INVESTIGATING INVERTER-BASED RESOURCES (IBR) IMPACTS ON THE TRANSMISSION LINE PROTECTION VIA HARDWARE-IN-THE-LOOP (HIL) SIMULATION

- Juergen Holbach, Zheyuan Cheng, and Srinidhi Narayanan
- Quanta Technology, LLC

QUANTA TECHNOLOGY

PRESENTATION OUTLINE

ABOUT QUANTA TECHNOLOGY

Our Mission: To enable your success with industry-best technical and business expertise, holistic and practical advice, and industry thought leadership.

Who

- Trusted advisors with global utility experience
- 180+ employees from diverse backgrounds, 100+ advanced degrees
- Experience spanning the entire lifecycle, from planning to Engineering Procurement and Construction (EPC) implementation, to asset management and renewal

Why

- Independent, objective, and practical advice and solutions
- Unique business, regulatory, and technical expertise and best practice know-how
- Technology Savvy: Testing, commissioning, integration, and post-installation evaluations of technologies

Quanta Technology End-to-End Capabilities

Strategic Capabilities: From Concept to Reality

1. Technology Strategy
2. Roadmap Development
3. Business Case Development
4. Financing, Benefit-Cost Analyses
5. T&D System Studies & Engineering Analyses
6. Regulatory Support
7. Planning, Conceptual & Engineering Design
8. System Integration
9. Testing (FAT & SAT)
10. Review & Update Engineering, Planning & Operations Guidelines
11. EPC Services via Quanta Services
12. Asset Life-Cycle Maintenance via Quanta Services

PROTECTION, CONTROL AND AUTOMATION

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T&D Settings

- T&D Settings
- Feeder Settings
- Third Party Peer Review of Settings
- Relay Setting Templates
- Protection Philosophy Review
- Fault Analysis
- SCADA Support
- RTDS Validation of Settings or Relay Testing

Studies & Compliance

- Wide Area Protection Coordination Studies
- PRC-023, PRC-024, PRC-025, PRC-026 and PRC-027 Compliance Studies
- CIP Compliance Studies
- Prioritization of Relay Asset Replacement Studies

Data Management & Tools

- Settings Repository Import to ASPEN, CAPE, CYME, Synergi etc.
- Data Standardization Across Applications (Maximo, IPS Cascade, PowerBase, RTS, etc.)
- Data Validation Techniques

Engineering Automation Tools

- Process Automation
- QT-Protection Data Manager Application to Automate Data Import
- QT-Protection System Analysis Application for Compliance and WAPC Studies
- Tools for Service or License

Synchronized Measurement Applications

- System Specification
- Roadmap Development
- System Integration
- PMU Based Applications
- Engineering Applications
- Equipment specifications
- Vendor selection and RFP review
- RTDS Verification

Digital Substation

- IEC 61850 Cost Benefit Analysis & Investment Strategy Framework
- Roadmap Development
- System Specification
- Vendor Selection and RFP Review
- RTDS Verification
- System analytics

IED Based Advanced Analytics

- System and Data Architecture
- Data Mining
- Settings& Port Configuration Verification
- Asset Health Analytics
- Fault Location
- Event Summaries

Innovation

- Investment Strategy Framework
- Technology Benchmarking
- Renewables Penetration Impacts and Standards
- Special Protection Schemes
- AMI and Smart Meters

In-Depth Expertise – Practical Results – Strategic Focus – Independent – Partnership Approach

SPEAKERS

Juergen Holbach, Ph.D., Senior Director of Automation and Testing with Quanta Technology, has more than 25 years of experience designing and applying protective relaying. An IEEE member and chairman, he has published over a dozen papers and holds three patents. In 2009, Juergen received the Walter A. Elmore Best Paper Award from the Georgia Tech Relay Conference. Juergen's areas of expertise include automation and protection, transmission protection, real-time digital simulator (RTDS) testing, and International Electrotechnical Commission (IEC) 61850 compliance.

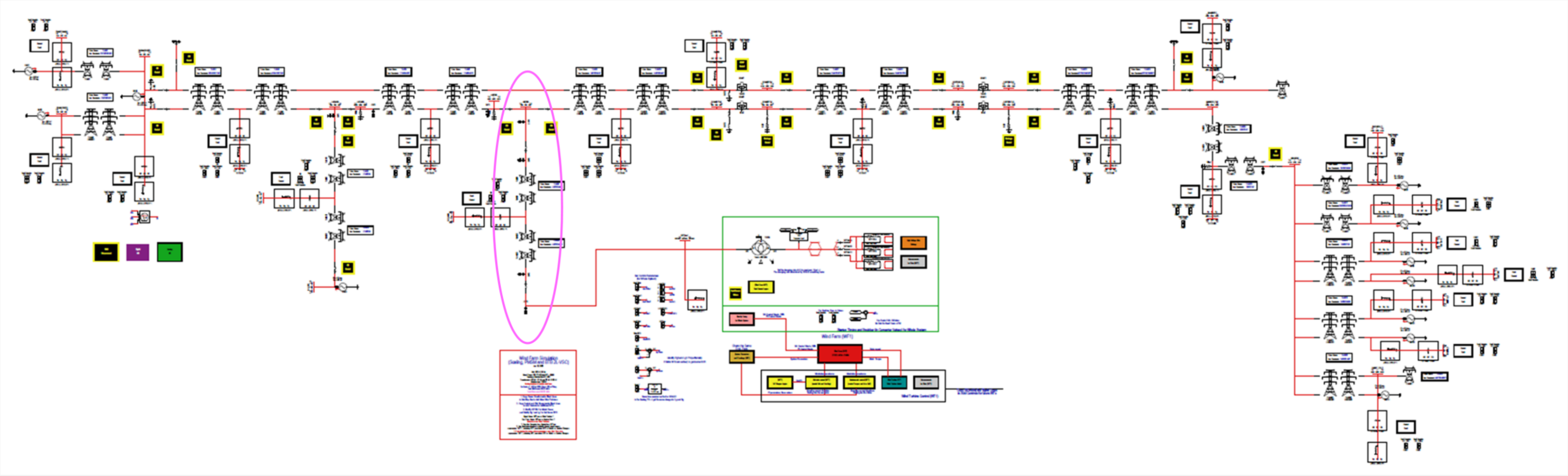
Zheyuan Cheng, Ph.D., Senior Engineer in Protection & Control with Quanta Technology, received his PhD in Electrical Engineering from North Carolina State University in 2020 and his BS degree in electrical engineering from Nanjing University of Aeronautics and Astronautics in 2015. He has been working on renewable distributed energy resource control related research and industry projects since 2016. He has published 18 (9 journal and 9 conference) IEEE papers and holds 1 patent. He is a recipient of the 2021 Best Paper Award from IEEE Industrial Electronics Magazine. His areas of expertise include distributed energy resources protection and control.

