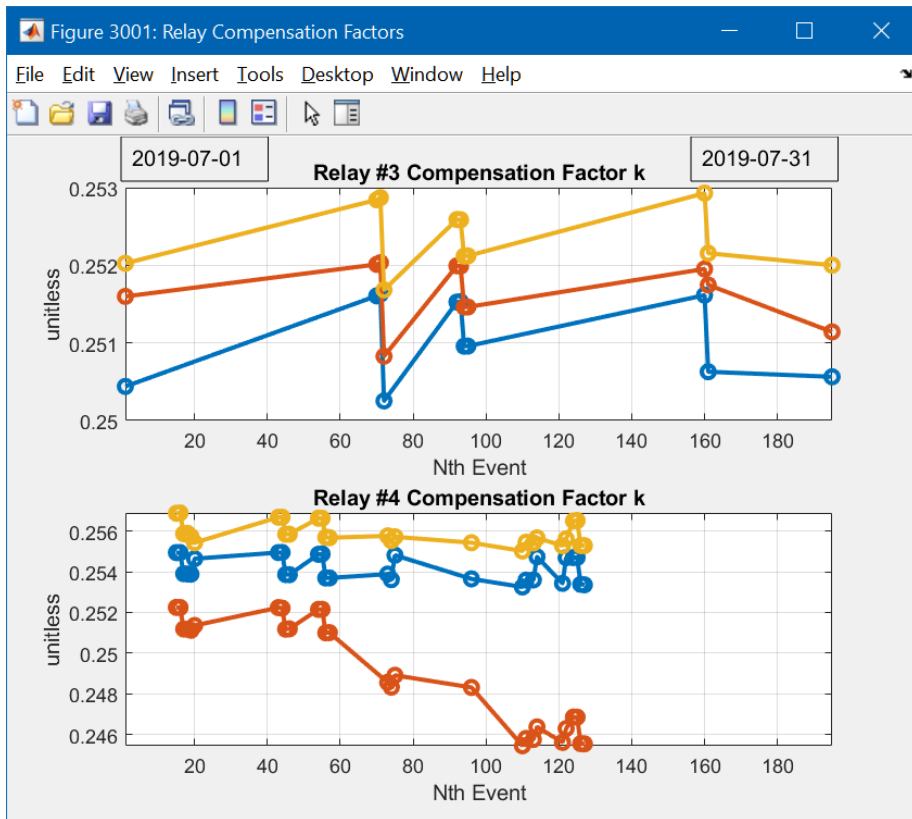
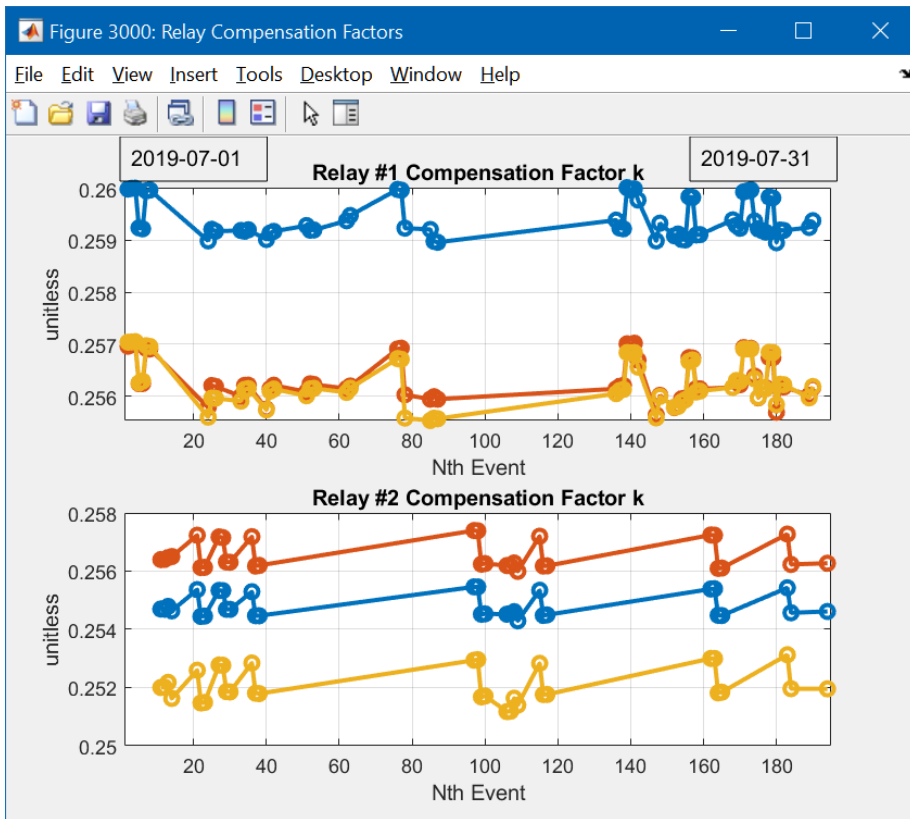


Shorted Capacitor Elements	String per unit capacitance	Affected wye capacitance	Affected phase capacitance	Voltage on affected elements	Impedance of bad unit	Impedance of main capacitors	% Voltage across LV caps	Voltage across LV caps (V)	Secondary voltage to relay (V)	dV
e	Cst	Cy	Cp	Ve	Xbad	Xmain	Vlvcap	Vlvcap	Vrelay	dV
0	1.000	1.000	1.0000	1.00000	3040.08	1520.04	0.267407%	256.28	80.09	0.00
1	1.020	1.010	1.0102	1.02041	2979.28	1504.69	0.270128%	258.89	80.90	0.70
2	1.042	1.021	1.0208	1.04167	2918.48	1489.02	0.272963%	261.61	81.75	1.42
3	1.064	1.032	1.0319	1.06383	2857.68	1473.03	0.275918%	264.44	82.64	2.18



