

# Inverter-Based Resource Negative Sequence Current Injection

ERCOT IBRWG Meeting



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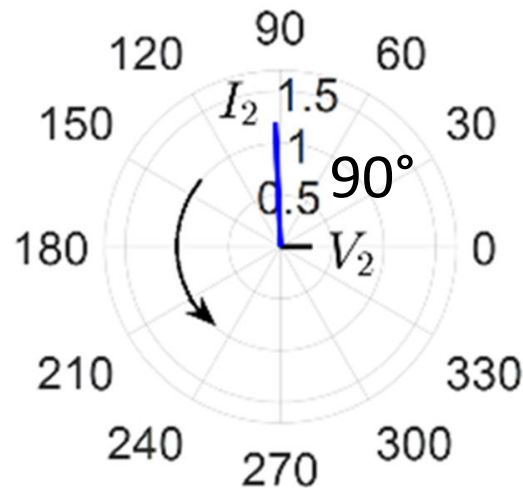
# Highlight & Key Questions

- Objectives:
  - Discussion on aligning transmission protection needs with achievable IBR capabilities and limitations.
  - Understand what IBRs can and cannot provide for negative sequence current injection while continuing to provide positive sequence current support for ride-through during unbalanced faults, considering IBR control capability, converter current limits, and current-priority logic.
- Key questions:
  - How NSCI is implemented in IBR controls
  - How positive sequence and negative sequence current priorities are managed during unbalanced faults
  - What converter current limit constraints or control limitations exist, compared to the conventional generators regarding fault contributions which may impact the system protection coordination
  - What models and control representations are needed for protection and short circuit studies
  - What practical challenges or field experience OEMs have observed with NSCI implementation

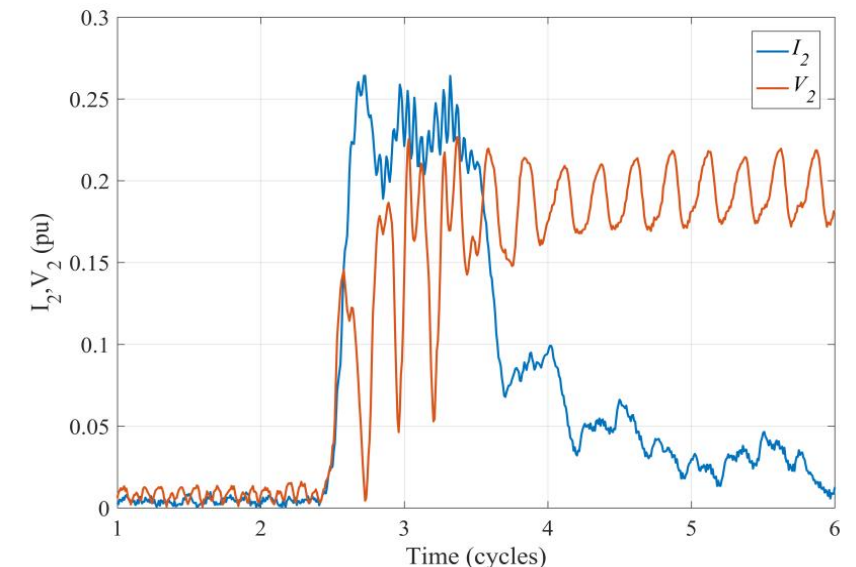
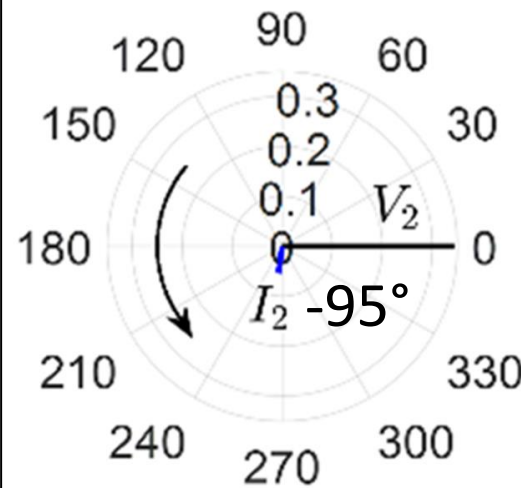
# Fault Current Power Factor/Phase Angle

- In the absence of clear requirement for NSCI, IBR OEMs traditionally suppressed negative-sequence current, which led to unpredictable NSCI.
- The unpredictable NSCI leads to protection misoperation and overvoltage issues.
- Recent grid codes and interconnection standards require NSCI, e.g., German VDE code, IEEE Std 2800-2022, etc.

Negative sequence current injection (NSCI) by a SG under an unbalanced fault



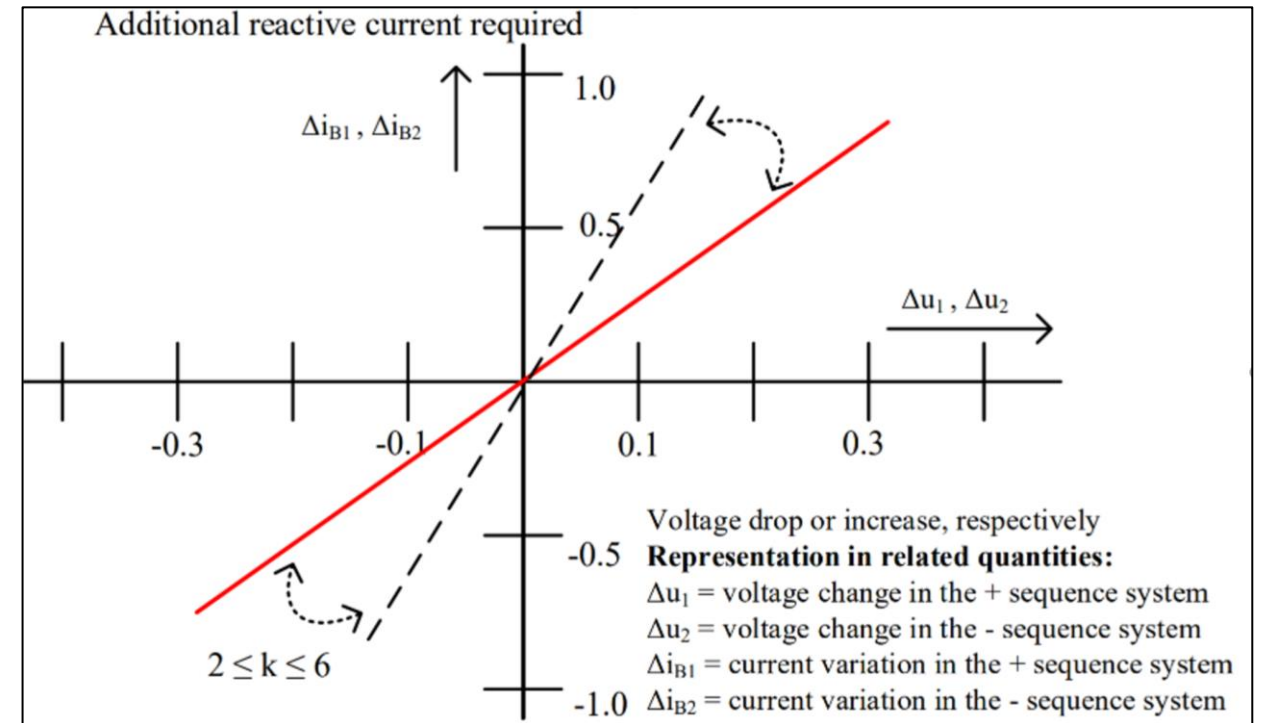
NSCI by a solar PV inverter with no negative sequence current control under an unbalanced fault



# German Grid Code (VDE Series)

- One of the first grid codes which required NSCI was the German grid code, eg Technical Connection Rules for High-Voltage (VDE-AR-N 4120-2018).
- Reactive negative-sequence current must be injected proportional to the negative-sequence voltage
- Gain/Slope:  $2 < k < 6$
- Appears similar to a synchronous generator with an effective negative-sequence reactance of  $1/k$  pu

VDE-AR-N 4120-2018

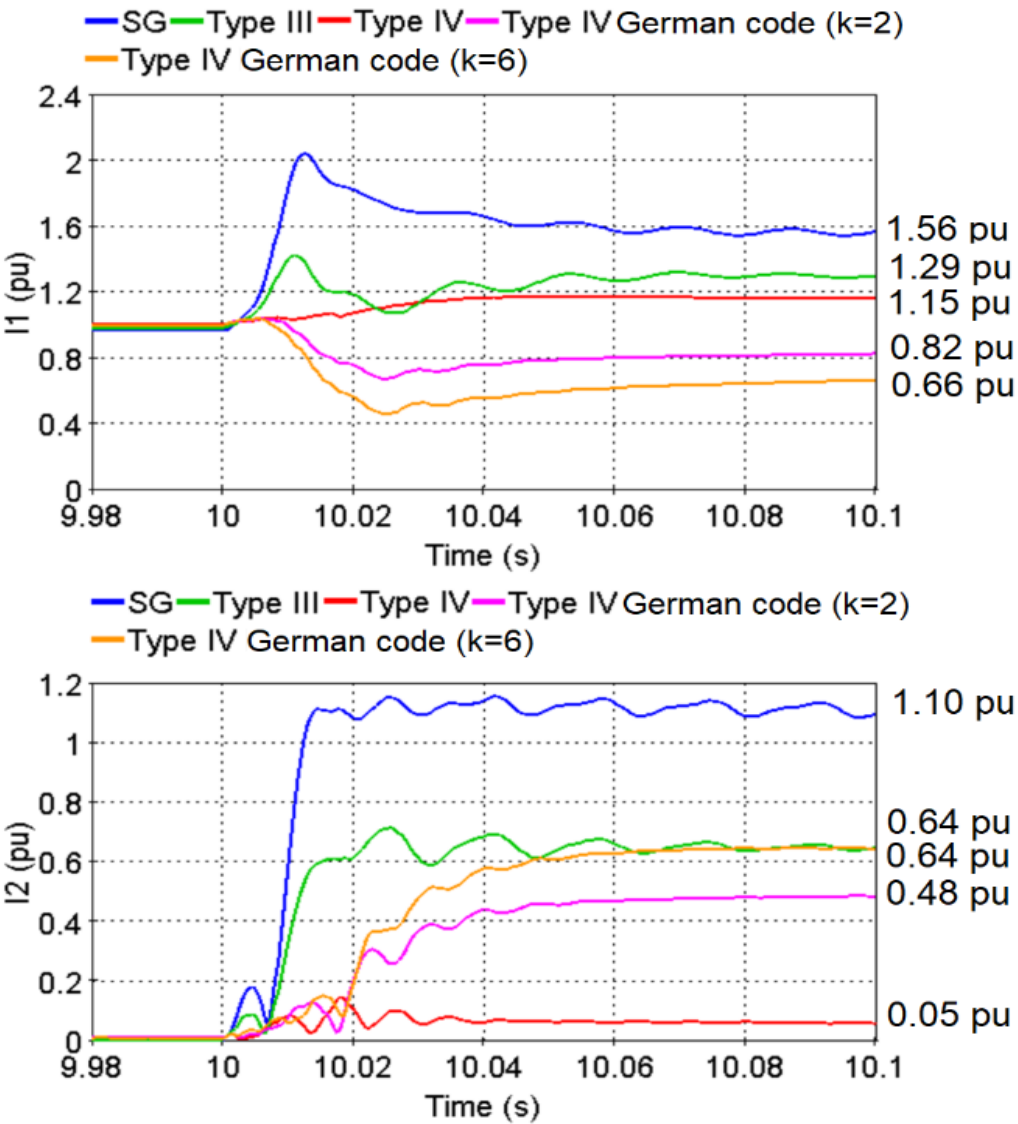


$$I_{neg} = k * (V_{neg})$$

Example: For  $V_{neg} = 0.25$  p.u and  $k = 2$

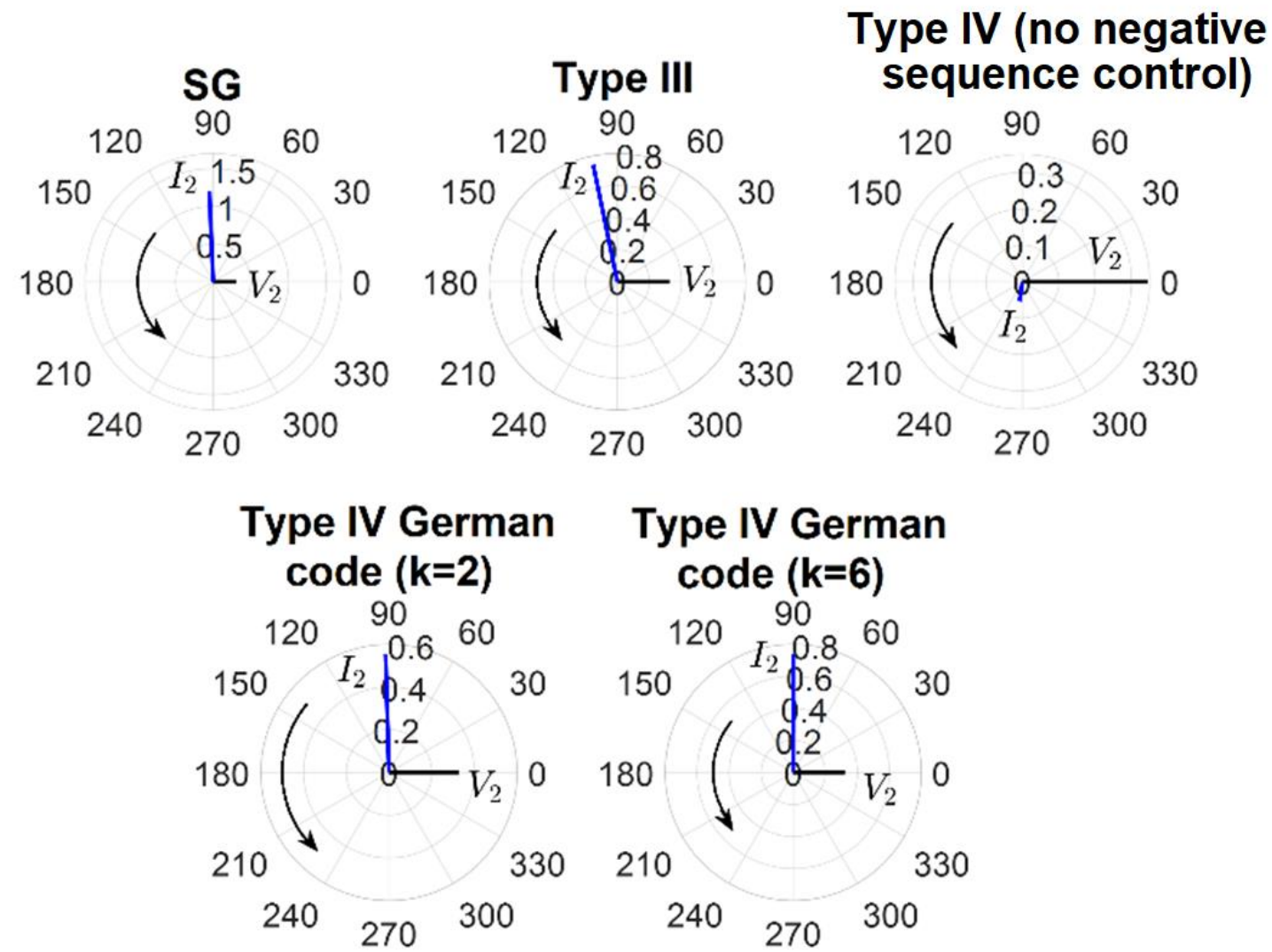
$$I_{neg} = 2 * 0.25 = 0.5 \text{ p.u}$$

# German Grid Code:



| Generator type                          | + seq current I1 (pu) | - seq current I2 (pu) |
|-----------------------------------------|-----------------------|-----------------------|
| Synchronous generator                   | 1.56                  | 1.10                  |
| Type III WTG                            | 1.29                  | 0.64                  |
| Type IV WTG (No - seq control)          | 1.15                  | 0.05                  |
| Type IV WTG (k-factor control with k=2) | 0.82                  | 0.48                  |
| Type IV WTG (k-factor control with k=6) | 0.66                  | 0.64                  |

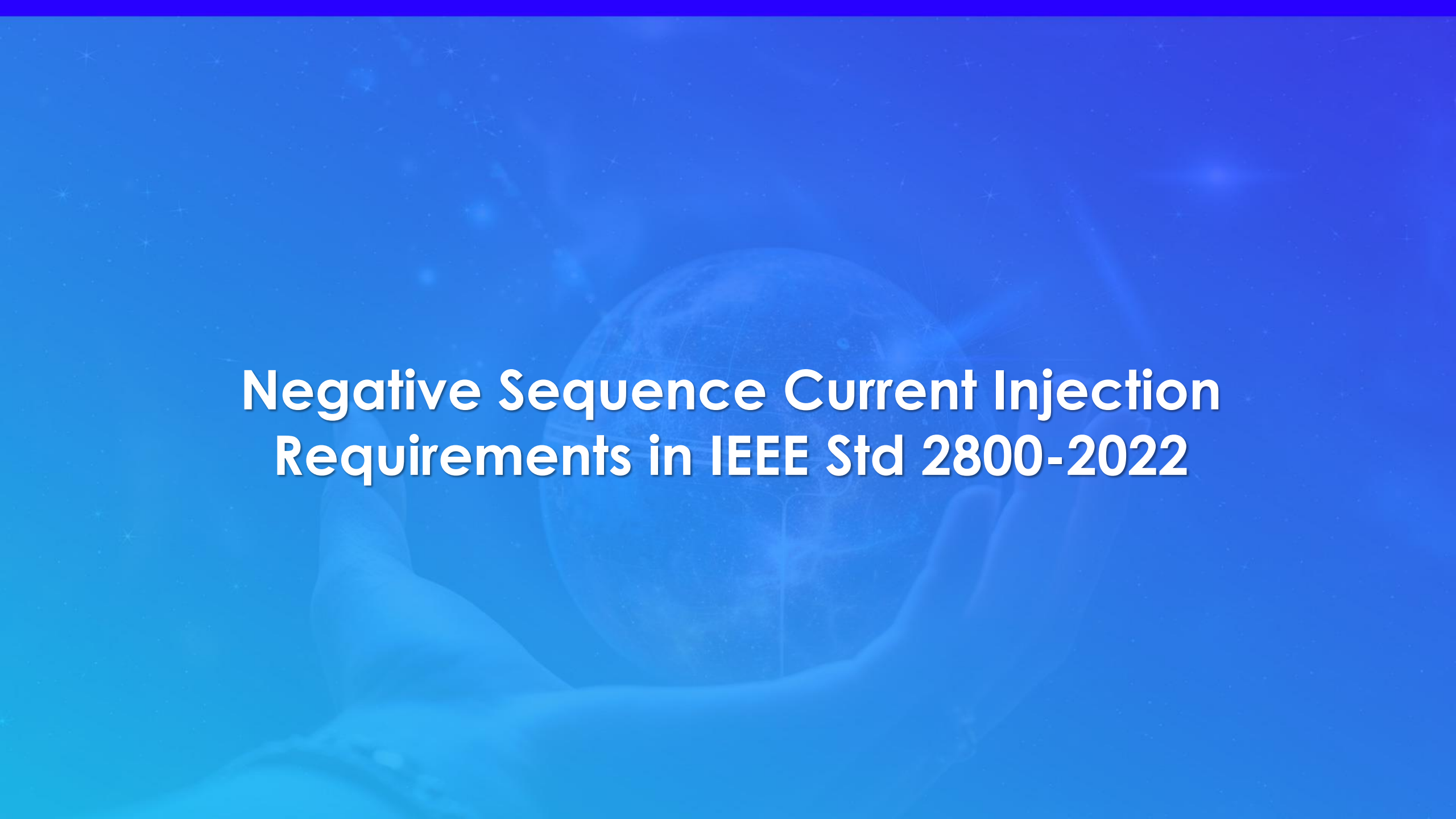
# German Grid Code: Demonstrating Results



| Generator type                          | Angle(I2)<br>(degrees) |
|-----------------------------------------|------------------------|
| Synchronous Generator                   | 90 (leading)           |
| Type III WTG                            | 100 (leading)          |
| Type IV WTG (no -seq control)           | -95 (lagging)          |
| Type IV WTG (k-factor with control k=2) | 90 (leading)           |
| Type IV WTG (k-factor control with k=6) | 90 (leading)           |

# Summary & Conclusions

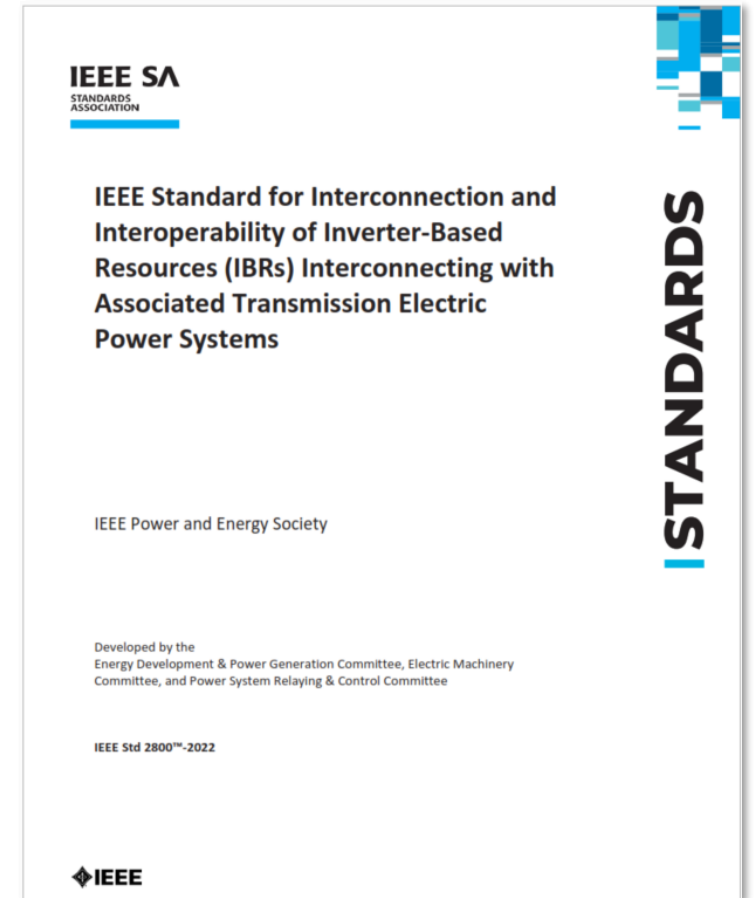
- IBR fault current response differs fundamentally from that of synchronous generators:
  - Lower current amplitude
  - Smaller negative-sequence contribution
  - Continuously varying power factor angle
- High IBR penetration alters overall short-circuit behavior and fault characteristics of the power system

The background of the slide features a pair of hands cupping a glowing globe, set against a deep blue space background filled with stars and nebulae. The entire image has a blue color overlay.

