NEW DEVELOPMENT AND APPLICATIONS ON TRAVELING WAVE PROTECTION

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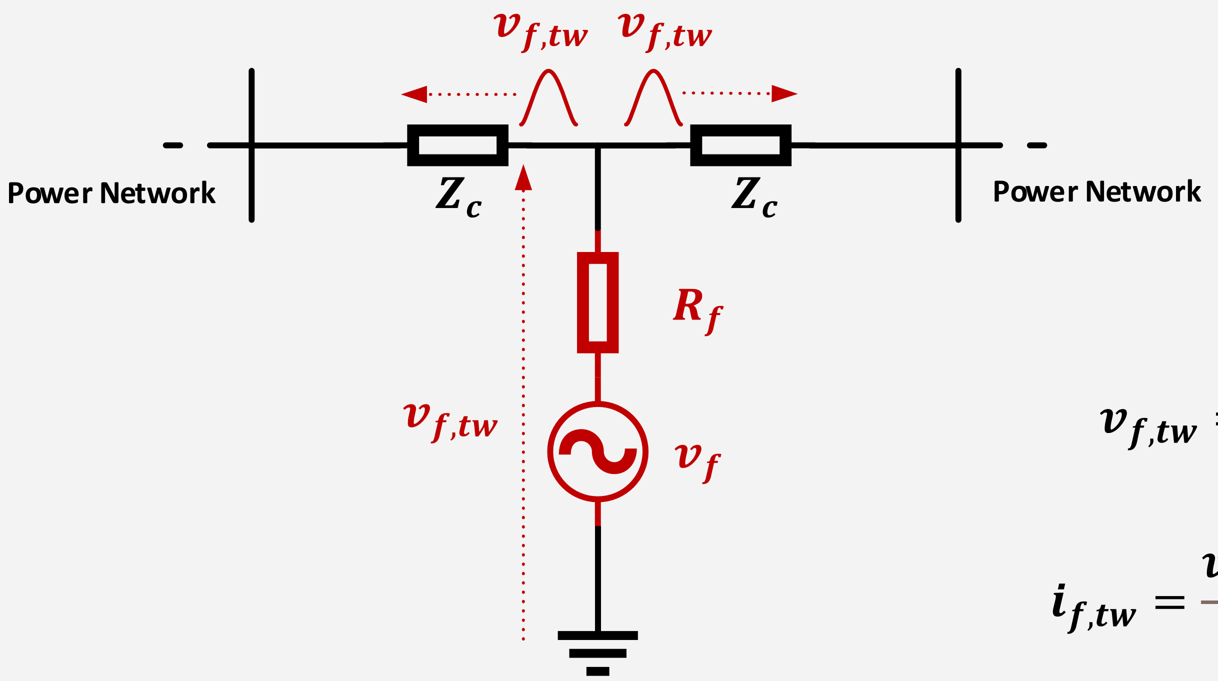
RTDS TECHNOLOGIES

BACKGROUND

- Modern traveling wave (TW-based) protection solutions for transmission lines have been increasingly applied in real-world power systems.
- Advantages include –
    - Fast tripping therefore improved system stability.
    - Protection of hybrid lines and series compensated lines.
    - Accurate fault locating.
- The adoption of TW-based protection solutions for transmission lines in power systems with high penetrations of Inverter-based Resources (IBRs) has gained more interests as the traditional phasor domain-based solutions become less effective due to lower fault current from inverters and the inherent latency and accuracy on fault locating.

BACKGROUND

Fault-Induced TW



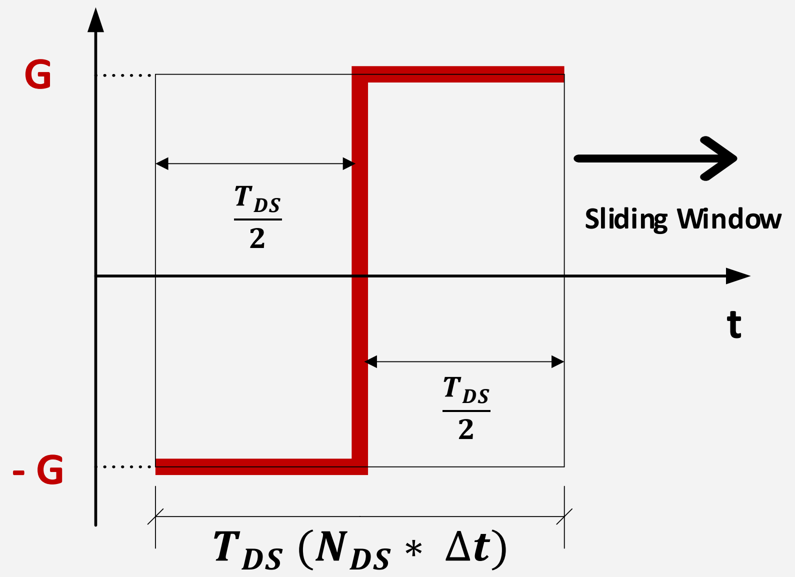
$$v_{f,tw} = \frac{Z_c * v_{rated} * \sin\theta}{Z_c + 2 * R_f}$$

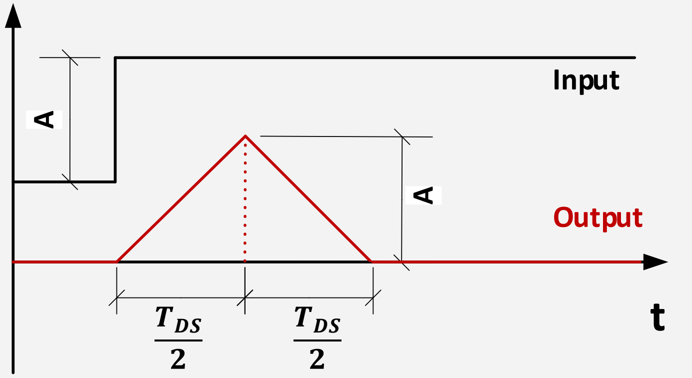
$$i_{f,tw} = \frac{v_{f,tw}}{Z_c} = \frac{v_{rated} * \sin\theta}{Z_c + 2 * R_f}$$

BACKGROUND

Differentiator-Smoother (DS) Filter

- A mature signal processing technique, relying on high-frequency sampled data, used in commercially available TW-based relays.
- Aims to process the current (and voltage), **measured at the terminal** which are a **superposition** of the **incident** and **reflected** waves, to generate –
  - **Triangular-shaped output** with unitary gain in case of a step-change in the input.
  - **Parabola-shaped output** in case of a ramp-change in the input.
- The **peak** of the output relates to the arrival time of TWs at the monitored terminal.

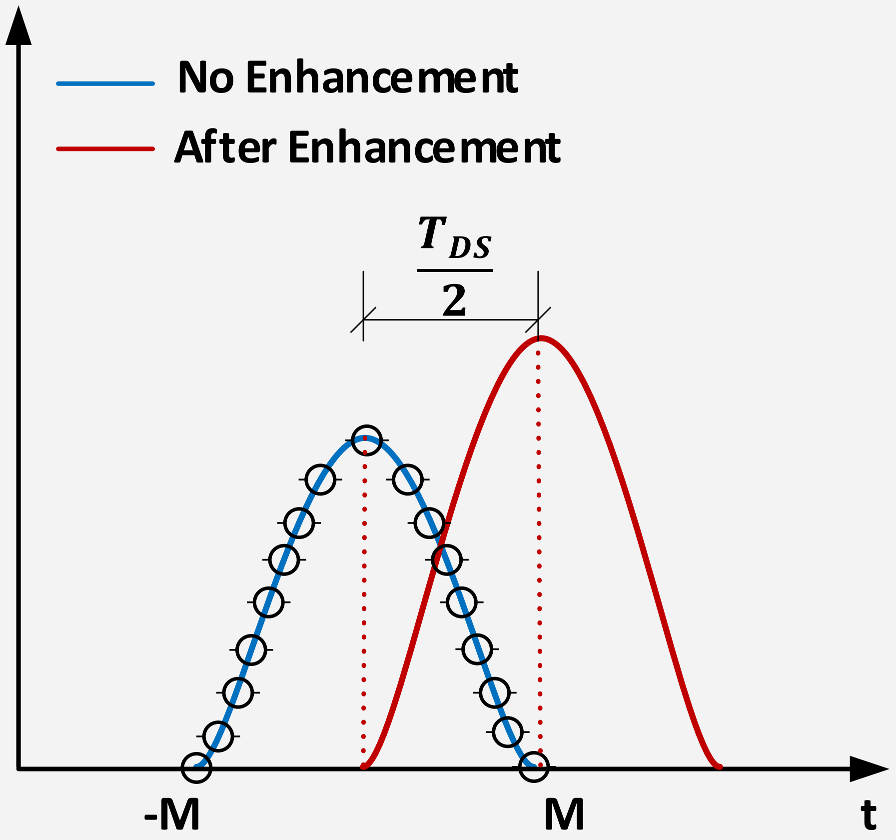




BACKGROUND

TW Amplitude Estimation

- The amplitude of a fault-induced TW is related to the point-on-wave where the fault takes place.
- Fault induced-TWs attenuate while propagating alone the line.
- Ramp-changes, instead of step-changes, are more often detected in the input at the monitored terminal.
- Signal enhancement is implemented to best estimate the TW amplitude at the output.

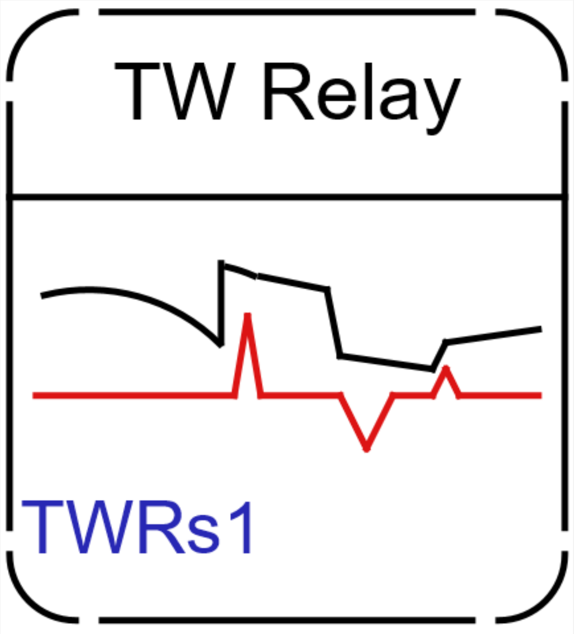


$$I = C * \sum_{n=-M}^{n=M} i_{TW}\,(N_{detect} - n)$$

NEW DEVELOPMENT

Traveling Wave Relay Model (TWR) – Based on DS Technique

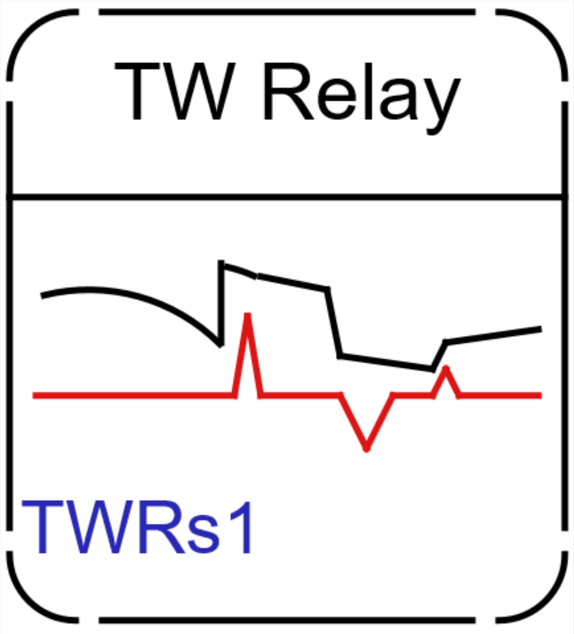
- Based on DS filtering technique to extract the **fault-induced** TW:
  - Filter window length is 20 us.
  - Number of coefficients varies based on the time-step.
  - Option to average the output for TW magnitude enhancement.
  - Provides phase and mode (alpha and beta) TW outputs.



