Advanced Fault Analysis System (or AFAS) for Distribution Power Systems

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Outline

- Objective
- Background
- Introduction
- Methodology Description
  - AFAS GUI Development and Software Integration
  - AFAS PSCAD Custom Simulation Set-up
  - AFAS PSCAD Implementation and Validation (DTE’s Orion Circuit)
- AFAS PSCAD Fault Prediction Capabilities (DTE’s Jewel Circuit)
- Technical and Economic Benefits
- Conclusions and Future Work
- Acknowledgements
- Live Demo of AFAS

Objective

- Development of an intelligent, operational, decision-support fault analysis tool (e.g., AFAS) for automatic detection and location of low and high impedance, momentary and permanent faults in distribution power systems

Background: Utility Needs

- Detecting and locating momentary and permanent faults are crucial to the planning and operation activities of utilities (DTE, AEP , Progress Energy, PG&E, etc.)
  - AEP (6230 circuits, a lot of underground cables): Very useful to predict location of low and high impedance faults
- Detecting quickly and accurately temporary and high impedance faults/failures including voltage dips/sags, distortions, will help utilities increasing the reliability of their distribution systems at a lower cost
  - Waveform distortions cause problems to:
    - Capacitor banks (maltrip of capacitor fuse);
    - Overheating of transformers and neutral conductors;
    - Inadvertent trip of circuit breaker or fuse;
    - Customer devices:
      - Malfunctioning of electronic equipment;
      - Digital clocks running fast

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Introduction: *CTC*'s DFSL

- *CTC*'s Distribution Systems Fault locator (DFSL) tool [1]:
  - Developed under the DOE-EI program (Fault location project)
  - Capable of quickly and accurately predicting the location of permanent faults in distribution power systems
  - Validated with fault data from DTE circuits
  - Hybrid evolutionary Approach consists of 3 main steps:
    1. **Fault Analysis**: Calculate short-circuit currents using fault analysis routine of commercially available modeling and simulation packages
    2. **Heuristic Rules**: A set of rules based on operator experience to predict fault locations
       - Compare measured and calculated fault current at substation
       - Use recloser information (open/closed status and currents)
       - Use location of customer phone calls to locate outages
    3. **Optimization using Genetic Algorithm**: Objective function optimizes for currents, distance and voltage sags; also minimizes the errors between measured and expected parameters

[1] L. Nastac and A. Thatte, A Heuristic Approach for Predicting Fault Locations in Distribution Power Systems, *Proceedings of IEEE NAPS2006*, SIU Carbondale, IL, September 15-17, 2006.

Introduction : DSFL Predictions

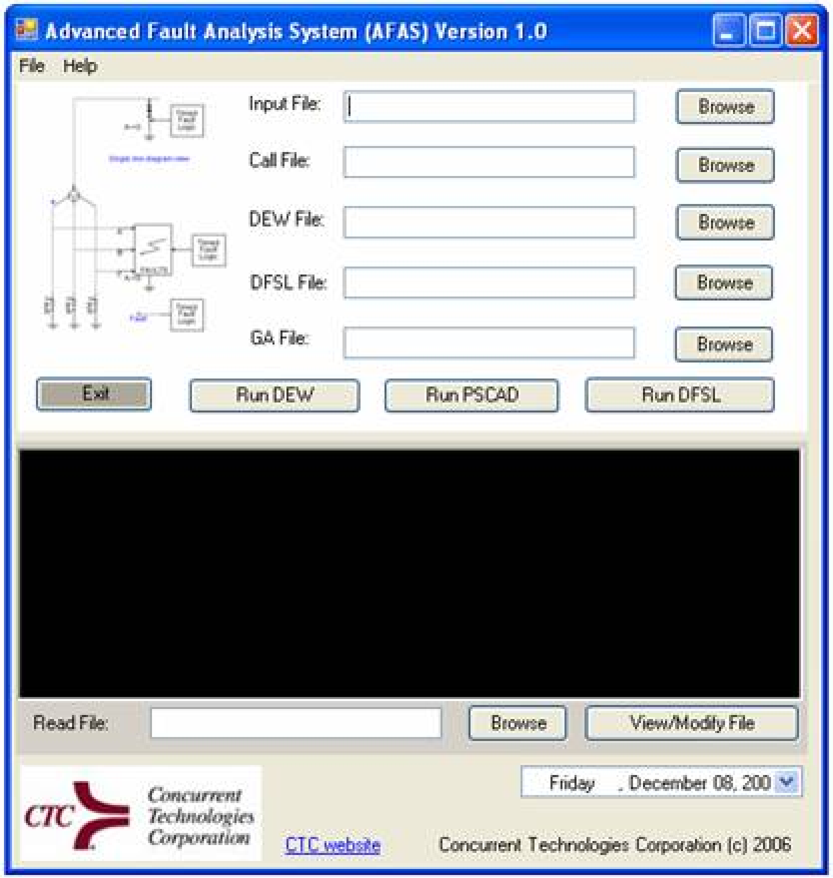
Potential Fault Locations Predicted by DSFL tool (Assuming 10% Difference in Currents) [2]

					Number of potential fault locations			
DTE Circuit Name*	Distance from fault location to substation [ft]	Number of system Compo-nents	Fault Type	Number of selected Compo-nents	Rule #1 Fault Current	Rule #2 Recloser Status – Recloser Current	Rule #3 Customer phone call	GA
Clark	6900	2300	A-C	188	12	8 – N/A	3	3
Orion #1	6900	1078	B-G	125	21	17 – N/A	6	6
Orion #2	6900	1078	C-G	125	21	19 – N/A	12	7
Mac	19,100	2401	C-G	169	23	8 – N/A	4	4
Jewel	26,700	1762	A-G	98	16	15 – 8	NA	4

*DTE's Orion circuit – Two different faults that occurred in different times at the same location
DTE's Jewel circuit – Real test performed at DTE on October 15, 2006

[2] L. Nastac et al., Methodology and Implementation Strategy for Predicting the Location of Permanent Faults in Distribution Power Systems, *Proceedings of IASTED2007*, January 3-5, 2007

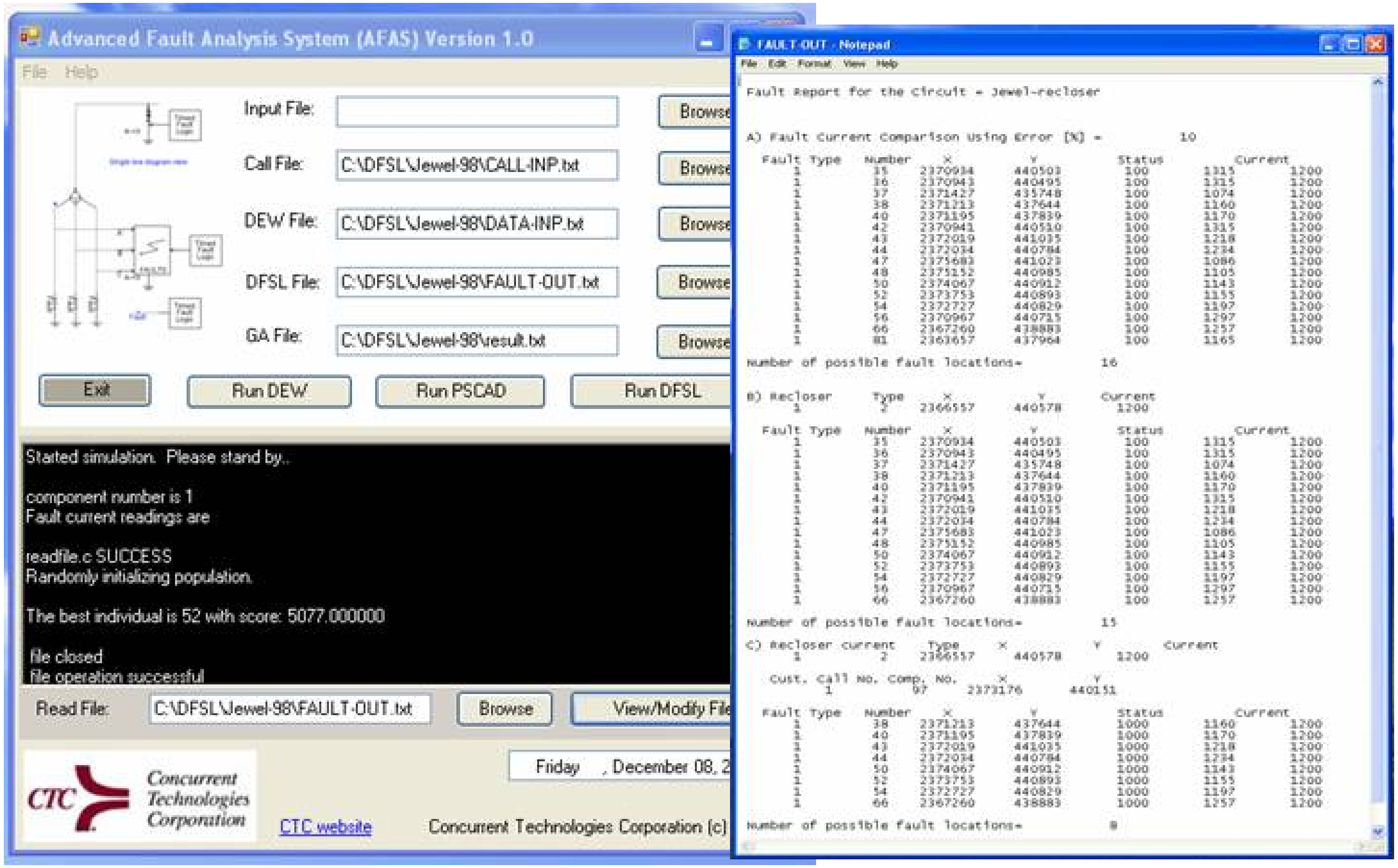
AFAS GUI Screen Design



- **Desktop based application: Graphical User Interface (GUI) + Console Based Simulation Engine (*e.g.*, Console)**
  - **GUI has a logon form**
  - **GUI can let user enter simulation parameters, choose input data files, simulation initialization file and output file.**
  - **GUI can communicate with Console seamlessly.**
  - **GUI can let user view the output data file.**
  - **GUI can let user access DEW, PSCAD, and DFSL software tools**

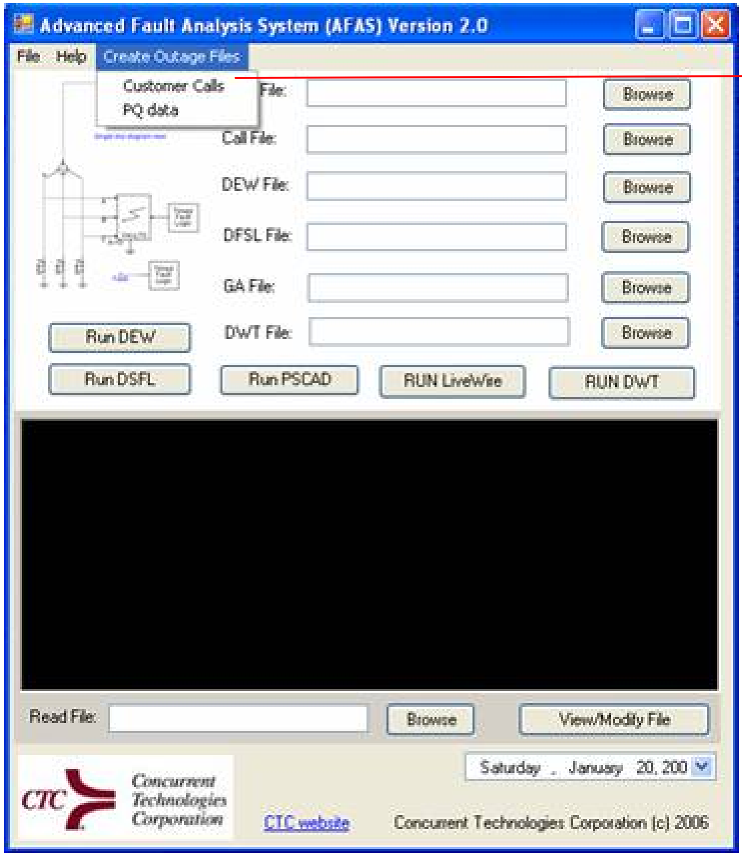
AFAS GUI Screen Design (cont'd)

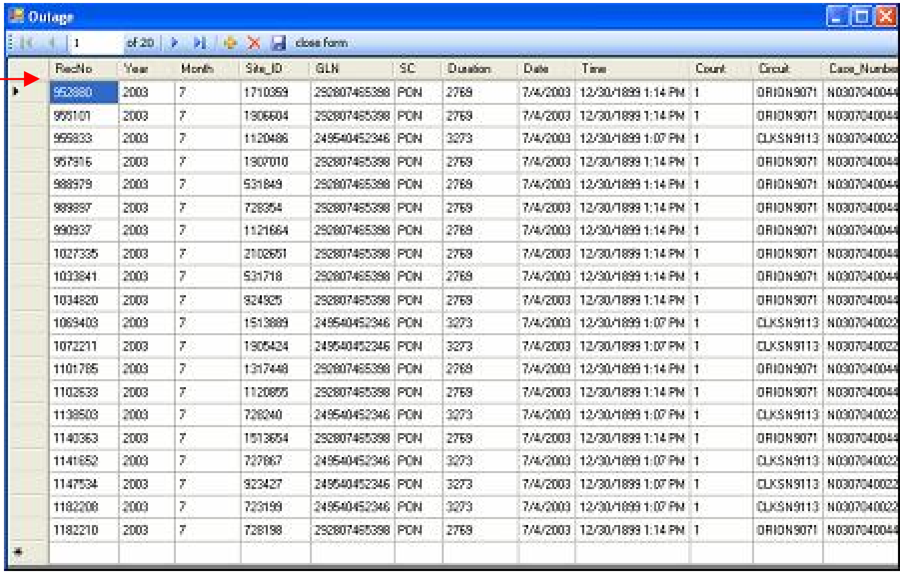
- **User Can View the Output Data File**



AFAS Screen Design (Version 2.0)

- **User can view and save/extract the Outage Call (Microsoft Access/Oracle/SQL/ODBC Database formats) and PQNode data (Comtrade format) Files specific to an outage event**





RecNo	Year	Month	Site_ID	GLN	SC	Duration	Date	Time	Count	Circuit	Case_Numbe
952880	2003	7	1710359	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
955101	2003	7	1306604	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
955833	2003	7	1120486	249540452346	PON	3273	7/4/2003	12/30/1899 1:07 PM	1	CLKSN9113	N030704002
957916	2003	7	1307010	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
988979	2003	7	531849	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
989897	2003	7	728354	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
990937	2003	7	1121664	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
1027335	2003	7	2102651	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
1033841	2003	7	531718	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
1034820	2003	7	924925	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
1069403	2003	7	1513889	249540452346	PON	3273	7/4/2003	12/30/1899 1:07 PM	1	CLKSN9113	N030704002
1072211	2003	7	1905424	249540452346	PON	3273	7/4/2003	12/30/1899 1:07 PM	1	CLKSN9113	N030704002
1101785	2003	7	1317448	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
1102633	2003	7	1120855	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
1138503	2003	7	728240	249540452346	PON	3273	7/4/2003	12/30/1899 1:07 PM	1	CLKSN9113	N030704002
1140363	2003	7	1513654	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004
1141652	2003	7	727867	249540452346	PON	3273	7/4/2003	12/30/1899 1:07 PM	1	CLKSN9113	N030704002
1147534	2003	7	923427	249540452346	PON	3273	7/4/2003	12/30/1899 1:07 PM	1	CLKSN9113	N030704002
1182208	2003	7	723199	249540452346	PON	3273	7/4/2003	12/30/1899 1:07 PM	1	CLKSN9113	N030704002
1182210	2003	7	728198	292807465398	PON	2769	7/4/2003	12/30/1899 1:14 PM	1	ORION9071	N030704004