# **Negative Sequence Current Injection Requirements in IEEE Std 2800-2022**

# IEEE Std 2800™-2022

- ❑ Establishes harmonized **technical minimum** interconnection and **capability** and performance requirements for **large solar, wind** and **storage plants**, and **any IBR connected via VSC-HVDC** like offshore wind
- ❑ A **consensus-based** standard developed by over ~175 Working Group participants from utilities, system operators, transmission planners, & OEMs over 2 years
- ❑ Includes both normal and abnormal conditions.
  - ❑ A specified abnormal condition is LVRT: Clause 7.2.2 Voltage disturbance ride-through requirements

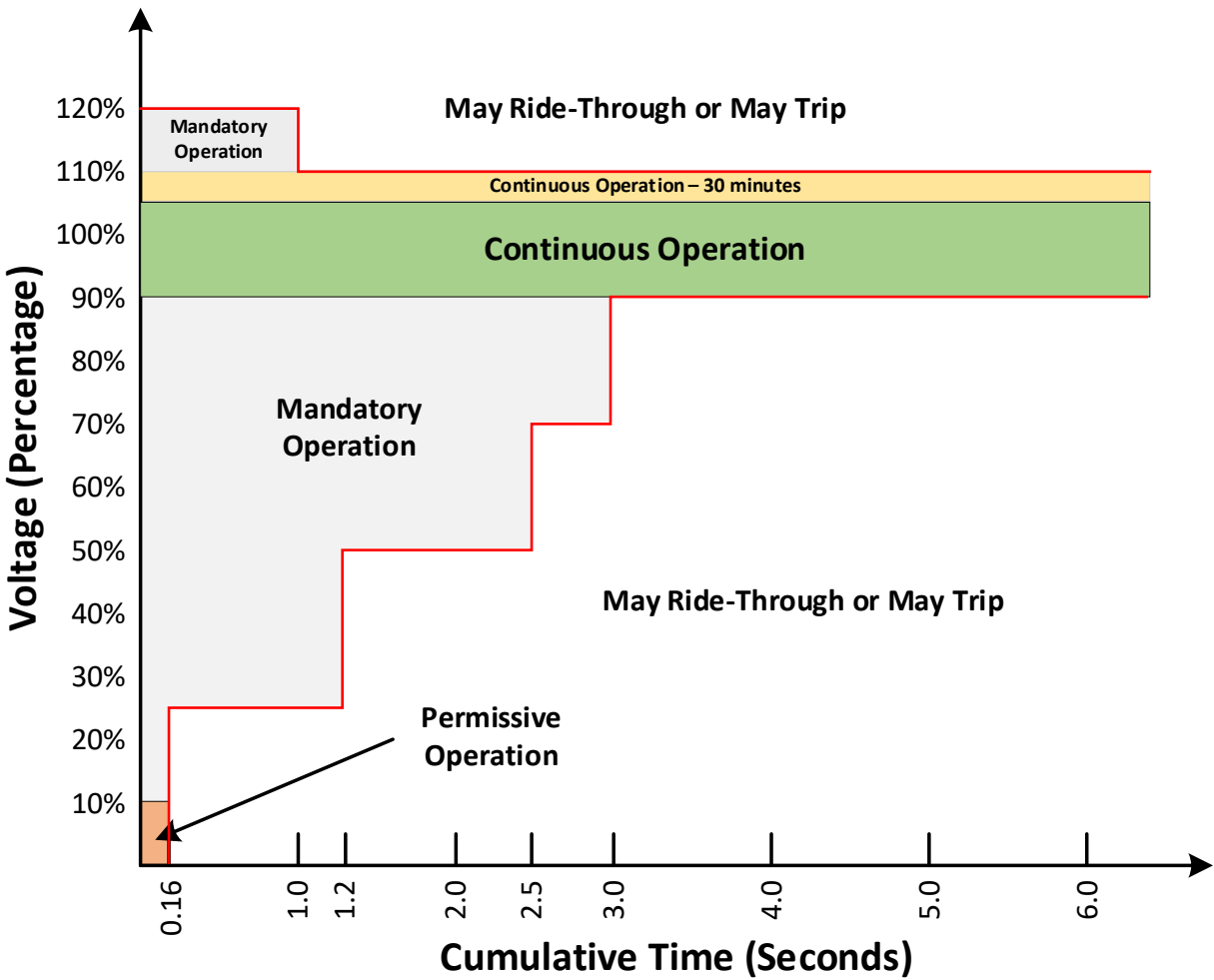


Available from IEEE at <https://standards.ieee.org/project/2800.html>  
and via IEEExplore: <https://ieeexplore.ieee.org/document/9762253/>

**A Technical Foundation Enables the Paradigm Shift Towards *Minimum Capabilities***

# Voltage Ride-Through Capability (Plants with Aux Load Limitations, e.g., Wind)

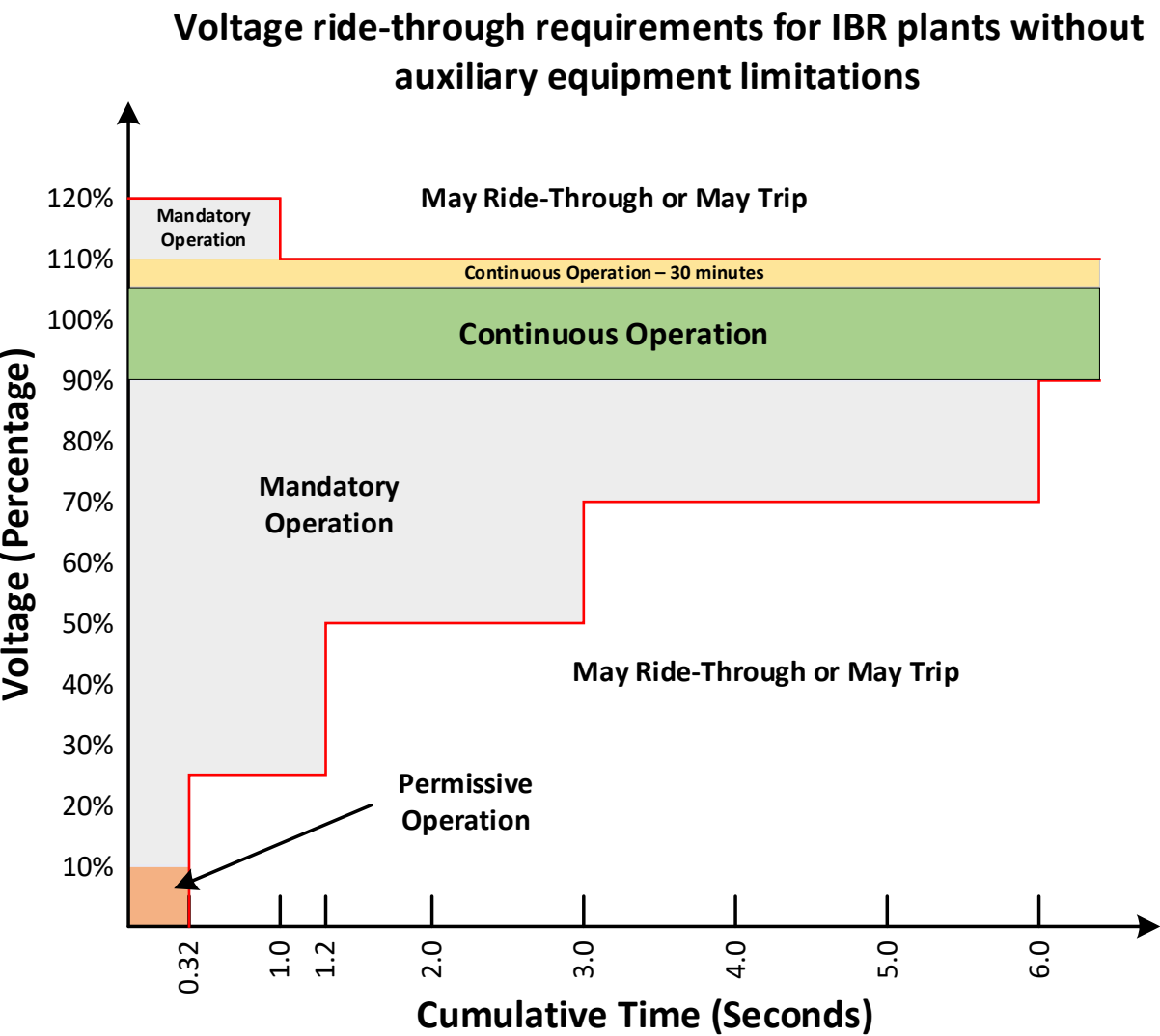
Voltage ride-through requirements for IBR plants with auxiliary equipment limitations



| Applicable Voltage (pu) | Operating Mode               | Minimum Ride-through Time (s) |
|-------------------------|------------------------------|-------------------------------|
| $V > 1.20$              | May Ride-Through or May Trip | NA                            |
| $V > 1.10$              | Mandatory Operation          | 1.0                           |
| $V > 1.05$              | Continuous Operation         | 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         | 0.16                          |

For 500kV nominal voltage,  
Continuous Operation –  
Infinite time extends to 110%  
voltage

# Voltage Ride-Through Capability (Plants without Aux Load Limitations, e.g., Solar)



| Applicable Voltage (pu) | Operating Mode               | Minimum Ride-through Time (s) |
|-------------------------|------------------------------|-------------------------------|
| $V > 1.20$              | May Ride-Through or May Trip | NA                            |
| $V > 1.10$              | Mandatory Operation          | 1.0                           |
| $V > 1.05$              | Continuous Operation         | 1800                          |
| $V < 0.90$              | Mandatory Operation          | 6.00                          |
| $V < 0.70$              | Mandatory Operation          | 3.00                          |
| $V < 0.50$              | Mandatory Operation          | 1.20                          |
| $V < 0.25$              | Mandatory Operation          | 0.32                          |
| $V < 0.10$              | Permissive Operation         | 0.32                          |

For 500kV nominal voltage,  
Continuous Operation –  
Infinite time extends to 110%  
voltage

# Important Details

- Ride-through duration is the same for three-phase and line-to-ground faults.
- The standard does **not** specify the TS operating and network conditions under which requirements apply
- **Mandatory Operation:** Continuous exchange of current between IBR plant and TS
- **Permissive Operation:** The IBR plant may either:

- Continue exchanging current, or
- Operate in a current-blocking mode

*Note:* Permissive operation below 10% voltage helps prevent IBR tripping from:

- Loss of synchronism or temporary
  - Overvoltage following fault clearance
  - Etc.
- Time duration is cumulative within a specified time window.  
*Example:* Duration is cumulative across one or multiple disturbances within a 10-second period.

# IEEE Std 2800™-2022 Voltage RT Requirements

- General requirements
- Requirements under balanced faults
- Requirements under unbalanced faults

# IEEE Std 2800-2022™ Fault Ride-Through Requirements

## General requirements

### Clause 7.2.2: Voltage disturbance ride-through requirements

- The type and magnitude of current injection during ride-through shall be **dependent on voltage deviation** from the IBR unit terminal (POC) **nominal voltage**.
- During ride-through, the IBR unit shall be capable to **inject current to its maximum limit** (i.e., maximum current).

## Balanced faults

- **Reactive current priority mode** (Syn: Q-Priority mode): A mode in which the reactive current output ( $I_q$ ) is given priority and has the full current rating of the inverter-based resource (IBR) available to it (i.e, maximum current ac,  $I_{max}$ ), while the active current output ( $I_p$ ) is constrained. The active current  $I_p$  range varies from a maximum of  $\sqrt{I_{max}^2 - I_q^2}$  to a minimum of zero for generating IBR, and to  $-\sqrt{I_{max}^2 - I_q^2}$  for energy storage IBR, where  $I_q$  is the present value of reactive current.
- The difference between reactive current injection during a fault and a pre-fault reactive current output is an **incremental positive-sequence reactive current ( $\Delta I_R-1$ )**. The incremental positive-sequence reactive current shall not be negative.
- During a fault condition, i.e., operating in a low-voltage ride-through mode, **priority shall be given to reactive current injection** with any residual capacity being supplied as active current unless the IBR unit is specified to operate in active current priority mode by the TS owner.

## Unbalanced faults

- For unbalanced faults, in addition to positive-sequence reactive current, the *IBR unit* shall inject **negative sequence current**:
  - Dependent on POC negative sequence voltage
  - That leads the POC negative sequence voltage by an allowable range as specified below:
    - **90 to 100 degrees** for full converter-based IBR units
    - **90 to 150 degrees** for type III WTGs
- Assuming pre-fault negative sequence current output is zero or negligible, the negative sequence reactive current injection during a fault is an **incremental negative sequence reactive current ( $\Delta I_R-2$ )**.
- If the IBR unit's total current limit is reached, either  $\Delta I_R-1$ , or  $\Delta I_R-2$ , or both may be reduced with a **preference of equal reduction**.
- Additionally,  $\Delta I_R-1$  injection shall not be reduced below  $\Delta I_R-2$ .
- In case of type III WTGs, the  $\Delta I_R-1$  and  $\Delta I_R-2$  injection during a fault is driven by machine parameters and control dynamics and may not be controllable in a manner described above.

# IEEE Std 2800™-2022 Voltage RT Performance Requirements

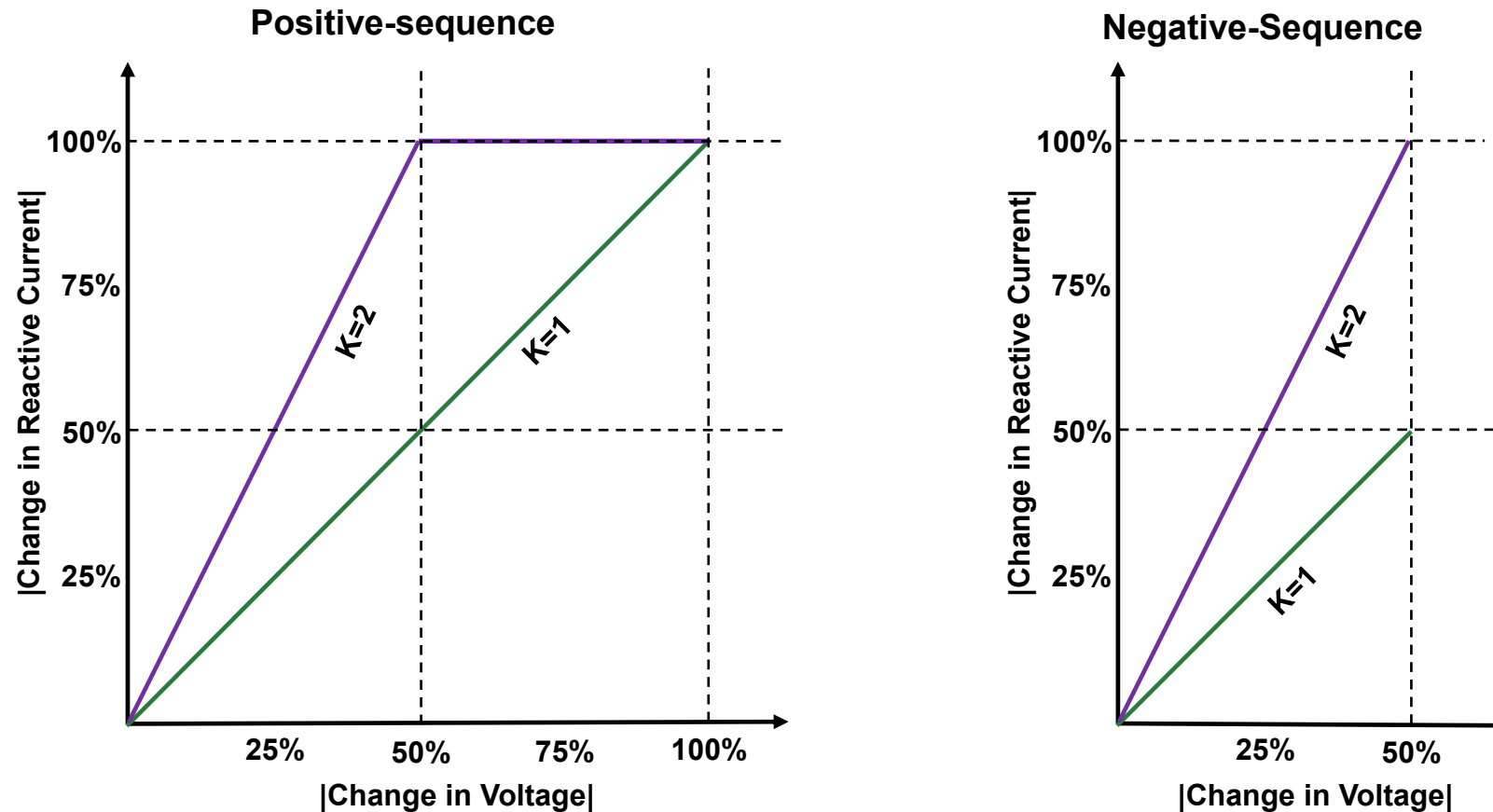
- Reference Point of Applicability for Voltage RT Performance Requirements is POC
- The ***type and magnitude*** of current shall be dependent on ***voltage deviation*** from nominal voltage.
- Operate in ***reactive current priority*** mode by default
- The ***fundamental frequency*** of ***current*** shall be same as fundamental frequency of ***terminal voltage*** with following exceptions:
  - ✓ Abnormal harmonic components due to the transients, transformer inrush, etc.
  - ✓ PLL not able to track terminal voltage frequency
  - ✓ For type III WTG, rotor is crowbarred or where control of rotor current is lost

# IEEE Std 2800™-2022 Voltage RT Performance Requirements – Cont'd

## Balanced Faults

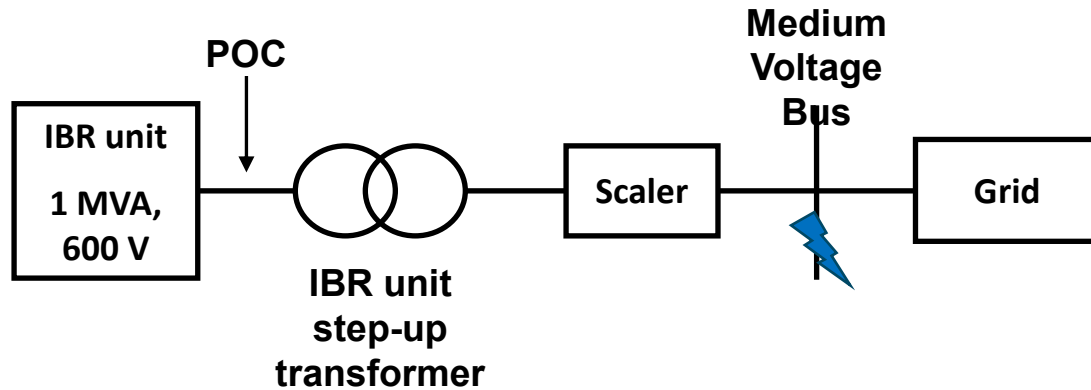
- An IBR unit shall inject reactive current dependent on IBR unit terminal (POC) voltage.
- Active or reactive current priority:
  - The IBR unit shall have capability to select operation in either active current priority mode or reactive current priority mode.
  - By default, the IBR unit shall operate in reactive current priority mode.
  - If requested by the TS owner, and mutually agreed with the IBR owner, the IBR unit may operate in active current priority mode.
- The difference between reactive current injection during a fault and a pre-fault reactive current output is an incremental positive-sequence reactive current ( $\Delta I_{R-1}$ ). The incremental positive-sequence reactive current shall not be negative.

# What is K-Factor Based Control?



- A dead-band may exist, but not shown in figures.
- Current limit needs to be respected.