NEW DEVELOPMENT

Traveling Wave Relay Model (TWR) – Based on DS Technique

- Includes current TW different protection scheme (TW87):
  - Uses double-ended TW-based method.
  - Supports single/three-pole tripping.
  - Provides calculated fault location and faulted mode information.
  - Option to detect an external fault on a parallel line.
- Recommended to use in Substep environment only.
- Available from RSCAD FX 1.4.

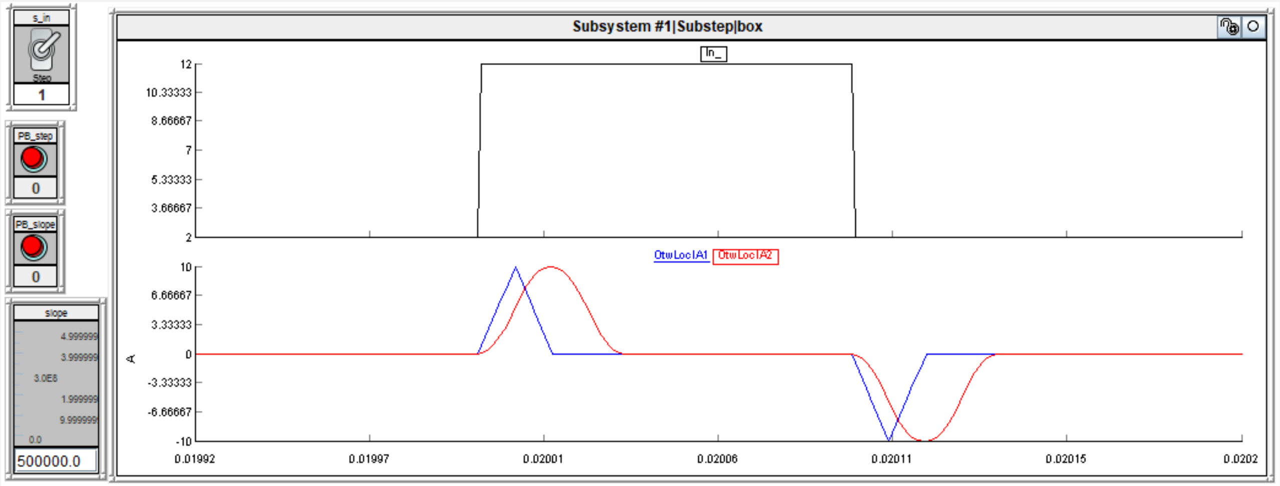


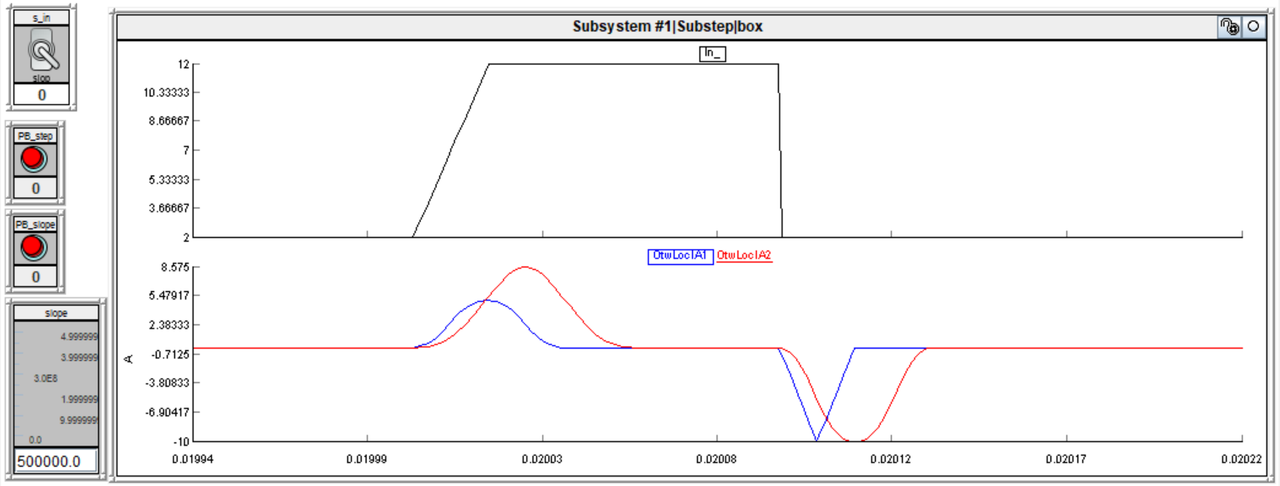
TWR

Simulation Results

- Responses to input of -
  - ideal step change (top).
  - Ramp change (bottom).

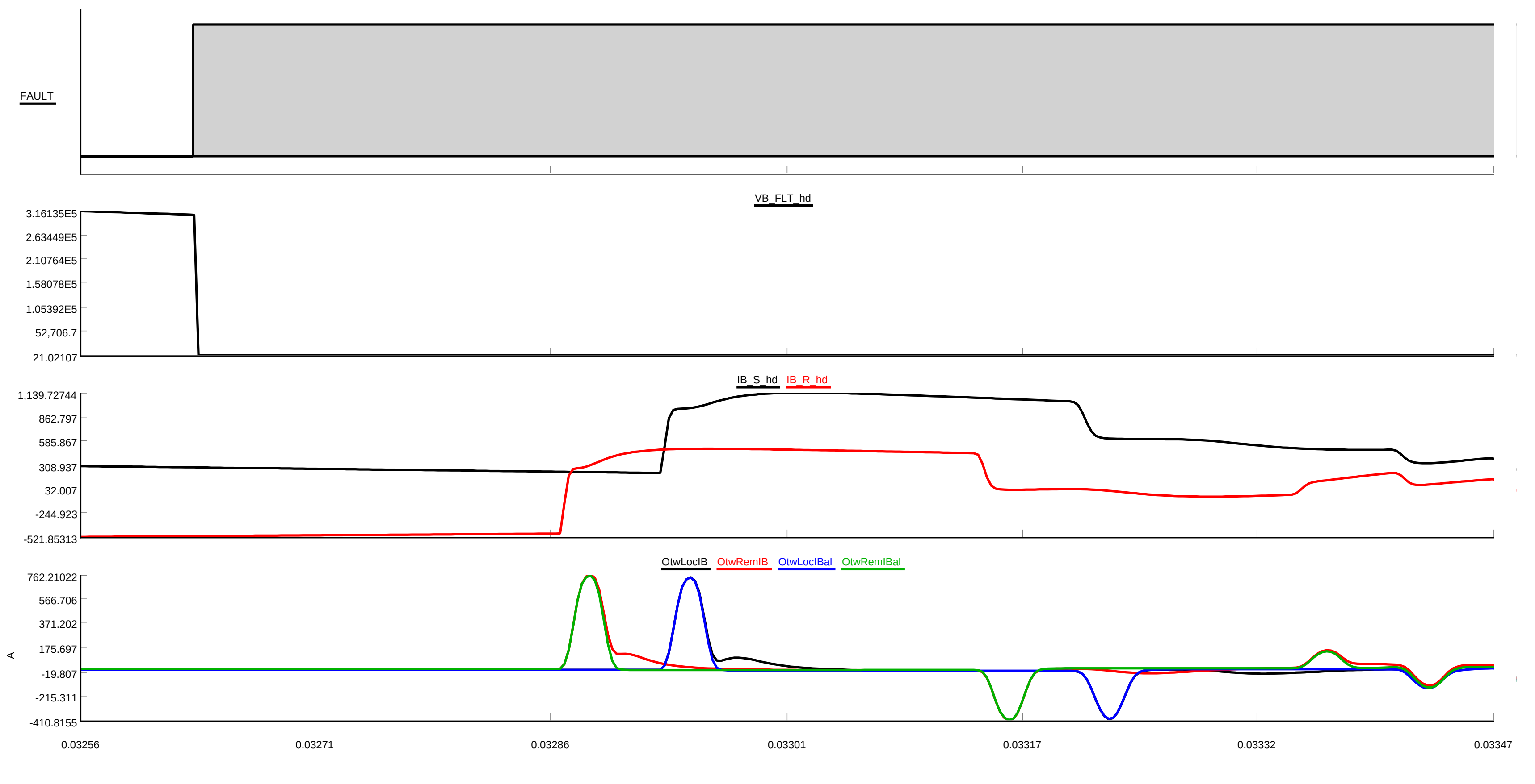
- Unenhanced vs enhanced output.





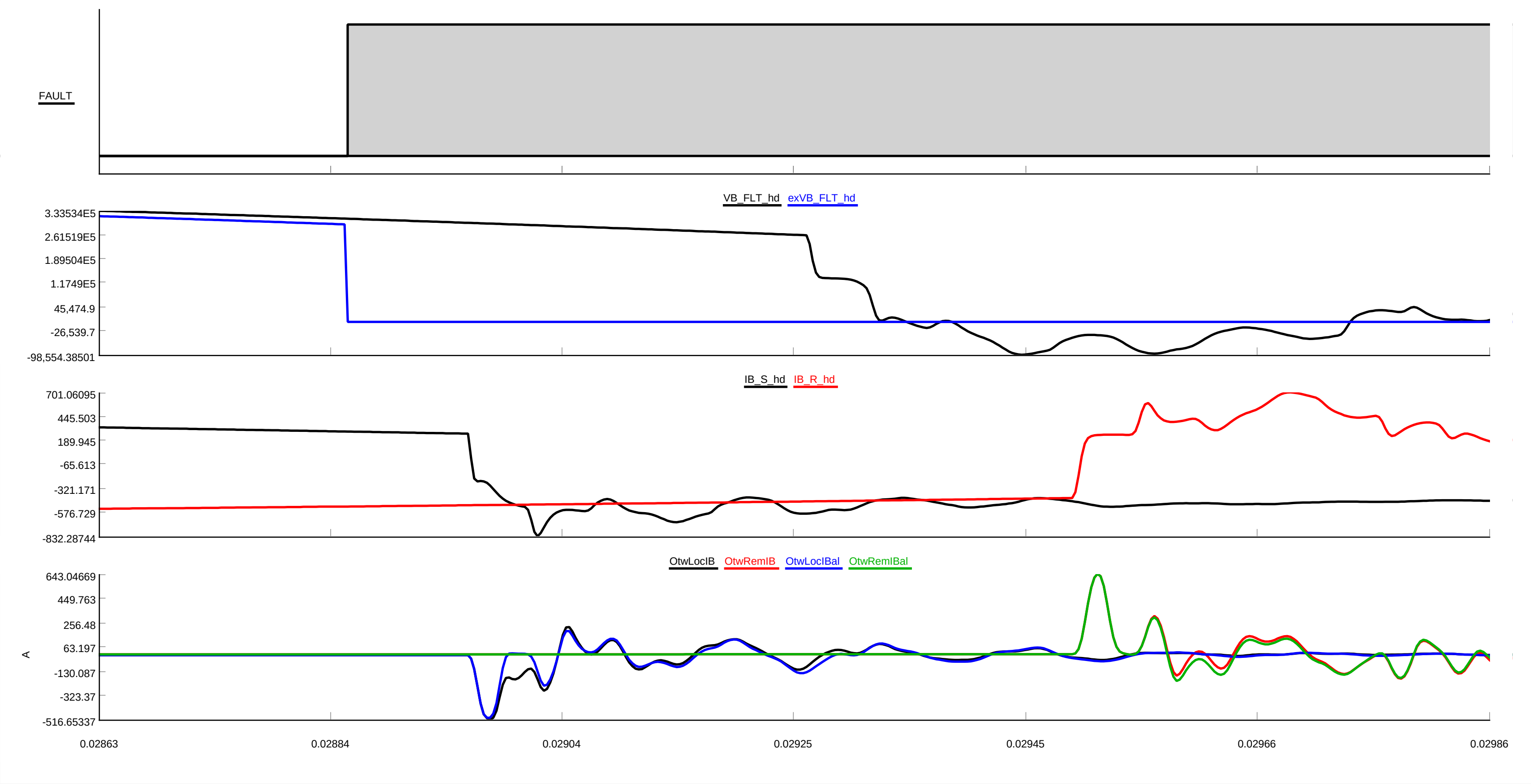
TWR - Simulation Results

- An internal BG fault at 56 miles away from the left terminal of a 100-mile long line.



