Line protection considerations for systems with inverter-based resources

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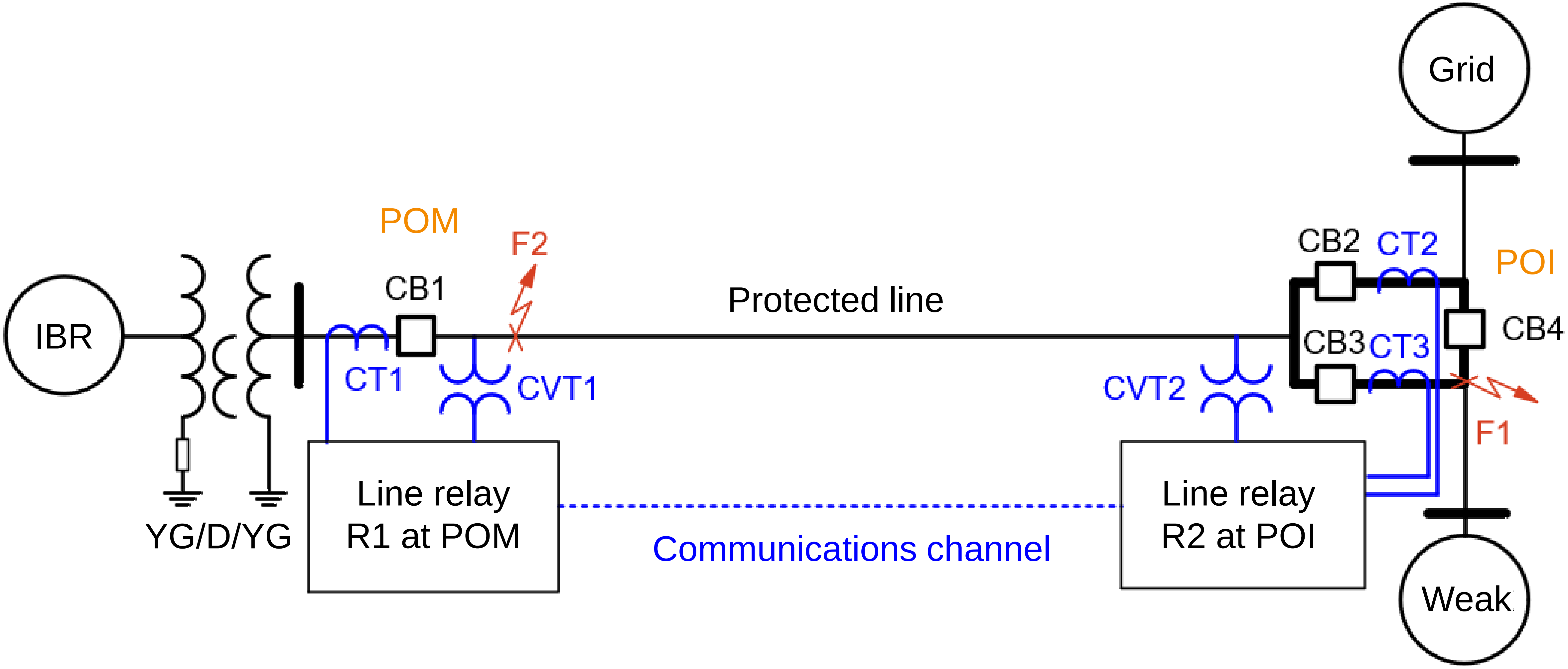
Overview

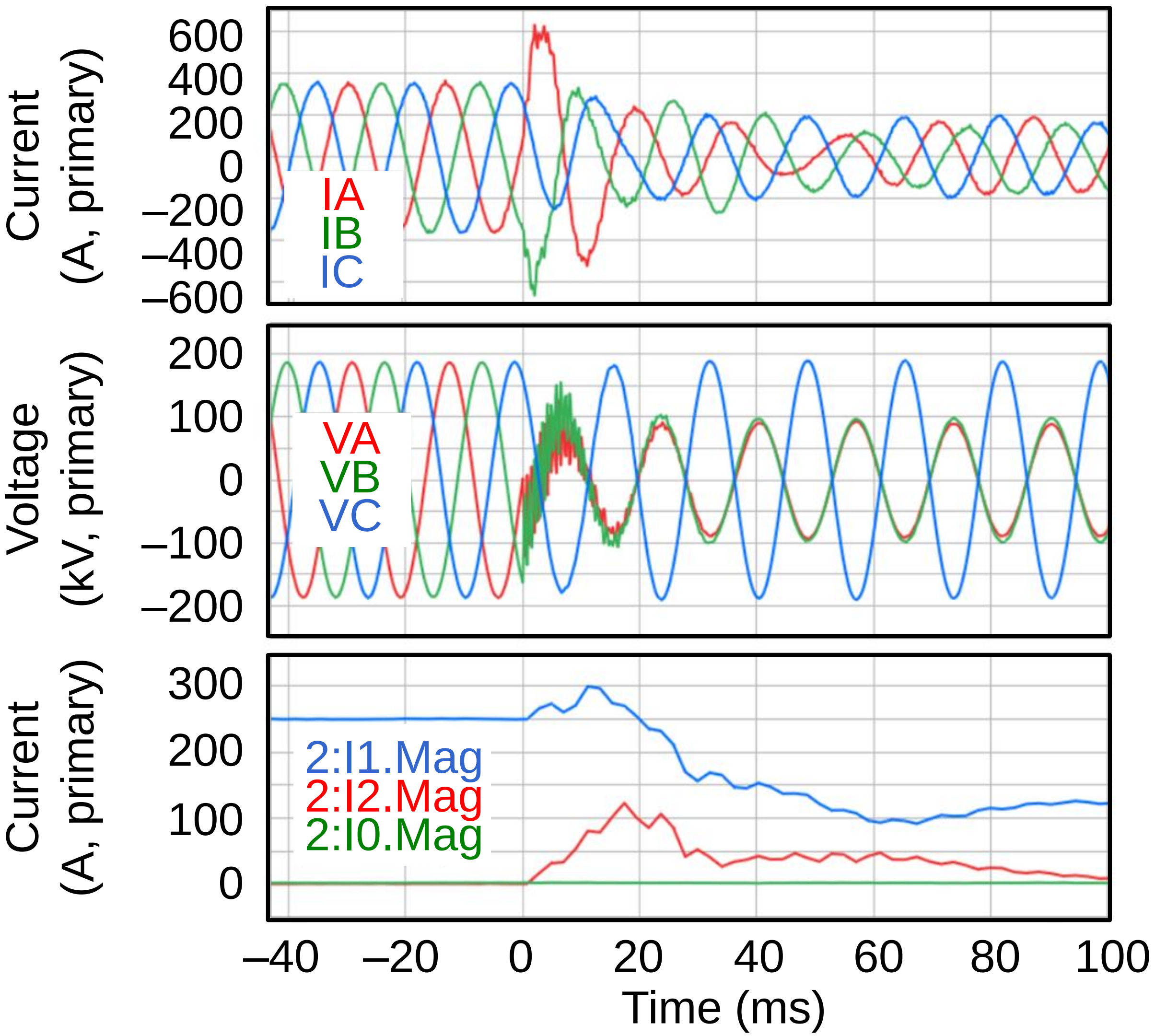
- Negative-sequence current challenges
- Distance element considerations
- Transient-based line protection and fault locating
- Source-to-line impedance ratio (SIR)
- Directional comparison pilot schemes
- Line current differential
- Power swing blocking
- Conclusion and References

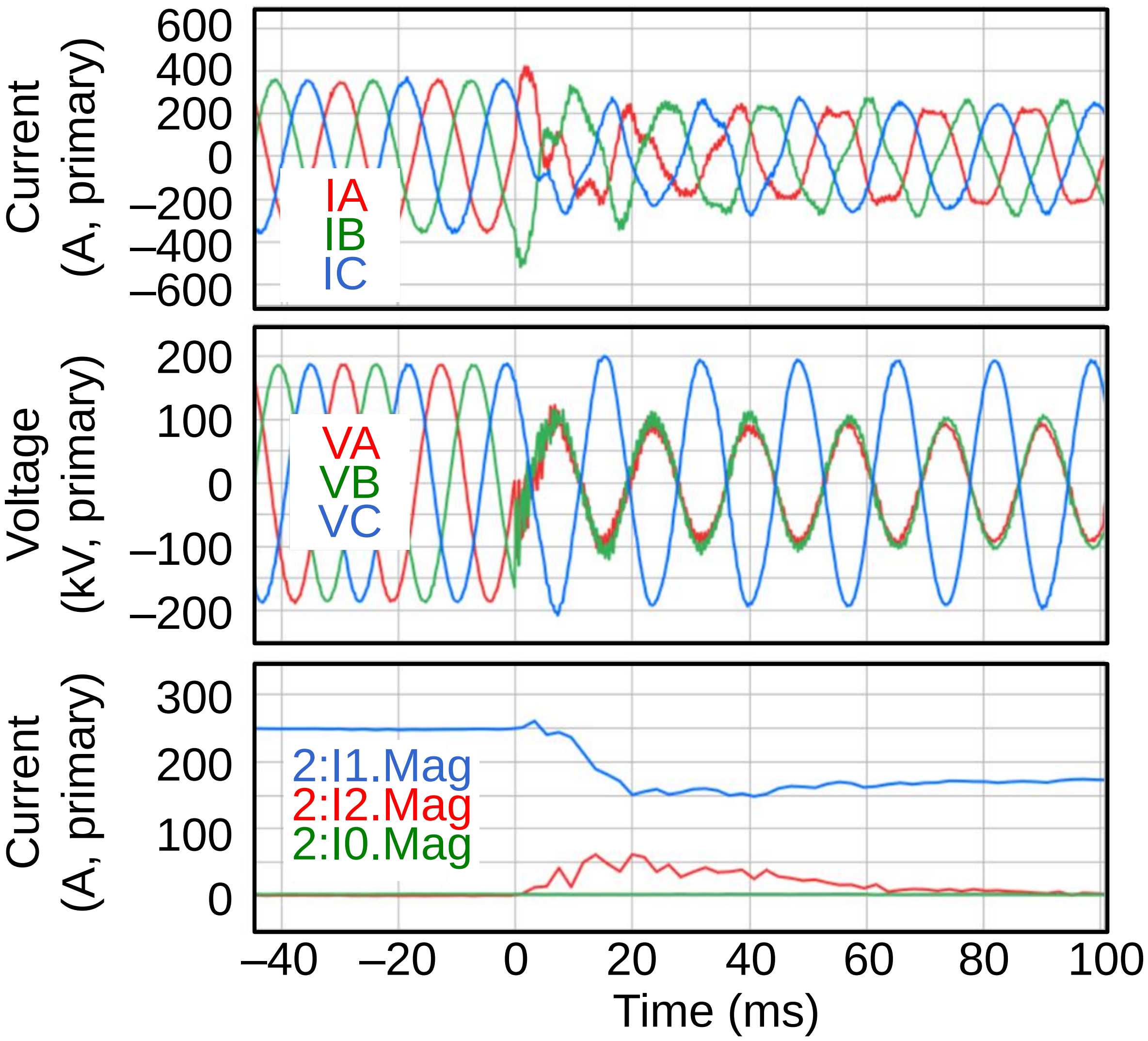
One-line diagram



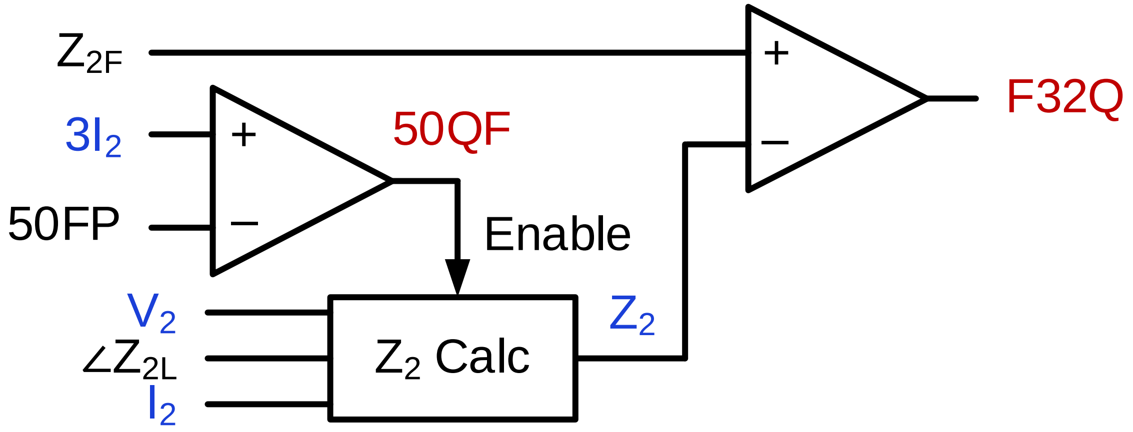
Negative-sequence current challenges

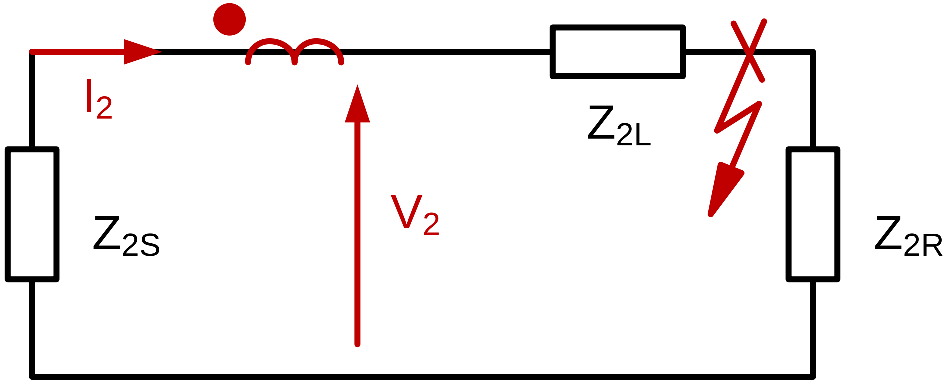
Type 4 Wind AB fault at remote bus

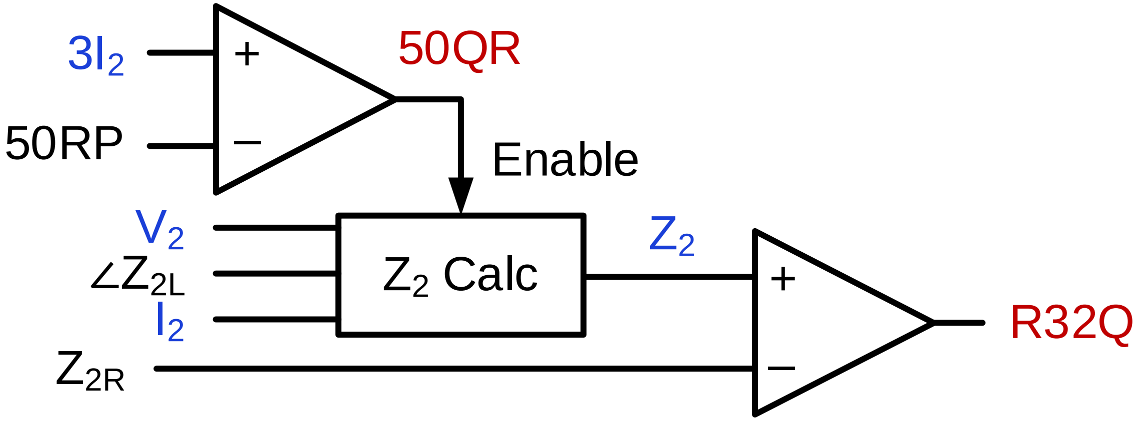


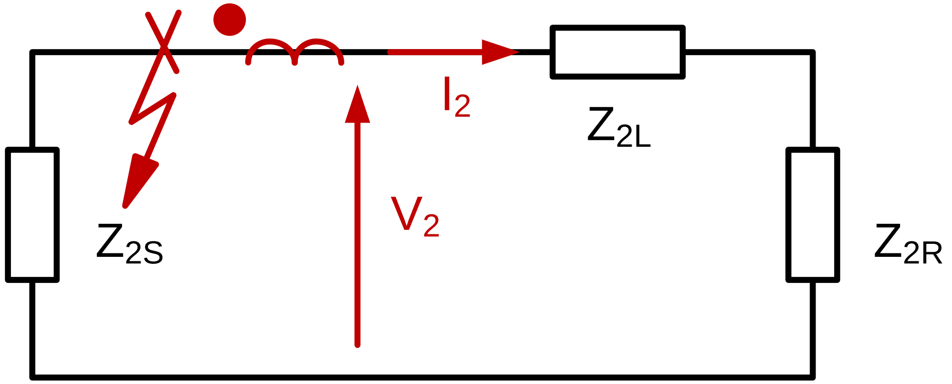


Directional element (32)