# Requirements for Balanced Faults – Cont'd



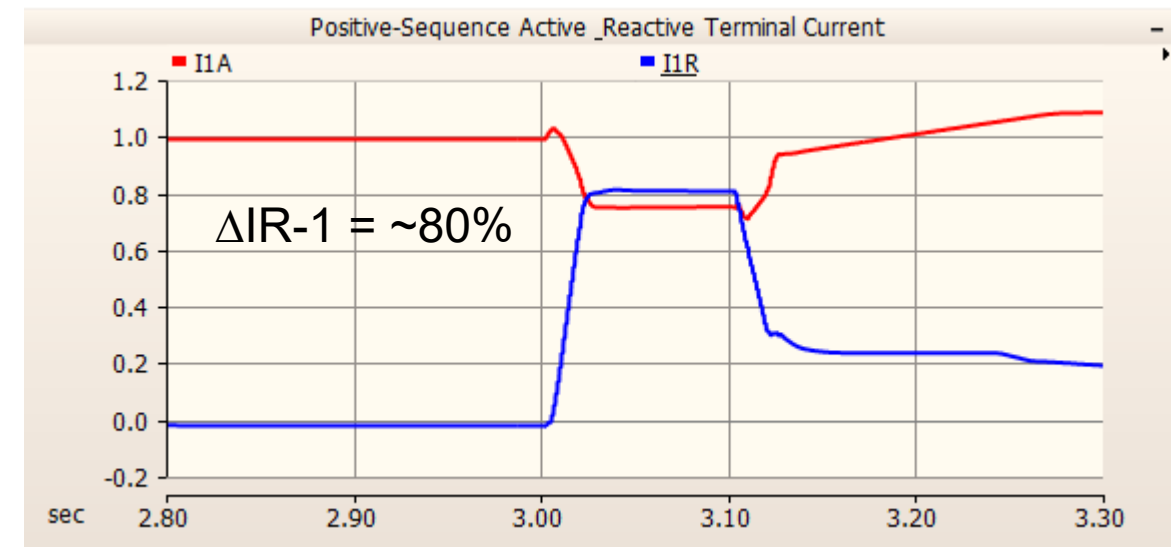
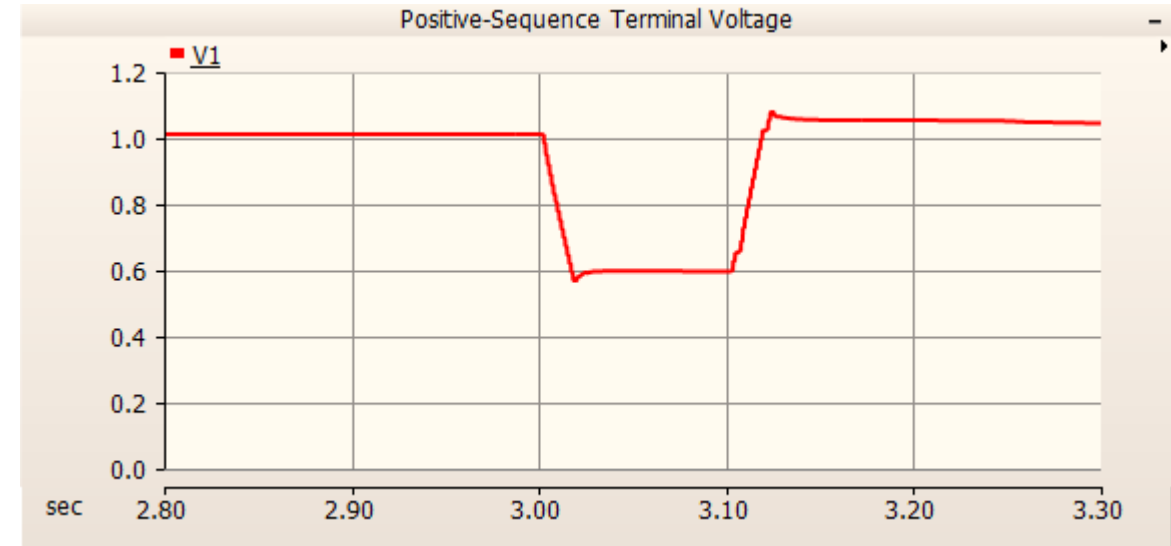
IBR unit current limit = 1.1 per unit

Scalar = 100 (to represent a 100 MVA plant)

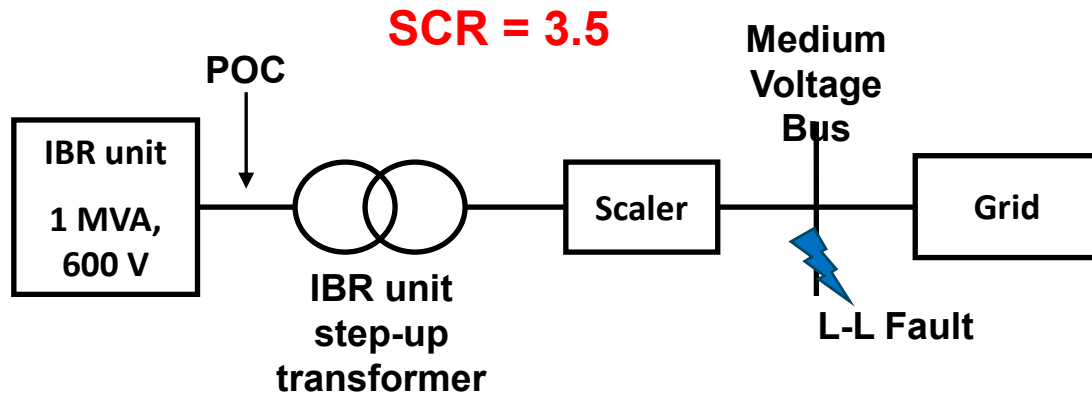
IBR unit operates in reactive current priority mode, with K-factor = 2.

SCR (Grid SC MVA/IBR plant MVA) = 10

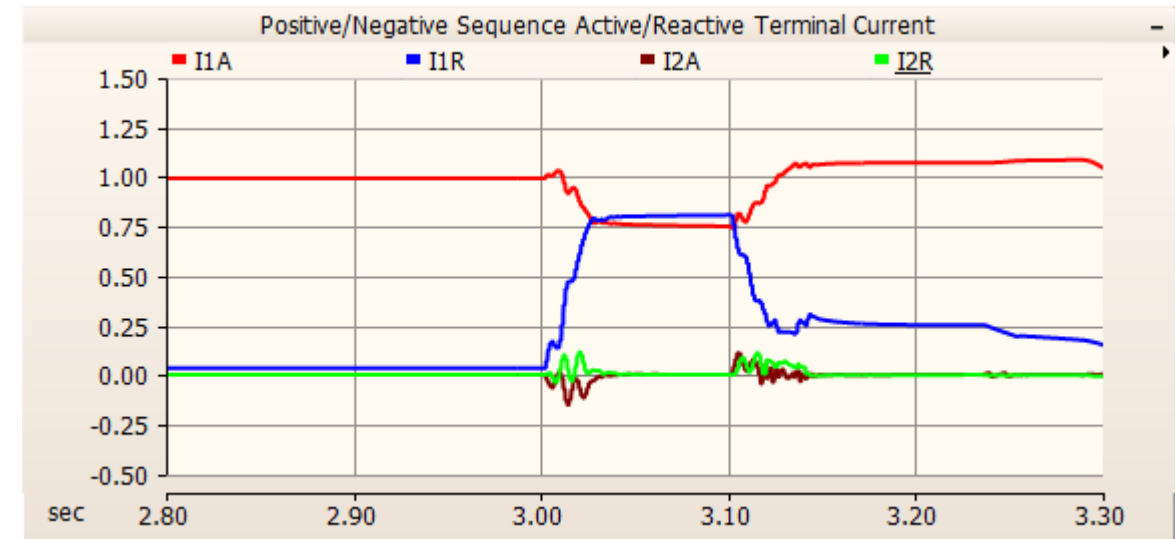
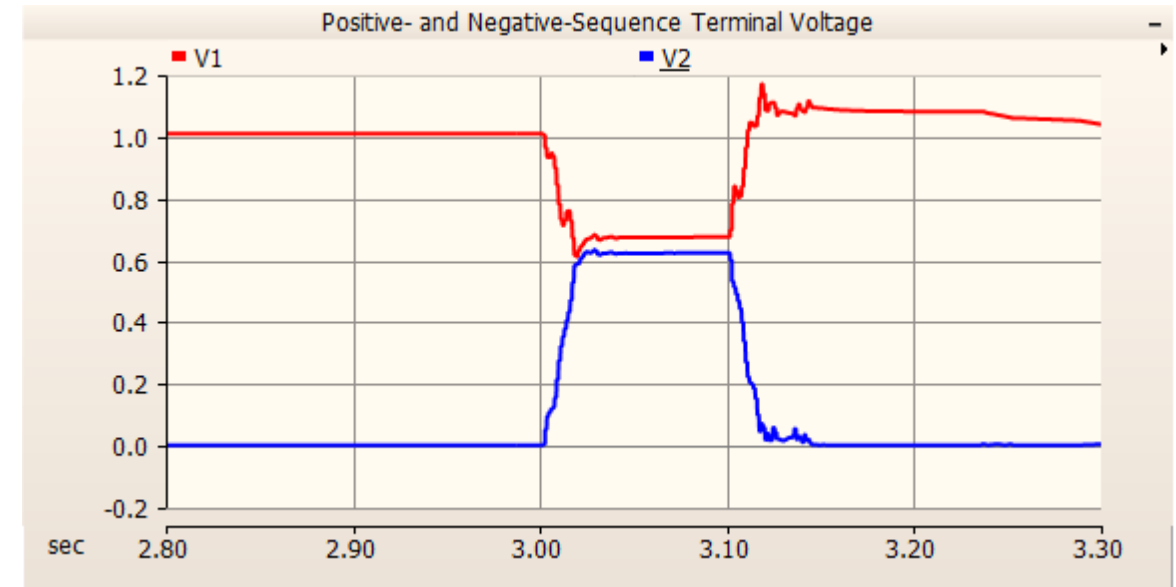
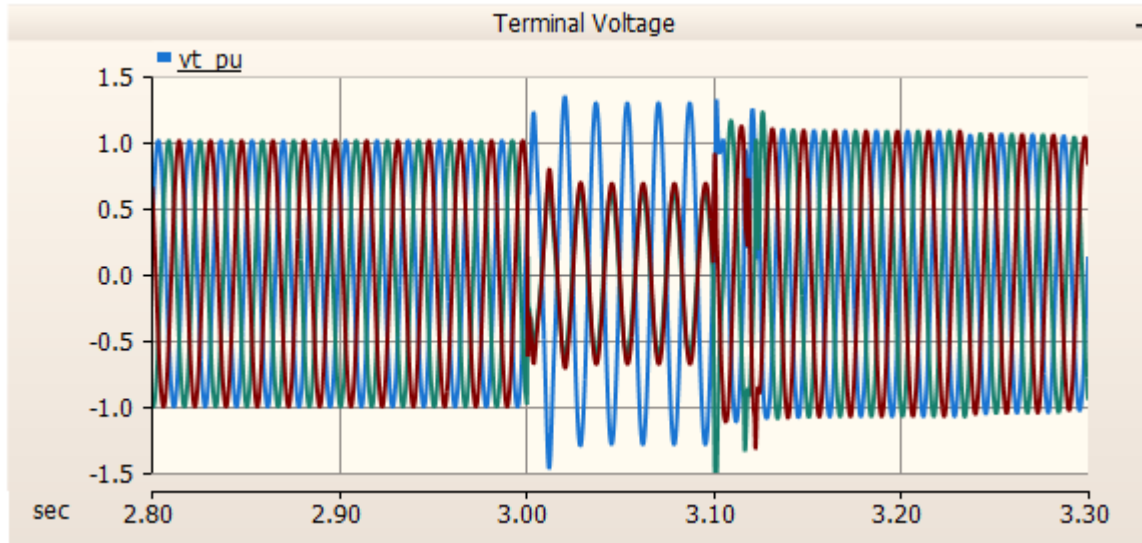
**$\Delta IR-1$** : incremental positive-sequence reactive current, shall be positive.



# Balanced Fault Current into Unbalanced Fault



Note overvoltage on unfaulted phase & V2 at IBR unit terminal



# IEEE Std 2800™-2022 Voltage RT Performance Requirements – Cont'd

## 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 for full converter-based IBR units
    - 90 degrees to 150 degrees for type III WTGs.

# IEEE Std 2800™-2022 Voltage RT Performance Requirements – Cont'd

## Unbalanced Faults

- Assuming pre-fault negative-sequence current injection is zero or negligible, the negative-sequence reactive current injection during a fault is an incremental negative-sequence reactive current ( **$\Delta I_{R-2}$** ).
- In case IBR unit's total current limit is reached, either  **$\Delta I_{R-1}$ , or  $\Delta I_{R-2}$ , or both** may be reduced with a preference of equal reduction in both currents.
- The  $\Delta I_{R-1}$  **shall not** be reduced below  $\Delta I_{R-2}$ .
- Type III WTGs –the  $\Delta I_{R-1}$  and  $\Delta I_{R-2}$  are driven by machine parameters and control dynamics and may not be controllable in a manner described above.

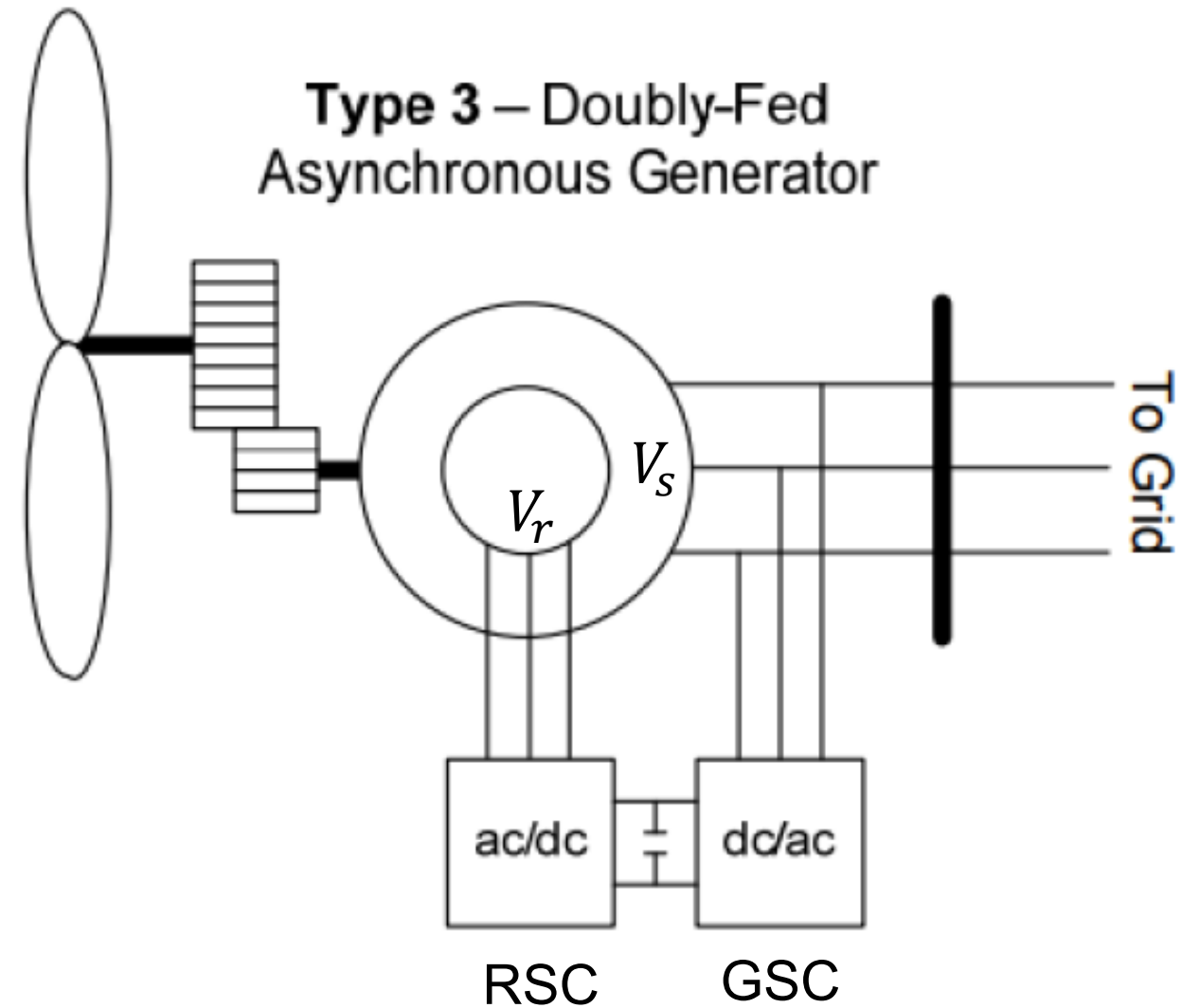
# Challenge with NSCI in Type III WTG

## Normal operating condition

- $V_r = V_s * s * TR$
- Slip is typically  $\pm 0.3$  pu of nominal frequency i.e.,  $V_r = \pm 0.3$  pu.

## During unbalanced faults

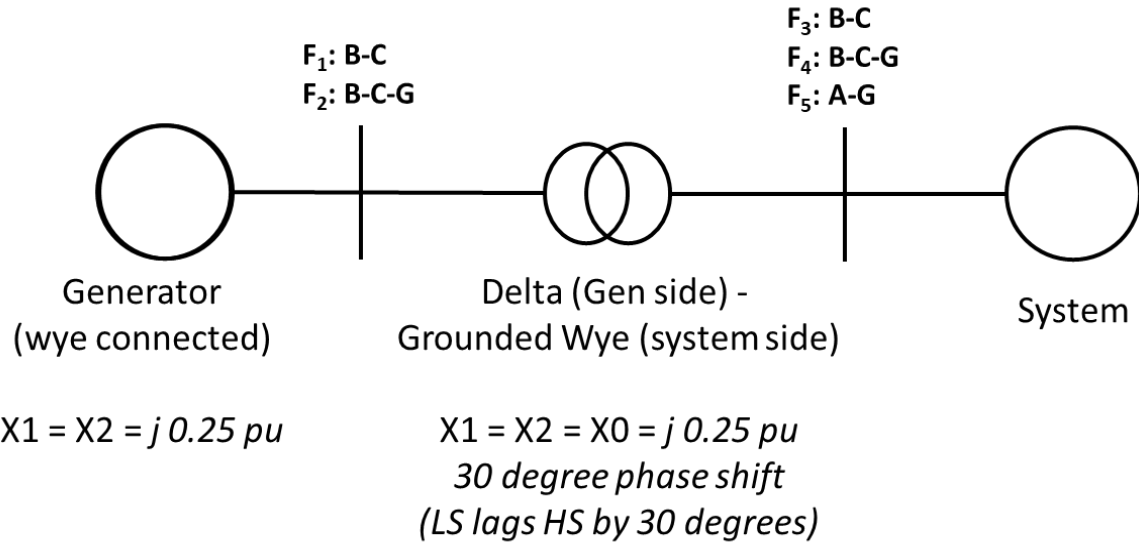
- $V_{1r} = V_{1s} * s * TR$
- $V_{2r} = V_{2s} * (2 - s) * TR$
- L-L fault where  $V_{2s}$  is 0.40 pu and for a slip of -0.3  $\rightarrow V_{2r} = 0.92$  pu.
- Induced voltages may exceed rotor side converter (RSC) rating, resulting in loss of RSC control.



Courtesy of Manish Patel, Silicon Ranch.

# Requirements for Unbalanced Faults

Why are requirements written using positive- & negative-sequence quantities?



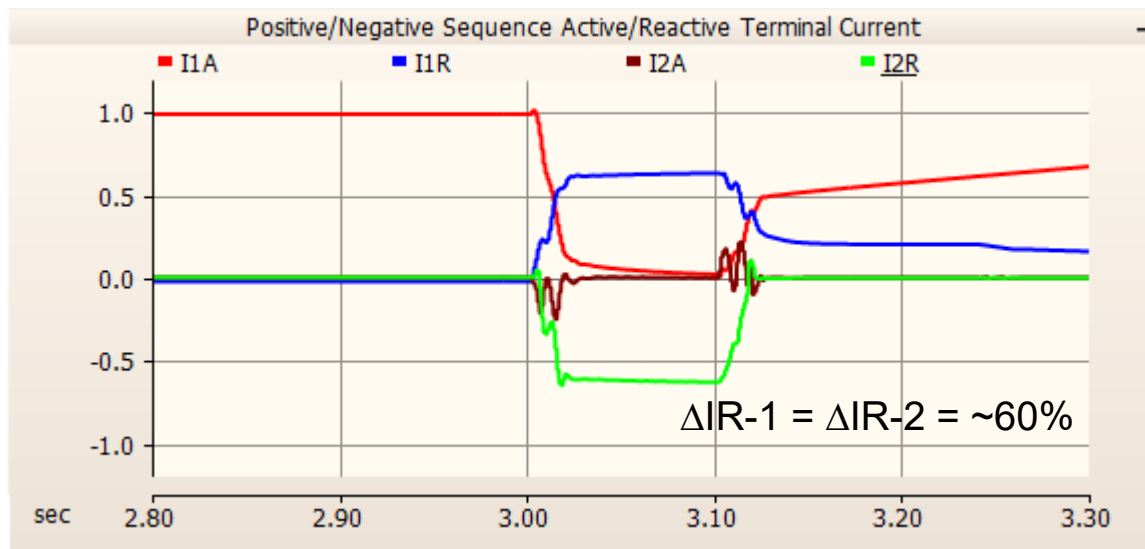
**$I_1$  lags  $V_1$  &  $I_2$  leads  $V_2$   
by 90 degrees for all faults**

| Fault                | Voltage  | Mag (p.u.) | Angle (degs) | Current  | Mag (p.u.) | Angle (degs) |
|----------------------|----------|------------|--------------|----------|------------|--------------|
| <b>F<sub>3</sub></b> | $V_A$    | 0.9        | 0            | $I_A$    | 1          | -164         |
|                      | $V_B$    | 0.9        | -148         | $I_B$    | 1          | -164         |
|                      | $V_C$    | 0.5        | 106          | $I_C$    | 2          | 16           |
|                      | $V_1$    | 0.75       | -14          | $I_1$    | 1          | -104         |
|                      | $V_2$    | 0.25       | 46           | $I_2$    | 1          | 136          |
|                      | $V_{AB}$ | 1.73       | 16           | $I_{AB}$ | 0          | 0            |
|                      | $V_{BC}$ | 1.14       | -123         | $I_{BC}$ | 3          | -164         |
|                      | $V_{CA}$ | 1.14       | 155          | $I_{CA}$ | 3          | 16           |
| <b>F<sub>4</sub></b> | $V_A$    | 0.8        | 0            | $I_A$    | 1.1        | -136         |
|                      | $V_B$    | 0.8        | -143         | $I_B$    | 1.1        | 174          |
|                      | $V_C$    | 0.5        | 109          | $I_C$    | 2          | 19           |
|                      | $V_1$    | 0.68       | -11.5        | $I_1$    | 1.26       | -102         |
|                      | $V_2$    | 0.18       | 48           | $I_2$    | 0.73       | 138          |
|                      | $V_{AB}$ | 1.5        | 18.4         | $I_{AB}$ | 0.92       | -70          |
|                      | $V_{BC}$ | 1.06       | -117         | $I_{BC}$ | 3.02       | -170         |
|                      | $V_{CA}$ | 1.06       | 153          | $I_{CA}$ | 3.02       | 27           |

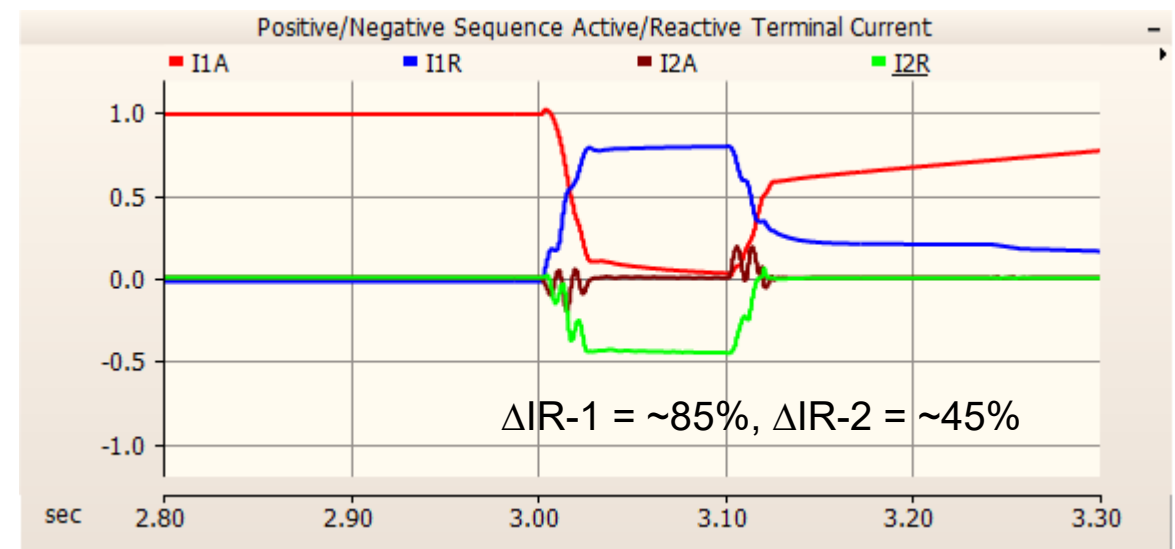
# Requirements for Unbalanced Faults

- IBR unit operates in reactive current priority mode, with K-factor = 2.
- $V_1$  &  $V_2$  deviate by ~45%.
- $\Delta I_R-1$  &  $\Delta I_R-2$  should be 90% each, but not possible due to current limit.