TWR - Simulation Results

- An external BG fault at 20 miles away from the left terminal.

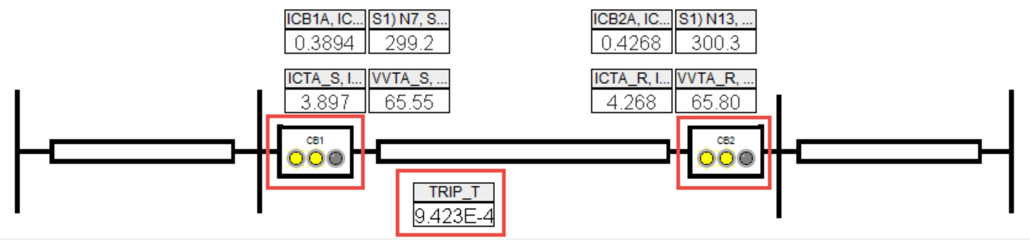


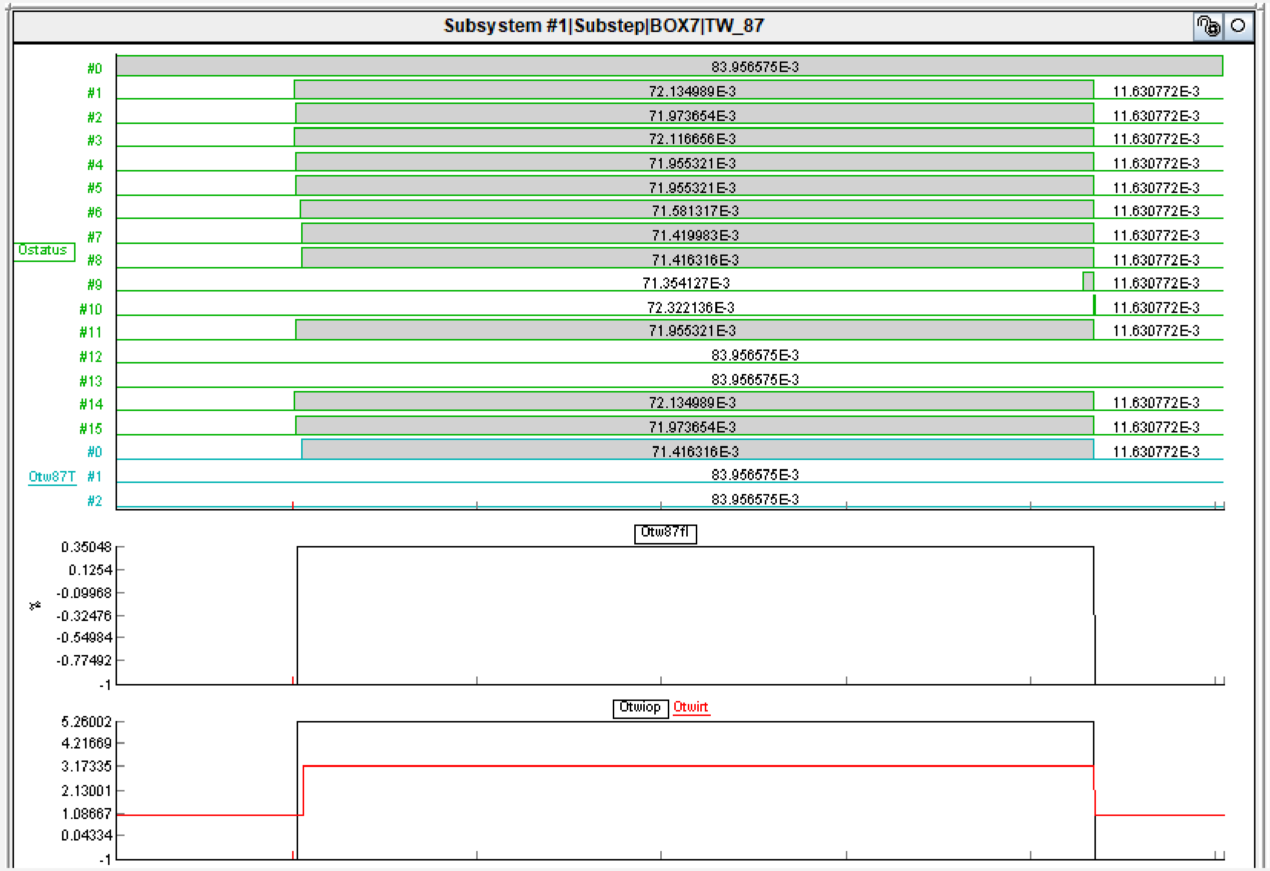
TWR - Simulation Results

- Comparison with relay captures.

TWR - Simulation Results

- TW87 – Current TW differential protection.
- An internal AG fault at 35% from left terminal.