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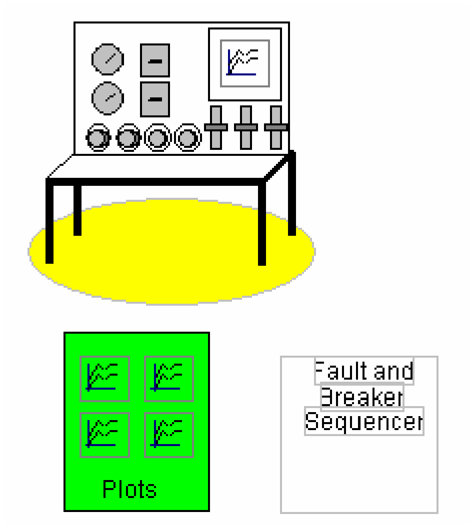
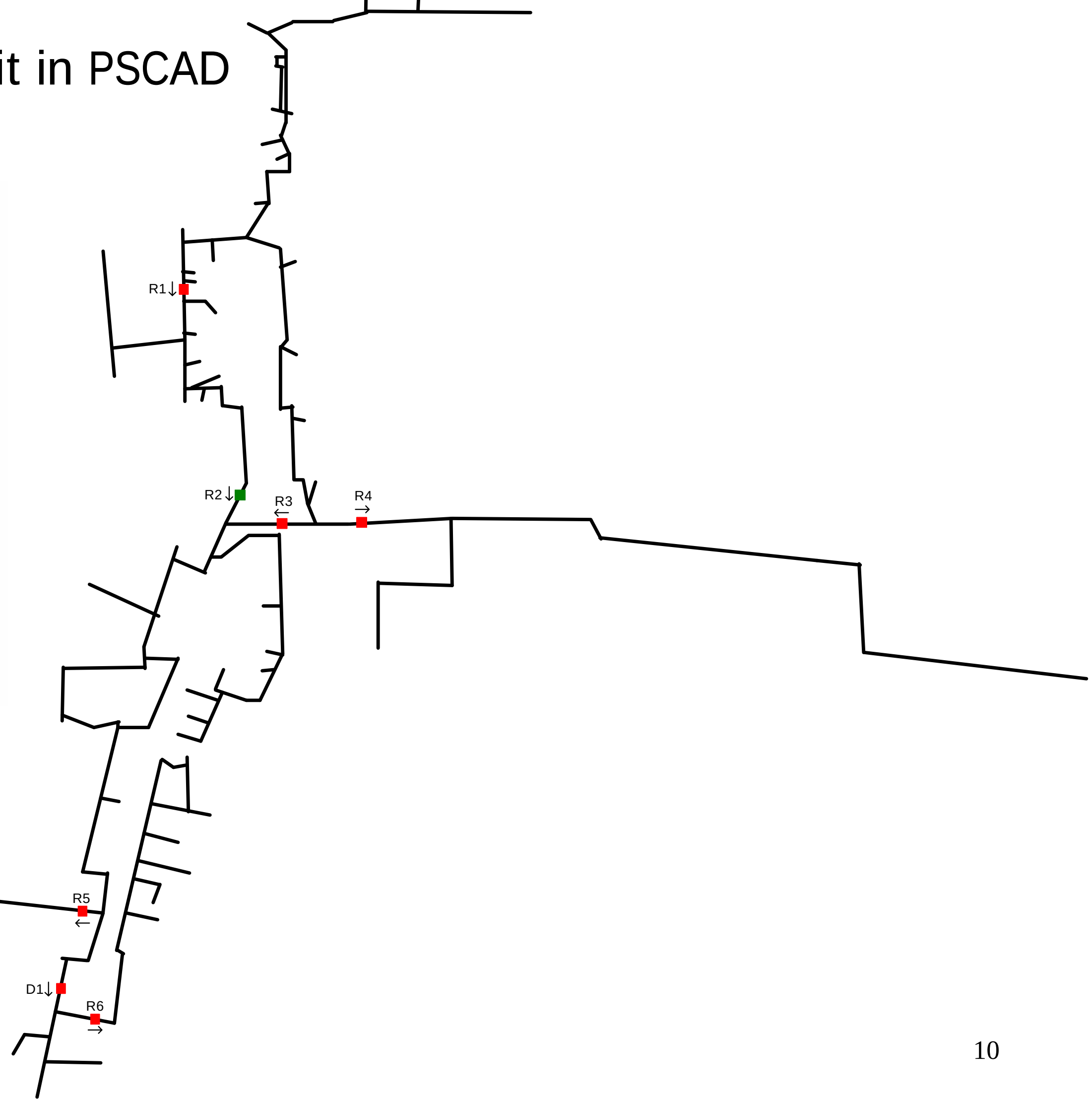
PSCAD Custom Simulation Setup

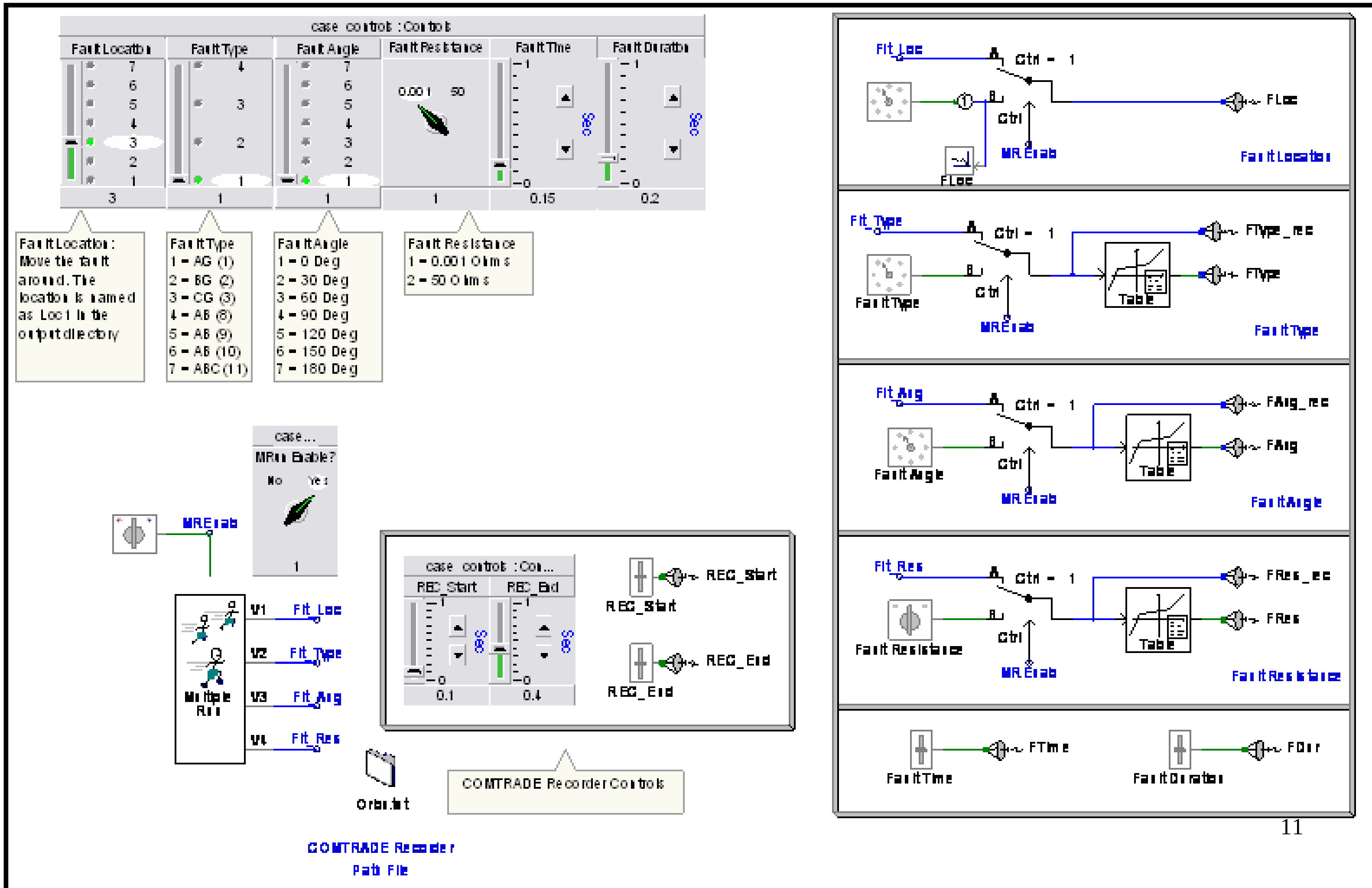
- DTE's Orion circuit in PSCAD





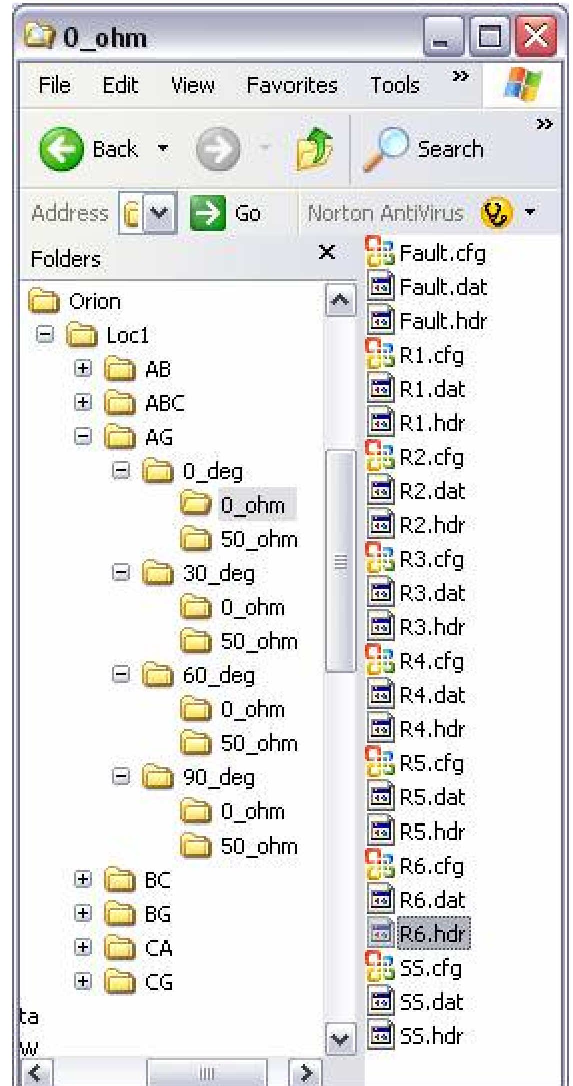
PSCAD Custom Simulation Setup (cont'd)

- Run Automation and Case Controls



PSCAD Custom Simulation Setup (cont'd)

- 7 Fault Types
- 4 Fault Incidence Angles
- 3 Fault Resistances (0-1, 5-15, 50-100 ohms)
- 8 Recorders for each run (Orion circuit)
  - substation
  - 6 reclosers
  - fault location
- 84 runs/fault location
- Typical 50-200 fault locations/circuit
- Total 4200-16800 runs
- Total CPU time = 6-24 hr
- Size (zipped Comtrade format): 0.7-2.8 Gb
- Search scheme – library of 16800 fault signature V&I indices/circuit



Recorder Data Directory Structure

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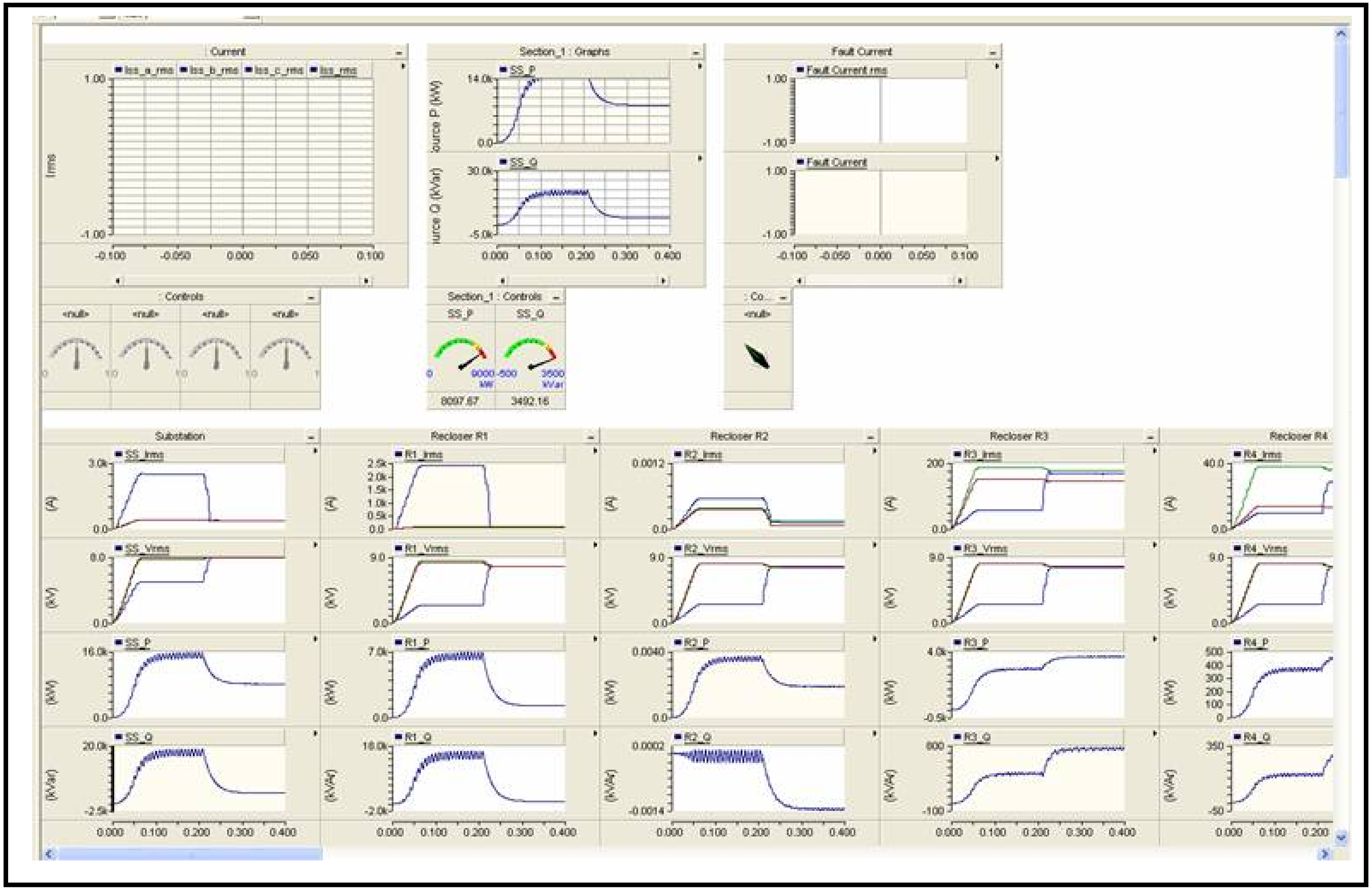
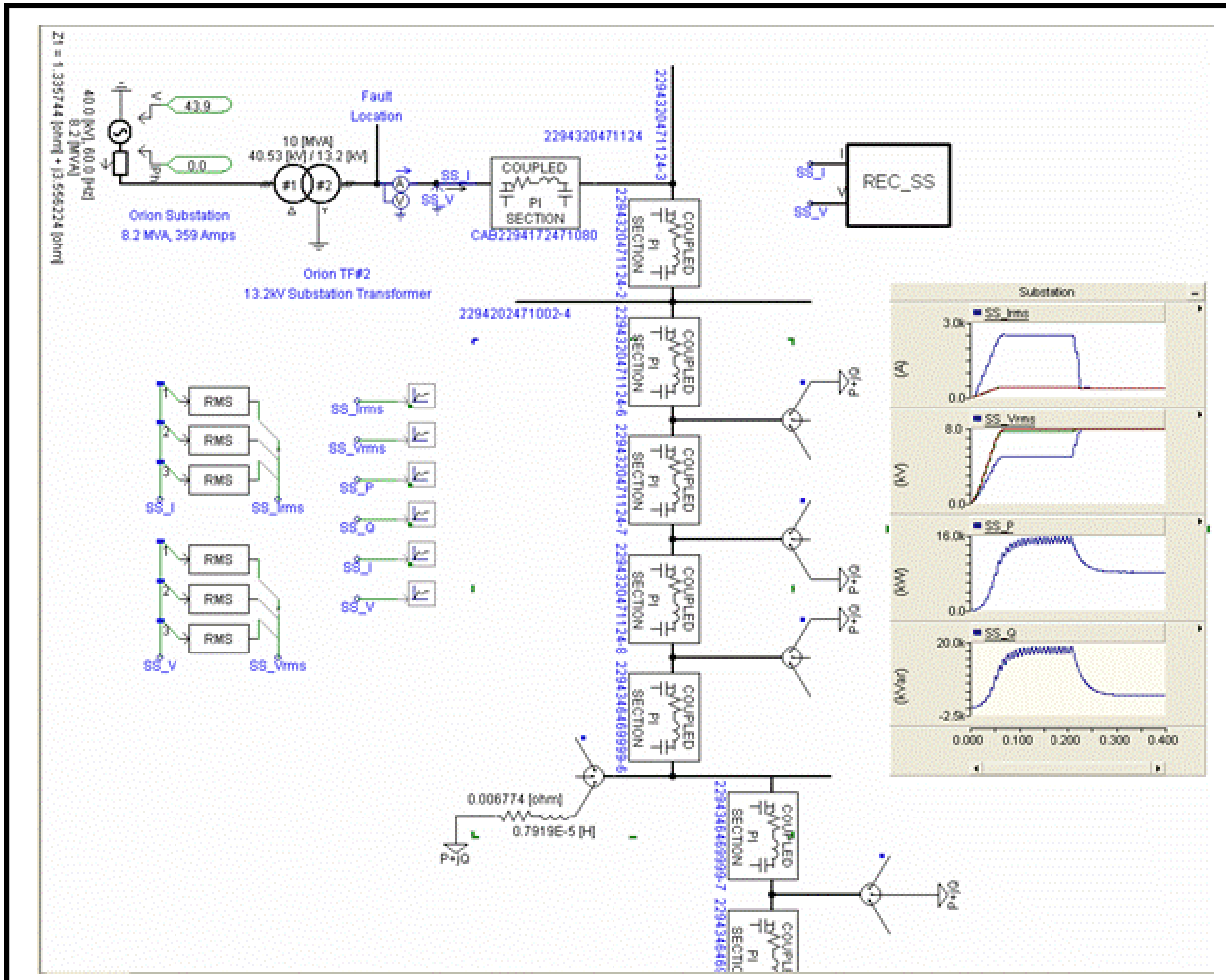
PSCAD Custom Simulation Setup (cont'd)