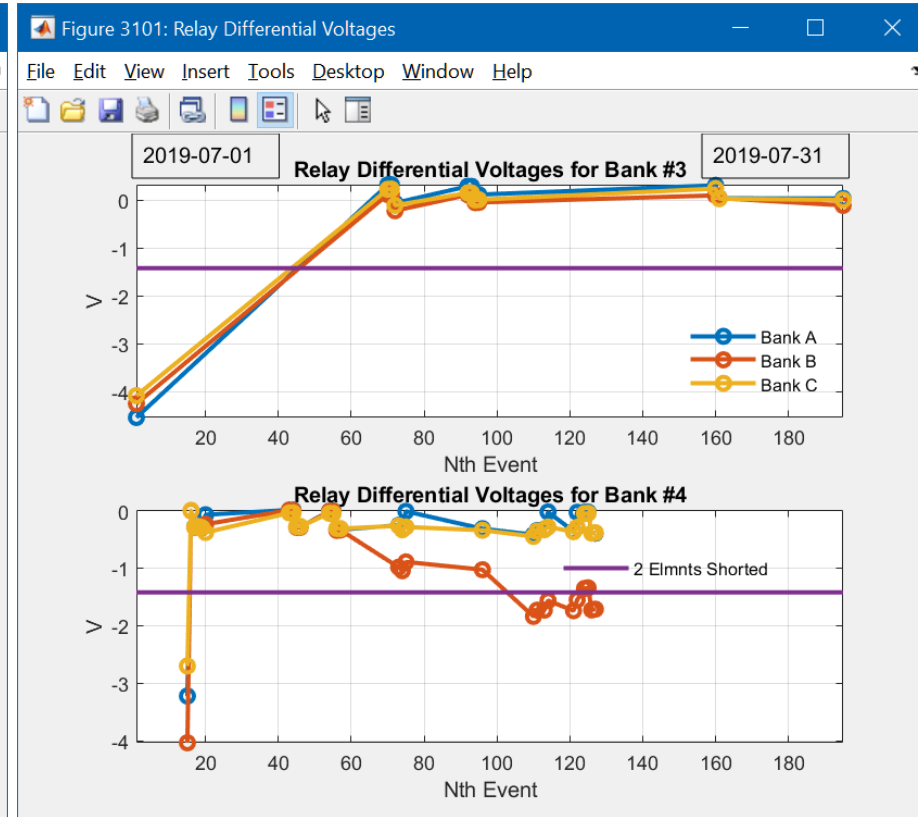
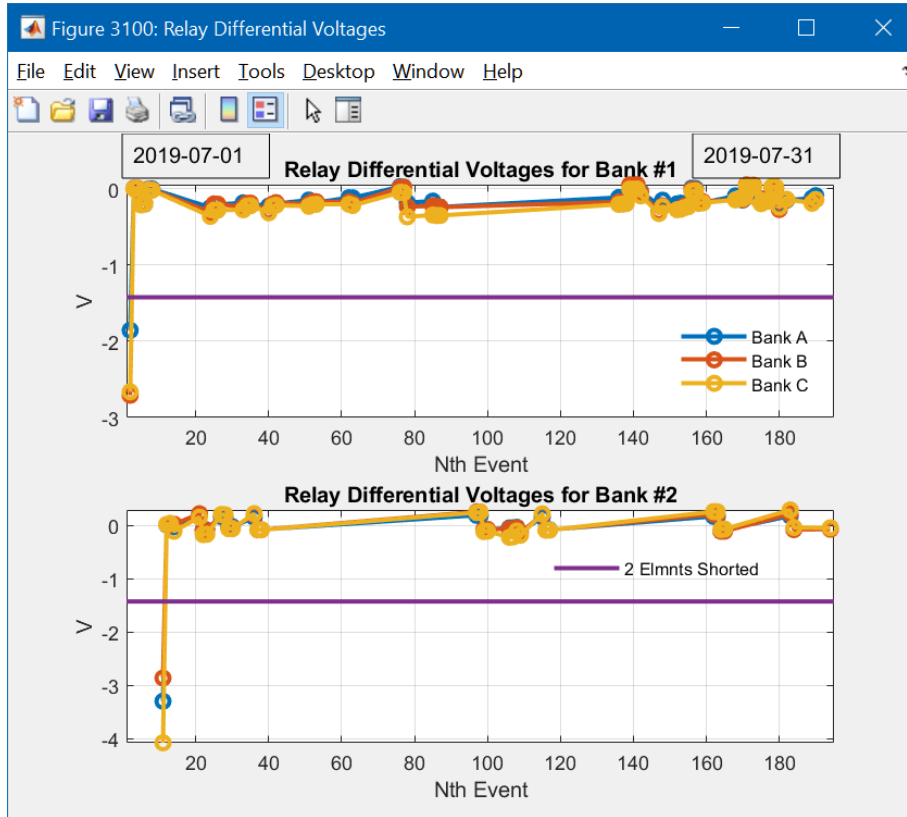
# Four Capacitors in a Substation - July 2019