Srinidhi Narayanan, Engineer III in Protection & Control with Quanta Technology, graduated with a master's degree in Electrical Power Systems Engineering from NC State University in 2021. The focus areas of her master's degree included power system protection, transient analysis, and communication and SCADA systems. She has also completed a capstone project as a part of her graduate program, called "Design of Protection Scheme for an Inverter-Based Microgrid Circuit," which was sponsored by Duke Energy. Srinidhi has more than 2 years of experience in the electrical power systems industry.

PROJECT OVERVIEW

- Objectives:
  - Test the protection settings on a 345kV parallel transmission line with series compensation and its adjacent tie line to wind farm facility
- RTDS system model
  - Reduced 38 bus system

- Data sources:
  - Customer ASPEN short circuit model
  - Wind farm plant PSCAD model
    - With IBR vendor PSCAD model
- Hardware relays used in the HIL testing
  - SEL 311L and SEL 411L



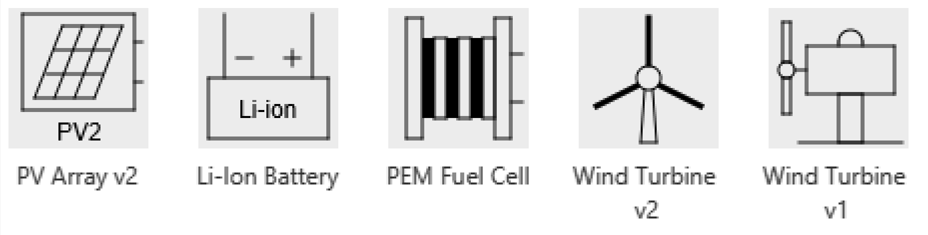
CHALLENGES TO THE TRANSMISSION LINE PROTECTION

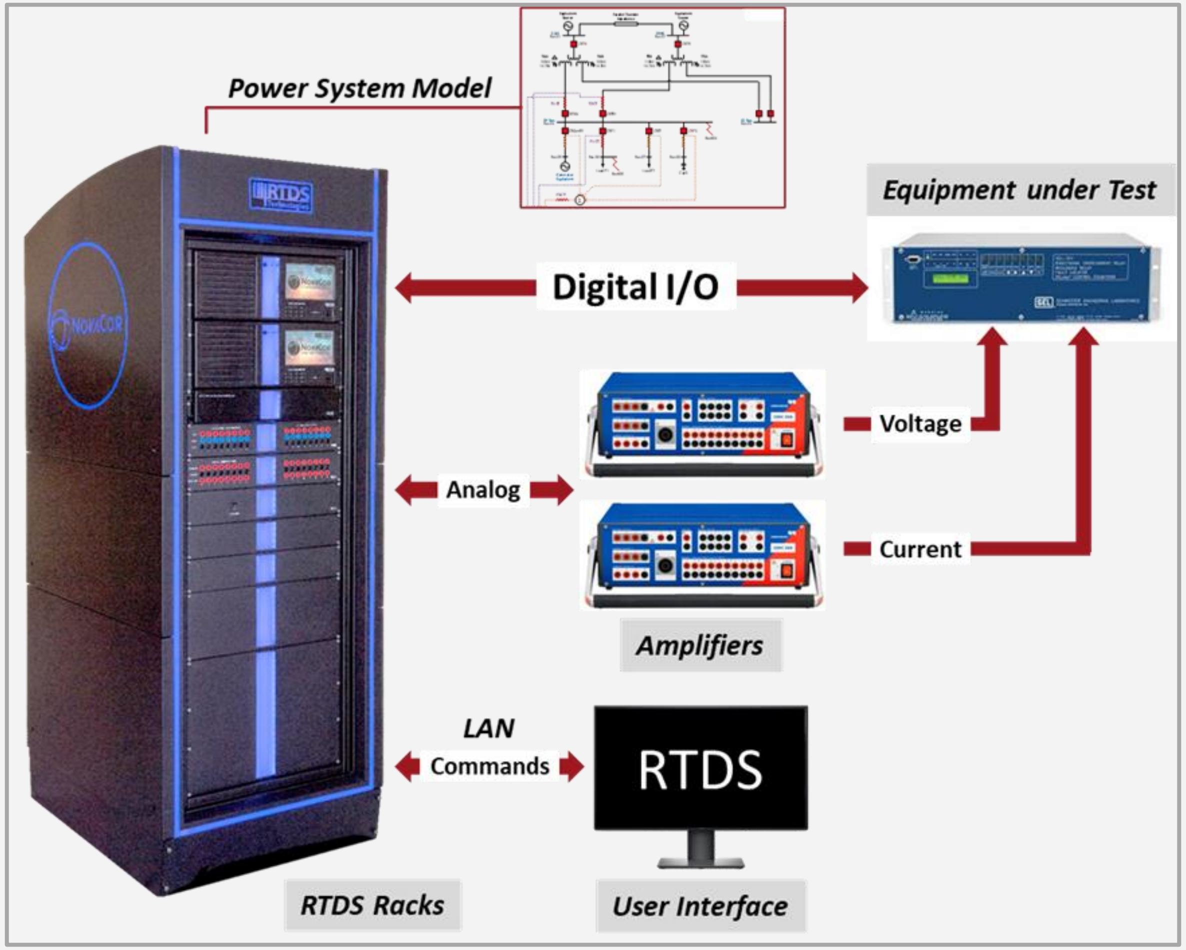
- Unique challenges introduced by IBRs
  - Limited fault current magnitude
    - Typically, 1.1-1.5 per unit
  - Control-determined current-voltage phase angle
    - Different behaviors in grid following and forming modes.
  - Different sequence components
    - Controller typically suppress negative sequence
  - Nonlinear fault current contribution
    - Flat-topped waveform throws off phasor calculation
  - Lack of standards for IBR fault responses