- Plots



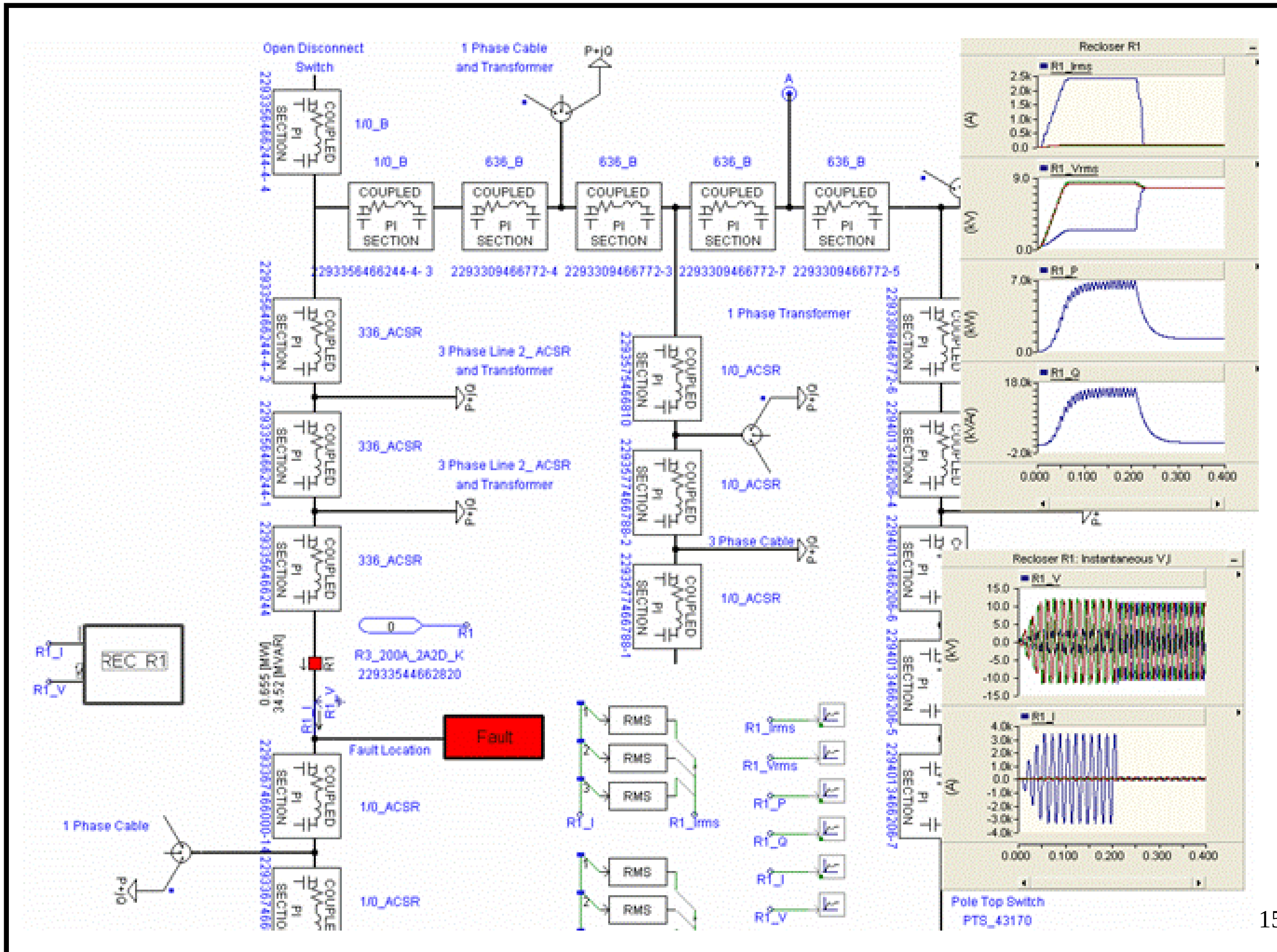
PSCAD Custom Simulation Setup (cont'd)

- Substation area



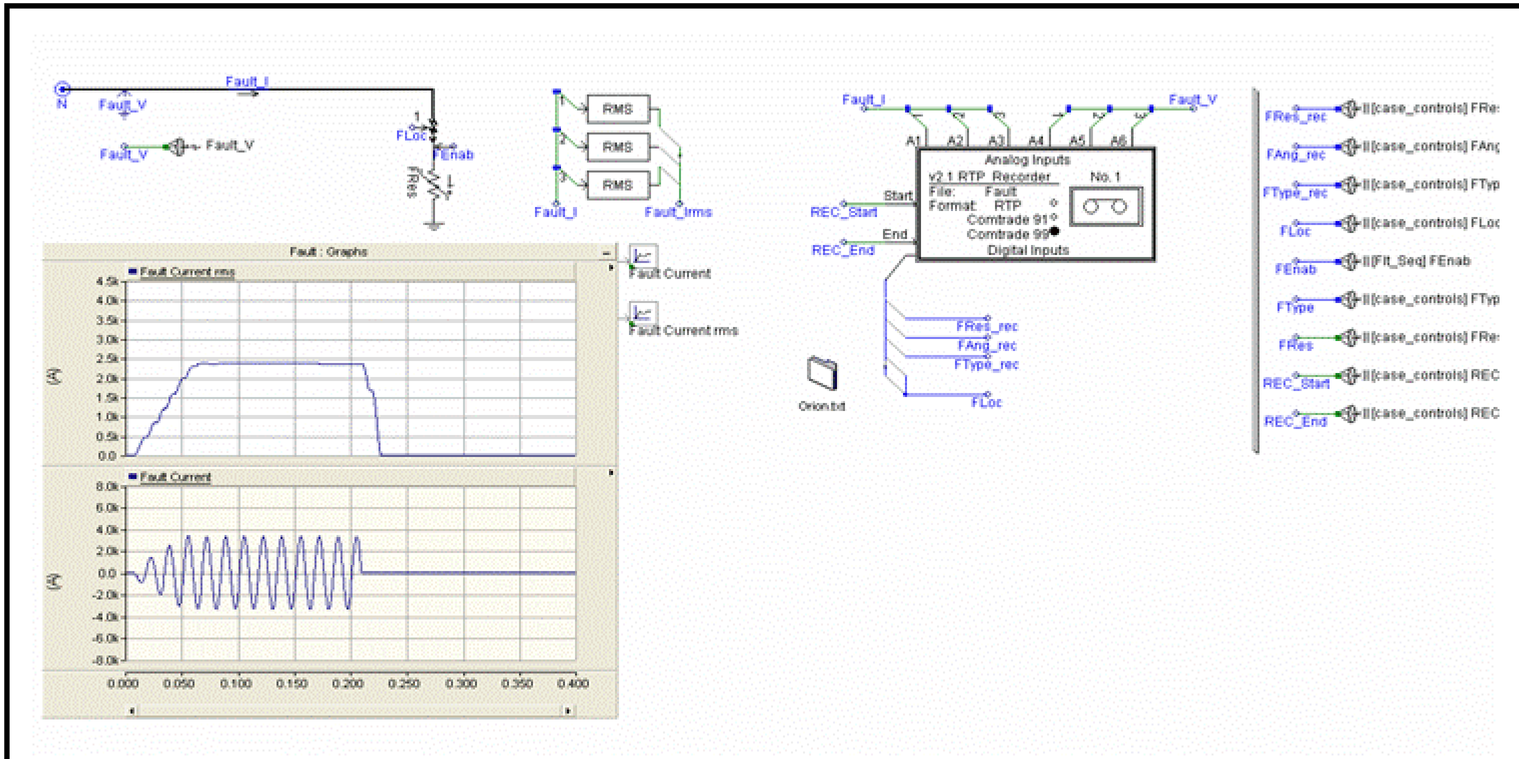
PSCAD Custom Simulation Setup (cont'd)

- Fault location (automatic setting for *n* number of fault locations)



PSCAD Custom Simulation Setup (cont'd)

- Fault module and fault recorder



DTE's Orion Circuit Validation

- Load Flow Validation (DEW vs. PSCAD)

Orion Load-Flow Validation

		Voltage (kV)		Current (A)		P (kW)		Q (kVar)	
		DEW	PSC	DEW	PSC	DEW	PSC	DEW	PSC
Station	A	7.90	7.90	359	370	2633		1049	
	B	7.90	7.90	359	370	2633		1049	
	C	7.90	7.90	359	373	2633		1049	
	3Ph	**7.90**	**7.90**	**359**	**371**	**7899**	**8091**	**3147**	**3480**
R1	A	7.69	7.70	64	66	429		238	
	B	7.77	7.71	45	46	313		161	
	C	7.76	7.73	65	67	441		247	
	3Ph	**7.74**	**7.71**	**58**	**60**	**1182**	**1205**	**646**	**690**
R2		0.00	0.00	0	0	0	0	0	0
R3	A	7.58	7.60	163	166	1211		230	
	B	7.68	7.61	172	176	1295		266	
	C	7.73	7.69	137	143	1055		112	
	3Ph	**7.66**	**7.63**	**157**	**162**	**3561**	**3635**	**608**	**752**
R4	A	7.58	7.60	27	28	175		111	
	B	7.68	7.61	35	36	228		144	
	C	7.73	7.69	12	13	81		52	
	3Ph	**7.66**	**7.63**	**25**	**26**	**485**	**485**	**306**	**320**
R5	A	7.50	7.52	57	61	362		229	
	B	7.63	7.55	10	15	66		39	
	C	7.71	7.56	20	25	128		80	
	3Ph	**7.61**	**7.54**	**29**	**34**	**556**	**647**	**348**	**405**
D1	A	7.49	7.52	40	40	266		135	
	B	7.62	7.53	75	75	497		279	
	C	7.71	7.66	33	33	226		109	
	3Ph	**7.61**	**7.57**	**49**	**49**	**990**	**975**	**522**	**545**
R6	A	7.49	7.51	32	32	214		105	
	B	7.62	7.53	27	27	186		86	
	C	7.71	7.55	30	30	205		99	
	3Ph	**7.61**	**7.53**	**29**	**30**	**605**	**601**	**290**	**302**

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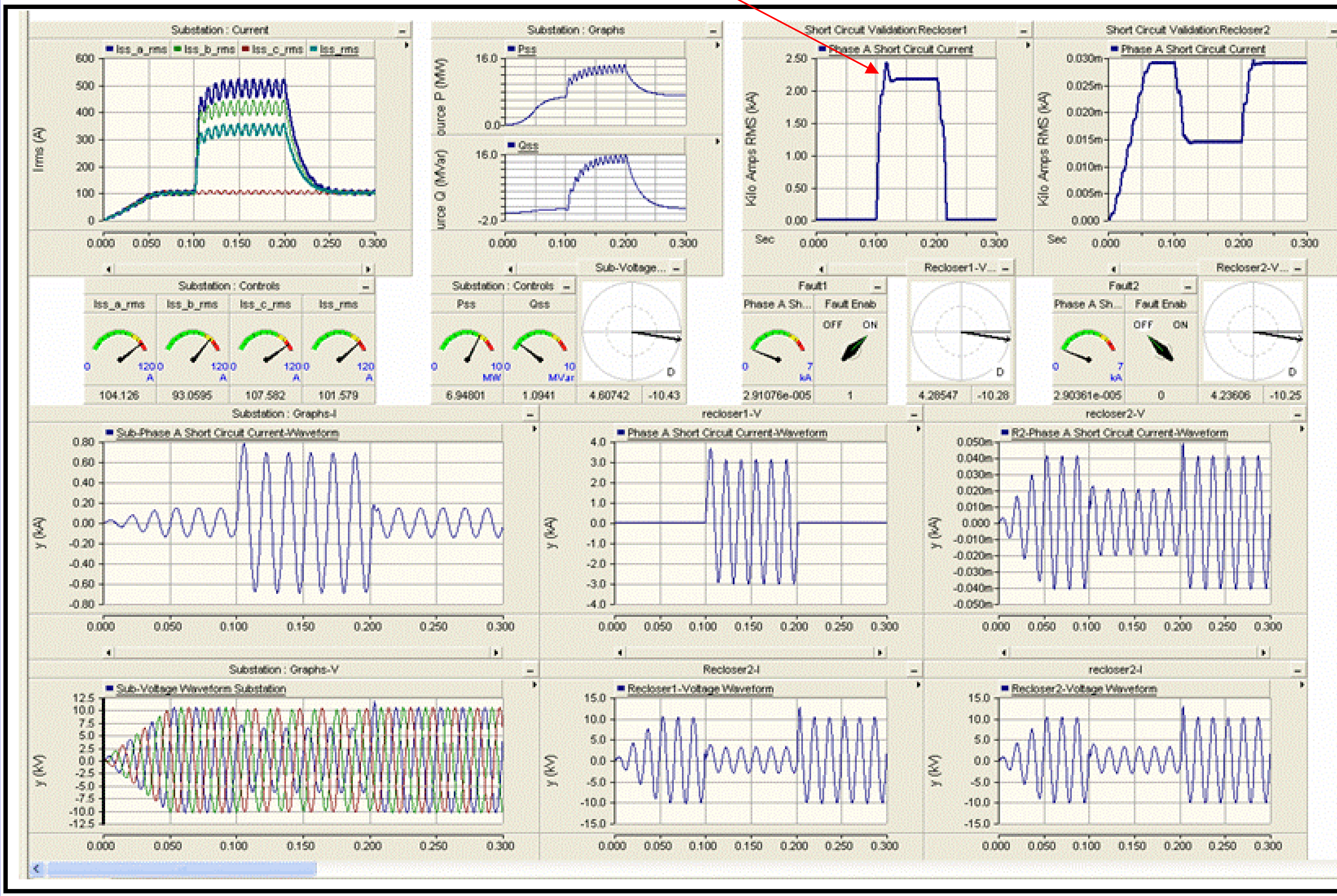
Orion Circuit Validation (cont'd)

- Fault Current Validation (DTE's measurement: 2291 A Phase AG at Recloser 1; predictions within 10% from measurements)