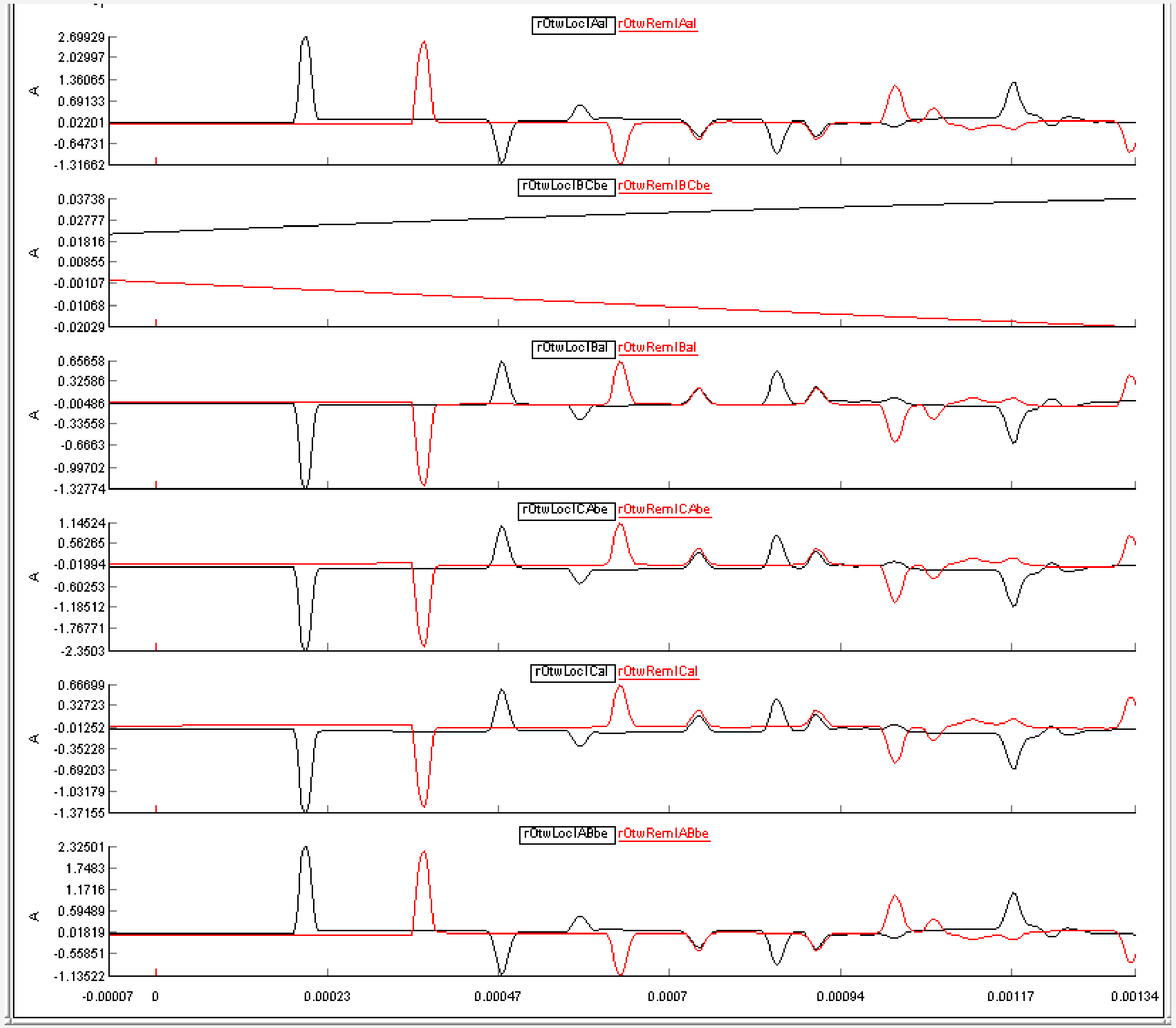


TWR

Simulation Results

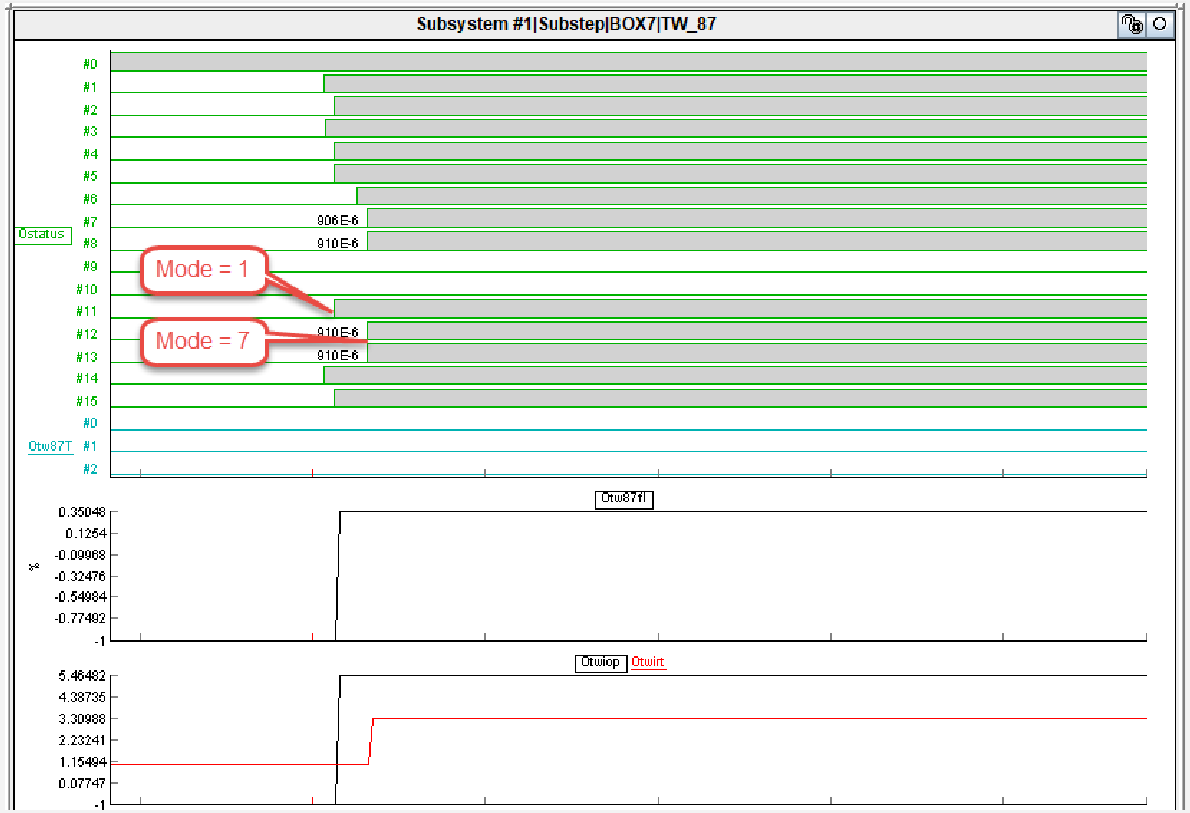
- Output TWs of –

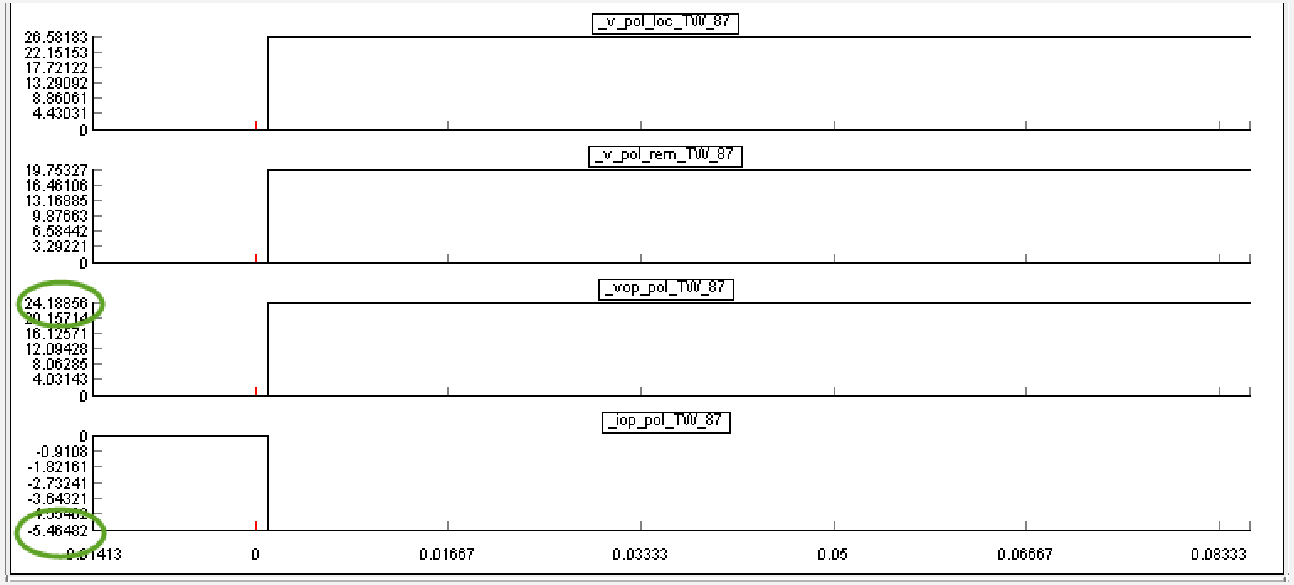
  Local vs remote mode currents.



TWR - Simulation Results

- An external AG fault on a parallel line, at 35% from left terminal.





NEW DEVELOPMENT - Incident Wave Calculator Model

Background

- The DS filtering technique extracts the transients related to **fault-induced** TWs in the **measured currents**, which are a **superposition** of the incident and reflected waves:
  - The magnitude of this transient, which is **dependent** on the termination characteristics of the transmission line, could be very small, if the termination impedance is high, potentially resulting in a poor accuracy in fault location estimation.
  - The inherited nature of DS filtering technique limits the TWR model to be used mainly in Substep environment only.

BACKGROUND

Measured Current Vs Incident Current

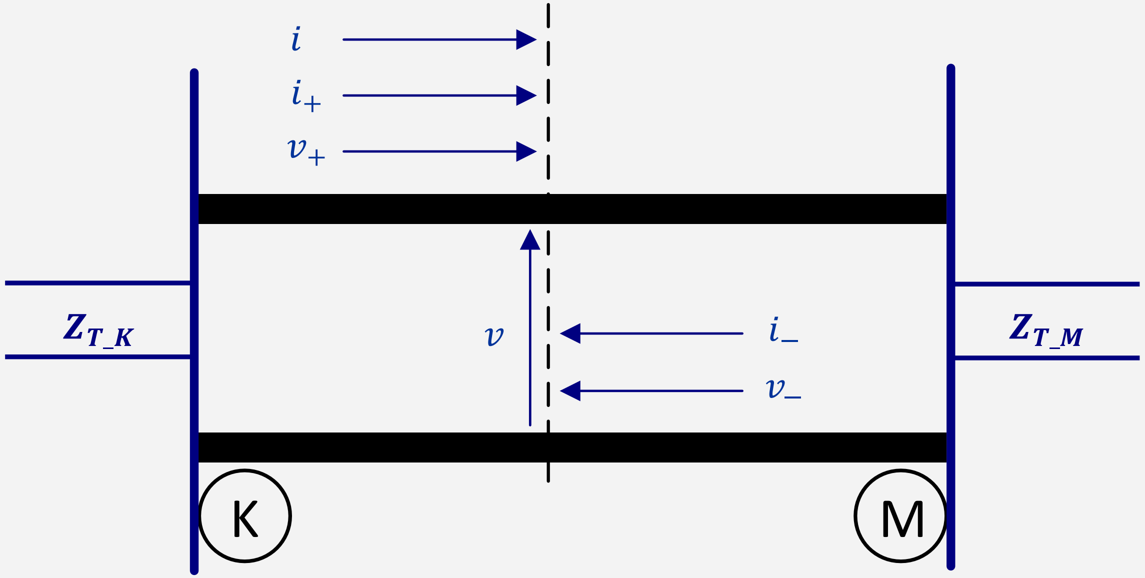
$$i = i_+ - i_- \quad v = v_+ + v_-$$

$$i_+ = Y_c v_+ \quad i_- = Y_c v_-$$

$$v = Z_c i_+ + Z_c i_- = Z_{T\_K}(i_- - i_+)$$

$$i_+ = \frac{Z_{T\_K} - Z_c}{Z_{T\_K} + Z_c} i_-$$

$$i = \frac{-2Z_c}{Z_{T\_K} + Z_c} i_-$$

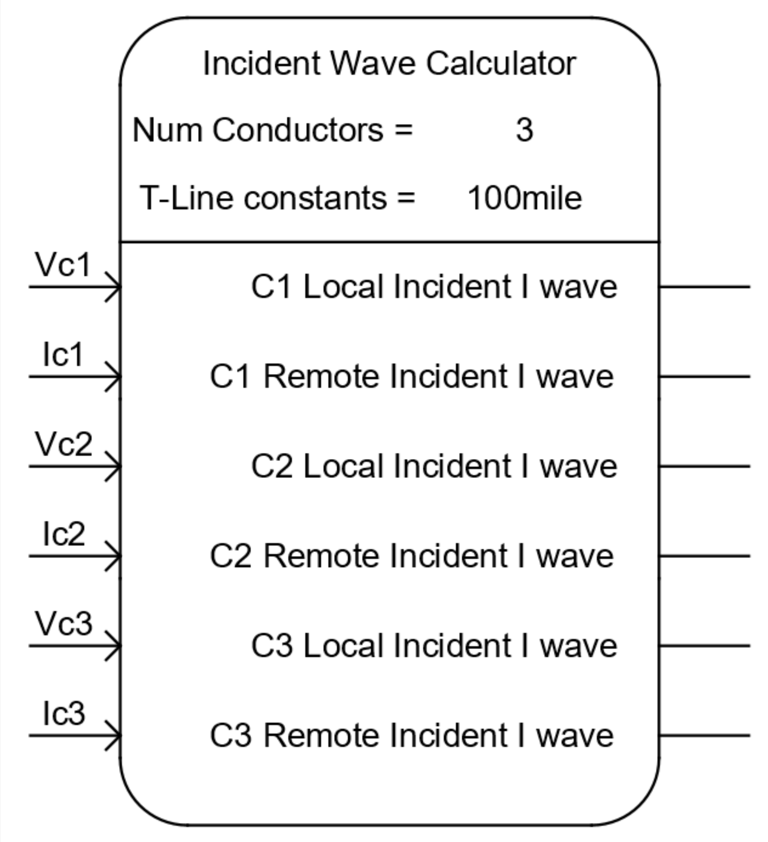


i / v	The actual current/voltage at any point on a transmission line
i_+ / v_+	The reflected traveling waves of current and voltage
i_- / v_-	The incident traveling waves of current and voltage
Y_c / Z_c	The characteristic admittance/impedance
Z_T	The termination impedance

NEW DEVELOPMENT

Incident Wave Calculator (IWC) Model

- Uses Frequency Dependent Phase Domain (Universal Line Model) transmission line theory to calculate:
  - The **local incident** current.
  - The **local reflected** current.
  - The **expected remote incident** current.
- To use in Mainstep or Substep.