- Impacts on the line protection schemes
  - Overcurrent
    - Not enough fault current.
    - Difficult to provide enough sensitivity and selectivity.
  - Directional
    - Not enough negative sequence current to pickup asymmetrical faults.
  - Coordination (distance element)
    - Impact tripping time and coordination between protection zones

RTDS MODELING CAPABILITY

- Real time electromagnetic transient simulation
- Pre-built average and switching IBR models
  - Solar
    - PV array/farm model with MPPT and Partial shading effect
  - Wind
    - Type I – IV wind turbine/farm models
  - Energy storage
    - Lithium battery, fuel cell, flywheel, and pumped hydro models





RTDS IBR MODEL VALIDATION CHALLENGES

- Data Source
  - Typically, black-box, and supposed be based on actual inverter controls or real-code
  - PSCAD model with compiled IBR model in the format of DLL (Dynamic link library)
  - ELECTRANIX provides an example vendor model requirement/checklist about model accuracy and level-of-details specifications in [Ref]
- Challenges
  - Hidden inverter parameters
  - Hidden protection logics, e.g., collector protection and plant protection
  - Sometimes requires third party software package to simulate plant PSCAD model
  - Simulating individual IBR, e.g., all wind turbines in a wind farm, will require a lot of RTDS cores.

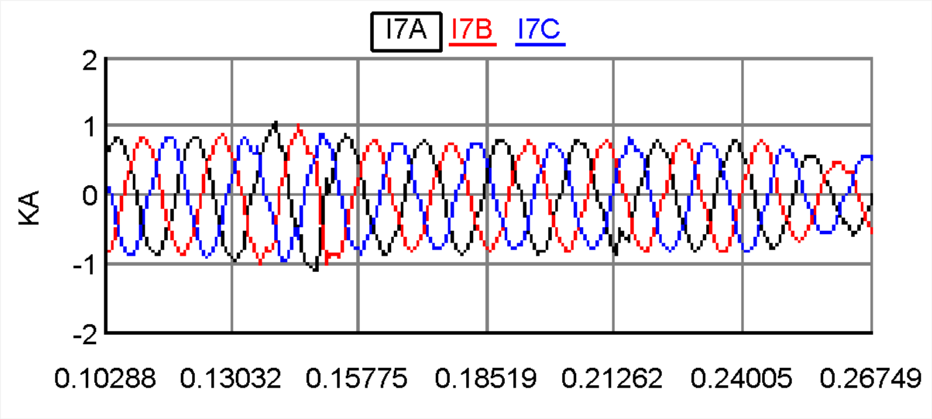
[REF] http://www.electranix.com/wp-content/uploads/2020/05/PSCAD-Requirements-Rev.-9-May-2020.pdf

LESSONS LEARNED FROM PAST IBR MODELING AND TESTING PROJECT

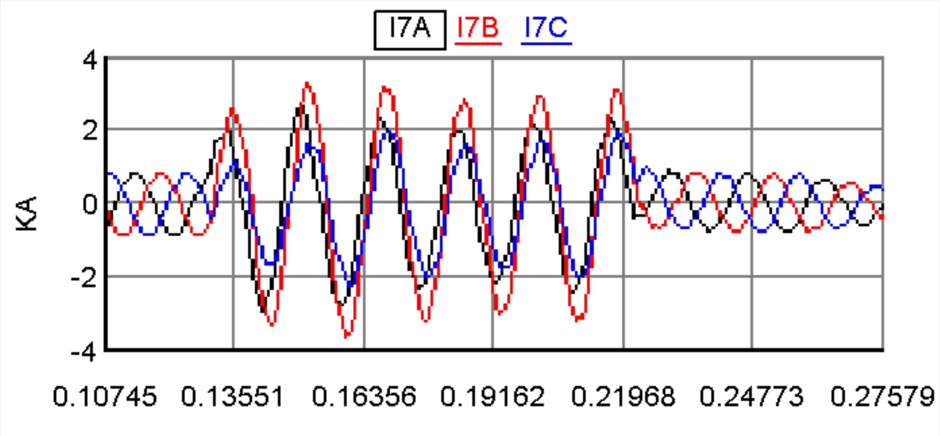
The rest of the system matters

- Interconnection transformer
  - Impact zero sequence fault current
- Adjacent transmission lines and generators
  - IBR may introduce problems such as subsynchronous oscillation with a series compensated transmission line
  - IBR may impact power swing trajectory and impedance.

- Wind farm connected via Y-Y transformer (AG)