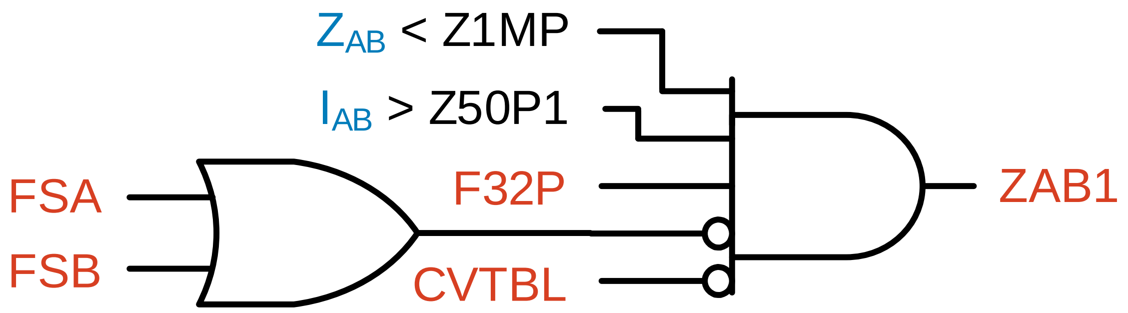


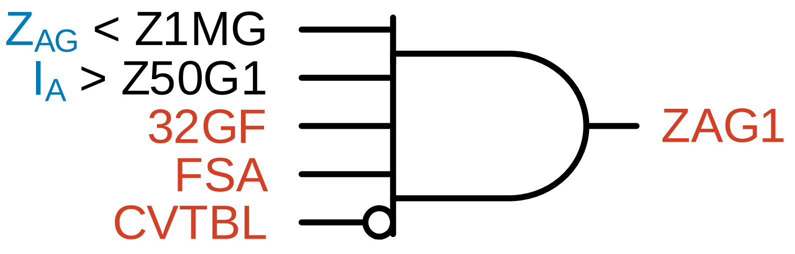




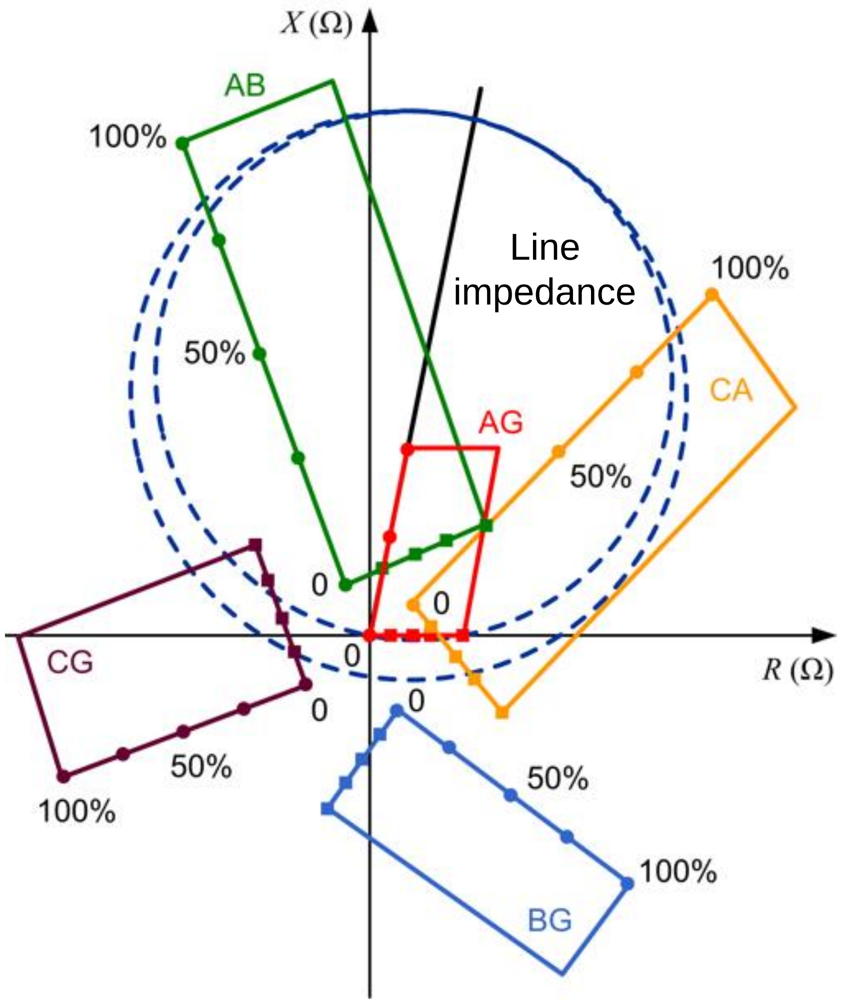
Distance element (21)

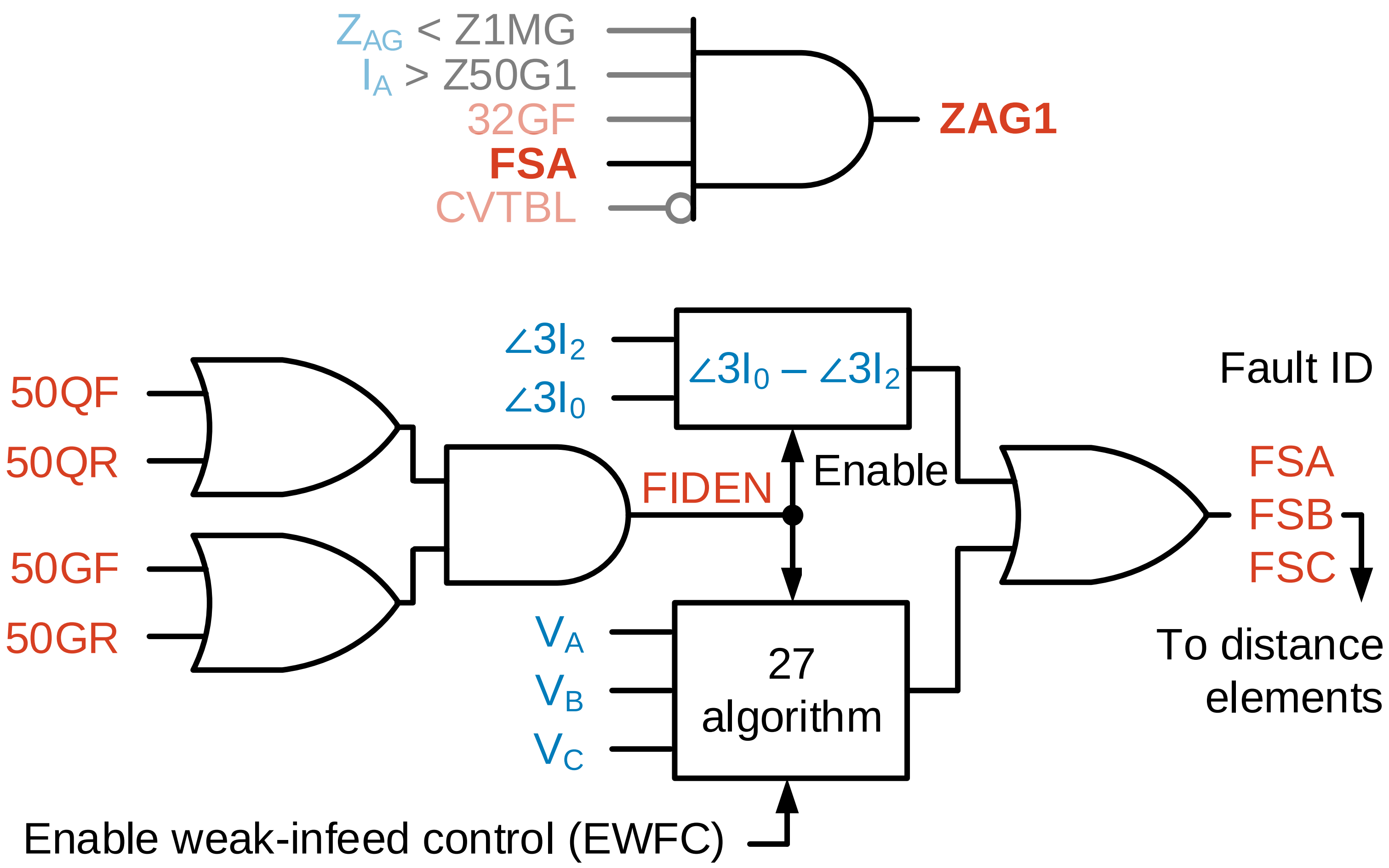
- Calculated impedance is less than set reach
- Loop current greater than fault-detector threshold (Zone 1)
- Directional element supervision (forward/reverse)
- Fault-type Identification and Selection (FIDS) logic does not block element
- No CVT transients detected (Zone 1)





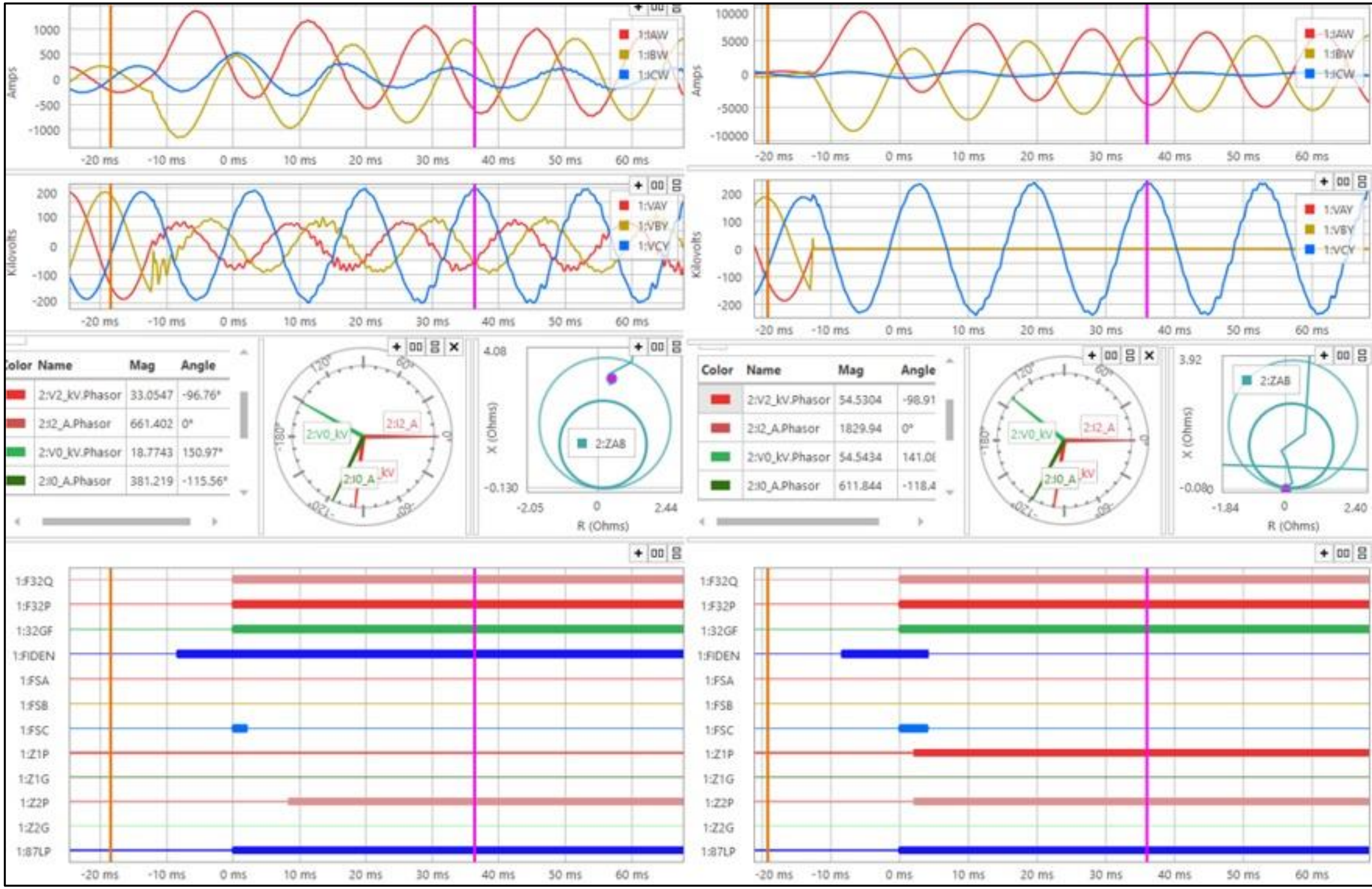
FIDS – AG fault





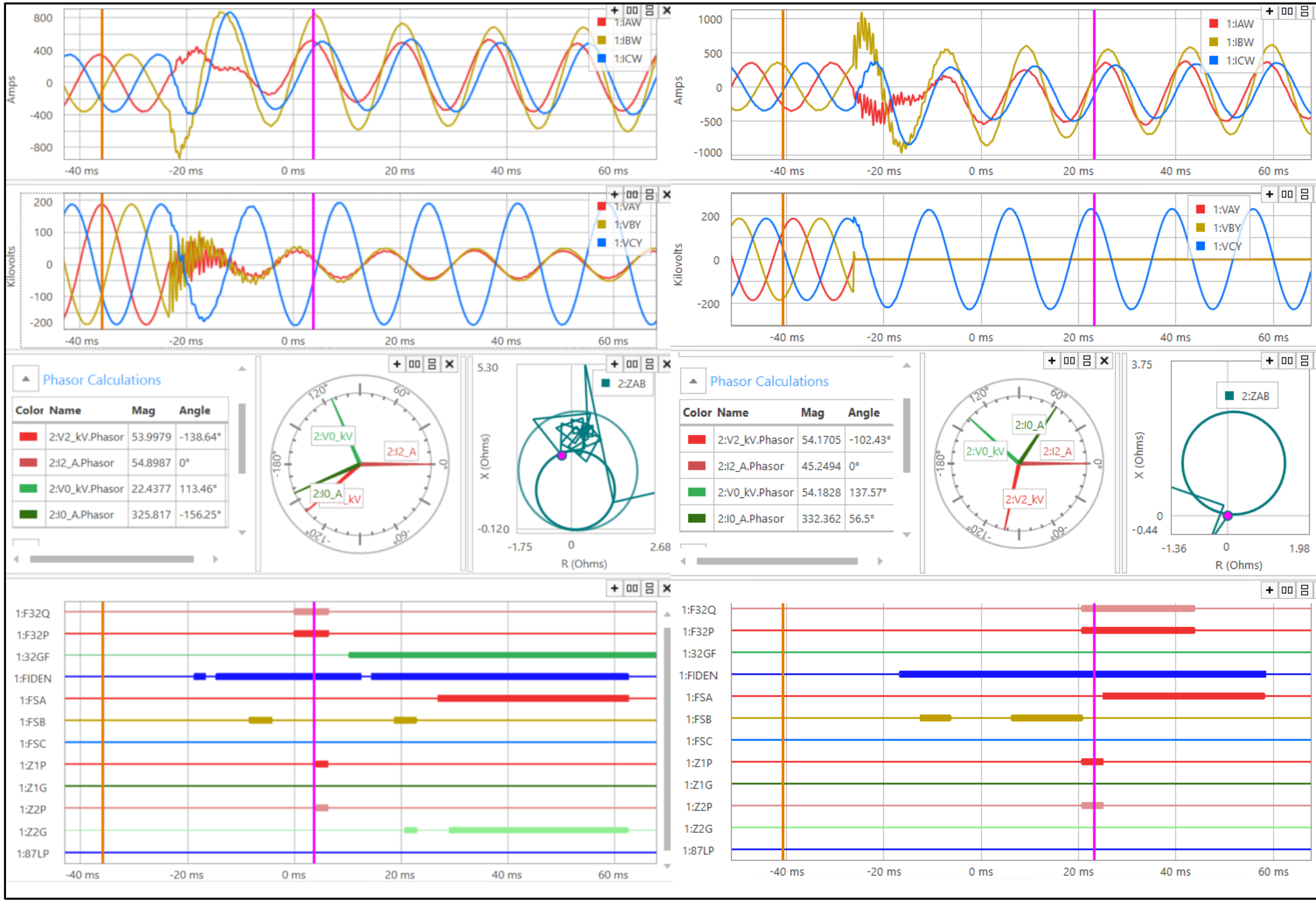
Internal ABG fault (reference)

