How Inverter-based Resources (IBRs) Affect Protection Relay Elements

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ESIG Webinar

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Overview

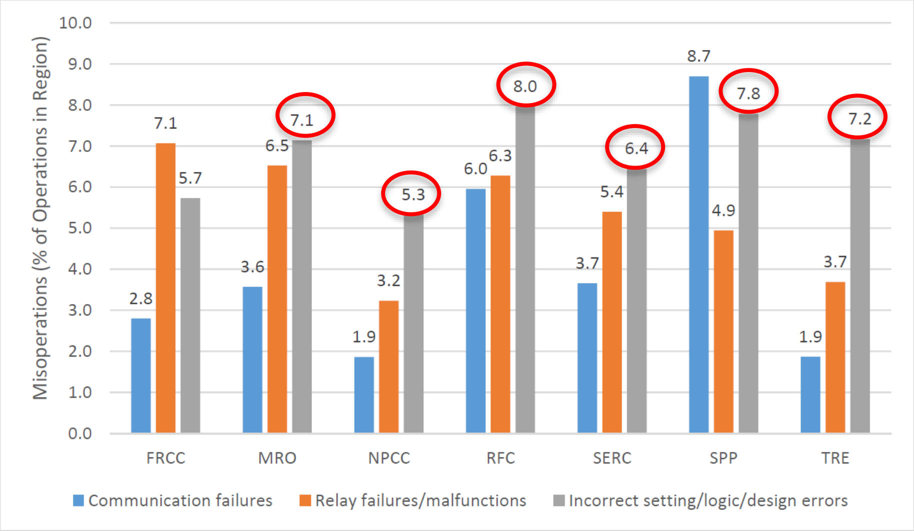
- Background
- IBR modelling for fault study
- Relay modeling
- Impact study
- Recommendations

Collaboration

An Industry Perspective of Real-World Protection Problems

Increasing levels of IBRs pose challenges in transmission protection

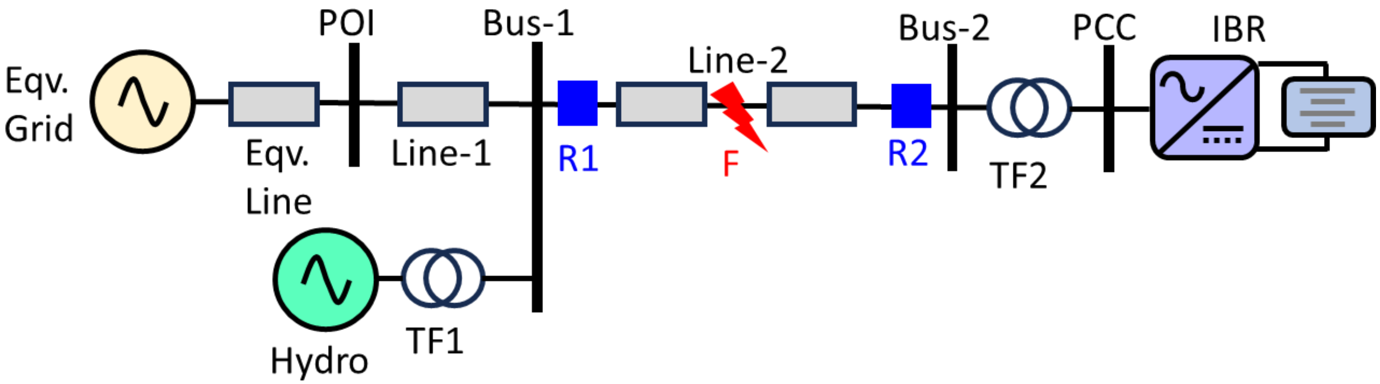
- Low and non-uniform fault current, variable power flow etc.
- Protective relay mis-operations mainly because of incorrect settings/logic/design errors
- Lack of coordination between protection design and IBR controls due to misunderstanding



Relay mis-operations by reginal entity.

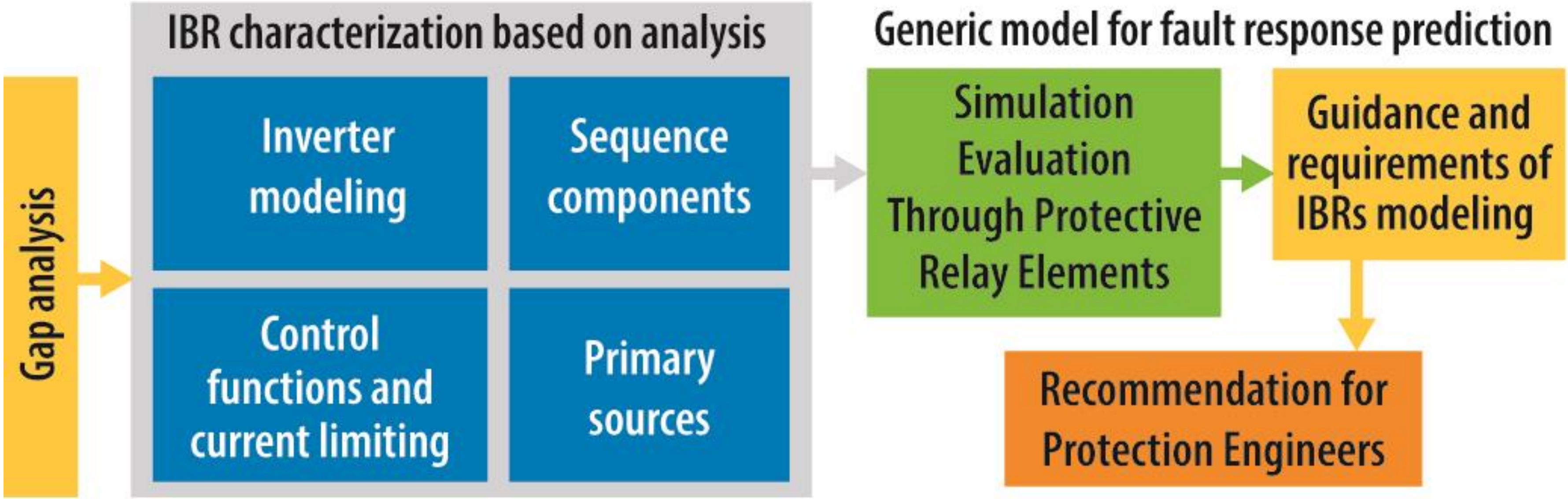
Credit: NERC Staff Analysis of System Protection Mis-operation.

Academic Insights of Real-World Protection Problems and Recommendations



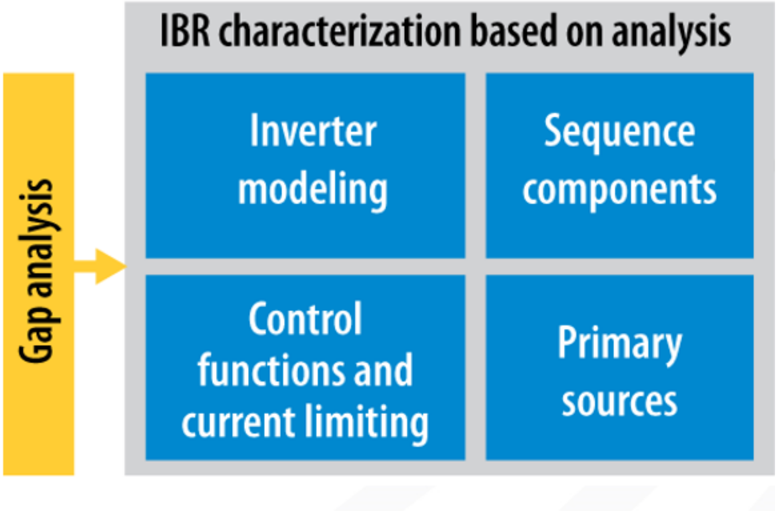
1. How exactly IBRs affect protection relay elements?
2. How should protection engineers and IBR engineers coordinate to achieve more reliable power system protection?

Overall R&D Approach



- The response in the **first three cycles** during a fault is crucial for transmission protection because the relays must decide whether to operate in that window.

IBR Characterization for the First-Three Cycle Response



How does the different variations of GFL/GFM IBRs modeling and control aspects impact the response of protective relay elements?

- Inverter Modeling: average vs switching model
- Primary Sources: PV, battery, combined PV and battery
- Power loop control
  - GFL: PQ control/Vdc-Vac control
  - GFM: Droop/VSM
- Inner current: phase dq or αβ, versus **sequence domain control**
  - IEEE 2800 complaint (response time requirement not only the magnitude and phase angle)
- Current limiting with dq priority: Instantaneous dynamic limiter/magnitude-based limiter/latch-based
- Momentary cessation and virtual impedance (from field experience)

A Versatile Generic IBR model

- A generic IBR model
  - can operate as either GFL-IBR or a GFM-IBR
  - VSI using switching or a switched-averaged model
  - DC-side is either a PV or battery or both
  - In case of GFL-IBR,
    - PQ-dispatch, Vdc-Vac control
    - dq, αβ, and sequence-domain
  - In case of GFM-IBR,
    - P-f/Q-V droop, VSM control
    - nested control in dq, αβ, and sequence-domain
  - Current limiting schemes with dq priority
    - Instantaneous dynamic limiter
    - Magnitude-based limiter
    - Latch-based limiter

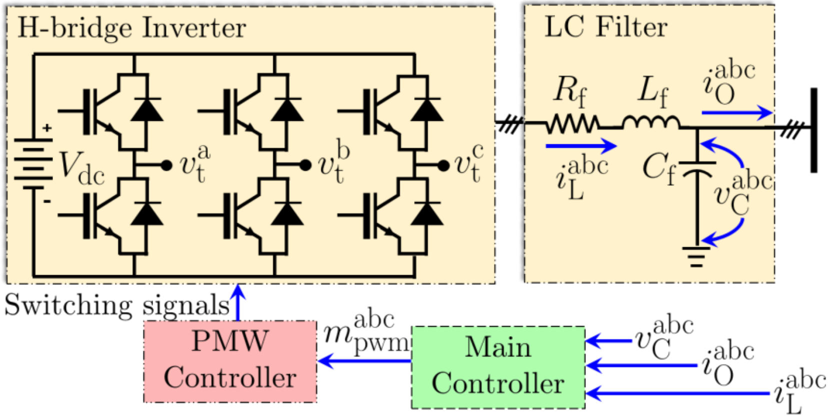


Figure: The IBR model under study.

IEEE 2800-2022 Requirements for IBR Fault Response

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]

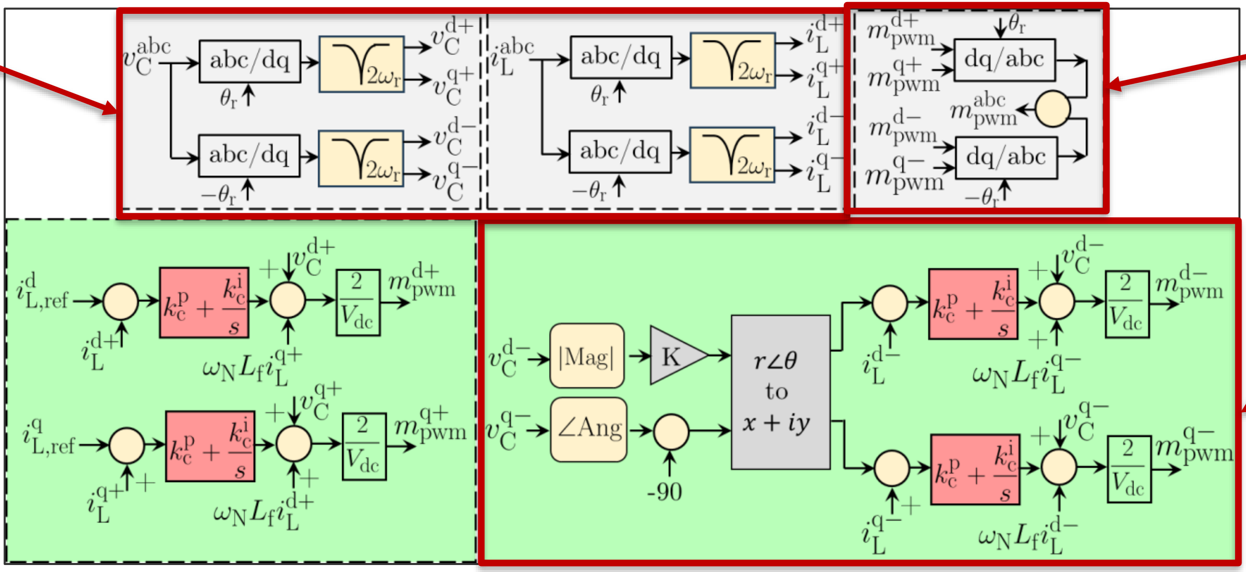
Table 13 —Voltage ride-through performance requirements

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*

Implementation of Negative Sequence Current Control

GFL IBR

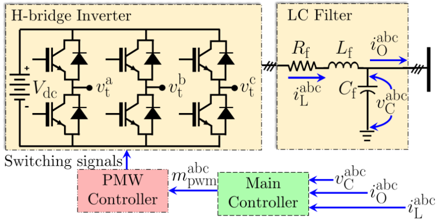
Extract positive and negative sequence components



Generate the final PWM signal

Negative sequence current control

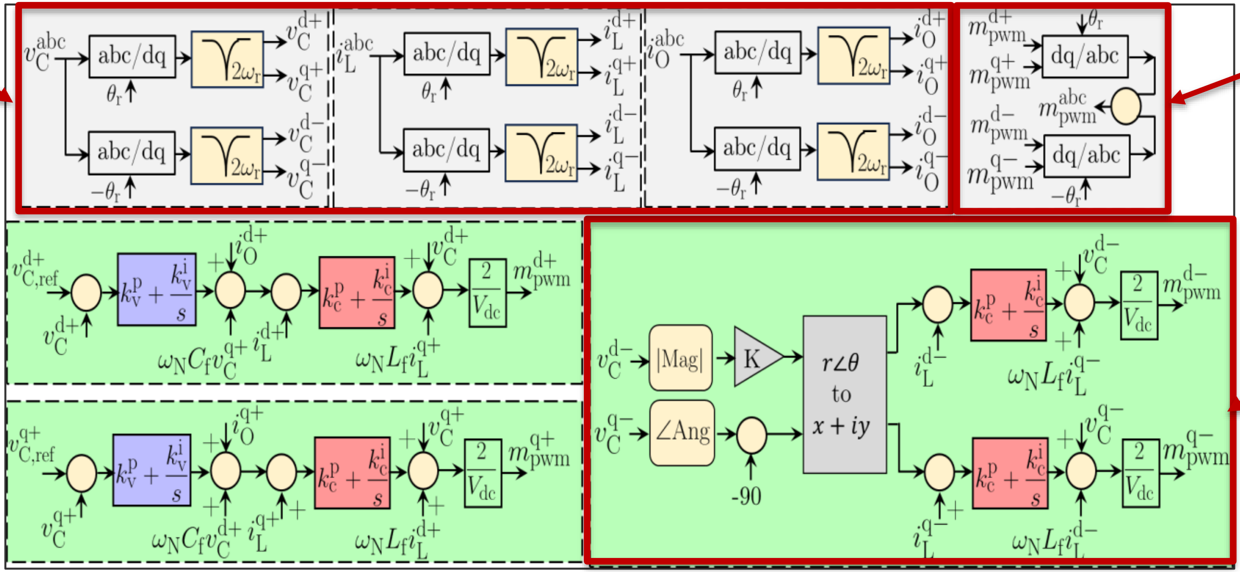
- It is straightforward to tune the positive and negative sequence current controller to achieve 4-cycle setting time of the output current.



Implementation of Negative Sequence Current Control

Extract positive and negative sequence components

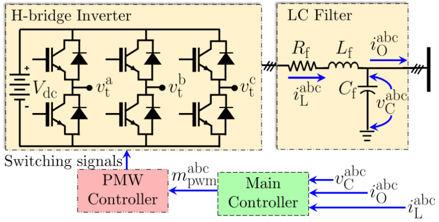
GFM IBR



Generate the final PWM signal

Negative sequence current control

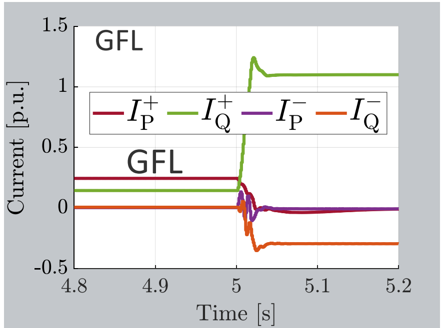
- It requires exhaustive tuning to tune the positive and negative sequence current controller to achieve 4-cycle setting time of the output current.

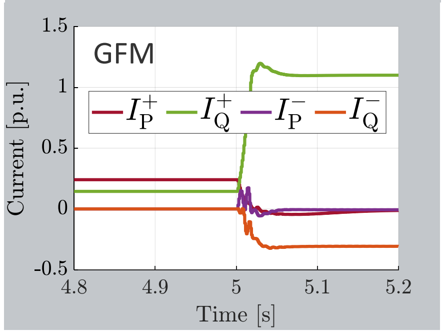


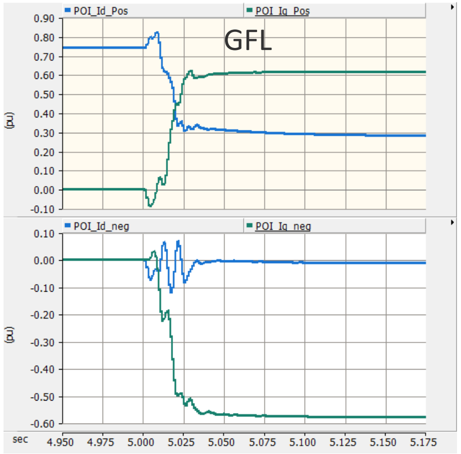
IEEE 2800 Compliant IBR Fault Response

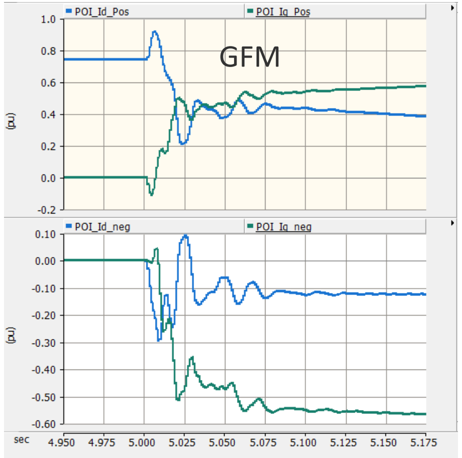
2800 compliant: (1) i2 lead v2 90° (2) settling time.

$$I_{\mathrm{P}}^{-} := |\bar{I}^{-}|\cos(\angle\bar{V}^{-} - \bar{I}^{-})$$
$$I_{\mathrm{Q}}^{-} := |\bar{I}^{-}|\sin(\angle\bar{V}^{-} - \bar{I}^{-})$$