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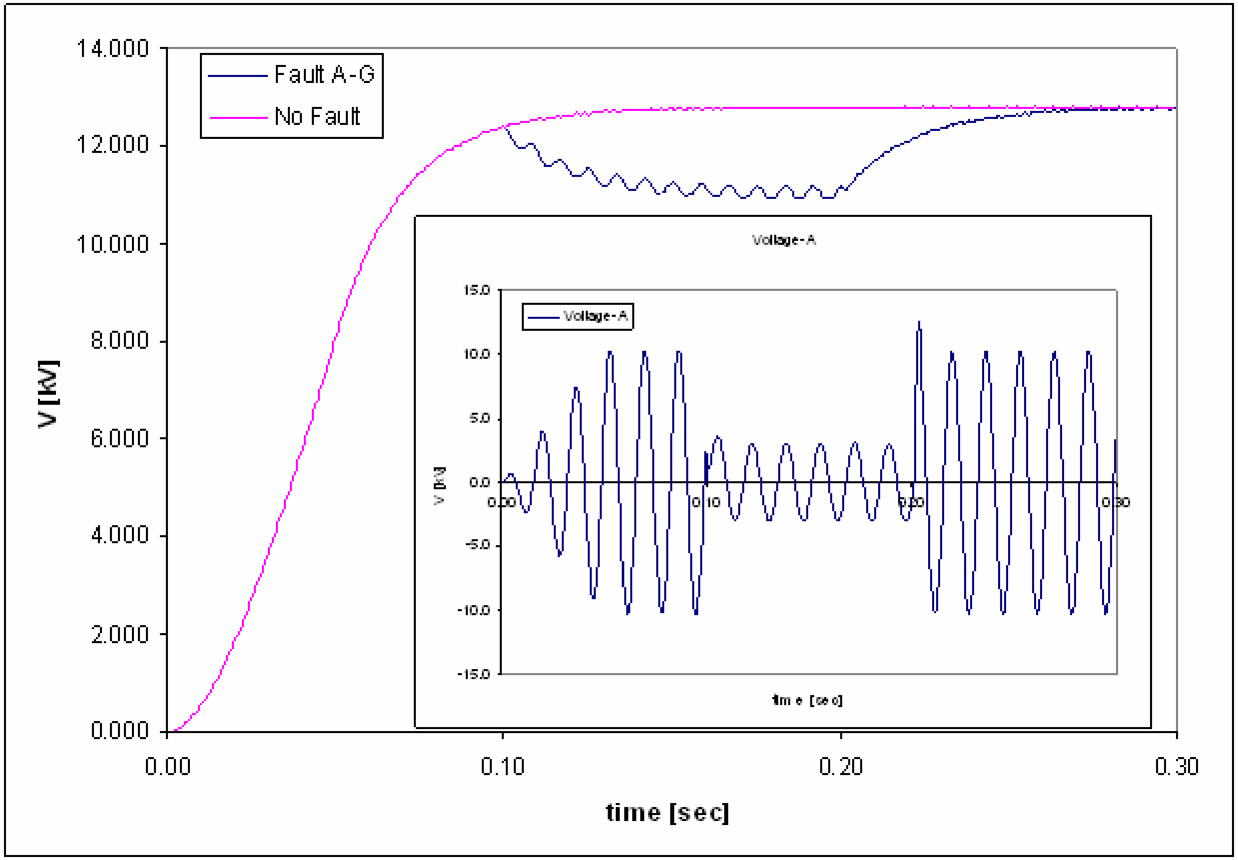
Example of PSCAD Predictions

- Voltage Sags/Dips (Orion circuit)
- Voltage-dip energy Index (E_{dip}) specific to a fault (defined as the integral of the drop in signal energy over the duration of the event)

*E*dip = 0.556



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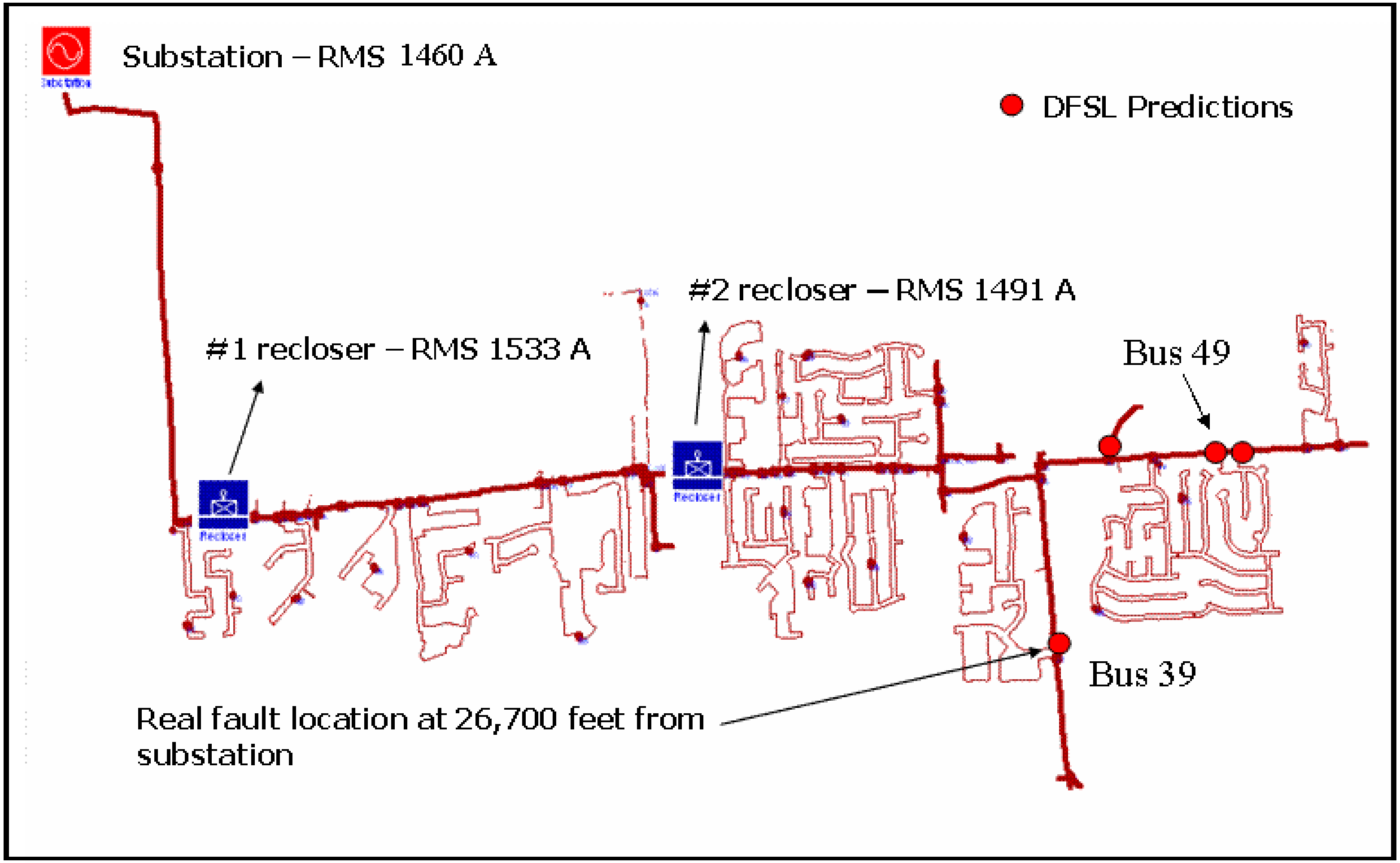
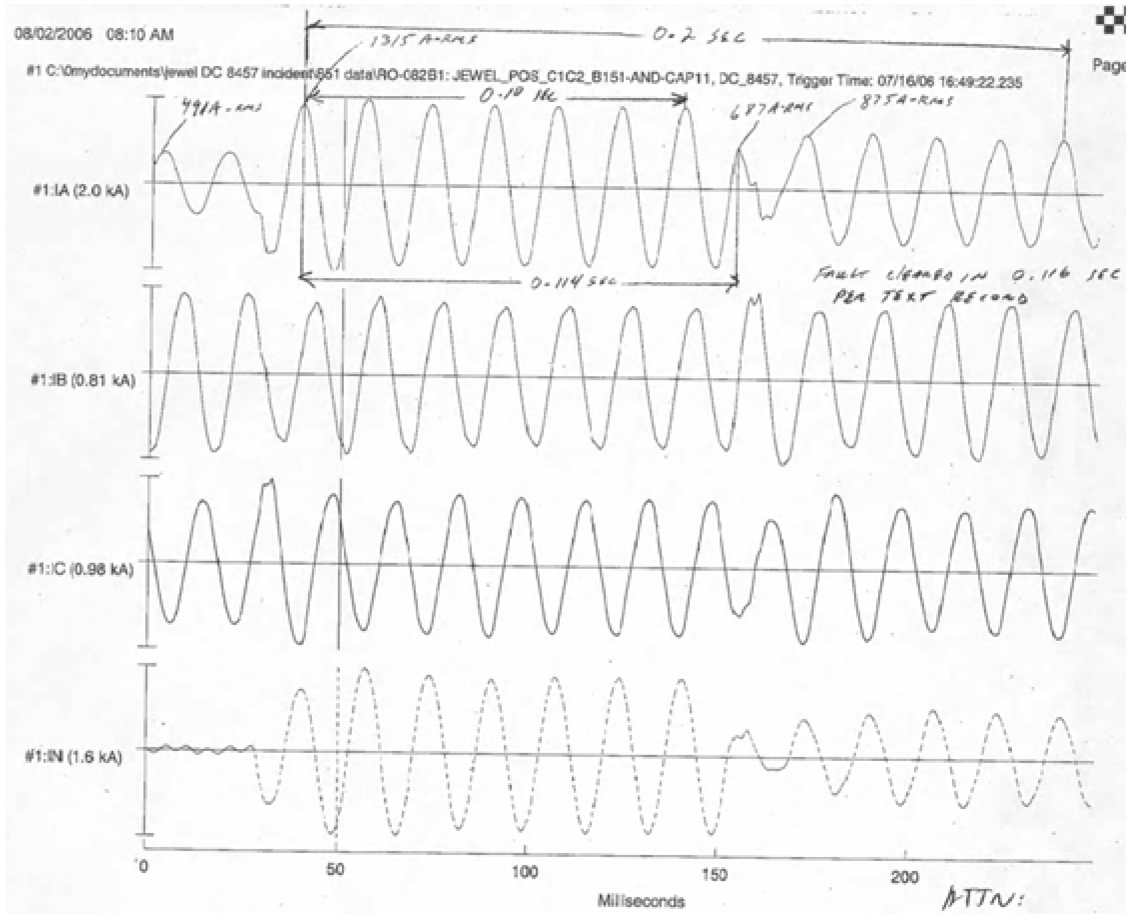
DTE's Jewel Circuit (A-G Fault)

- Fault Current (RMS) data at reclosers and substation



DTE's Jewel Circuit (A-G Fault) (cont'd)

- Oscillogram record: Fault Current Data at Substation (Comtrade format, 24 samples/cycle)



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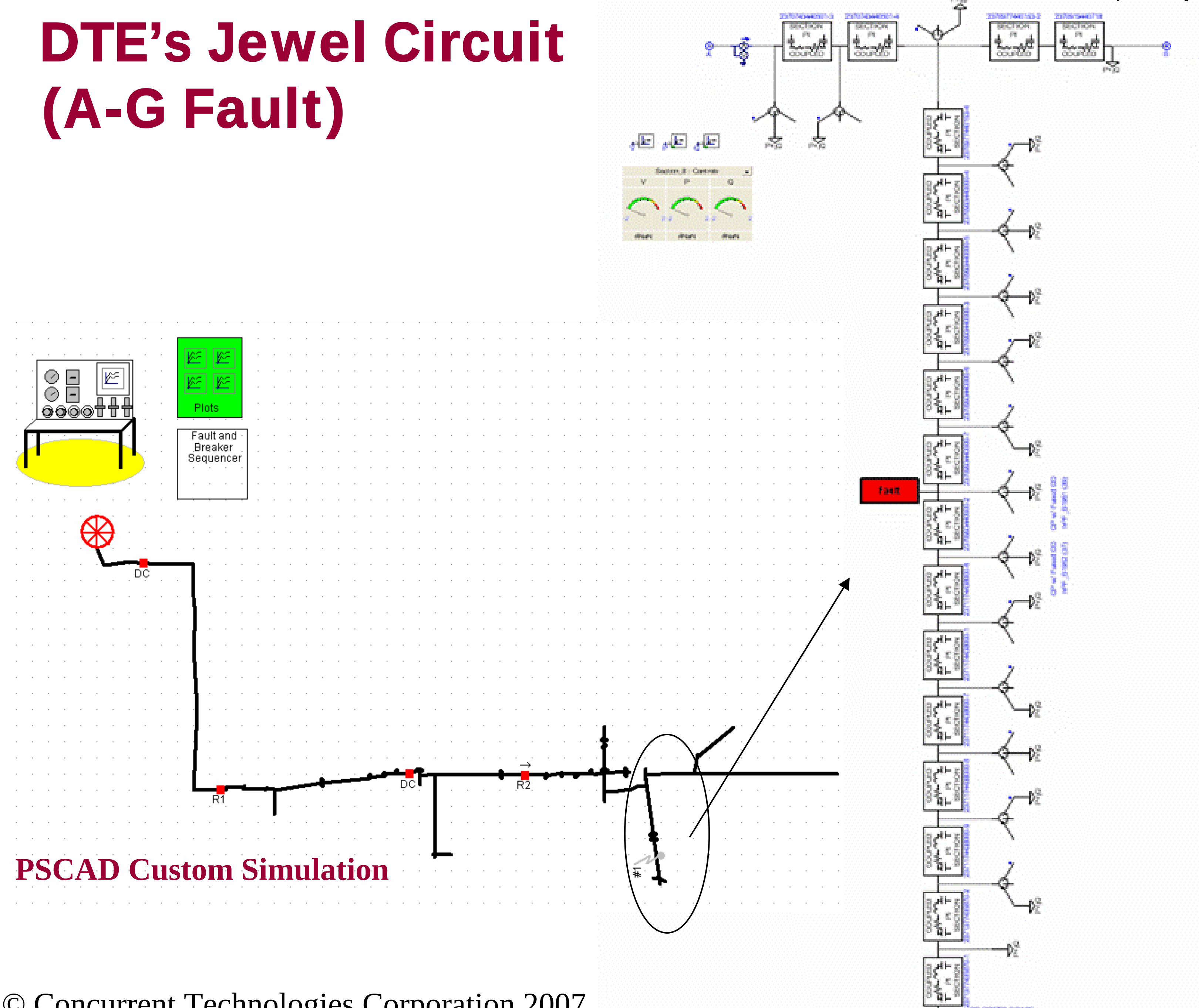
DTE's Jewel Circuit (A-G Fault)



PSCAD Custom Simulation

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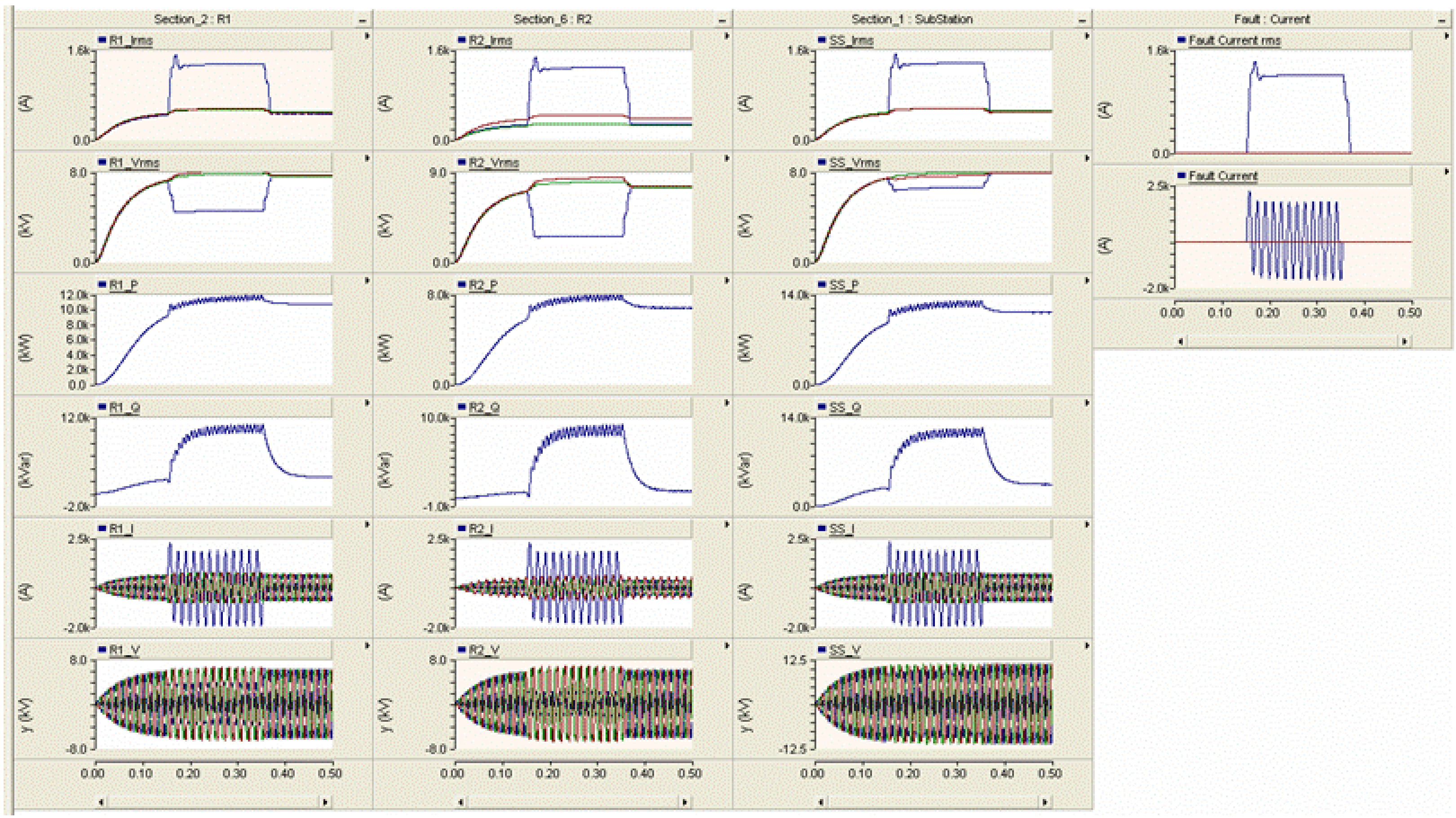
PSCAD Simulation Results

- **Jewel circuit:** Single-phase fault prediction (voltage sags/dips and fault currents) in PSCAD (from digital signature library, Jewel circuit, bus 39, V&I records at substation and reclosers).