Equal reduction in  $\Delta I_R-1$  &  $\Delta I_R-2$



$\Delta I_R-2$  reduced more than  $\Delta I_R-1$



# Amplitude of Fault Current

- IEEE Std 2800-2022 intentionally **does not** specify amplitude of  **$\Delta I_R-1$**  and  **$\Delta I_R-2$**  during a fault condition.
- It is **impractical** to specify a value or range of values that meets the needs for all *IBR plant* interconnections.
- The *TS owner* should consider specifying required magnitude of incremental positive and negative sequence reactive currents during faults per respective system needs.
- The commonly used approach is to specify a relationship between voltage change at *IBR unit* terminals (POC) and required incremental reactive current (e.g., k-Factor based control).

# Opportunities for Revision of IEEE Std 2800-2022: Existing Language & Issues

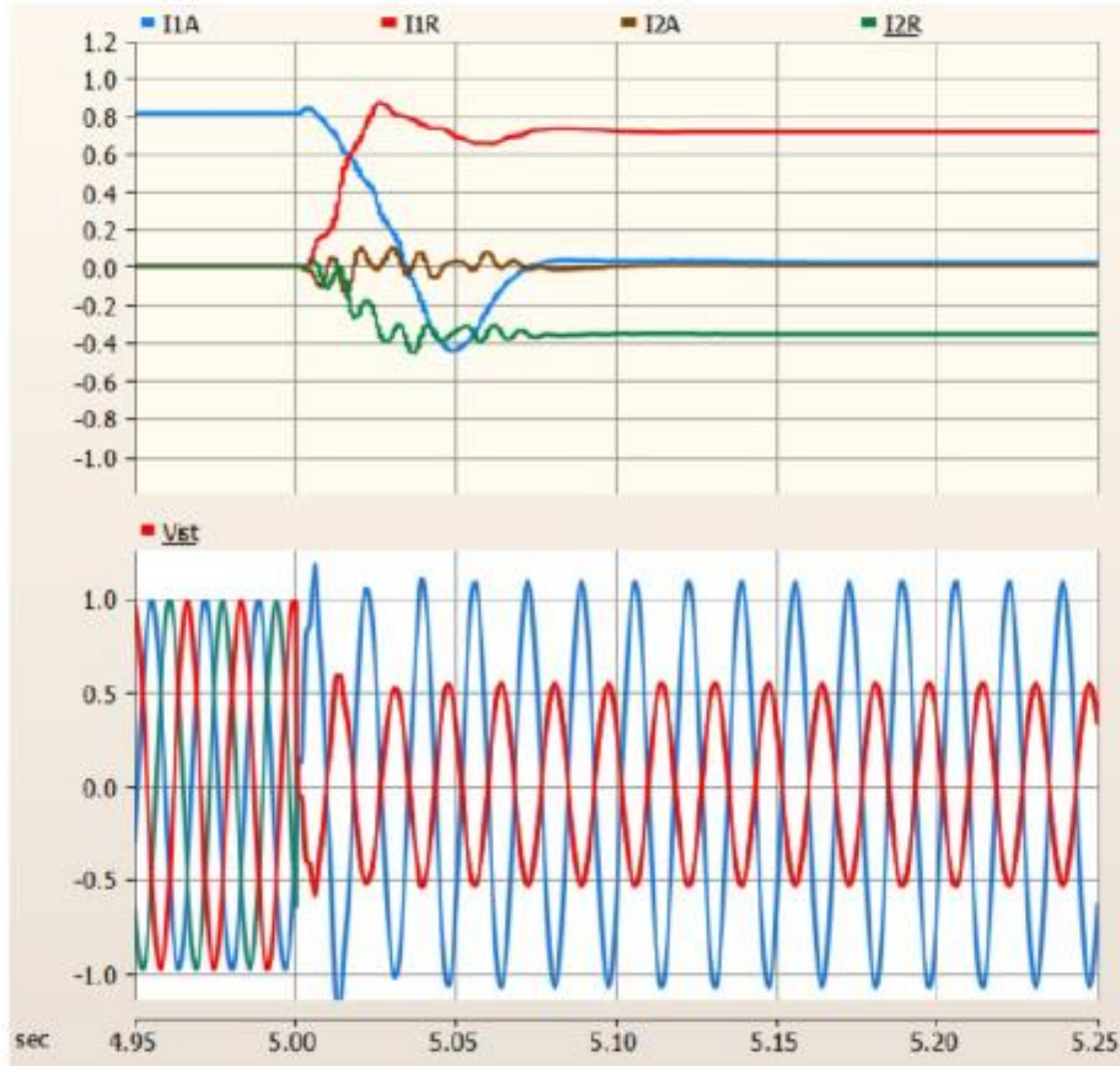
Reducing “either” can result in undesired current during a fault condition

Ambiguous when  $\Delta I_{R-1}$  and  $\Delta I_{R-2}$  are not increased equally prior to current limiting

- If the IBR unit's total current limit is reached, *either*  $\Delta I_{R-1}$ , or  $\Delta I_{R-2}$ , or both may be reduced with *a preference of equal reduction* in both currents. Additionally, *the  $\Delta I_{R-1}$  injection shall not be reduced below  $\Delta I_{R-2}$ .*

$\Delta I_{R-1} > \Delta I_{R-2}$  may result in undesired fault current injection. Also, may not be meaningful for all unbalanced faults, e.g., LG fault

## Example: $\Delta IR-1 > \Delta IR-2$



Line-to-line fault on IBR unit terminals

Sequence currents:

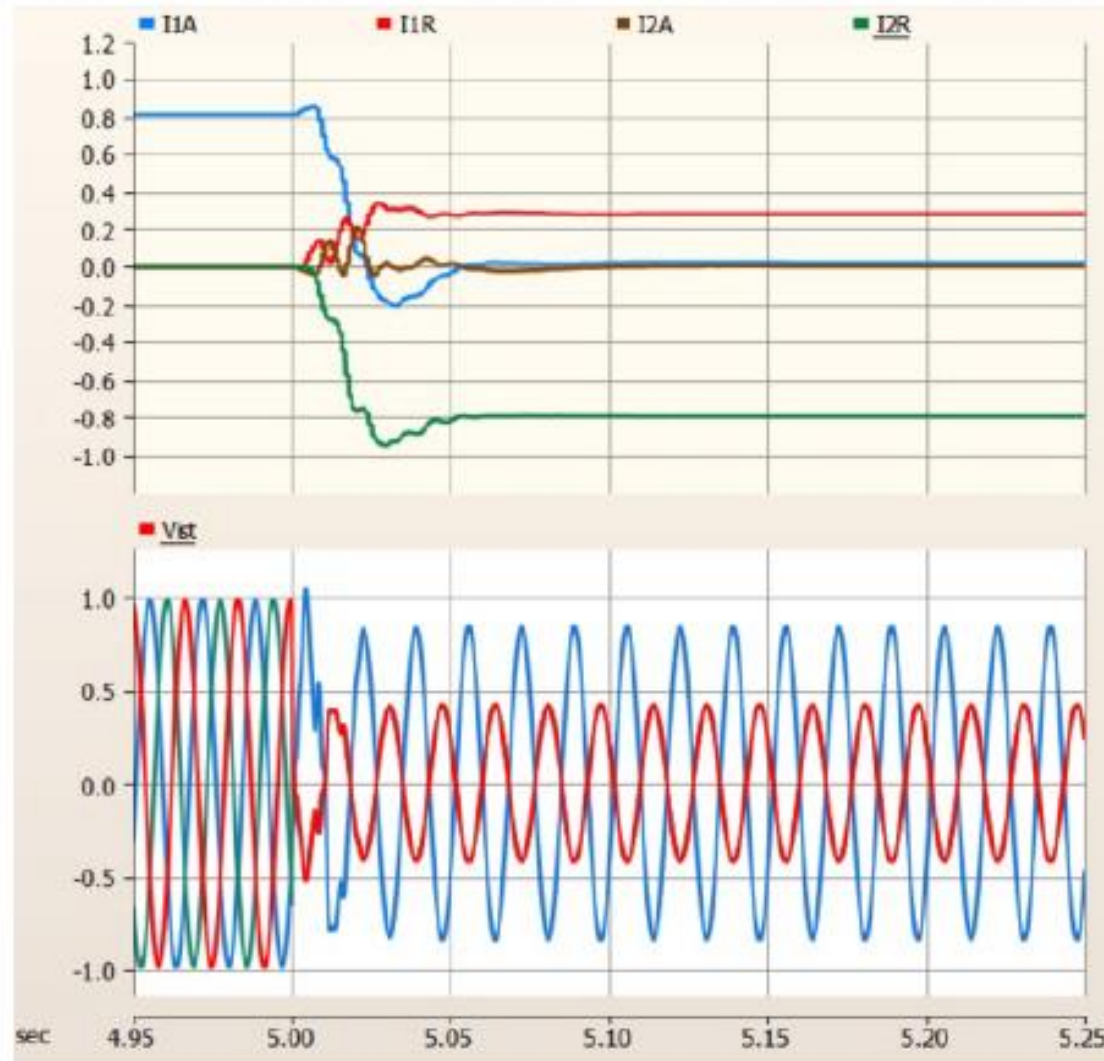
- $I_{1R} = 0.70 \angle -90$  and
- $I_{2R} = 0.35 \angle 90$

Phase currents:

- $I_a = 0.35 \angle -90$ ,
- $I_b = 0.93 \angle 169$ , and
- $I_c = 0.93 \angle 11$

The condition  $\Delta IR-1 > \Delta IR-2$  leads to positive-sequence reactive current injection in the unfaulted phase causing a voltage rise of approximately 10%.

## Example: $\Delta I_R-1 < \Delta I_R-2$



Line-to-line fault on IBR unit terminals

Sequence currents:

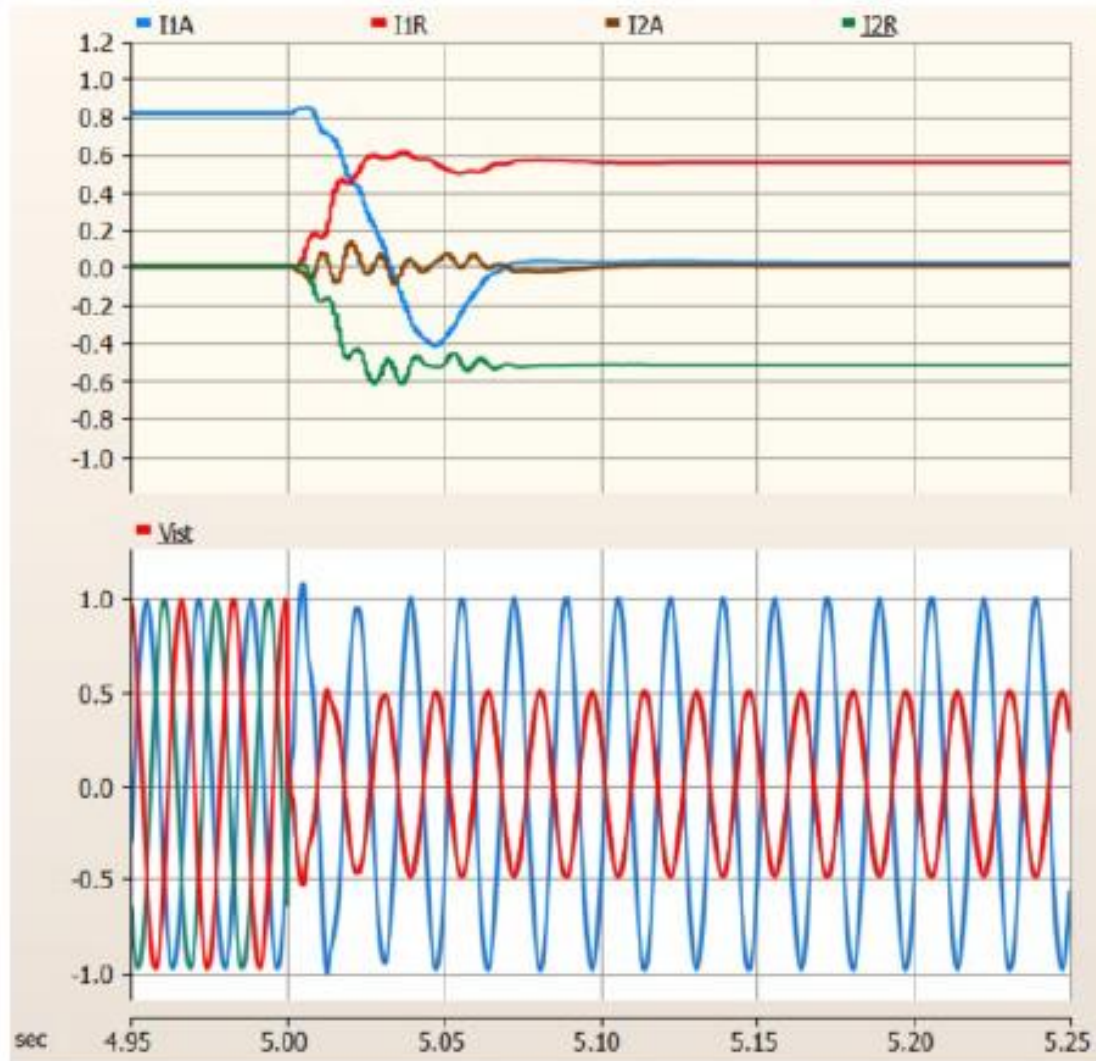
- $I_{1R} = 0.30 \angle -90$  and
- $I_{2R} = 0.80 \angle 90$

Phase currents:

- $I_a = 0.50 \angle 90$ ,
- $I_b = 0.98 \angle -165.3$ , and
- $I_c = 0.98 \angle -14.7$

The condition  $\Delta I_R-1 < \Delta I_R-2$  leads to positive-sequence reactive current absorption in the unfaulted phase causing a voltage drop of approximately 10%.

# Example: $\Delta I_R - 1 = \Delta I_R - 2$



Line-to-line fault on IBR unit terminals

Sequence currents:

- $I_{1R} = 0.55 \angle -90$  and
- $I_{2R} = 0.525 \angle 90$

Phase currents:

- $I_a = 0.025 \angle -90$ ,
- $I_b = 0.93 \angle 179.2$ , and
- $I_c = 0.93 \angle 0.8$

Current injection in unfaulted phase is minimal and unfaulted phase voltage remains essentially unchanged during the fault.

# Recommended Language

- If the IBR unit's total current limit is reached, the reduction in  $\Delta I_{R-1}$  or  $\Delta I_{R-2}$  shall be such that the relationship between positive- and negative-sequence voltage and current deviation is maintained, as follows:

$$\frac{\Delta V_1}{\Delta I_{R-1}} \approx \frac{\Delta V_2}{\Delta I_{R-2}}$$

- Recognizing the practical challenges associated with implementing controls, the standard should permit a reasonable tolerance, on the order of less than 5%. A requirement written in this manner would also yield acceptable performance for all types of unbalanced faults.

M. Patel, W. Baker, J. Glidewell and K. Dowling, "Technical Perspectives on Fault Current Injection Requirements in IEEE Std 2800-2022: Clarifications and Recommendations for Improvement," 2026 IEEE Power & Energy Society General Meeting (PESGM).

# IEEE Std 2800™-2022 Voltage RT Performance Requirements – Cont'd

No specification of current magnitude

The 1-cycle time required for DFT (to derive phasor quantities) is included in specified response/settling time.

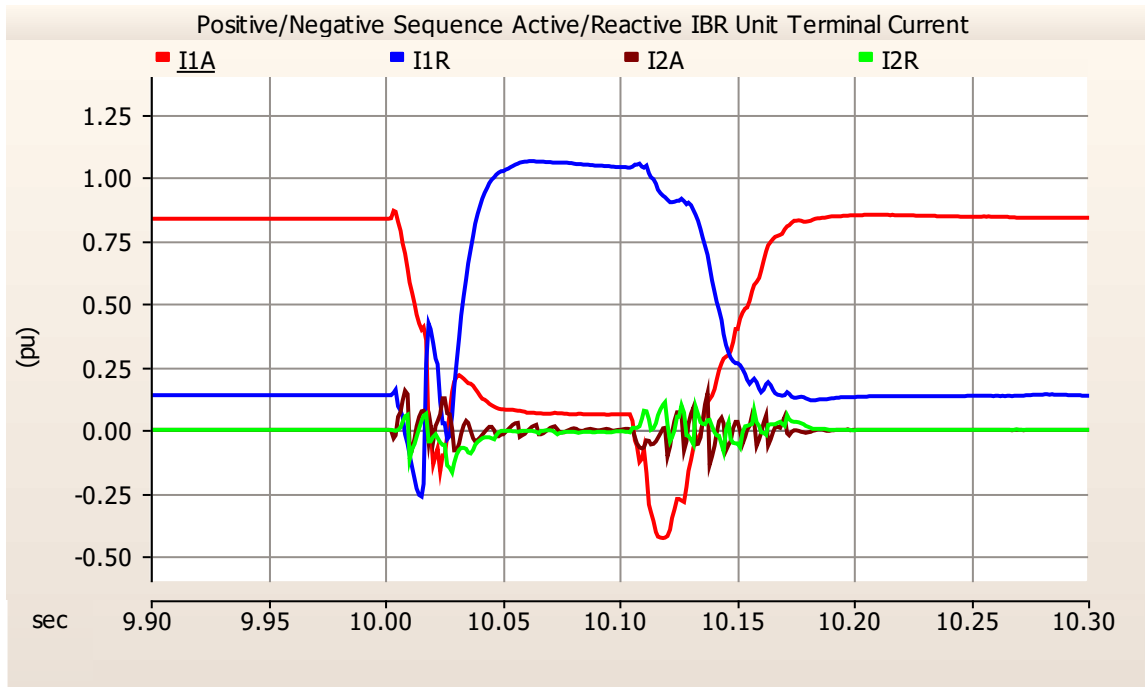
|                    | Type III WTGs                                                                      | All other IBR Units                                                                |
|--------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| Step Response Time | NA <sup>1</sup>                                                                    | $\leq 2.5$ cycles                                                                  |
| Settling Time      | $\leq 6$ cycles                                                                    | $\leq 4$ cycles                                                                    |
| Settling Band      | Max of ( $\pm 10\%$ of required change or $\pm 2.5\%$ of IBR unit maximum current) | Max of ( $\pm 10\%$ of required change or $\pm 2.5\%$ of IBR unit maximum current) |

**Note 1:** Initial response is driven by machine characteristics, & not the control system.

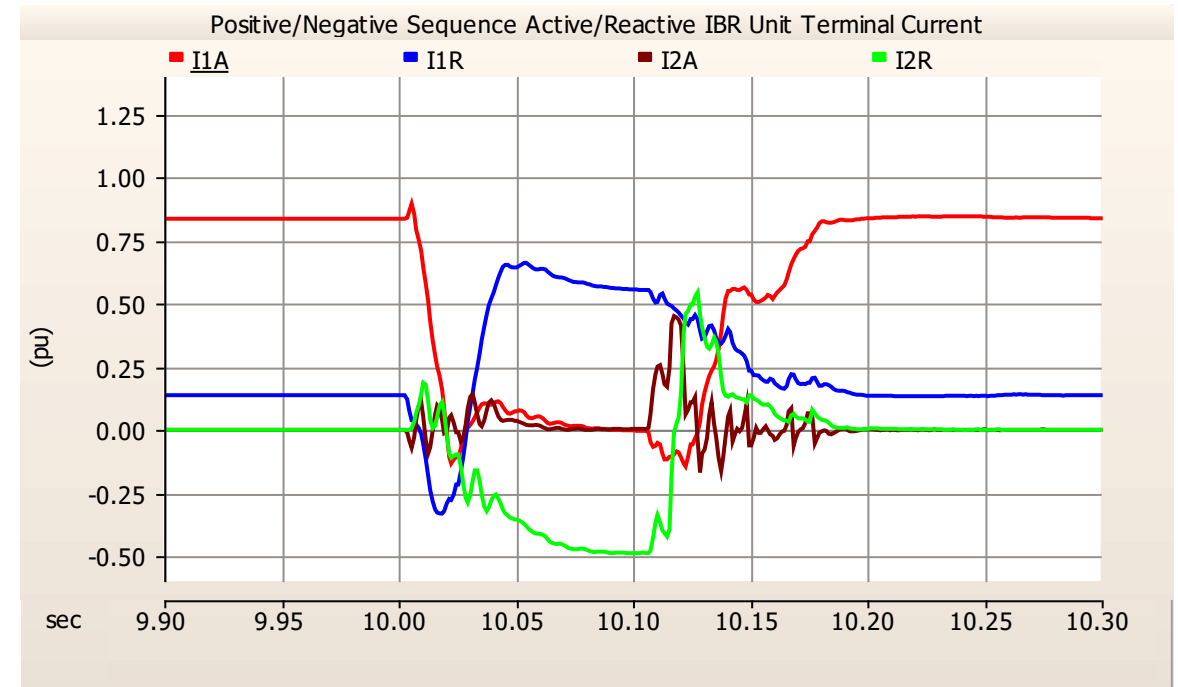
Slower response/settling time is permitted with mutual agreement between TS owner and IBR owner.