## Relay Compensation Factors: Relay 1 - 4



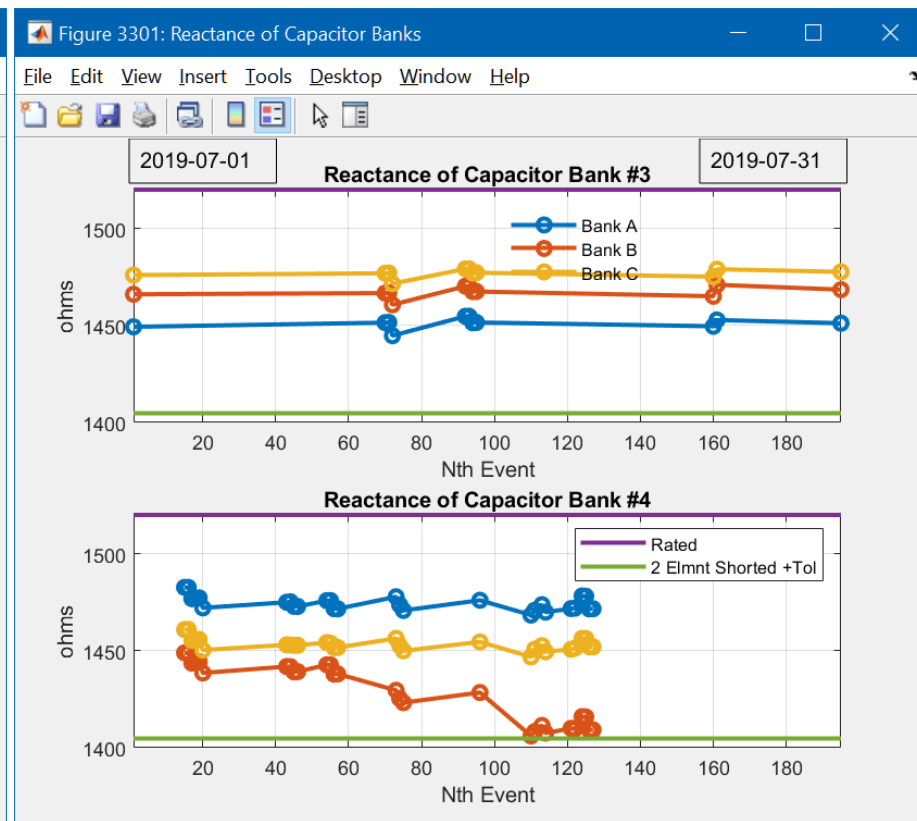
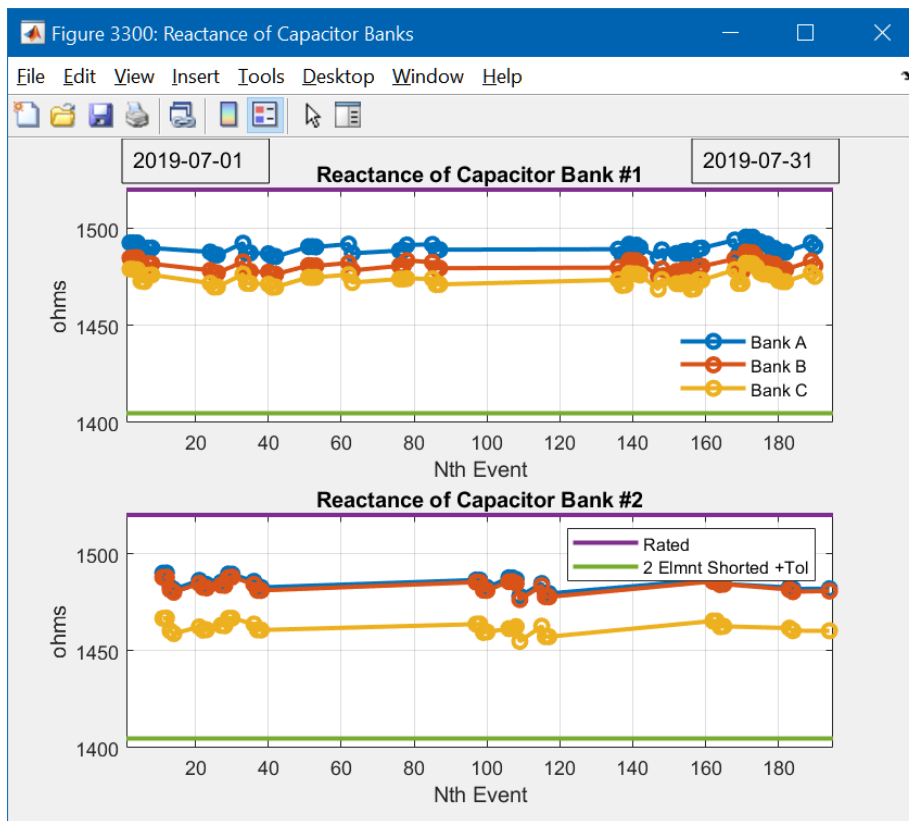
# Four Capacitors in a Substation - July 2019