NEW DEVELOPMENT

IWC

$$\mathbf{Y_c * v = i_+ + i_-}$$

$$\mathbf{i_{kr} = i_K + i_{ki}}$$

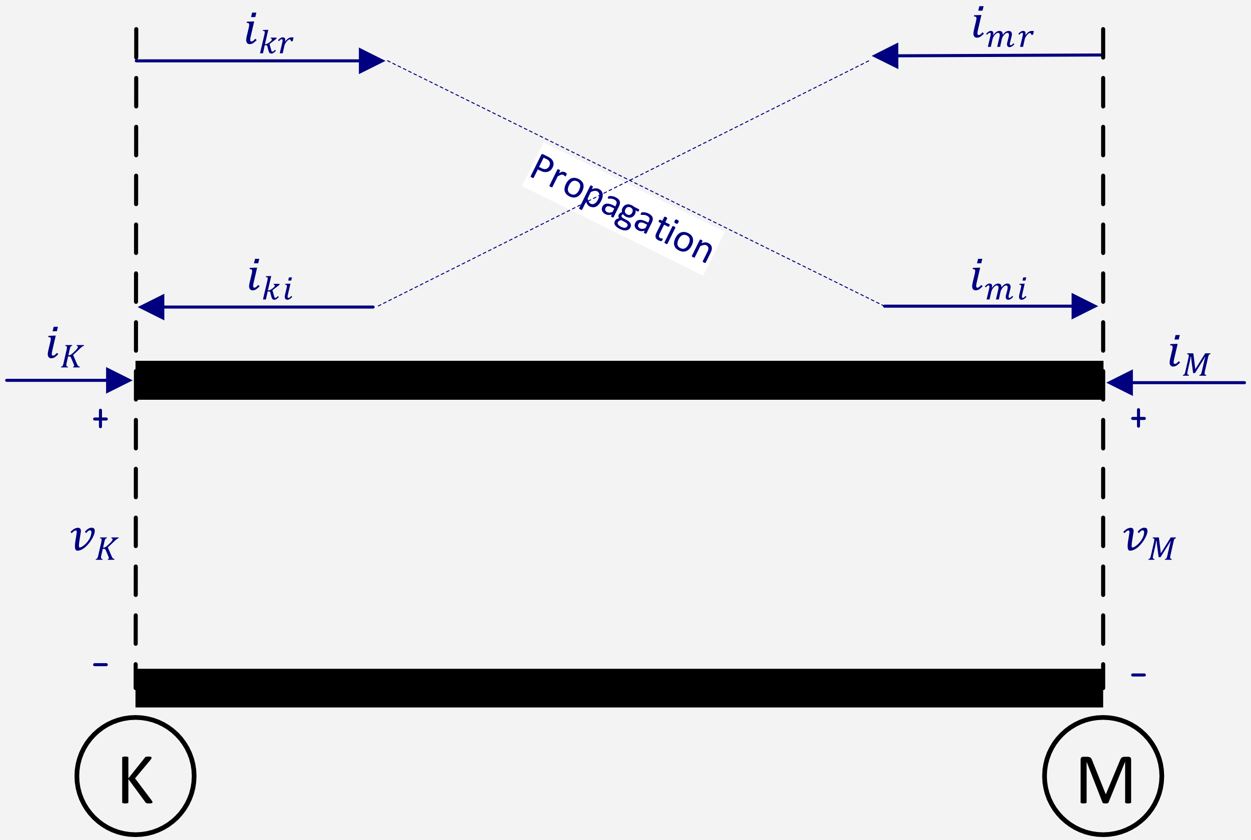
$$\mathbf{i_K = Y_c * v_k - 2i_{ki}}$$

$$\mathbf{i_{mr} = i_M + i_{mi}}$$

$$\mathbf{i_M = Y_c * v_m - 2i_{mi}}$$

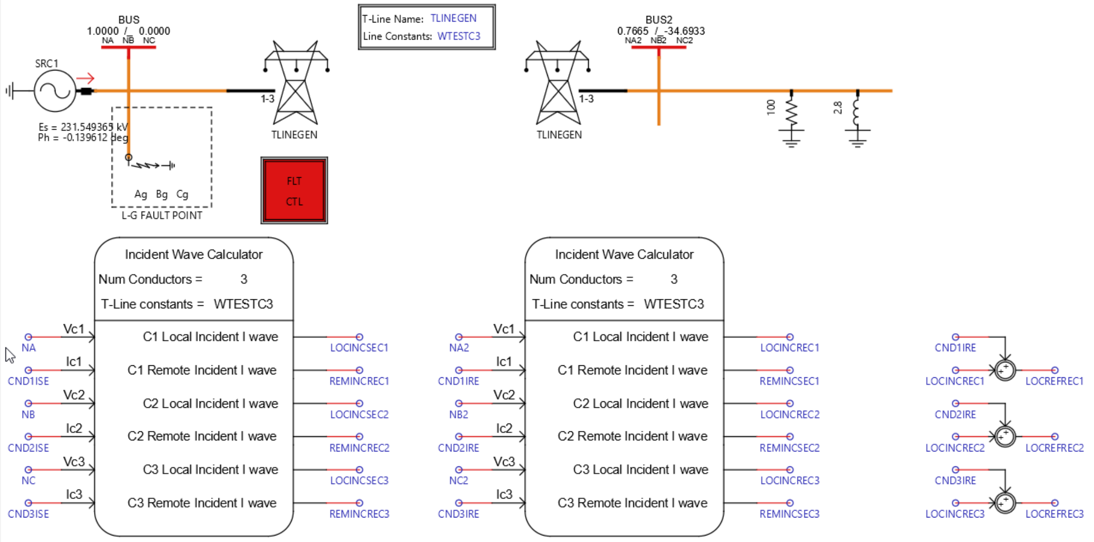
$$\mathbf{i_{mi} = H * i_{kr}}$$

$$\mathbf{i_{ki} = H * i_{mr}}$$

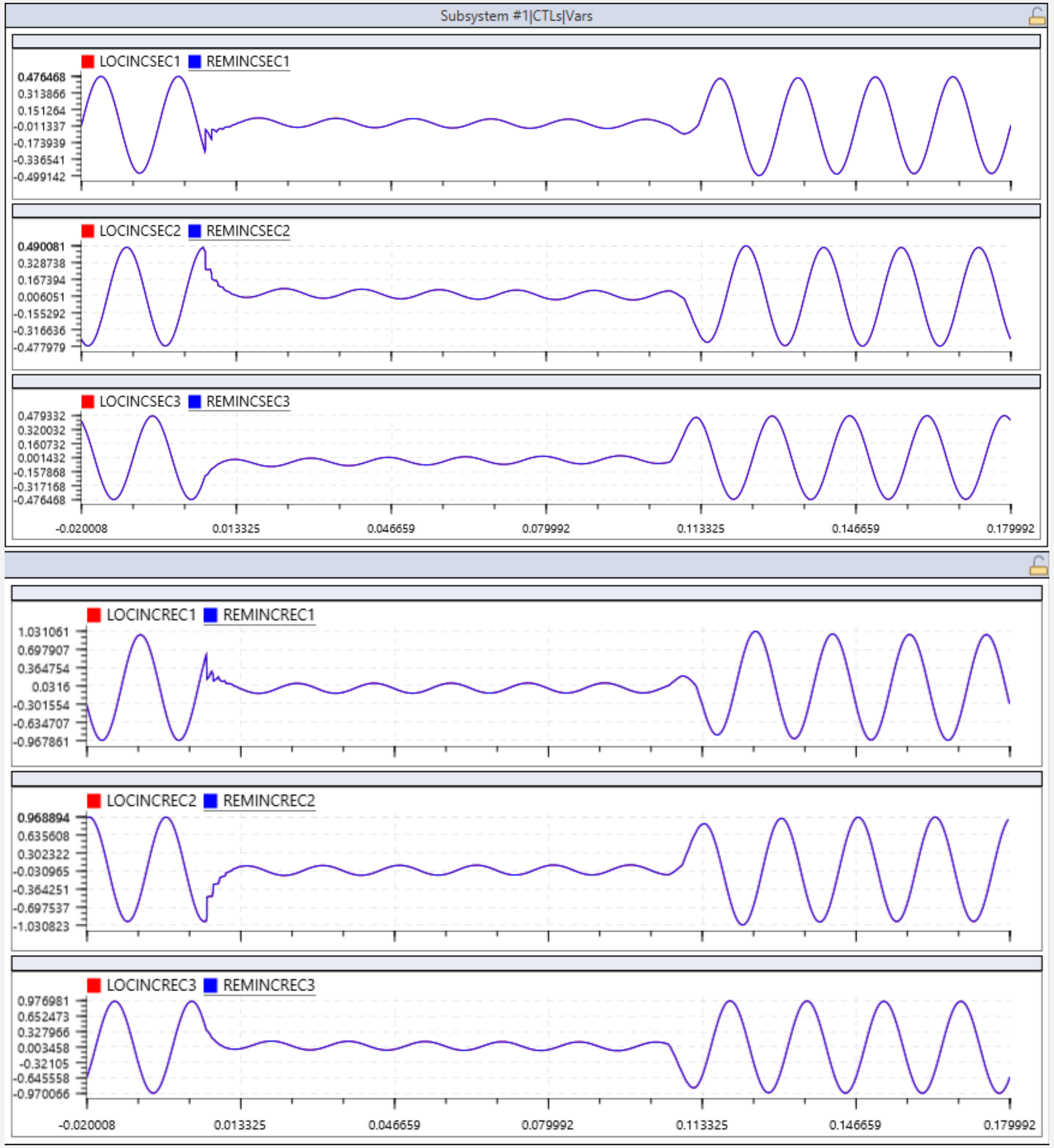


** Recursive Convolution - A. Semlyen and A. Dabuleanu, "Fast and accurate switching transient calculations on transmission lines with ground return using recursive convolutions," IEEE Transactions on Power Apparatus and Systems, vol. 94, pp. 561-571, 1975.*

IWC - Simulation Results

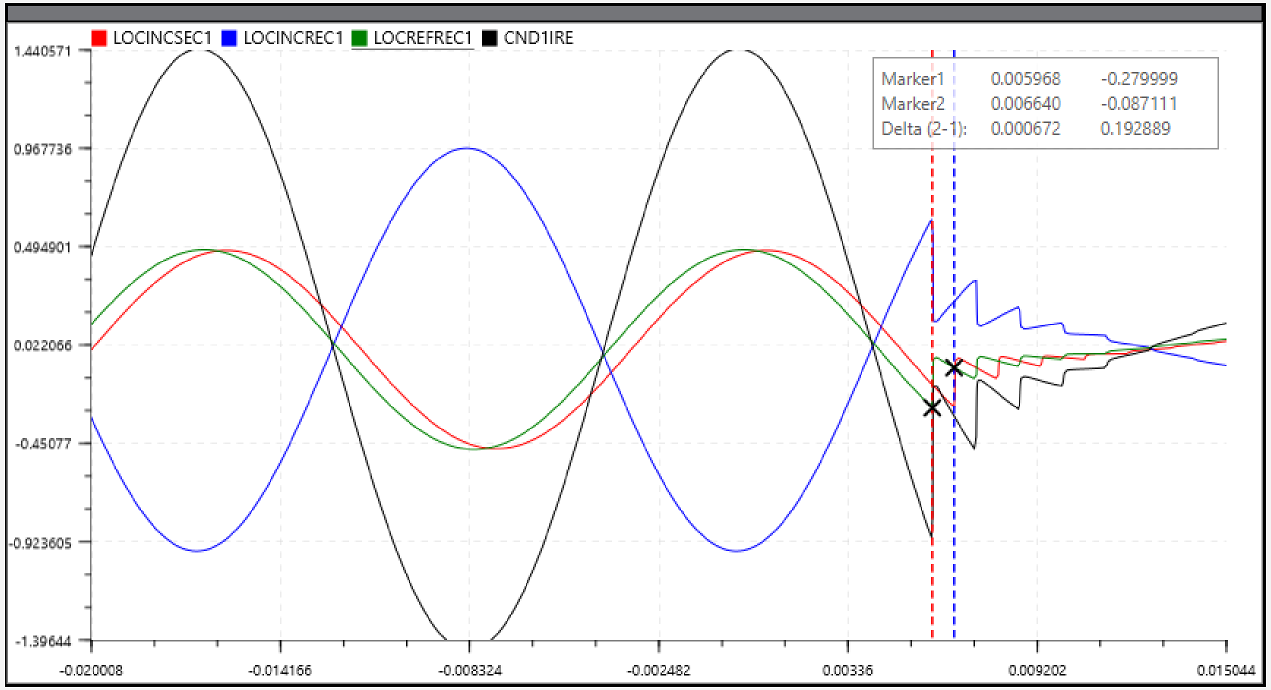


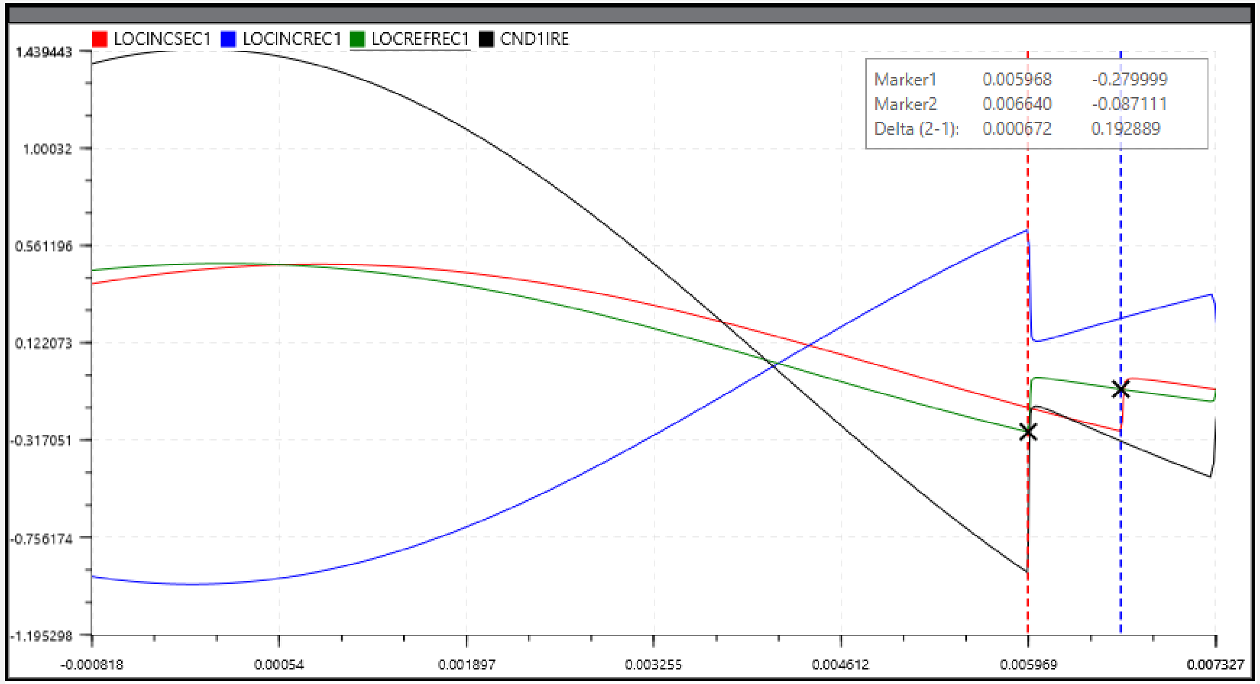
- **Local** incident currents at the **sending** end vs **remote** incident currents at the **receiving** end (top-right).
- **Local** incident currents at the **receiving** end vs **remote** incident currents at the **sending** end (bottom-right).



IWC - Simulation Results

- Waveforms associated with Conductor #1.
- Incident current + cond. current (black) = reflected current.