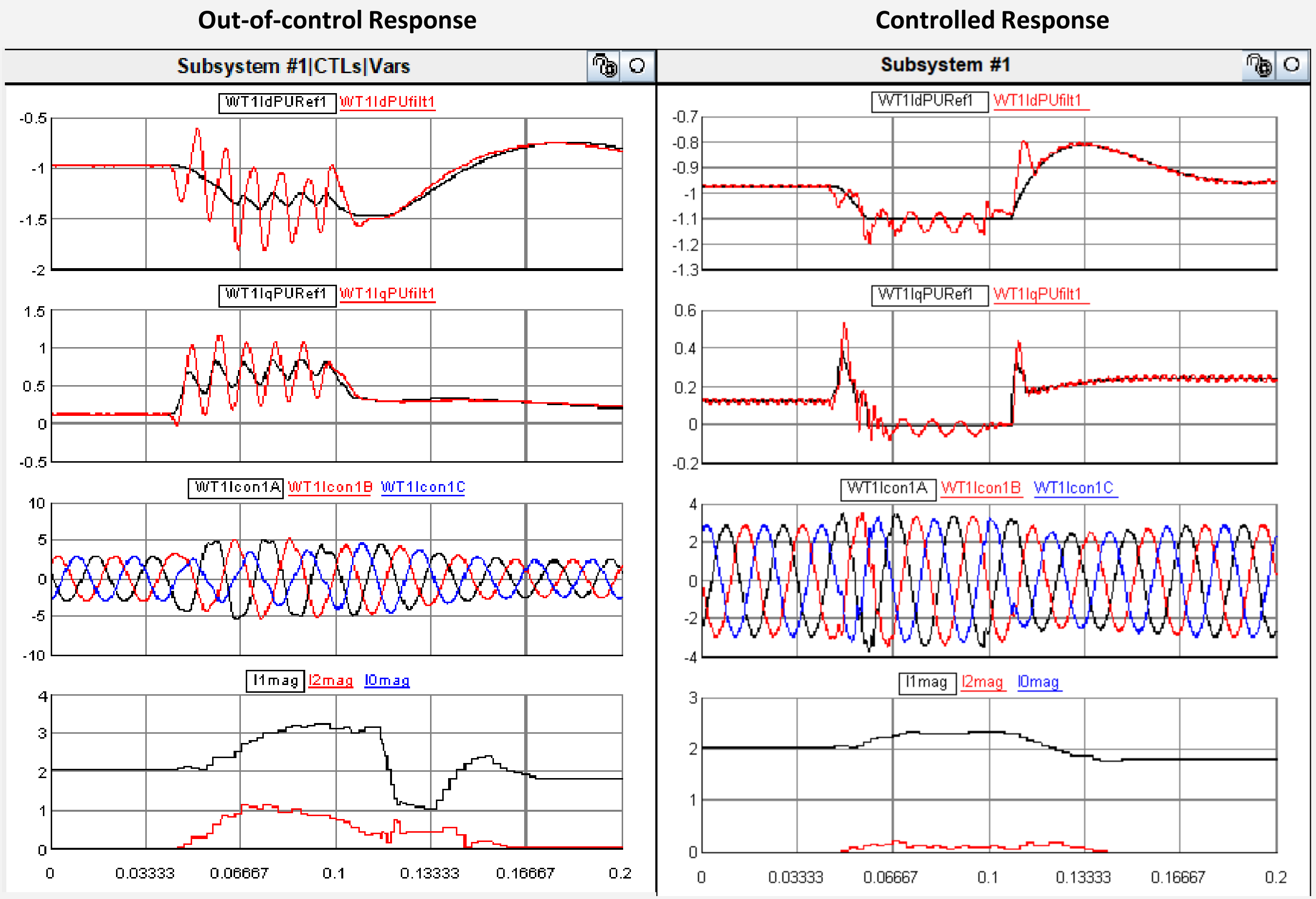
- Wind farm connected via Y-D-Y transformer (AG)



LESSONS LEARNED FROM PAST IBR MODELING AND TESTING PROJECT

Correct controller response is the key

- Out-of-control inverter response
  - May have larger fault current magnitude
  - May have more negative sequence current
  - It is okay to have out-of-control fault response in the first 1 or 2 cycle, after which the controller should kick in and regulate fault current
- Controlled inverter response
  - IBR controller generally limit the fault current magnitude
  - Controller naturally suppress negative sequence current
- Tunning the PID gains when matching the RTDS and PSCAD vendor is very important



LESSONS LEARNED FROM PAST IBR MODELING AND TESTING PROJECT

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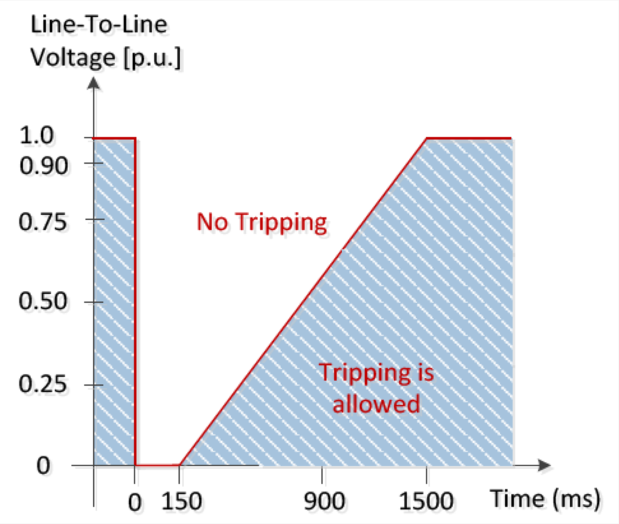
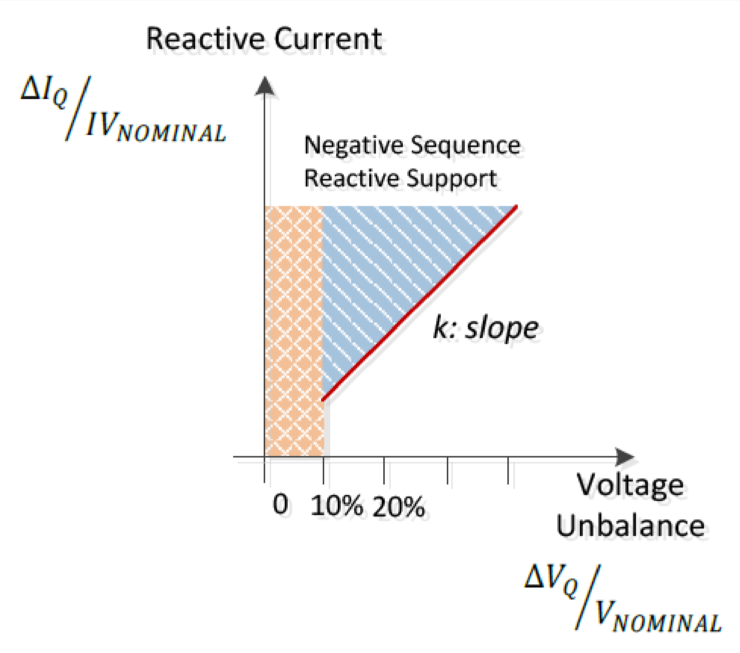
Protection control functions will impact IBR fault response a lot