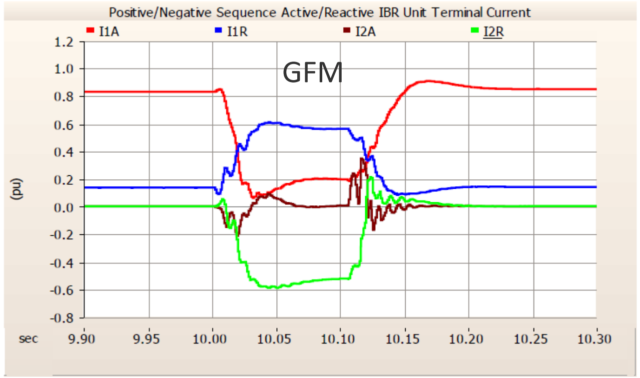


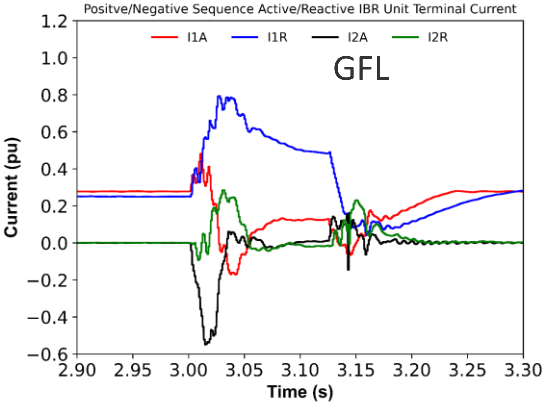




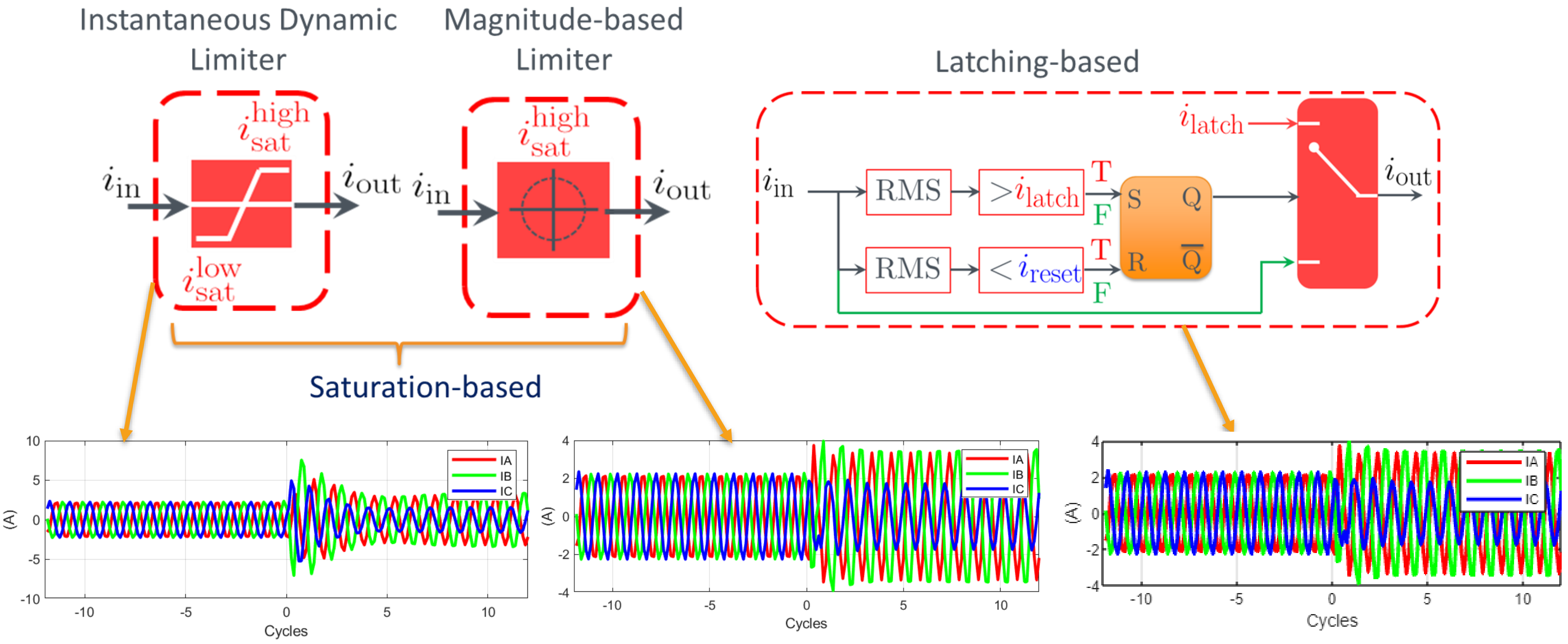


How so many different IBR's negative sequence current responses affect protection relay elements?





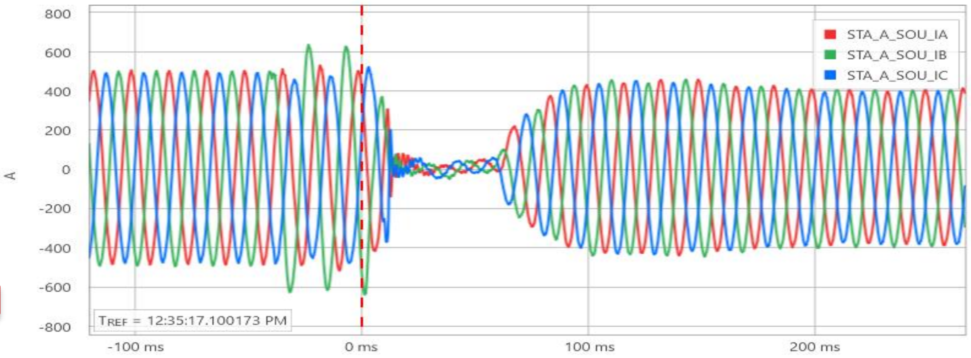
Priority-based Current Limiter



Addition of Momentary Cessation

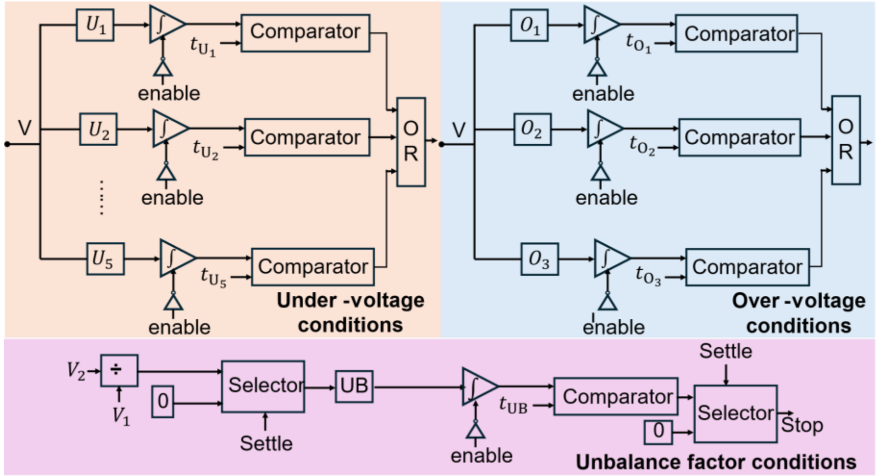
Table 11 of IEEE Std. 2800

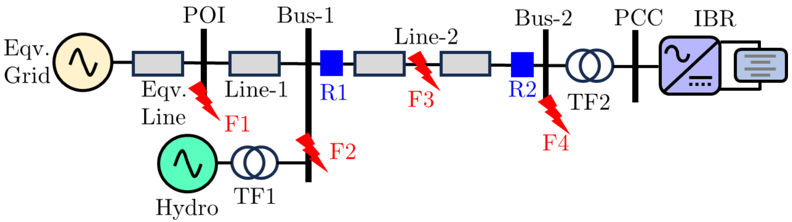
Applicable voltage (p.u.) at the RPA	Operating mode/response	Minimum ride-through time (s) (design criteria)
V > 1.20	May ride-through or may trip	NA
V > 1.10	Mandatory operation	1.0
V > 1.05	Continuous operation[90]	1800
V < 0.90	Mandatory operation	3.00
V < 0.70	Mandatory operation	2.50
V < 0.50	Mandatory operation	1.20
V < 0.25	Mandatory operation	0.16
V < 0.10	Permissive operation[91]	0.16



Credit: Mike Jersen from PG&E.

Implementation logics

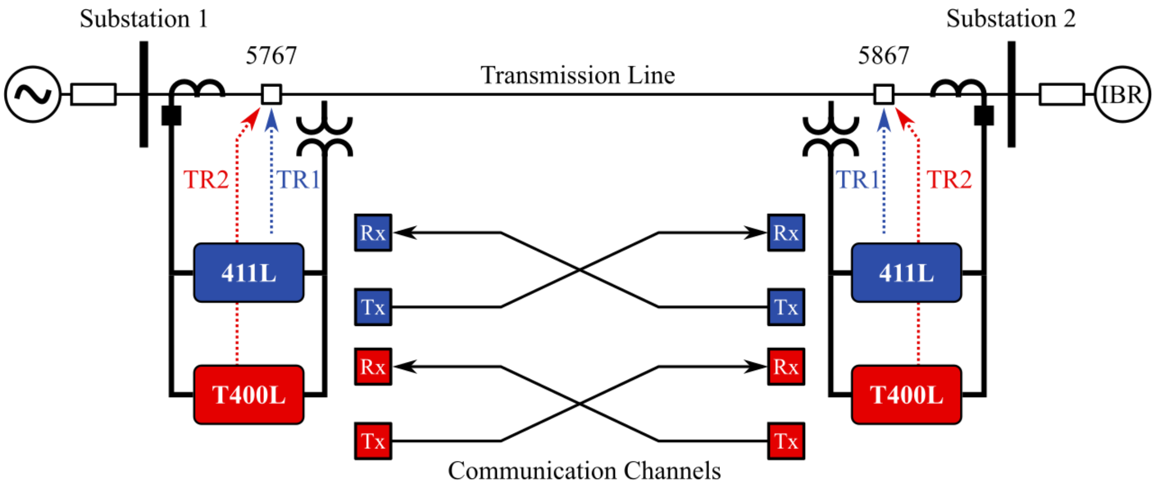




- Point-of-measurement (PoM) is at Bus-2
- Considered according to Annex B of IEEE Std. 2800
- IBR enters current blocking time is adjustable (e.g., 1, 2, 3.. 10 cycles).

Protective Relay Elements for IBR Characterization Evaluation

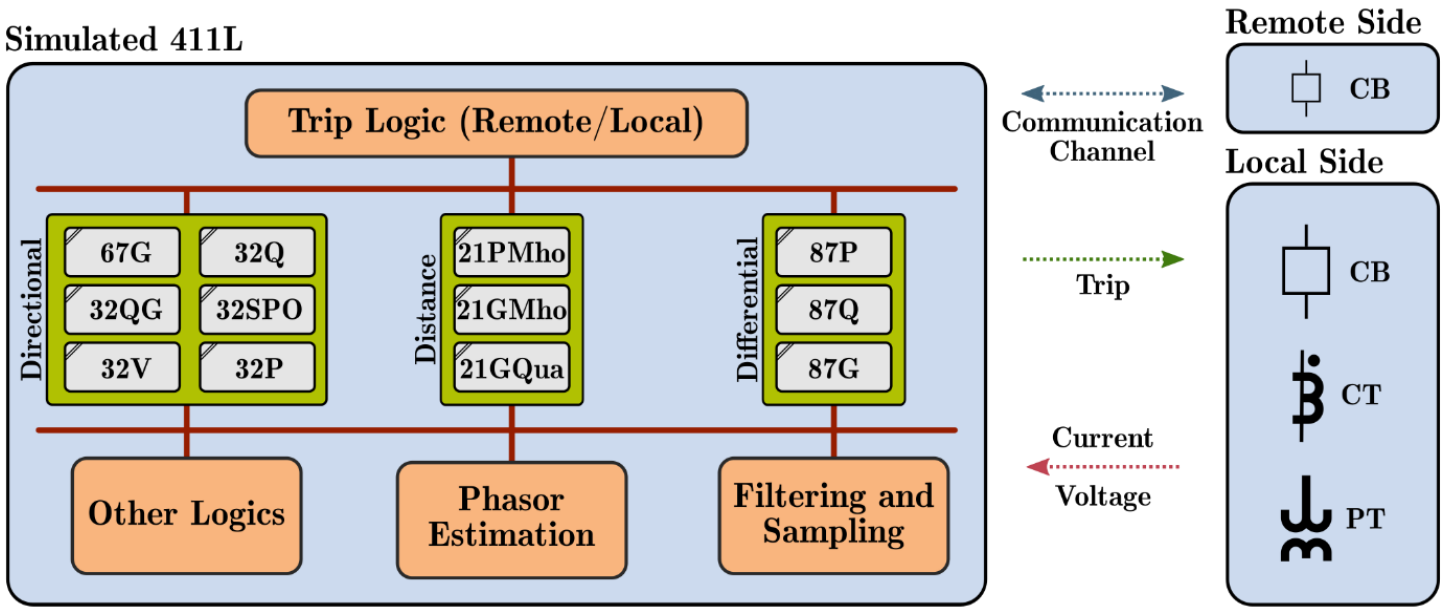
Transmission line Protection from Utility Partner



Identify the transmission lines between Substation 1 and Substation 2 will be studied (primary use case)

- 57 kV system
- The project team will evaluate the protective relays for the two breakers
- The system is ungrounded at one end
- Will develop protective relay elements (411L and T400L) for IBR characterization evaluation

Relay development in MATLAB



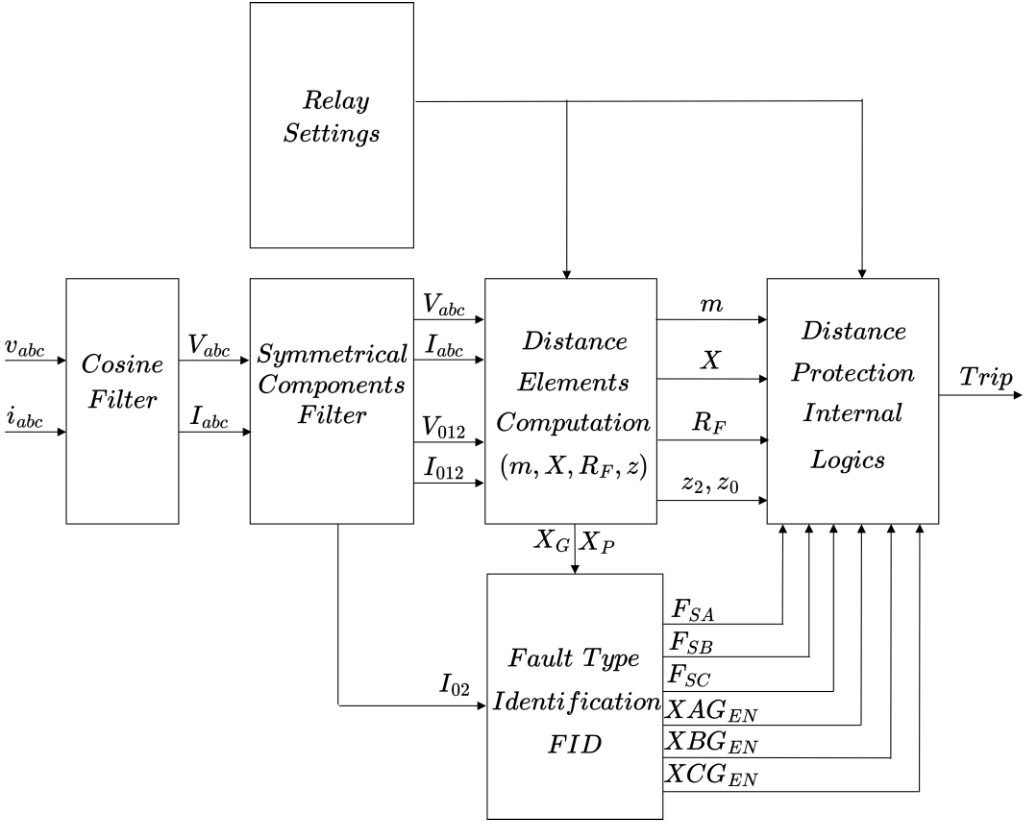
- Identify additional functions that impact protection elements and model
  - For example: fault type selection logic

Relay Elements Implemented in MATLAB

- *Update on protection relay element models implemented in MATLAB*
- *The following elements have been implemented and tested, with response tested against SEL 411L relay*
  - ✓ *87LP: Phase current differential protection*
  - ✓ *87LQ: Negative-sequence current differential protection*
  - ✓ *87LG: Zero-sequence current differential protection*
  - ✓ *M21P: Phase distance protection using positive-sequence memory polarized mho element*
  - ✓ *M21G: Ground distance protection using positive-sequence memory polarized mho element*
  - ✓ *X21P: Phase distance protection using negative-sequence polarized quad element*
  - ✓ *X21G: Ground distance protection using zero/negative-sequence polarized quad element*
  - ✓ *32Q: Negative-sequence directional element for unbalanced phase faults*
  - ✓ *32QG: Negative-sequence directional element for ground faults*
  - ✓ *32V: Zero-sequence directional element (active for ground faults only)*

Relay model was validated using field data and compare with SEL hardware relay

Mho Distance Protection



Mho distance protection tripping schematic diagram

Distance Elements

- Ground distance-MAG, MBG, MCG
- Phase distance-MAB, MBC, MCA

Polarizing Reference

- Self (VAG supervises MAG, etc.)
- Cross (VBC supervises MAG, etc.)
  - Mho expansion/contraction
- Memory (positive sequence-V1MEM)
  - Mho-expansion

Supervision

- Fault type identification
- Direction (ground, negative sequence)
- Minimum current

Scenarios and Dataset Creation for the IBR Characterization Evaluation

System Under Study

- the equivalent grid:
  - 3-ϕ, 57.1 kV, stiff synchronous generator
  - behind the equivalent line impedance
  - connected to Bus-1 via Line-1
- 3-ϕ, 0.48 kV, 14 MVA IBR at PCC
  - 3-ϕ, Δ-Y (or Y-Δ), 57.1/0.48 kV, 15 MVA step-up transformer (TF2)
- Test system under study is now incorporating equivalent grid impedance, determined from a Shrimp Farm event data captured by the KIUC system.

Z_{12}^{p} = 1.0433 + j*3.218;	Z_{12}^{0} = 1.5649 + j*4.827;
Z_{eq}^{p} = 5.91 + j*12.53;	Z_{eq}^{0} = 5.65 + j*18.93;

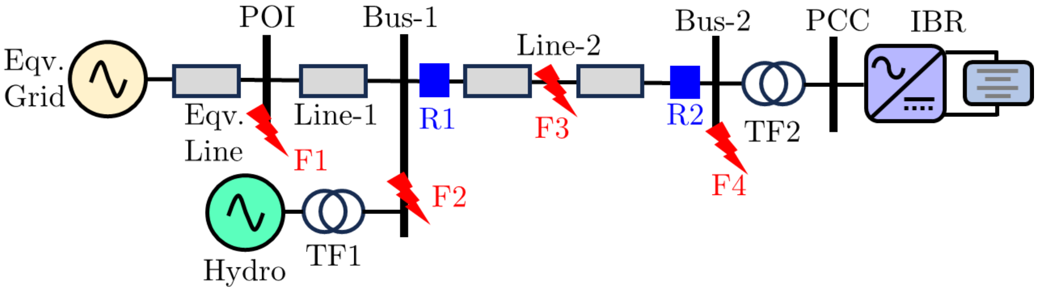


Figure 1: The transmission system under study.