Internal fault



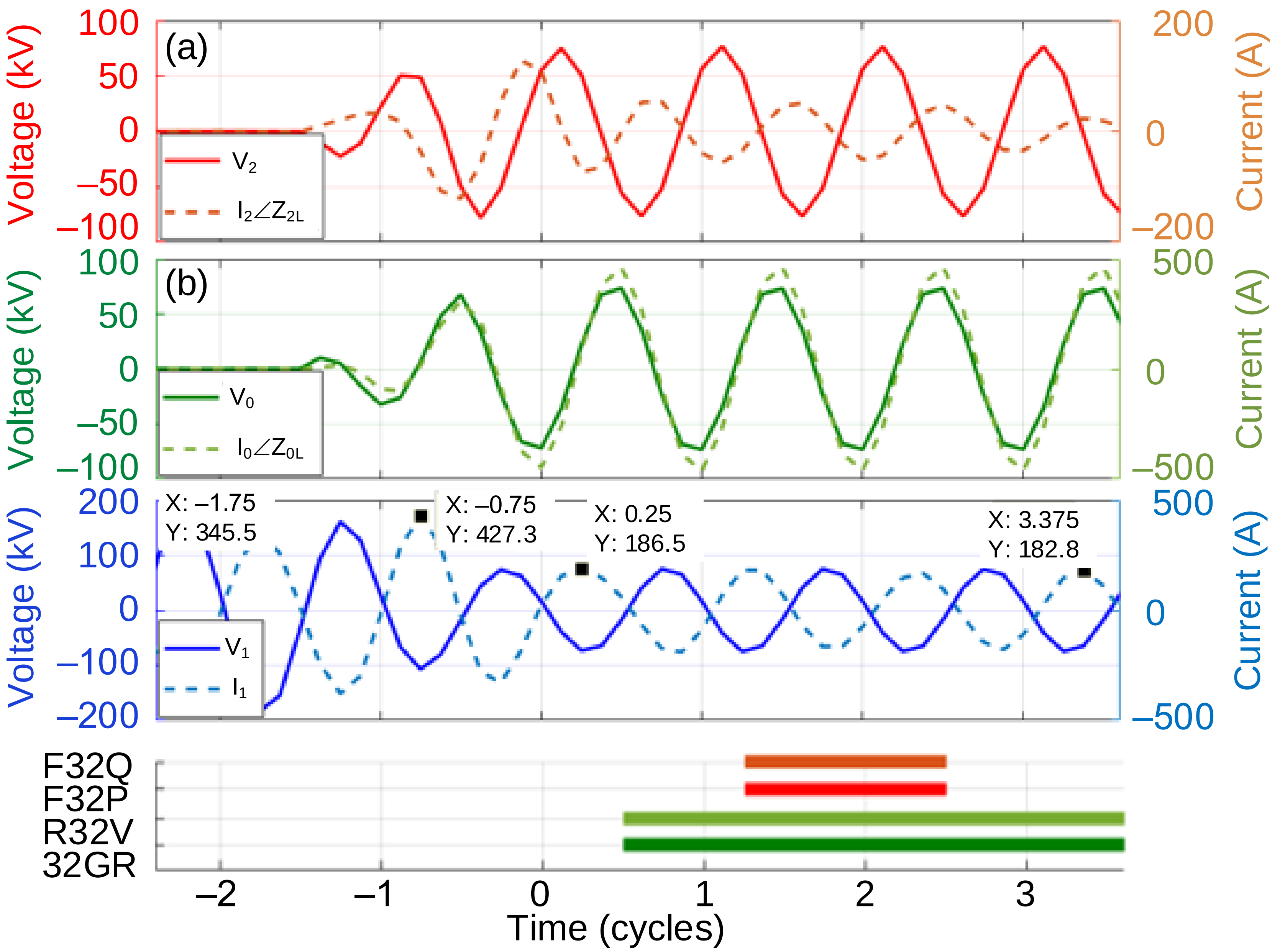
Type 4 Wind ABG fault

External fault

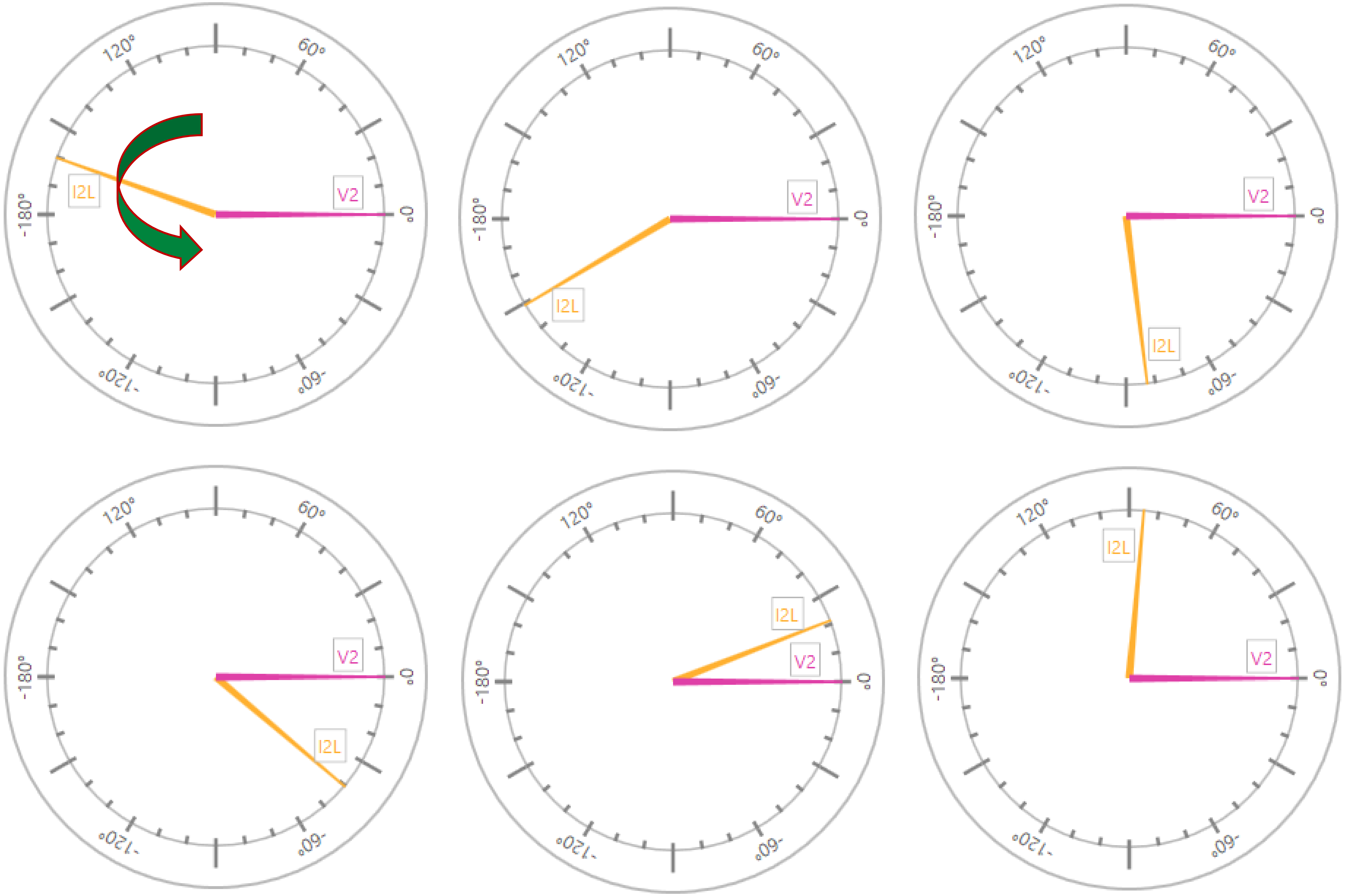


Type 4 Wind ABG fault

Sequence element behavior



I2 vs. V2



Improved performance of directional and fault type selection

IEEE Std 2800-2022 performance requirements

For unbalanced faults, in addition to increased positive-sequence reactive current, the *IBR unit* shall inject negative sequence current:

- Dependent on *IBR unit* terminal (POC) negative sequence voltage and
- That leads the *IBR unit* terminal (POC) negative sequence voltage by an allowable range as specified below:
  - 90 degrees to 100 degrees[106] for full converter-based *IBR units*
  - 90 degrees to 150 degrees for type III WTGs[107]

Table 13—Voltage ride-through performance requirements

Parameter	Type III WTGs	All other IBR units
Step response time[b, c, d]	NA[a]	≤ 2.5 cycles
Settling time[b, c, d]	≤ 6 cycles	≤ 4 cycles
Settling band	–2.5%/+10% of *IBR unit maximum current*	–2.5%/+10% of *IBR unit maximum current*

[a] The initial response from the type III WTG is driven by machine characteristics and not the control system. DC component, if present, has an impact on response, which is driven by machine parameters and time of fault occurrence. Even though the control system takes an action, it cannot control machine's natural response. As such, defining response time for type III WTGs is not necessary.

[b] System conditions may require a slower response time, or *IBR units* may not be able to meet response times noted in this table for certain system conditions. If so, greater response time and *settling time* are allowed with mutual agreement between an *IBR owner* and the *TS owner*.

[c] The DFT with a one-cycle moving average window is used to derive phasor quantities such as active, reactive, positive-sequence, negative-sequence currents, etc. The time delay required for the DFT measurements is included in the *step response time* and *settling time* specified in this table.

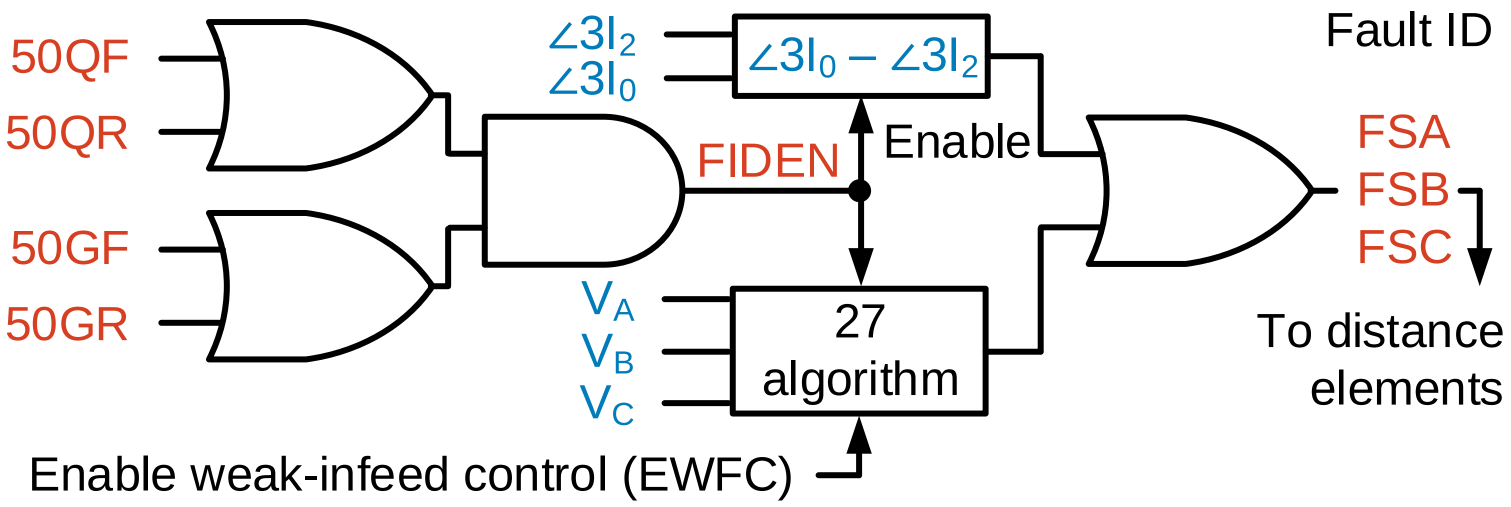
[d] The specified *step response time* and *settling time* applies to both 50 Hz and 60 Hz systems.

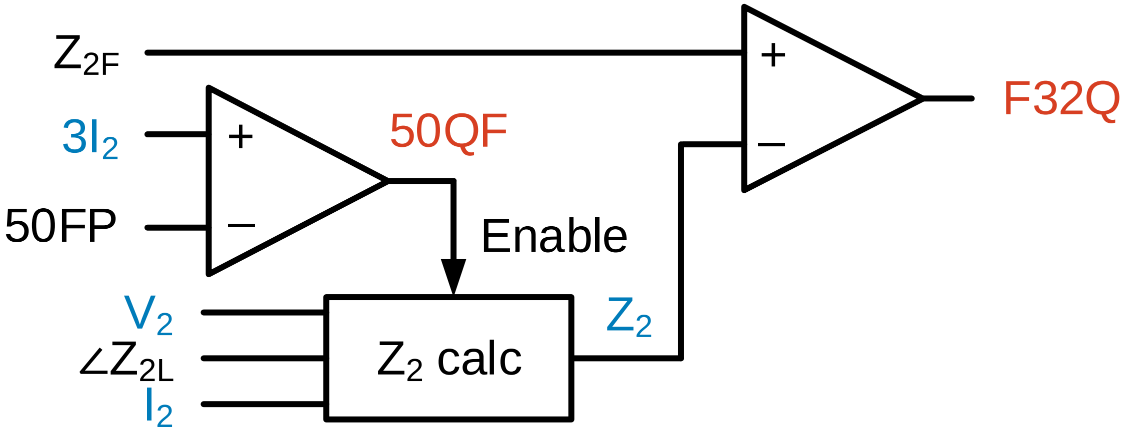
Improved performance of directional and FIDS

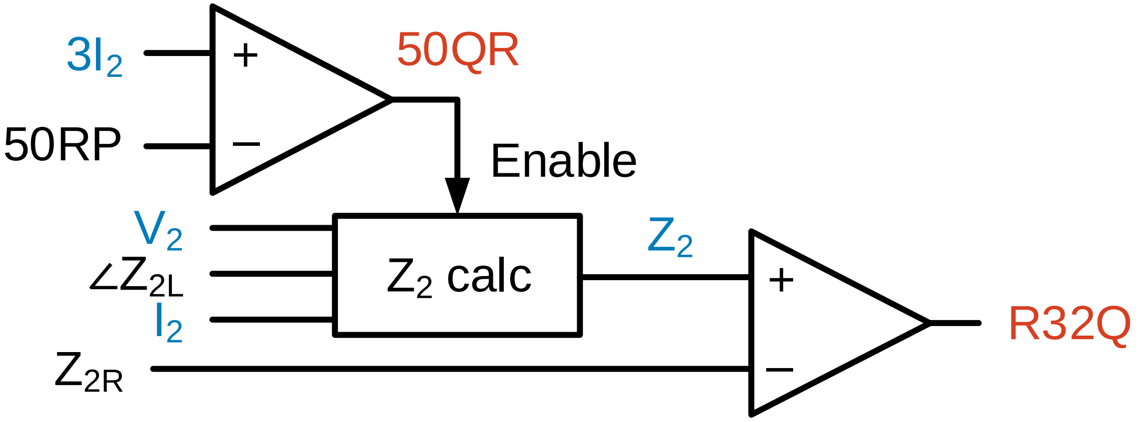
Increase overcurrent supervisory thresholds to improve 32Q security and FIDS security and dependability

$$50FP = 1.25 \text{ pu} \bullet I_{MAX}$$

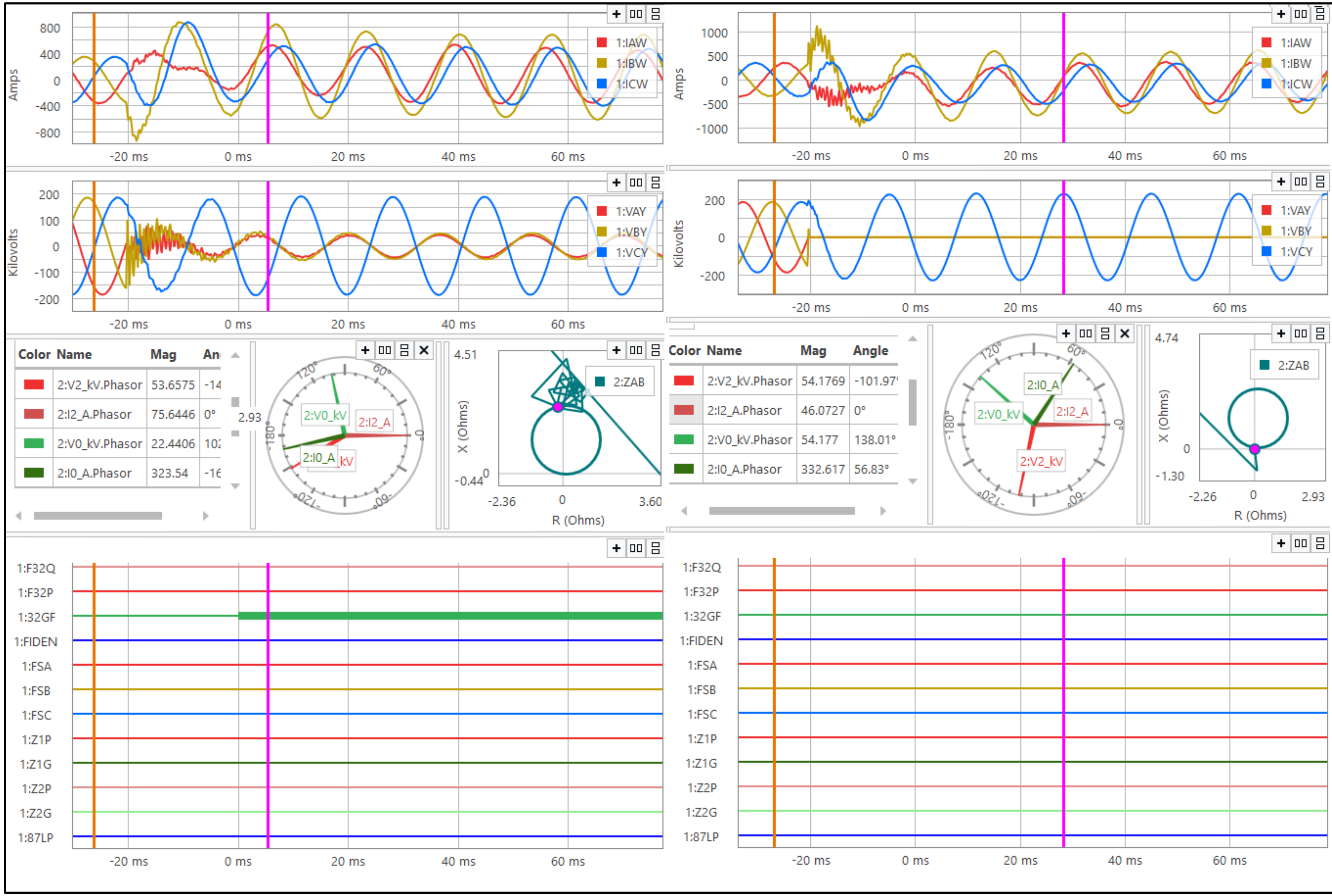
$$50RP = 1.00 \text{ pu} \bullet I_{MAX}$$