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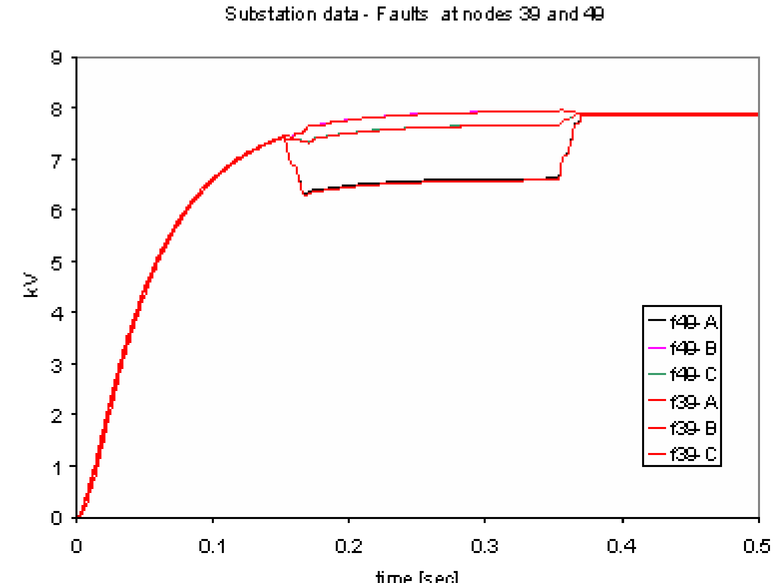
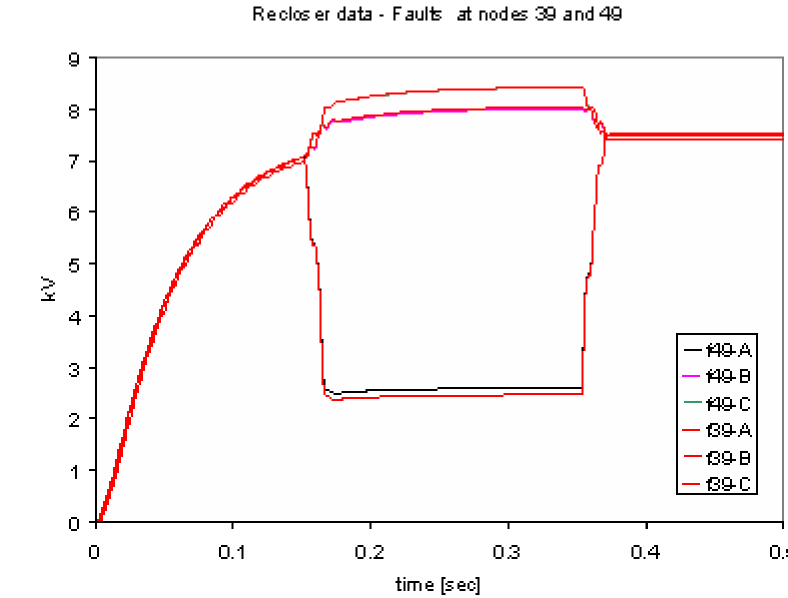
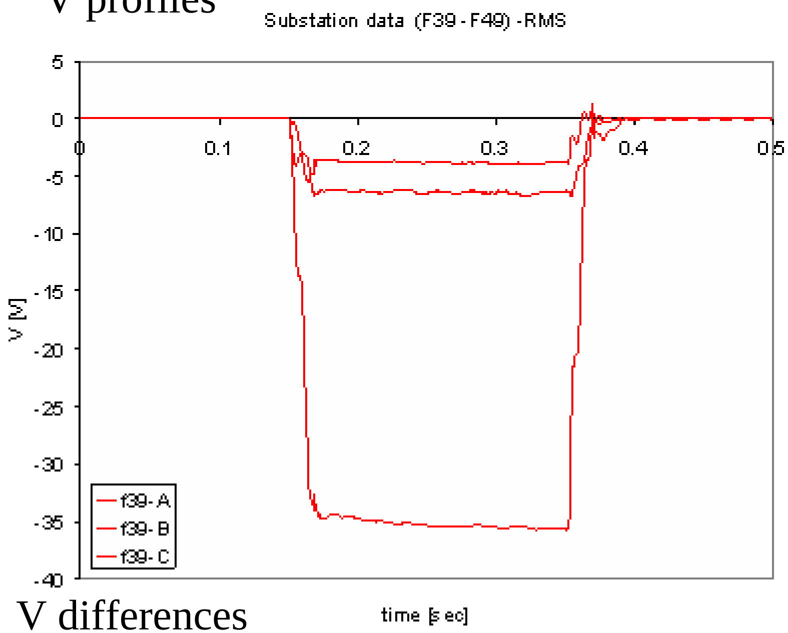
PSCAD Simulation Results (cont'd)

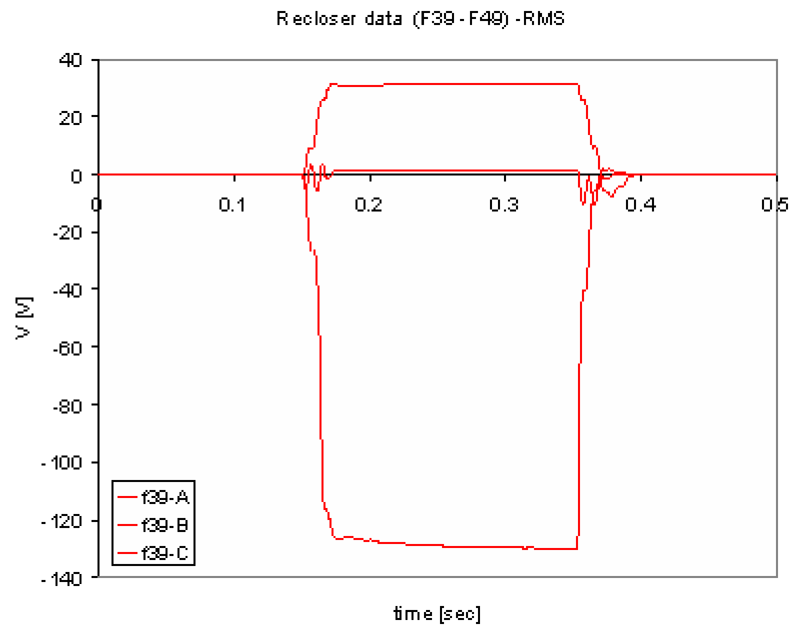
- RMS Voltages at buses 39 and 49; substation (left); recloser (right)





V profiles

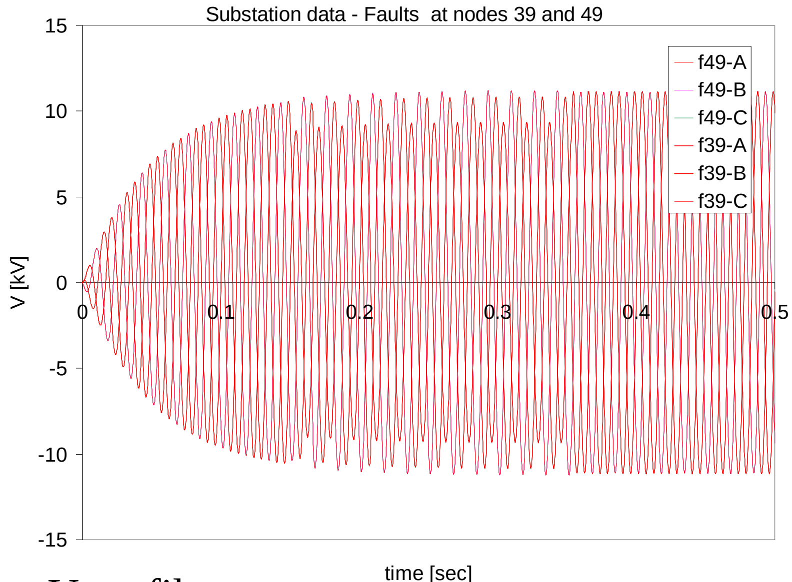


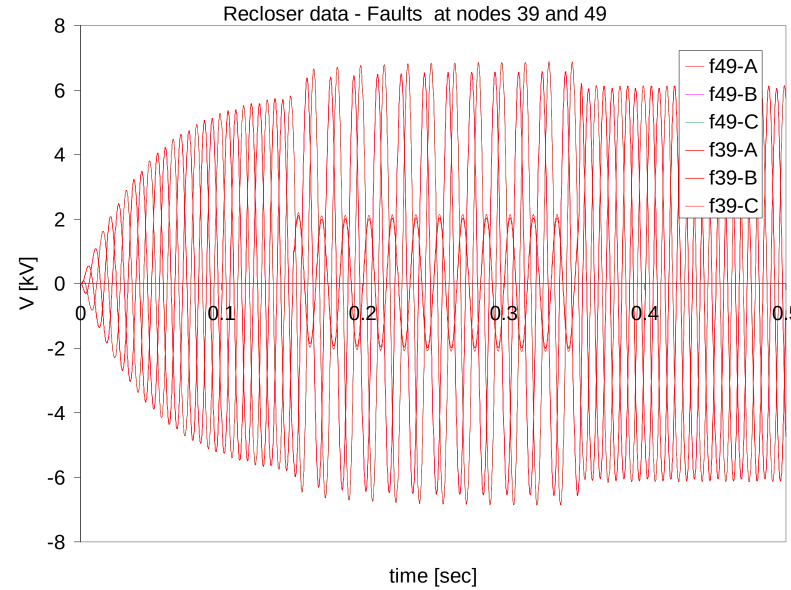


V differences

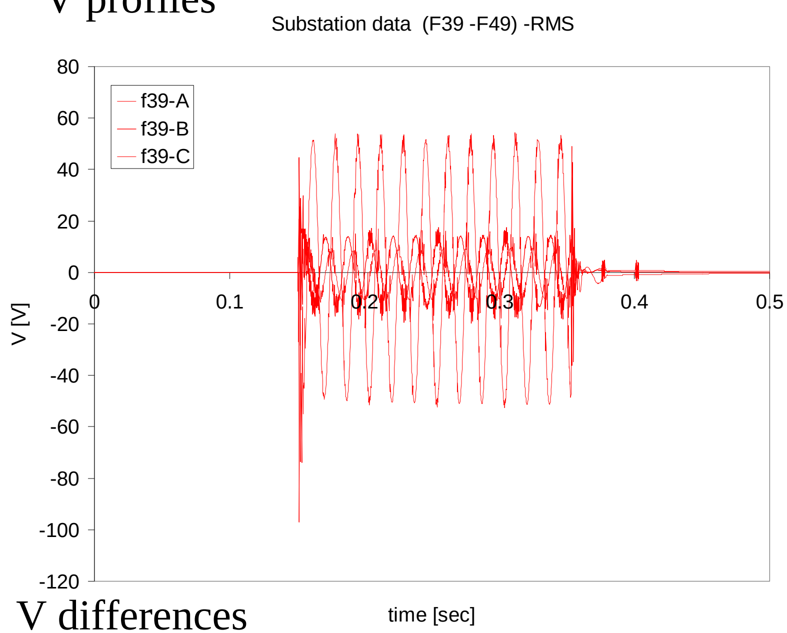
PSCAD Simulation Results (cont'd)

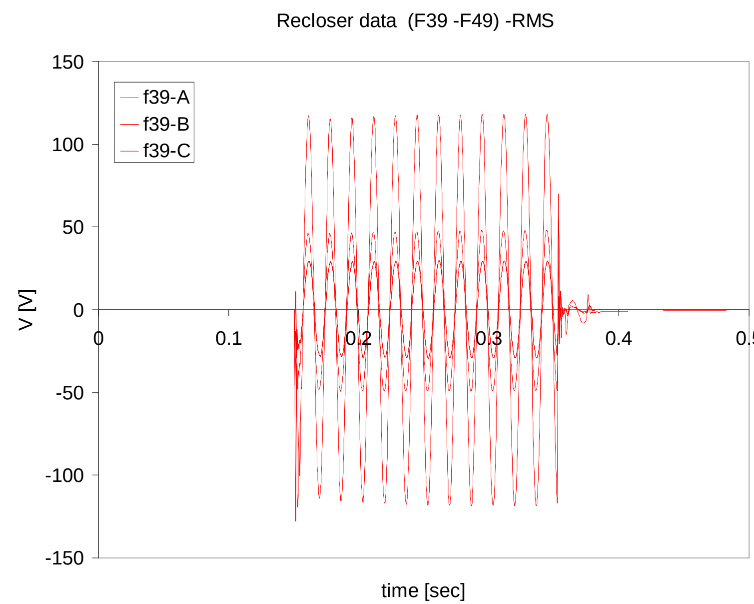
- Voltage waveforms at buses 39 and 49; substation (left); recloser (right)





V profiles





V differences

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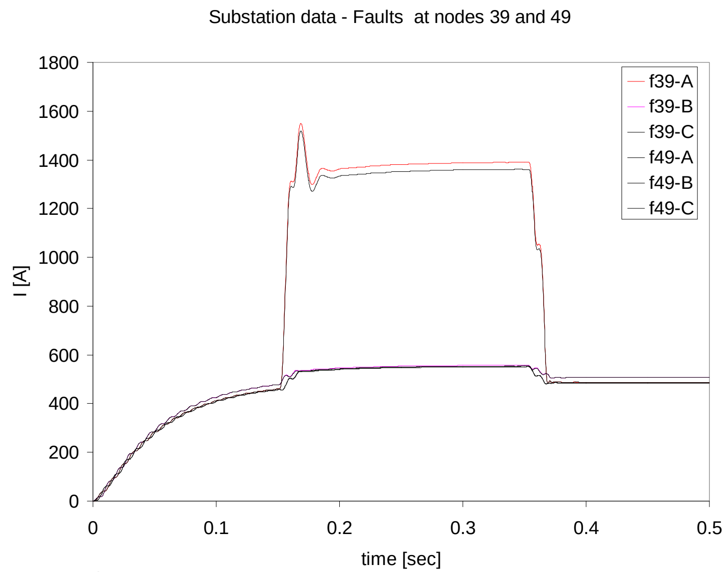
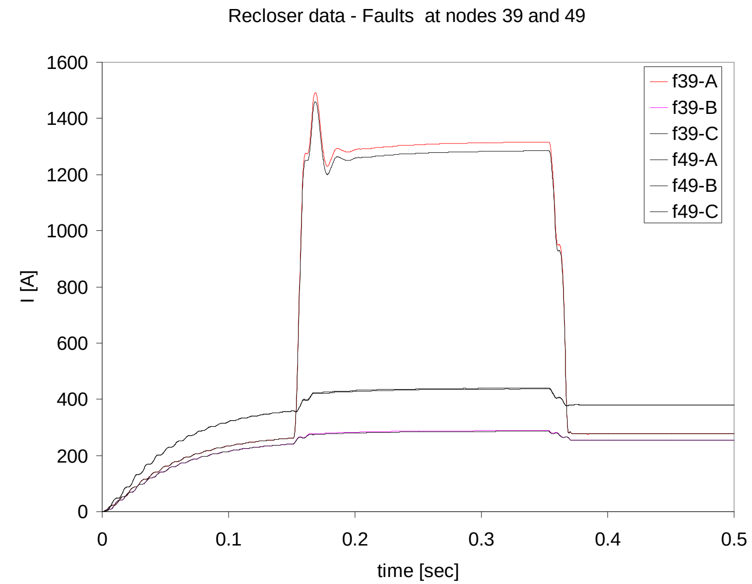
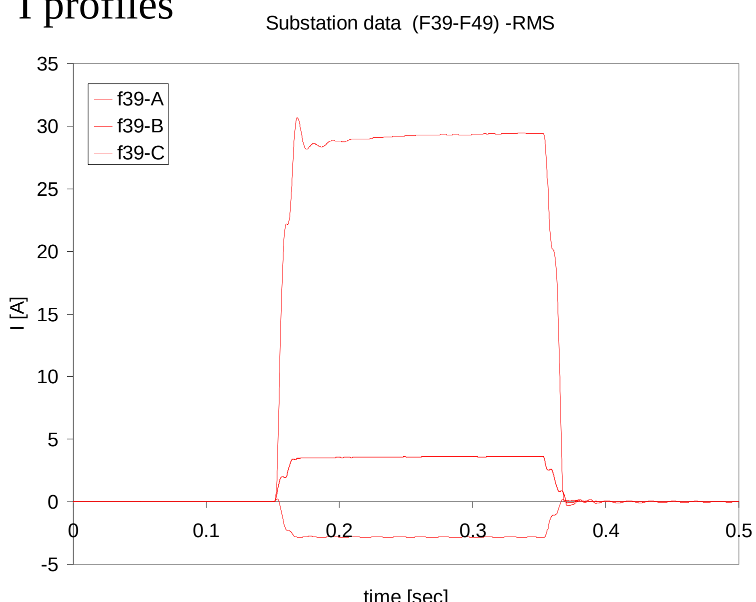
PSCAD Simulation Results (cont'd)