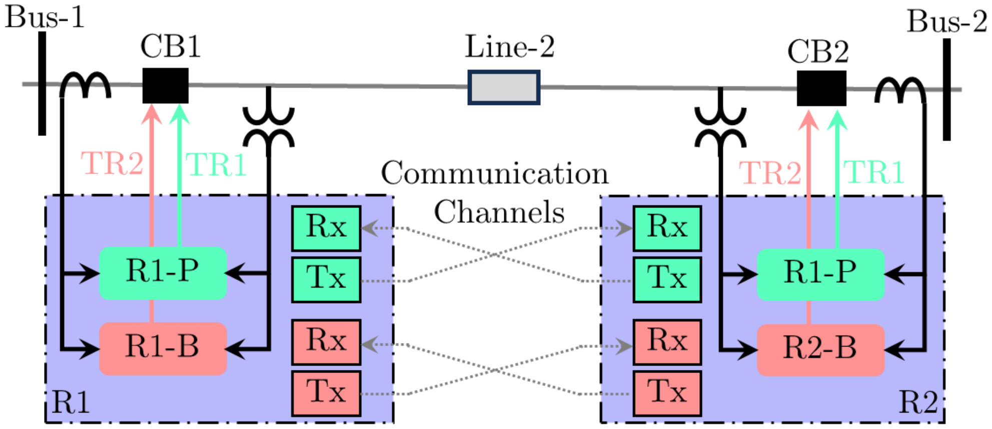


Figure 2: The protection system under study

Case Studies

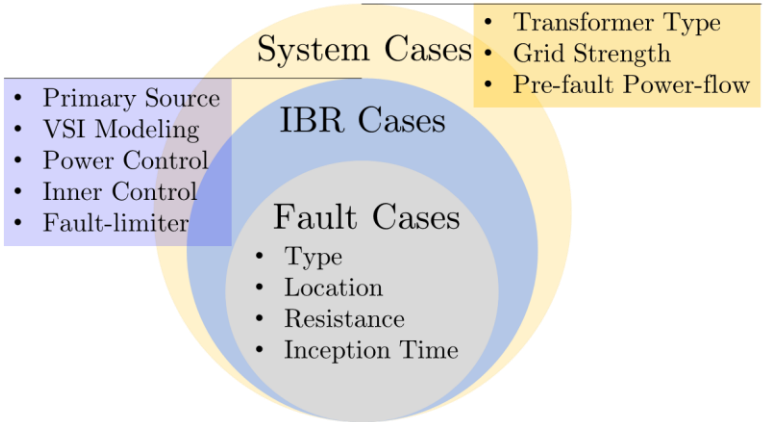


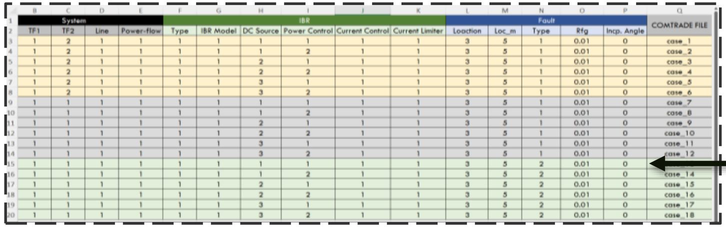
Figure 1: The process flow diagram of the EMT study.

A Smaller Set (impact of IBR aspects on the protection logic)

- ❑ **system cases**: we select TF2 as
  - ➢ YgD transformer (Yg facing the transmission)
  - ➢ DYg transformer (D facing the transmission).
- ❑ **IBR cases:** all combinations
- ❑ **Fault cases**: we selected
  - ❑ AG fault for both TF2 connections (YgD and DYg)
  - ❑ BC fault for TF2 only as DYg.
- ❑ Always at F3, with 0^o inception angle, 0.01Ω
- ❑ **66** cases for GFL inverters: varying DC source, inverter model, power loop, current controls, and current limiter
- ❑ **36** cases for GFM inverters: varying power control, current control and current limiter

Momentary cessation, fast/slow response, different grid strength, different fault location and different IBR operating points are considered.

Data generation



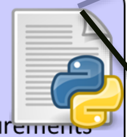
System				IBR						Fault					COMTRADE FILE
TF1	TF2	Line	Power-flow	Type	IBR Model	DC Source	Power Control	Current Control	Current Limiter	Loaction	Loc_m	Type	Rfg	Incp. Angle	
1	2	1	1	1	1	1	1	1	1	3	5	1	0.01	0	case_1
1	2	1	1	1	1	1	2	1	1	3	5	1	0.01	0	case_2
1	2	1	1	1	1	2	1	1	1	3	5	1	0.01	0	case_3
1	2	1	1	1	1	2	2	1	1	3	5	1	0.01	0	case_4
1	2	1	1	1	1	3	1	1	1	3	5	1	0.01	0	case_5
1	2	1	1	1	1	3	2	1	1	3	5	1	0.01	0	case_6
1	1	1	1	1	1	1	1	1	1	3	5	1	0.01	0	case_7
1	1	1	1	1	1	1	2	1	1	3	5	1	0.01	0	case_8
1	1	1	1	1	1	2	1	1	1	3	5	1	0.01	0	case_9
1	1	1	1	1	1	2	2	1	1	3	5	1	0.01	0	case_10
1	1	1	1	1	1	3	1	1	1	3	5	1	0.01	0	case_11
1	1	1	1	1	1	3	2	1	1	3	5	1	0.01	0	case_12
1	1	1	1	1	1	1	1	1	1	3	5	2	0.01	0	[illegible]
1	1	1	1	1	1	1	2	1	1	3	5	2	0.01	0	case_14
1	1	1	1	1	1	2	1	1	1	3	5	2	0.01	0	case_15
1	1	1	1	1	1	2	2	1	1	3	5	2	0.01	0	case_16
1	1	1	1	1	1	3	1	1	1	3	5	2	0.01	0	case_17
1	1	1	1	1	1	3	2	1	1	3	5	2	0.01	0	case_18

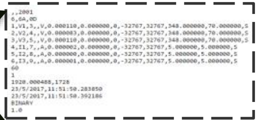
Input configuration file containing

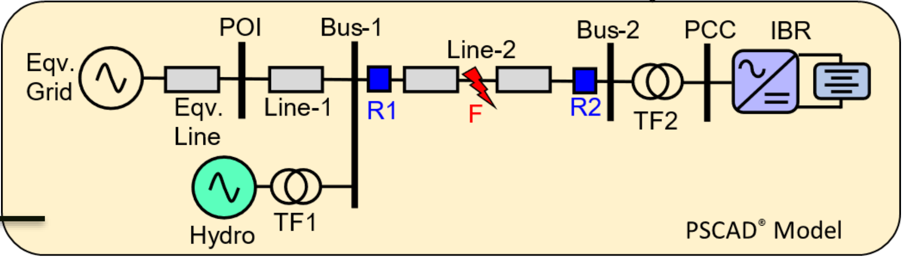
1. Simulation scenarios
2. Stored data tagging

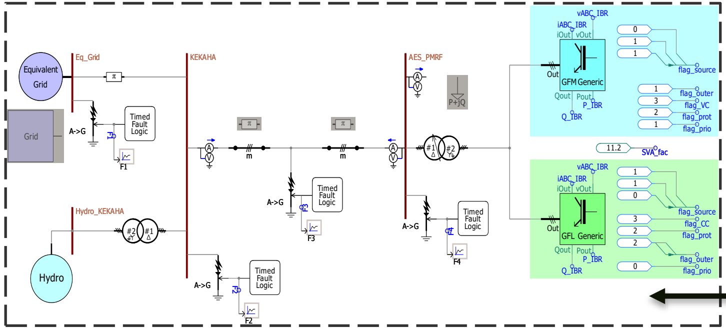
Automated Python-based Script for

1. Reading the Scenario
2. Configure the PSCAD® model
3. Running the PSCAD® model
4. Acquire and save the relay measurements in COMTRADE format



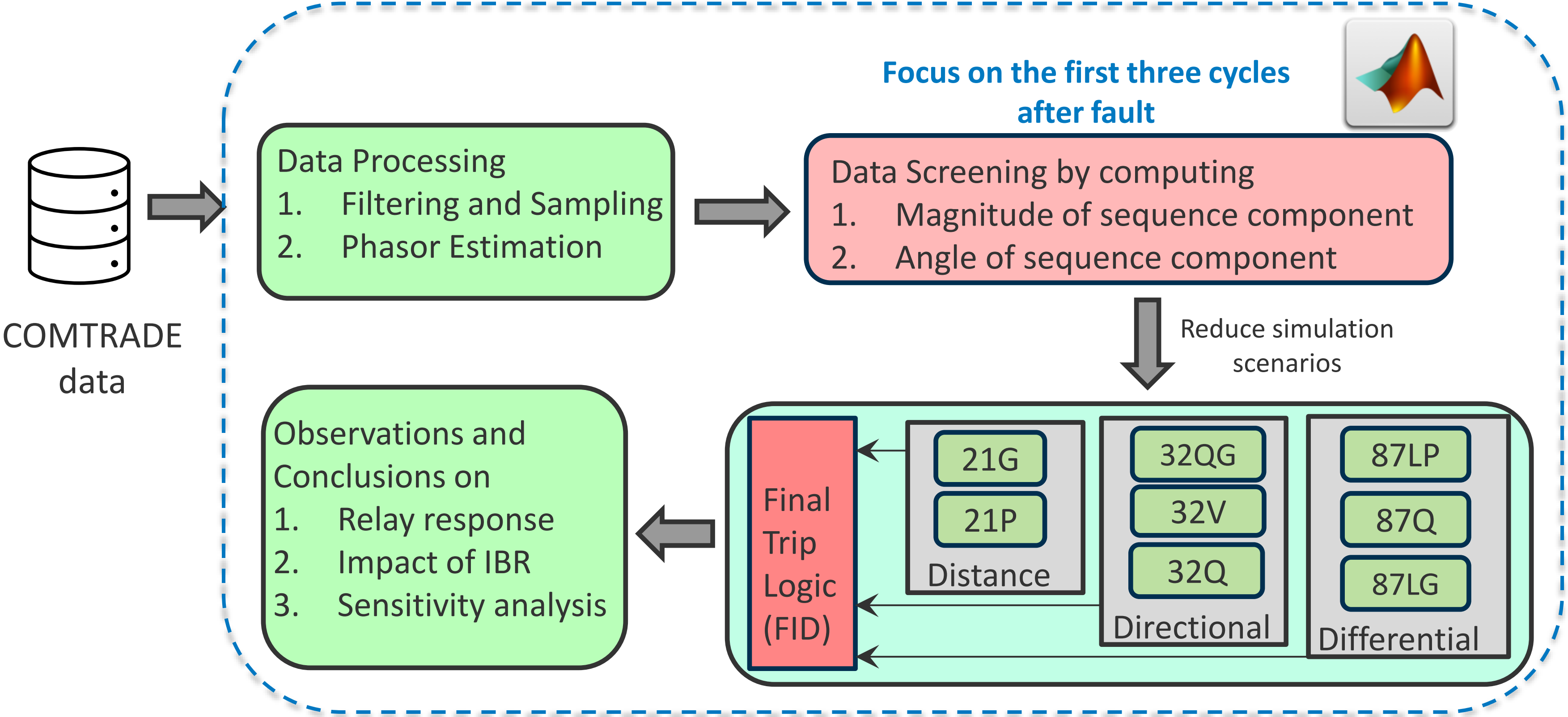






IBR Characterization Evaluation Results and Analysis

Analysis Framework



IBR Characterization Aspects and High-level Results

Does not impact IBR fault response seen by the protective relay

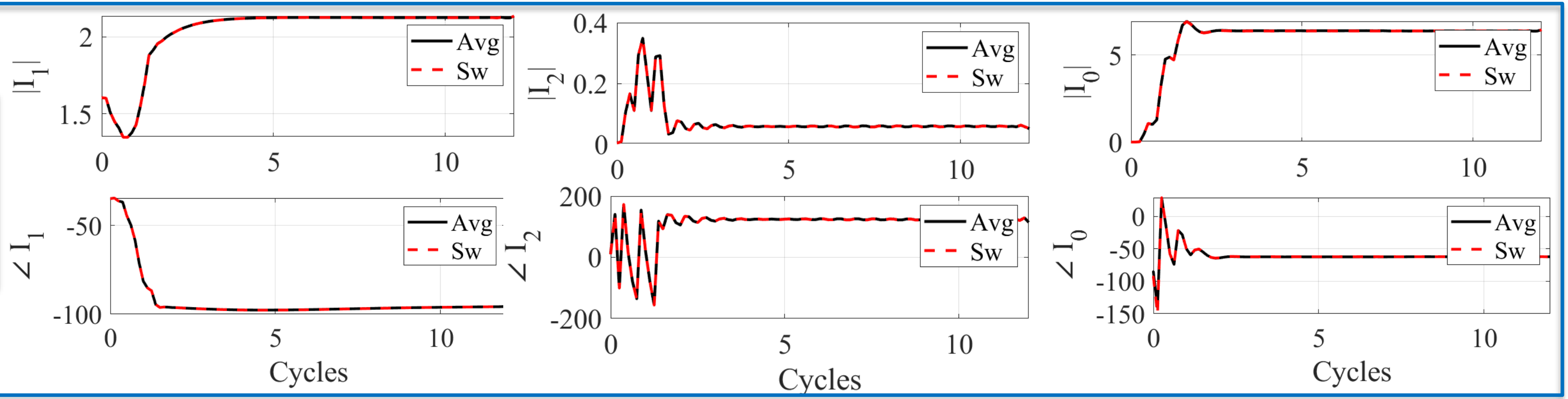
- Inverter modeling: average model vs switching model
- Primary source: PV, battery or combined
- Outer-loop: GFL: PQ vs Vac-Vdc control; GFM: droop vs VSM

Does affect IBR fault response and relay response too

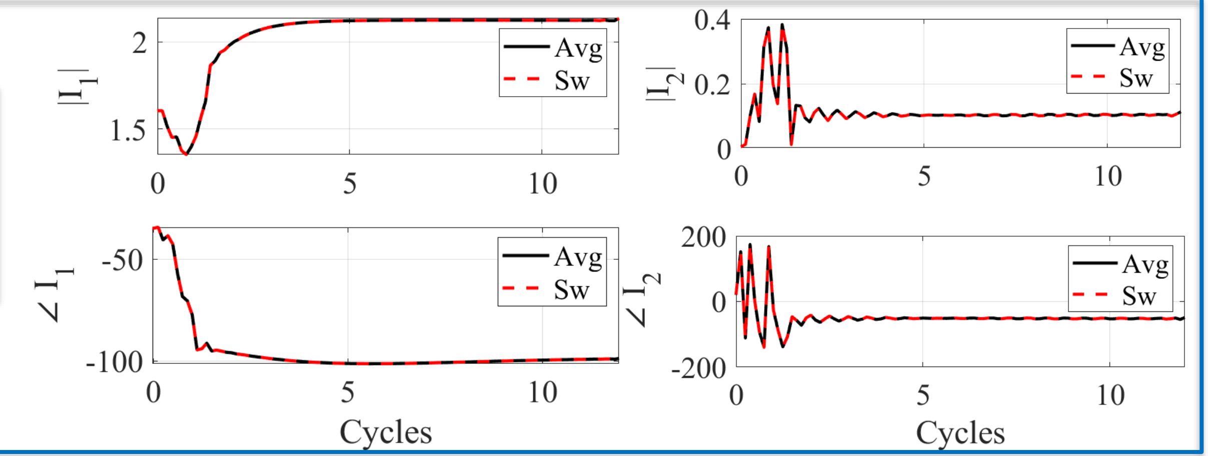
- Inner current loop: phase current based dq and αβ versus sequence control based dq
- Current limiting: Instantaneous dynamic limiting (d/q priority), magnitude-based limiting (d/q priority) versus Latch based limiting (d/q priority)
- Momentary cessation & 2800 compliance, grid strength, different power level