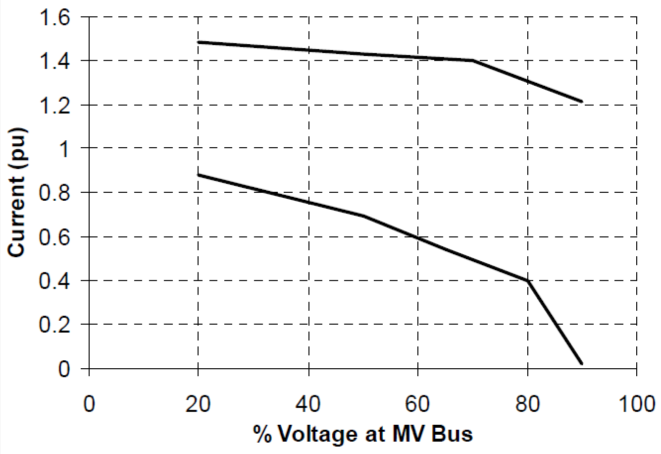
- Low voltage ride through
  - Example: German grid code



- Decoupled sequence control
  - Example: German grid code



- Fault current limiter
  - Typical fault current envelope about 3 cycles after the fault



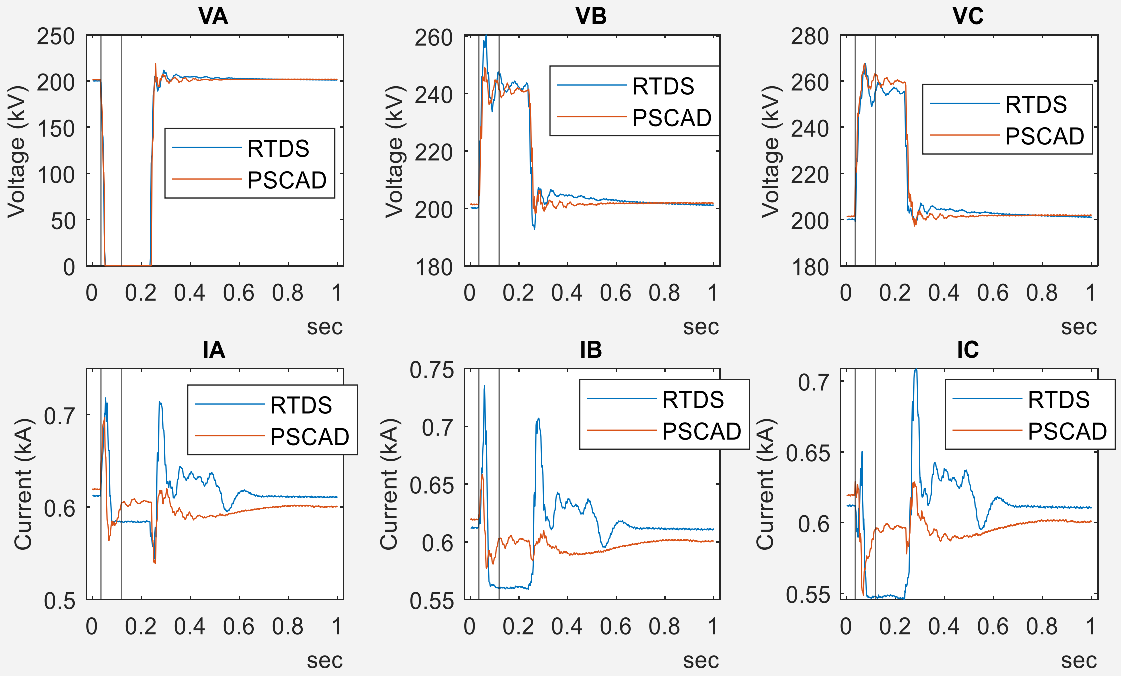
It is important to create probe cases to verify if the IBR controller has certain protection control functions

Power System Relaying and Control Committee (PSRC), Subcommittee C - System Protection, Working Group C32, Technical Report PES-TR81, “Protection Challenges and Practices for Interconnecting Inverter Based Resources to Utility Transmission Systems”, 2020.

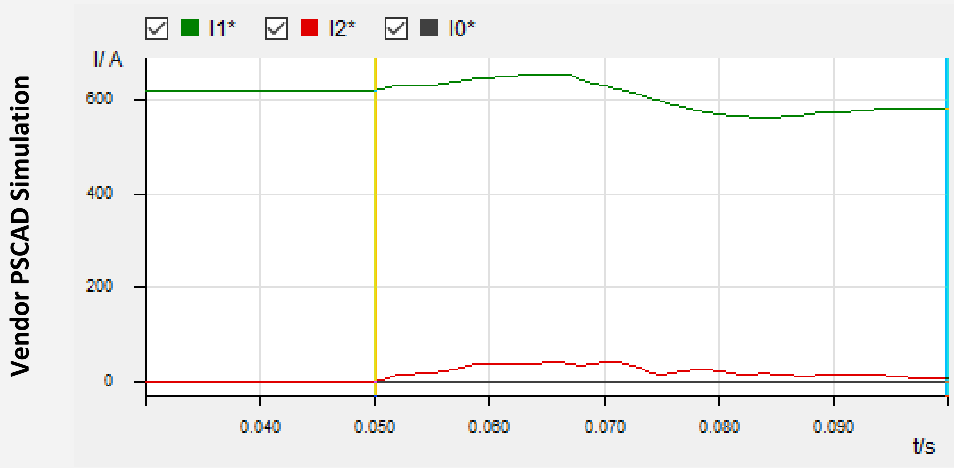
VENDOR AND RTDS IBR MODEL MATCHING EXPERIENCE