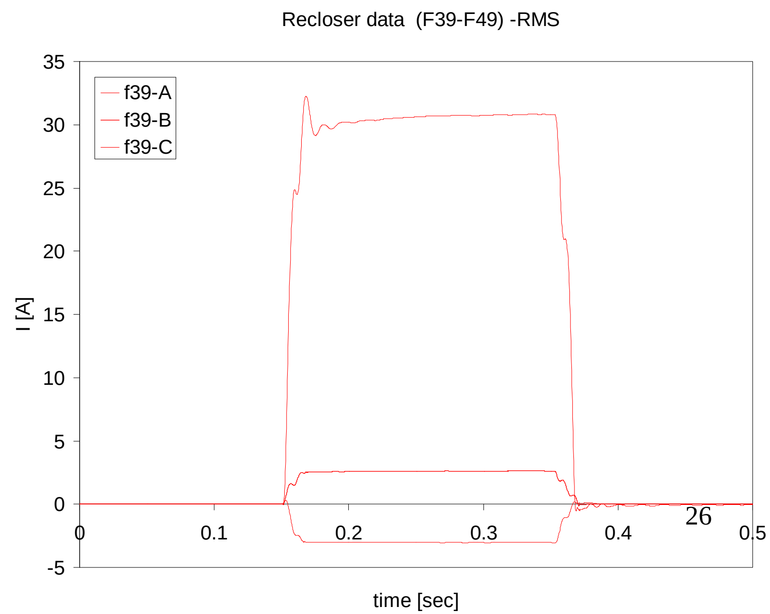
- RMS currents at buses 39 and 49; substation (left); recloser (right)





I profiles

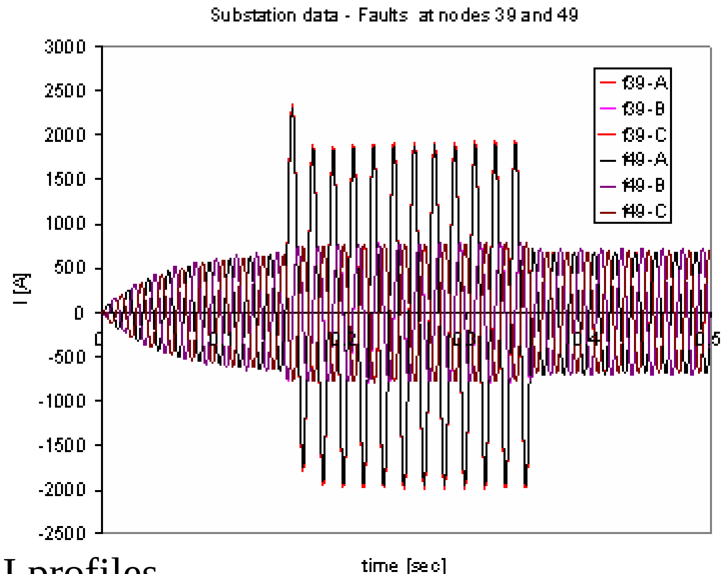


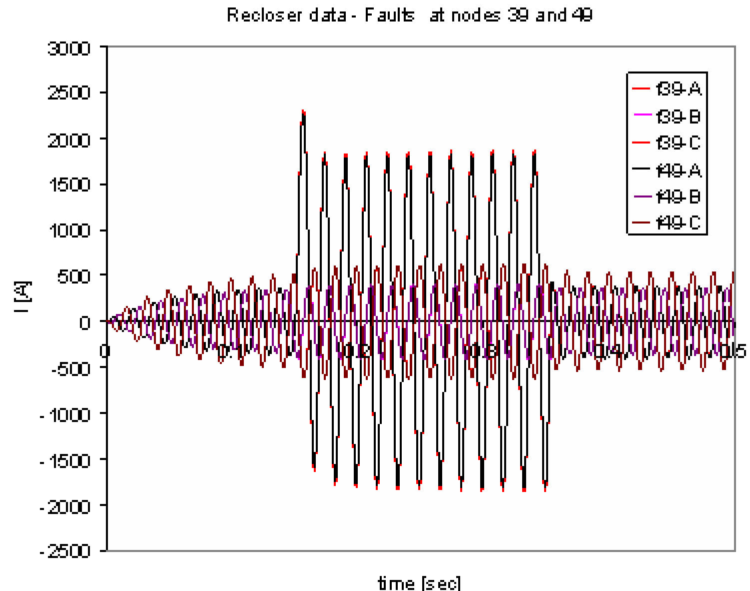


I differences

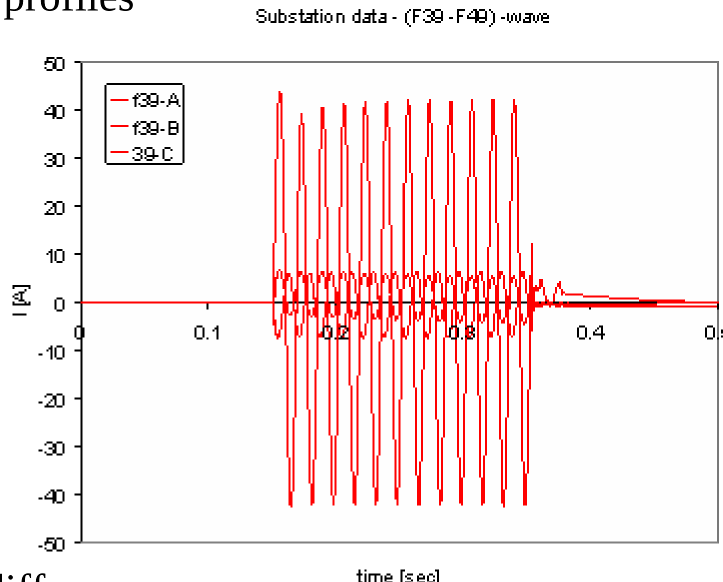
PSCAD Simulation Results (cont'd)

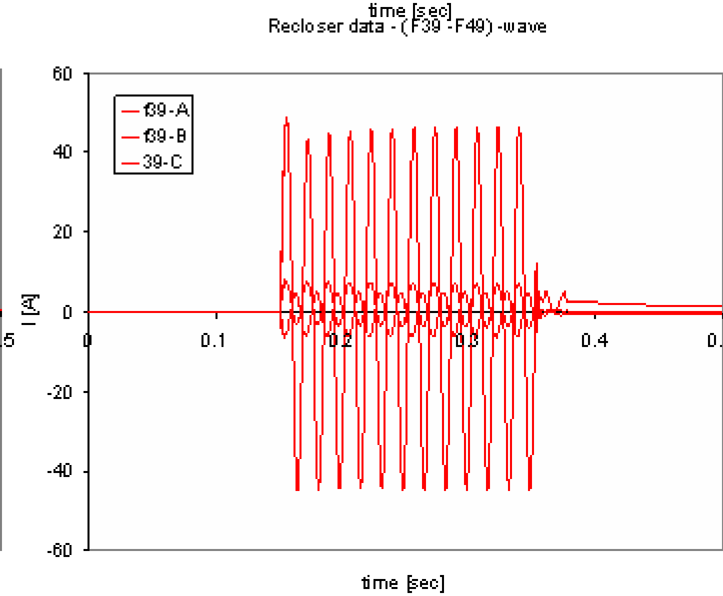
- Current waveforms at buses 39 and 49; substation (left); recloser (right)





I profiles





I differences

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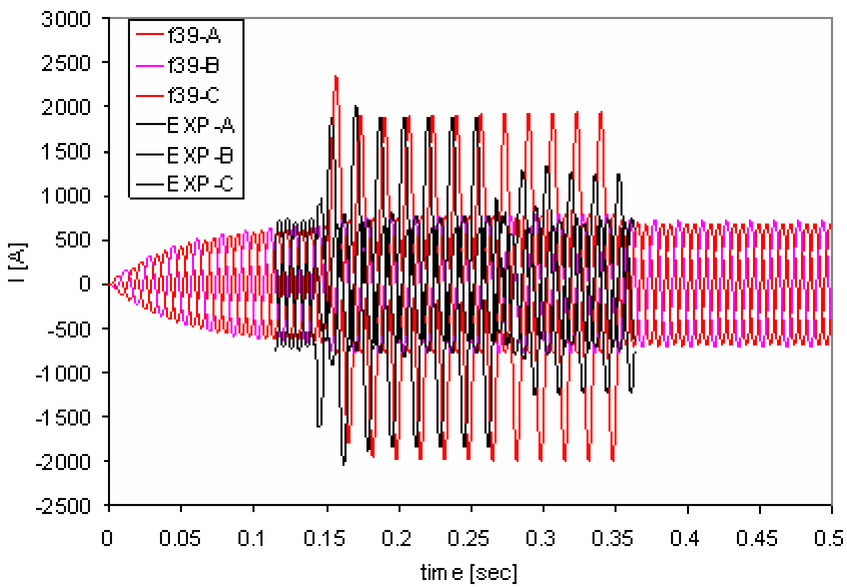
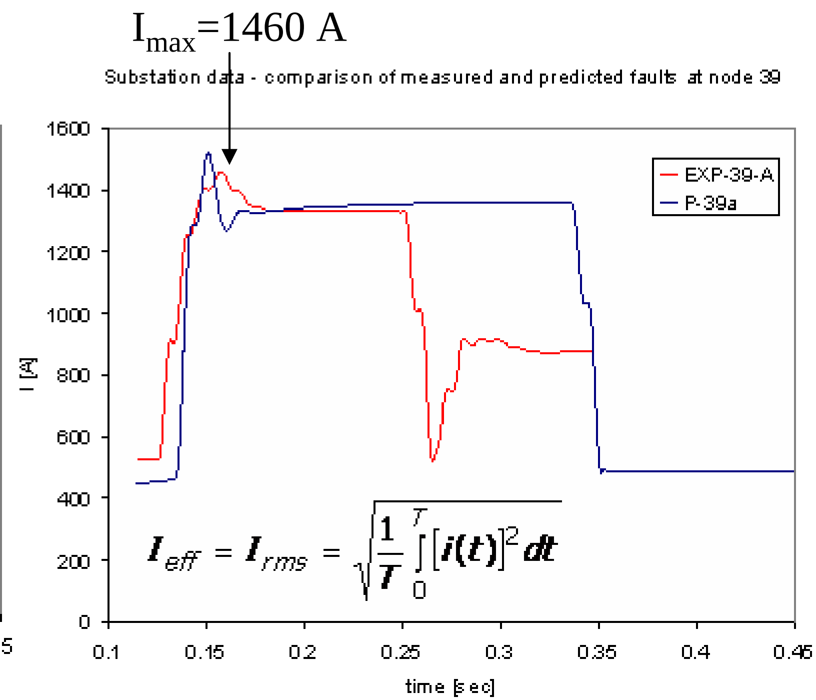
Jewel circuit: Comparison of Predictions and Measurements at Node 39

- RMS Currents (no smoothing): (left) Waveforms; (right) RMS





Sampling rate:
Experimental: 1.440 kHz
PSCAD = 4 kHz

Characterization of DTE's Jewel Outage Event on July 17, 2006

- Average of RMS Currents ($\bar{I}_{rms}$): Comparison between measurements and predictions at buses 39, 43, 49, 51 (locations predicted by DSFL (see page 6)
- Minimum I_{index} is at bus 39 (real fault location)

$$\bar{I}_{rms} = \frac{1}{t_f}\int_0^t \left(\sqrt{\frac{1}{T}\int_0^T [i(t)]^2 dt} \right) dt$$

$$I_{index} = \sqrt{\frac{1}{2}\sum_k \left[1 - \left(\frac{\bar{I}^{p}_{rms}}{\bar{I}^{exp}_{rms}} \right)^2 \right]}$$

Bus #	I_{index}
39	0.071
43	0.188
49	0.159
51	0.146

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AFAS Predictive Capabilities versus Measured Sampling Rate Data

Low impedance bolted faults (0-10 ohms)	High impedance faults (50-100 ohms faults)	High impedance faults/failures with 3rd order harmonics	High impedance failures with 7th order harmonics
10 samples/cycles	10 samples/cycles	30 samples/cycles	70 samples/cycles

- Spectral resolution of PQNode is 128 samples/cycle or 7.68 kHz, enough to capture any type of faults/failures in distribution systems.
- DWT requires a frequency range of 0-300 Hz for voltage and 0-600Hz for current to capture all types of low and high impedance faults.
- Literature on DWT for high impedance faults suggest a spectral resolution of 3.2-6 kHz

Technical and Economic Benefits

- AFAS software will significantly enhance ability of distribution utilities to provide protection, operational and planning personnel with
  - Improved fault diagnosis technologies that enable anticipating, locating, isolating and restoring faults/failures with minimum human input and fast response time
- Specific benefits, unique to the current approach, not easily addressed with current technologies:
  - Location of “nagging” temporary faults causing momentary outages
  - Detection of high impedance faults
  - Reduced patrol time to locate faults on inaccessible facilities (including rural and underground)
  - Improved system analysis (protection, planning and operational)
  - Reduced the overall outage time (improved restoration time)
  - Increased service and component reliability

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Integration Challenges at Utilities

- Interface to existing software systems and need for communications
  - AFAS GUI used for software integration and easy communication/integration with utility databases
  - Some specific software adaptations will be required at each utility
- Utilization of PQ monitoring devices for waveform capture
  - PQNode, transportable Dranetz-BMI 7100's and Dranetz PP1's, Oscillographs, Cooper's Nova reclosers, etc.
  - Voltage information recorded at both substation and reclosers is useful
- Integration into the current outage analysis process
  - AFAS will plot the fault locations/characteristics in OMS, PQView, etc., based on utility desires/needs
  - Faults will also be graphically shown in PSCAD/DEW/etc. or a simple visualization module will be developed under AFAS platform

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Integration Challenges at Utilities (cont'd)

- Keeping circuit models up-to-date
- Pre- and post-processing with the following attributes
  - Custom simulation set up that allows for full automation (fault location module is moved automatically based on a predetermined list of fault locations (selected/all circuit components))
  - Search scheme is quick/efficient based on V&I indices (typically less than 20,000 indices/circuit)
  - Time-normalized indices; fault duration not an issue; indices account for initial transient behavior of faults; valid for both momentary and permanent faults
  - Measured waveforms are processed in real time; their calculated V&I indices are then compared with pre-processed ones from fault library