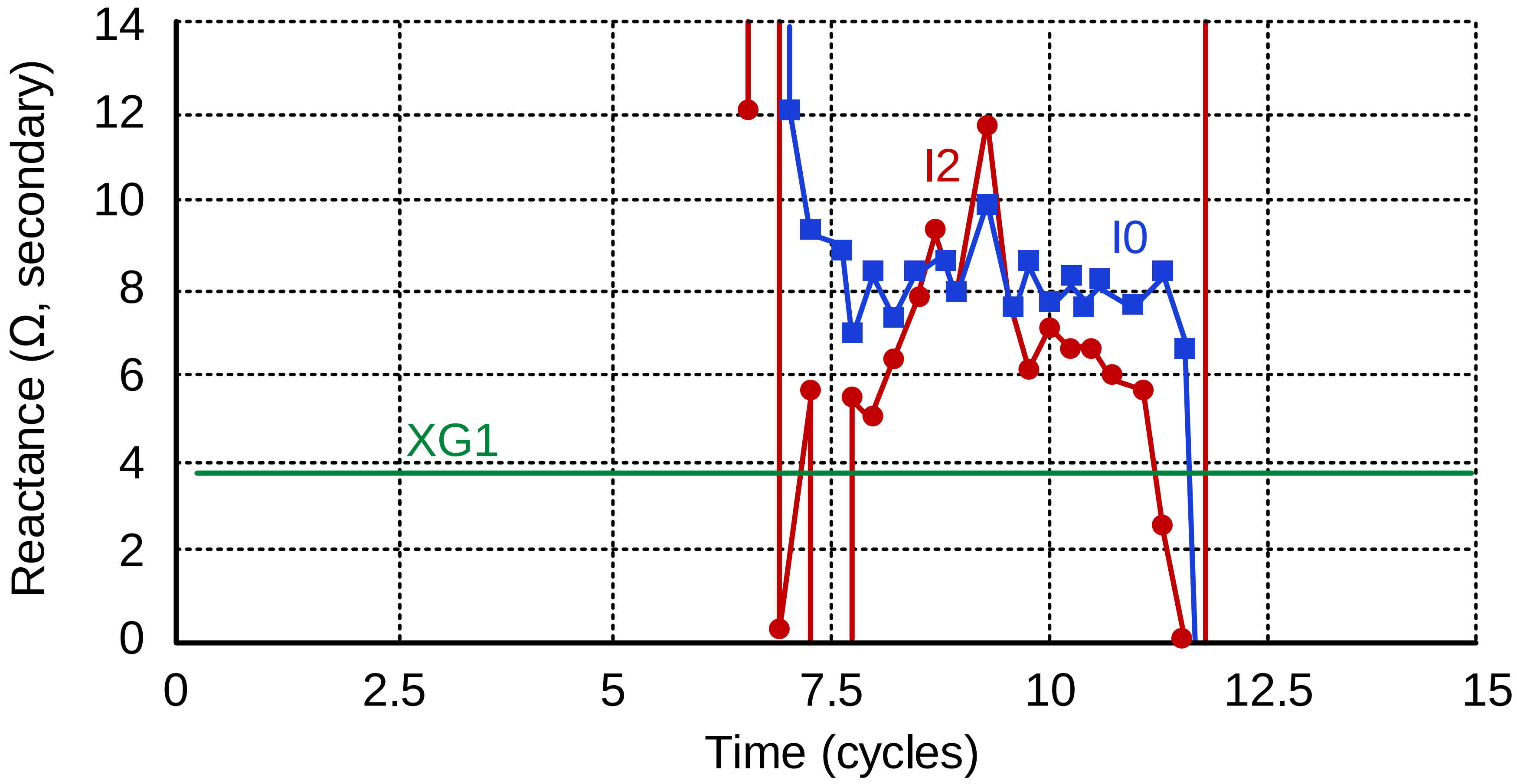


Type 4 Wind ABG fault

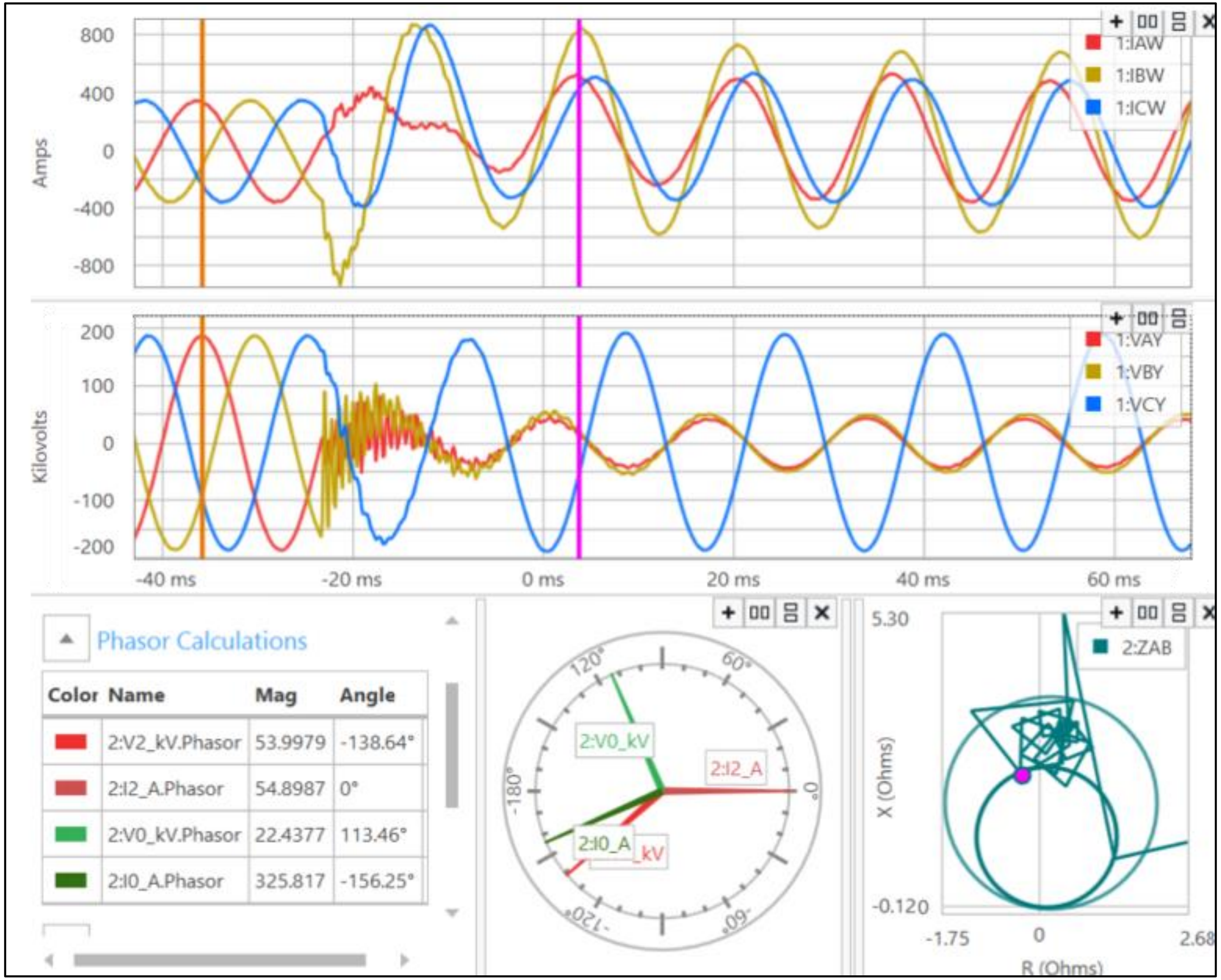


Distance element additional considerations

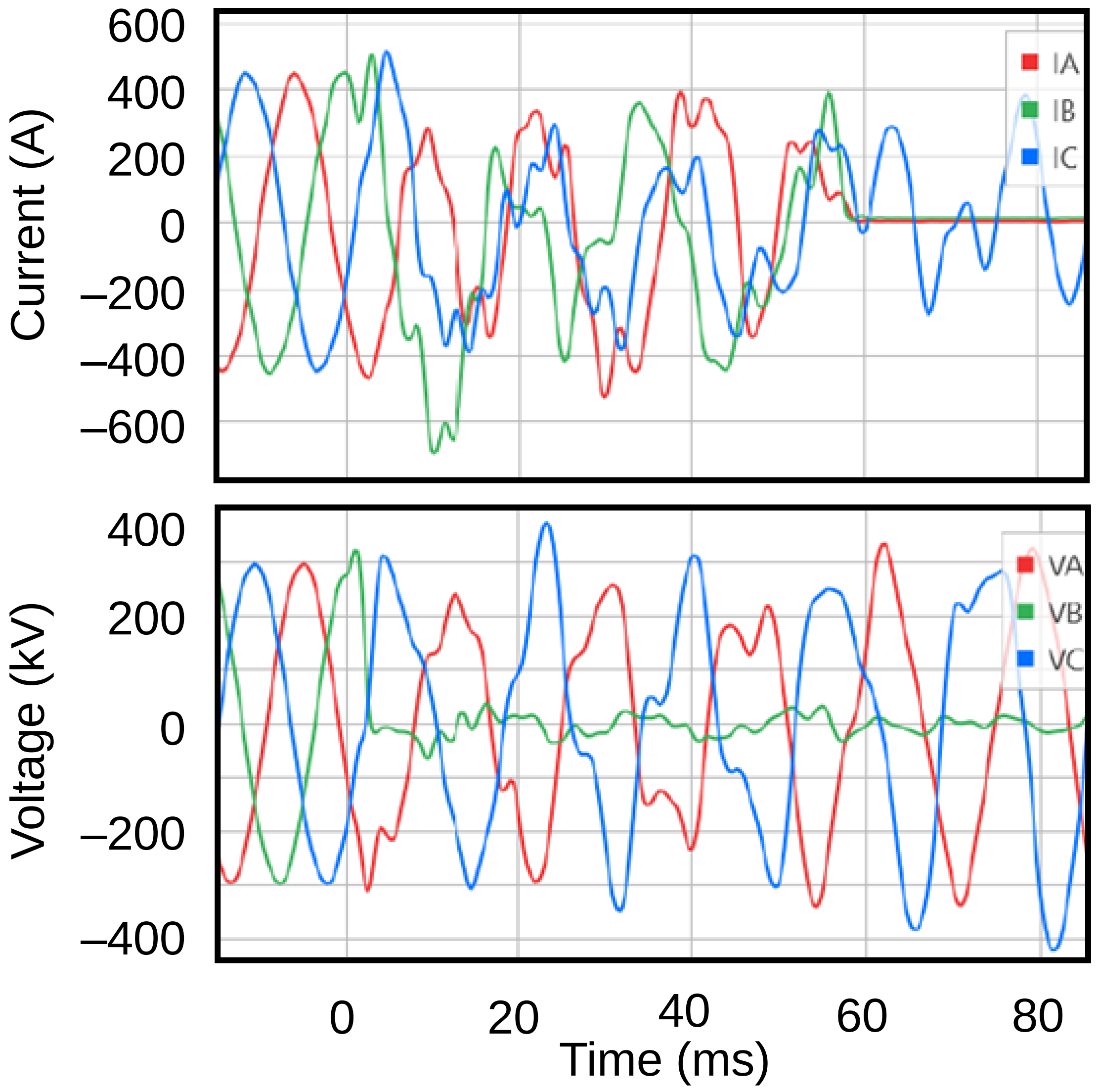
I2-polarized ground quadrilateral

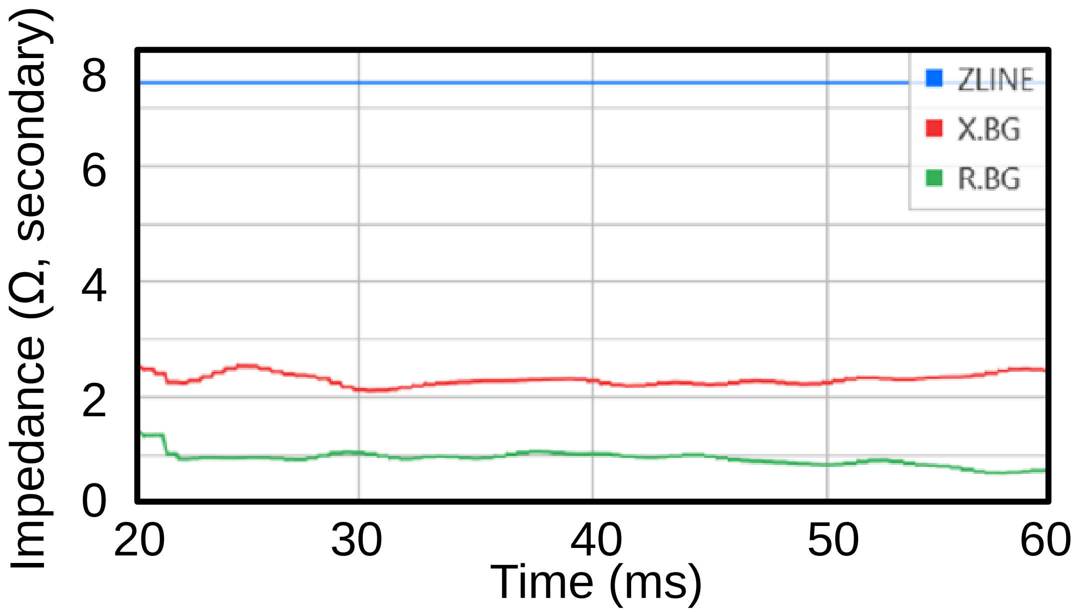


Memory-polarized phase mho

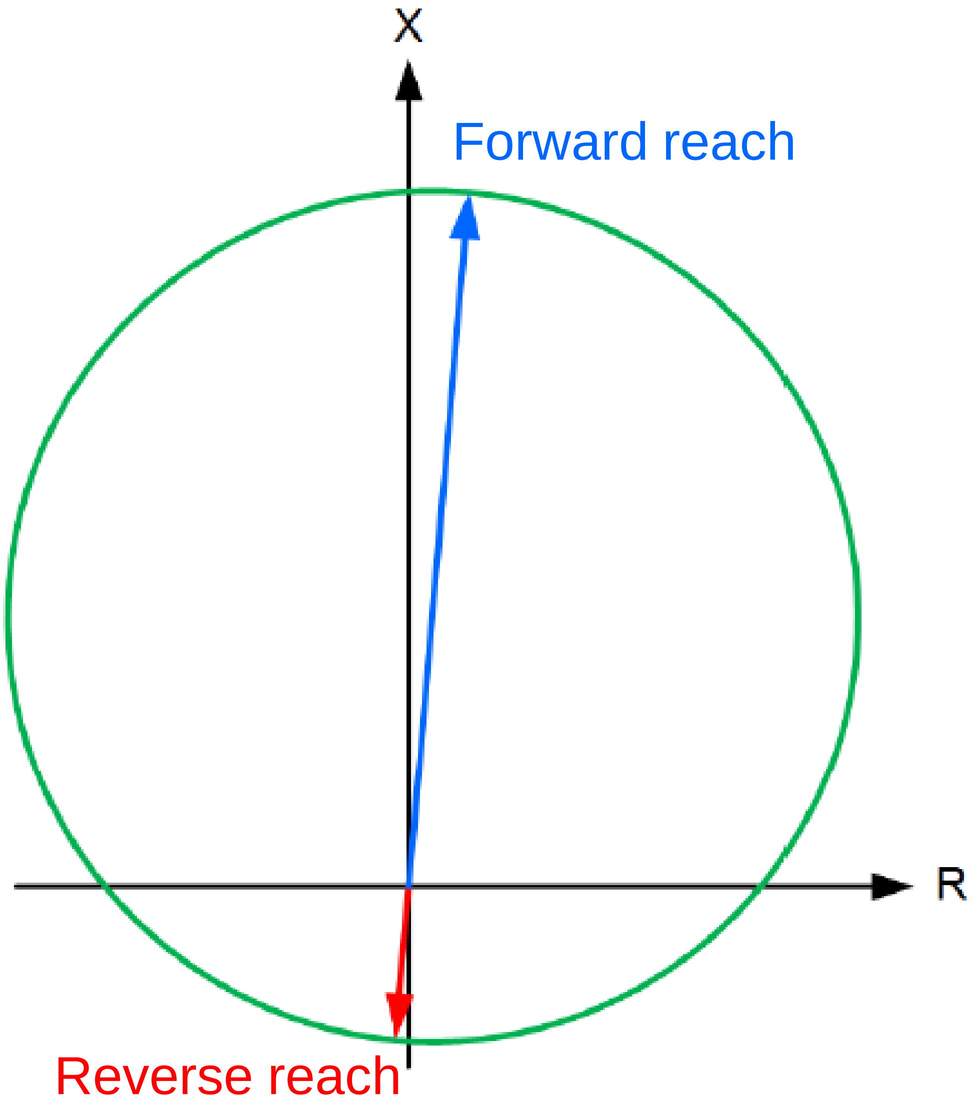


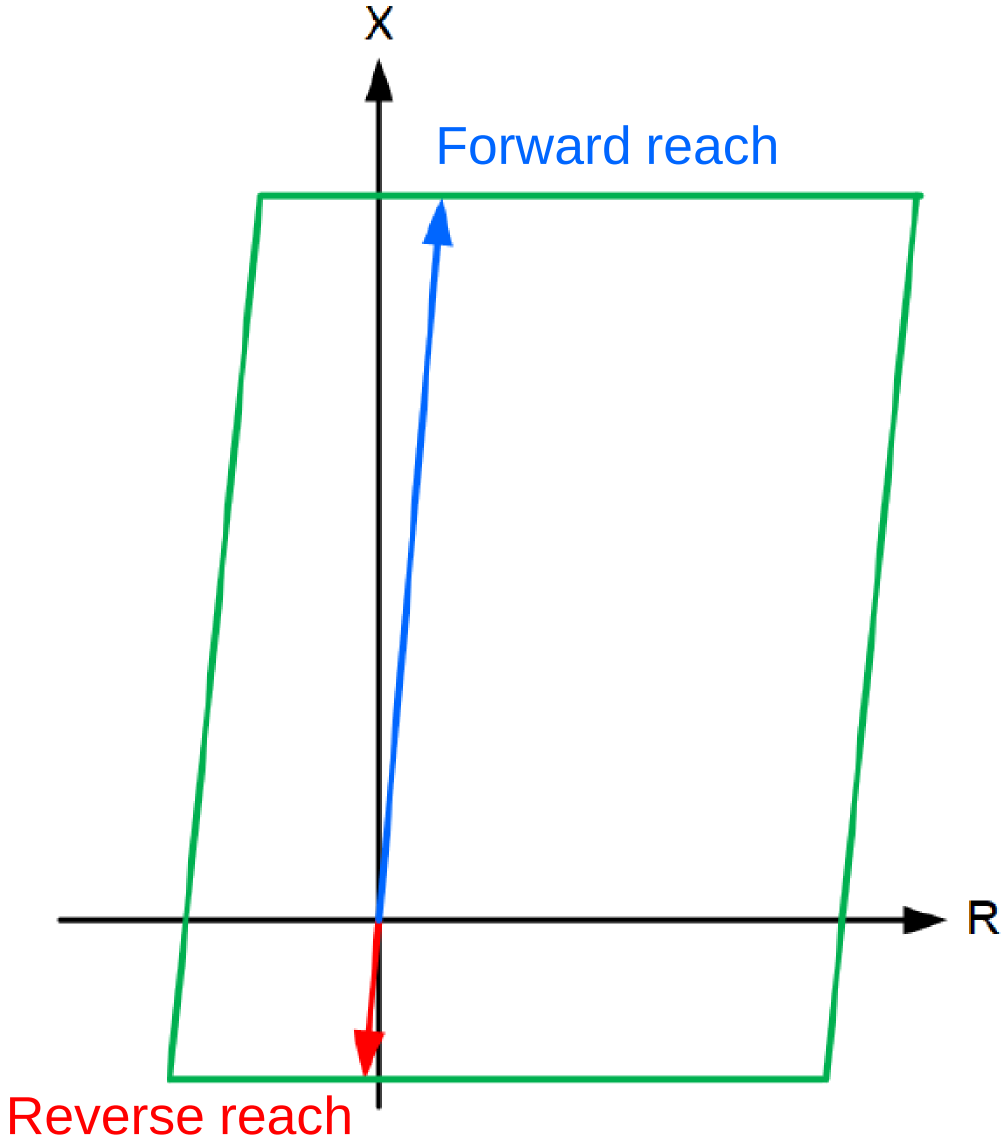
Distance element operating quantity



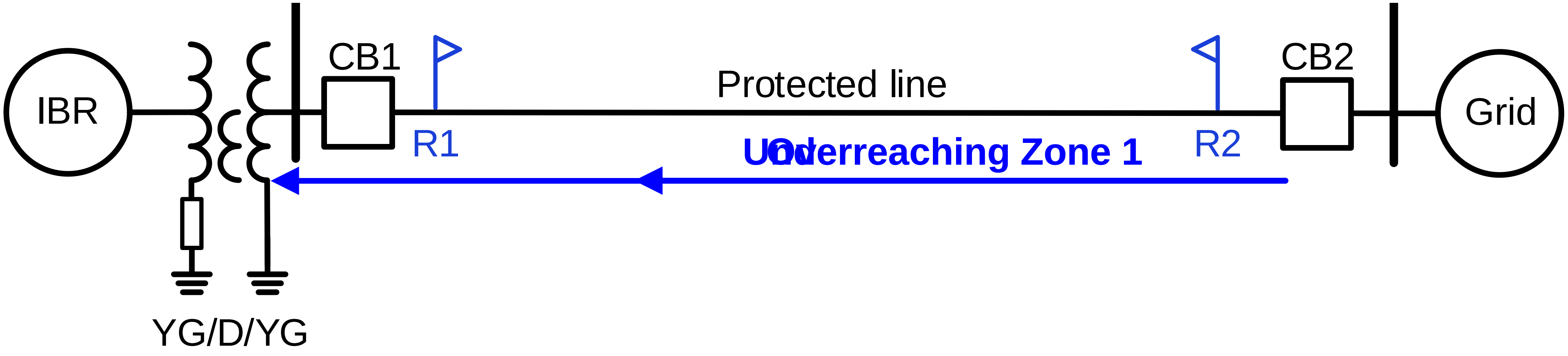


Self-polarized offset distance elements



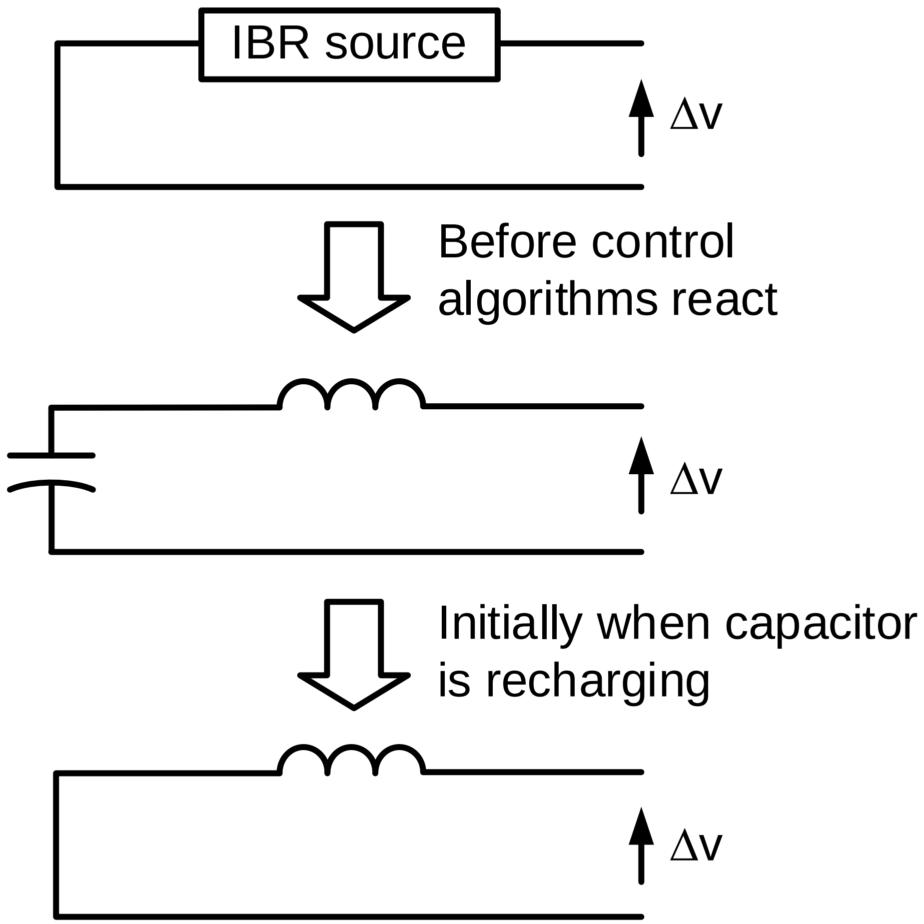


