NovaCor™

A revolution in real time.

The new world standard for real-time digital power system simulation

RTDS Technologies

On Traveling-Wave Relay Testing (TWRT)

NovaCor
A revolution in real time.

RTDS Technologies Inc.
October 2019

OUTLINES

1. Introduction of TWRT on NovaCor and GTFPGA
2. Discussion on Line Models
3. Remarks and Future Considerations

TWRT on NovaCor™

Traveling Wave Relay Testing

Traveling Wave Relay Testing

- **Simulation Algorithms**
  - Phase Domain Frequency dependent Transmission Line Model
  - Accurately Modelling The Transients and Coupling of AC and DC Transmission Line

- **Simulation Hardware**
  - NovaCor Chassis - Latest RTDS Real Time Simulation Platform
  - GTFPGA – VC707 FPGA Based Simulation Support Unit

Traveling Wave Relay Testing

- **NovaCor - Substep Simulation**
  - ❑ Leverage processing power of NovaCor
  - ❑ Split network into small sections modelled on different cores to keep timestep small
  - ❑ Runs all standard component and CBuilder models
  - ❑ Optimized network solution
  - ❑ Optimized 3 conductor transmission line

TWRT
on NovaCor™

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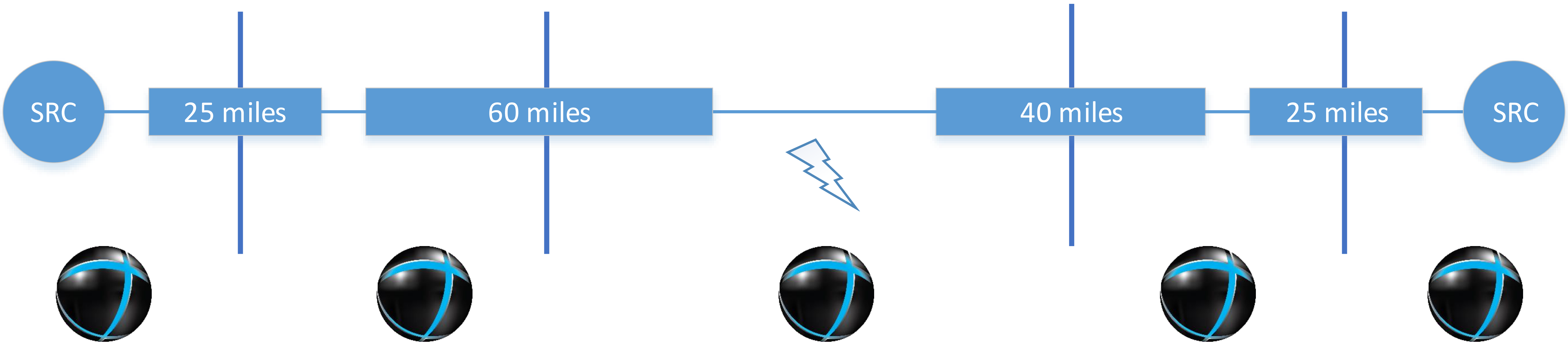
Substep Case 1, 4 Lines



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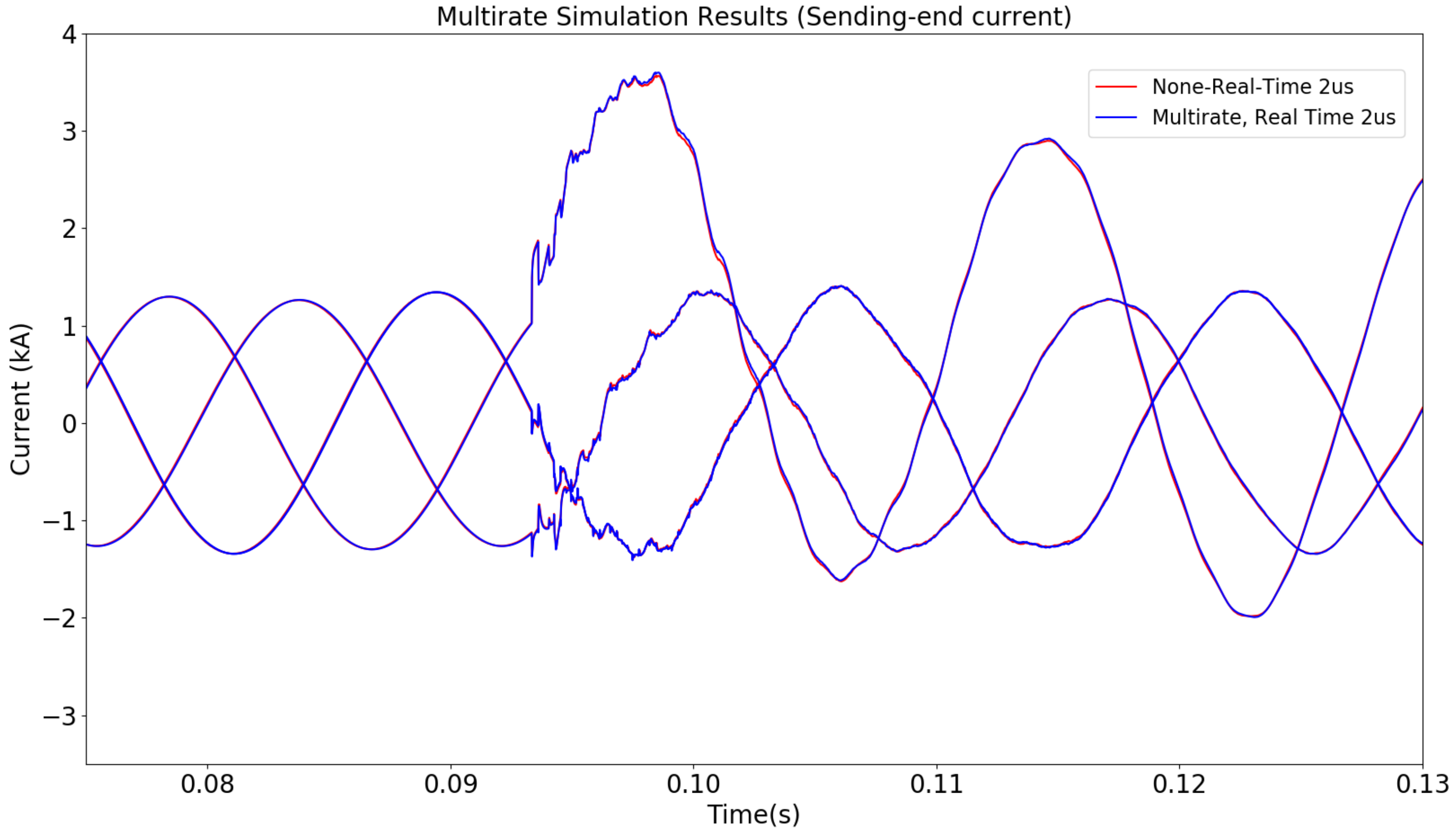
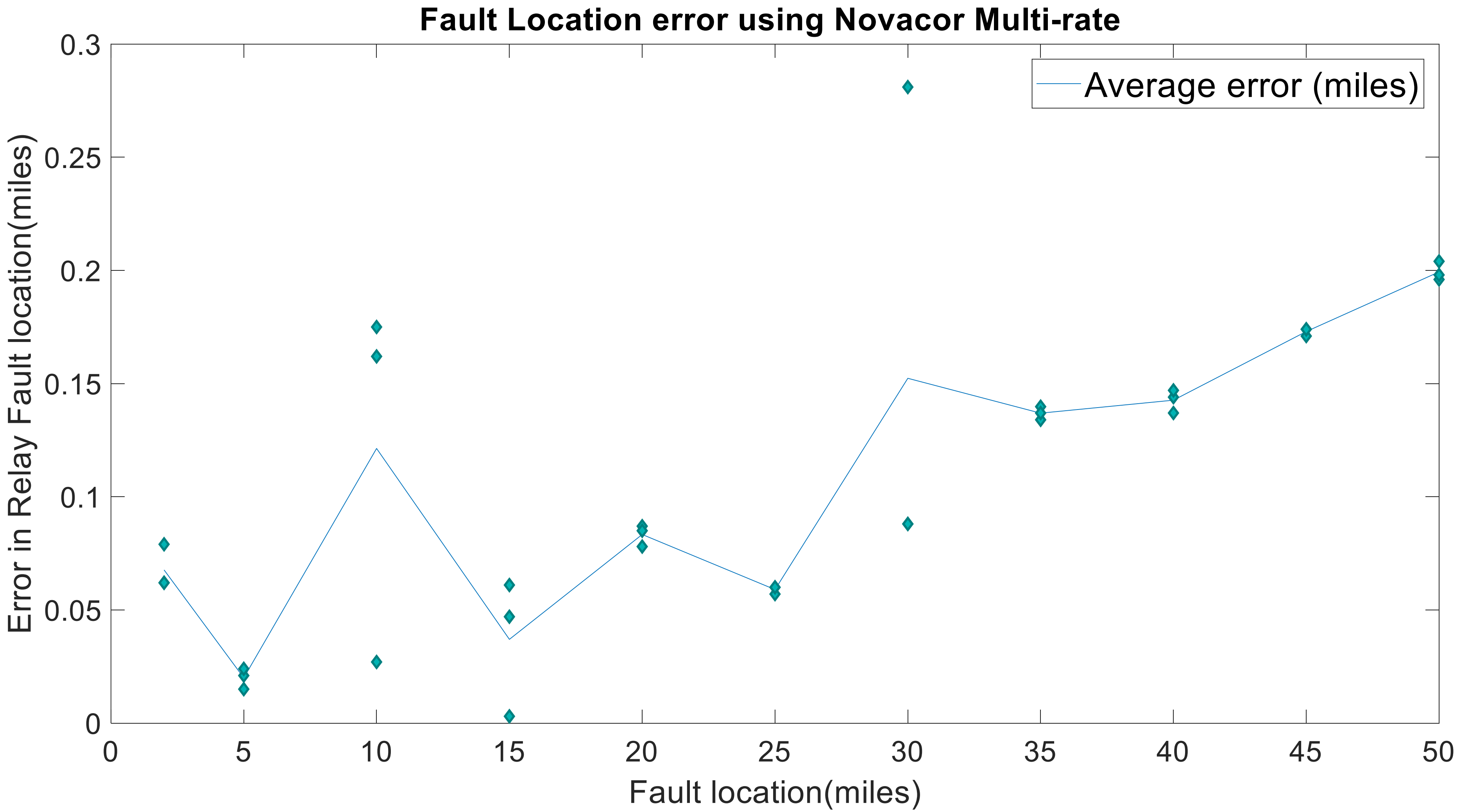
Multirate Simulation