Conclusions

- AFAS software is a powerful transient software tool
  - It can be used for both planning and operational needs to study, detect and locate faults/failures in distribution power systems
  - V&I fault signature indices can be used to help to determine the location of low impedance momentary and permanent faults
- A great feature of the AFAS is its ability to use:
  - Only substation (PQNode) and perhaps recloser recordings (Nova recloser from Cooper that can record waveform V&I values)
  - No additional sensors are needed to detect faults and anticipate problems in distribution power systems
  - Smart switches may only be needed for restoration purposes

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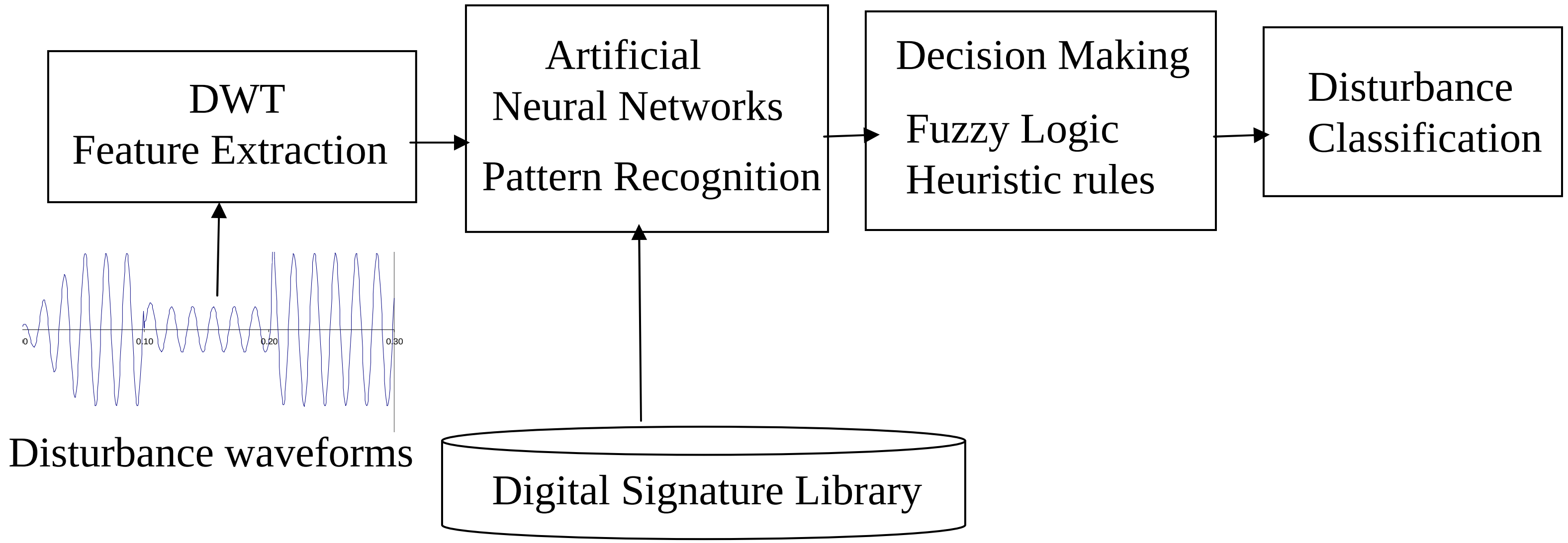
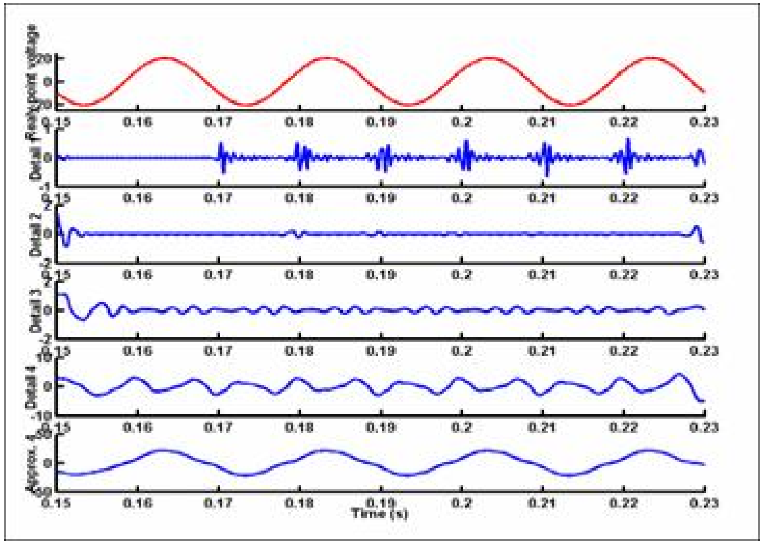
Future Work

- AFAS Predictive capabilities will be significantly enhanced in the next phase:
  - Develop filters between PSCAD and DEW/CymDist/PSS-E/AEMPFAST) to ease software communication and speed-up and decrease cost of AFAS implementation at utilities
  - PQ and remote (Cooper's Nova reclosers) monitoring over 3-6 months of low and high impedance momentary faults at AEP and DTE on several of their worst performing circuits
  - Develop an Automatic Disturbance Recognition System:
    - Heuristic rules to match simulation waveform records from the digital signature library in Comtrade format, extract waveform distortions, develop RMS records, etc.
    - Discrete Wavelet transform (DWT) for feature extraction to be used in a pre-processing mode; an index search scheme will be used
    - NN multi-layered perceptron for pattern recognition
    - Fuzzy logic/heuristic rules for decision making on the disturbance/transient category
  - Develop a specialized post-processing software tool to detect, localize and graphically alarm the user about any kind of faults

Automatic Disturbance Recognition System

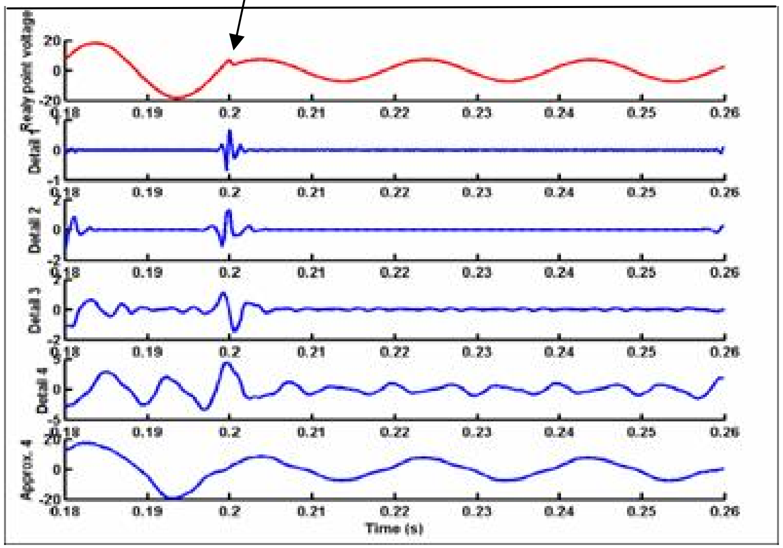


Literature Examples of Wave-fault Disturbance Detection using Daubichies mother wavelet of order 4 (Db4)



High Impedance Fault (time = 0.17 s)

distortion



Bolted Fault (time =0.2 s)

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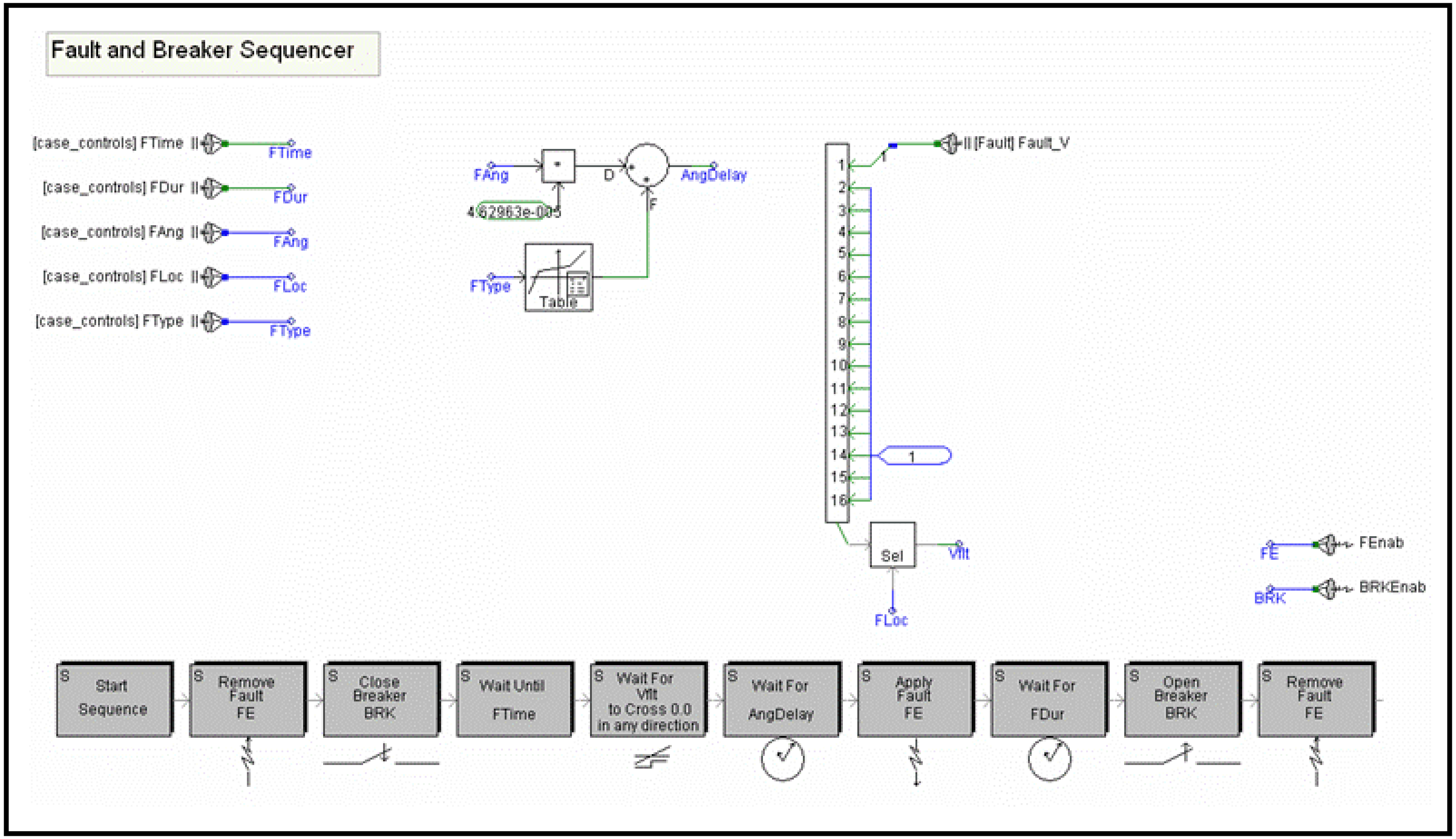
Backup slides

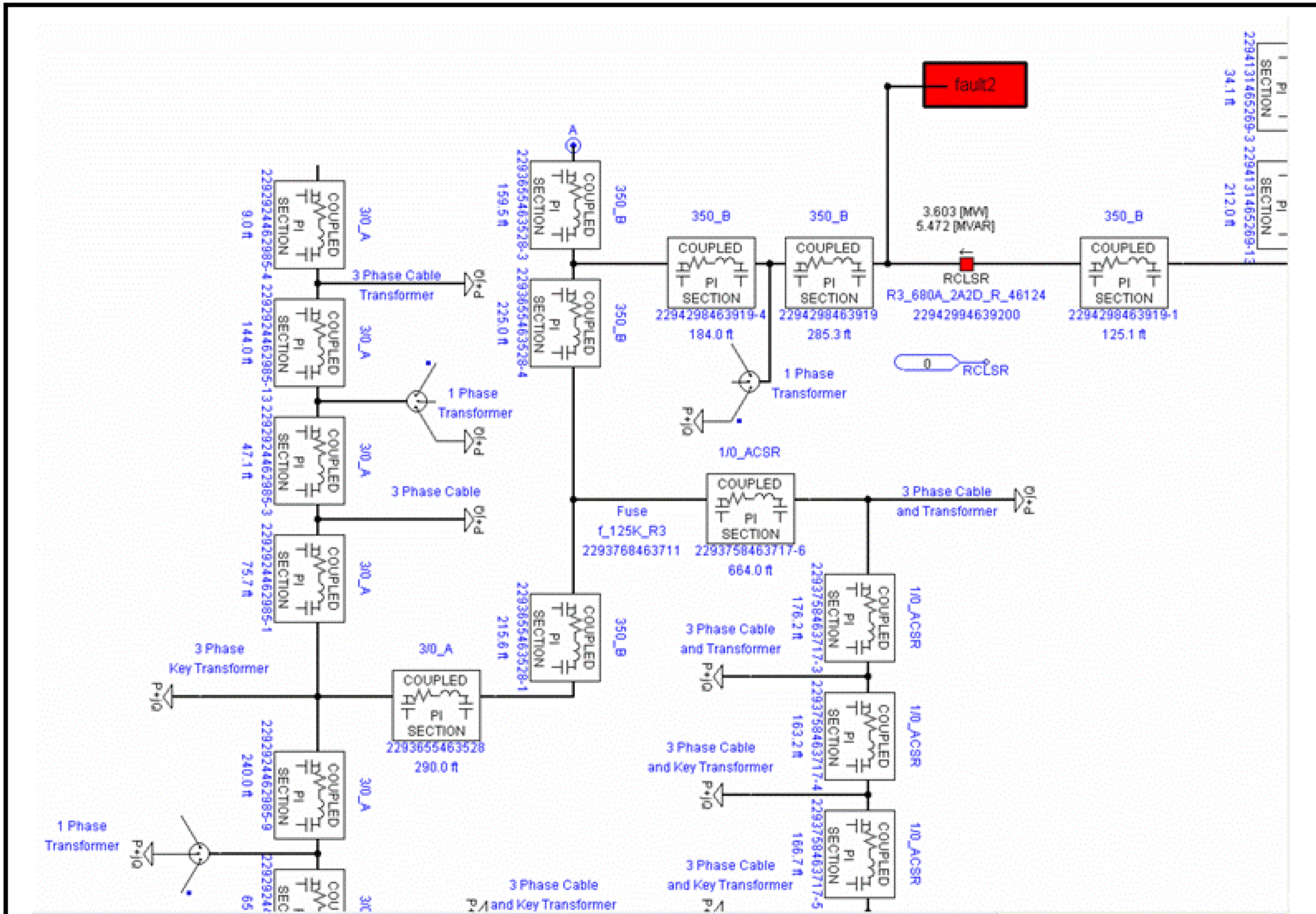
PSCAD Custom Simulation Setup (cont'd)