## Relay Differential Voltages: Relay 1 - 4

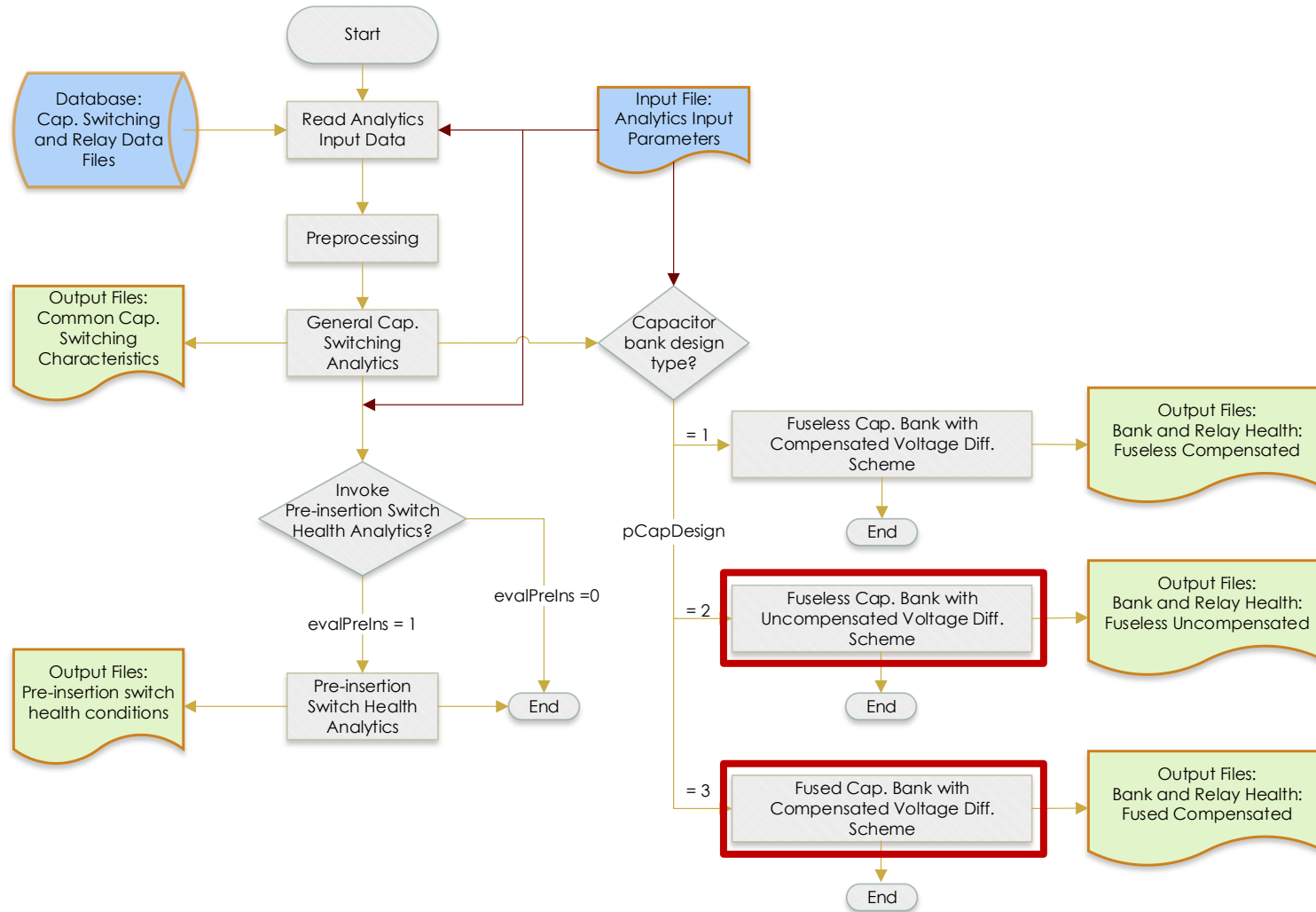


# Four Capacitors in a Substation - July 2019

## Reactance of Capacitor Banks: Bank 1 - 