# OEM #1 Fault Response

## Three-Phase Fault



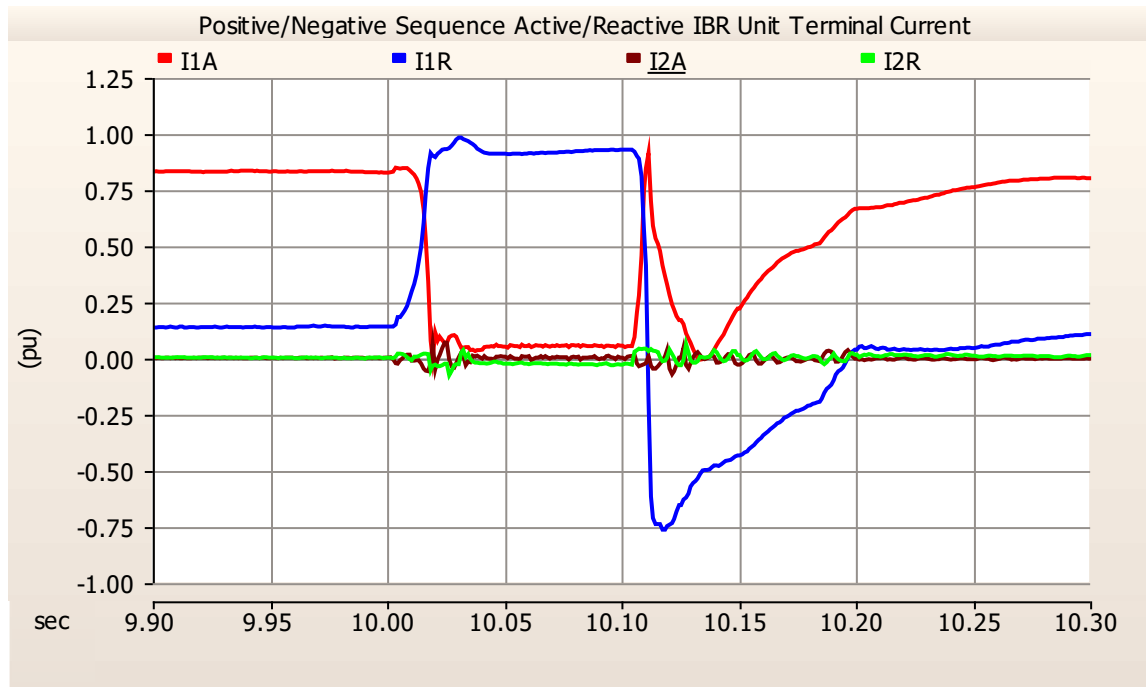
## Line-to-Line Fault



- Absorbs positive-sequence reactive immediately after fault inception
- Absorbs active current immediately after fault clearance
- L-L Fault: Change in  $I_1$  faster than  $I_2$ ,  $\Delta I_R-2 > \Delta I_R-1$  (does not meet standard reqs.)

# OEM #2 Fault Response

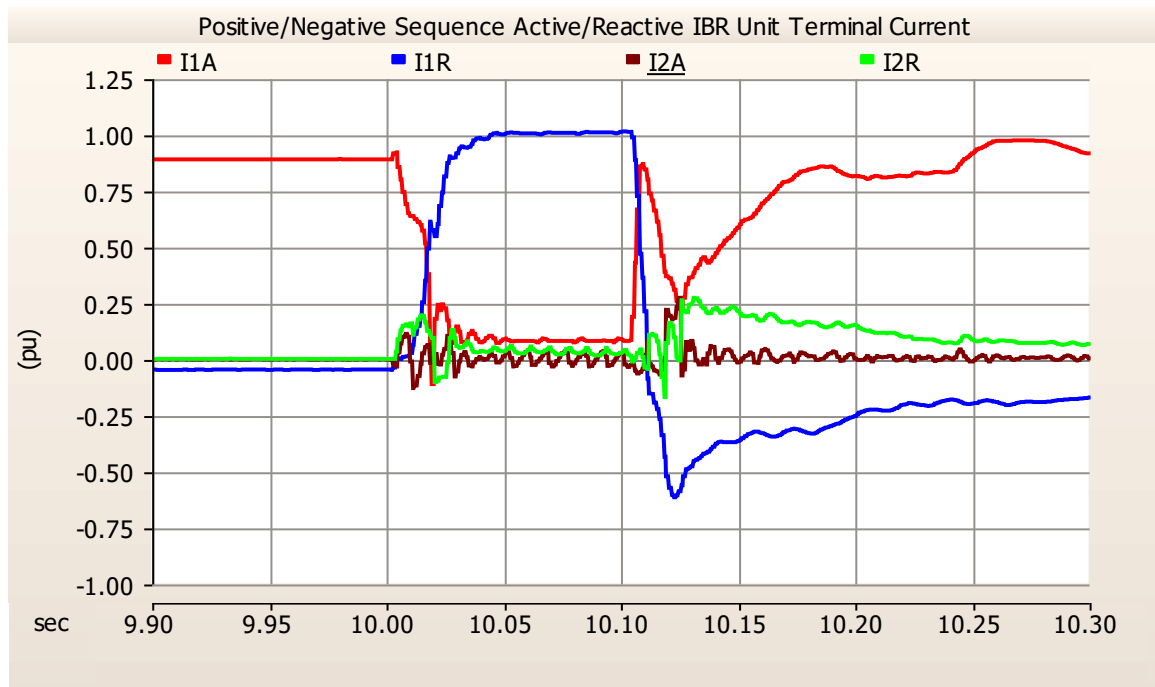
## Three-Phase Fault



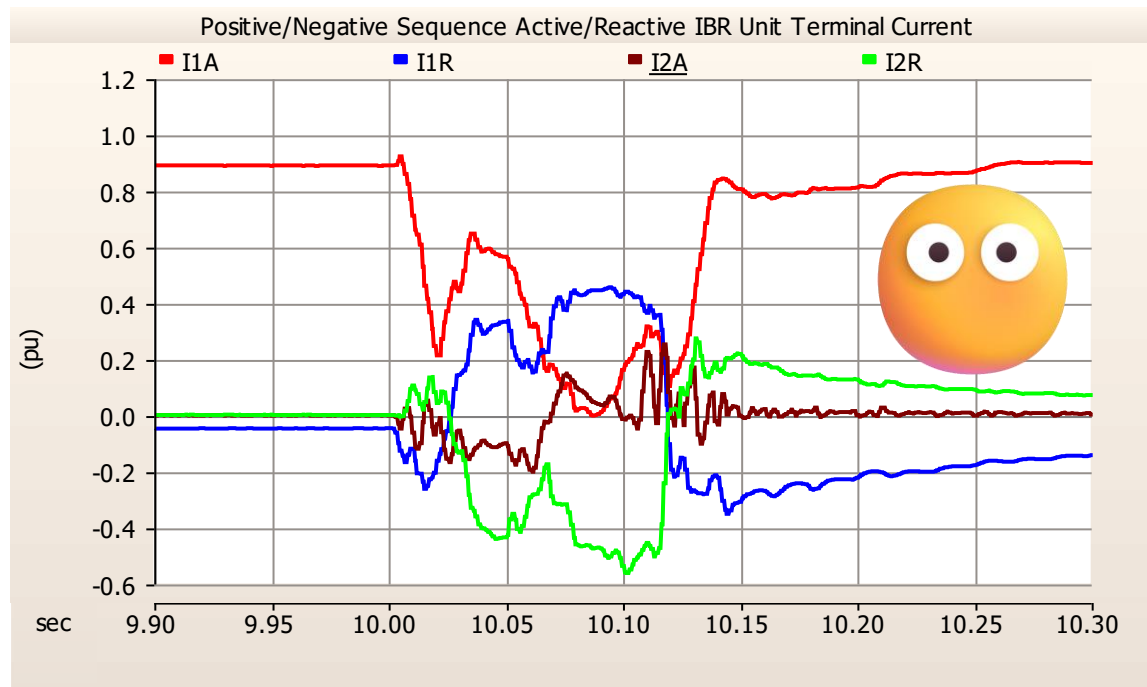
- Very fast response upon fault inception
- Absorbs significant reactive current immediately upon fault clearance
- Spike in active current immediately upon fault clearance.

# OEM #3 Fault Response

## Three-Phase Fault



## Line-to-Line Fault



- Absorbs positive-sequence reactive current immediately after fault clearance
- L-L Fault response is like Random Thoughts 😊

# NSCI in Grid Forming Inverters

- Existing NSCI requirements (eg, VDE-AR-N 4120-2018, IEEE Std 2800-2022) are developed with grid-following technology in mind.
- Those requirements may not be applicable to grid forming inverter (GFM).
- The recent IEEE P2800 series of standard aims to establish GFM fault current injection requirements.

# Overview of IEEE P2800 Series of Standards

IEEE/PES/ED&PG-C Inverter-Based Resources  
Interconnection Working Group (IBRI-WG) and  
IEC TC8 SC8A JWG5

# New IEEE 2800/.x Projects Aligned under one IBR-Interconnection WG

## Inverter-Based Resources Interconnection Working Group (IBRI-WG)

- **P2800**, Standard for Interconnection and Interoperability of Inverter/Converter-Based Resources (IBRs/CBRs) Interconnecting with Transmission Electric Power Systems
  - ☐ Scope: Incorporation of industry learning
- **P2800a** IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems
  - ☐ Scope: Reduce Barriers for IBRs with Grid-Forming Equipment
- **P2800.1**, Recommended Practice for Functional Capabilities and Performance of Grid Forming Equipment in Inverter-Based Resources (IBRs) / Converter-Based Resources (CBRs)
  - ☐ Scope: Framework for GFM IBR
  - ☐ The intent is to develop this document jointly with the International Electrotechnical Commission via a Category C liaison with IEC TC8 SC8A JWG 5, System issues regarding integration of wind and PV generation into bulk electrical grid (under establishment)

We encourage you to join this effort by expressing your interest at  
<https://development.standards.ieee.org/myproject-web/public/view.html#/interest/8899>

# New IEEE 2800/.x Projects Aligned under one IBR-Interconnection WG

| PAR                                 | Type                     | Scope                               | Request Date | Approval Date | Expected Date of SA Initial Ballot | Projected Date Submittal to RevCom | Publication Date | Expiration Date <sup>1</sup> | Joint with IEC? |
|-------------------------------------|--------------------------|-------------------------------------|--------------|---------------|------------------------------------|------------------------------------|------------------|------------------------------|-----------------|
| <a href="#">P2800a Individual</a>   | Standard (individual)    | Minimize barriers to GFM            | Sep 12, 2025 | Dec 2025 ✓    | Q4 2026                            | Q2 2027                            | April 2028       | September 2029               | No              |
| <a href="#">P2800.1 Individual</a>  | Rec. Pract. (individual) | Framework for GFM-IBRs              | Sep 12, 2025 | Dec 2025 ✓    | Q4 2026                            | Q2 2027                            | April 2028       | September 2029               | Yes             |
| <a href="#">P2800 R1 Individual</a> | Standard (individual)    | Incorporation of industry learnings | Sep 12, 2025 | Dec 2025 ✓    | March 2028                         | December 2028                      | April 2029       | September 2029               | No              |

<sup>1</sup> Date by when balloted draft must go to RevCom. Typically, four years from request date.

IEC & IEEE  
GFM TF

P2800 & P2800.2  
Subgroups

Normative References & Definitions

General Requirements

Reactive Power & Voltage Control

Active-power—frequency response

Response to TS abnormal conditions

Power Quality

Protection

Modeling Data & Measurement Data

Test & Verification

Frequency Scanning

Type tests

Design evaluations

Com.Test & As-built ev.

Monitor., M&MV, PT

Mandatory  
(Standard, “shall”)

Legend

Optional  
(Recommended Practice, “should”)

Futuristic  
(Guide, “may”)

→

“should”-reference

# Role of PSRCC WG C60 in relation to P2800 Series

Identify P2800 draft requirements for response to abnormal voltage:

- LVRT/HVRT
- Current injection
- Current limiting
- Transient OV

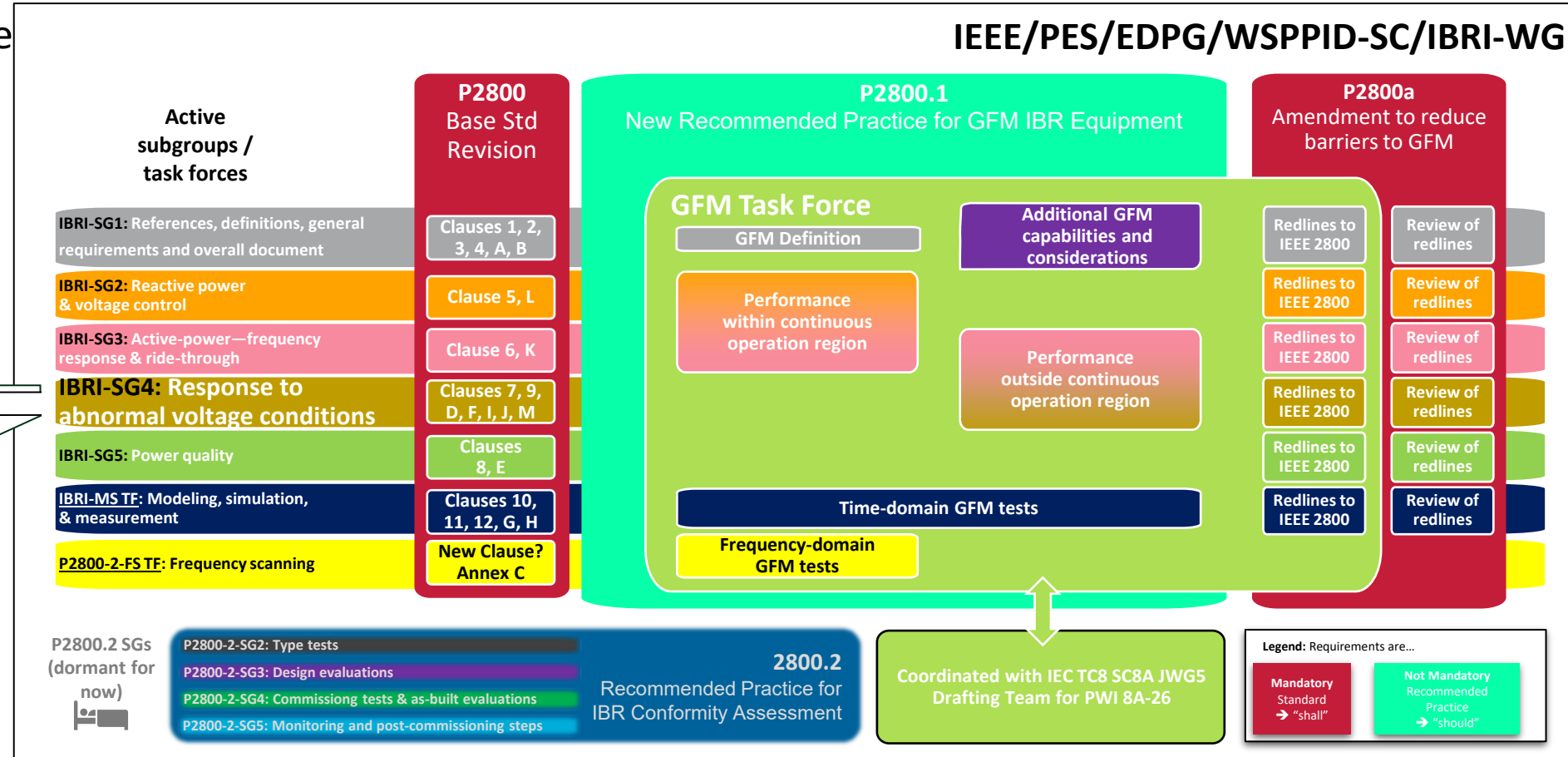
**PSRCC**



**C60**

Provide feedback from protection SMEs:

- Revised language
- New requirements



[Click here to sign up for SG4 listserv](#)

# IBRI-WG SG4 – Response to abnormal voltage conditions

- **Leads:** Aboutaleb Haddadi (EPRI), Sid Pant (GE Vernova), Mike Ropp (Sandia National Labs)
- **Objective 1:** limiting impact of grid faults on generators and consumers in wider area of the fault, avoids risk of immediate voltage collapse.
- **Objective 2:** ensure functionality of protection equipment in the grid.

## Step 1

P2800a: Reduce Barriers for IBRs with Grid-Forming Equipment → *produce redline*

Fundamental question: *Can GFM meet the LVRT requirements of the base standard?*

- *What can GFM do?* → This is what this SG should answer.
- *What does the grid need?* → This has been largely covered by the base standard.

## Step 2

P2800.1: Specifying GFM fault requirements\* → *revise D0.1*

\*requires further research **when operating at power or current limits**

- modifying **angle**
- modifying **magnitude**

[Click here to sign up for SG4 listserv](#)

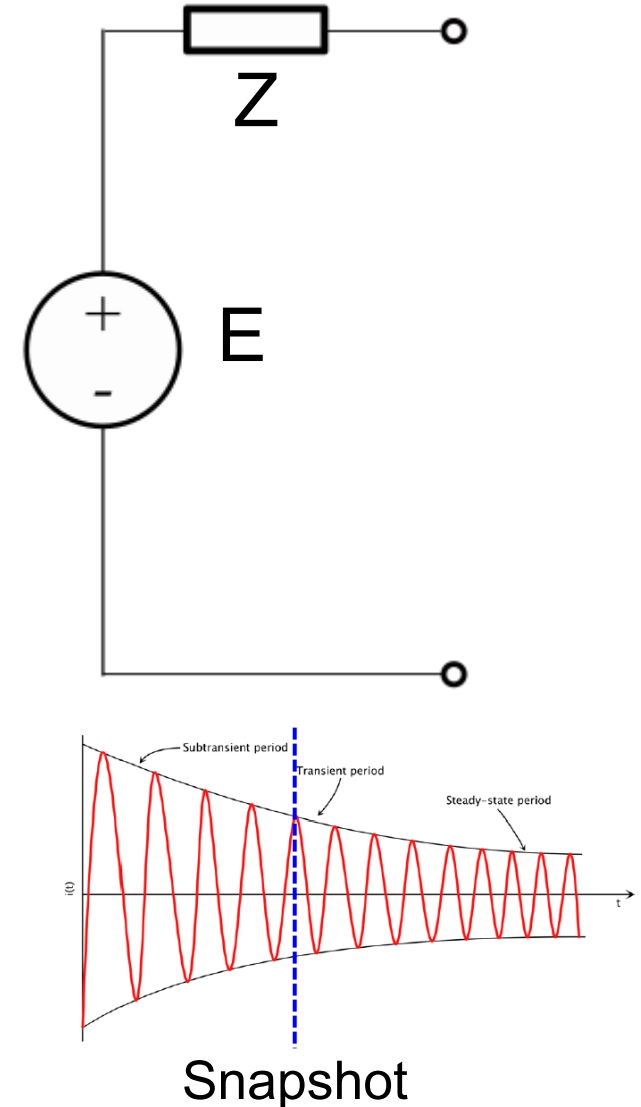


# IBR Short Circuit Model

# Background: Classical Voltage Source Model

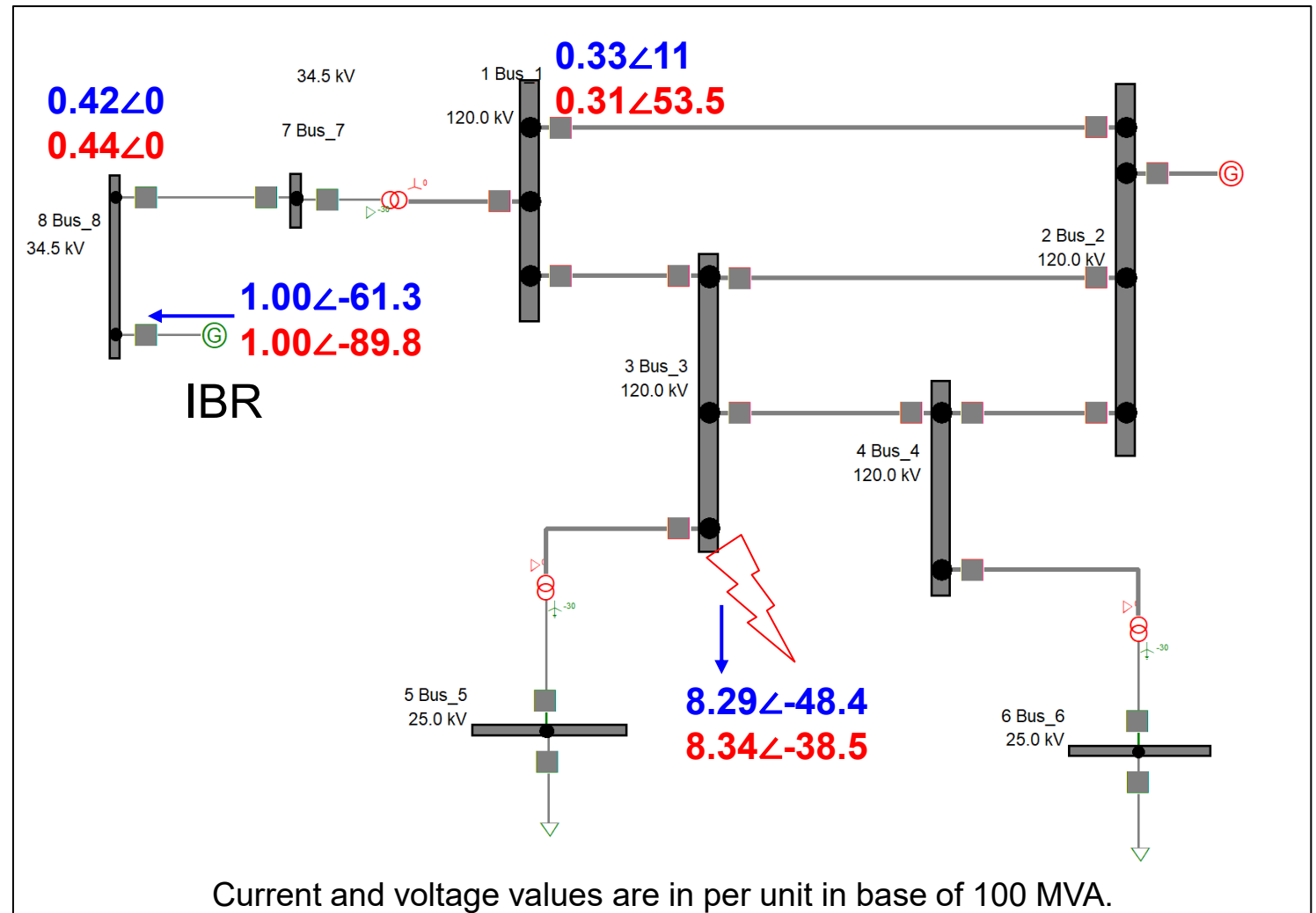
- Why is the model adequate for a synchronous generator?
  - During a typical short circuit, a classical synchronous generator behaves like a voltage source.
    - Field excitation is maintained.
    - Prime mover drives the generator at normal speed.
    - Induced voltage  $E$  does not considerably change.
- Model is in phasor-domain & linear.
- Short circuit current calculation:  $I = E/Z_f$