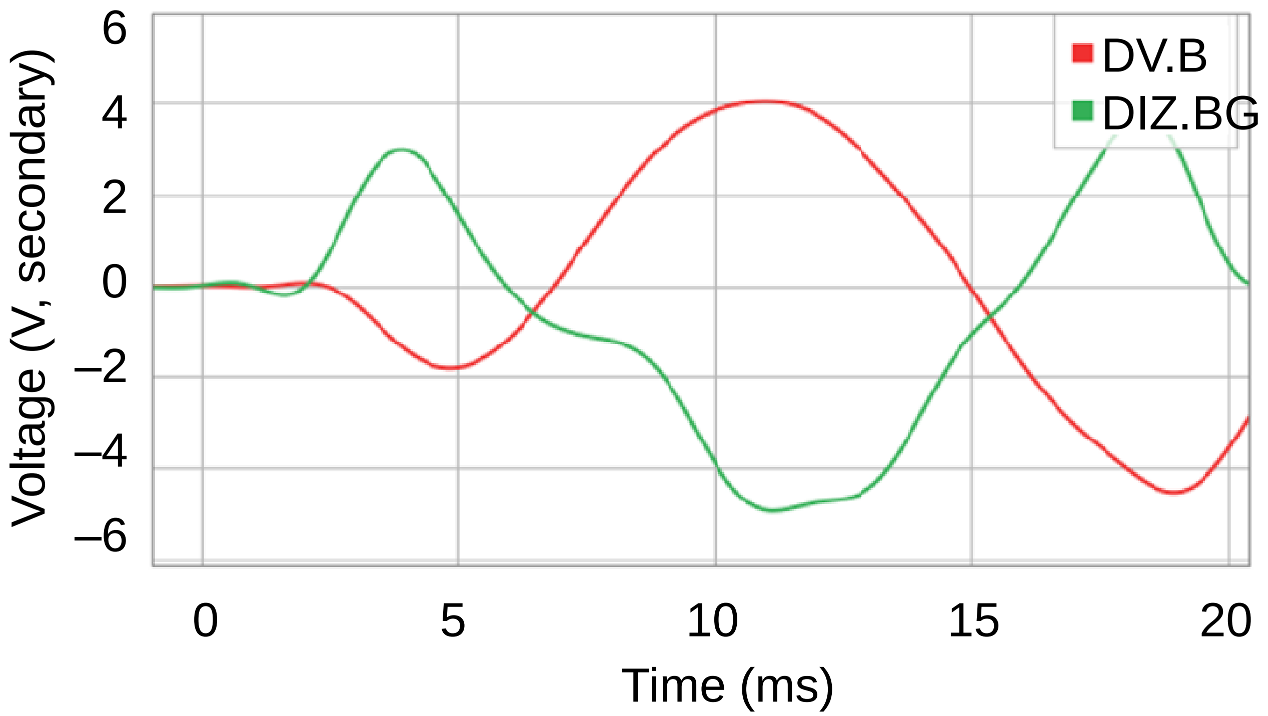
Increase Zone 1 reach for tie-lines without parallel path in a meshed network



Transient-based methods

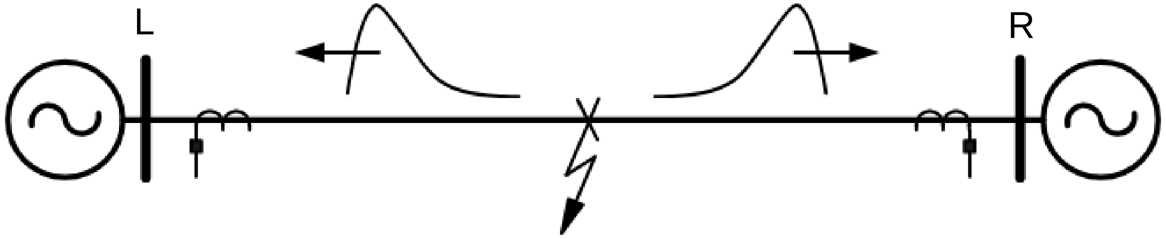
Transient-based directional element

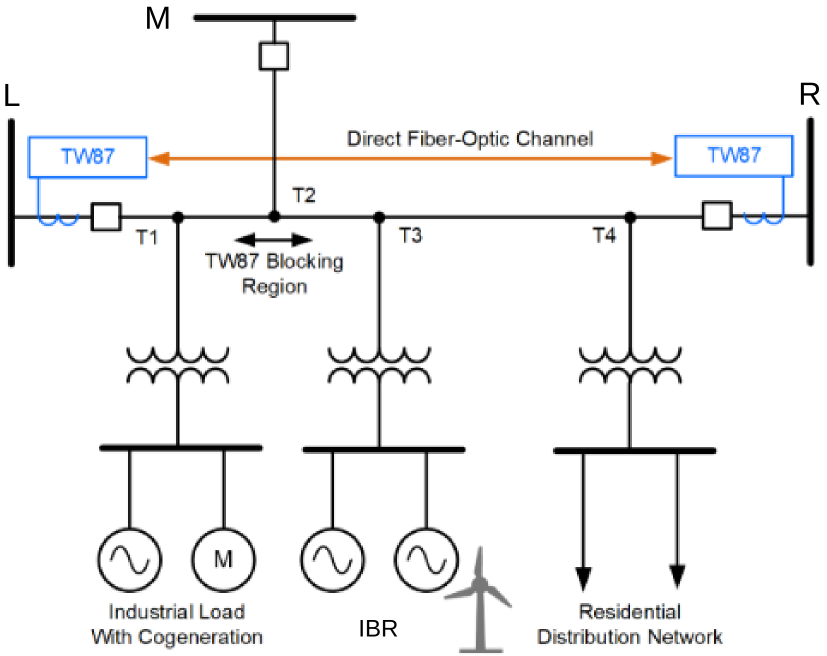


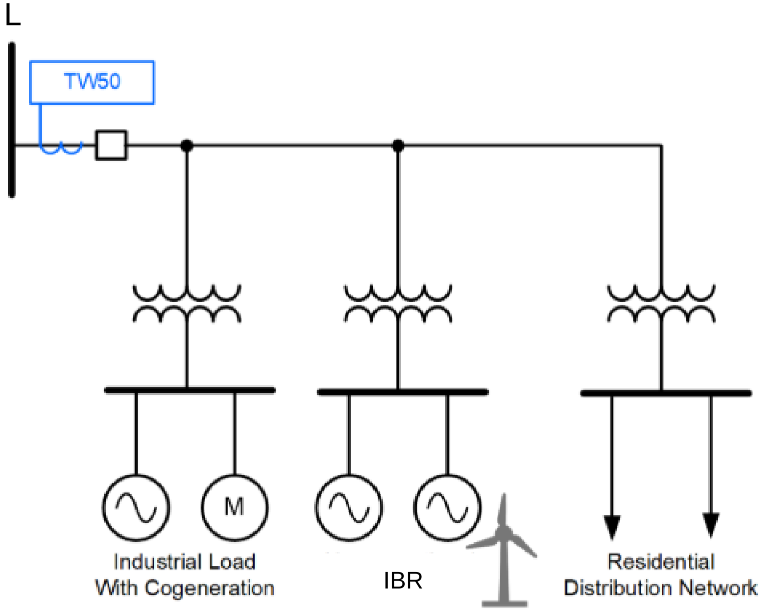


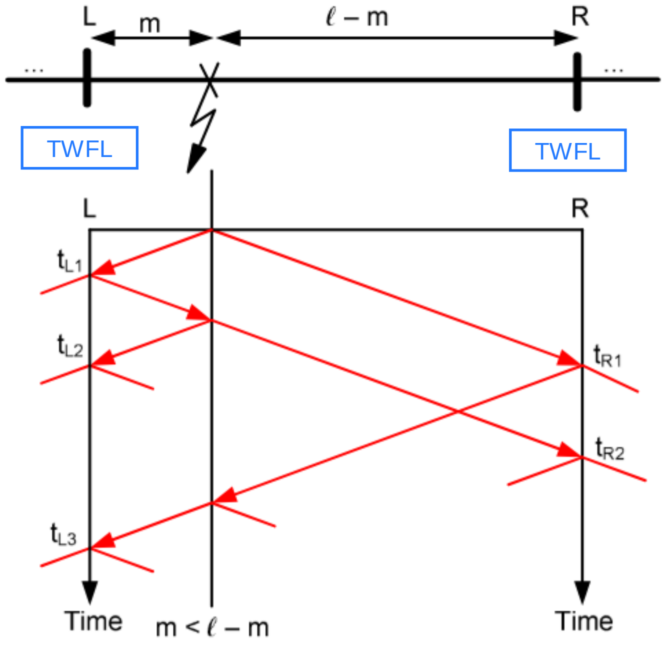
Traveling waves

Protection and fault location



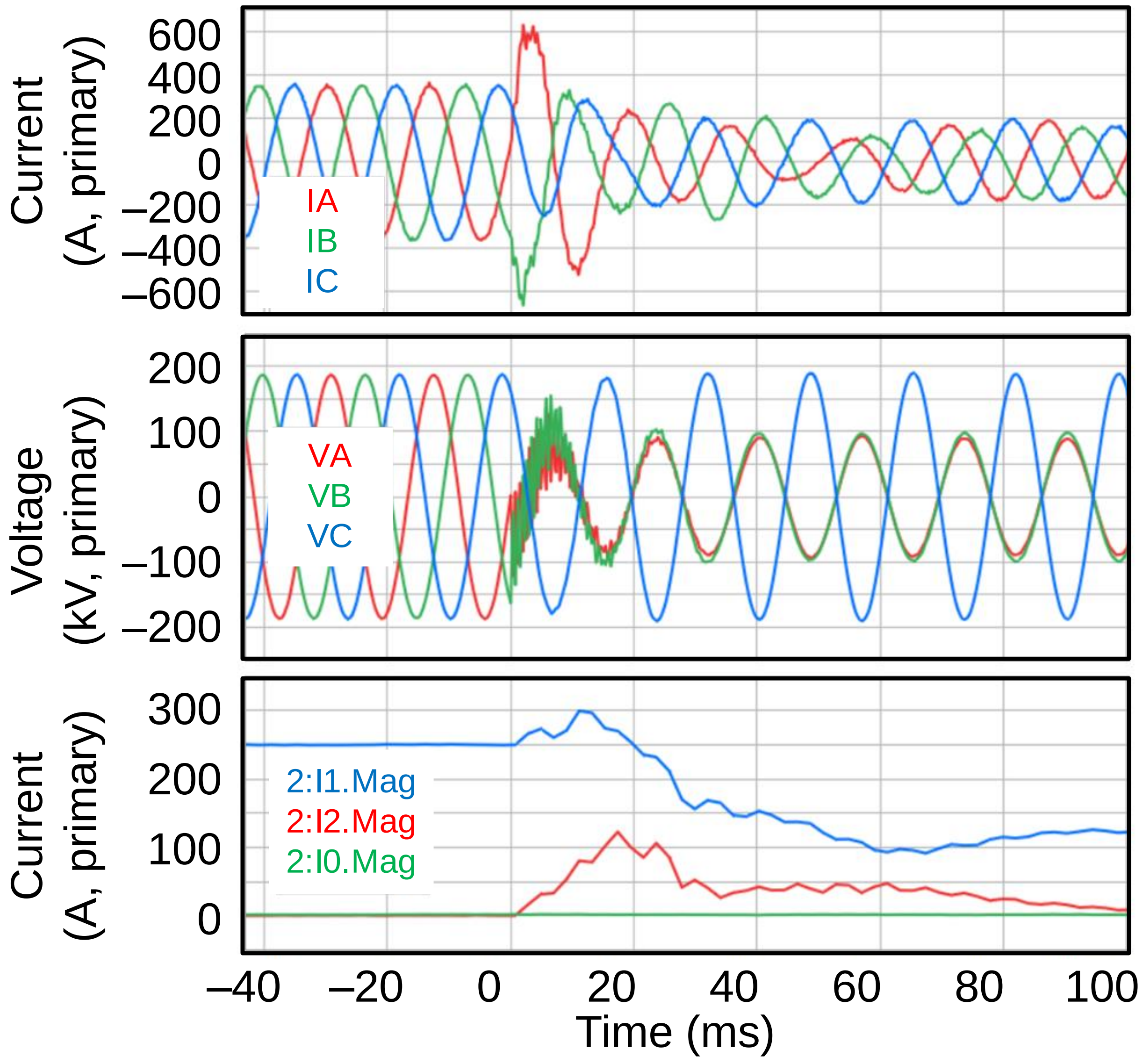


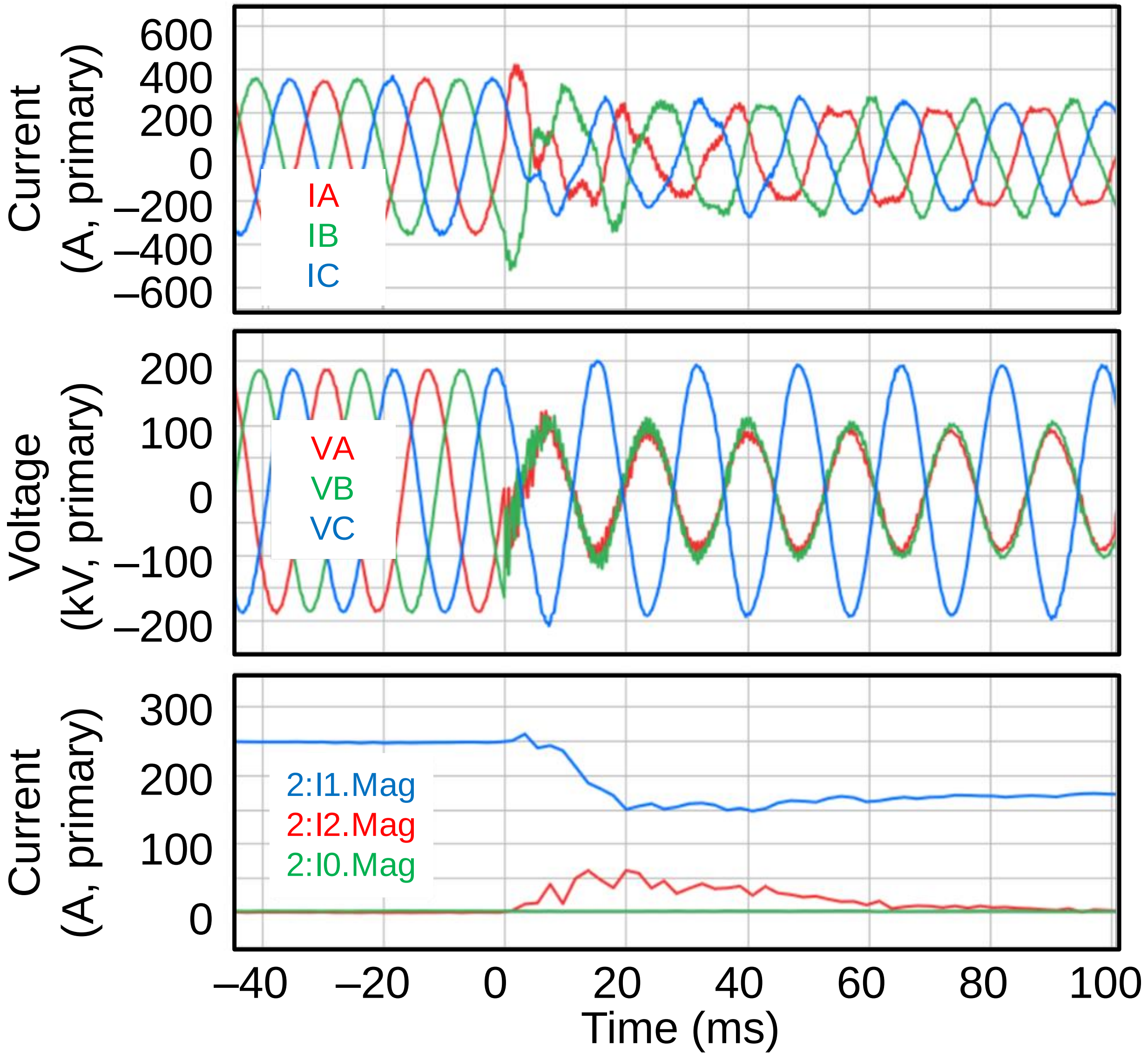




Source-to-line impedance ratio (SIR)