4



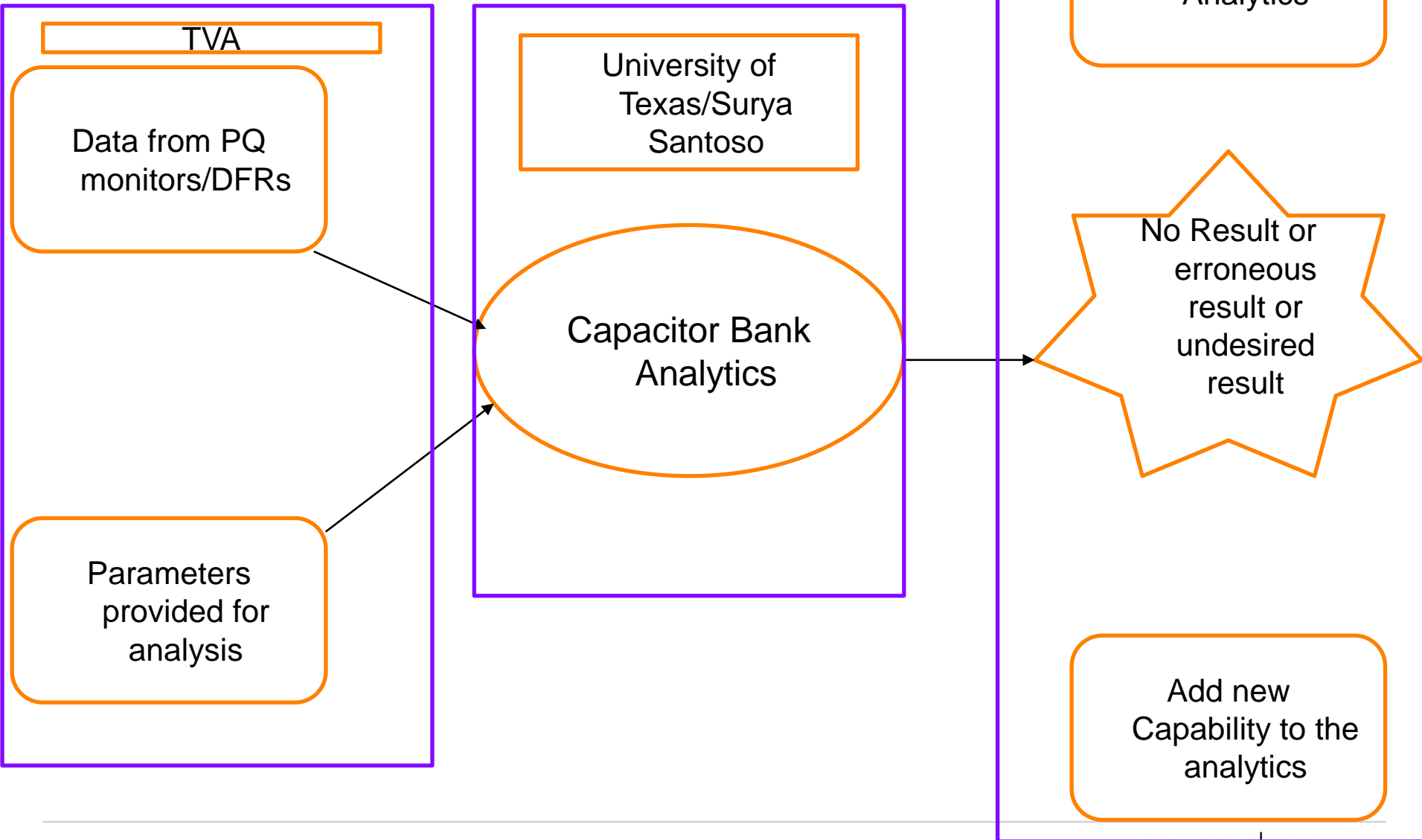
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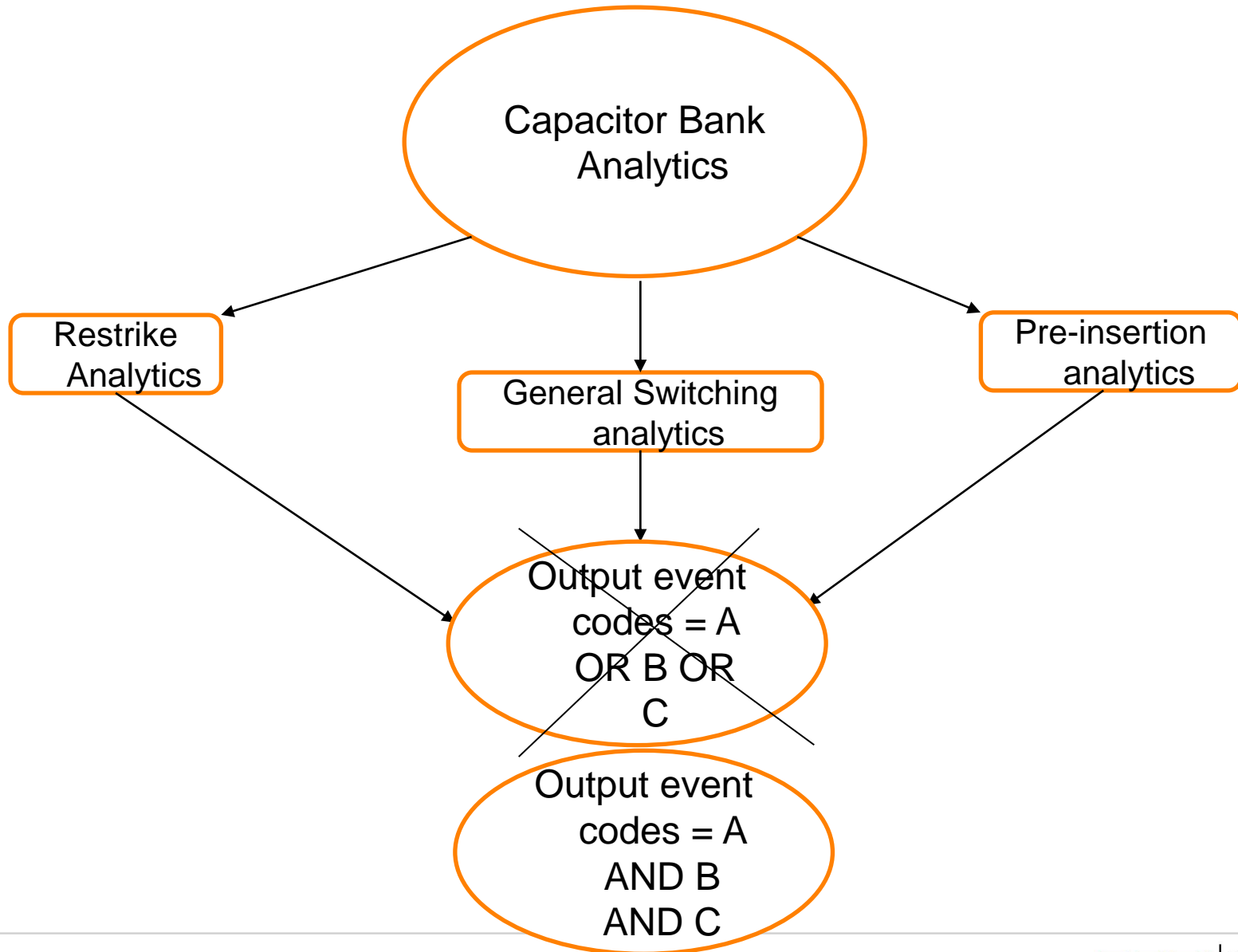
# **EPRI Software Quality Assurance**