**However, this model does not apply to IBR. Why?**



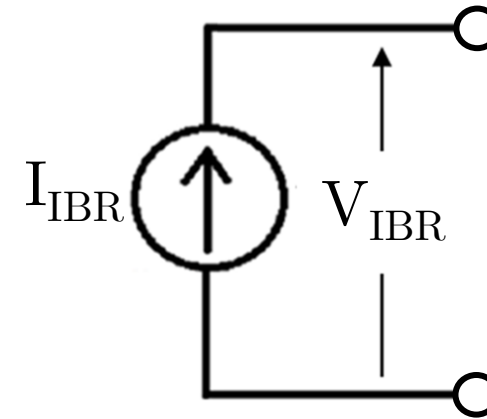
# Inaccuracy of the Classical Model when Applied to IBR

- Accurate solution (benchmarked with EMT)
- Solution with the classical voltage source model with current limit



# IBR Voltage Controlled Current Source Representation

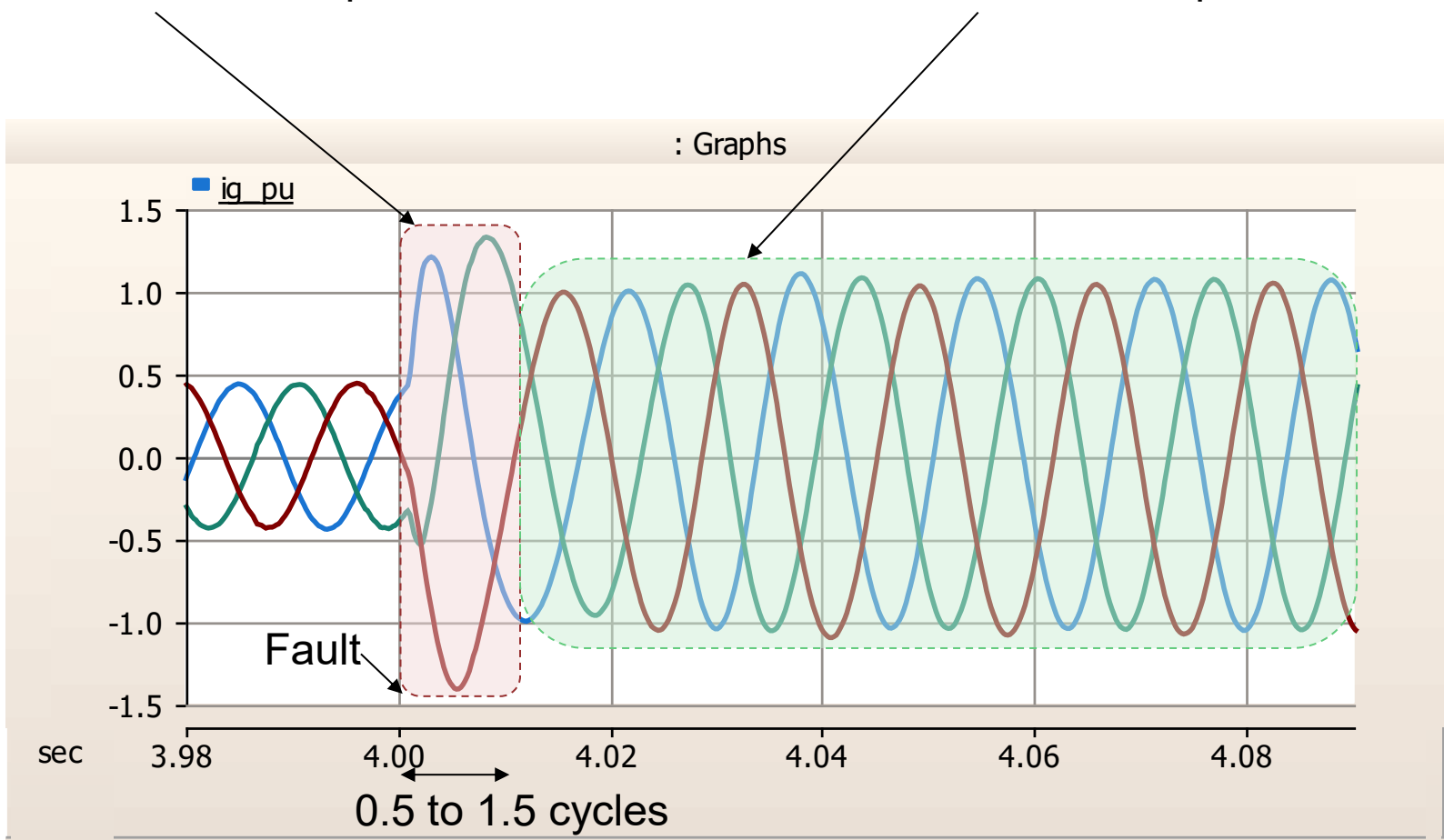
- Recommended by IEEE PSRCC WG C24.
- Phasor domain model  $I_{IBR} = |I_{IBR}| \angle I_{IBR}$
- Model input/output:
  - Input:  $V_{IBR}$
  - Output:  $I_{IBR}$
- Amplitude and phase angle of output current depend on the amplitude of terminal voltage:
  - $I_{IBR} = f(V_{IBR})$
- Model is nonlinear and requires iterative solution:
  - Includes nonlinear IBR control and current limiter.



# Time Scale of IBR Short Circuit Model

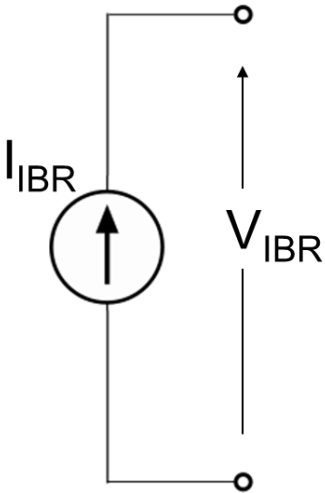
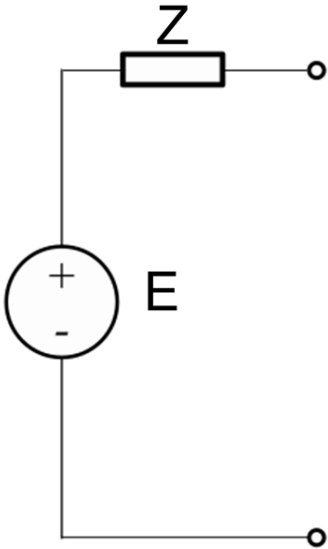
Transient, uncontrolled response

Post-transient, controlled response

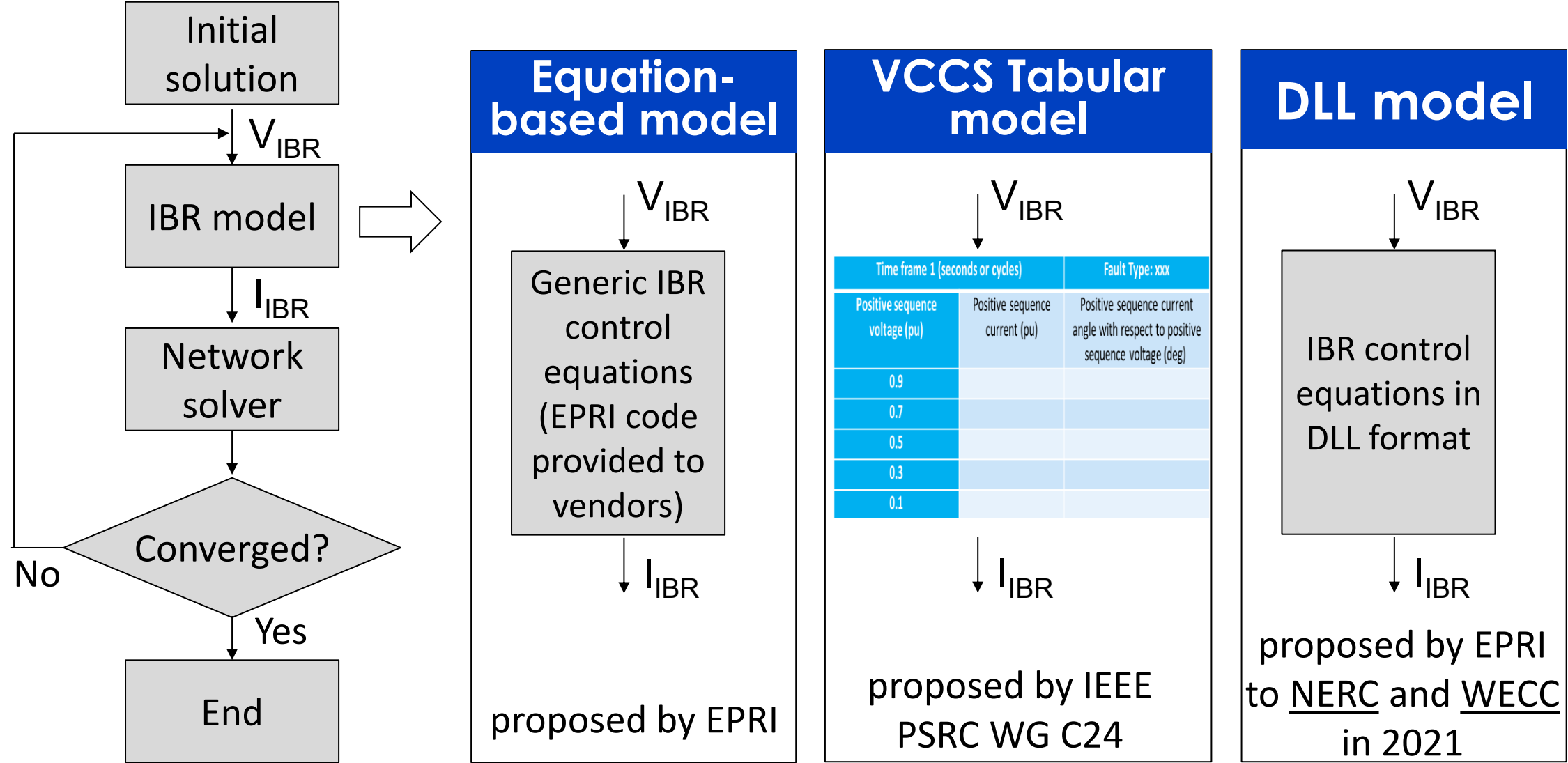


# Short Circuit Model: Synchronous Generator vs. IBR

| Classical model                                                | IBR model                                            |
|----------------------------------------------------------------|------------------------------------------------------|
| Voltage source behind impedance                                | Voltage-dependent current source                     |
| Linear                                                         | Nonlinear                                            |
| Does not require iteration                                     | Requires iteration with network solver               |
| No representation of machine controls                          | Represents IBR control                               |
| No inherent limit on current                                   | Current-limited                                      |
| Parameters depend on electrical characteristics of the machine | Voltage-dependency of current depends on IBR control |



# IBR Short Circuit Model Implementation



Each implementation comes with its own applicability, advantages, and limitations → Applying the models in an informed manner is essential.

# EPRI Type-4 IBR Model – Fact Sheet

## Purpose

- Represents the fault current characteristics of a fully rated converter-based IBR
  - Type-4 wind turbine
  - Solar PV inverter
  - Battery energy storage system

## Modeling Approach

- Uses a voltage controlled current source representation
- Provides an aggregate IBR park model
- Phasor-domain representation → Models fundamental frequency current
- Captures post-transient fault current response

## Control Method

- Implements a generic IBR control model
- With parameterization, can reflect manufacturer-specific fault behavior with reasonable accuracy
- Aligned with IEEE Std 2800™-2022 IBR fault ride-through requirements

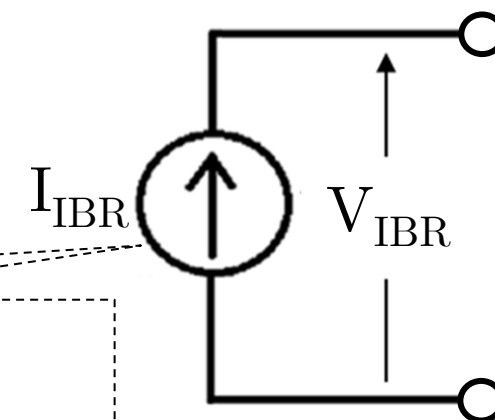
## Sequence Components

- Includes positive and negative sequence fault currents

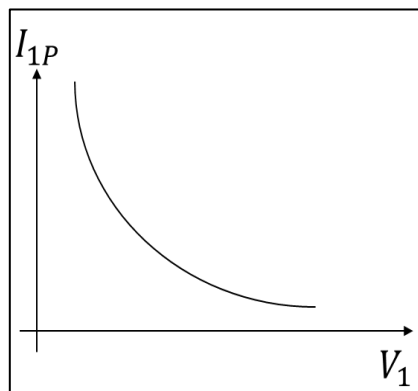
# A Generic IBR FRT Control

- Four main functions:

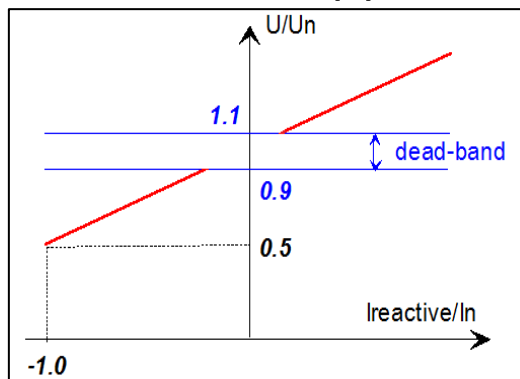
1. Dynamic Positive Sequence Active Current;
2. Dynamic Positive Sequence Reactive Current Support;
3. Dynamic Negative Sequence Reactive Current Support;
4. Current Limiter.



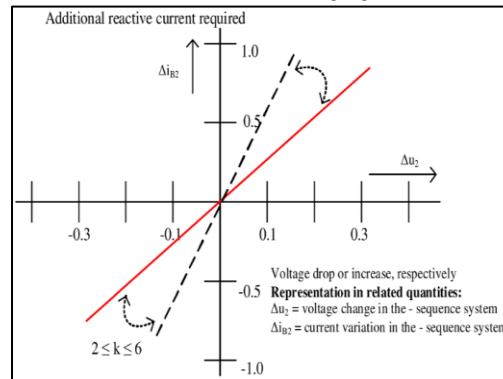
Dynamic Positive Sequence Active Current



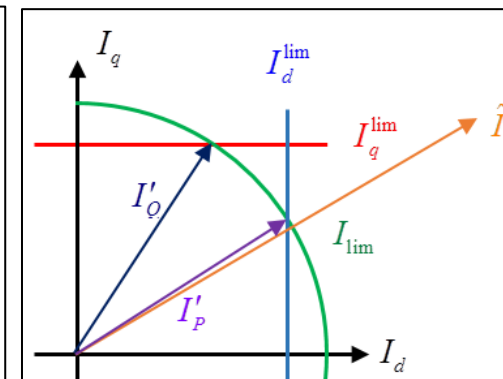
Dynamic Positive Sequence Reactive Current Support



Dynamic Negative Sequence Reactive Current Support



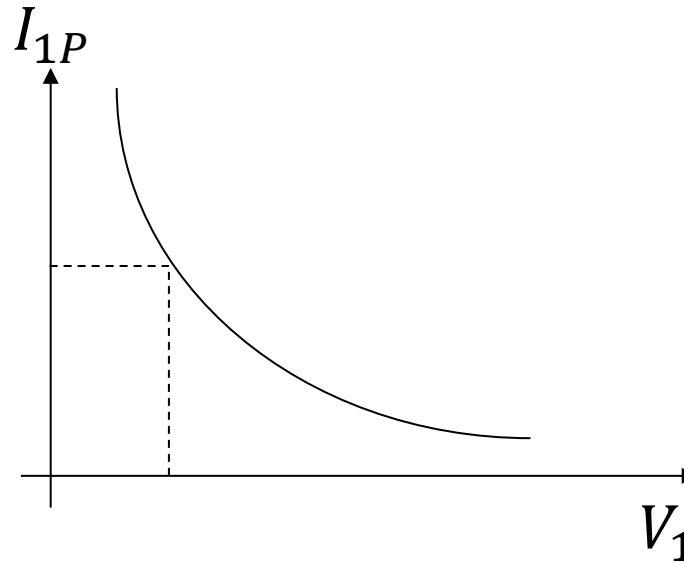
Current Limiter



# Positive Sequence Active Current

- IBR *tries* to maintain prefault output active power:

- $I_{1P} = \frac{P_{prefault}}{V_1}$ .

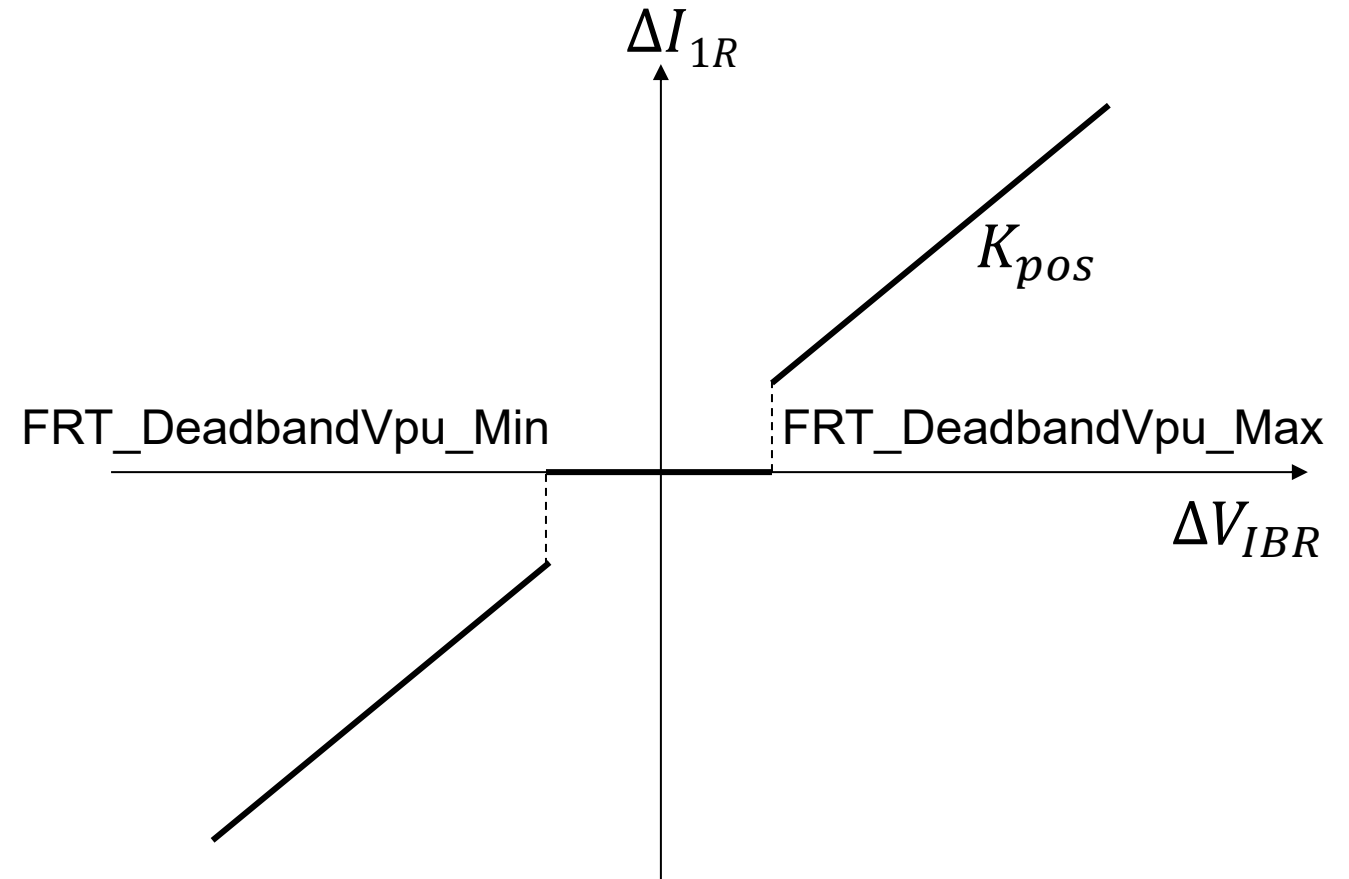


Example: For  $P_{prefault} = 1$  p.u. and  $V_1 = 0.5$  p.u.:

$$I_{1P} = \frac{1}{0.5} = 2 \text{ p.u.}$$

# Dynamic Positive Sequence Reactive Current Support

- Implements the k-factor control:
  - $\Delta I_{1R} = -K_{pos} \Delta V_{IBR}$ .
- How  $\Delta V_{IBR}$  is calculated:
  - Method 1:  $\Delta V_{IBR} = |V_{1,prefault} - V_1|$ ;
  - Method 2:  $\Delta V_{IBR} = |1 - V_1|$   
→ Aligned with IEEE 2800.