Line-to-line fault at remote bus

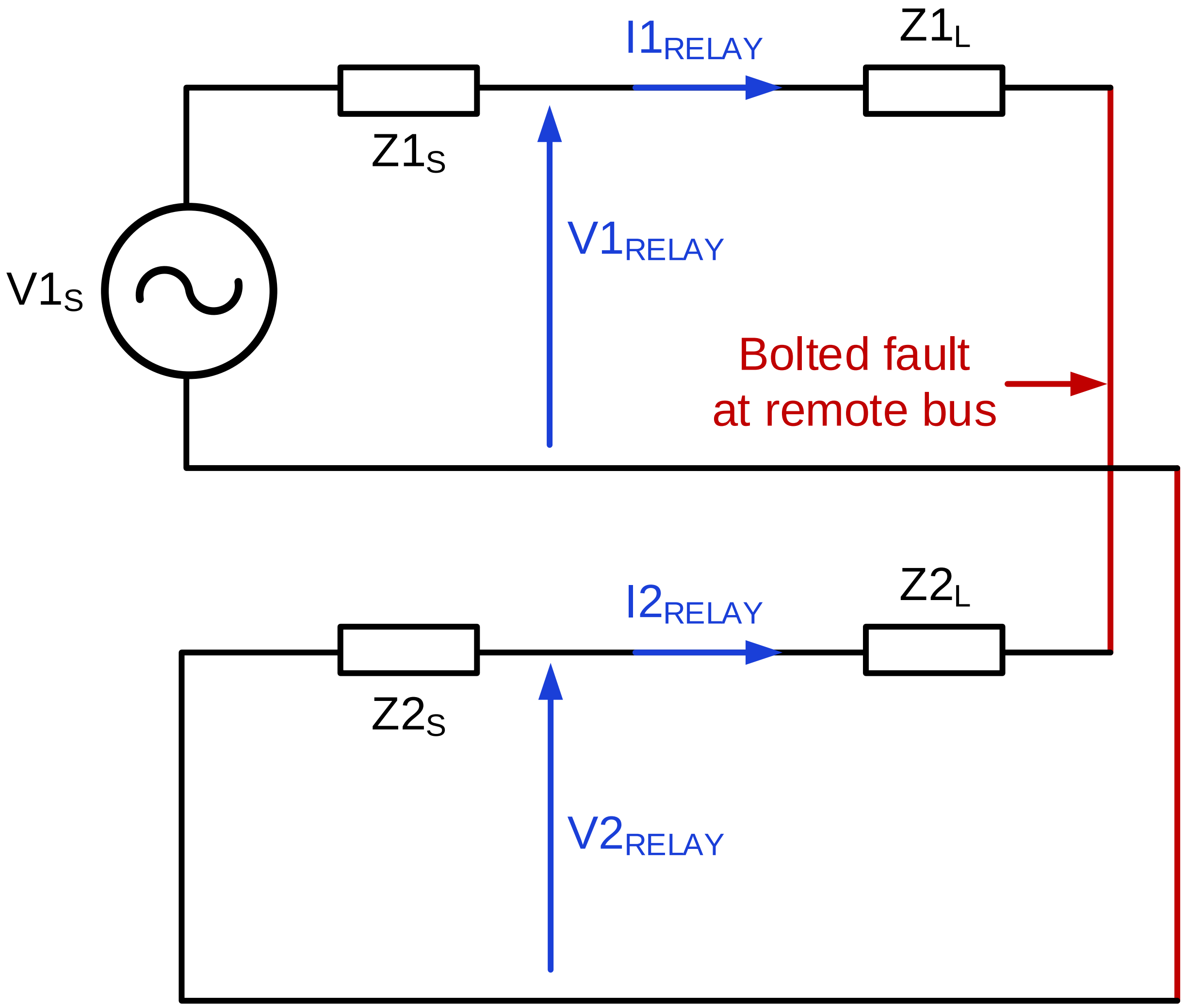




Relay voltage for line-to-line faults

$$\frac{V_{RELAY\ LL(LL\ FAULT)}}{V_{RELAY\ LL(3P\ FAULT)}} = \frac{Z1_S + Z1_L}{\left(\frac{Z1_S + Z2_S}{2}\right) + Z1_L}$$

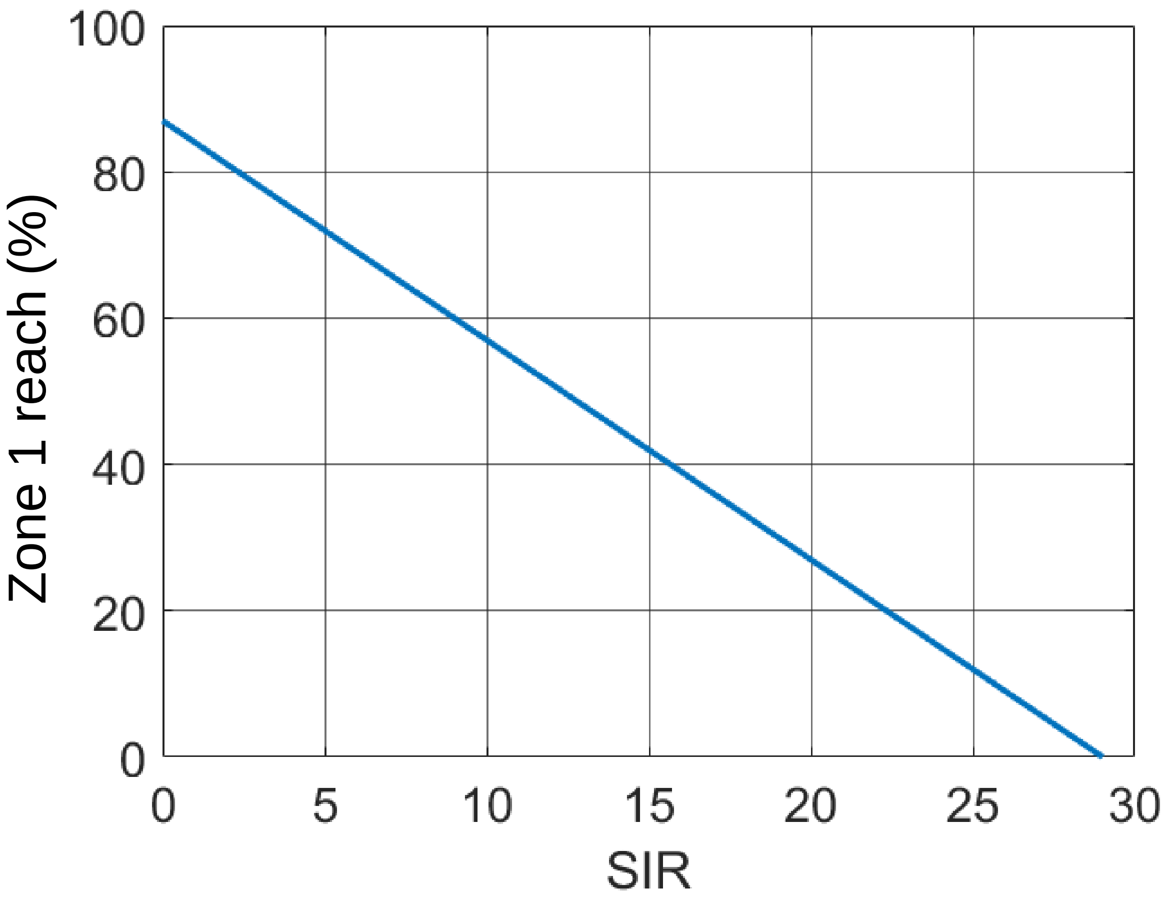
- If $Z1_S = 10 \cdot Z1_L$ and $Z2_S = 10 \cdot Z1_S$,
  - $SIR_{P(3P\_FAULT)} = 10$
  - $SIR_{P(LL\_FAULT)} = 50.9!$
- Consider LL faults also when calculating SIR_P



Improve 21P Zone 1 security due to high SIR

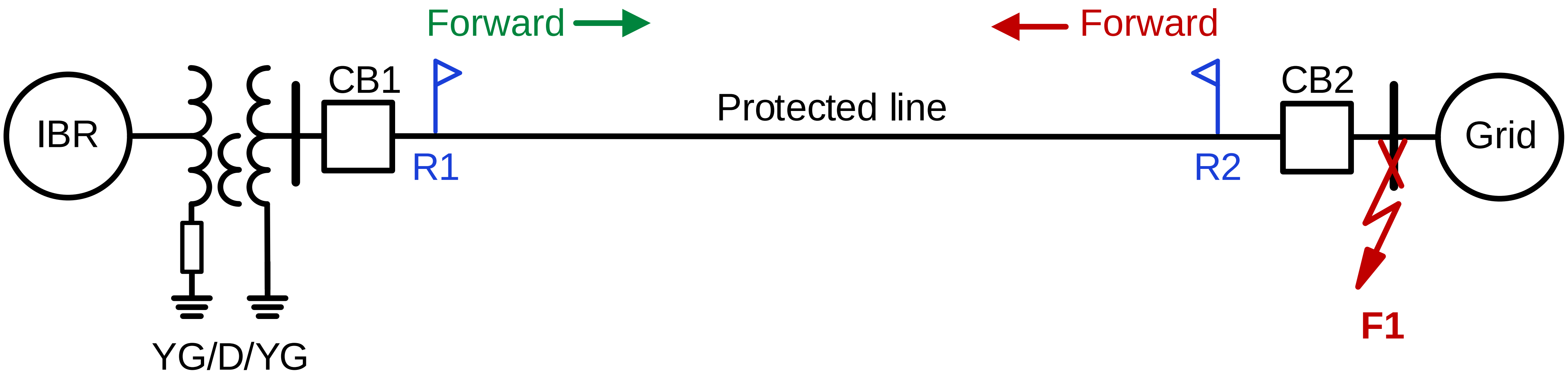
Reduce reach and/or add time delays

- m1 < m1RATIO – ESS • (SIR + 1)
  - m1 = secure reach considering SIR
  - m1RATIO = reach considering ratio errors (e.g., 0.90 pu)
  - ESS = Steady-state error (e.g., 0.03 pu)
- Consider transient CCVT errors