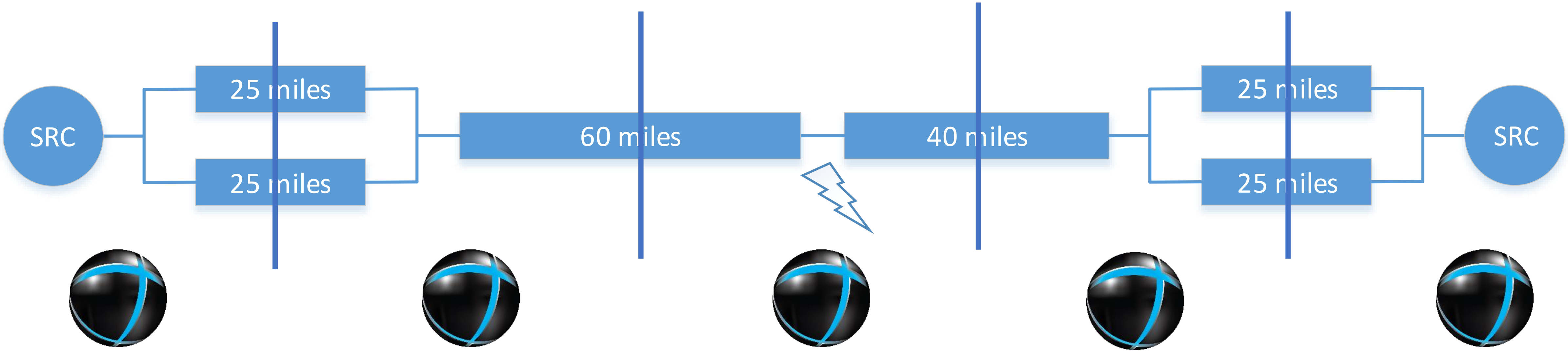
Relay Test Results

	Test 1			Test 2			Test 3		
Fault Location (miles)	Relay 1	Relay 2	Error	Relay 1	Relay 2	Error	Relay 1	Relay 2	Error
2	1.938	98.062	0.062	1.921	98.079	0.079	1.938	98.062	0.062
5	5.015	94.985	0.015	5.021	94.979	0.021	5.024	94.976	0.024
10	10.162	89.838	0.162	10.175	89.825	0.175	9.973	90.027	0.027
15	15.047	84.953	0.047	15.003	58.997	0.003	15.061	84.939	0.061
20	20.078	79.922	0.078	20.087	79.913	0.087	20.085	79.915	0.085
25	25.06	74.94	0.06	25.057	74.943	0.057	25.06	74.94	0.06
30	30.281	69.719	0.281	30.088	69.912	0.088	30.088	69.912	0.088
35	35.1398	64.861	0.1398	35.134	64.866	0.134	35.137	64.863	0.137
40	40.144	59.856	0.144	40.137	59.863	0.137	40.147	59.853	0.147
45	45.171	54.829	0.171	45.174	54.826	0.174	45.174	54.826	0.174
50	50.196	49.804	0.196	50.198	49.802	0.198	50.204	49.796	0.204