**Dr. Gaurav Singh, EPRI**

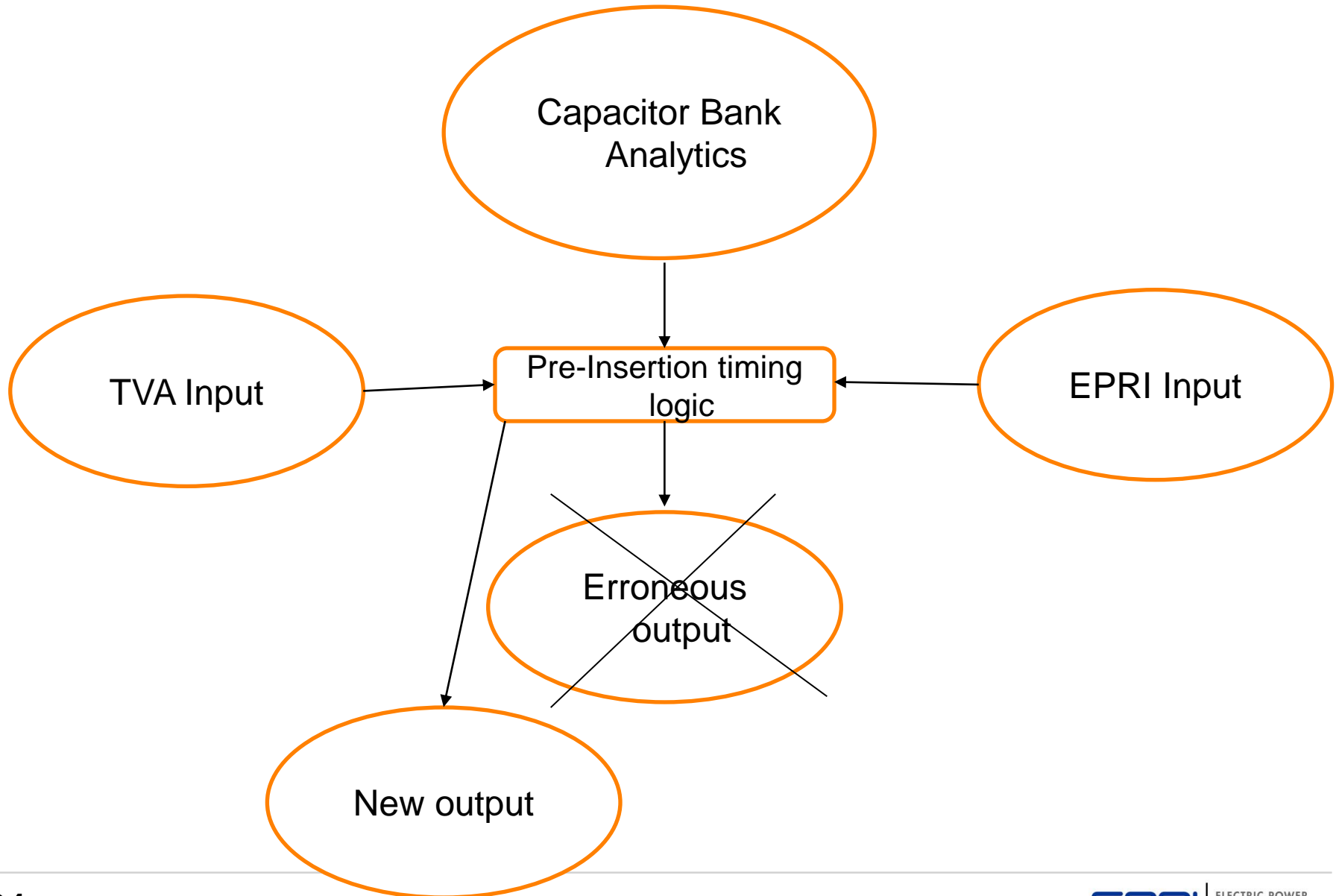
# EPRI's role in the process



# Some notable changes made by EPRI to the analytics

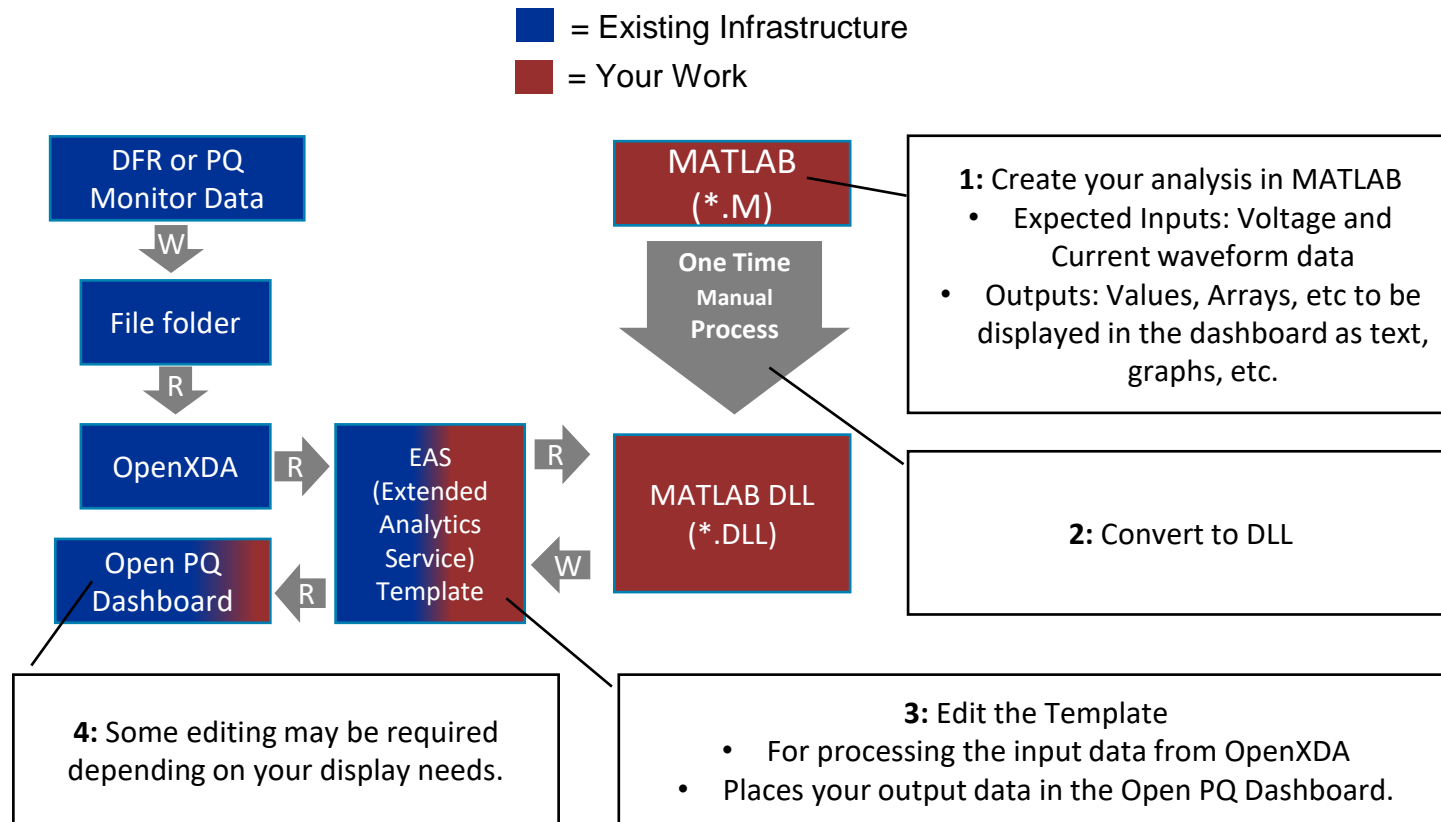


# Some notable changes made by EPRI to the analytics





# Deploying analytics into PQ Dashboard



# OpenXDA Integration

Tony Murphy, TVA

# System Center – Cap Bank Configuration



Sign out

System Center

Alamo TN 161kV Cap Banks 1-4 (S5712B1004Cap)