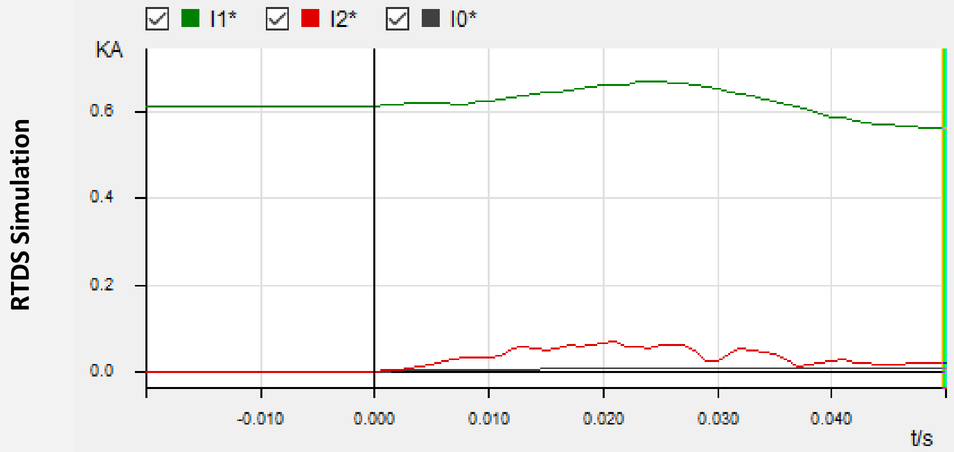
It is possible to create close-but-not-exact match in RTDS

- RMS value comparison
  - AG fault at wind farm bus
  - Objective is to match the first 5 cycles
  - MAPE (mean absolute percentage error): 4.6%



- Sequence component comparison





RTDS SETUP AT QUANTA TECHNOLOGY LAB

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RTDS circuit diagram

Terminal A

Terminal B

IBR

SEL 311

87L 21

SEL 311

87L 21

C37.94 Fiber

SEL 411L

87L 21

SEL 411L

87L 21

C37.94 Fiber

- The IBR is connected to the grid through a 345 kV transmission line.
- The primary protection considered for this line is 87L differential protection with fiber-optic communication.
- 21 Distance protection is considered as the back-up protection method.

RTDS SETUP AT QUANTA TECHNOLOGY LAB

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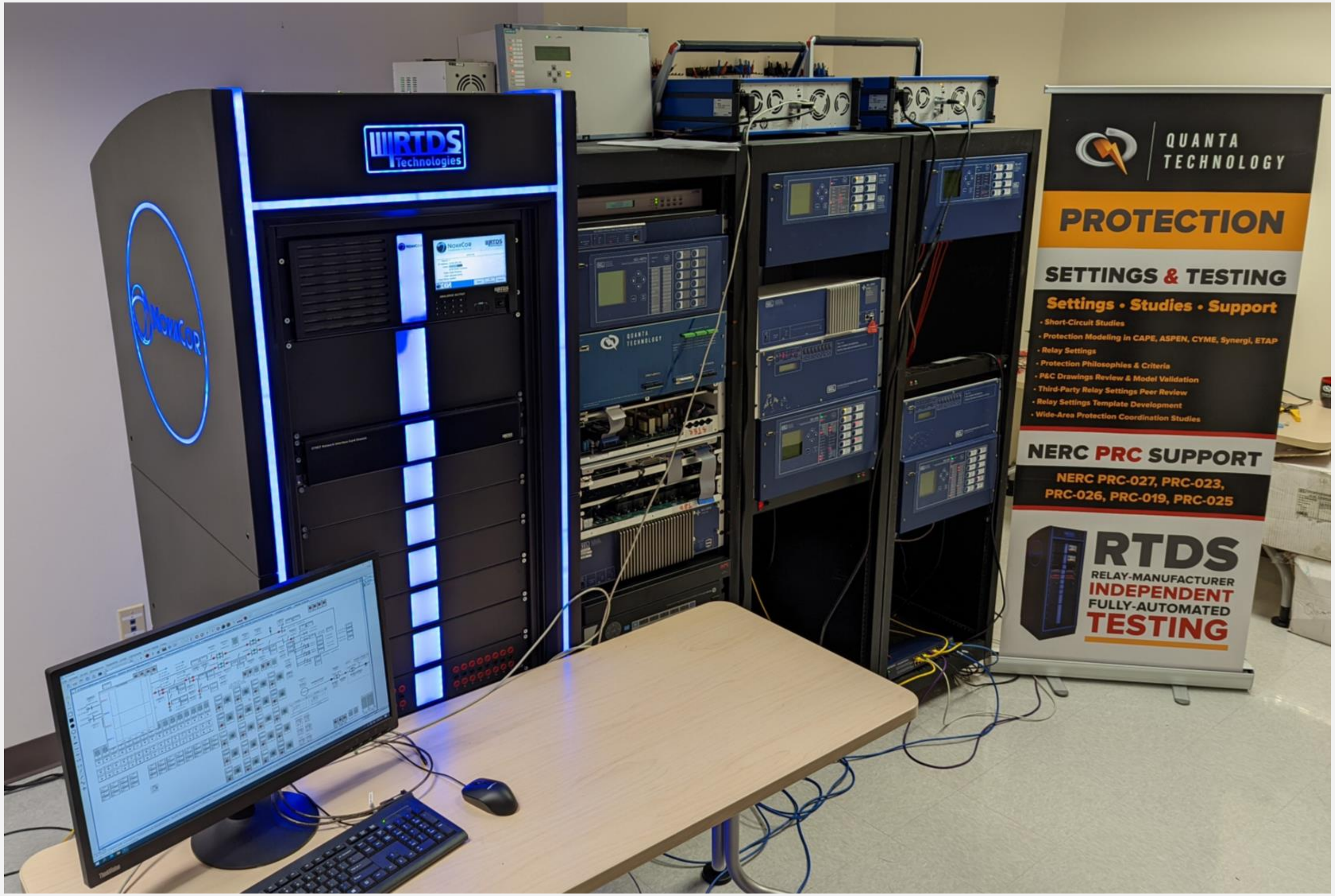
RTDS lab setup



RTDS TESTING

Testing of 87L and 21 protection elements

- The performance of the protection scheme is tested for various faults on the transmission line connecting the IBR to the rest of the grid.
- Considerations while testing the system:
  - Fault type – SLG, LL, LLL & LLG.
  - Fault location on the transmission line – 0%, 50% and 100% of the line.
  - Fault inception angle – Various angles ranging from 0 – 180 deg.
  - Fault resistance – 0 – 30 ohm.