Relay Test Results



Substep Case 2, 6 Lines

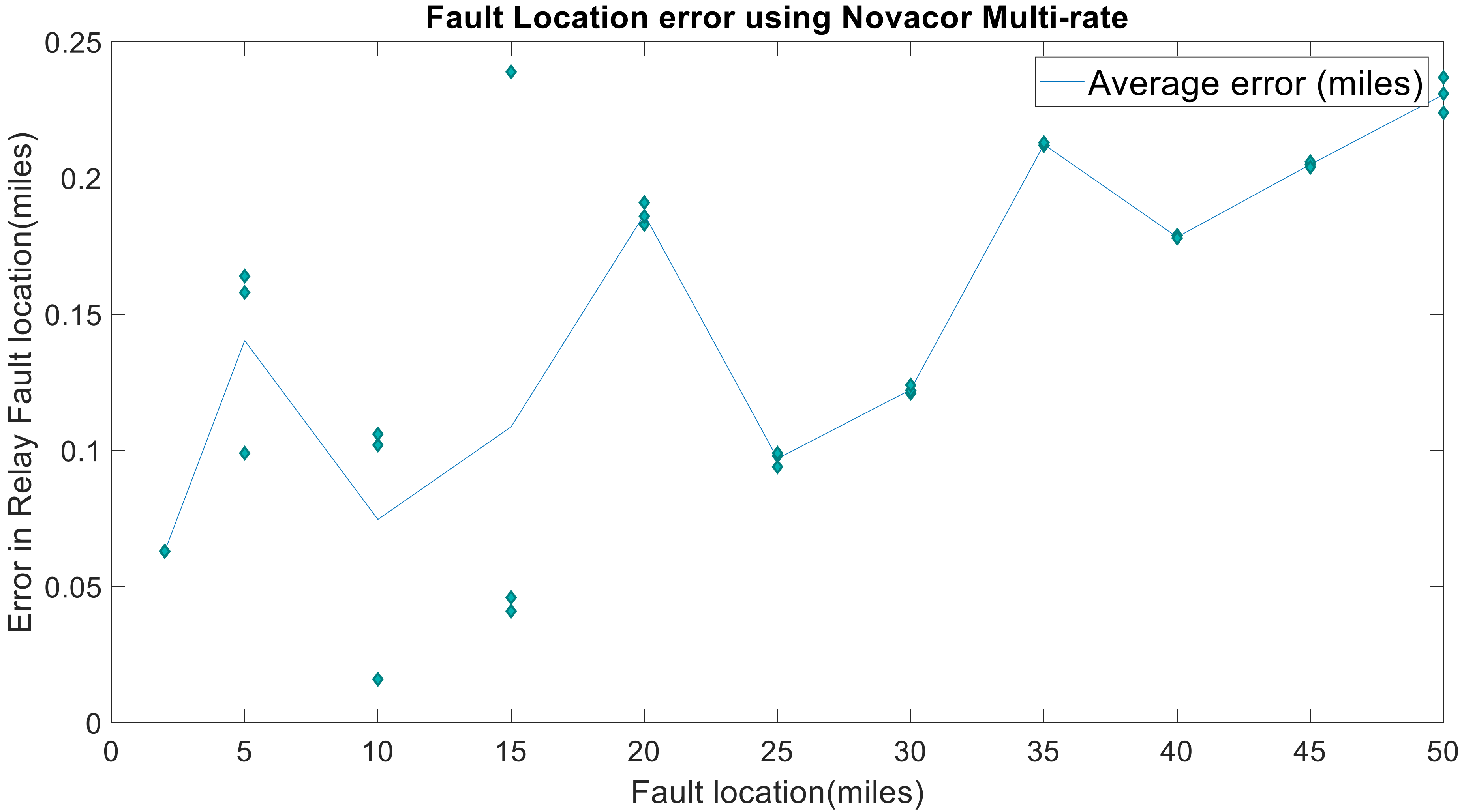


Demo

Relay Test Results

	Test 1			Test 2			Test 3		
Fault Location (miles)	Relay 1	Relay 2	Error	Relay 1	Relay 2	Error	Relay 1	Relay 2	Error
2	2.063	97.937	0.063	2.063	97.937	0.063	2.063	97.937	0.063
5	5.099	94.901	0.099	5.158	94.842	0.158	5.164	94.836	0.164
10	10.102	89.898	0.102	10.106	89.894	0.106	10.016	89.984	0.016
15	15.041	84.959	0.041	15.046	84.954	0.046	15.239	84.761	0.239
20	20.183	79.817	0.183	20.191	79.809	0.191	20.186	79.814	0.186
25	25.098	74.902	0.098	25.094	74.906	0.094	25.099	74.901	0.099
30	30.121	69.879	0.121	30.122	69.878	0.122	30.124	69.876	0.124
35	35.212	64.788	0.212	35.212	64.788	0.212	35.213	64.787	0.213
40	40.179	59.821	0.179	40.178	59.822	0.178	40.178	59.822	0.178
45	45.205	54.795	0.205	45.206	54.794	0.206	45.204	54.796	0.204
50	50.237	49.763	0.237	50.231	49.769	0.231	50.224	49.776	0.224

Relay Test Results



Traveling-Wave Relay Testing

TWRT

on the GTFPGA Unit

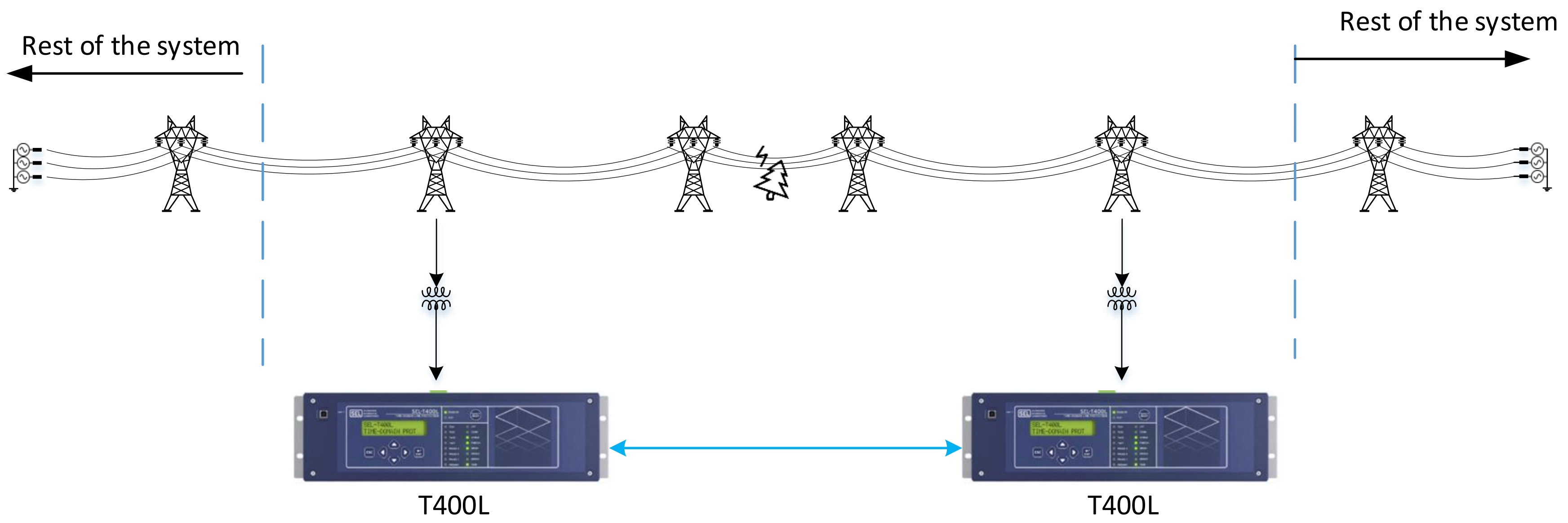
Traveling Wave Relay Testing

- **GTFPGA – TWRT**
  - FPGA based simulation
  - I/O fed through small dt subnetwork
  - Limited models (lines, sources, switches, faults)
  - Small, targeted size network
    (36 nodes, 4 line segments, 2 sources, etc.)
  - Compatible with NovaCor or PB5

TWRT
on the GTFPGA Unit

Application

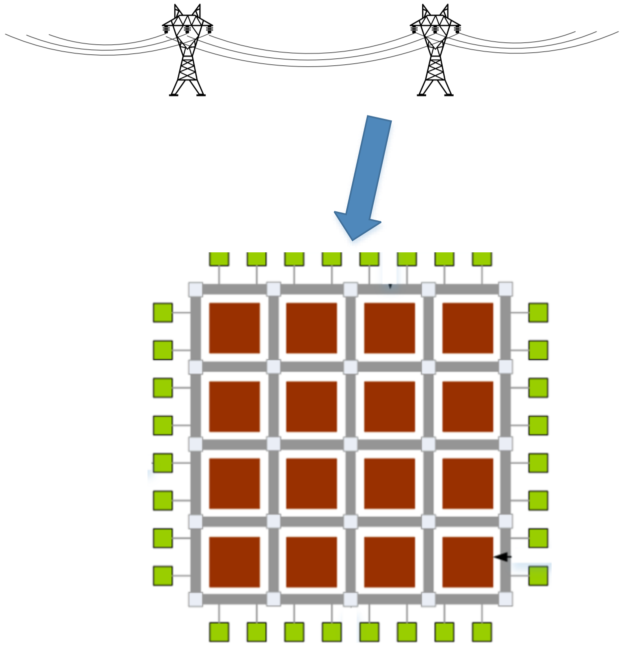
- Application:
  Small-size cases with targeted topologies



FPGA-based Line Model

Requirement:

- No artificial reflection
- Precise line model with small time-step

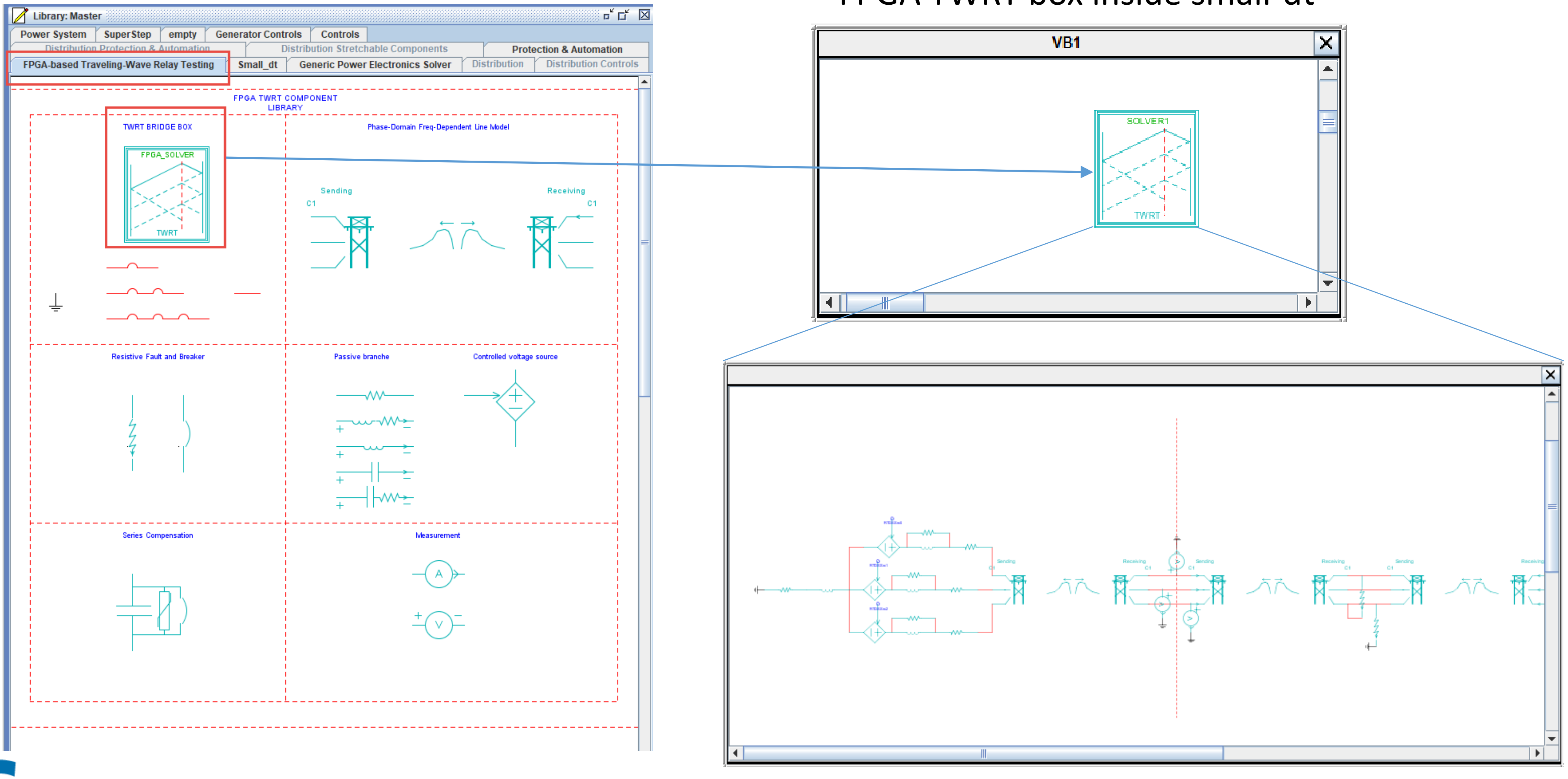


FPGA Line Model: **Frequency-dependent Phase-Domain Model**

- Accurate representation of line model on a wide frequency range
- Precise simulation for **Transposed** and **Non-Transposed** lines

FPGA TWRT Library

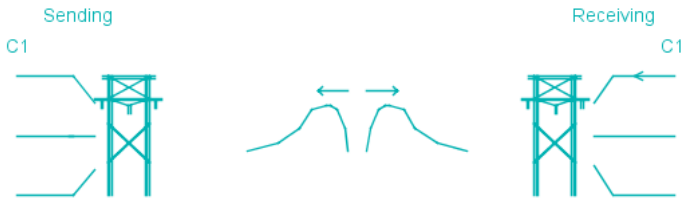
FPGA TWRT box inside small-dt



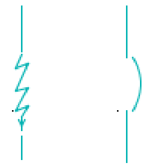
FPGA-based TWRT Library

FPGA TWRT components:

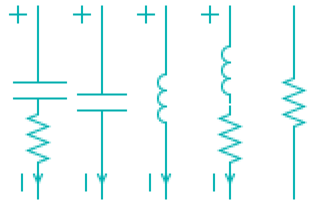
- FPGA TWRT Phase-Domain Line



- FPGA TWRT Resistive fault and breaker

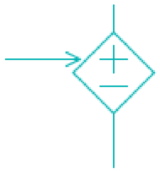


- Inductor and capacitor branches



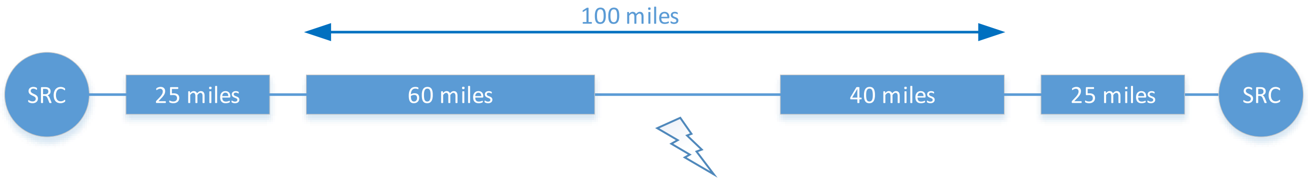
- Series compensation

- Controlled voltage sources

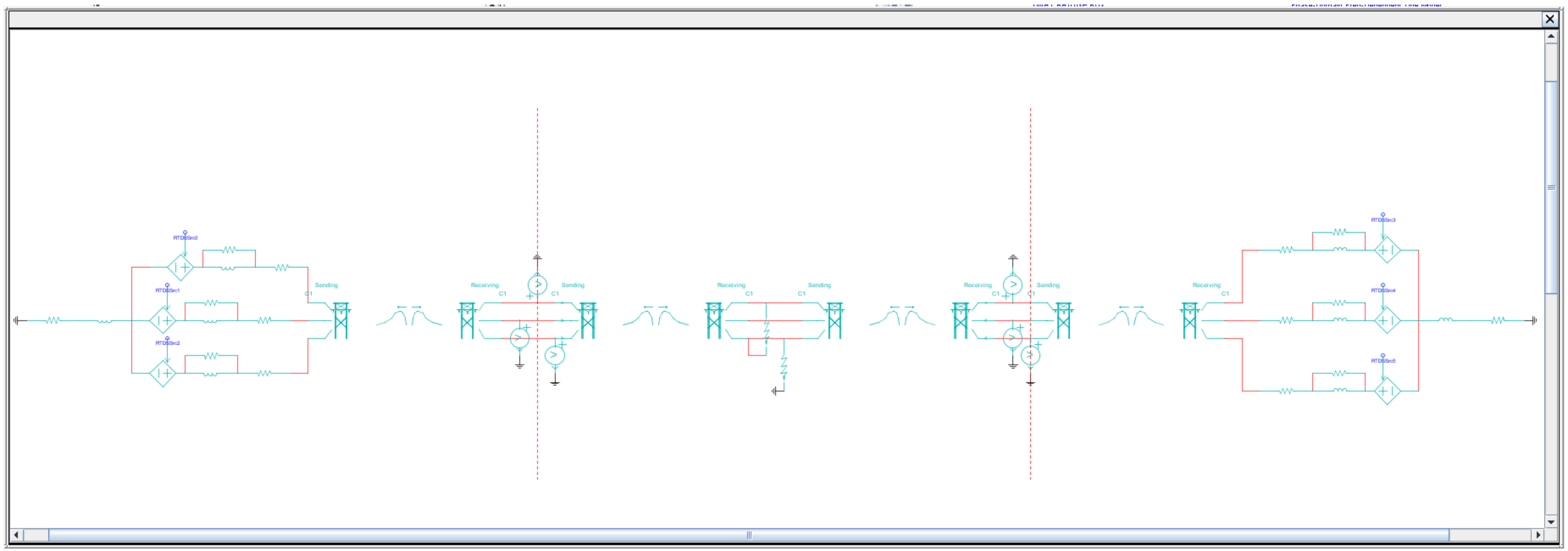


Test system

Test system



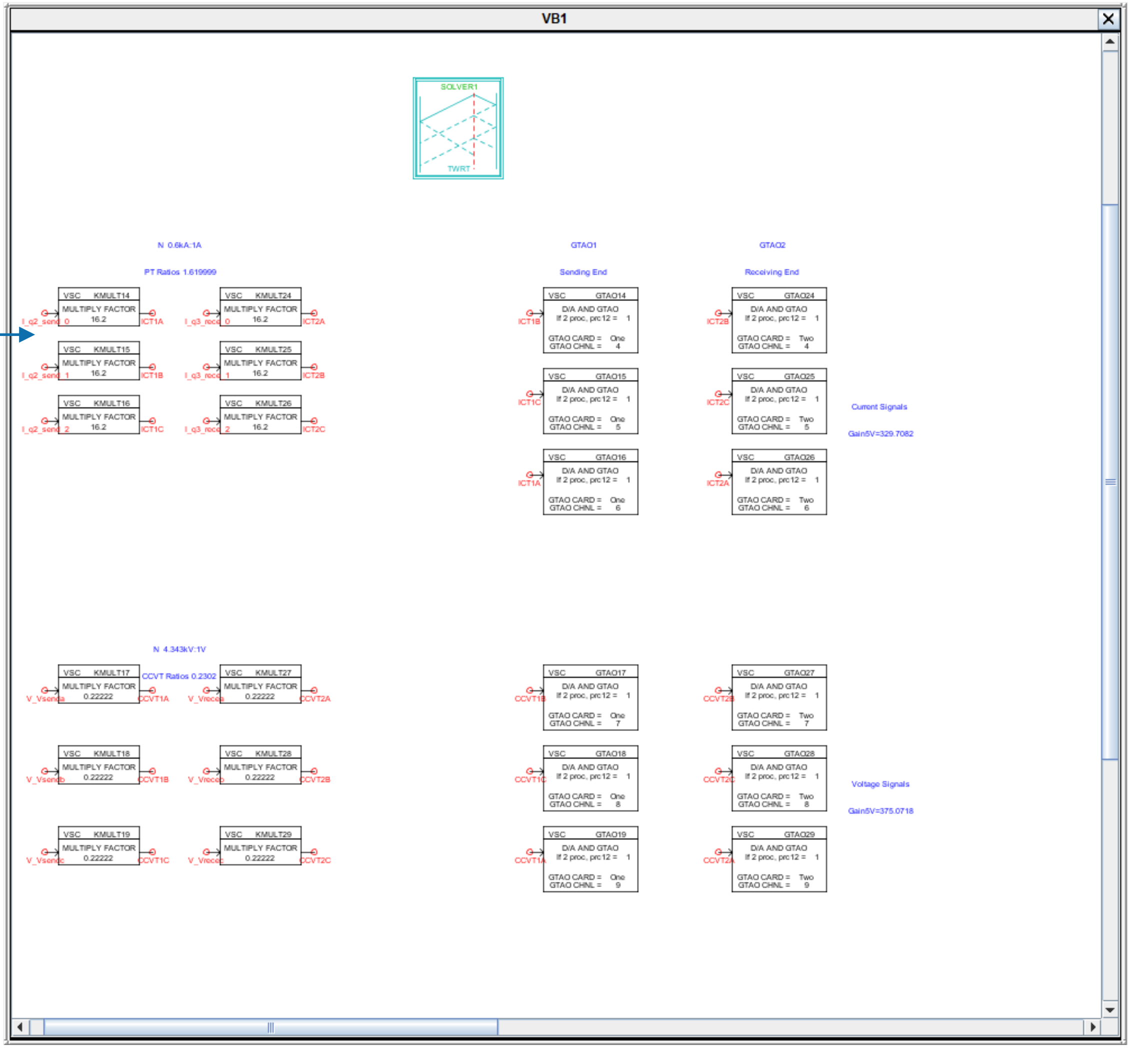
Inside TWRT box
1.42μs



Test system

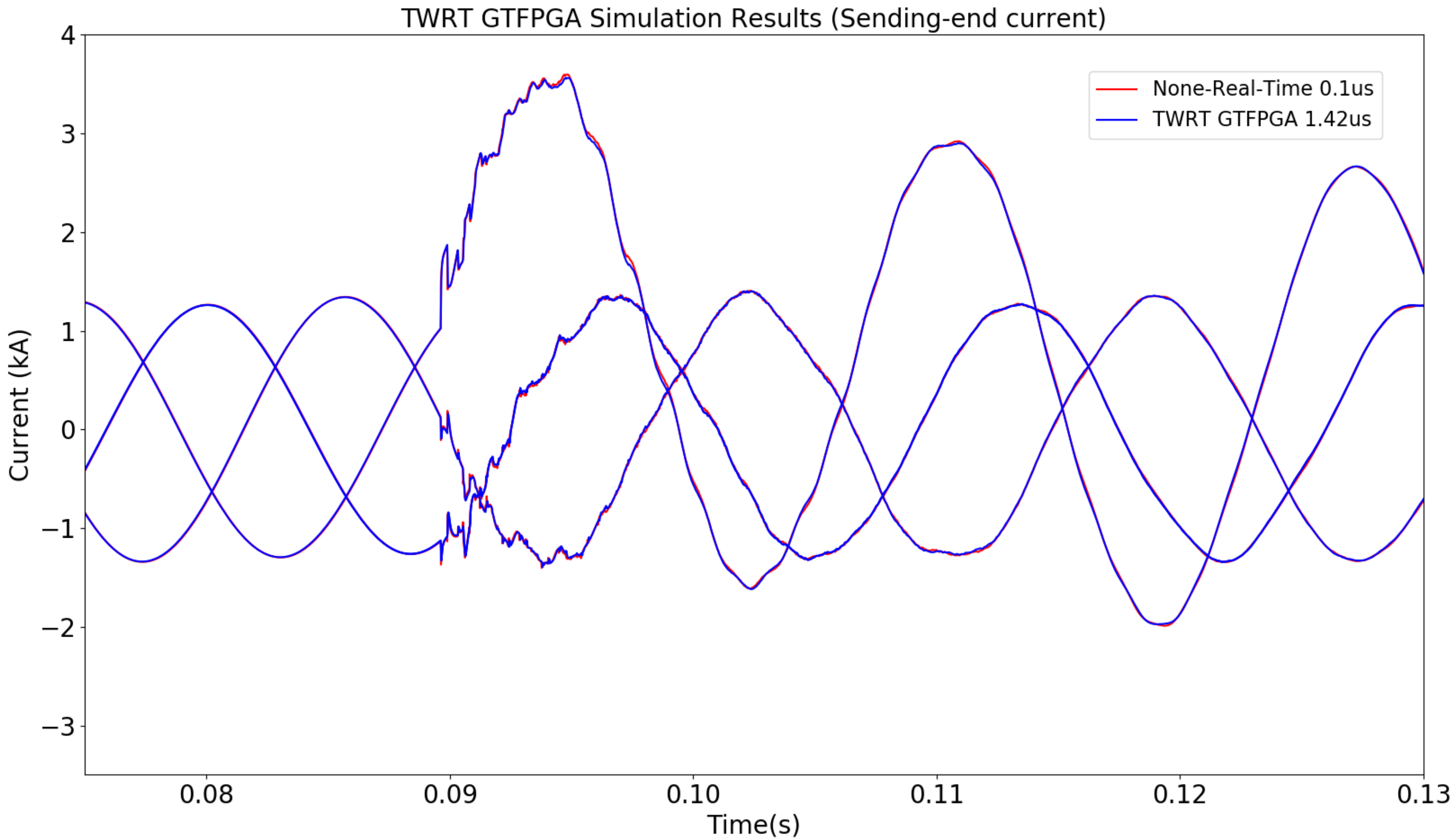
Inside small-dt box

CT and PT are modeled using gains



Simulation Results

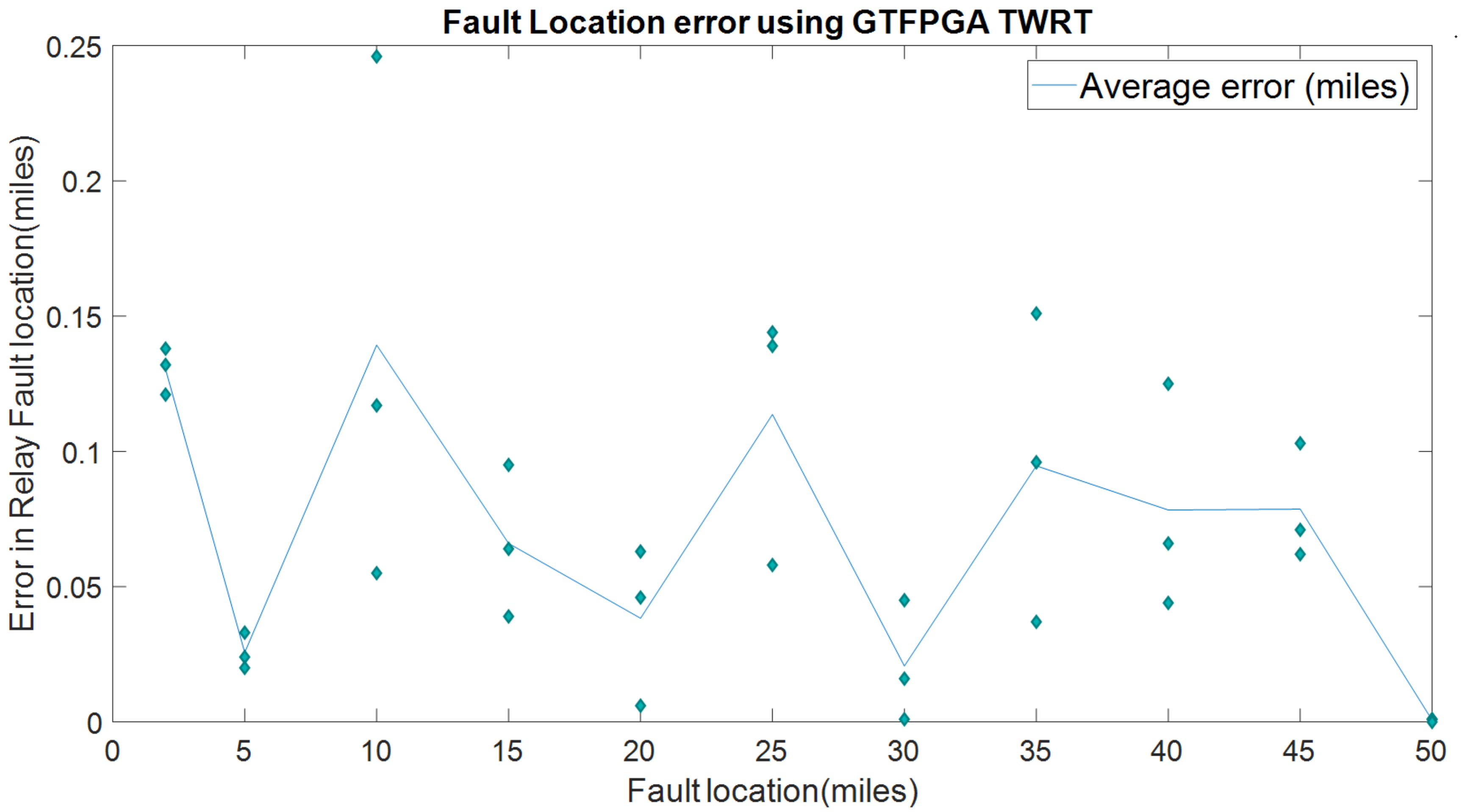
Fault scenario:
B->G at 40miles



Fault Location

	Test 1			Test 2			Test 3		
Fault Location (miles)	Relay 1	Relay 2	Error (miles)	Relay 1	Relay 2	Error (miles)	Relay 1	Relay 2	Error (miles)
2	1.868	98.132	0.132	1.879	98.121	0.121	1.862	98.138	0.138