- Fault and Breaker Sequencer



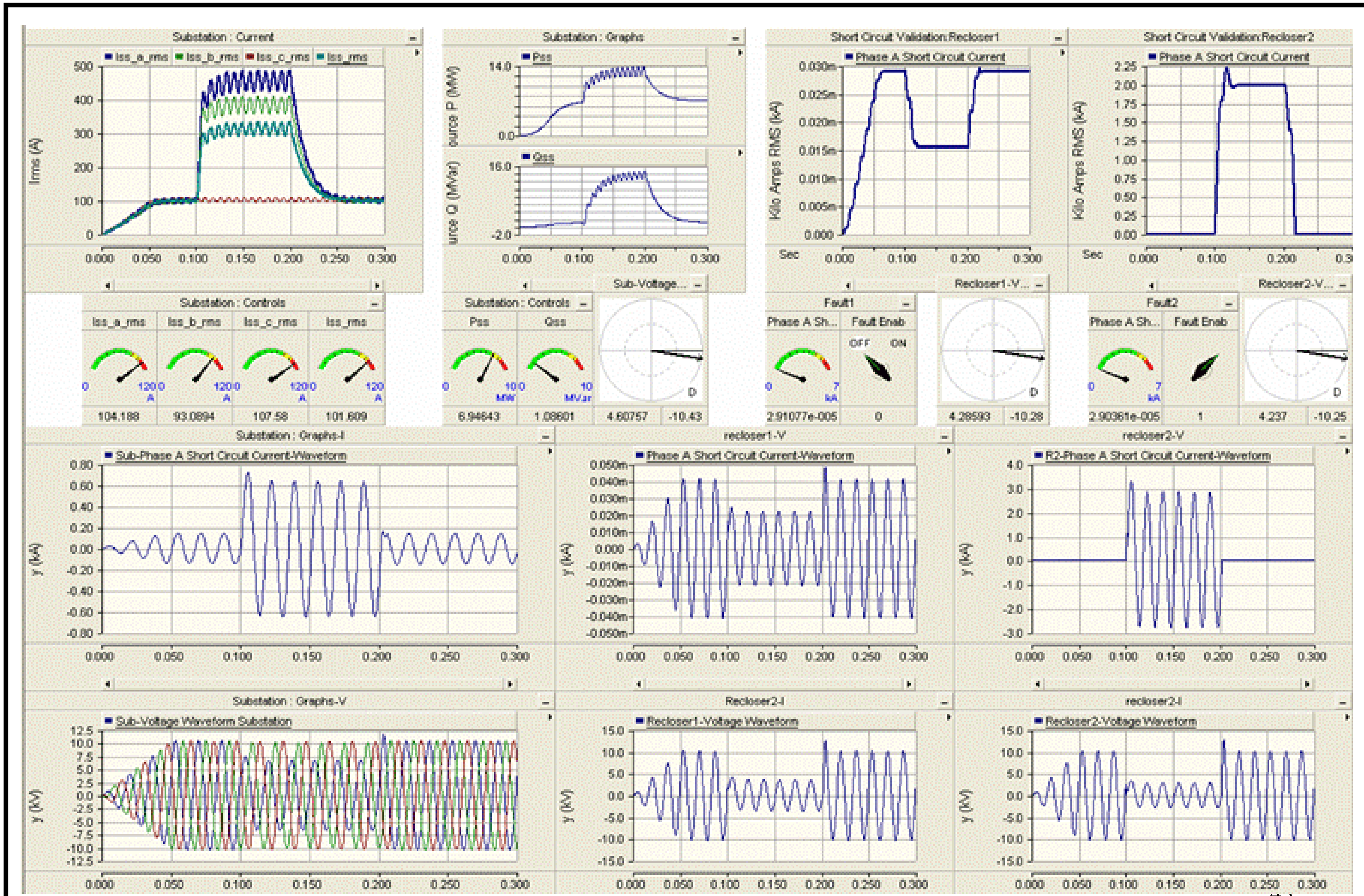
Orion Circuit: Fault at Recloser #2

- Recloser #2 area



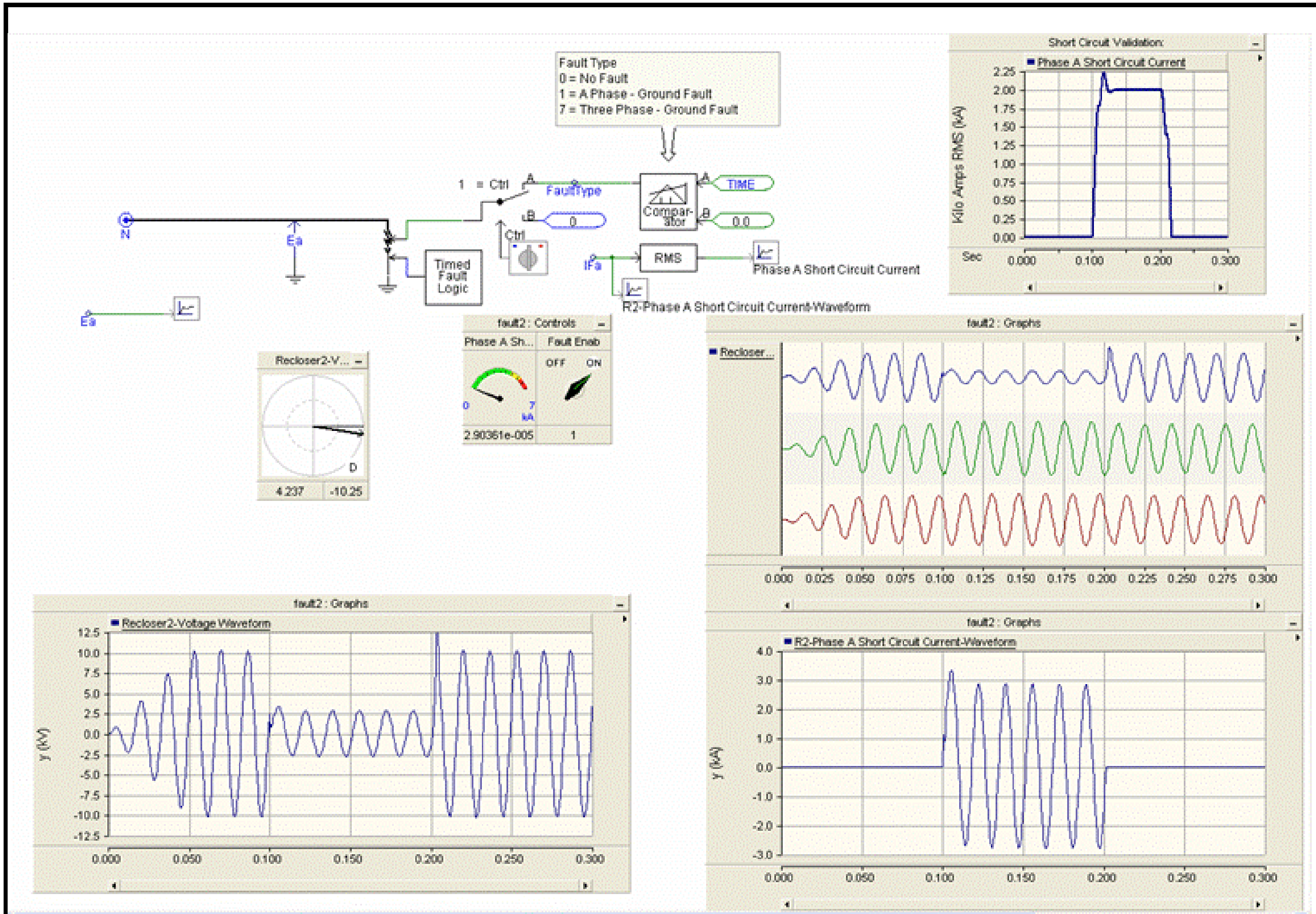
Orion Circuit: Fault at Recloser #2

- Fault at Recloser #2



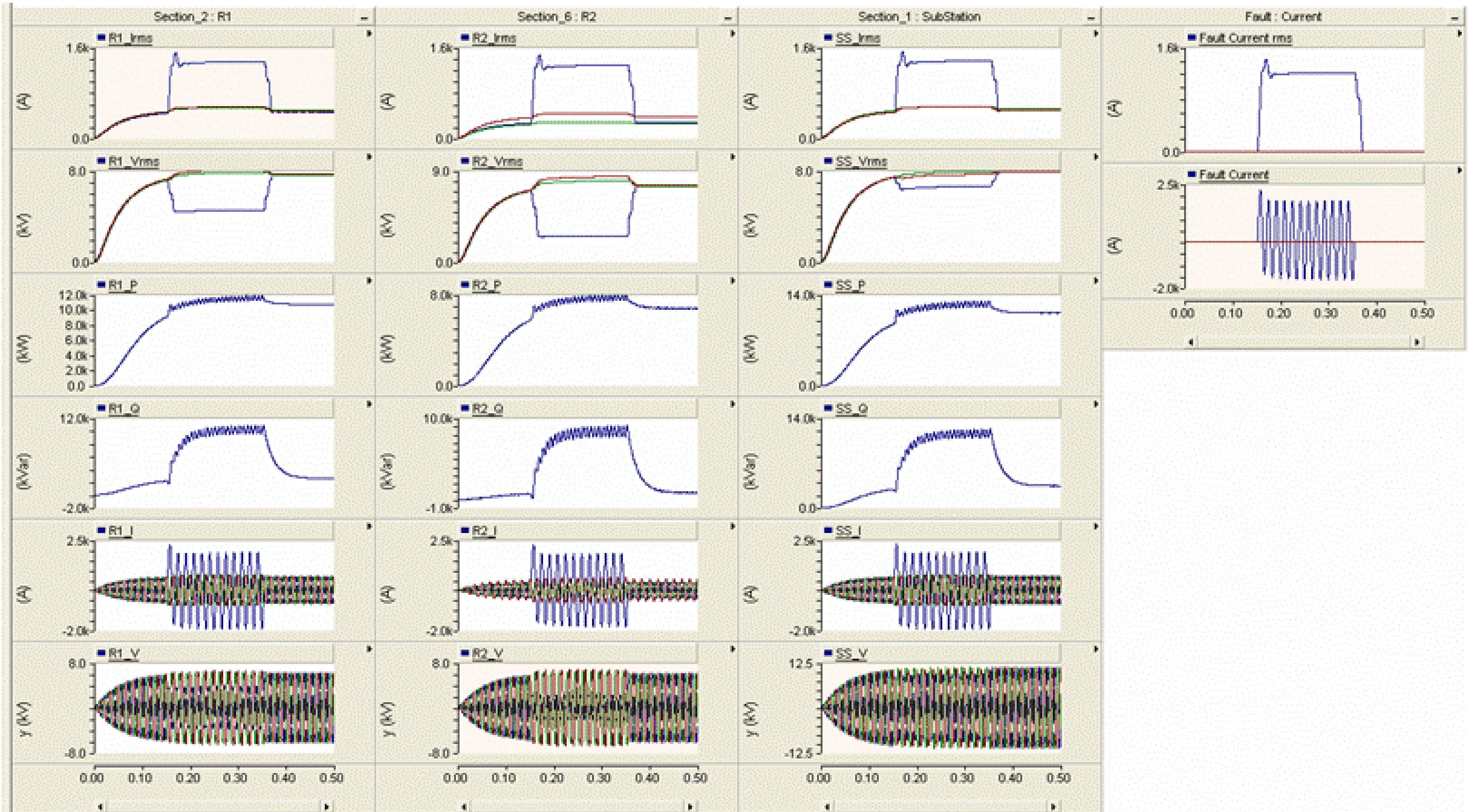
Orion Circuit: Fault at Recloser #2

- Fault at Recloser #2

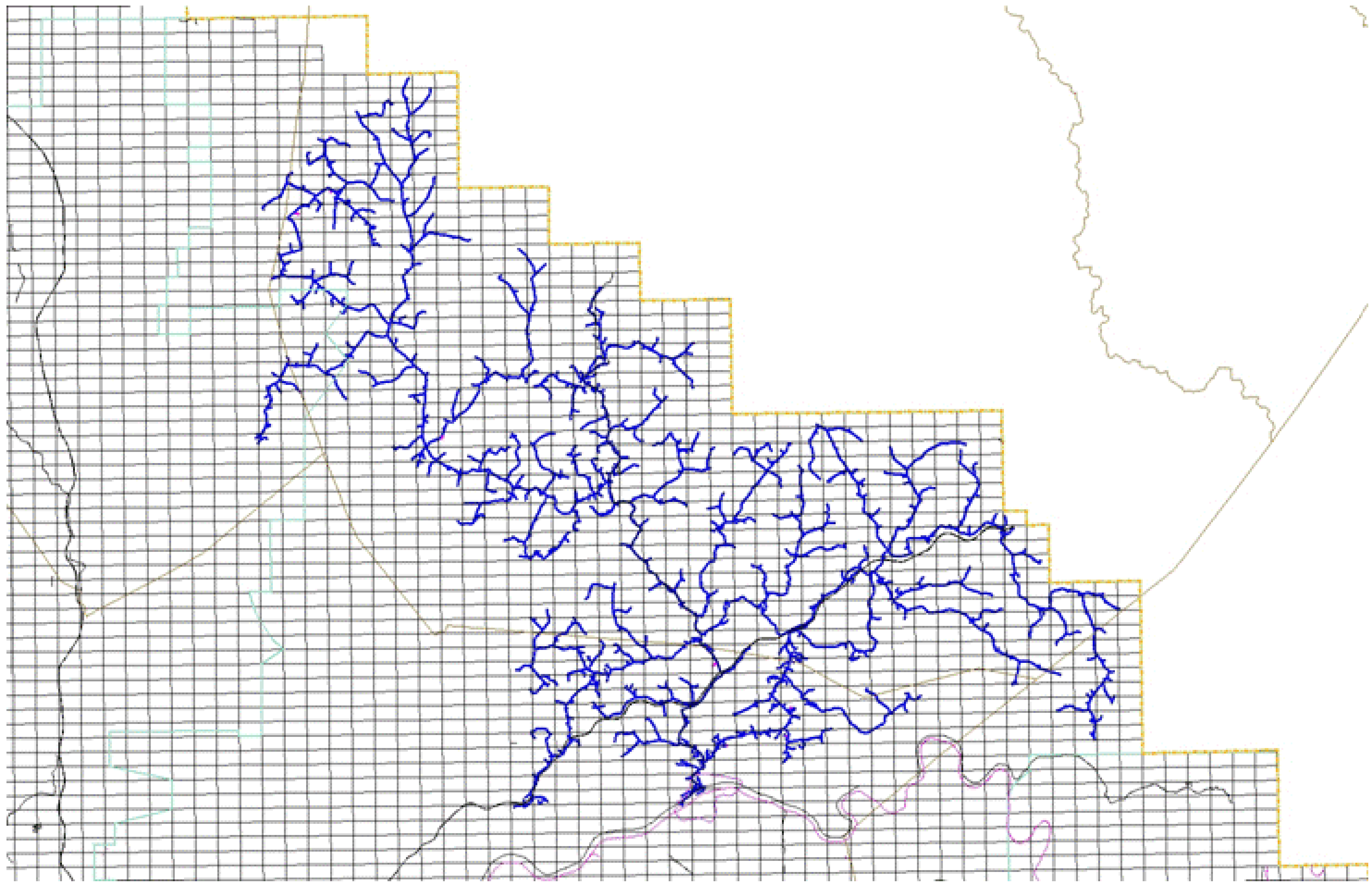


Example of PSCAD Predictions

- **Jewel circuit:** Single-phase fault prediction (voltage dips and fault currents) in PSCAD (From signature library of faults, Jewel circuit, bus 49, V&I records at substation and reclosers).



AEP's Walton Circuit (Clenderin Station)



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AEP's Walton Circuit (Clenderin Station)

- Walton circuit had 5 recorded faults in 2006

	Date	Time	Station	Circuit	Iso Pole	Fault Pole	Ticket #
PQ Data	7/13/2006	17.43	Clendenin	Walton	39811084D00105	1084-D-105	56761-1
	6/27/2006	11.03	Clendenin	Walton	39811133B00066	39811133B00014	62012-1
	6/23/2006	11.53	Clendenin	Walton	39811085D00090	1085D90	60699-1
	6/18/2006	18.46	Clendenin	Walton	39811010B40077	1010B77	54486-1
	7/6/2006	19.18	Clendenin	Walton	39811010B40077	1010B77	66293-1
PQ Data	5/26/2006	20.46	Clendenin	Walton	39811133B00066	1109-D-1	60410-1
	5/25/2006	23.42	Clendenin	Walton	39811085D00090	1086C22	59166-1
	10/20/2006	19.47	Clendenin	Walton	39811133B00066	1133B10	52797-1
PQ Data	8/17/2006	12.44	Clendenin	Walton	39811133B00066	1133C15	58391-1
	7/17/2006	2.00	Clendenin	Walton	39811085D00090	1086C31	59153-1
PQ Data	10/23/2005	18.43	Clendenin	Walton	39811107A00004	39811107A00016	39273-1
	10/11/2006	19.46	Clendenin	Elk River	38810055A30121	55A32	64087-1
	7/20/2006	23.10	Clendenin	Elk River	38810030A00044	6B2	62783-1
	7/17/2006	14.45	Clendenin	Elk River	38810055A30121	55A121	59375-1
	7/16/2006	17.03	Clendenin	Elk River	38810030A00099	30A99	59049-1
PQ Data	7/11/2006	8.21	Clendenin	Elk River	Feeder	4-C-42	55113-1
	5/26/2006	21.28	Clendenin	Elk River	38810030A00099	102-C-35	60459-1
	10/21/2005	12.07	Cloverdale	College	37800158D20012	37800158D02051	38687-1
	2/24/2006	1.21	Cloverdale	College	37800182C20515	182-5763	58511-1
	6/17/2006	12.57	Cloverdale	Tinker	37800159B32079	159-131	54209-1
PQ Data	11/2/2005	16.57	Cloverdale	Tinker	37800159C04054	37800159C00233	42792-1
	9/27/2006	9.02	Cloverdale	Troutville	37800111C00162	111-172	58608-1

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AEP's Walton Circuit (Clendenin Station) (cont'd)

- Typical PQNode Fault Current Data at Clendenin Station, 128 samples/cycle)