Switching Model vs Average Model

AG fault

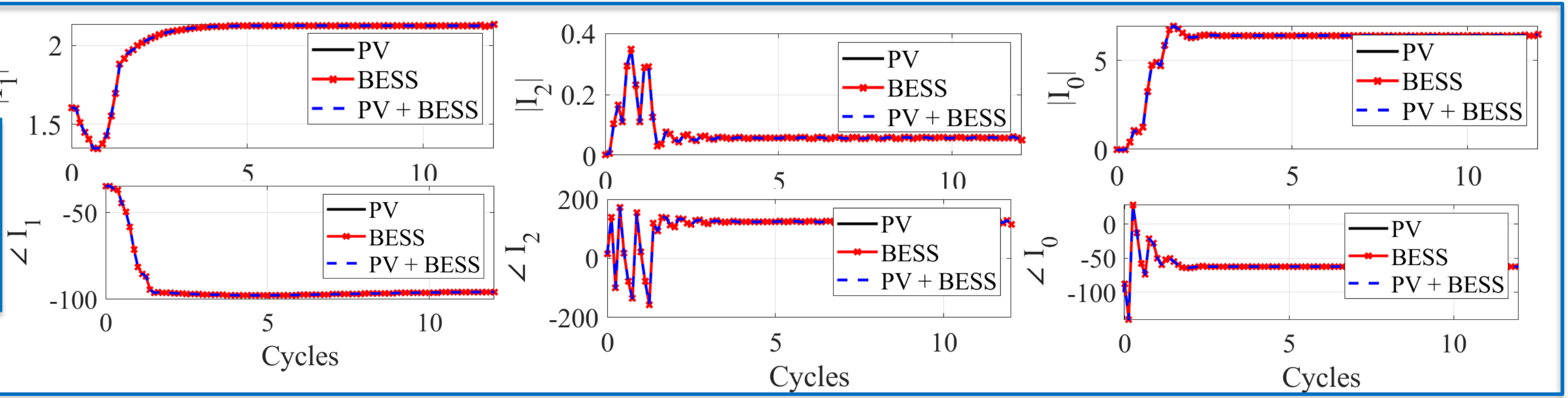


BC fault

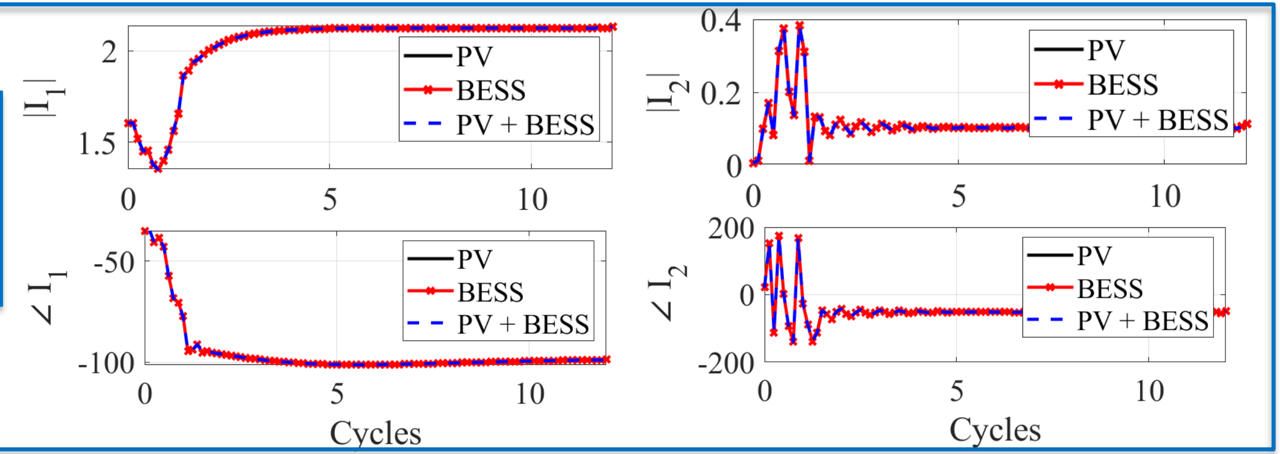


DC source: PV, Battery and Combined

AG fault

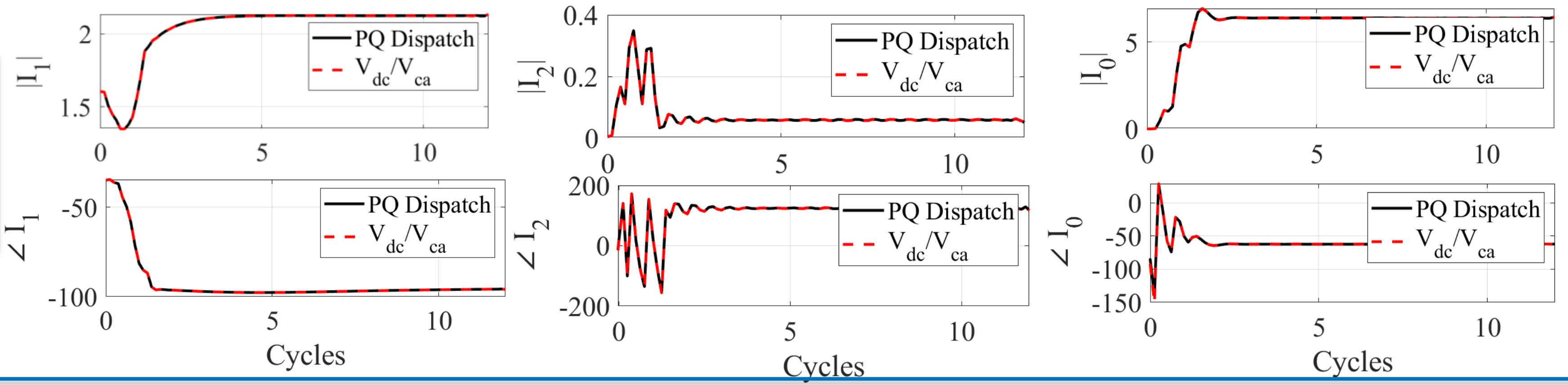


BC fault

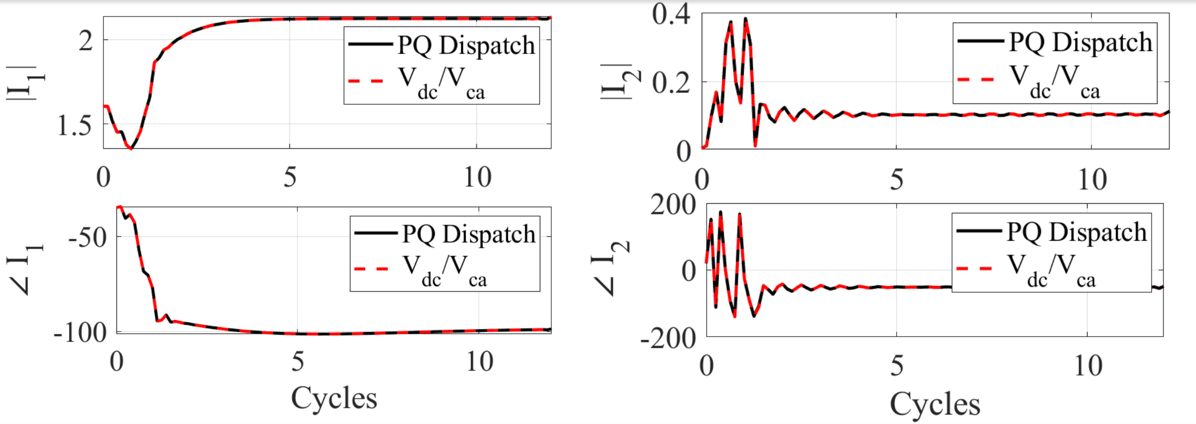


Outer Loop: PQ vs Vdc-Vac (GFL)

AG fault

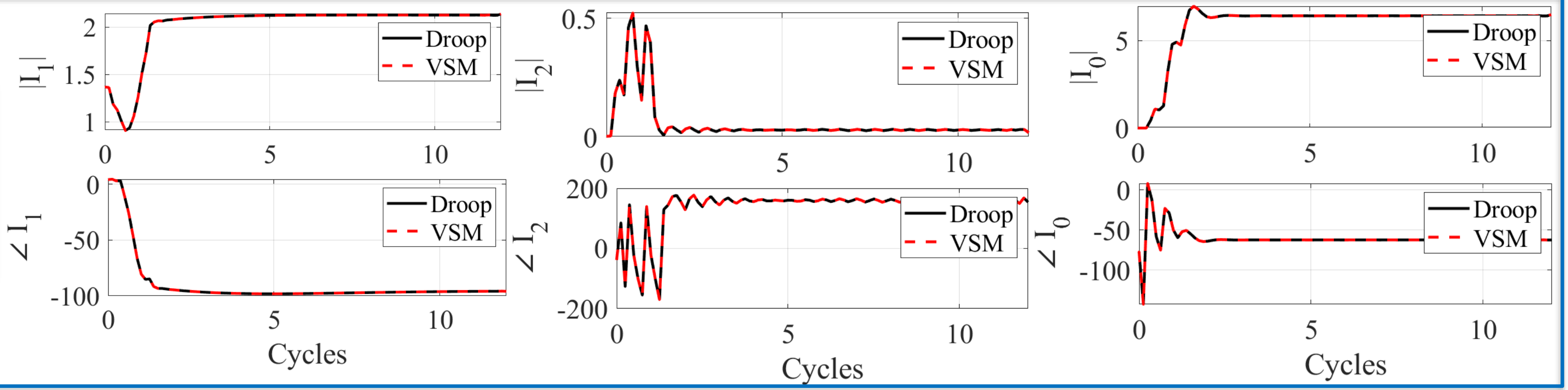


BC fault

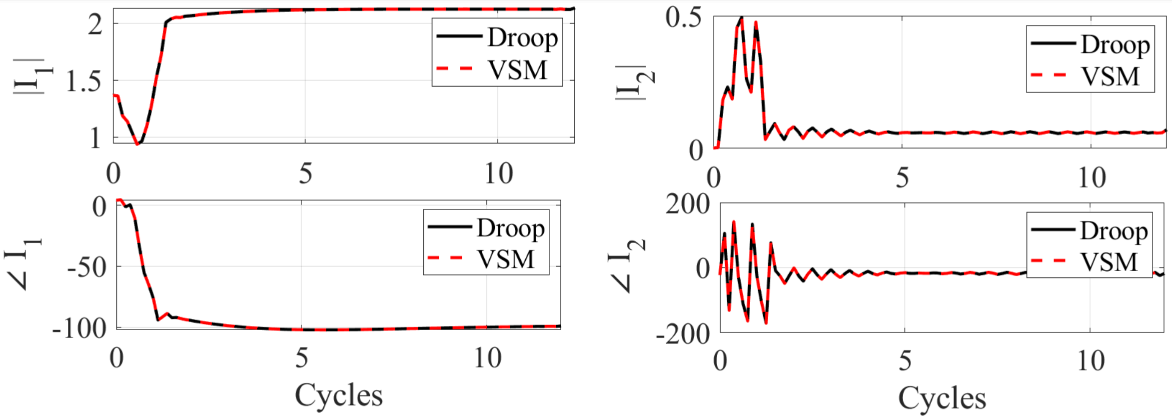


Outer loop: droop control vs VSM (GFM)

AG fault

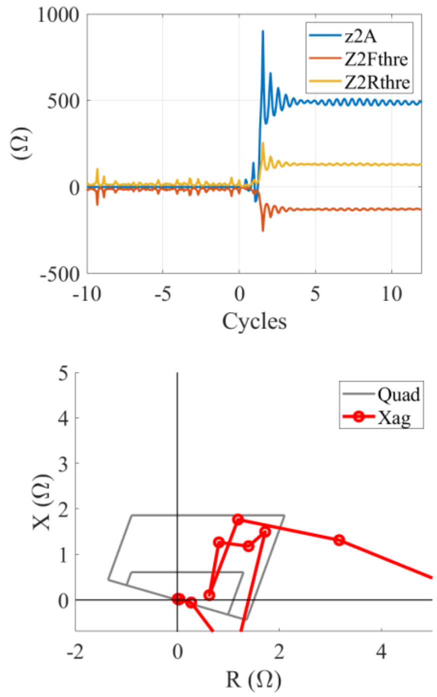


BC fault

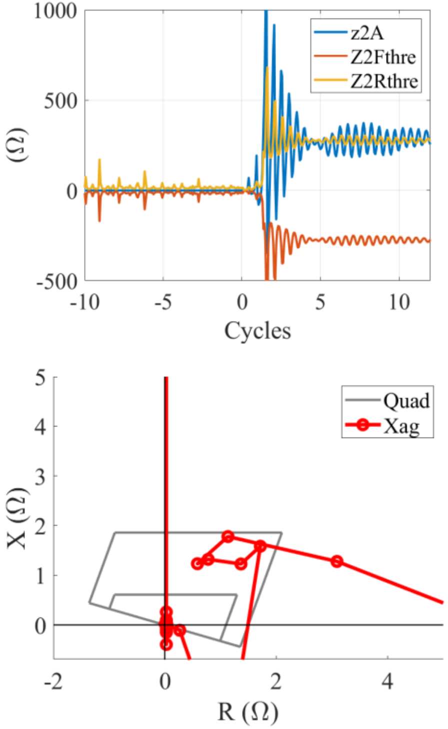


Impacts of different current control on I2

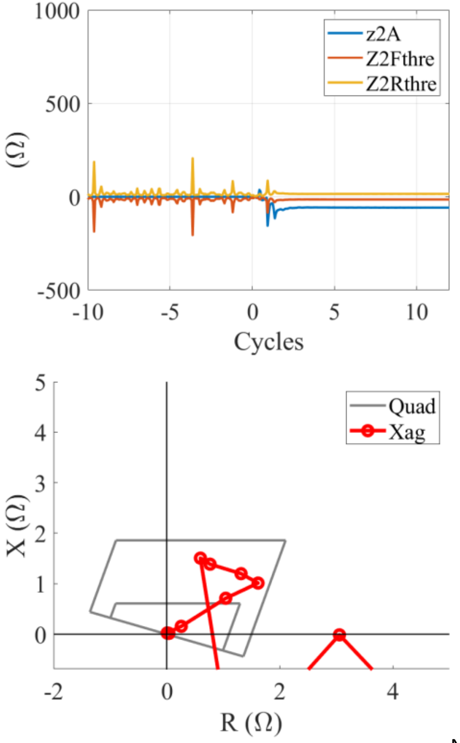
dq-control



αβ-control



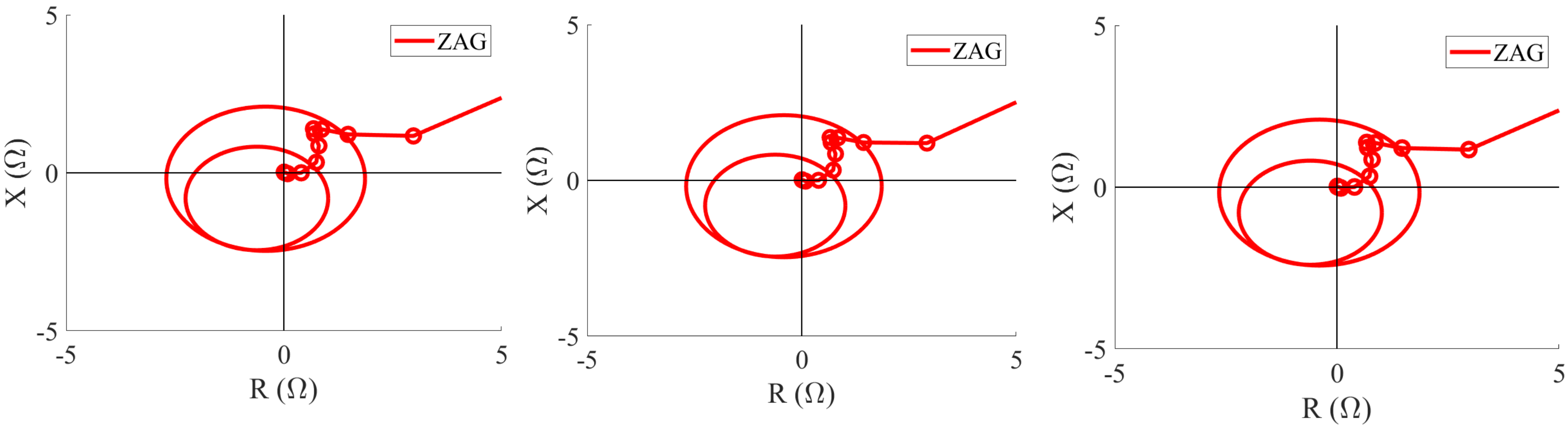
sequence-control



Quad ground directional element relay response.

Examples of Mho Element Response

- Investigated scenarios for protection elements response

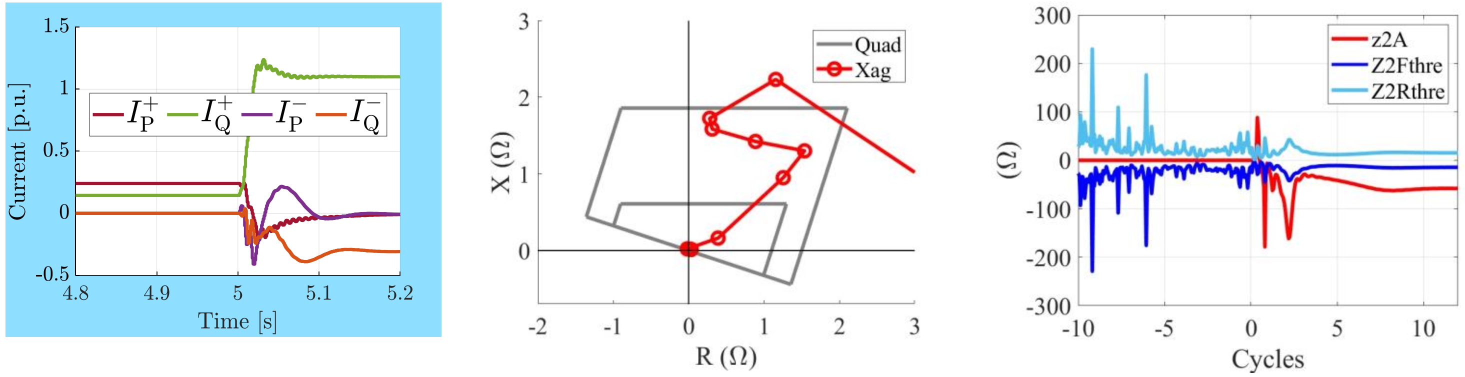


a) dq **b) αβ** **c) seq. comp.**

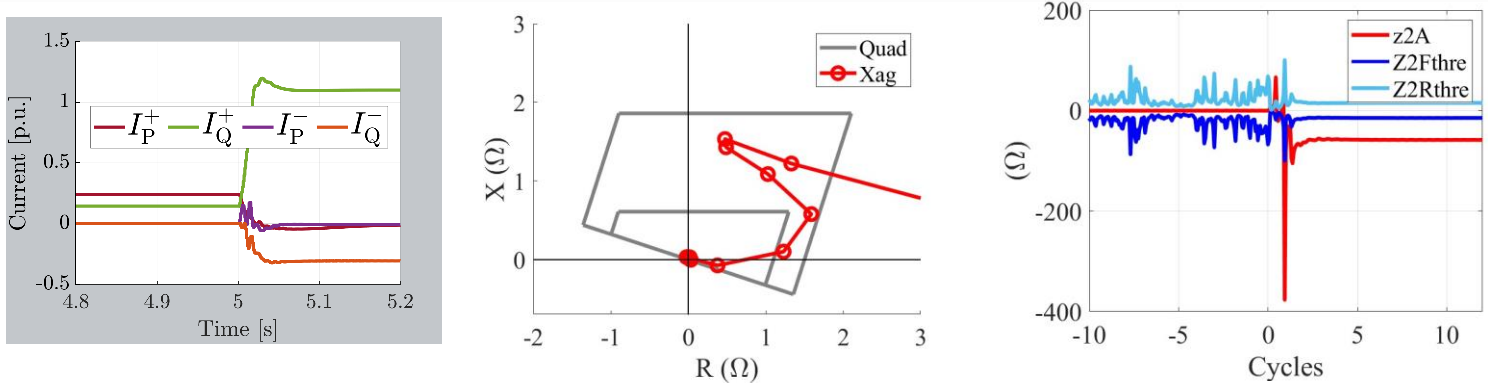
V1 memory polarized mho element for AG fault with TF2 using YgD connection.

Slow and faster current regulator impacts

Slow

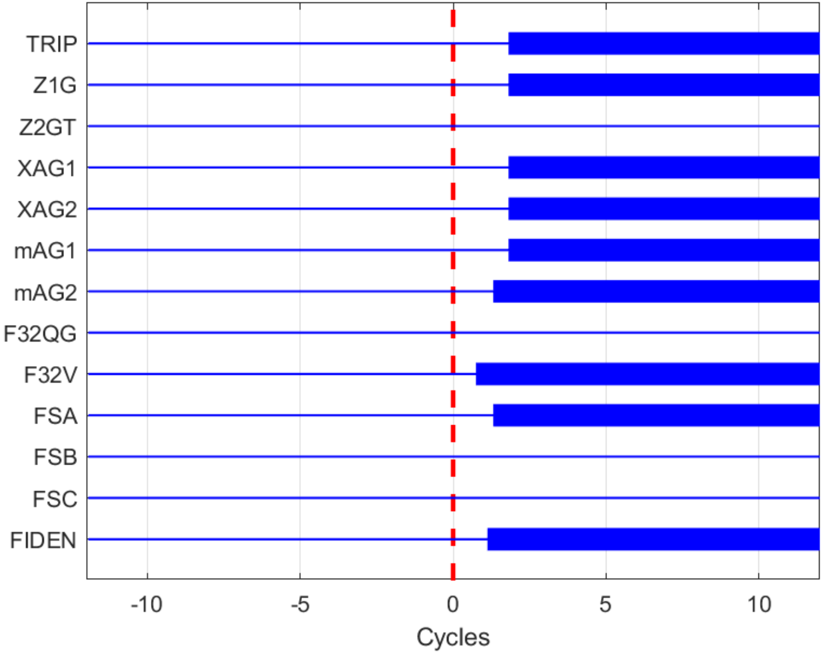


Fast

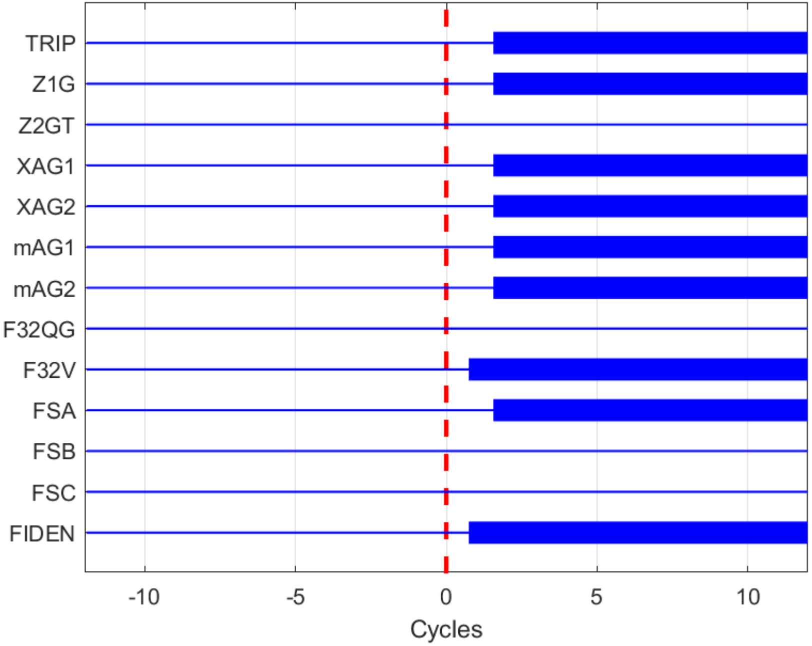


Slow and fast response of IBR current controllers a) Slow b) Fast

Impact of IBR current control time constants



a) Slow

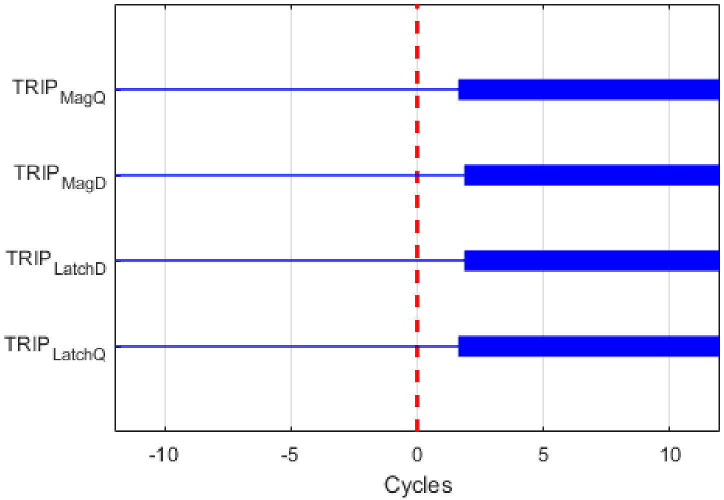


b) Fast

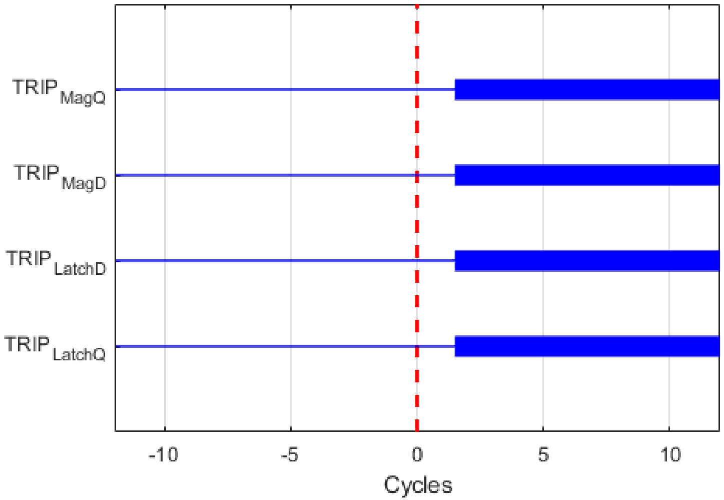
Slow and fast response of IBR controllers using 32V directional element