5	5.024	94.976	0.024	5.033	94.967	0.033	5.02	94.98	0.02
10	10.055	89.945	0.055	9.754	90.246	0.246	9.883	90.117	0.117
15	14.905	85.095	0.095	15.039	84.961	0.039	14.936	85.064	0.064
20	19.994	80.006	0.006	20.046	79.954	0.046	20.063	79.937	0.063
25	25.058	74.942	0.058	24.856	75.144	0.144	24.861	75.139	0.139
30	30.001	69.999	0.001	29.955	70.045	0.045	29.984	70.016	0.016
35	34.963	65.037	0.037	35.151	64.849	0.151	34.904	65.096	0.096
40	39.956	60.044	0.044	39.934	60.066	0.066	40.125	59.875	0.125
45	44.929	55.071	0.071	44.938	55.062	0.062	45.103	54.897	0.103
50	49.999	50.001	0.001	49.999	50.001	0.001	50	50	0

Fault Location



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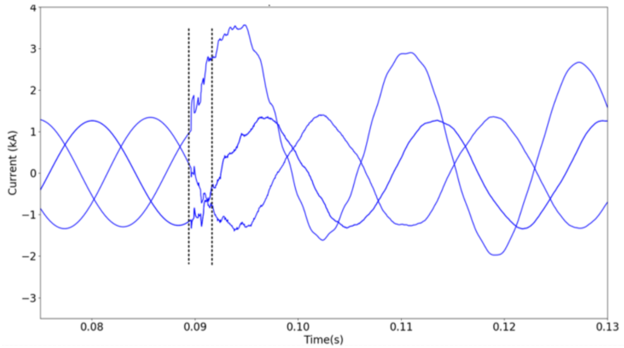
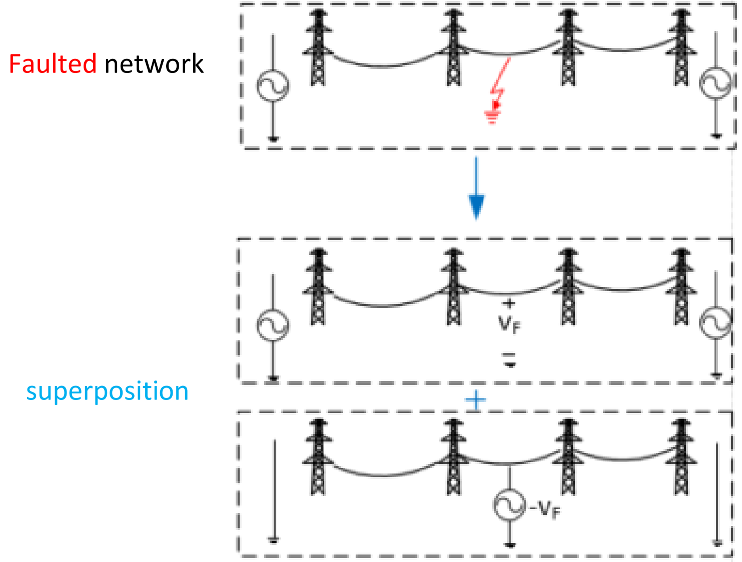
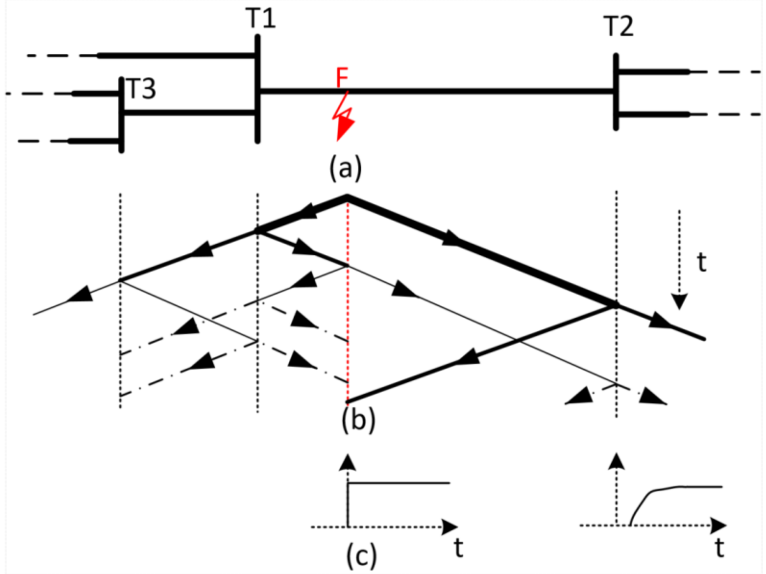
Traveling Wave based Protection