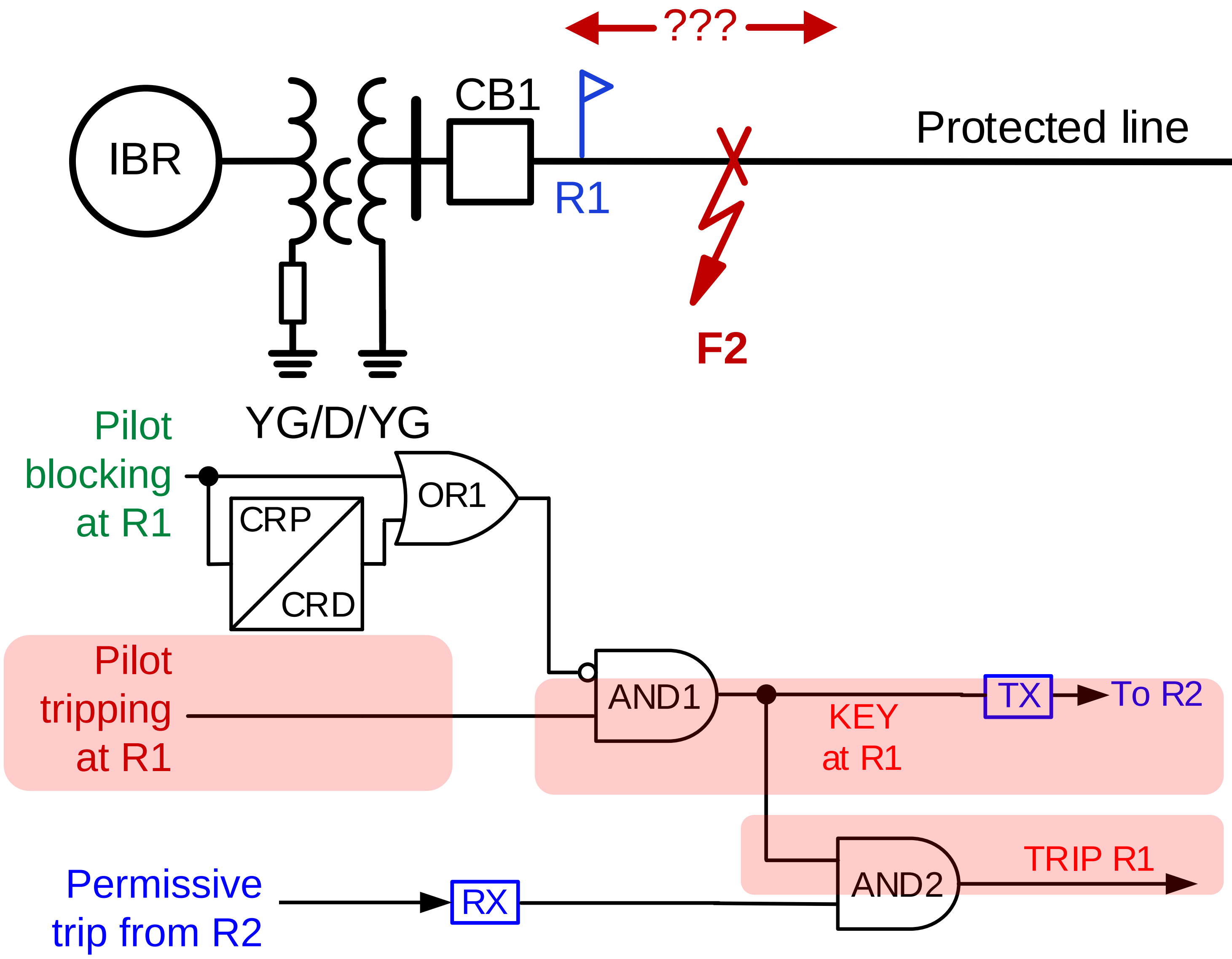


Directional comparison pilot schemes

Directional element security

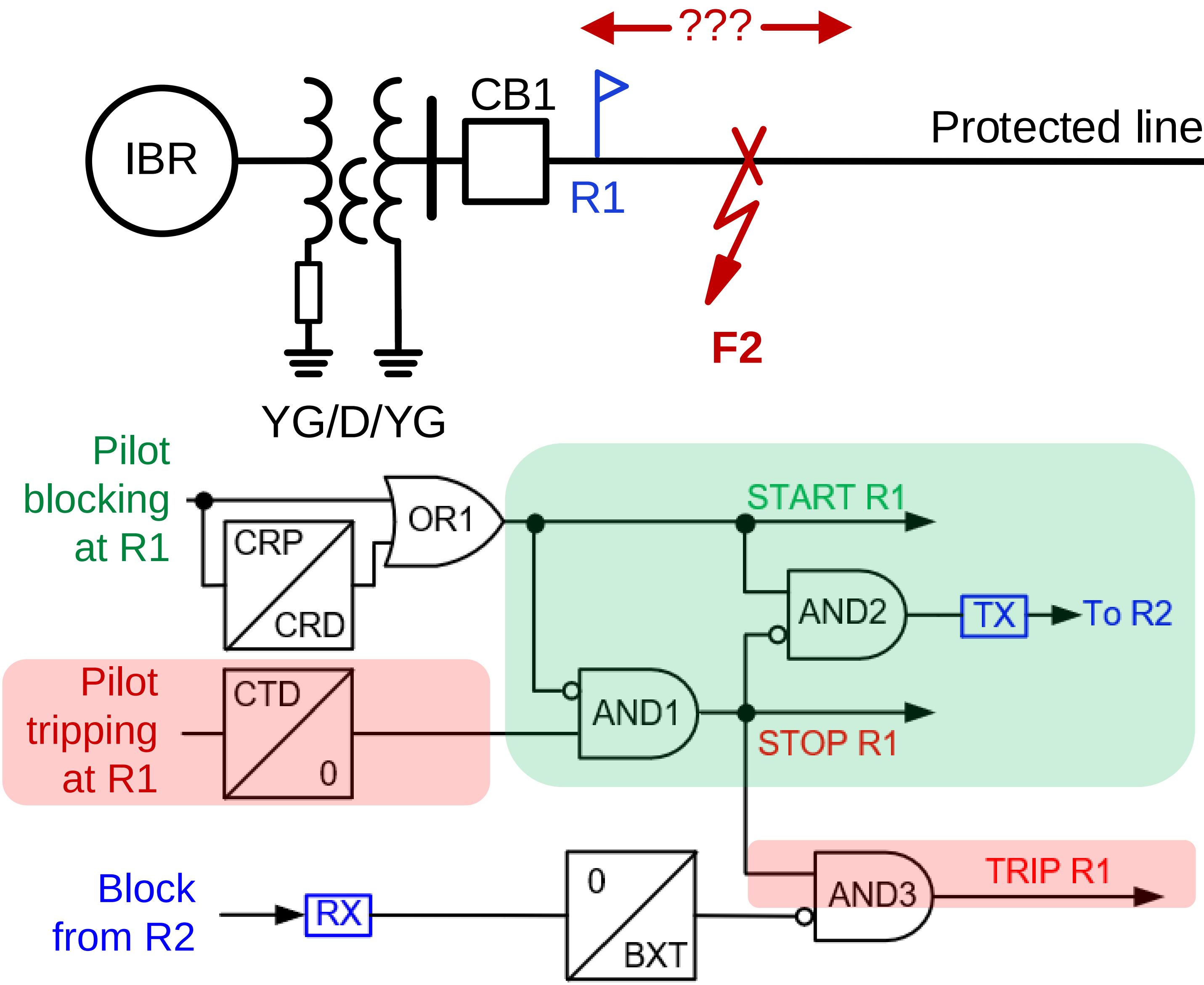


POTT scheme dependability



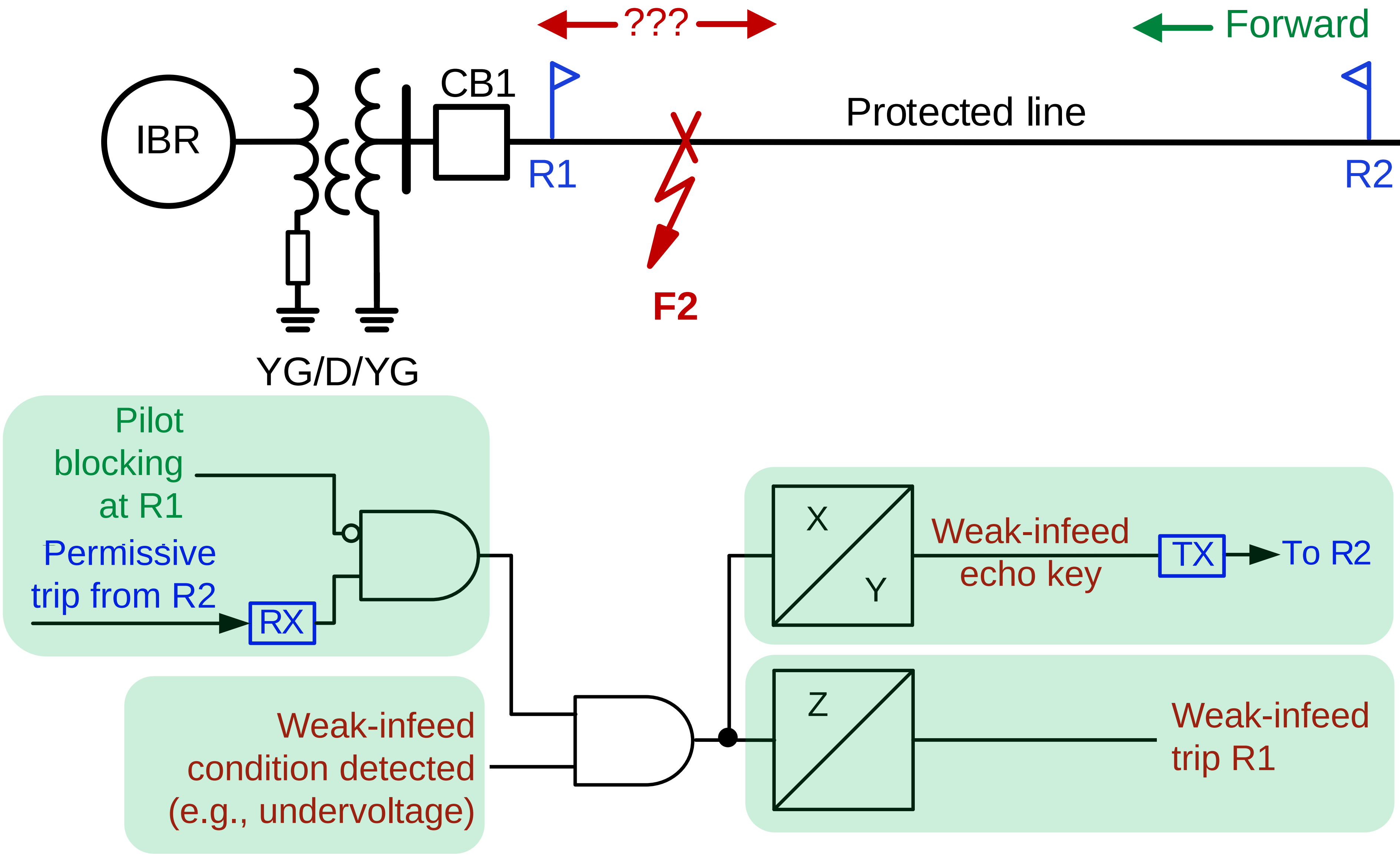
- R1 observes reduced dependability
- R2 also observes reduced dependability