Compare of Magnitude and Latch-based Limiting Priority on Timing of Trip

- Ground faults: memory polarized mho element, I0 polarized quad element, I2 polarized quad element, 32V, 32QG, FID
- Phase faults: memory polarized mho element, I2 polarized quad element, and 32Q



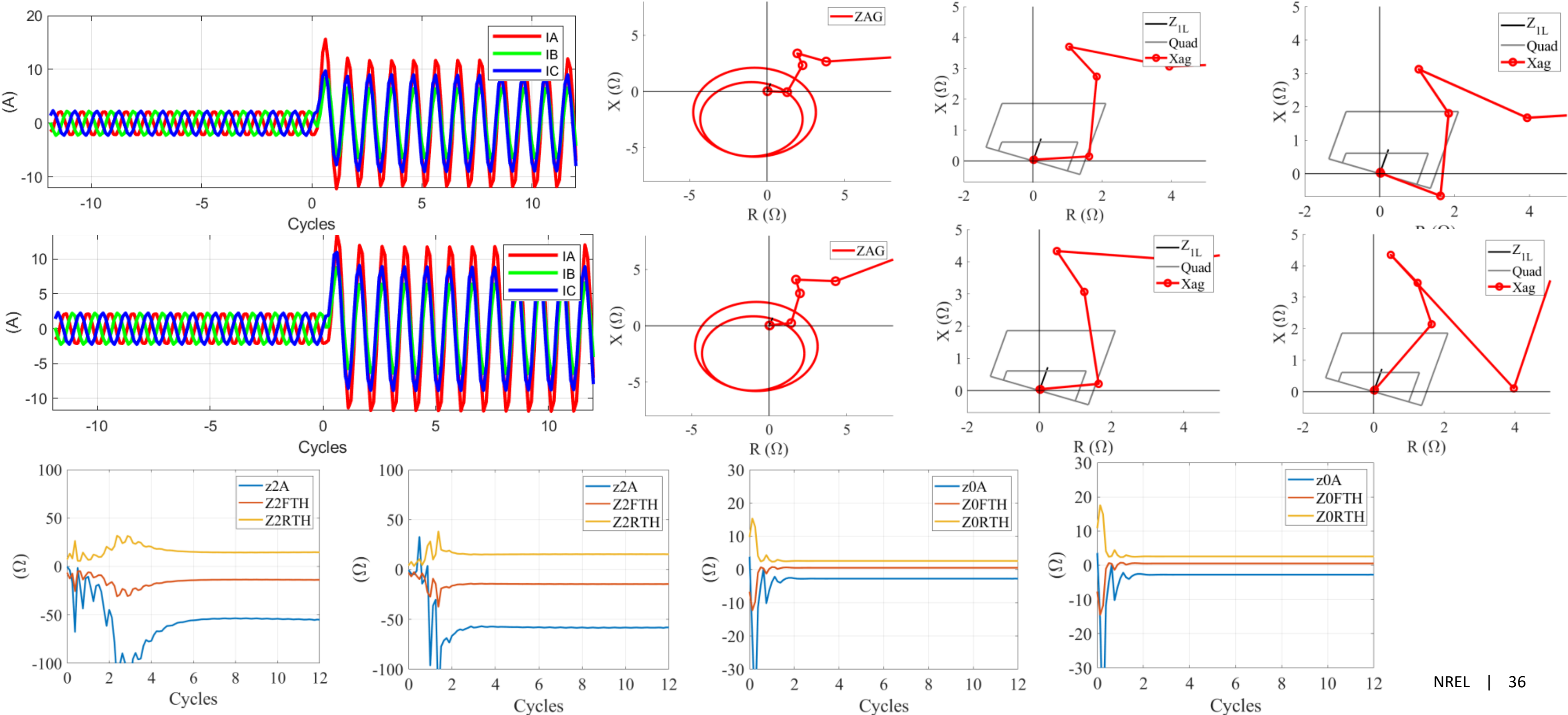
a) AG fault



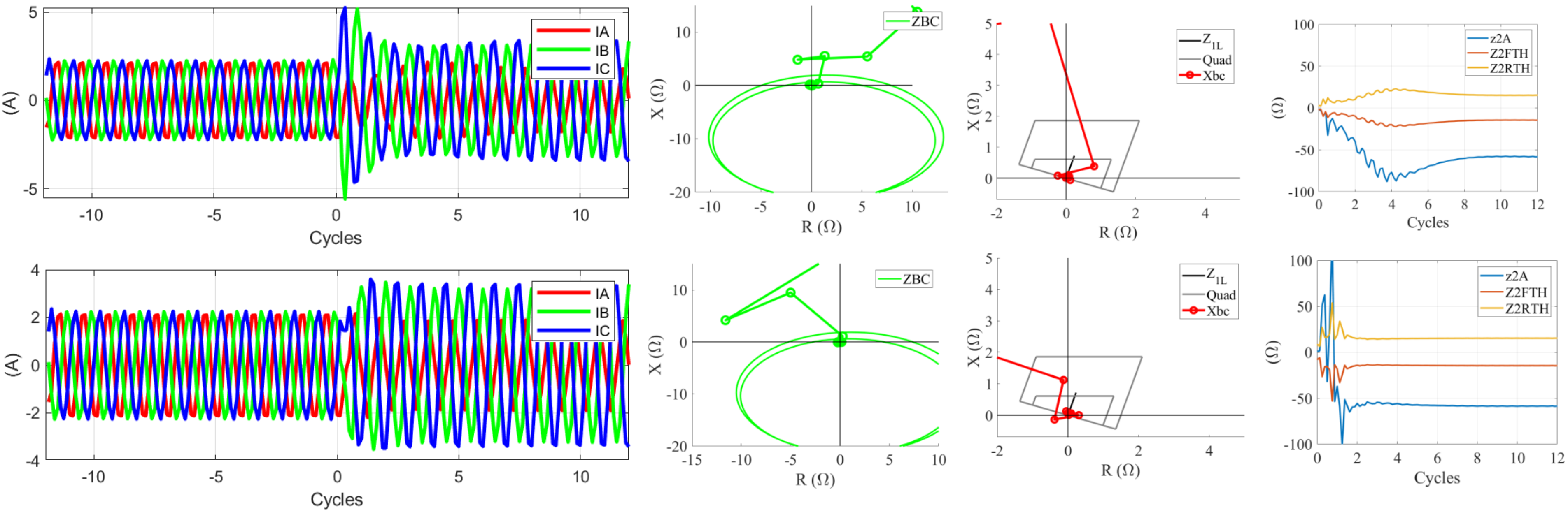
b) BC fault

Trip time for different current limiting logics

Compare of Instantaneous Dynamic Limiter versus Magnitude-based Limiter- q-priority (AG fault)

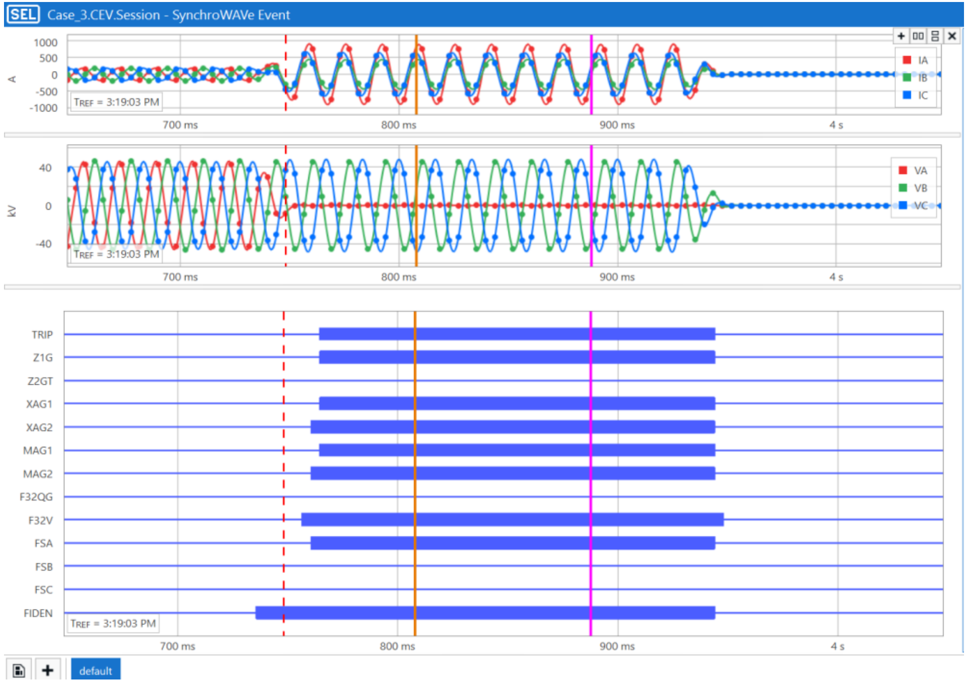


Compare of Instantaneous Dynamic Limiter versus Magnitude-based Limiter- q-priority (BC fault)

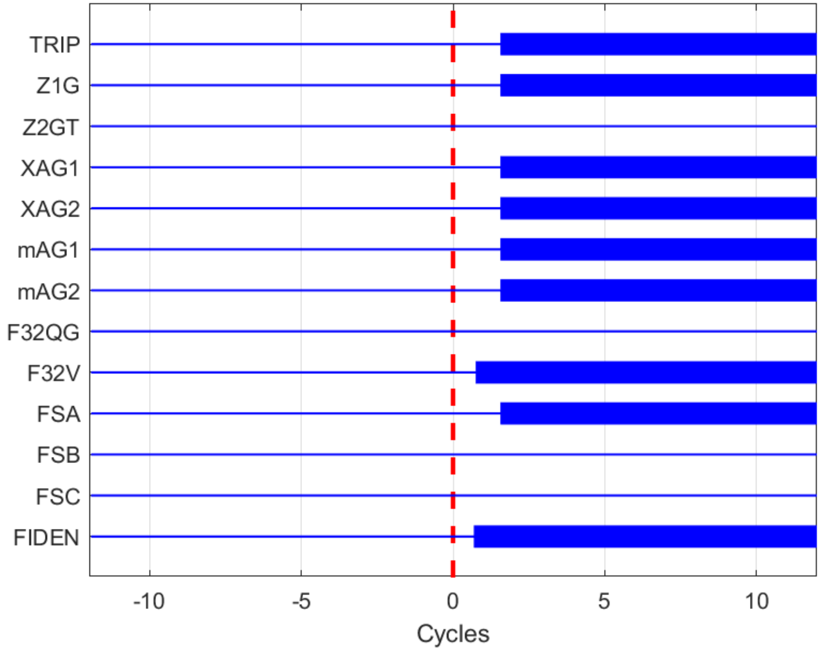


Impact of Momentary Cessation On Protection Relay – Severe fault with |V| < 10% of nominal

- Investigated scenarios for protection elements response



a) Commercial Relay

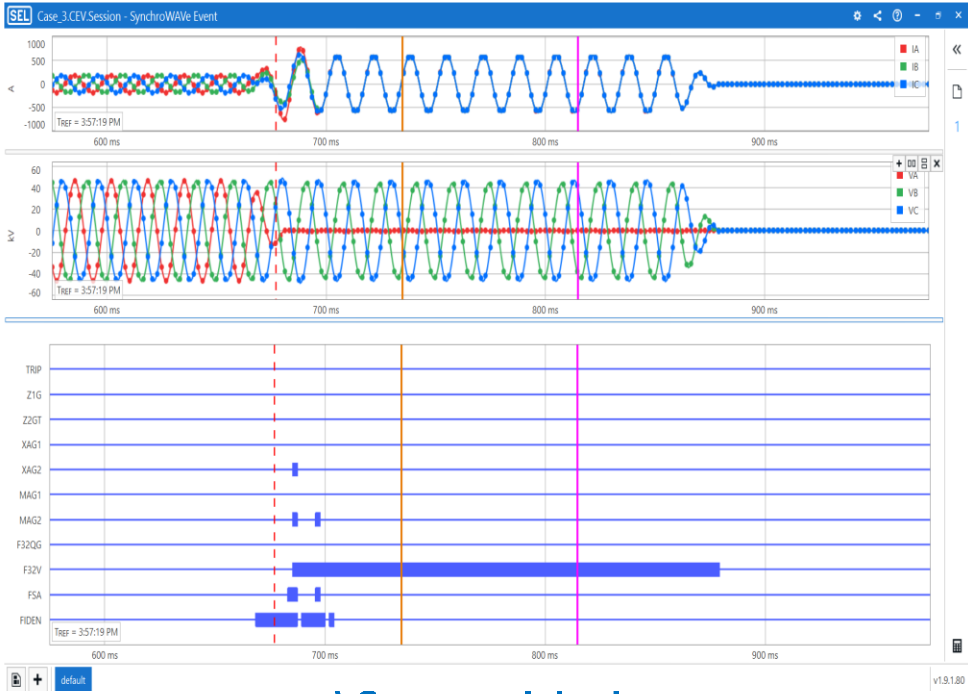


b) MATLAB

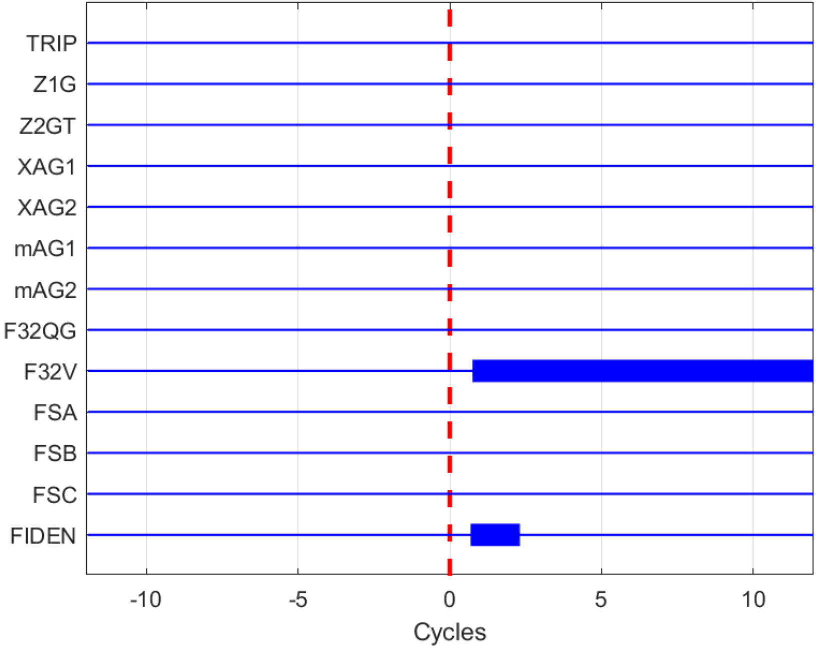
Momentary AG faults – no cessation – successful trip

Momentary Cessation after 1 cycle

- Investigated scenarios for protection elements response



a) Commercial relay



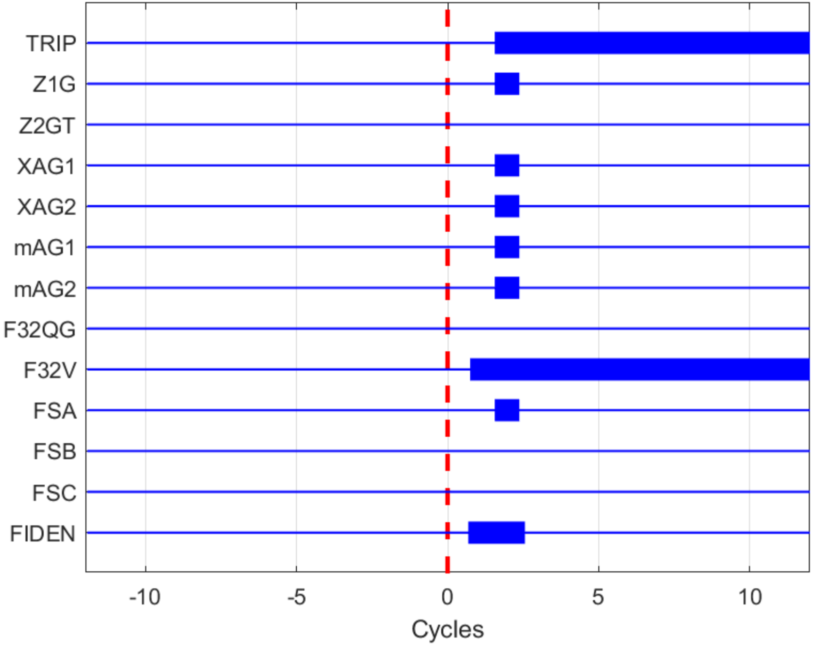
b) Matlab

Momentary cessation for AG faults – 1 cycle – fails to trip

Momentary Cessation – 2 cycles

- Investigated scenarios for protection elements response – no element drop outs– by trip latches