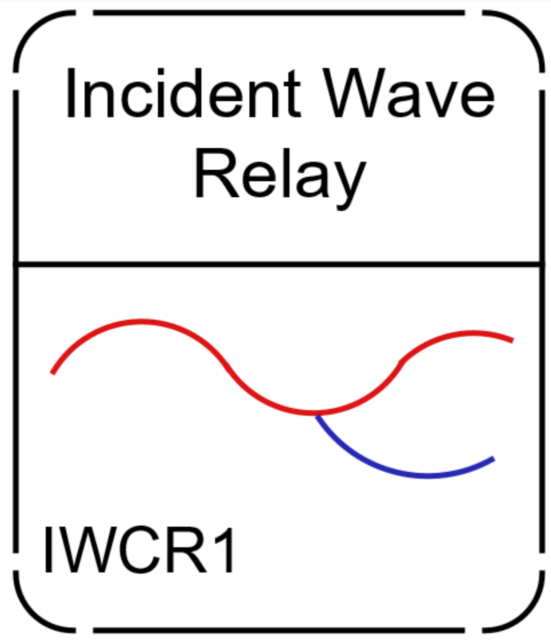


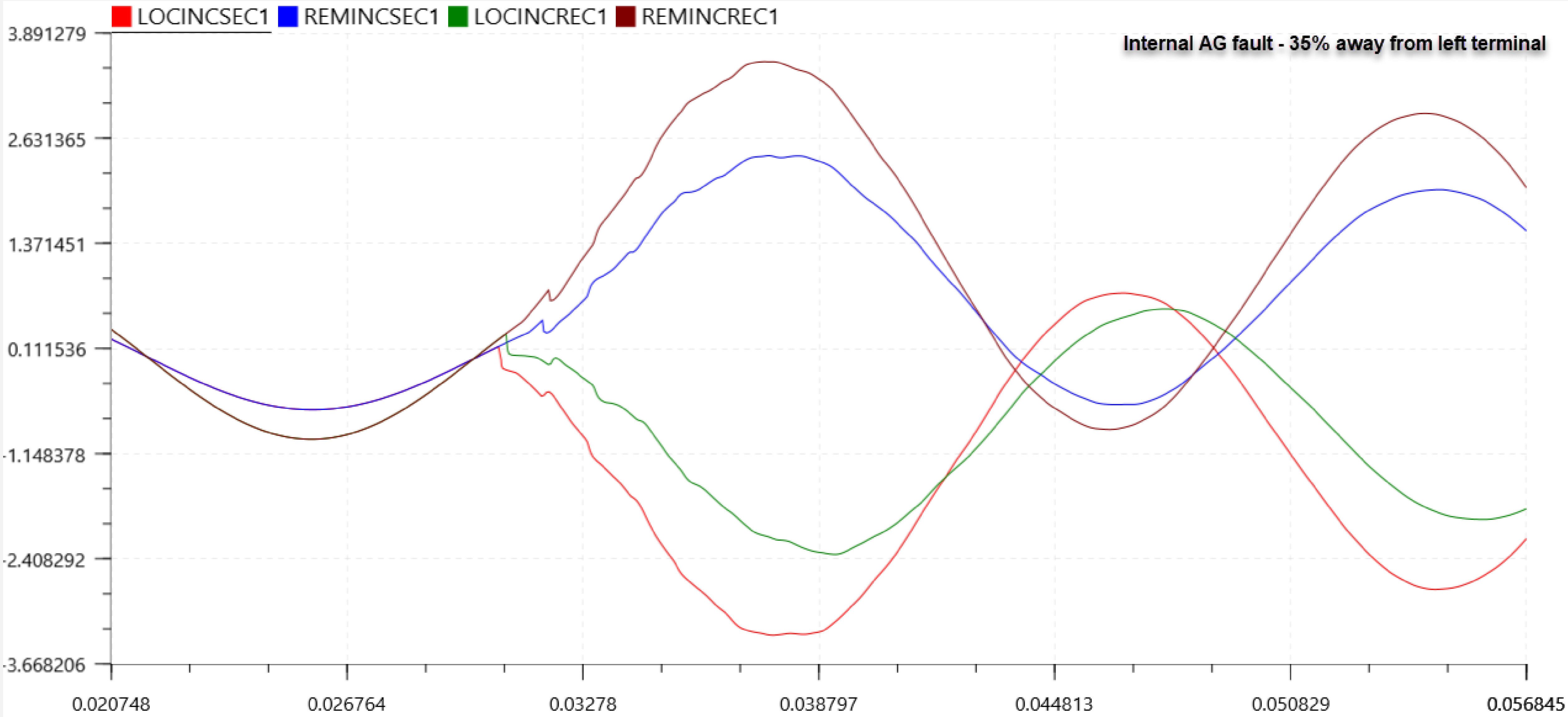


NEW DEVELOPMENT

Incident Wave Relay Model (IWCR)

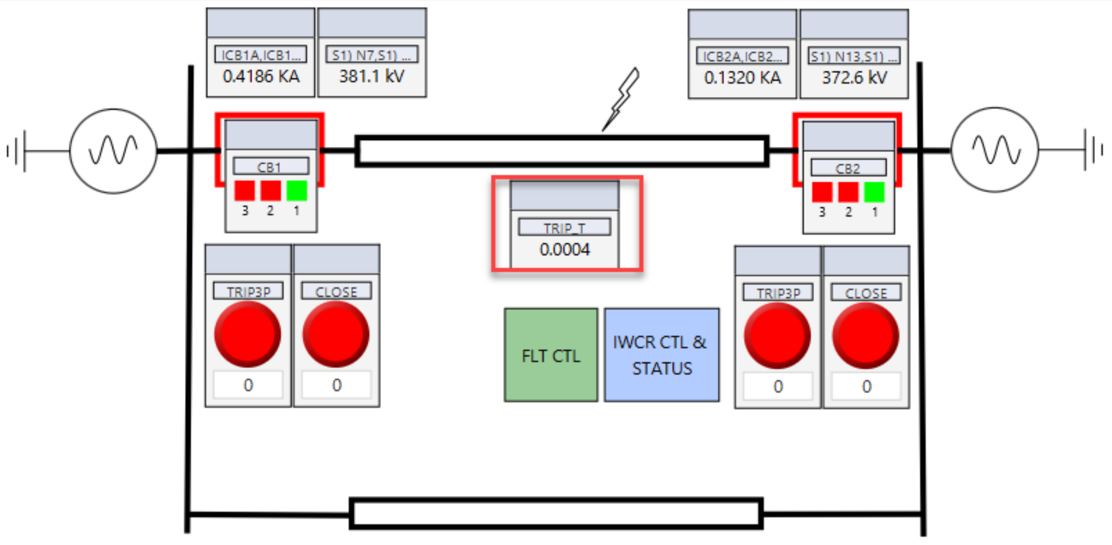
- Uses outputs from the IWC component at each end of the terminal, to compare the local and remote incident waves.
- Incident current-based protection scheme -
  - Uses double-ended method.
  - Supports single/three-pole tripping.
  - Provides calculated fault location and faulted mode information.
  - Naturally immune to external faults on a parallel line.
  - Provides phase and mode (alpha and beta) outputs.
- To use in Mainstep or Substep.

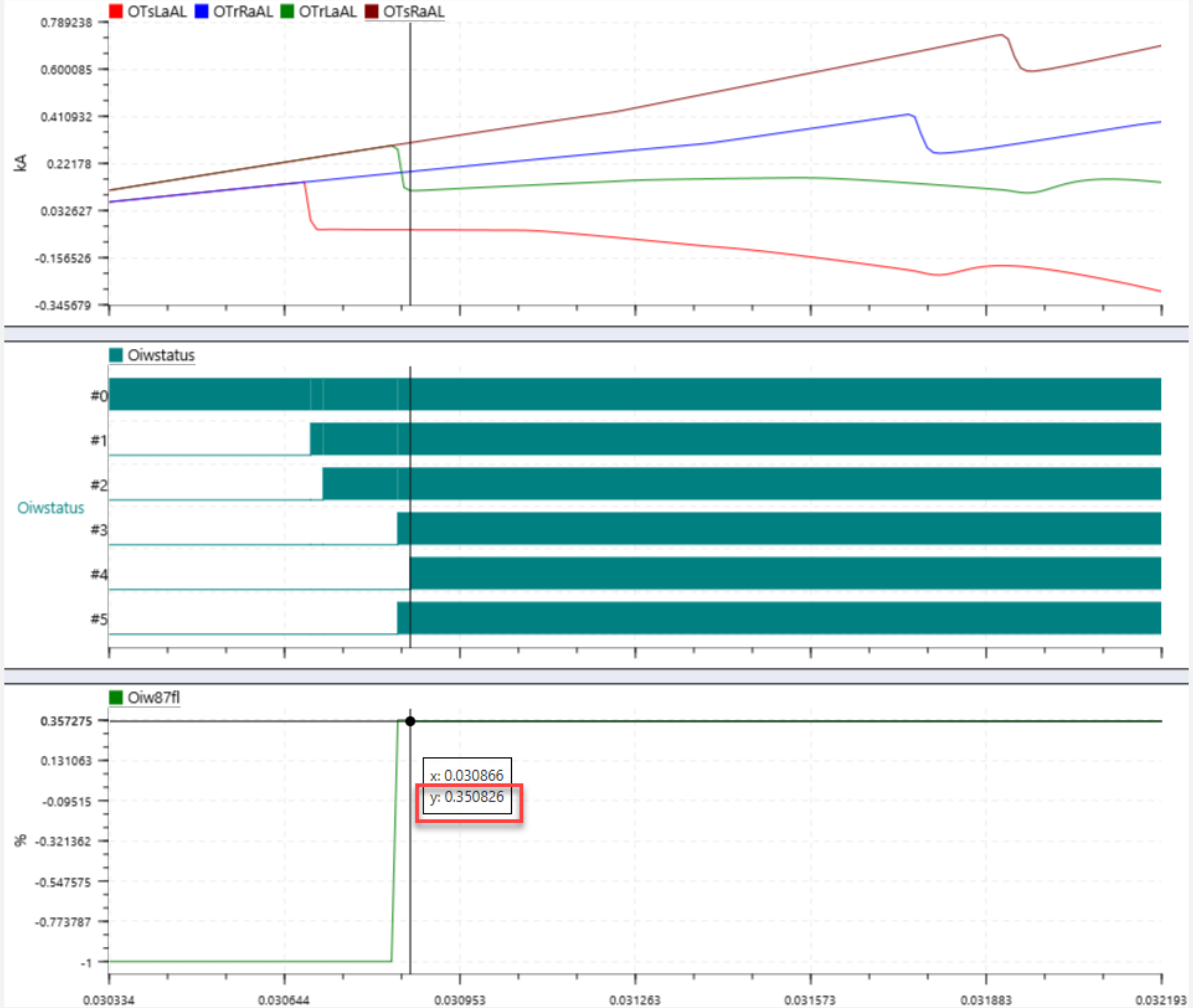



LOCINCSEC1
REMINCSEC1
LOCINCREC1
REMINCREC1
Internal AG fault - 35% away from left terminal
3.891279
2.631365
1.371451
0.111536
-1.148378
-2.408292
-3.668206
0.020748
0.026764
0.03278
0.038797
0.044813
0.050829
0.056845

IWCR - Simulation Results

- Mainstep real-time DT = 11us.