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Test results

Faults on the transmission line with fiber optic communication in place and zero fault resistance:

Case	Type	Location (%)	Angle (degree)	Fault resistance (ohm)	Terminal A SEL 311 Trip (sec)	Terminal A SEL 411L Trip (sec)	Terminal B SEL 311 Trip (sec)	Terminal B SEL 411L Trip (sec)	Pass/Fail
1	AG	0	0	0	0.031	0.019	0.022	0.018	Pass
2	ABG	0	30	0	0.023	0.018	0.017	0.017	Pass
3	BC	0	60	0	0.026	0.021	0.020	0.032	Pass
4	ABC	0	90	0	0.025	0.017	0.016	0.027	Pass
5	BG	50	60	0	0.027	0.022	0.020	0.021	Pass
6	CAG	50	75	0	0.024	0.017	0.016	0.017	Pass
7	CA	50	90	0	0.025	0.022	0.020	0.032	Pass
8	ABC	50	105	0	0.025	0.021	0.020	0.029	Pass
9	CG	99	120	0	0.023	0.019	0.017	0.018	Pass
10	BCG	99	135	0	0.032	0.025	0.022	0.025	Pass
11	AB	99	150	0	0.031	0.025	0.023	0.038	Pass
12	ABC	99	165	0	0.025	0.021	0.019	0.035	Pass

IBR IMPACTS ON 87L ELEMENT

QUANTA TECHNOLOGY

Test results

Faults on the transmission line with fiber optic communication in place and 30-ohm fault resistance:

Case	Type	Location (%)	Angle (degree)	Fault resistance (ohm)	Terminal A SEL 311 Trip (sec)	Terminal A SEL 411L Trip (sec)	Terminal B SEL 311 Trip (sec)	Terminal B SEL 411L Trip (sec)	Pass/Fail
1	AG	0	0	30	0.022	0.017	0.016	0.021	Pass
2	ABG	0	30	30	0.024	0.020	0.017	0.018	Pass
3	BC	0	60	30	0.027	0.027	0.020	0.051	Pass
4	BG	50	60	30	0.025	0.018	0.017	0.019	Pass
5	CAG	50	75	30	0.029	0.023	0.022	0.025	Pass
6	CA	50	90	30	0.029	0.023	0.021	0.047	Pass
7	CG	99	120	30	0.030	0.023	0.021	0.024	Pass
8	BCG	99	135	30	0.029	0.021	0.020	0.021	Pass
9	AB	99	150	30	0.039	0.033	0.030	0.046	Pass

IBR IMPACTS ON 87L ELEMENT

QUANTA TECHNOLOGY

Test results

- The 87L element passes all the test cases and can successfully protect the transmission line.
- However, this differential scheme must be backed up by the 21 element in case of communication failure.

IBR IMPACTS ON 21 ELEMENT

Test results

Faults on the transmission line <u>without fiber optic communication</u> in place and zero fault resistance:

Case	Type	Location (%)	Angle (degree)	Fault resistance (ohm)	Terminal A SEL 311 Trip (sec)	Terminal A SEL 411L Trip (sec)	Terminal B SEL 311 Trip (sec)	Terminal B SEL 411L Trip (sec)	Pass/Fail
1	AG	0	0	0	No Op	No Op	0.024	0.024	Only Terminal B Relays passed
2	ABG	0	30	0	No Op	No Op	0.033	0.024	Only Terminal B Relays passed
3	BC	0	60	0	No Op	No Op	0.038	0.028	Only Terminal B Relays passed
4	ABC	0	90	0	No Op	No Op	0.037	0.027	Only Terminal B Relays passed
5	BG	50	60	0	No Op	No Op	0.041	0.027	Only Terminal B Relays passed
6	CAG	50	75	0	No Op	No Op	0.033	0.028	Only Terminal B Relays passed
7	CA	50	90	0	No Op	No Op	0.036	0.029	Only Terminal B Relays passed
8	ABC	50	105	0	No Op	No Op	0.035	0.028	Only Terminal B Relays passed
9	CG	99	120	0	No Op	No Op	0.363	0.356	Only Terminal B Relays passed
10	BCG	99	135	0	No Op	No Op	0.377	0.356	Only Terminal B Relays passed
11	AB	99	150	0	No Op	No Op	0.380	0.364	Only Terminal B Relays passed
12	ABC	99	165	0	No Op	No Op	0.375	0.356	Only Terminal B Relays passed

(IBR is connected to Terminal A)

IBR IMPACTS ON 21 ELEMENT

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Test results

The 21 element does not pass the required tests. The reasons for this failure are listed below:

- No negative sequence current injection from the IBR
- Low fault current magnitude
- Loop selection error in relay

Comtrade record of a simulated fault in RTDS:

- Forward AG fault
- Type-IV wind farm
- Y-D-Y interconnection transformer

IBR IMPACTS ON 21 ELEMENT

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Improving 21 element reliability