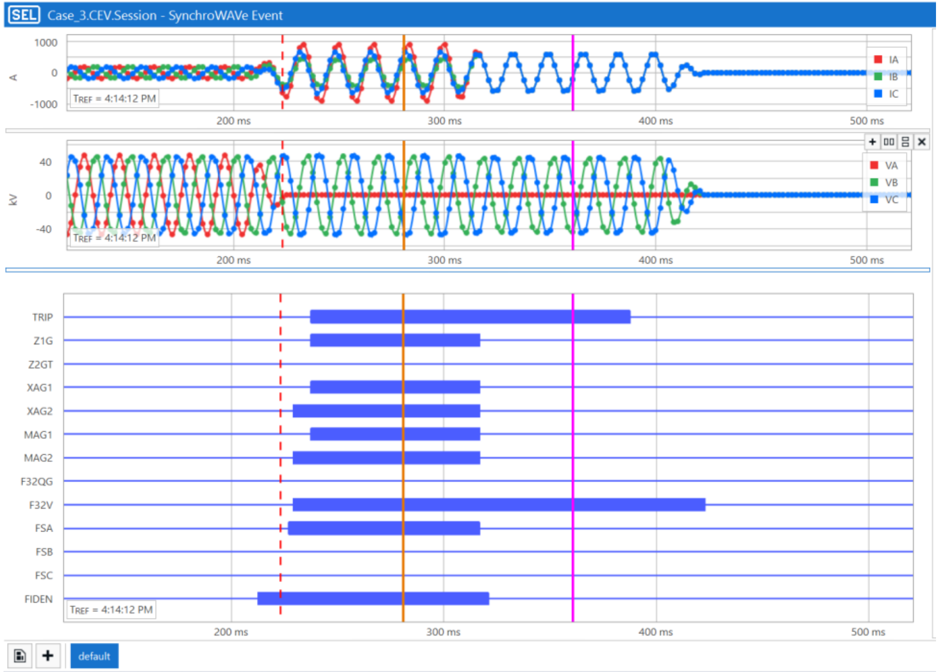
a) Commercial Relay



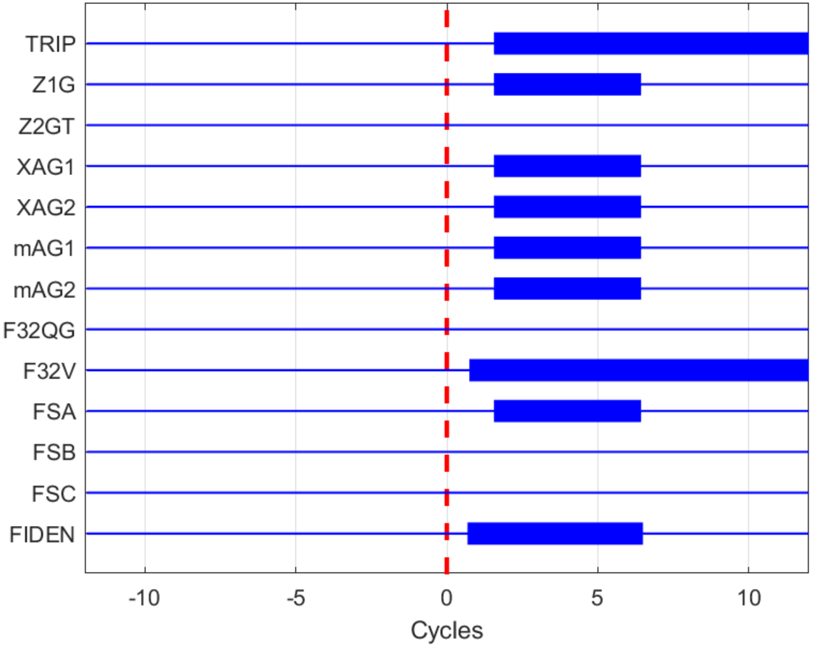
b) Matlab

Momentary cessation for AG faults – 2 cycles – successful trip

Momentary Cessation – 4 cycles



a) Commercial Relay

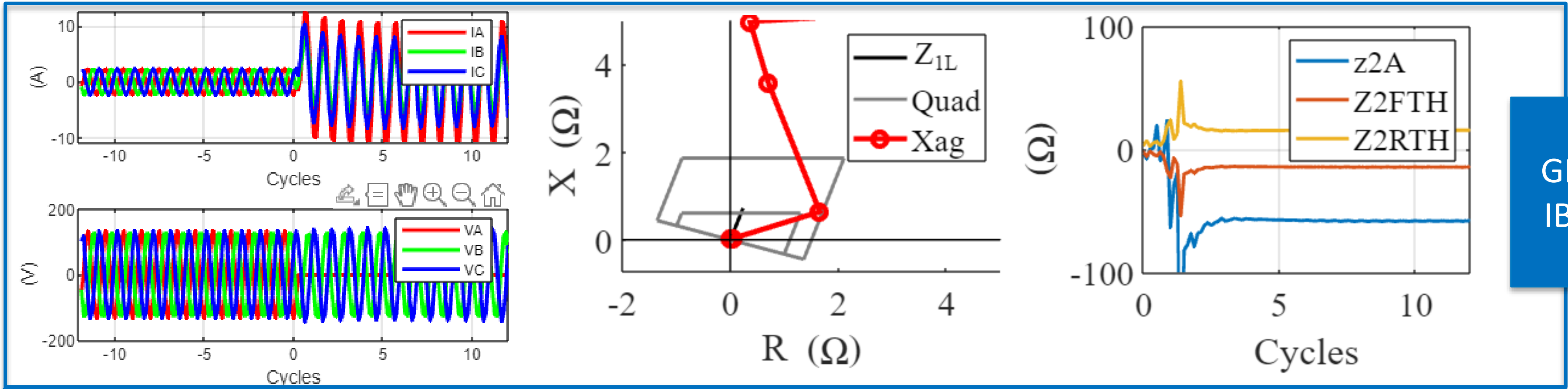


b) Matlab

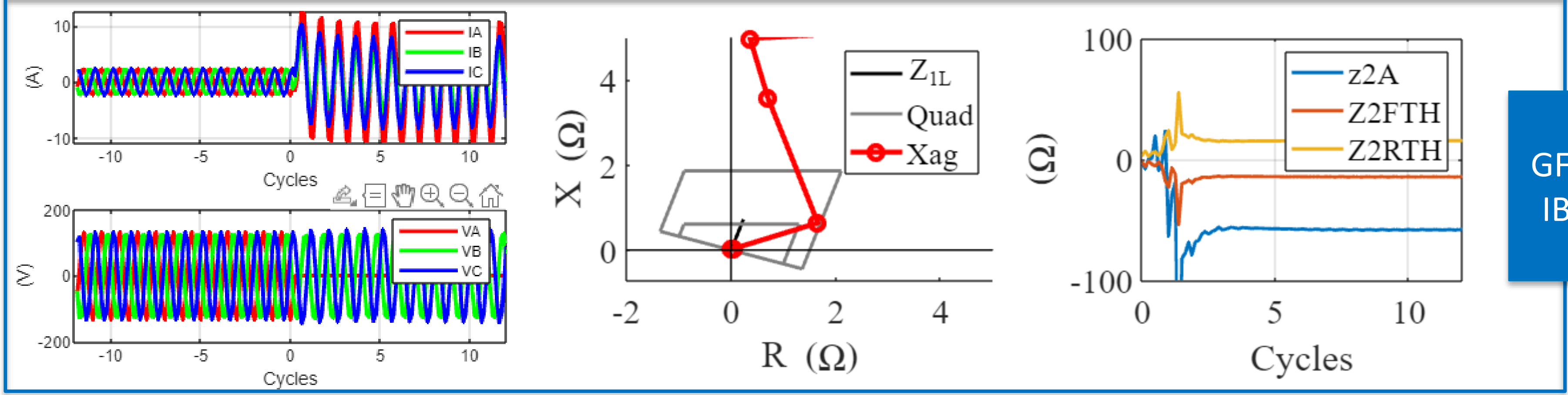
Momentary cessation for AG faults – 4 cycles – successful trip

Recommendation: IBR needs to connect at least 2 cycles to enable relay proper trip for faults with |V| < 10% of nominal

Explore GFM and GFL IBR Fault Responses – AG fault



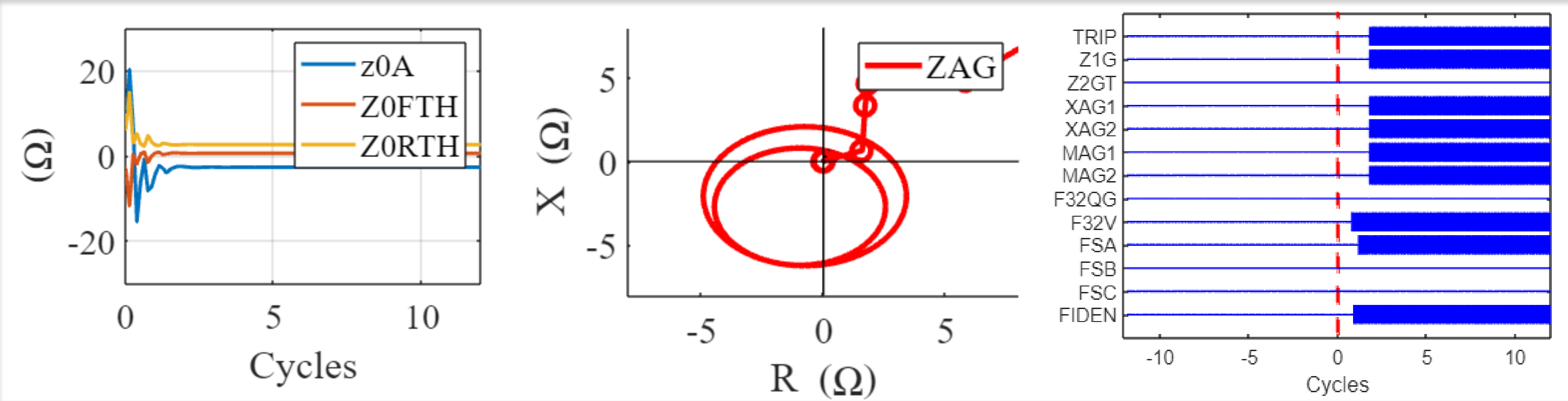
GFL IBR



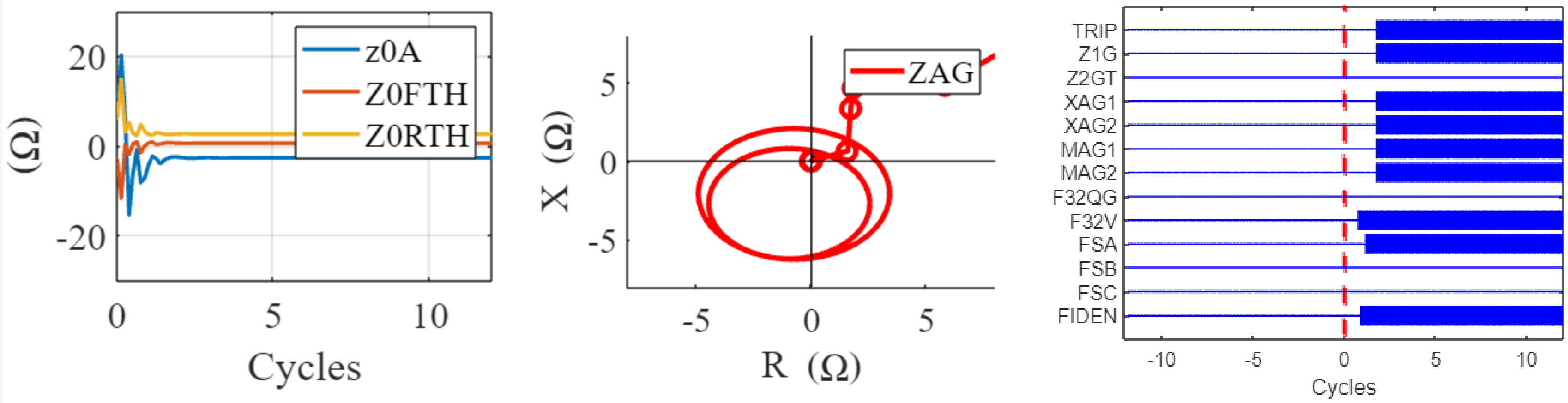
GFM IBR

GFL and GFM IBR are configured with the same DC source, inner control loops (regulated negative sequence current), current limiting and operating points.