Delete Asset

- MONITORS AND ASSETS
  - Meters
  - Substations
  - Transmission Assets
  - Asset Groups
  - Customer
  - Device Health Report
- PROCESSED FILES
  - Data Files
- EXTERNAL LINKS
  - Companies
  - Remote openXDA Instances
  - PQView Sites
  - External Databases
  - Application Categories
- SYSTEM SETTINGS
  - Value Lists
  - SystemCenter
  - OpenXDA
  - OpenXDA Data Operations
  - OpenXDA Data Readers
  - MIMD
  - SSO Applications
  - DB Cleanup
- USER SETTINGS
  - User Statistics

Notes Asset Info Additional Fields Substations Meters Channels Connections External DB

Asset Information:

<p>Type</p> <input type="text" value="CapacitorBank"/>	<p>Design</p> <input type="text" value="Fuseless Compensated"/>	<p>Num. of Parallel Strings</p> <input type="text" value="2"/>	<p>Num. of Elements per Relay Cap</p> <input type="text" value="1"/>
<p>Key</p> <input type="text" value="S5712B1004Cap"/>	<p>Number Of Banks</p> <input type="text" value="4"/>	<p>Num. Units in each String</p> <input type="text" value="5"/>	<p>Low Voltage Cap size (kVAR)</p> <input type="text" value="167"/>
<p>Name</p> <input type="text" value="Alamo TN 161kV Cap Banks 1-4"/>	<p>CapBank with Pre-insertion Switcher</p> <input checked="" type="checkbox"/> 1 <input checked="" type="checkbox"/> 2 <input checked="" type="checkbox"/> 3 <input checked="" type="checkbox"/> 4	<p>Num. of Series Groups in each Unit</p> <input type="text" value="10"/>	<p>Low Voltage Cap rating (V)</p> <input type="text" value="825"/>
<p>Nominal Voltage (L-L kV)</p> <input type="text" value="161"/>	<p>Capacitor Step Size (kVAR)</p> <input type="text" value="18000"/>	<p>Num. of Elements in each Group</p> <input type="text" value="3"/>	<p>neg. Reactance Tolerance of LV Unit (%)</p> <input type="text" value="-3"/>
<p>Description</p> <input type="text" value="Four 161kV, 18MVAR Cap Banks"/>	<p>Maximum Operating Voltage (kV)</p> <input type="text" value="173"/>	<p>Relay PT Ratio (primary - secondary V)</p> <input type="text" value="800 : 250"/>	<p>pos. Reactance Tolerance of LV Unit (%)</p> <input type="text" value="3"/>
	<p>Rated Voltage of a Unit (kV)</p> <input type="text" value="19.1"/>	<p>Vt Input Resistor (Ohm)</p> <input type="text" value="100"/>	<p>Initial guess of shorted elements</p> <input type="text" value="0"/>
	<p>Rating of a Unit (kVAR)</p> <input type="text" value="600"/>	<p>Vt Input Resistor Wattage (W)</p> <input type="text" value="10"/>	
	<p>pos. Reactance Tolerance of a Unit (%)</p> <input type="text" value="6"/>	<p>Bus VT Ratio</p> <input type="text" value="1400"/>	
	<p>neg. Reactance Tolerance of a Unit (%)</p> <input type="text" value="0"/>	<p>Num. of Relay Caps</p> <input type="text" value="1"/>	

# System Center – Cap Bank Configuration



Sign out

## System Center

### Alamo TN 161kV Cap Banks 1-4 (S5712B1004Cap)

Delete Asset

#### MONITORS AND ASSETS

- Meters
- Substations
- Transmission Assets
- Asset Groups
- Customer
- Device Health Report

#### PROCESSED FILES

- Data Files

#### EXTERNAL LINKS

- Companies
- Remote openXDA Instances
- PQView Sites
- External Databases
- Application Categories

#### SYSTEM SETTINGS

- Value Lists
- SystemCenter
- OpenXDA
- OpenXDA Data Operations
- OpenXDA Data Readers
- MIMD
- SSO Applications
- DB Cleanup

#### USER SETTINGS

- User Statistics
- Users

Notes Asset Info Additional Fields Substations Meters Channels Connections External DB

#### Channels:

Channel Name	Meter Name	Asset Name	Type	Phase	Description
A1	Alamo TN AHM	Alamo TN 161kV Main Bus	Voltage	AN	161kV (Main Bus) - Van
A2	Alamo TN AHM	Alamo TN 161kV Main Bus	Voltage	BN	161kV (Main Bus) - Vbn
A3	Alamo TN AHM	Alamo TN 161kV Main Bus	Voltage	CN	161kV (Main Bus) - Vcn
A4	Alamo TN AHM	Alamo TN B1004	Current	AN	B1004 (Cap Bank) - Ia
A5	Alamo TN AHM	Alamo TN B1004	Current	BN	B1004 (Cap Bank) - Ib
A6	Alamo TN AHM	Alamo TN B1004	Current	CN	B1004 (Cap Bank) - Ic
A19	Alamo TN AHM	Alamo TN B1004	Current	RES	B1004 (Cap Bank) - Ir

Notes Asset Info Additional Fields Substations Meters Channels Connections External DB

#### Connections:

Asset	Relationship	
S5712Bus161-M	Bus-CapBank	
S5712B1004	CapBank-(Single)Breaker	
S5712B1004CR1	Relay-CapBank	
S5712B1004CR2	Relay-CapBank	
S5712B1004CR3	Relay-CapBank	
S5712B1004CR4	Relay-CapBank	

Add Connection

# SE Browser – Cap Bank Report

## System Event Browser

Event Search

Meter Activity

---

Custom Reports

Breaker Report

TripCoil Report

CapBank Report

Capacitor Bank:

Substation: ALAMO, TN 161KV SWITCHING STATION (S5712)