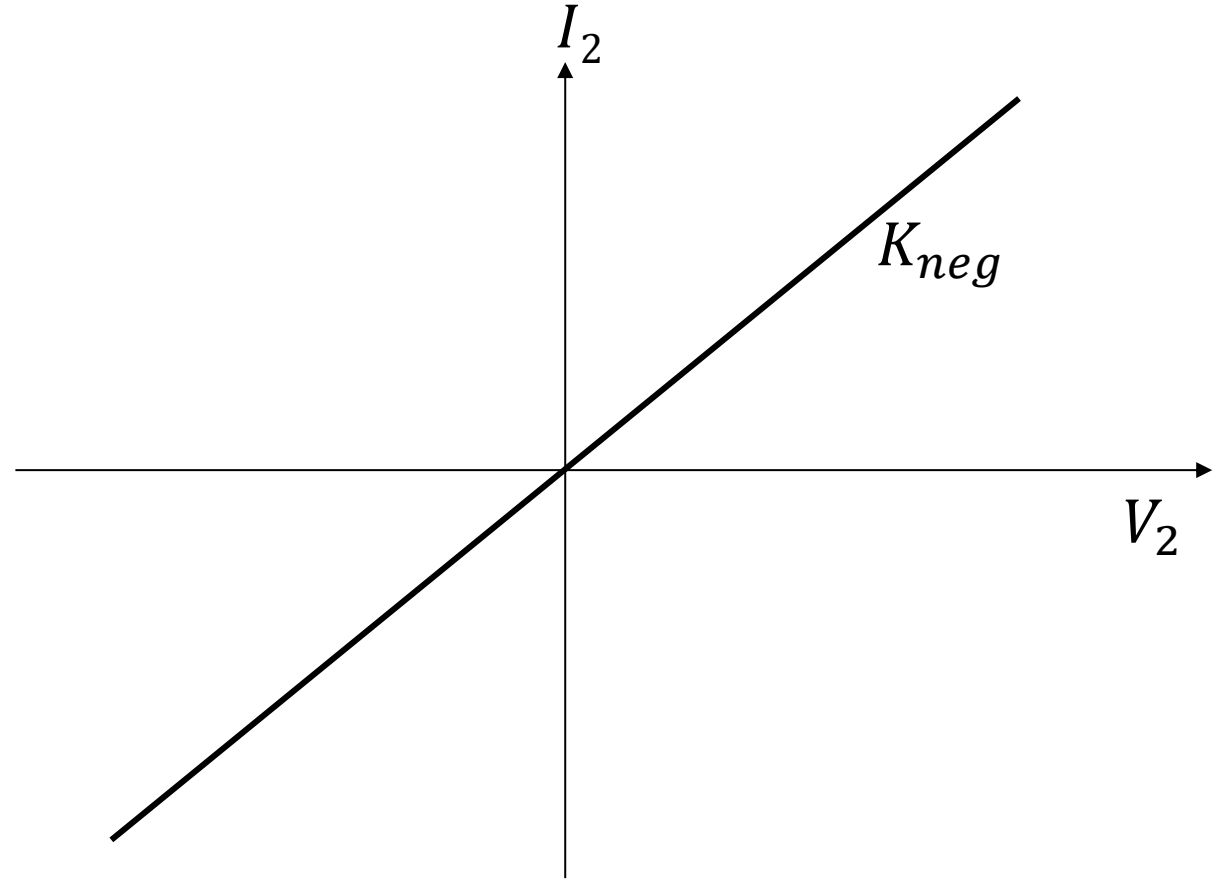


Example: For  $V_1 = 0.5$  p.u and  $K_{pos} = 2$  under Method 2:  
 $\Delta I_{1R} = -2 * (1 - 0.5) = -1$  p.u.

# Dynamic Negative Sequence Reactive Current Support

- Implements the k-factor control:

- $|I_2| = K_{neg}|V_2|$
- $\angle I_2 = \angle V_2 + 90^\circ$



Example: For  $V_2 = 0.25$  p.u. and  $K_{neg} = 2$   
 $|I_2| = 2 * 0.25 = 0.5$  p.u.

# Current Limiter

$$\begin{aligned}I_{1P} &= 2 \text{ p.u.} \\ \Delta I_{1R} &= -1 \text{ p.u.} \\ I_2 &= 0.5 \text{ p.u.}\end{aligned}$$

But the inverter current limit is 1.1 p.u.

- Current limiter implementation is not standardized → Implementation details vary depending on the manufacturer.
- IEEE Std 2800-2022 requirements:
  - Reactive current is prioritized;
  - Equal reduction of incremental positive sequence & negative sequence reactive currents when current limit is reached;
  - The amplitude of negative sequence reactive current is limited to that of the incremental positive sequence reactive current;
  - Any remaining current capacity is given to positive sequence active current;
  - An option is provided to maximize current injection up to the inverter's current limit.

# Current Limiter

## Example:

- $V_1 = 0.5 \angle 0^\circ$  p.u.
- $V_2 = 0.25 \angle 30^\circ$  p.u.
- $K_{pos} = K_{neg} = 2$
- $I_{max} = 1.1$  p.u.
- $I_{1P} = 2$  p.u.
- $\Delta I_{1R} = -1$  p.u.
- $I_2 = 0.5 \angle 120^\circ$  p.u.
- $I_{R,total} = 1.5$  p.u.
- $I_{1,desired} = 2 - j1$  p.u.
- $I_{2,desired} = -0.25 + j0.43$  p.u.

## Current limiter steps:

- **Step 1:** Check  $|I_2| < \Delta I_{1R}$
- **Step 2:**  $\Delta I_{1R} = -1 * 1.1 / 1.5 = -0.73$  pu  
 $|I_2| = 0.5 * 1.1 / 1.5 = 0.37$  pu
- **Step 3:**  $I_{1P} = \sqrt{I_{max}^2 - I_{r,total}^2} = 0$
- **Output:**  $I_1 = 0.73 \angle -90^\circ$  pu  
 $I_2 = 0.37 \angle 210^\circ$  pu  
 $I_A = 0.45 \angle -113.79^\circ$  pu  
 $I_B = 0.82 \angle 176.57^\circ$  pu  
 $I_C = 1.07 \angle 20.10^\circ$  pu

# Current Limiter & Maximization

## Example:

- $V_1 = 0.5 \angle 0^\circ$  p.u.
- $V_2 = 0.25 \angle 30^\circ$  p.u.
- $K_{pos} = K_{neg} = 2$
- $I_{max} = 1.1$  p.u.
- $I_{1P} = 2$  p.u.
- $\Delta I_{1R} = -1$  p.u.
- $I_2 = 0.5 \angle 120^\circ$  p.u.
- $I_{R,total} = 1.5$  p.u.
- $I_{1,desired} = 2 - j1$  p.u.
- $I_{2,desired} = -0.25 + j0.43$  p.u.

## Current limiter steps:

- **Step 1:** Check  $|I_2| < \Delta I_{1R}$
- **Step 2:**  $\Delta I_{1R} = -1 * 1.1 / 1.5 = -0.73$  pu  
 $|I_2| = 0.5 * 1.1 / 1.5 = 0.37$  pu
- **Step 3:**  $I_{1P} = \sqrt{I_{max}^2 - I_{r,total}^2} = 0$
- **Step 4:**  $I_{ABC,max} = 1.07 < 1.1$  pu  
scale\_phmax =  $1.1 / 1.07 = 1.028$   
 $|I_A| = 0.45 * \text{scale\_phmax} \rightarrow I_A = 0.46 \angle -113.79^\circ$  pu  
 $|I_B| = 0.82 * \text{scale\_phmax} \rightarrow I_B = 0.84 \angle 176.57^\circ$  pu  
 $|I_C| = 1.07 * \text{scale\_phmax} \rightarrow I_C = 1.10 \angle 20.10^\circ$  pu

# Role of Prefault Reactive Power

- Determines the available reactive current headroom

$$I_{R,prefault} = -\frac{Q_{prefault}}{V_{1,prefault}}$$

$$I_{R,headroom} = I_{max} + I_{R,prefault}$$

- Is added to the limited incremental positive sequence current.

Example with  $Q_{prefault}=0.1$  pu

$$I_{R,prefault} = -0.1 \text{ pu}$$

$$I_{R,headroom} = 1.1 + (-0.1) = 1 \text{ pu}$$

- **Step 1:** Check  $I_2 < \Delta I_{1R}$
- **Step 2:**  $\Delta I_{1R} = -1 * 1 / 1.5 = -0.67$  pu

$$I_2 = 0.5 * 1 / 1.5 = 0.33 \text{ pu}$$

- **Step 3:**  $I_{1P} = \sqrt{I_{max}^2 - I_{r,total}^2} = 0$
- **Output:**  $I_1 = 0.77 \angle -90^\circ$  pu

$$I_2 = 0.33 \angle 120^\circ \text{ pu}$$

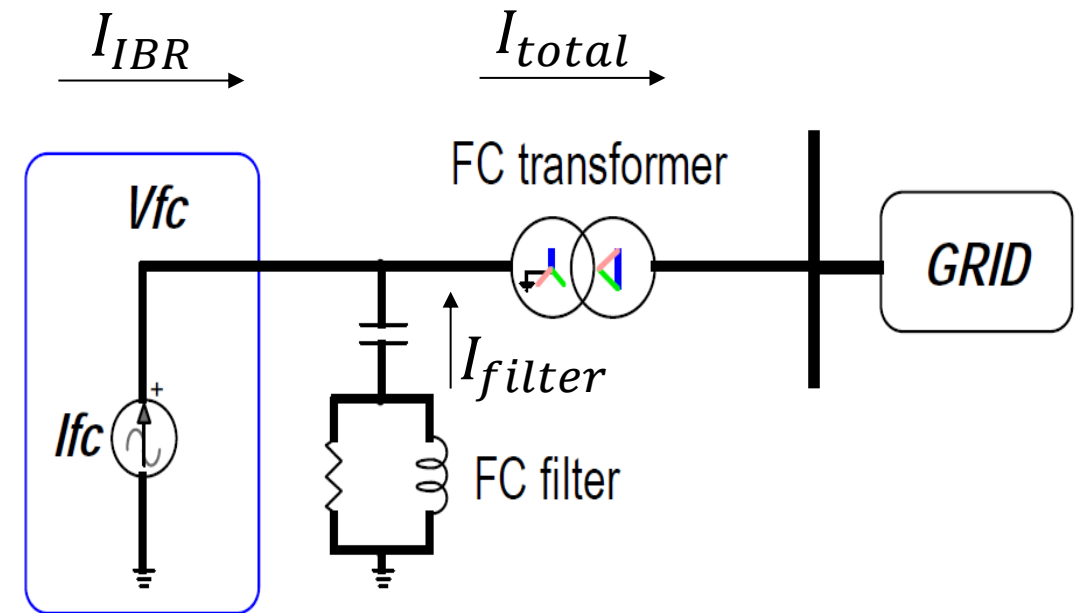
$$I_A = 0.51 \angle -109.22^\circ \text{ pu}$$

$$I_B = 0.84 \angle 173.50^\circ \text{ pu}$$

$$I_C = 1.07 \angle 21.03^\circ \text{ pu}$$

# Role of Shunt Filter

- Filters switching harmonics in an actual IBR.
- At the fundamental frequency, the shunt filter acts like a shunt capacitor.
- The filter current augments the IBR output current.
  - $I_{total} = I_{IBR} + I_{filter}$
- Typically:  $Z_{filter} = -j25$  pu (at 60 Hz)



# Practical Considerations

- $K_{pos}$  is typically set between 2 and 10 with a default value of 2:
  - Larger values result in higher reactive current and less room for active current injection.
- $K_{neg}$  is typically set between 2 and 6 with a default value of 2:
  - $K_{neg}$  is typically less than or equal to  $K_{pos}$ ;
  - Even with a larger  $K_{neg}$ , the amplitude of -seq current is still limited to that of incremental +seq reactive current.
- FRT deadband is typically between 0.95 pu and 1.05 pu.
- The shunt filter can be neglected with minimal impact on accuracy;
  - Can be done by setting  $Z_{xfilter\_pu}$  to a large value.
- The model's accuracy may be limited for manufacturer-specific IBRs not aligned with IEEE Std 2800.

# Model Validation – Case Study 1

- Inverter OEM conforms with IEEE 2800.
- The results show an acceptable consistency.
- Relevant IEEE 2800-2022 requirements are met.

| Fault Type              | OEM Model - Voltage         | Quantity                 | Lab Inverter - Data | EPRI Model - Limiter Option 1 (Error) |
|-------------------------|-----------------------------|--------------------------|---------------------|---------------------------------------|
| Case 1<br>(LL_V30_SCR5) | $ V_1  = 0.7052 \text{ pu}$ | $ I_1 $                  | 0.6026 pu           | 0.6354 pu (5.17 %)                    |
|                         |                             | $\angle \frac{I_1}{V_1}$ | $-42.4800^\circ$    | $-41.3200^\circ$ (2.81%)              |
|                         | $ V_2  = 0.3023 \text{ pu}$ | $ I_2 $                  | 0.4006 pu           | 0.4195 pu (4.51 %)                    |
|                         |                             | $\angle \frac{I_2}{V_2}$ | $90.3768^\circ$     | $90.0000^\circ$ (0.42 %)              |
| Case 2<br>(LL_V50_SCR5) | $ V_1  = 0.7860 \text{ pu}$ | $ I_1 $                  | 0.5031 pu           | 0.4984 pu (0.94 %)                    |
|                         |                             | $\angle \frac{I_1}{V_1}$ | $-28.4511^\circ$    | $-27.2300^\circ$ (4.48 %)             |
|                         | $ V_2  = 0.2224 \text{ pu}$ | $ I_2 $                  | 0.2326 pu           | 0.2280 pu (2.03%)                     |
|                         |                             | $\angle \frac{I_2}{V_2}$ | $90.3044^\circ$     | $90.0000^\circ$ (0.34 %)              |
| Case 3<br>(LL_V70_SCR5) | $ V_1  = 0.8663 \text{ pu}$ | $ I_1 $                  | 0.4459 pu           | 0.4483 pu (0.52%)                     |
|                         |                             | $\angle \frac{I_1}{V_1}$ | $-9.3227^\circ$     | $-8.6600^\circ$ (7.65 %)              |
|                         | $ V_2  = 0.1414 \text{ pu}$ | $ I_2 $                  | 0.0671 pu           | 0.0674 pu (0.38 %)                    |
|                         |                             | $\angle \frac{I_2}{V_2}$ | $90.5418^\circ$     | $90.0000^\circ$ (0.60 %)              |

# Model Validation – Case Study 2

- Inverter OEM does not fully conform with IEEE 2800.
- Differences are due to this non-conformity → confirmed with manufacturer.

| Fault Type | OEM Model - Voltage         | Quantity                 | OEM Model - Data | EPRI Model - Limiter Option 1 (Error) | EPRI Model - Limiter Option 2 (Error) |
|------------|-----------------------------|--------------------------|------------------|---------------------------------------|---------------------------------------|
| AG         | $ V_1  = 0.7564 \text{ pu}$ | $ I_1 $                  | 0.5773 pu        | 0.6497 pu (12.54%)                    | 0.5627 pu (2.52%)                     |
|            |                             | $\angle \frac{I_1}{V_1}$ | $-91.1524^\circ$ | $-90.0000^\circ$ (1.26%)              | $-90.0000^\circ$ (1.26%)              |
|            | $ V_2  = 0.2326 \text{ pu}$ | $ I_2 $                  | 0.5513 pu        | 0.6204 pu (12.53%)                    | 0.5373 pu (2.54%)                     |
|            |                             | $\angle \frac{I_2}{V_2}$ | $90.2147^\circ$  | $90.0000^\circ$ (0.24%)               | $90.0000^\circ$ (0.24%)               |
| BC         | $ V_1  = 0.5654 \text{ pu}$ | $ I_1 $                  | 0.5740 pu        | 0.6415 pu (11.76%)                    | 0.5556 pu (3.21%)                     |
|            |                             | $\angle \frac{I_1}{V_1}$ | $-90.6350^\circ$ | $-90.0000^\circ$ (1.26%)              | $-90.0000^\circ$ (1.26%)              |
|            | $ V_2  = 0.4259 \text{ pu}$ | $ I_2 $                  | 0.5443 pu        | 0.6286 pu (15.49%)                    | 0.5444 pu (0.02%)                     |
|            |                             | $\angle \frac{I_2}{V_2}$ | $89.9996^\circ$  | $90.0000^\circ$ (0.24%)               | $90.0000^\circ$ (0.24%)               |

# EPRI Type-3 IBR Model – Fact Sheet

## Purpose

- Represents the fault current characteristics of a Type-3 wind turbine

## Modeling Approach

- Uses a voltage controlled current source representation
- Provides an aggregate IBR park model
- Phasor-domain representation → Models fundamental frequency current
- Captures post-transient fault current response

## Control Method

- Implements a generic IBR control model
- With parameterization, can reflect manufacturer-specific fault behavior with reasonable accuracy
- Aligned with IEEE Std 2800™-2022 IBR fault ride-through requirements

## Sequence Components

- Includes positive and negative sequence fault currents

# Model Algorithm

- The Type-3 model is more complex (in terms of equations & algorithm) than the Type-4 model.
- Step 1: Calculate the stator current:
  - Step 1.1: Calculate the desired q-axis\* component of rotor-side converter (RSC) current (active) based on prefault MW;
  - Step 1.2: Calculate the desired d-axis\* component of RSC current (reactive);
    - Step 1.2.1: first calculate the stator reactive current based on control mode;
    - Step 1.2.2: Translate that into RSC d-axis current.
  - Step 1.3: Limit the RSC current to converter's limit (typically 0.35pu);
    - Similar to Step 1 to Step 3 of the EPRI IBR Type-4 model.
  - Step 1.4: The limited RSC currents are then translated into stator currents;
- Step 2: Calculate the grid-side converter (GSC) current:
  - Similar to the EPRI IBR Type-4 model.
- Step 3: Output current = stator current + GSC current.

\*Note: For the RSC current calculation, d-axis is reactive current and q-axis is active current.

# DLL Model Framework

- **Purpose:**

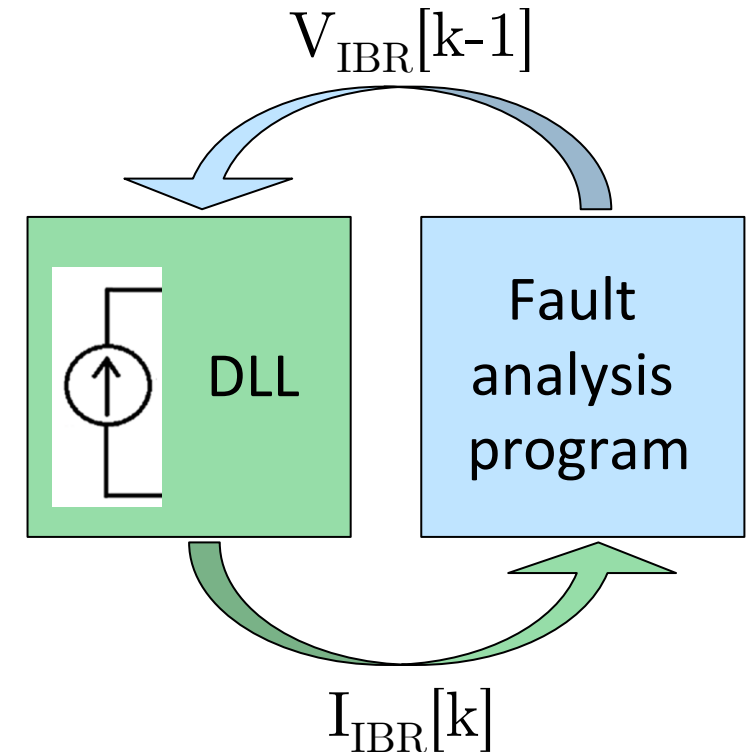
- Integrate manufacturer-specific or user-defined IBR models into commercial fault analysis programs via a DLL interface.

- **Key Features:**

- Represents IBR as a voltage-controlled current source:
  - Calculates amplitude and phase angle of IBR fault current based on terminal voltage and user-defined control equations in the phasor domain.
- Supports alternative representations (e.g., voltage source) → Compatible with GFM and GFL inverter controls.

- **Current Status:**

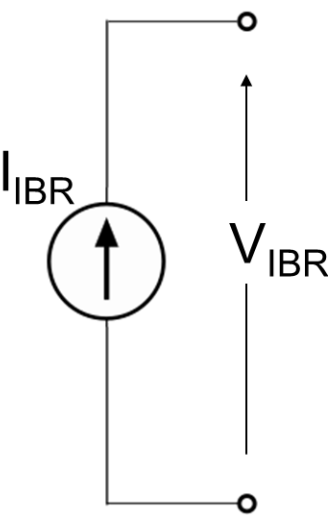
- Beta version DLL implemented in commercial programs.
- Industry adoption requires collaboration between IBR manufacturers and software vendors.



# VCCS Tabular Model

- Allows IBR manufacturers to provide short circuit data without revealing proprietary inverter control.
- Manufacturer provides a tabular output of positive and negative sequence voltages, currents, and power factors at the machine terminals.
- Tabular data structure indicates voltage dependency of current.
- Model is agnostic to control.