Explore GFM and GFL IBR Fault Responses – AG fault

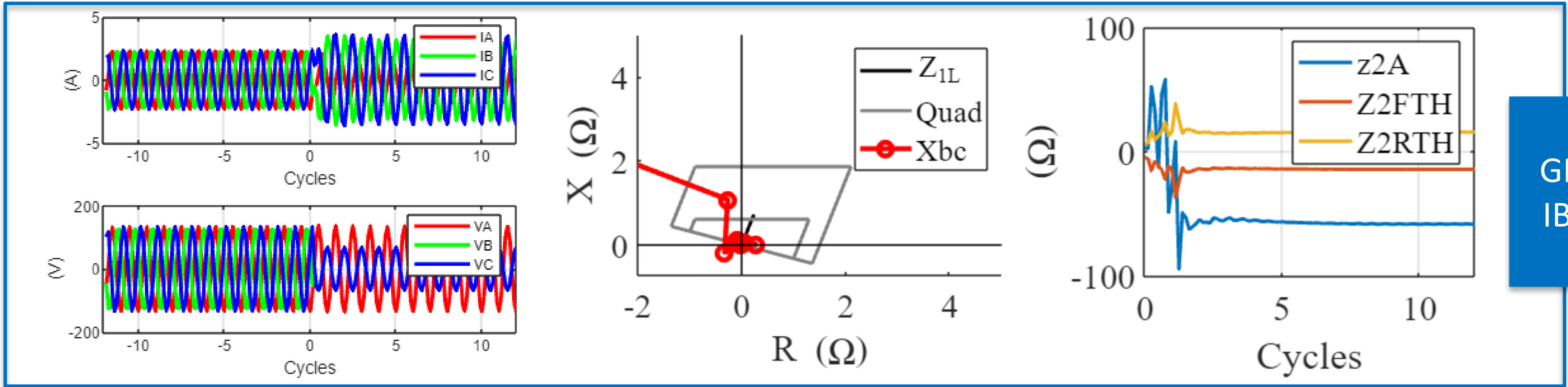


GFL IBR

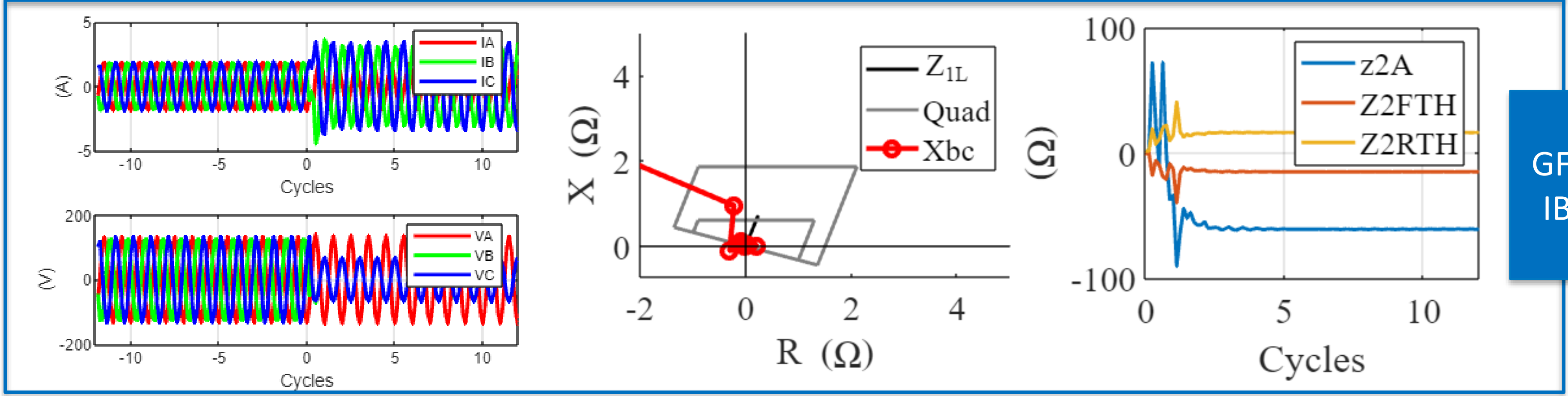


GFM IBR

Explore GFM and GFL IBR Fault Responses – BC Fault

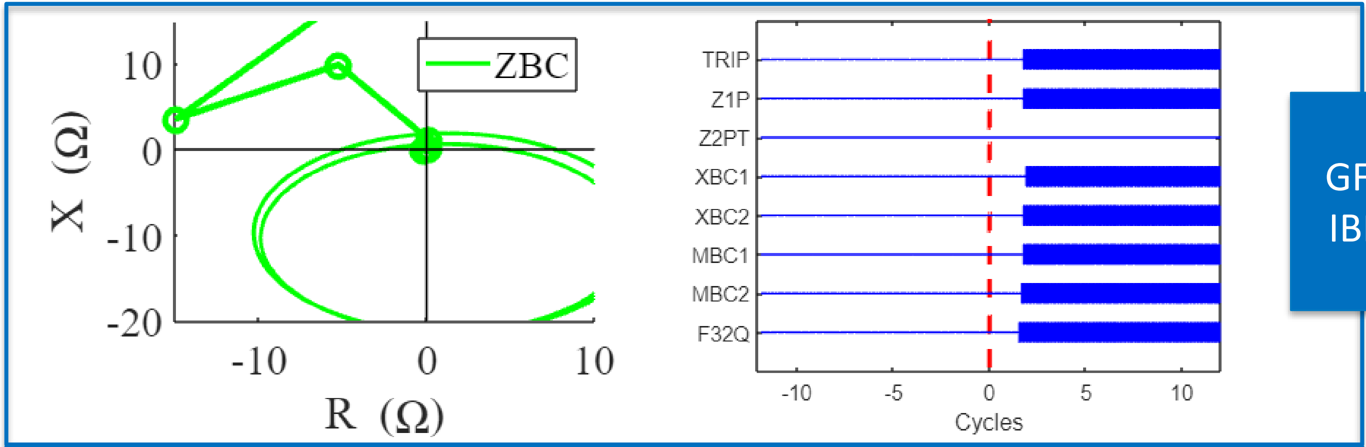


GFL IBR

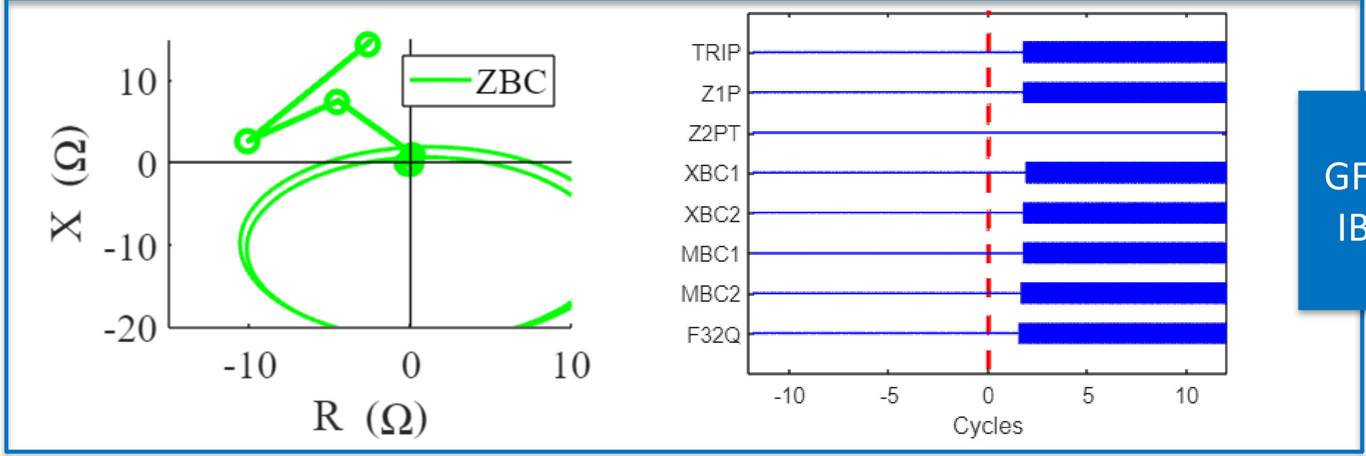


GFM IBR

Explore GFM and GFL IBR Fault Responses – BC Fault

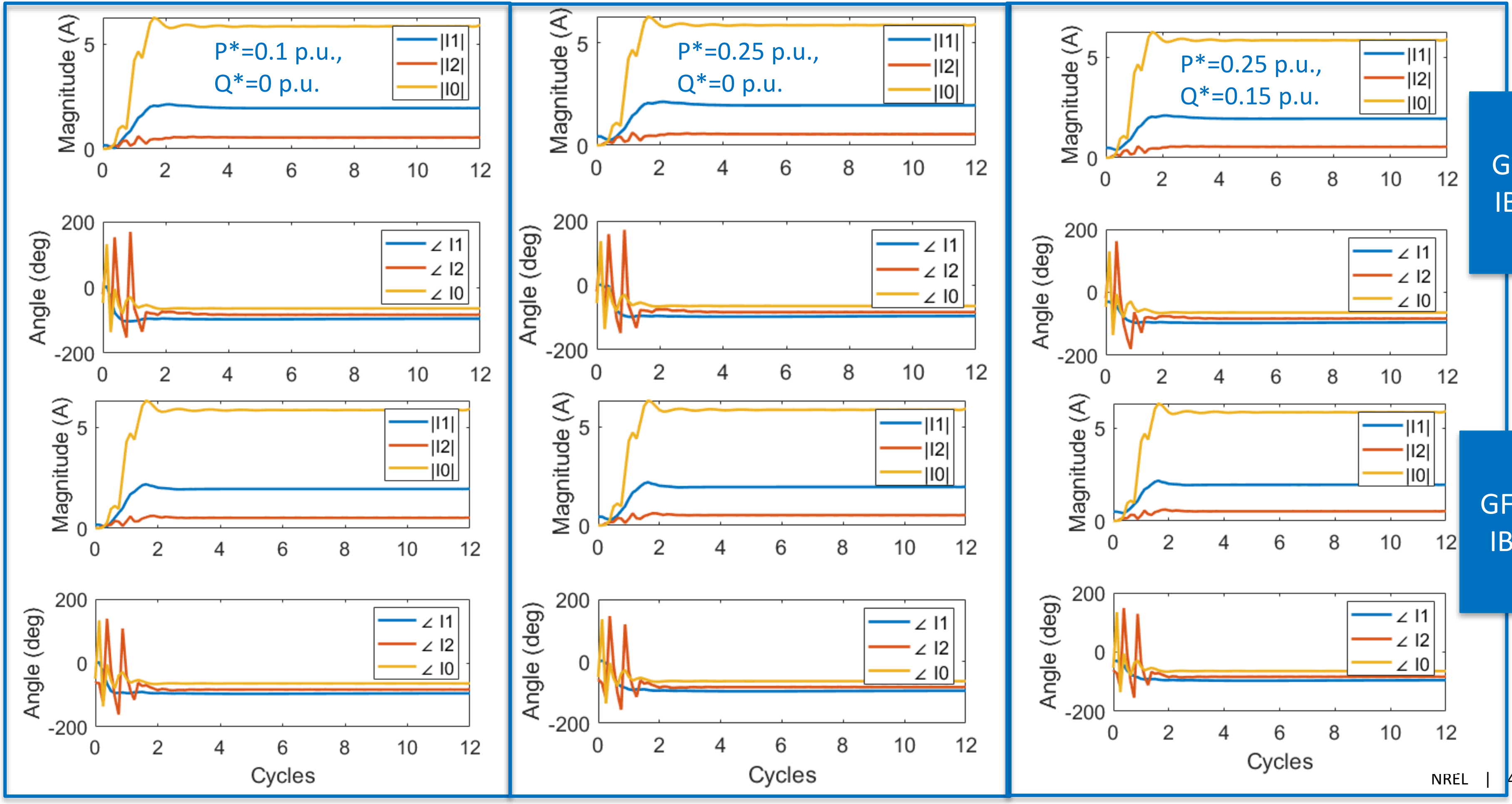


GFL IBR



GFM IBR

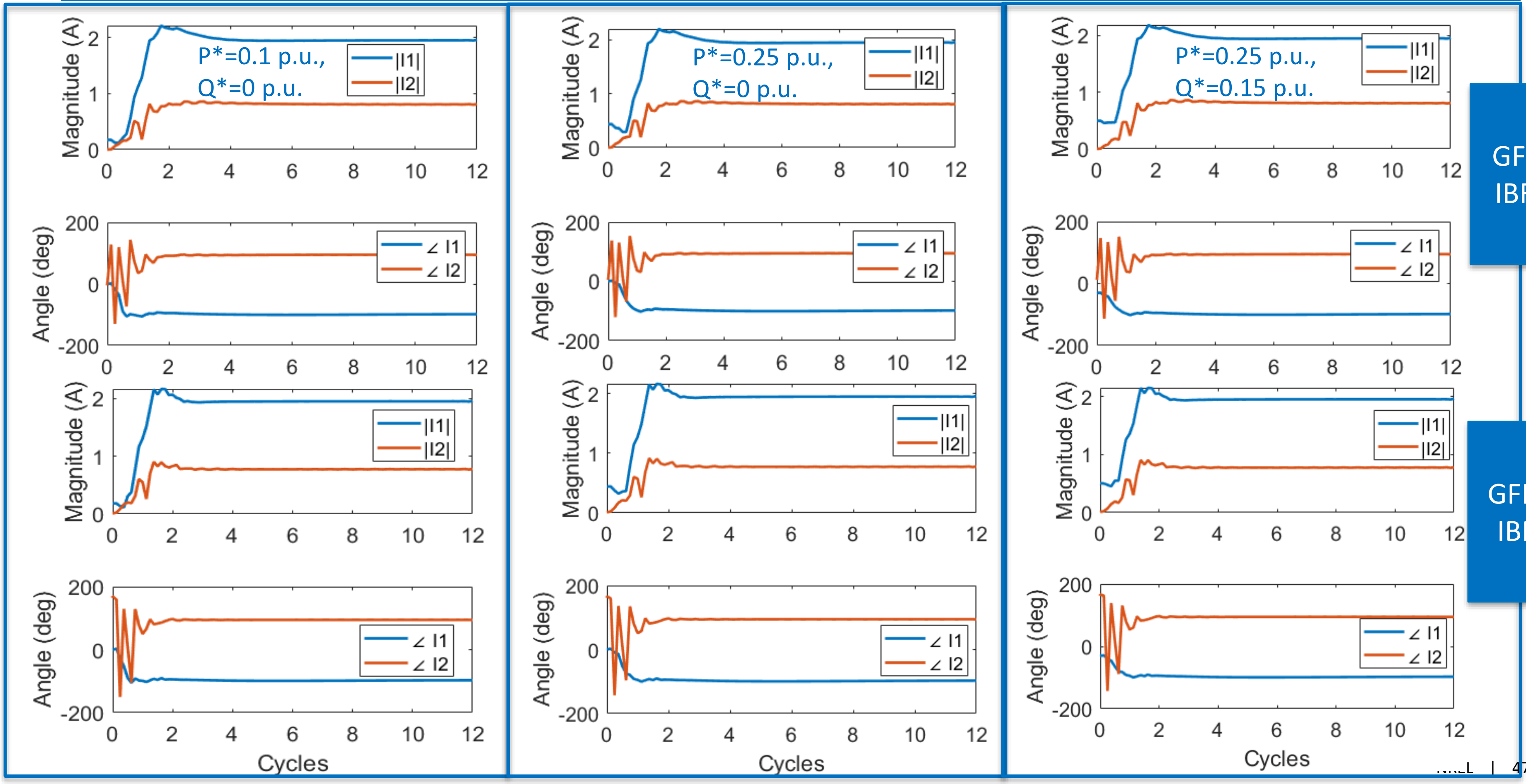
Explore GFM and GFL IBR Fault Responses- AG Fault



GFL IBR

GFM IBR

Explore GFM and GFL IBR Fault Responses – BC Fault



GFL IBR

GFM IBR

Guidance and Suggested Requirements of IBRs Modeling

GFL Modeling and Control Aspects

GFL Modeling aspect	Observation	Recommendation
Average versus switching inverter model	Fault response does not vary with modeling	Using averaged model will reduce simulation time
DC Source: PV, battery and combined PV and battery	Fault response does not vary for cases with batteries charged	Use the simplest model to implement
Power loop control: PQ dispatch versus Vdc-|Vac| control	• Slightly impacted negative sequence current and interconnecting bus voltage behavior • Trip behavior was not impacted	There may be cases where need to consider when modelling IBR. Need to know what control mode is used in the converter and the set points. More study needed.

GFL Modeling and Control Aspects (slide 2)

GFL Modeling aspect	Observation	Recommendation
Current control: • Synchronous reference frame dq control based on phase currents, • Stationary reference frame (αβ) based on phase currents, • Synchronous reference control with separate positive and negative sequence (I1 and I2) control meeting IEEE 2800	• The current control loop affected the IBR negative sequence response. • Relay response with phase current based control significantly different than controlling sequence currents. • Especially αβ control,	Must be considered. • The correct type of current control needs to be provided modeler and represented when building simulation model. • If the sequence control is used, the settings and time constants for the negative sequence current magnitude (|I2|) and angle need to be provided and modeled.

GFM Modeling and Control Aspects

GFM Modeling aspect	Observation	Recommendation
Droop or Virtual Synchronous Machine (VSM)	• The type of voltage control loop type affects the fault current response of the IBR. • But did not impact protection response. • Results did not differ significantly from GFL cases when controls hit limits (1.2 p.u.)	The type of voltage control implemented needs to be provided, and included in the simulation, along with the model parameters and set points.

GFM Modeling and Control Aspects

GFM Modeling aspect	Observation	Recommendation
Current control: • Phase current based synchronous reference frame (dq), • Phase current based stationary reference frame (αβ), • Synchronous reference frame based control of positive and negative sequence currents	• There was a noticeable change in the negative sequence current with the different current control schemes. • Again, little different from GFL with converter hitting limits	• The type of current control in use needs to be provided and represented when building simulation model. • If the sequence control is used, the settings for the negative sequence current magnitude and angle need to be provided and modeled, along with time constants.

Negative Sequence Control

• Modeling and control of IBR aspects	• Observation	• Recommendation
• Negative sequence component current compliance to IEEE 2800 (|I2| and angle I2)	• The GFL and GFM inverter that don't have I2 control will not have appropriate I2 (and resulting V2). This will affect the response of several protective elements. • Ratio of |I2|/I0| may block z2 supervision in Ygrounded transformer cases	• IEEE 2800 compliant I2 current control should be included in the GFL and GFM inverters • Time constants for I2 control should be set smaller than upper 2800 limit • Protection engineers should desensitize negative sequence dependent element if the IBR does not to use support compliant I2 control

Negative sequence control limit time constants

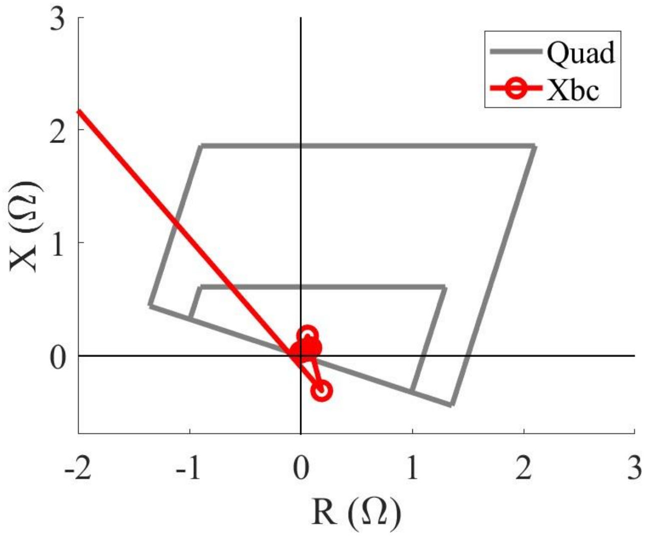
Modeling and control of IBR aspects	Observation	Recommendation
Negative sequence current response time (or time constant of sequence current regulator) for IEEE 2800 compliant IBRs	• IEEE 2800 compliant IBRs (GFL or GFM) from different vendors may have different response times for the sequence current control. • Impacts the transients of the I2 (mag. and angle) fault response of IBR. • In many cases little impact • Can impact relay response, depending on how angle if I2 varies in first 2 cycles.	• IBR model needs to include time constants of current regulator • Transient response of negative sequence current control matters as much as steady-state • Faster negative sequence current response is required for protection so that within few cycles rather than the upper limit of IEEE 2800 range – relays make decision in 1 cycle • The sequence controller and associated feed-forward compensations in the control architecture should be designed such that angle in transient period is consistent with steady-state.

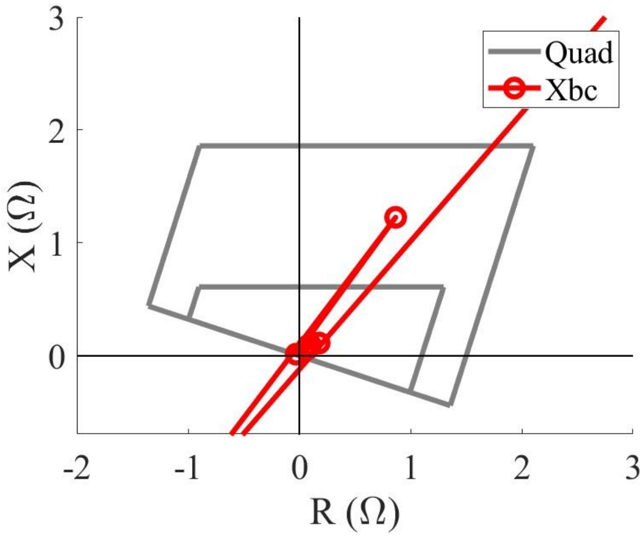
Current Limiting Priority Impact

GFL Modeling aspect	Observation	Recommendation
• Current limiter: saturation/latching with emphasis on d or q axis (or α-β) • Same behavior with GFL and GFM since GFM his limits	• With the updated current limiting strategy model, we didn't see any impact on protect response • There may be resistive fault cases where it makes a difference in memory or cross-polarized mho elements • Industry advisors mentioned wider variation in responses than we have seen	• Preliminary recommendation is that the current limiting doesn't impact protection response. • More study needed for cases with fault resistance and mho distance elements

Magnitude-based Limiting Q versus D for LL faults: Quad

- Impedance trajectory changes



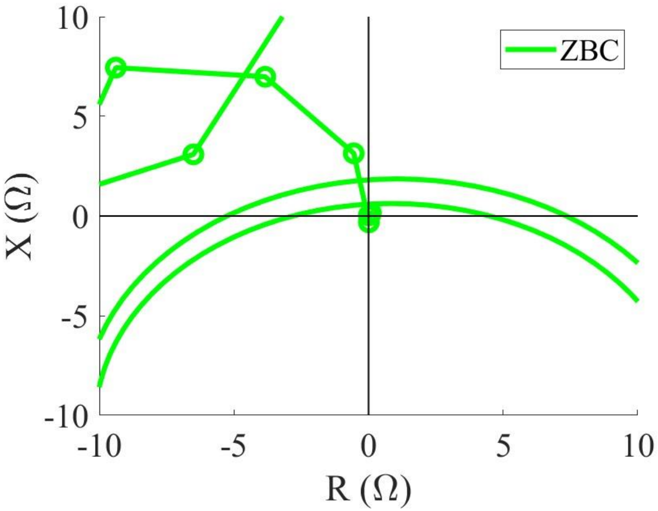


Mho expansion/trajectory – saturation Q

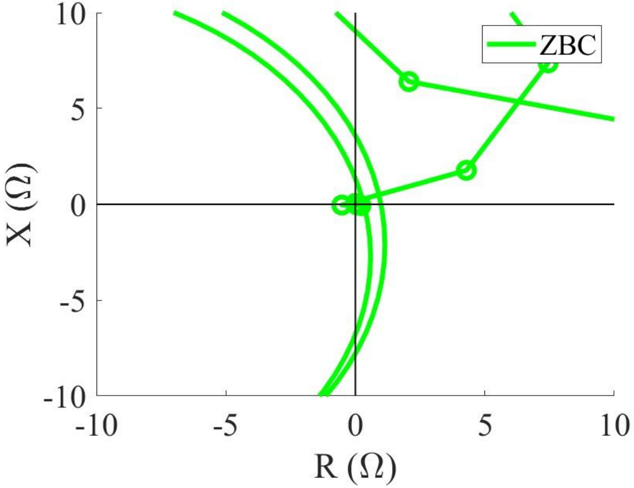
Mho expansion/trajectory – saturation D

Magnitude-based Limiting Q versus D for LL faults: Mho

- Impedance trajectory changes
- Angle of effective source impedance changes with Saturation D or Saturation Q
  - Very large expansion (small current). Lose some fault resistance coverage
  - Directional supervision more important



Mho expansion/trajectory – saturation Q



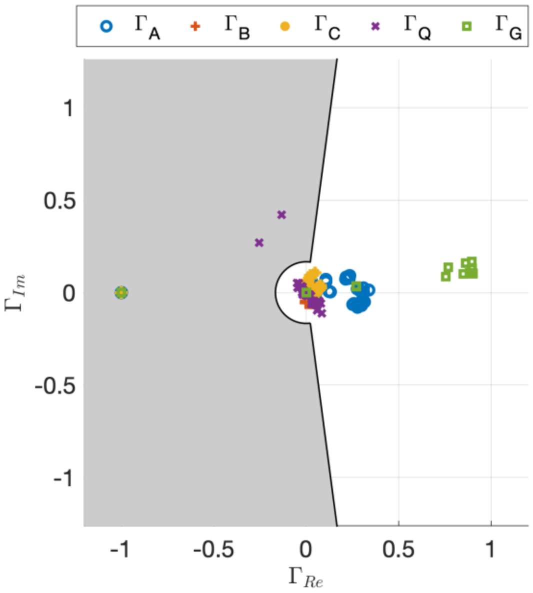
Mho expansion/trajectory – saturation D

Guidance and Suggested Requirements

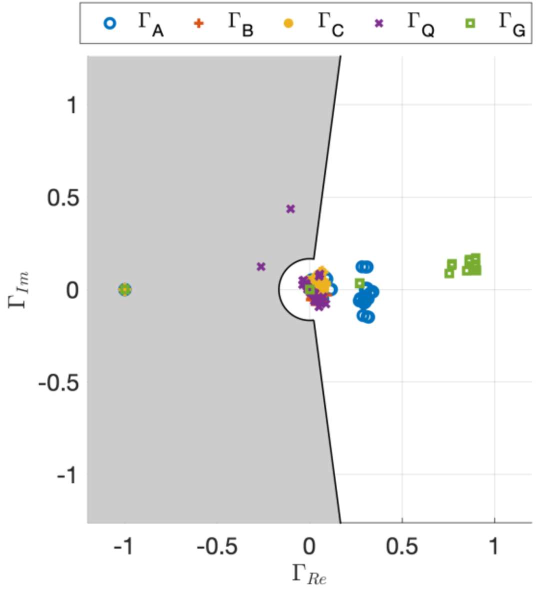
Modeling and control of IBR aspects	Observation	Recommendation
Momentary cessation with different time delays	• Duration of minimum fault-ride-through (FRT) time prior to cessation the IBR impacts the correct operation of the relay. • For cases with correct operation • If the IBR goes into momentary cessation quickly (less than 2 cycles), the protection will not have sufficient time to pick up. • A slower response allowed the protection to respond if other criteria were met.	• Need to know FRT settings and timing and incorporate in model • Criteria that will cause the IBR to go into momentary cessation need to be modeled.