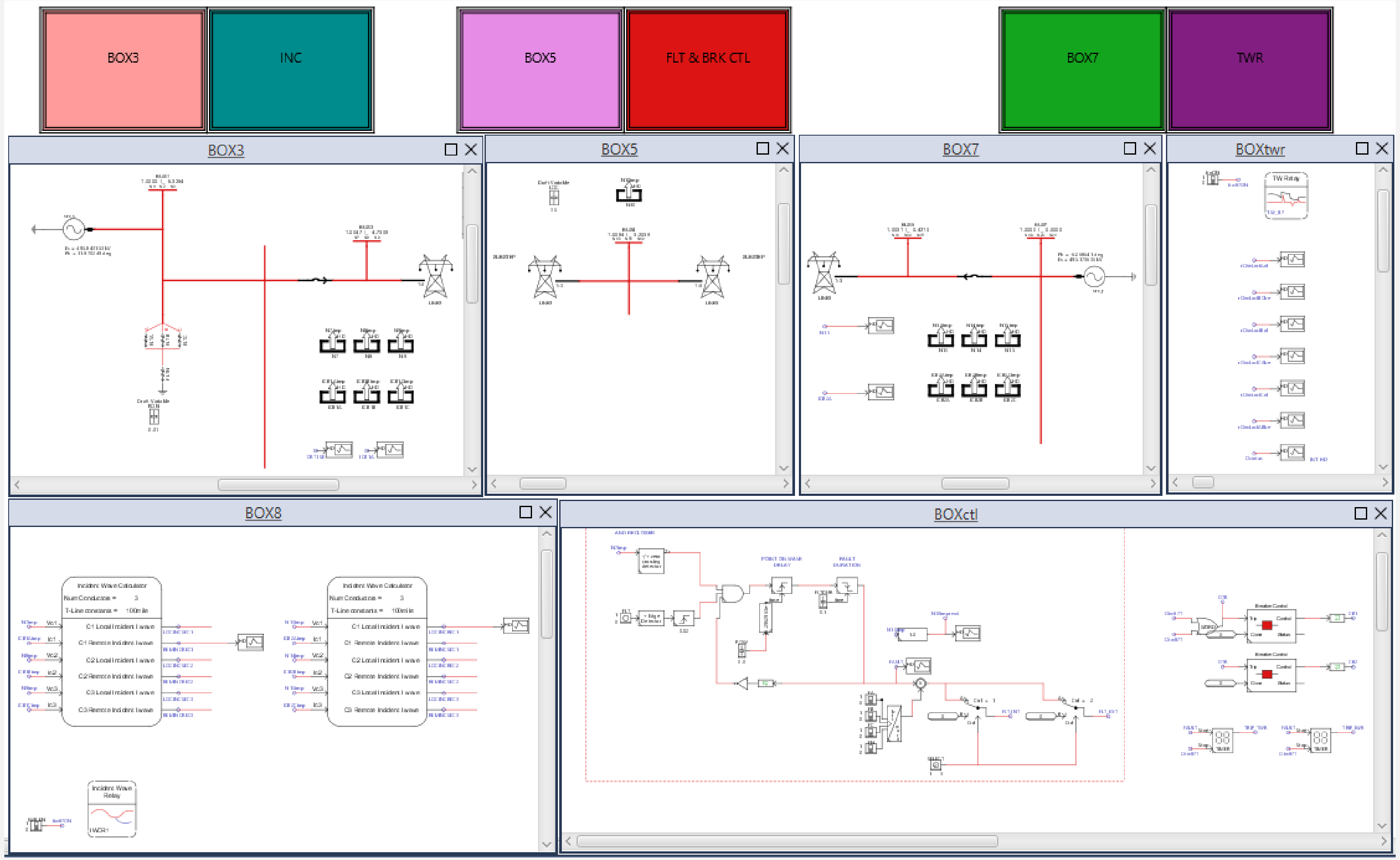




TWR vs IWCR

$$i = \frac{-2Z_c}{Z_{T\_K} + Z_c} i_-$$

- Substep real-time DT = 1.667 us.
- Internal ABG fault 35 % away from left terminal.



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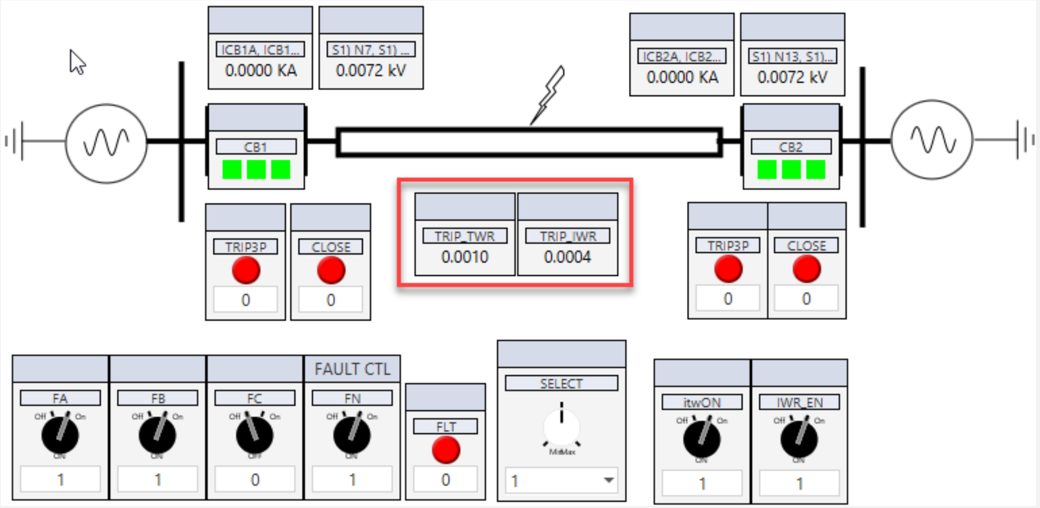
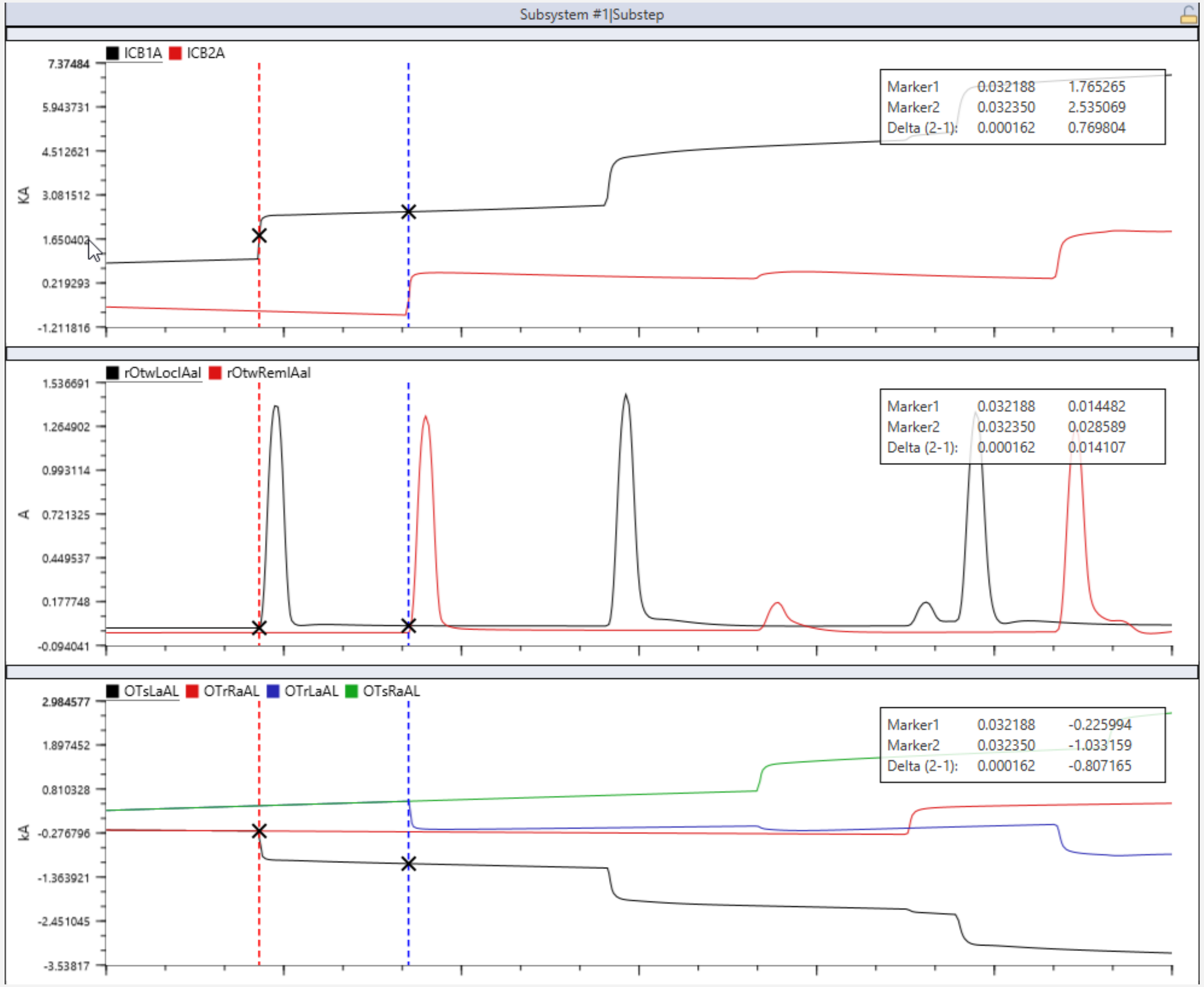
TWR vs IWCR -
Simulation Results

$$i = \frac{-2Z_c}{Z_{T\_K} + Z_c} i_-, \qquad with\ Z_{T\_K} = R$$

- Fault location
  - TWR - 35.017 %.
  - IWCR - 35.007 %.