Cap Bank Group: Alamo TN 161kV Cap Banks 1-4

Bank: System

Time Window:

Date: 09/26/2022

Time Window(+/-): 2

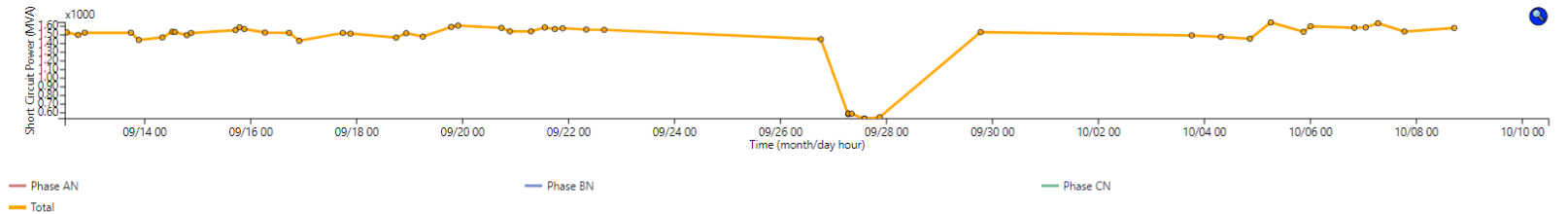
12:00:00.000

Week

Additional Filter:

[Edit Filter](#)

Short Circuit Power



Short Circuit Power

Time	Phase AN (MVA)	Phase BN (MVA)	Phase CN (MVA)	Total (MVA)
09/22/22 08:00:30.000	509.110	547.350	505.680	1562.14
09/22/22 16:10:30.000	511.860	547.950	499.640	1559.45
09/26/22 18:15:30.000	467.370	509.850	472.680	1449.90
09/27/22 06:37:00.000	191.680	201.890	191.260	584.830
09/27/22 06:45:30.000	195.270	204.530	193.120	592.920
09/27/22 08:13:02.000	193.260	204.280	192.780	590.320
09/27/22 13:50:31.000	173.960	182.930	175.330	532.220
09/27/22 14:05:30.000	175.920	183.610	174.560	534.090
09/27/22 20:52:39.000	178.380	190.290	180.270	548.940
09/29/22 18:38:34.000	500.180	534.120	497.630	1531.93
10/03/22 18:15:30.000	484.280	519.150	491.200	1494.63

# SE Browser – Cap Bank Report

**System Event Browser**

Event Search  
Meter Activity

Custom Reports  
Breaker Report  
TripCoil Report  
CapBank Report

Capacitor Bank:  
Substation: ALAMO, TN 161KV SWITCHING STATION (S5712)  
Cap Bank Group: Alamo TN 161kV Cap Banks 1-4  
Bank: System

Time Window:  
Date: 09/26/2022 12:00:00.000  
Time Window(+/-): 2 Week

Additional Filter: [Edit Filter](#)

## Filter CapBank Events

Phase:  
 All  
 AN  
 BN  
 CN

Status:  
 All  
 Error  
 Normal  
 > 2 cyc/ Between Poles  
 Abnormal Health  
 Failed Opening  
 Failed Closing  
 Restrike/ Reignition  
 Abnormal Preinsertion Switching  
 Missing Pole  
 Shorted Units  
 Blown Fuse  
 Other

Operation:  
 All  
 Sag/Swell  
 No Switching  
 Not Determined  
 Opening  
 Closing

Resonance:  
 Resonance  
 No Resonance

CapBank Health:  
 All  
 Normal  
 Shorted Units  
 Blown Fuses  
 Tap Voltages Missing

Restrike:  
 All  
 No Restrike  
 Possible Restrike  
 Restrike  
 Reignition  
 Reversed Polarity

Switching Health:  
 All  
 Normal  
 Transient  
 Too Short  
 Unknown

Close

09/26/22 18:15:30.000	467.370	509.850	472.680	1449.90
09/27/22 06:37:00.000	191.680	201.890	191.260	584.830
09/27/22 06:45:30.000	195.270	204.530	193.120	592.920
09/27/22 08:13:02.000	193.260	204.280	192.780	590.320
09/27/22 13:50:31.000	173.960	182.930	175.330	532.220
09/27/22 14:05:30.000	175.920	183.610	174.560	534.090
09/27/22 20:52:39.000	178.380	190.290	180.270	548.940
09/29/22 18:38:34.000	500.180	534.120	497.630	1531.93
10/03/22 18:15:30.000	484.280	519.150	491.200	1494.63

# SE Browser – Cap Bank Report

**System Event Browser**

Event Search

Meter Activity

---

Custom Reports

Breaker Report

TripCoil Report

CapBank Report

**Capacitor Bank:**

Substation: ALAMO, TN 161KV SWITCHING STATION (55712)

Cap Bank Group: Alamo TN 161kV Cap Banks 1-4

Bank: System

**Time Window:**

Date: 10/07/2022

Time Window(+/-): 12:00:00.000

12 Hour

**Additional Filter:**

Edit Filter

**Short Circuit Power**

**CapBank Analytic Event Overview**

Time	Phase	Analysis Status	CapBank Operation	Resonance	CapBank Health	Restrike	PreInsertionSwitching Condition
10/07/22 01:05:30.000	CN	The longest time between two closing or opening poles is more than 2 cycles and Some fuseless units are shorted, or fused units shorted and fuses failed to clear	Opening operation: final opening. After de-energizing, the number cap bank is zero.	No	Some fuseless units are shorted, or fused units shorted because fuses failed to clear	No restrike	N/A
10/07/22 06:38:30.000	BN	The longest time between two closing or opening poles is more than 2 cycles and Some fuseless units are shorted, or fused units shorted and fuses failed to clear	Opening operation: final opening. After de-energizing, the number cap bank is zero.	No	Some fuseless units are shorted, or fused units shorted because fuses failed to clear	No restrike	N/A

# OpenSEE – Cap Bank Analysis