Phase differential element responses

- Summary for all scenarios – restraining (blocking) cases are high resistance fault cases



a) GFL



b) GFM

87L elements using all five Alpha Plane elements—all fault cases

Protection Setting Guidance (more later in the project)

Recommendation

• Protection engineers should desensitize negative sequence dependent elements if the IBR does not to use support compliant I2 control
  • Negative sequence directional elements require min. |I2|
  • Correct angle of I2 from IBR with respect to the negative sequence voltage at the terminal is crucial
  • Negative sequence polarized quad elements can have erratic response (use I0)
• Only use negative sequence polarized current for quad elements if IBR has sequence current controllers
• For quad ground elements |I2|/|I0| could block negative sequence element
• Difficult negative sequence source impedance for negative sequence tilt angle
• Rapid IBR momentary cessation can block distance elements & directional elements
• Line current differential elements not impacted if one end can supply sufficient fault current

Summary & Future Work

- Evaluating impacts of different modeling and control aspects of GFM and GFL IBRs have on commonly applied protective relay elements
  - IBR model, DC source, and power loop doesn’t matter much
  - Current limiter and current controller matters
  - Other aspects also matter: momentary cessation, fast/slow response of IBR, …
- GFM and GFL IBR both are limited by their current limiters and there are no distinct differences of their fault behavior with the same settings and configurations. And there are no cases showing GFM has better fault response. If GFL also produces 2800 compliant negative-sequence current, the relay will make the correct decision.
- IEEE 2800-2022 may loosen the settling time requirement for GFM IBRs
- Developed Recommendations for both IBR and protection engineers
  - IBR and protection engineers need to communicate and coordinate for proper protection function
- Future work will focus on protection studies of two utility systems plus new protection approaches
  - One compatible with existing relays

Publications

1. J. Gui, H. Lei, R. G. Bainy, and B. K. Johnson, "Influence of adjacent systems on inverter-based resource-penetrated power system protection," 2024 IEEE Power & Energy Society General Meeting (PESGM).
2. S. Chakraborty, J. Wang, R. Mahmud, A. Hoke, B. Johnson, R. G. Bainy, and H. Lei, "A Generic and Multi-Functional Electromagnetic Transient Model for Grid-Following Inverter," 2024 IEEE 50th Photovoltaic Specialists Conference (PVSC) .
3. S. Chakraborty, Y. Chen, A. Zamzam, and J. Wang, "A SVM-based Synchronized Fault Detection Method for 100% Renewable Microgrids," 2024 IEEE IECON.
4. S. Chakraborty, et al., "A Generic and Multi-functional Electromagnetic Transient Model for Grid-Forming Inverter," 2024 IEEE IECON.
5. S. Chakraborty, et al., "Study the Impact of IBR Modeling of the Commonly Applied Transmission Line Protective Elements," IEEE ECCE.
6. P.H. Pinheiro, et al., "Benefits and Recommendations for Using Classic Protection Functions in Transmission Lines Interfacing IBRs Compliant to IEEE 2800," 2024 CIGRE USNC Grid of the Future Symposium.
7. Jing Wang and Brian Johnson, UNIFI 2024 Fall Semester Talk.
8. Brian Johnson, et al., "Teaching Protection of IBRs in engineering courses and labs," IEEE PESGM 2025 (Accepted).
9. Soham Chakraborty, et al., "Study Impact of Momentary Cessation of IBRs on Power System Protection Relay Elements," IEEE PESGM 2025.
10. Brian Johnson, et al., "Developing Hands-On Exercises for Teaching Transmission Protection for Systems with Inverter Based Generation," American Society for Engineering Education Annual meeting, 2025.
11. Brian Johnson, et al., "Protecting IBR-Penetrated Systems: Settings Recommendations and Control Requirements," Journal of Electric Power Systems Research (Under review).
12. Soham Chakraborty, et al., "A Comprehensive Study of Impact of Different Current Limiter Strategies Impact on Protection Relay elements," IEEE ECCE 2025 (submitted).
13. Soham Chakraborty, et al., "Tuning of A Generic IBR Model Matching with An OEM Model Using Transmission Line Protection Elements," IEEE ECCE 2025 (Submitted).
14. Rasel Mahmud, et al., "Modeling, Analysis, and Experimental Validation of Inverter Fault Response under Grid Disturbances", IEEE ECCE (Submitted).
15. Soham Chakraborty, et al., "A Comprehensive Study of Impact of Negative Sequence Current Control on Protection Relay Elements," IEEE Tran. Power Delivery (under preparation).
16. **J. Wang, et al., "A Comprehensive Study of Impact of Inverter-based Resources (IBRs) Modeling and Control on Protection Relay Elements", NREL Technical Report (to be published in May)**

Thank you

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Questions?

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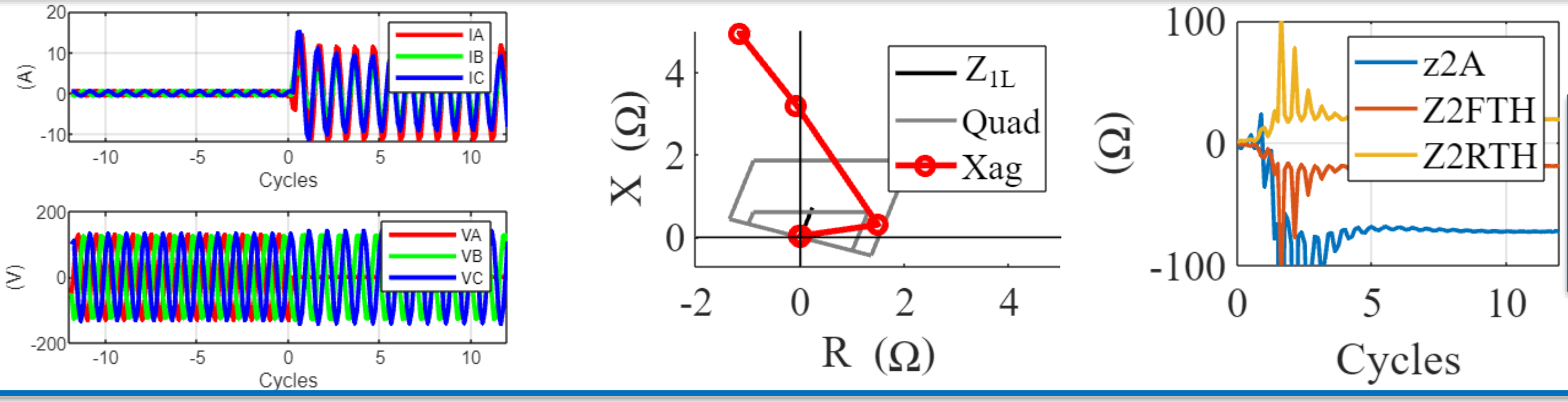
GFM IBR Discharging and Charging – AG Fault



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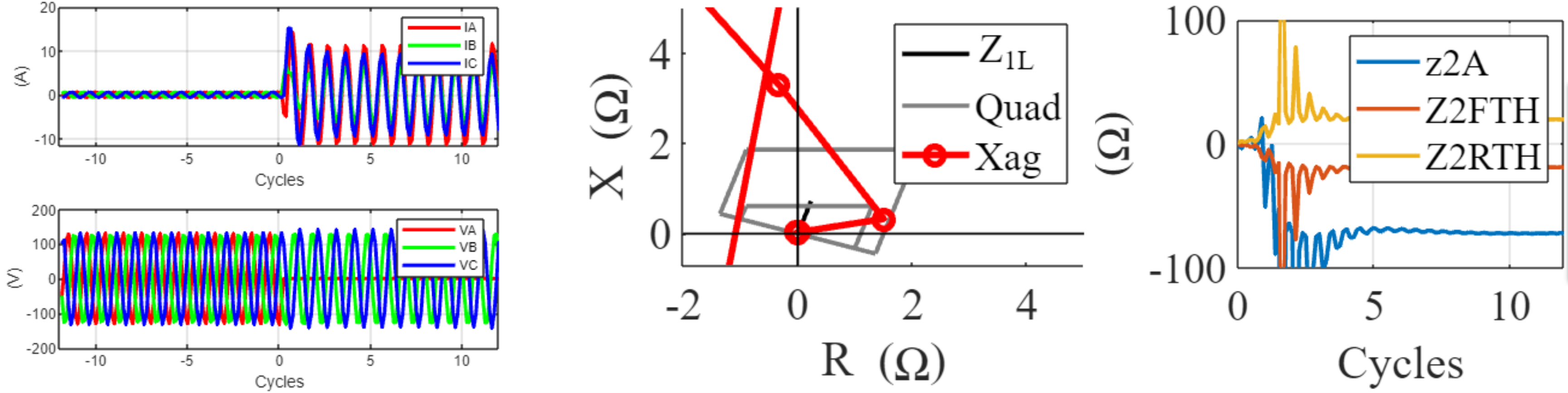

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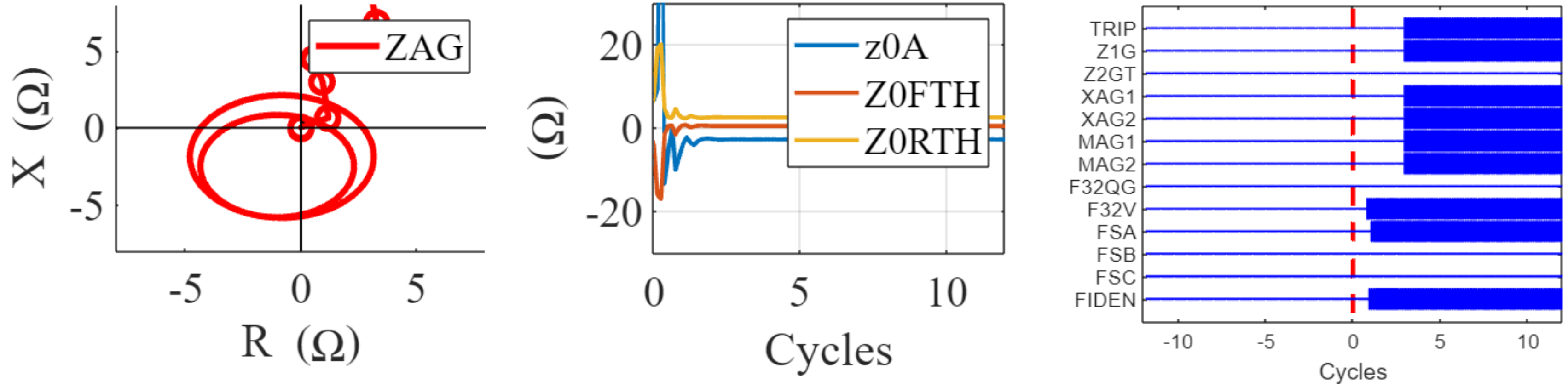
GFM IBR Discharging and Charging – AG Fault



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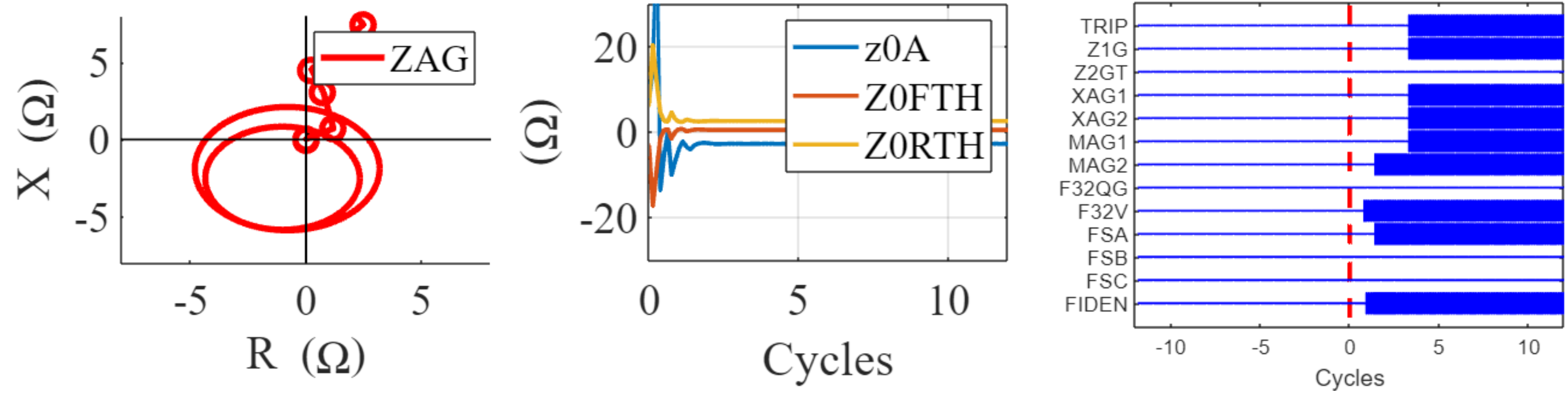

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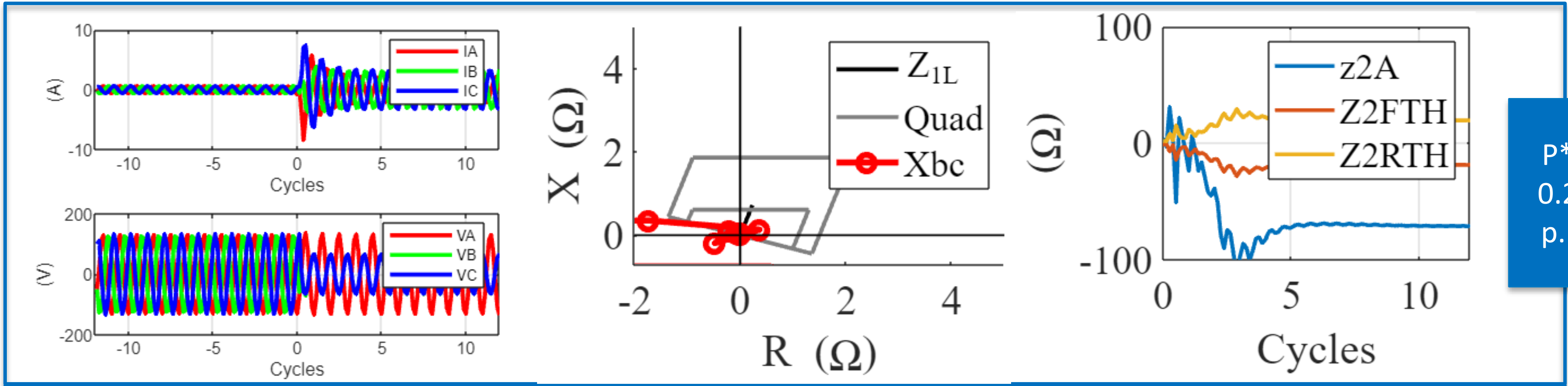
GFM IBR Discharging and Charging – BC Fault



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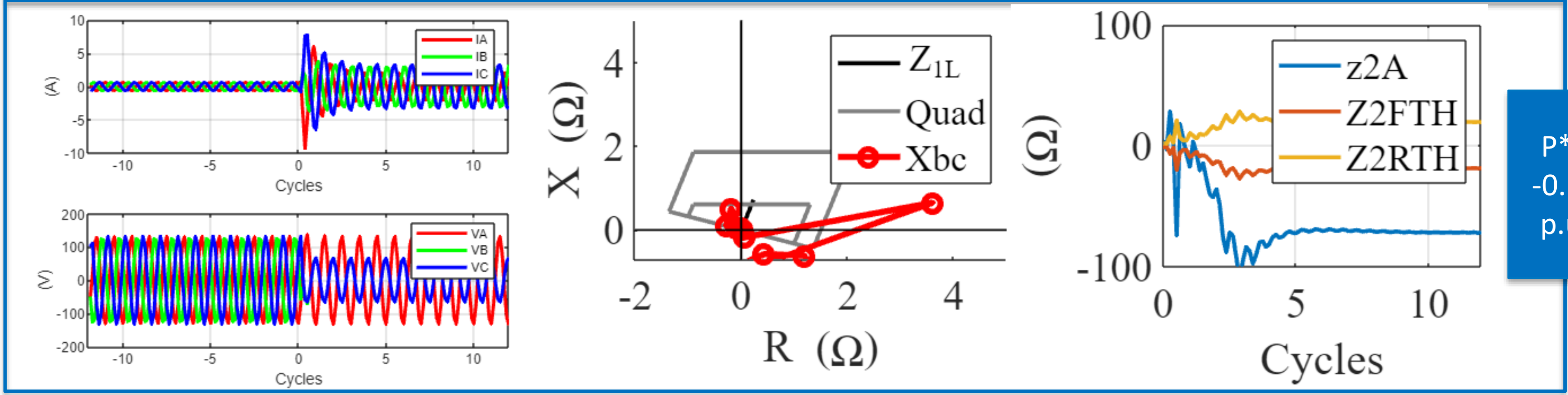

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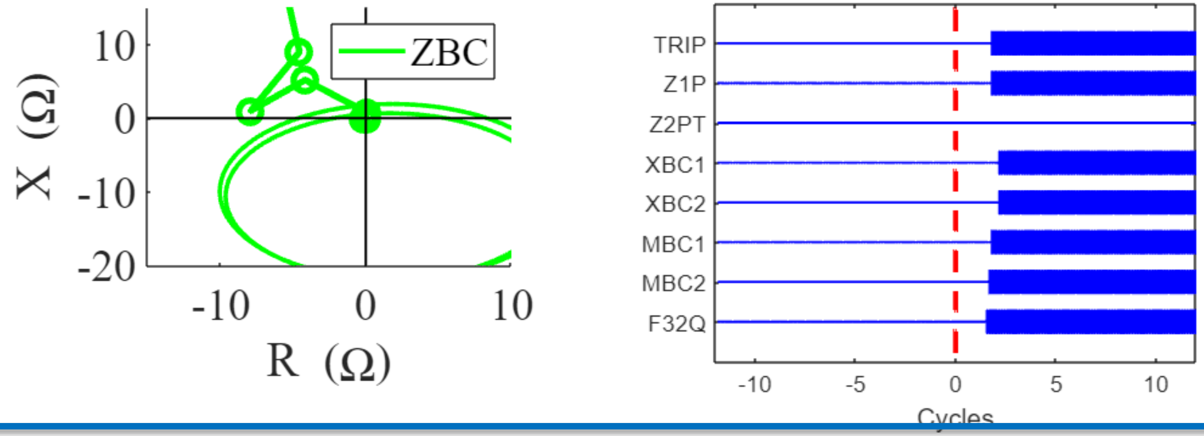

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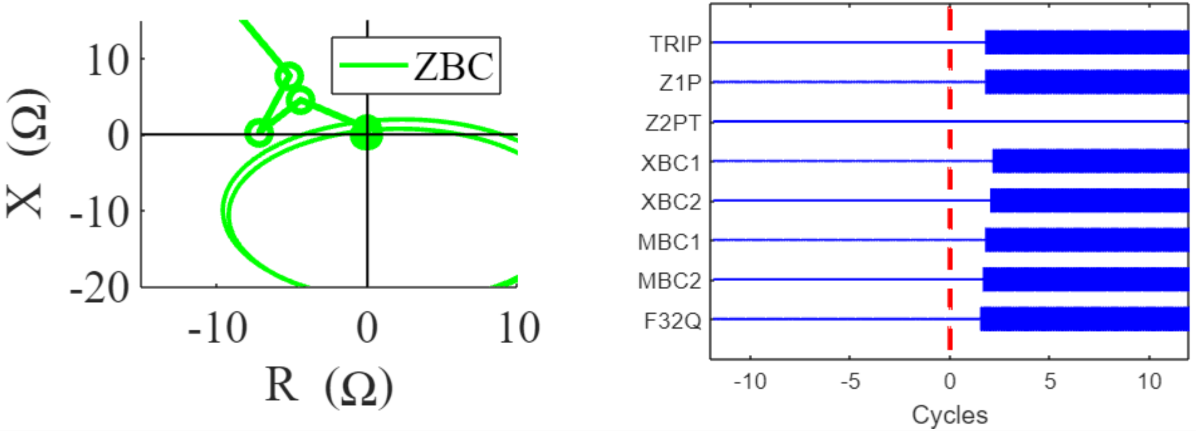

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