DCB scheme dependability



- R1 observes reduced dependability
- R2 trips

Hybrid POTT with weak-infeed echo and trip

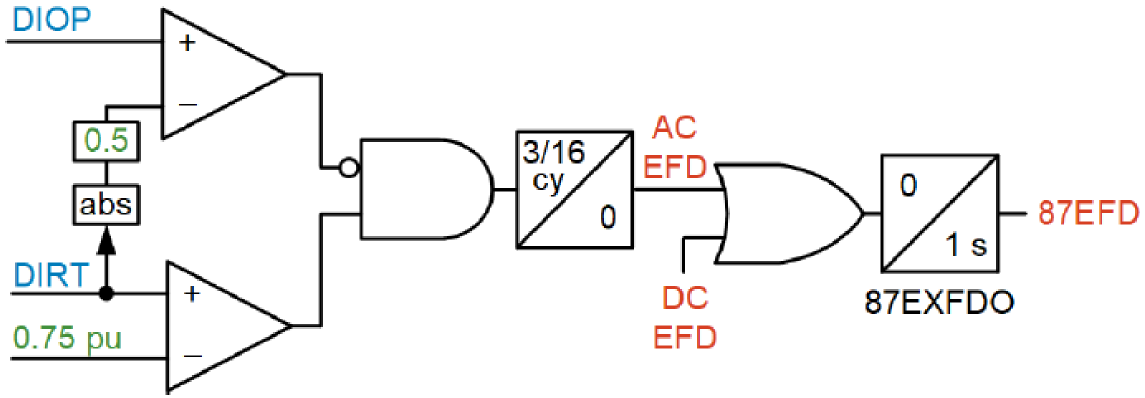


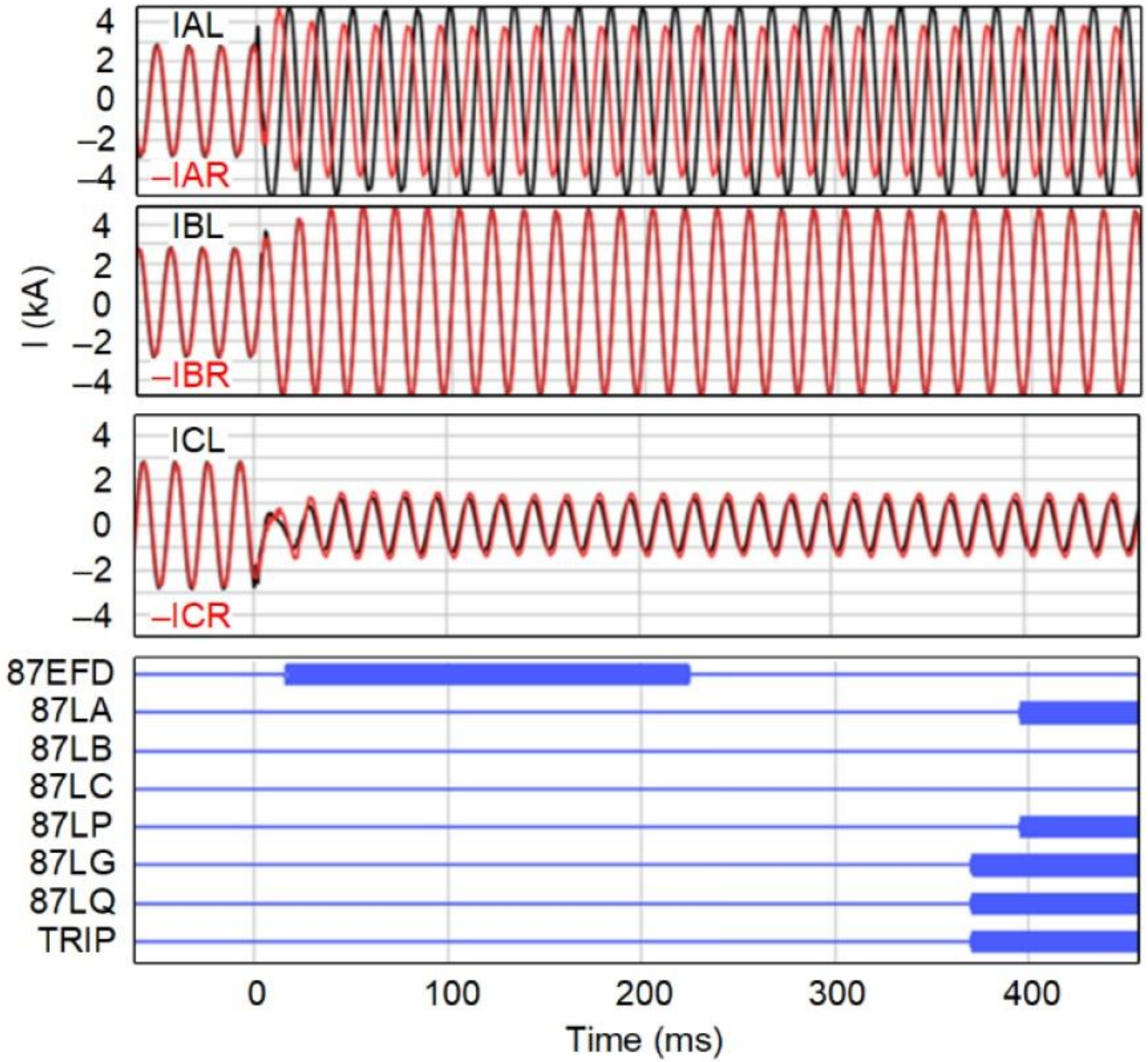
- R1 trips
- R2 trips

Line current differential

Internal AG fault

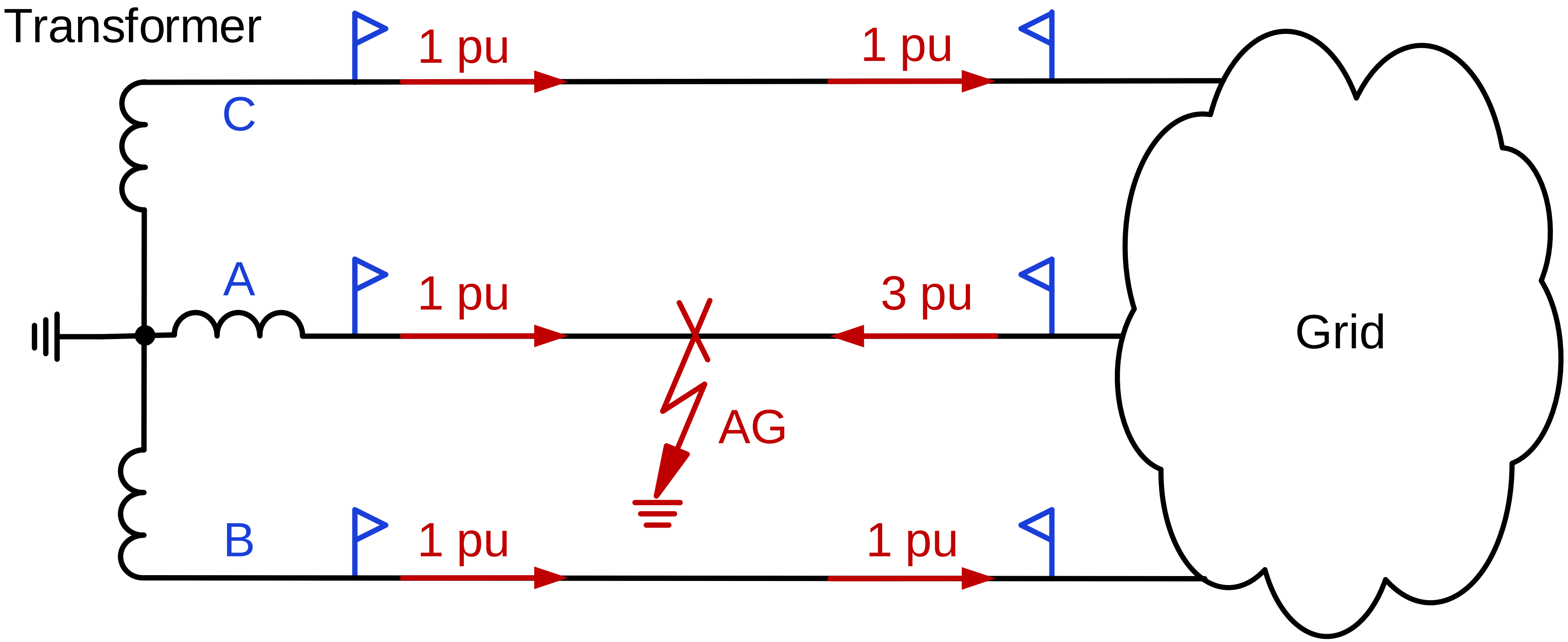
15 ohms



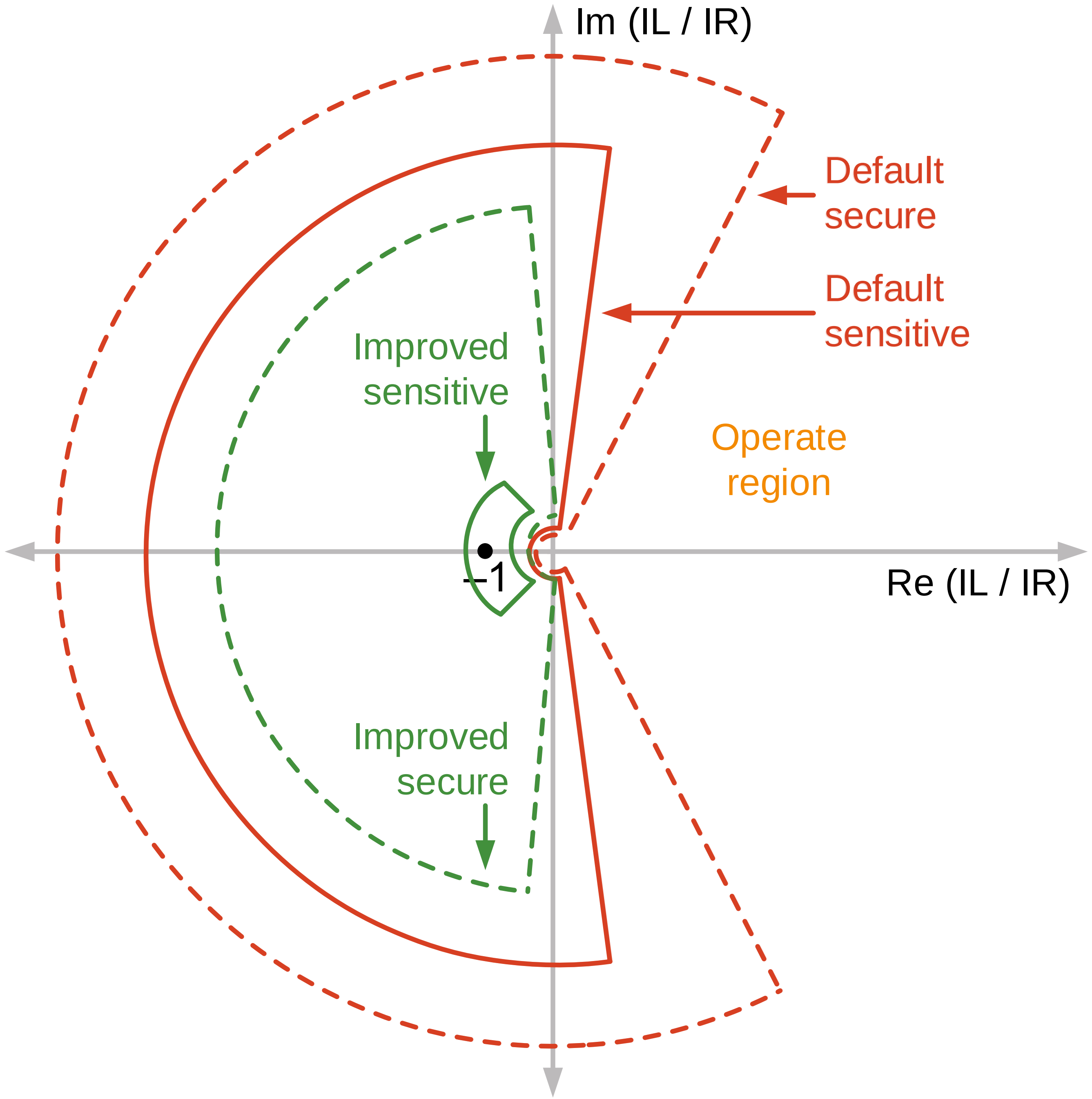


IBR fault response

Strong zero-sequence, but weak otherwise

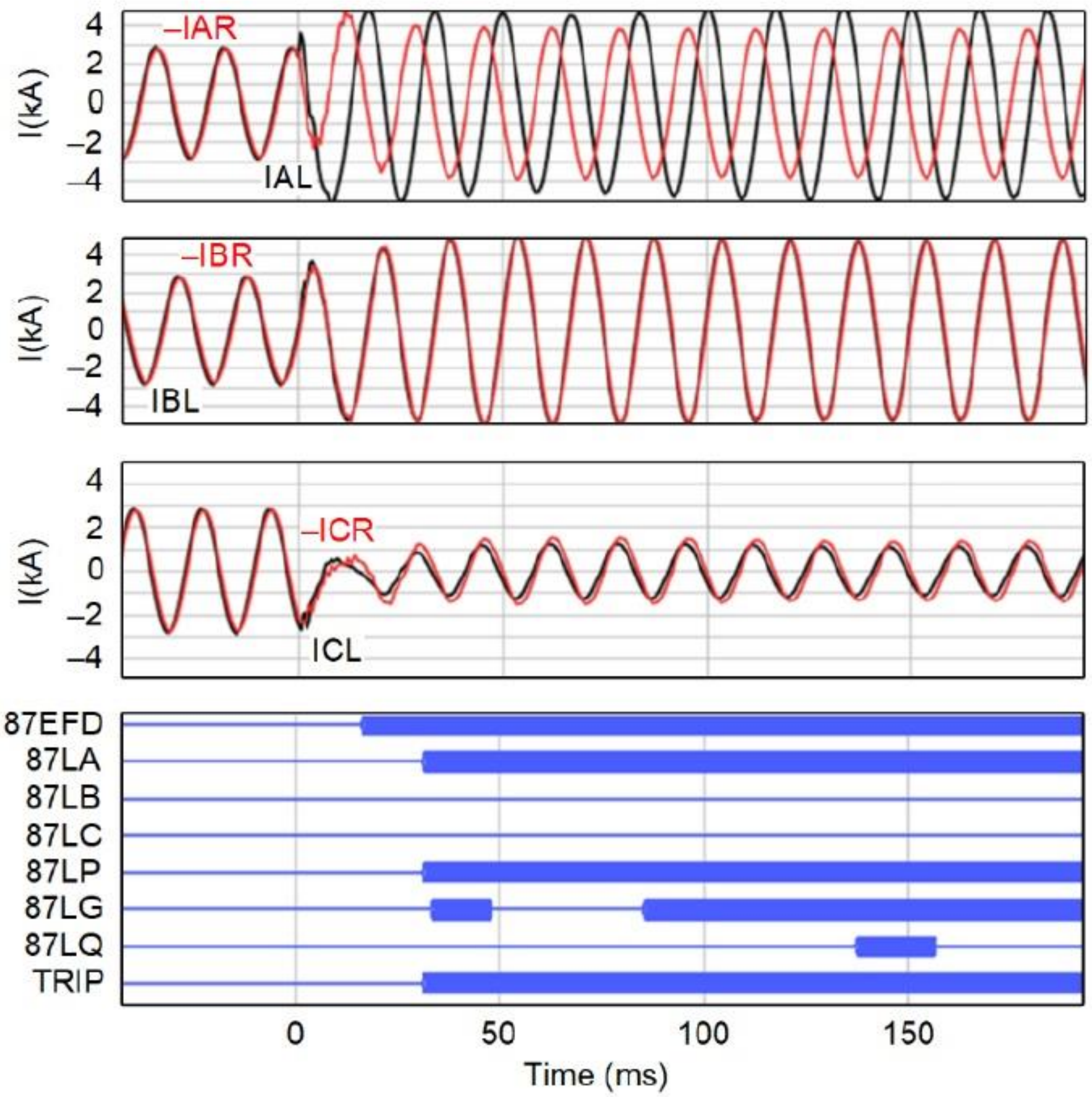


Improved dependability



Internal AG fault

Improved settings



No fault

Harmonics

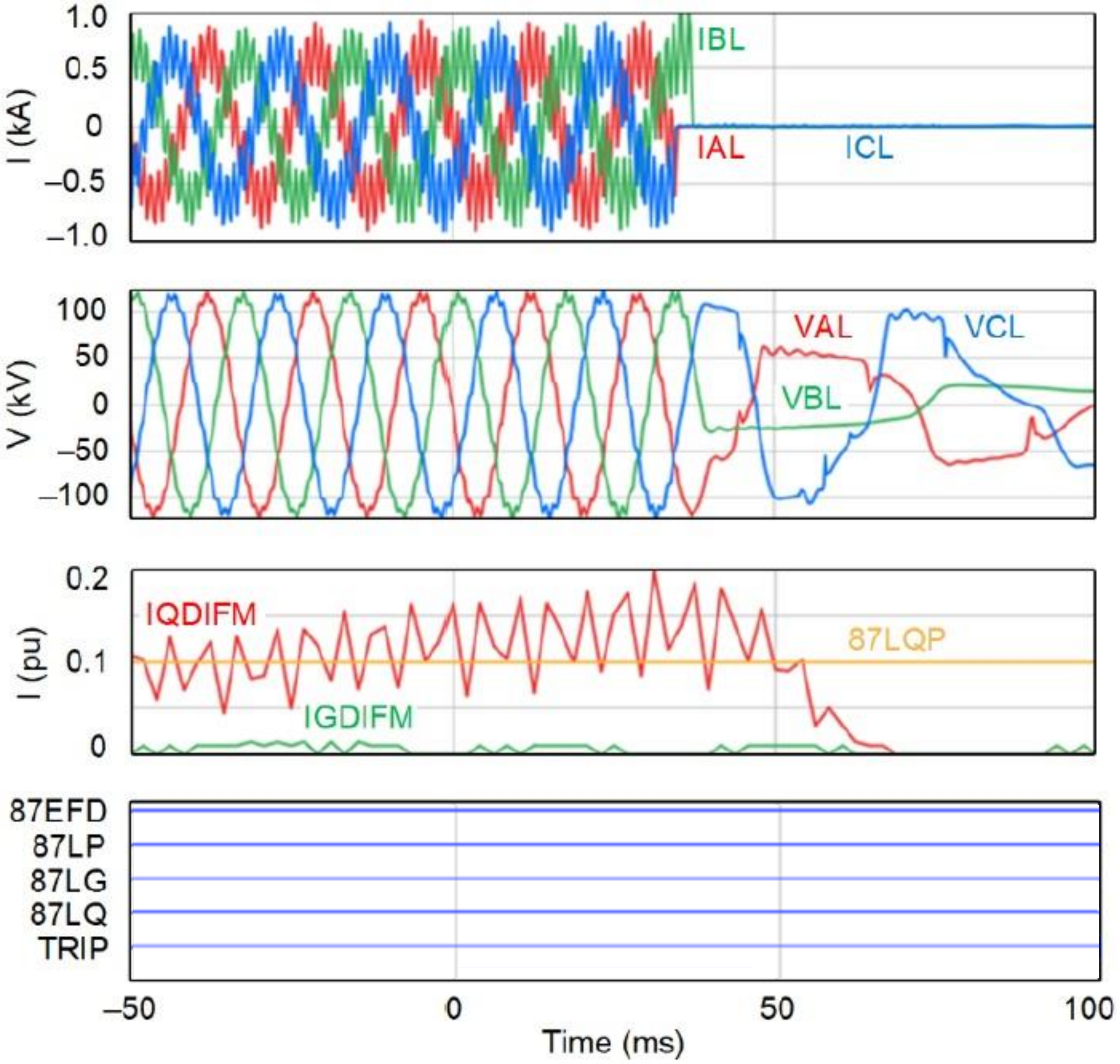
$$87LQP_{SENS} =$$

$$1.25 \cdot \frac{S_{IBR}}{\sqrt{3} \cdot V_{HV} \cdot (CTR \cdot I_{NOM})} \text{pu}$$

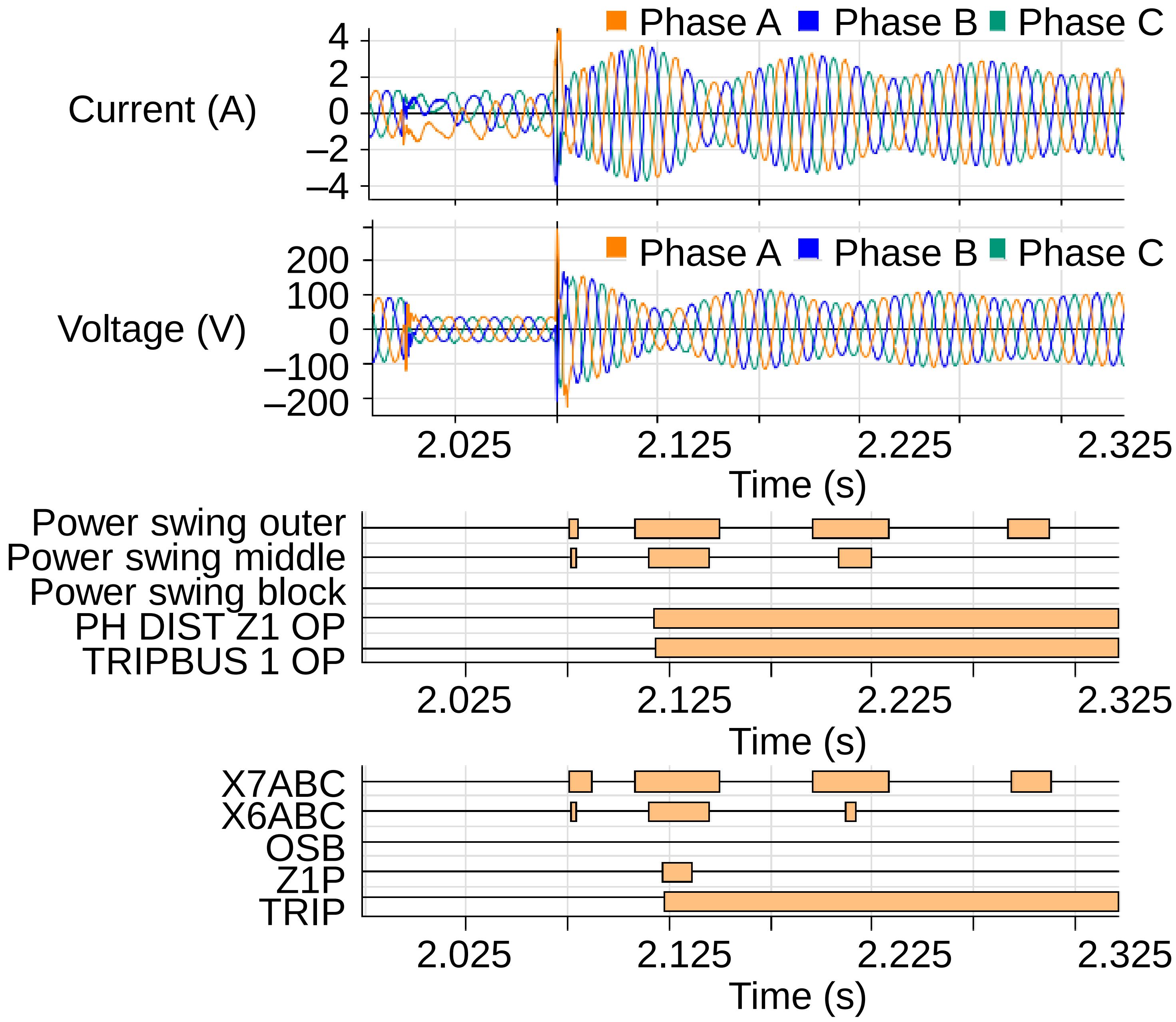
$$87LQP_{SECURE} =$$

$$1.30 \cdot 87LQP_{SENS} \text{ pu}$$

- $87LQP_{SENS}$ = 0.48 pu
- $87LQP_{SECURE}$ = 0.63 pu

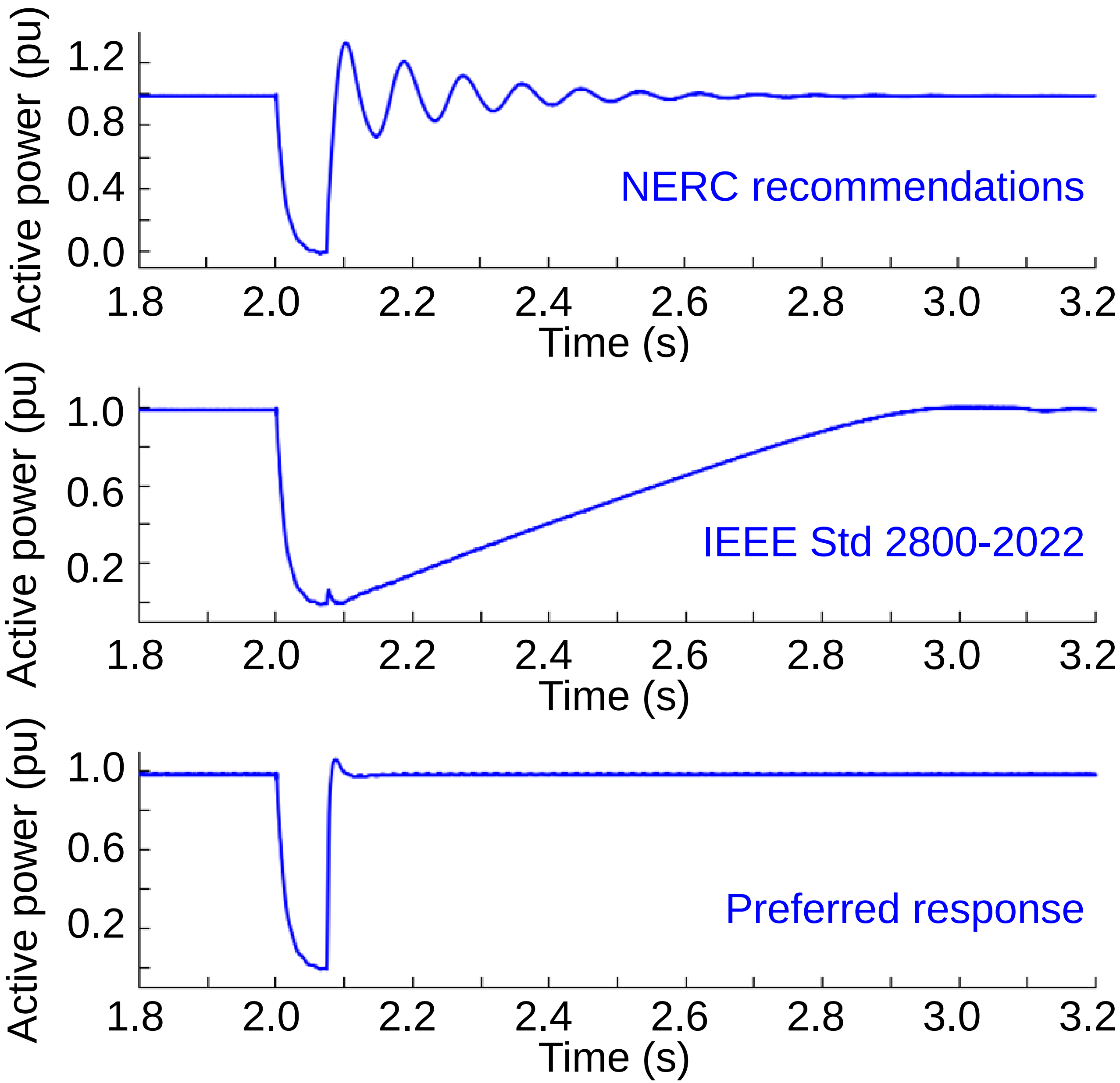


Power swing blocking



Power swing blocking

Transient security challenges



IBR active power

Control responses

Conclusion

Conclusion

1. Raise negative-sequence current thresholds to improve directional element and FIDS logic performance
   – Reliable directionality, especially for phase-to-phase faults in which 32Q may be the only element to provide directionality
   – Voltage-based FIDS logic adds dependability and security
2. Use self-polarized phase distance with possibly offset characteristics supplemented by transient directional elements
3. Use ground mho or zero-sequence polarized quadrilateral
4. Increase Zone 1 reach at strong terminal in tie-line applications without parallel paths

Conclusion

5. Source-to-line impedance ratio (SIR) can be very high
   - Consider line-to-line faults also to calculate SIR
   - Reduce Zone 1 reach and/or add time delay for security or, if required, disable Zone 1 and rely on communications-assisted protection
6. Use Hybrid POTT scheme with weak-infeed echo and trip
7. Use line current differential protection with improved settings
8. Re-evaluate power swing blocking application and settings
9. Transient-based line protection elements including traveling-wave-based schemes can add dependability

References for further reading

References

IBR protection: general challenges and solutions

1. IEEE/NERC Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, “Impact of Inverter Based Generation on Bulk Power System Dynamics and Short-Circuit Performance,” July 2018.
2. M. Nagpal and C. Henville, “Impact of Power-Electronic Sources on Transmission Line Ground Fault Protection,” *IEEE Transactions on Power Delivery*, Vol. 33, Issue 1, February 2018, pp. 62–70.
3. IEEE PSRC C32 Report, “Protection Challenges and Practices for Interconnecting Inverter Based Resources to Utility Transmission Systems,” July 2020.
4. R. Chowdhury and N. Fischer, “Transmission Line Protection for Systems With Inverter-Based Resources – Part I: Problems,” *IEEE Transactions on Power Delivery*, Vol. 36, Issue 4, August 2021, pp. 2,416–2,425.

References

IBR protection: general challenges and solutions

5. R. Chowdhury and N. Fischer, “Transmission Line Protection for Systems With Inverter-Based Resources – Part II: Solutions,” *IEEE Transactions on Power Delivery*, Vol. 36, Issue 4, August 2021, pp. 2,426–2,433.
6. B. Kasztenny, “Distance Elements for Line Protection Applications Near Unconventional Sources,” proceedings of the 75th Annual Conference for Protective Relay Engineers, College Station, TX, March 2022.
7. R. Chowdhury, R. McDaniel, and N. Fischer, “Line Current Differential Protection in Systems with Inverter-Based Resources—Challenges and Solutions,” proceedings of the 49th Annual Western Protective Relay Conference, Spokane, WA, October 2022.
8. R. McDaniel, R. Chowdhury, K. Zimmerman, and B. Cockerham, “Applying SEL Relays in Systems With Inverter-Based Resources,” SEL Application Guide (AG2021-37), 2024.

References

High SIR challenges and solutions

9. M. Thompson, D. Heidfeld, and D. Oakes, “Transmission Line Setting Calculations – Beyond the Cookbook Part II,” proceedings of the 48th Annual Western Protective Relay Conference, Spokane, WA, October 2021.
10. B. Kasztenny, “Settings Considerations for Distance Elements in Line Protection Applications,” proceedings of the 74th Annual Conference for Protective Relay Engineers, College Station, TX, March 2021.
11. B. Kasztenny and R. Chowdhury, “Security Criterion for Distance Zone 1 Applications in High SIR Systems With CCVTs,” proceedings of the 76th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 2023.
12. R. Chowdhury, C. Sun, and D. Taylor, “Review of SIR Calculations for Distance Protection and Considerations for Inverter-Based Resources,” *IEEE Transactions on Power Delivery*, Vol. 39, Issue 3, June 2024, pp. 1,420–1,427.

References

Transient-based protection and fault location solutions

13. E. O. Schweitzer, III, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, “Locating Faults by the Traveling Waves They Launch,” proceedings of the 40th Annual Western Protective Relay Conference, Spokane, WA, October 2013.
14. E. O. Schweitzer, III, B. Kasztenny, A. Guzmán, V. Skendzic, and M. V. Mynam, “Speed of Line Protection – Can We Break Free of Phasor Limitations?” proceedings of the 41st Annual Western Protective Relay Conference, Spokane, WA, October 2014.
15. B. Kasztenny, M. V. Mynam, S. Marx, and R. Barone, "Traveling-Wave Overcurrent – A New Way to Protect Lines Terminated on Transformers," proceedings of the 48th Annual Western Protective Relay Conference, Spokane, WA, October 2021.
16. B. Kasztenny, A. Guzmán, N. Fischer, M. V. Mynam, and D. Taylor, "Practical Setting Considerations For Protective Relays That Use Incremental Quantities and Traveling Waves," proceedings of the 43rd Annual Western Protective Relay Conference, Spokane, WA, October 2016.

References

Power swing blocking challenges and solutions

17. M. A. Nasr and A. Hooshyar, "Power Swing in Systems With Inverter-Based Resources – Part I: Dynamic Model Development,“ *IEEE Transactions on Power Delivery*, Vol. 39, Issue 3, June 2024, pp. 1,889–1,902.
18. M. A. Nasr and A. Hooshyar, "Power Swing in Systems With Inverter-Based Resources – Part II: Impact on Protection Systems," *IEEE Transactions on Power Delivery*, Vol. 39, Issue 3, June 2024, pp. 1,903–1,917.
19. “Industry Recommendation: Inverter-Based Resource Performance Issues,” NERC, Atlanta, GA, March 2023.
20. IEEE Std 2800-2022, *IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems*.

Questions?