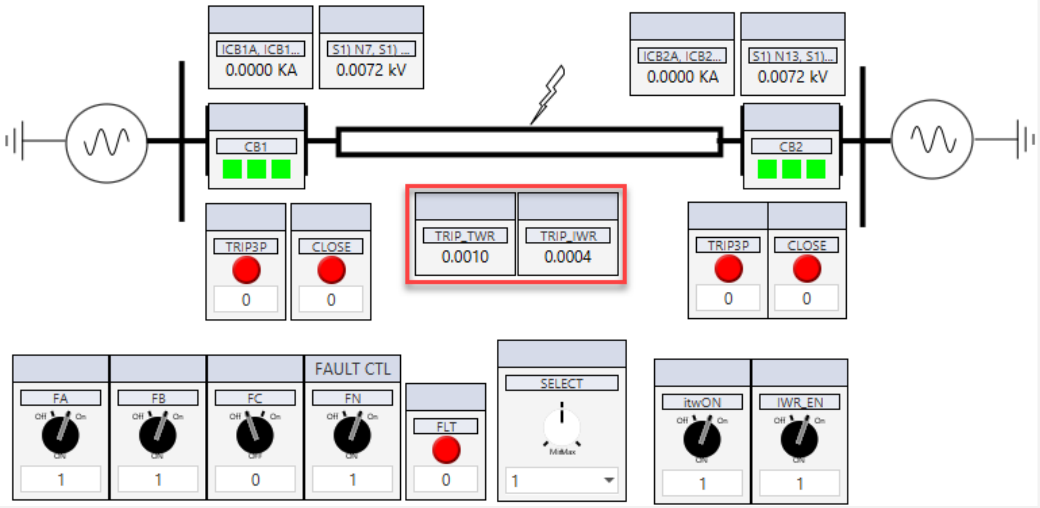


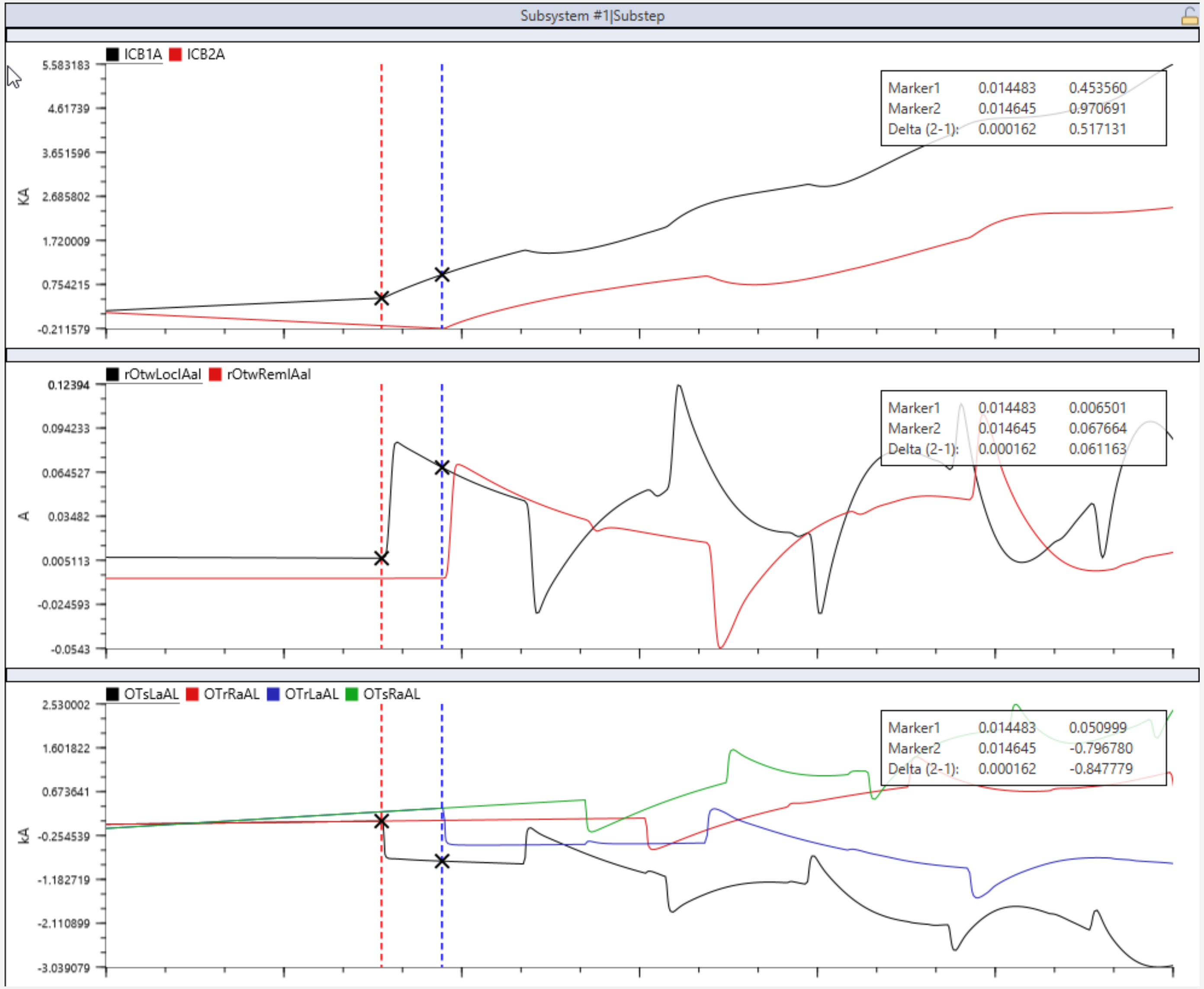
TWR vs IWCR -

Simulation Results

$$i = \frac{-2Z_c}{Z_{T\_K} + Z_c} i_-, \qquad with\ Z_{T\_K} = L$$

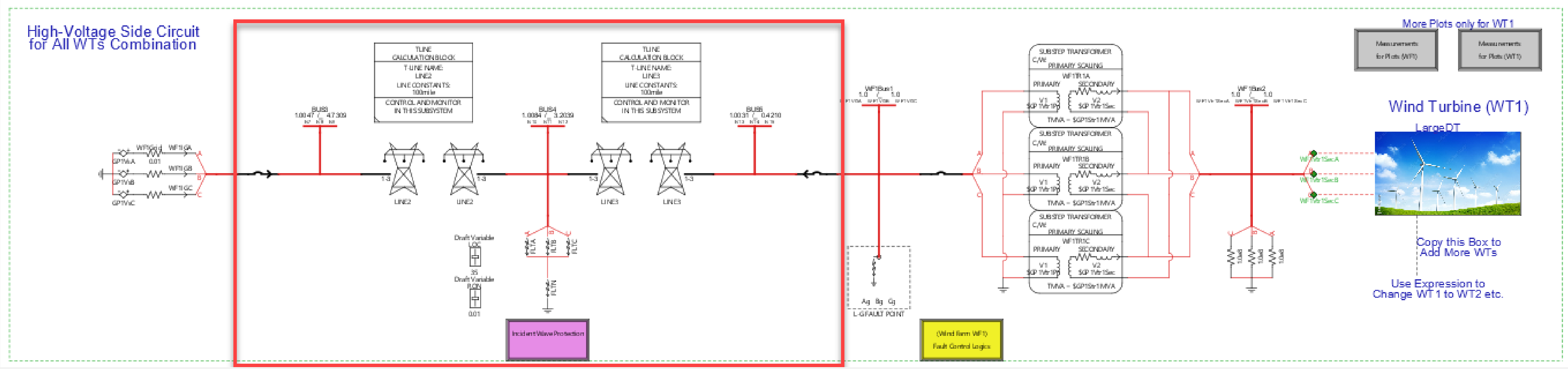
- Fault location
  - TWR - 34.708 %.
  - IWCR - 35.012 %.





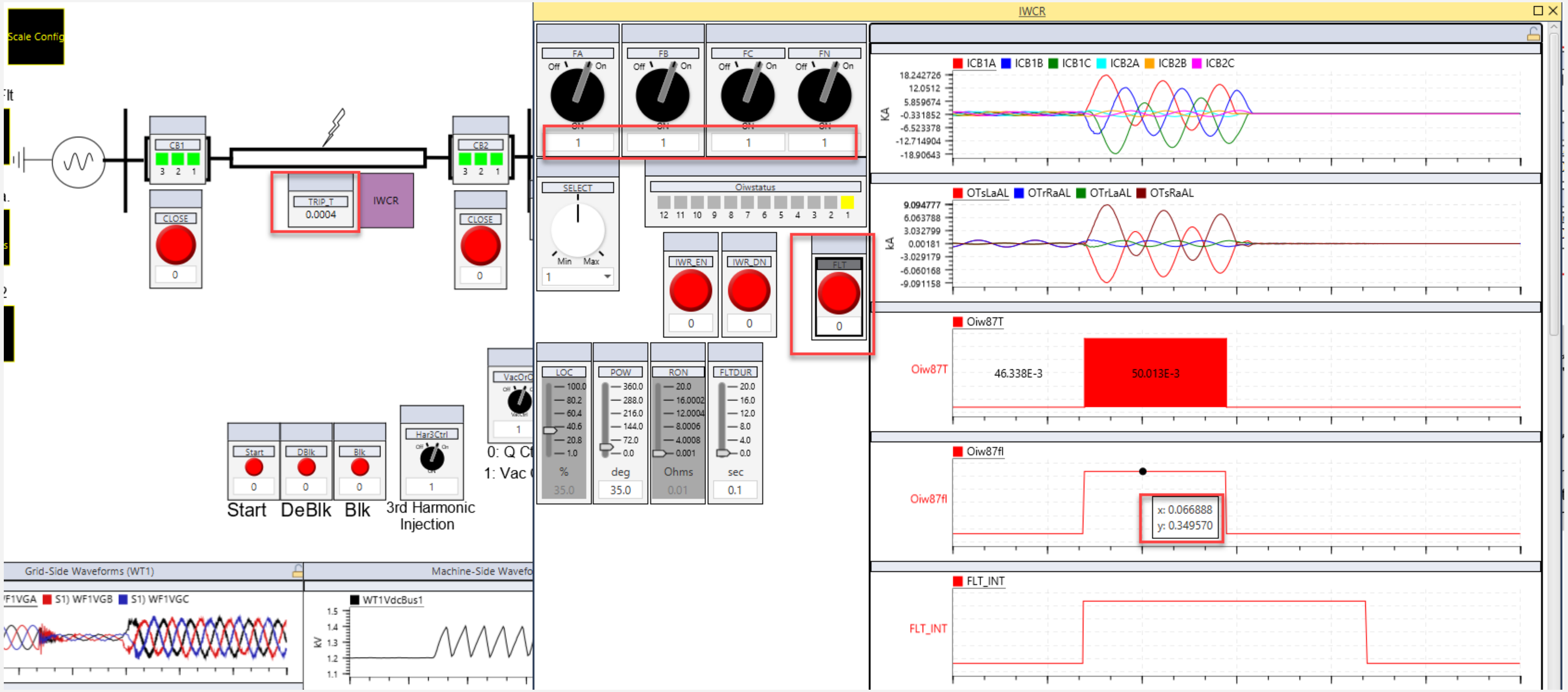
IWCR –
Used in a renewable application

- Base case - ***PMSM_Farm_LrgDT***, from –
  03 Renewables\Wind Energy\Type 4\PMSM.
- Mainstep DT = 15 us.
- The ac-grid impedance is replaced with a 100-mile long transmission line.



IWCR –
Used in a renewable application

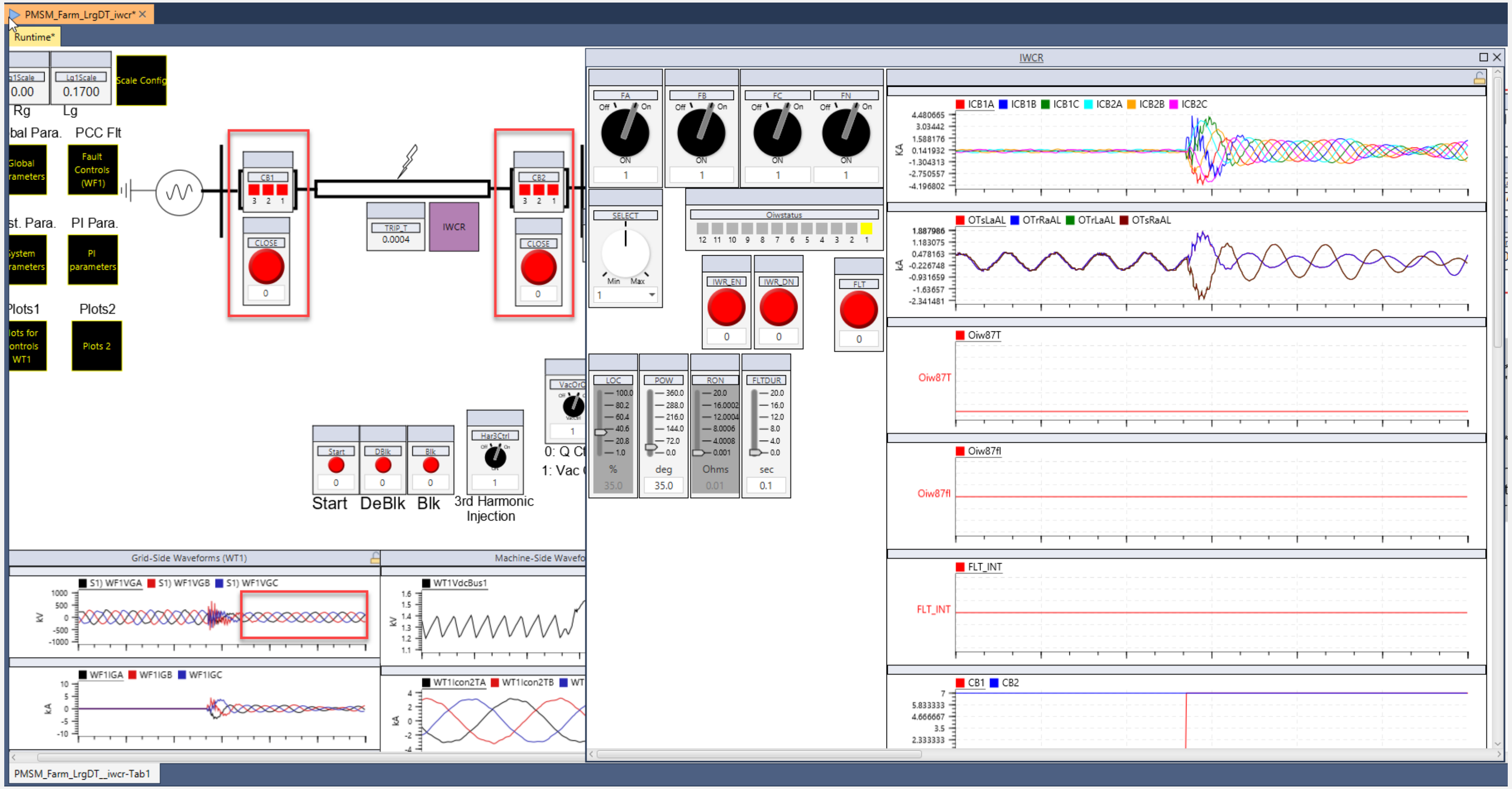
- Internal ABCG fault at 35% away from the left terminal.



IWCR –

Used in a renewable application

- Recovery of the system after breakers are manually reclosed.



THANK YOU!