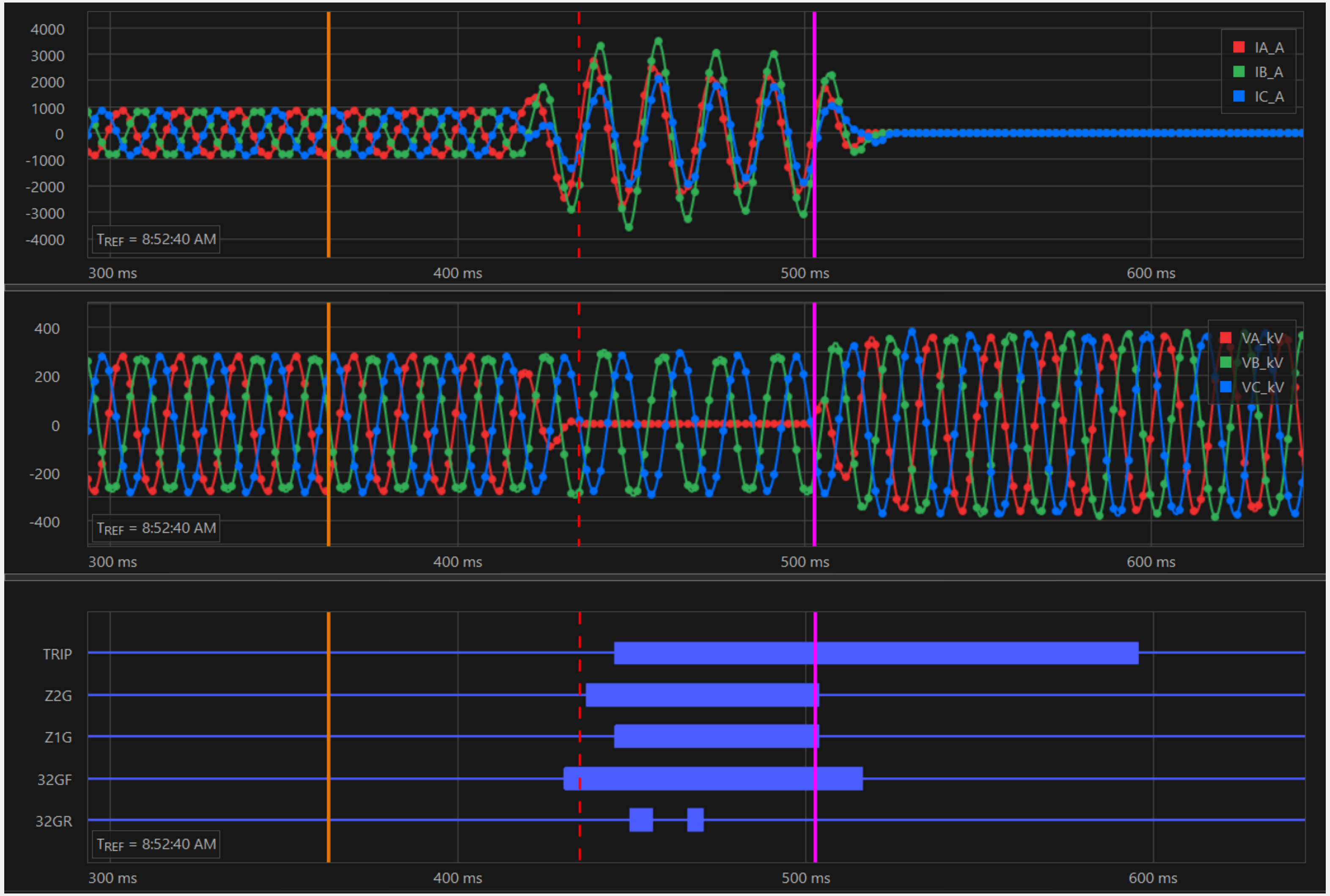
- The relay manufacturer was contacted to understand and improve reliability in the presence of IBR. The manufacturer was helpful and responsive.
- Loop selection error is caused by low negative sequence current, which impacts the negative-sequence direction logic in the relay. This is explained in [1].
- The manufacturer had a solution to overcome this problem, which involved a few setting changes for the relays connected to the IBR terminal, as explained in [2].
- Setting changes:
  - Enabling POTT in the relay
  - Adding Zone 3 settings
  - Enabling Week infeed (EWFC)
  - Updating 50PF and 50PR to improve relay sensitivity

[1] R. Chowdhury and N. Fischer, "Transmission Line Protection for Systems With Inverter-Based Resources – Part I: Problems," in IEEE Transactions on Power Delivery, vol. 36, no. 4, pp. 2416-2425, Aug. 2021, doi: 10.1109/TPWRD.2020.3019990.
[2] R. Chowdhury and N. Fischer, "Transmission Line Protection for Systems With Inverter-Based Resources – Part II: Solutions," in IEEE Transactions on Power Delivery, vol. 36, no. 4, pp. 2426-2433, Aug. 2021, doi: 10.1109/TPWRD.2020.3030168.

IBR IMPACTS ON 21 ELEMENT

Overcoming loop selection error

After implementing the setting changes recommended by the manufacturer, improvements were observed in the test results for ground faults.



IBR IMPACTS ON 21 ELEMENT

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Improving 21 element reliability

- From the results, we can observe an improvement in the performance of 21 element for ground faults. The presence of zero-sequence currents because of the usage of Y-D-Y interconnection transformer, coupled with increased sensitivity of the relay settings, helped in detecting ground faults.
- However, this solution did not help clear LL faults on our system.
- Further analysis can be performed to clear these faults by making use of the undervoltage element. This is discussed in the PSRC C32 report.

Power System Relaying and Control Committee (PSRC), Subcommittee C - System Protection, Working Group C32, Technical Report PES-TR81, “Protection Challenges and Practices for Interconnecting Inverter Based Resources to Utility Transmission Systems”, 2020.

LESSONS LEARNED

- RTDS simulations using hardware-in-the-loop is necessary for analyzing the effects of IBRs on protection systems.
- Matching black-box vendor models of IBRs in RSCAD is challenging.
- In our case, the 87L protection element is not affected by the IBR and can be used to successfully protect the transmission line.
- The operation of the 21 element is affected by including an IBR source. The solution provided by relay manufacturer helped improve the reliability of this element.
- Another method of backing up 87L element using undervoltage (27) element can be further analyzed using RTDS and HIL simulations.