TW-based Protection is based on a short window of power system response after fault inception.

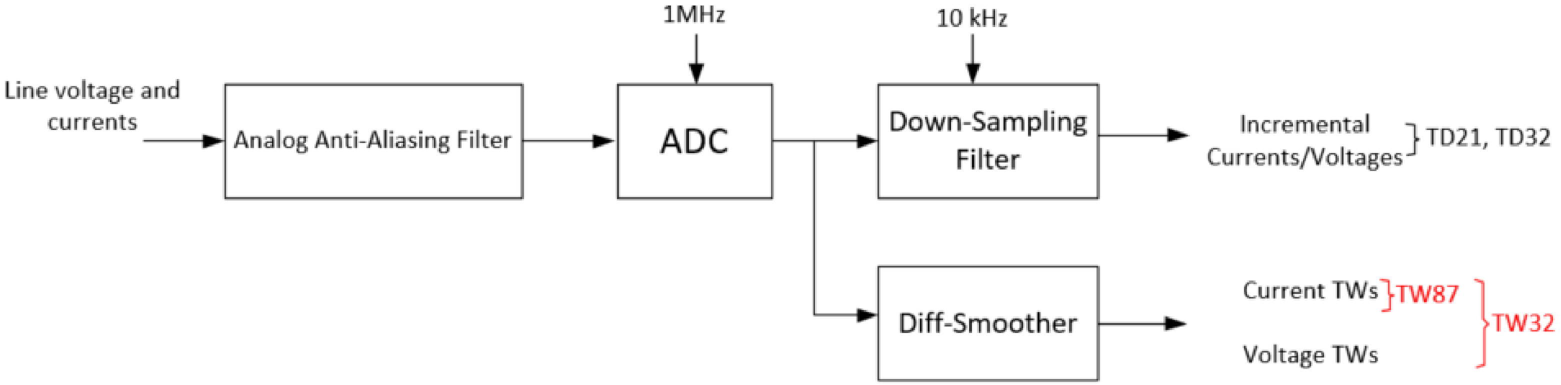






Commercially Available TWRs

T400L from SEL

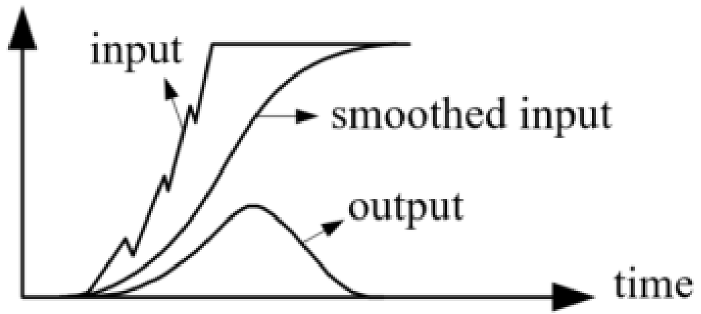


[1]-SEL-t400L time-domain line protection online: www.selinc.com.

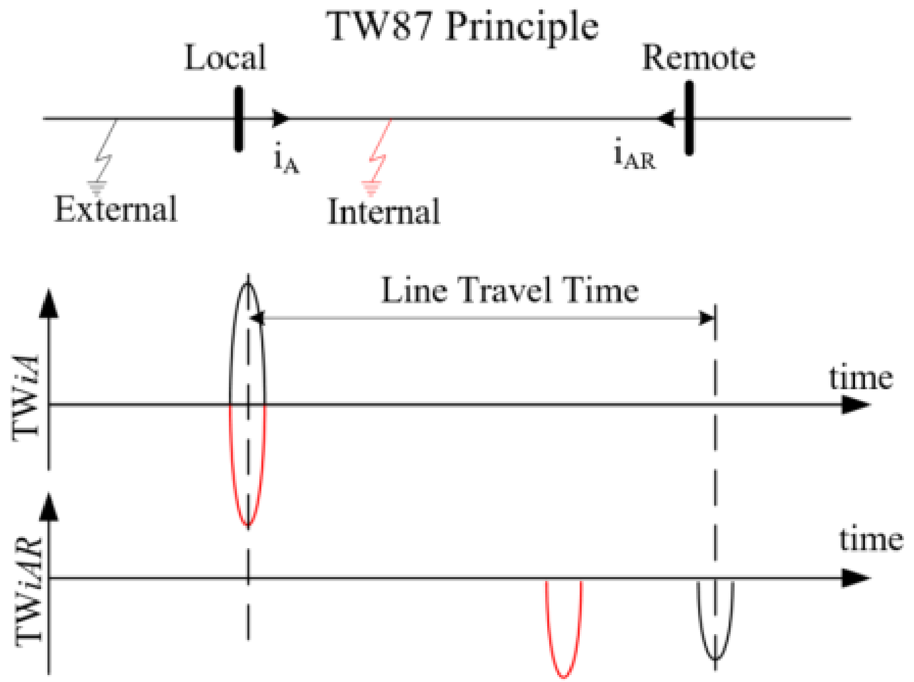
[1]

Differential Element: TW87

- TW protection element are based on the Differentiator Smoother (DS) output signal
- DS output signals are called TW current/voltage signals and primarily depend on the HF response of the system

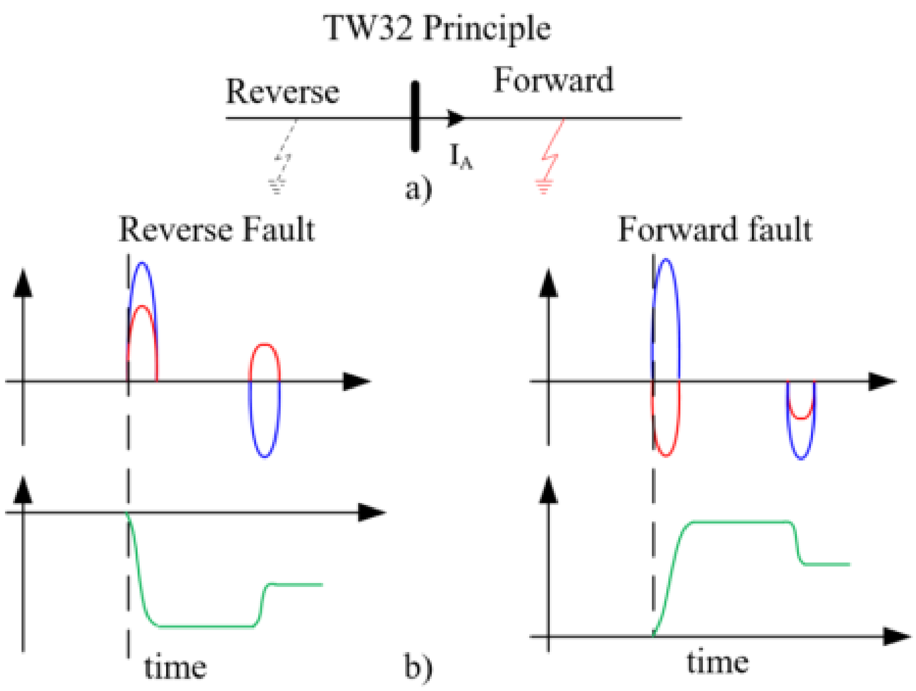


Differentiator smoother typical signals[1]



TW87 Principles. Local (TWIA) and remote (TWIAR) current TW signals for an internal (red) and an external (black) fault.

Directional Element: TW32



TW32 Principles. a) Forward and reverse faults. b) Voltage (blue) and current (red) TW signals, and TW32 integrated torque (green).

FDPD vs Bergeron

Bergeron Line or FD Line? Is the line valid for TWRT?

- Bergeron is a simplified version of the FD line, which is correct at the nominal frequency
- How Bergeron line behaves? Conservative or Optimistic?
- Bergeron line may work well to have a good fault location, does that means anything?
- In fact, we can get the exactly time series variables from control. The reason using TLINE is more close to the situation in the real world.
- Therefore the relay gets good results of fault locating doesn't means the testing model is sufficient or necessary correct.
- The criterion should be providing an environment for TWRs as if they are operating in the real power systems

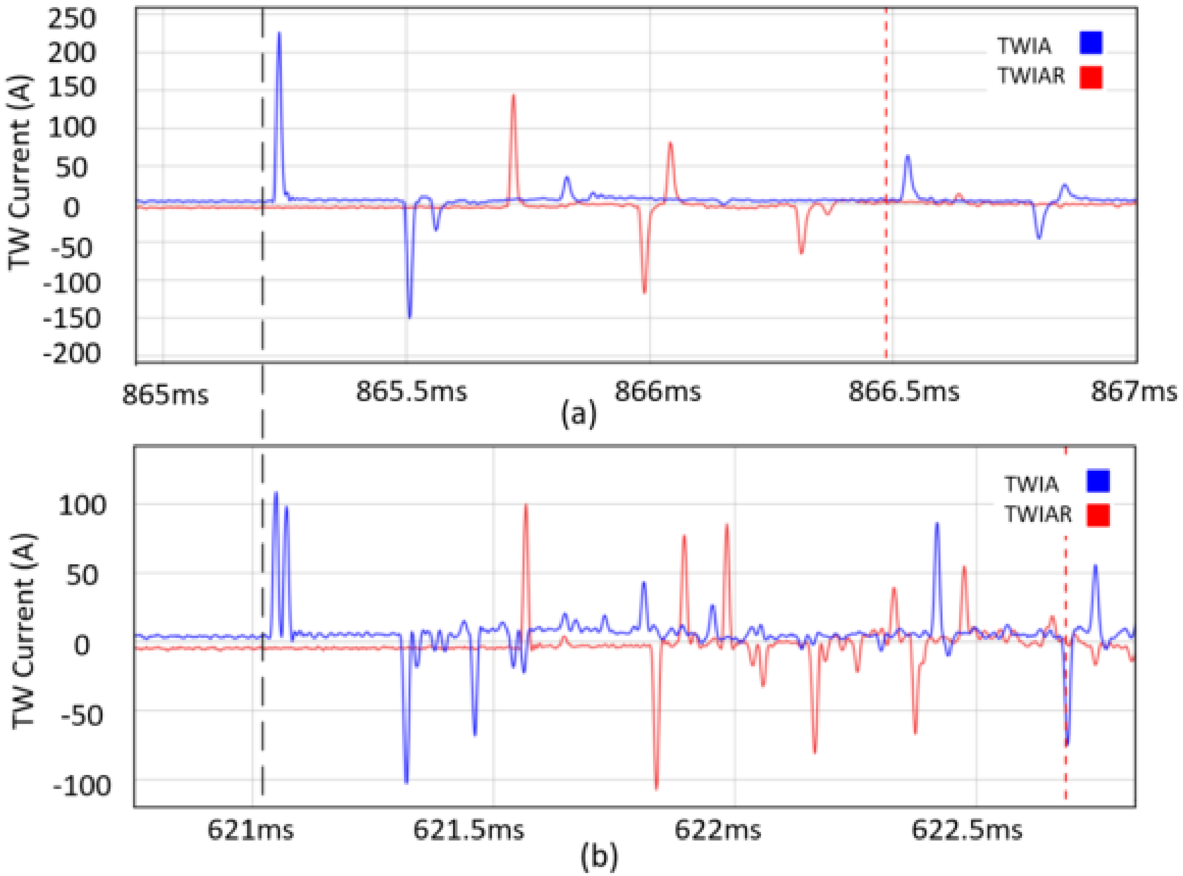
In that sense, the FD is better than the Bergeron line or other simplified methods.

FDPD vs Bergeron

Phase A to ground fault

- The case with Bergeron line failed to trip
- The case with FD line tripped correctly

Not only the TWRT but also the algorithm within the TW relay plays role in whether the line will trip correctly



Phase A current TW signals for local (blue) and remote buses (red), using (a) FDPD model and (b) Bergeron model. The time reference of (a) and (b) are different.

FDPD vs Bergeron

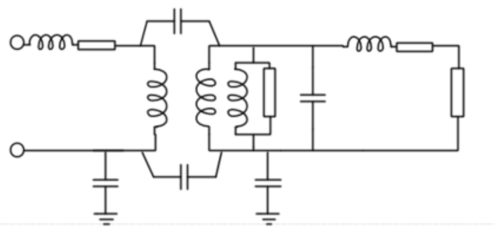
Is Bergeron Line useful in testing?

- Bergeron Line is simpler, so more lines can be modelled.
- Each small time step box, 11 Bergeron lines can be modelled.
- The accuracy of Bergeron lines in TRWT depends on the different scenarios. If the fault currents of Bergeron line and FD line are close, the accuracy and reliability will be higher.
- It is recommended to compare the fault currents against FD line before the Bergeron line can be used.
- It is expected the Bergeron lines to be sufficient to testing the location of the faults.
- It is also expected that Bergeron lines may have flaw in fault detections but once this happens, the FD line can be used to double check the tripping failure or miss-tripping.

A hybrid testing scheme with FD line and Bergeron line is worth to try.

Other Requirement of System Modeling

- Current transformers (CT)
  - The lump magnetic models cannot exhibit flat high-frequency characteristics.
  - Ideally, HF magnetic models should be used. However, parameters for such models are not usually available.



  - Ideal gains are used in this work. This does not represent CT saturation.
- Faults and Breakers
  - Two-value resistor fault model are employed.
  - LC switch representation should be avoided.

Requirements for the HIL Setup

- time-step
  - 1MHz range sampling requires µs-range time-step.
- Connection between TWRS and RTDS:
  - Current amplifiers have limited bandwidth, therefore, amplifiers are avoided.
  - Low-voltage connection is used in this work. But this is bypassed the internal transducers.
  - Fully digital connection would be advantageous to avoid the need for low-voltage analog terminals.
  - Wide band amplifier is needed to do the complete testing of the TWRs

Conclusions

- TWRT facilities on RTDS are introduced: NovaCor and GTFPGA
- Line models are discussed: FD and Bergeron
- Other modelling requirement are discussed

Questions