## C24 –recommended table for WTG short circuit model in commercial platforms



| Time frame 1 (seconds or cycles) |                                | Fault Type:                                                                     |
|----------------------------------|--------------------------------|---------------------------------------------------------------------------------|
| Positive sequence voltage (pu)   | Positive sequence current (pu) | Positive sequence current angle with respect to positive sequence voltage (deg) |
| 1.0                              |                                |                                                                                 |
| 0.9                              |                                |                                                                                 |
| 0.8                              |                                |                                                                                 |
| 0.7                              |                                |                                                                                 |
| 0.6                              |                                |                                                                                 |
| 0.5                              |                                |                                                                                 |
| 0.4                              |                                |                                                                                 |
| 0.3                              |                                |                                                                                 |
| 0.2                              |                                |                                                                                 |
| 0.1                              |                                |                                                                                 |

| Time frame 1 (seconds or cycles) |                                | Fault Type:                                                                     |
|----------------------------------|--------------------------------|---------------------------------------------------------------------------------|
| Negative sequence voltage (pu)   | Negative sequence current (pu) | Negative sequence current angle with respect to negative sequence voltage (deg) |
| 1.0                              |                                |                                                                                 |
| 0.9                              |                                |                                                                                 |
| 0.8                              |                                |                                                                                 |
| 0.7                              |                                |                                                                                 |
| 0.6                              |                                |                                                                                 |
| 0.5                              |                                |                                                                                 |
| 0.4                              |                                |                                                                                 |
| 0.3                              |                                |                                                                                 |
| 0.2                              |                                |                                                                                 |
| 0.1                              |                                |                                                                                 |



# Features of VCCS Tabular Model

- Table can represent balanced and unbalanced faults
  - sequence domain (positive, negative and zero sequence) or
  - phase domain (phase A, B and C)
- Sequence domain table is preferred.

| Positive sequence:<br>After two cycles |        |                         |
|----------------------------------------|--------|-------------------------|
| Magnitude [pu]                         |        | Angle [deg]             |
| Vp                                     | Ip     | $\angle Vp - \angle Ip$ |
| 0.7876                                 | 1.1760 | 21.8530                 |
| 0.7979                                 | 1.1924 | 19.6035                 |
| 0.8105                                 | 1.1846 | 18.3179                 |
| 0.8243                                 | 1.1726 | 17.0125                 |
| 0.8386                                 | 1.1522 | 15.5151                 |
| 0.8584                                 | 1.1349 | 13.4458                 |
| 0.8791                                 | 1.1087 | 11.2699                 |
| 0.9046                                 | 1.0892 | 7.8513                  |
| 0.9255                                 | 1.0924 | 1.3338                  |
| 0.9581                                 | 1.0518 | -2.5559                 |
| 0.9718                                 | 1.0385 | -11.9985                |

| Negative sequence:<br>After two cycles |        |                         |
|----------------------------------------|--------|-------------------------|
| Magnitude [pu]                         |        | Angle [deg]             |
| Vn                                     | In     | $\angle Vn - \angle In$ |
| 0.2002                                 | 0.3426 | 21.8530                 |
| 0.1943                                 | 0.3223 | 19.6035                 |
| 0.1868                                 | 0.3107 | 18.3179                 |
| 0.1784                                 | 0.3002 | 17.0125                 |
| 0.1693                                 | 0.2838 | 15.5151                 |
| 0.1561                                 | 0.2680 | 13.4458                 |
| 0.1411                                 | 0.2433 | 11.2699                 |
| 0.1201                                 | 0.2194 | 7.8513                  |
| 0.0992                                 | 0.1911 | 1.3338                  |
| 0.0603                                 | 0.1174 | -2.5559                 |
| 0.0311                                 | 0.0600 | -11.9985                |

Presently Siemens APA provides only 1 table for positive sequence quantities.

# Features of VCCS Tabular Model – Cont'd

- Since response of IBR control may be time dependent, separate tables may be provided for various time-frames (e.g., 1 cycle, 3 cycles, 5 cycles).

| Positive sequence: |        |             |                  |        |             |                   |        |             |
|--------------------|--------|-------------|------------------|--------|-------------|-------------------|--------|-------------|
| After one cycle    |        |             | After two cycles |        |             | After five cycles |        |             |
| Magnitude [pu]     |        | Angle [deg] | Magnitude [pu]   |        | Angle [deg] | Magnitude [pu]    |        | Angle [deg] |
| Vp                 | Ip     | ∠Vp - ∠Ip   | Vp               | Ip     | ∠Vp - ∠Ip   | Vp                | Ip     | ∠Vp - ∠Ip   |
| 0.8054             | 1.1888 | 12.0715     | 0.7876           | 1.1760 | 21.8530     | 0.7789            | 0.9209 | 35.4431     |
| 0.8154             | 1.2030 | 10.1268     | 0.7979           | 1.1924 | 19.6035     | 0.7897            | 0.9266 | 32.7271     |
| 0.8270             | 1.2074 | 8.6089      | 0.8105           | 1.1846 | 18.3179     | 0.8030            | 0.9139 | 31.2061     |
| 0.8394             | 1.2080 | 7.0407      | 0.8243           | 1.1726 | 17.0125     | 0.8176            | 0.9012 | 28.7639     |
| 0.8520             | 1.2104 | 5.4620      | 0.8386           | 1.1522 | 15.5151     | 0.8327            | 0.8825 | 26.4088     |
| 0.8690             | 1.2028 | 3.7161      | 0.8584           | 1.1349 | 13.4458     | 0.8535            | 0.8692 | 22.9081     |
| 0.8865             | 1.1917 | 1.6888      | 0.8791           | 1.1087 | 11.2699     | 0.8752            | 0.8657 | 18.5833     |
| 0.9082             | 1.1763 | -0.9331     | 0.9046           | 1.0892 | 7.8513      | 0.9019            | 0.8593 | 13.6866     |
| 0.9274             | 1.1525 | -2.9314     | 0.9255           | 1.0924 | 1.3338      | 0.9235            | 1.0527 | 1.9856      |
| 0.9568             | 1.1038 | -5.9754     | 0.9581           | 1.0518 | -2.5559     | 0.9574            | 1.0145 | -2.1162     |
| 0.9712             | 1.0703 | -11.6987    | 0.9718           | 1.0385 | -11.9985    | 0.9712            | 1.0357 | -12.3578    |

Presently Siemens APA provides only 1 table for positive sequence quantities.

# Features of VCCS Tabular Model – Cont'd

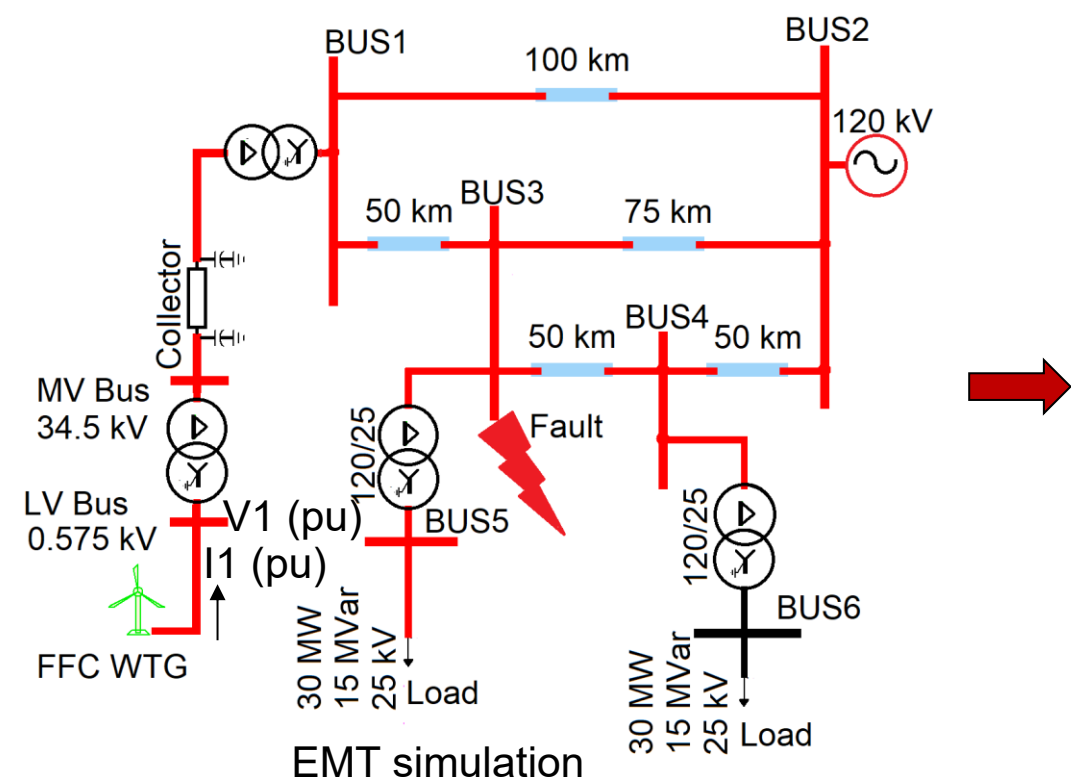
- IBR fault response depends on pre-fault conditions
  - Separate tables may be needed for various pre-fault conditions.
- The manufacturers may provide a separate table (or sets of tables) for different control setting of the converter.
  - Separate tables may be needed for various grid strength conditions.
  - Example in Appendix C of [PES-TR78](#).

Table C.1: Three-phase-to-ground Fault Positive Sequence Voltage-Current for SCR 2

| Time<br>(Cycle) | Parameter    | Residual Voltage Scenario |        |        |        |        |        |        |        |        |       |
|-----------------|--------------|---------------------------|--------|--------|--------|--------|--------|--------|--------|--------|-------|
|                 |              | 1                         | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10    |
| -1              | Voltage (pu) | 1.10                      | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10  |
|                 | Current (pu) | 0.91                      | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91  |
|                 | Angle (Deg)  | 7.70                      | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70  |
| 0               | Voltage (pu) | 1.10                      | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10   | 1.10  |
|                 | Current (pu) | 0.91                      | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91   | 0.91  |
|                 | Angle (Deg)  | 7.69                      | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70   | 7.70  |
| 1               | Voltage (pu) | 0.00                      | 0.13   | 0.25   | 0.39   | 0.53   | 0.65   | 0.75   | 0.84   | 0.93   | 1.02  |
|                 | Current (pu) | 1.59                      | 1.33   | 1.17   | 1.16   | 1.14   | 1.03   | 0.93   | 0.91   | 0.94   | 0.92  |
|                 | Angle (Deg)  | —                         | -62.31 | -56.01 | -51.54 | -49.88 | -48.04 | -33.92 | -18.58 | -7.52  | -0.26 |
| 2               | Voltage (pu) | 0.00                      | 0.09   | 0.20   | 0.31   | 0.43   | 0.62   | 0.75   | 0.87   | 0.96   | 1.04  |
|                 | Current (pu) | 0.41                      | 0.45   | 0.78   | 0.82   | 0.75   | 1.30   | 1.31   | 1.22   | 1.06   | 0.98  |
|                 | Angle (Deg)  | —                         | -71.11 | -46.88 | -42.43 | -41.67 | -34.18 | -29.15 | -25.77 | -17.67 | -4.73 |
| 3               | Voltage (pu) | 0.00                      | 0.13   | 0.26   | 0.39   | 0.53   | 0.68   | 0.81   | 0.92   | 0.99   | 1.05  |
|                 | Current (pu) | 1.22                      | 1.20   | 1.38   | 1.42   | 1.31   | 1.44   | 1.41   | 1.20   | 1.00   | 0.97  |
|                 | Angle (Deg)  | —                         | -84.84 | -59.09 | -54.13 | -52.58 | -47.69 | -41.53 | -34.40 | -21.67 | -5.77 |
| 4               | Voltage (pu) | 0.00                      | 0.13   | 0.25   | 0.38   | 0.53   | 0.68   | 0.82   | 0.95   | 1.02   | 1.05  |
|                 | Current (pu) | 1.33                      | 1.29   | 1.41   | 1.33   | 1.33   | 1.35   | 1.25   | 1.22   | 1.06   | 0.97  |
|                 | Angle (Deg)  | —                         | -81.14 | -52.05 | -54.92 | -52.89 | -46.75 | -44.52 | -38.51 | -24.99 | -6.67 |
| 5               | Voltage (pu) | 0.00                      | 0.12   | 0.23   | 0.38   | 0.52   | 0.66   | 0.81   | 0.95   | 1.02   | 1.06  |
|                 | Current (pu) | 1.21                      | 1.24   | 1.28   | 1.20   | 1.22   | 1.36   | 1.29   | 1.23   | 1.09   | 0.97  |
|                 | Angle (Deg)  | —                         | -78.92 | -51.20 | -65.27 | -59.05 | -42.08 | -40.84 | -37.08 | -25.29 | -7.43 |
| 6               | Voltage (pu) | 0.00                      | 0.12   | 0.24   | 0.38   | 0.53   | 0.65   | 0.80   | 0.95   | 1.03   | 1.06  |
|                 | Current (pu) | 1.20                      | 1.15   | 1.21   | 1.15   | 1.18   | 1.37   | 1.33   | 1.26   | 1.10   | 0.97  |
|                 | Angle (Deg)  | —                         | -83.61 | -58.28 | -76.48 | -63.98 | -40.17 | -37.79 | -35.04 | -24.68 | -8.12 |

# Data Needed for VCCS Table

- Methods to obtain the values of the table:
  - Provided by manufacturer;
  - Obtained via simulation models, preferably EMT models & simulations
  - Generated through algorithms for generic control modes/logic of IBR (e.g., EPRI VCCS Tool).



+Seq table

| V1 (pu) | I1 (pu) | Angle(I1/V1) (degrees) |
|---------|---------|------------------------|
| 1.00    | 1.00    | 0                      |
| 0.90    | 0.99    | -17                    |
| 0.72    | 0.74    | -50                    |
| 0.70    | 0.62    | -60                    |

# Considerations for the VCCS Tabular Model

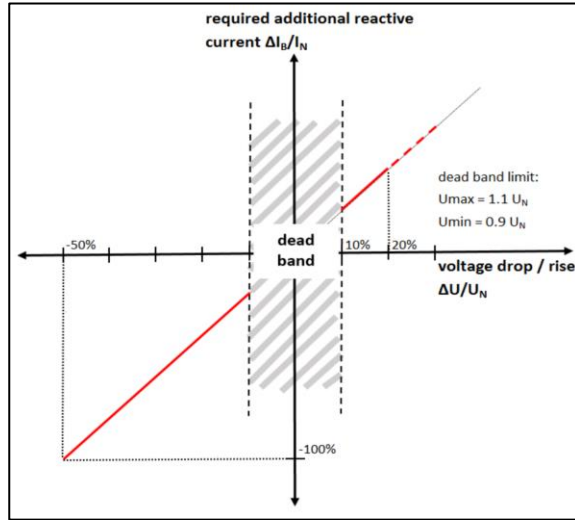
What table format can represent both positive & negative sequence?

|         |         | Time since initiation of a fault (cycles) |                           |         |                           |
|---------|---------|-------------------------------------------|---------------------------|---------|---------------------------|
| V1 (pu) | V2 (pu) | 3 cycles                                  |                           |         |                           |
|         |         | I1 (pu)                                   | Angle(I1/V1)<br>(Degrees) | I2 (pu) | Angle(I2/V2)<br>(Degrees) |
| 0.9     | 0.0     |                                           |                           |         |                           |
|         | 0.1     |                                           |                           |         |                           |
|         | 0.2     |                                           |                           |         |                           |
|         | 0.3     |                                           |                           |         |                           |
|         | 0.4     |                                           |                           |         |                           |
|         | 0.5     |                                           |                           |         |                           |
|         | 0.0     |                                           |                           |         |                           |
|         | 0.1     |                                           |                           |         |                           |
|         | 0.2     |                                           |                           |         |                           |
|         | 0.3     |                                           |                           |         |                           |
|         | 0.4     |                                           |                           |         |                           |
|         | 0.5     |                                           |                           |         |                           |
|         | 0.0     |                                           |                           |         |                           |
|         | 0.1     |                                           |                           |         |                           |
|         | 0.2     |                                           |                           |         |                           |
| 0.7     | 0.3     |                                           |                           |         |                           |
|         | 0.4     |                                           |                           |         |                           |
|         | 0.5     |                                           |                           |         |                           |
|         | 0.0     |                                           |                           |         |                           |
|         | 0.1     |                                           |                           |         |                           |
|         | 0.2     |                                           |                           |         |                           |
|         | 0.3     |                                           |                           |         |                           |
|         | 0.4     |                                           |                           |         |                           |
|         | 0.5     |                                           |                           |         |                           |
|         | 0.0     |                                           |                           |         |                           |
| .....   | .....   | .....                                     | .....                     | .....   | .....                     |



# Sample IBR Fault Ride Through (FRT) Control

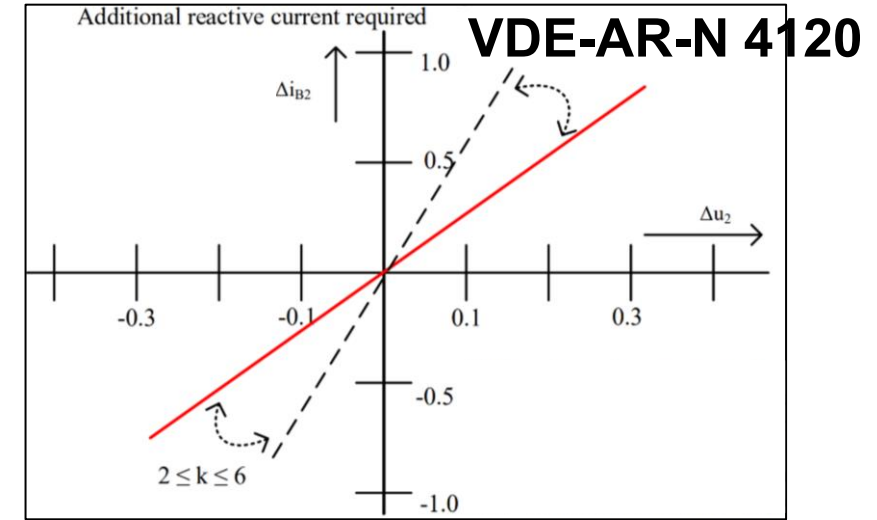
+Seq dynamic reactive current injection



$$I_1 = k_{FRT} * (1 - V_1)$$

Example: For  $V_1 = 0.5$  p.u. and  $k_{FRT} = 2$ ,  $I_1 = 2 * (1 - 0.5) = 1$  p.u.

-Seq dynamic reactive current injection



$$I_2 = k * (V_2)$$

Example: For  $V_2 = 0.25$  p.u. and  $k = 2$ ,  $I_2 = 2 * 0.25 = 0.5$  p.u.

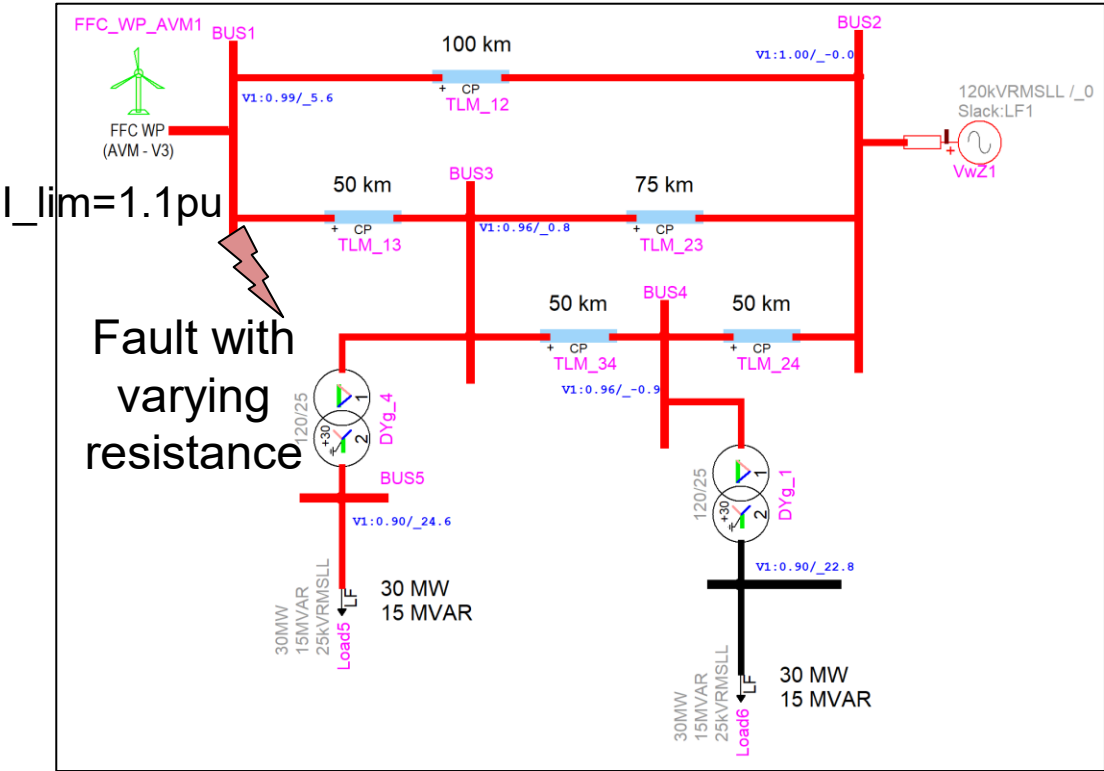
**But the converter current is limited (e.g., 1.1 pu)**

In reality,  $I_1$  and  $I_2$  get limited by the converter current limiter logic.

$I_1$  &  $I_2$  are coupled

# I1 & I2 Coupling Example

- Challenge: Separate tables for +seq and -seq may not provide sufficient accuracy
- Example:
  - +Seq and –Seq tables produced using an EMT IBR model (PSCAD, EMTP, etc)



| +Seq table |         |                        | -Seq table |         |                        |
|------------|---------|------------------------|------------|---------|------------------------|
| V1 (pu)    | I1 (pu) | Angle(I1/V1) (degrees) | V2 (pu)    | I2 (pu) | Angle(I2/V2) (degrees) |
| 1.00       | 1.00    | 0                      | 0.00       | 0.00    | 0                      |
| 0.90       | 0.99    | -17                    | 0.11       | 0.22    | -90                    |
| 0.72       | 0.74    | -50                    | 0.21       | 0.41    | -90                    |
| 0.70       | 0.62    | -60                    | 0.28       | 0.53    | -90                    |

**BUT**  
If the table is used to represent the inverter under a different fault with a different combination of V1 and V2, the table may not give correct I1 and I2 values.

Example: For a fault with V1=0.72 pu and V2=0.28 pu, the table gives I1 = 0.74@-50° and I2=0.53@-90°;

**I1+I2 > 1.1 pu which is not realistic!**

**A joint +seq and -seq table is needed.**

# Negative Sequence Representation in Tabular Model

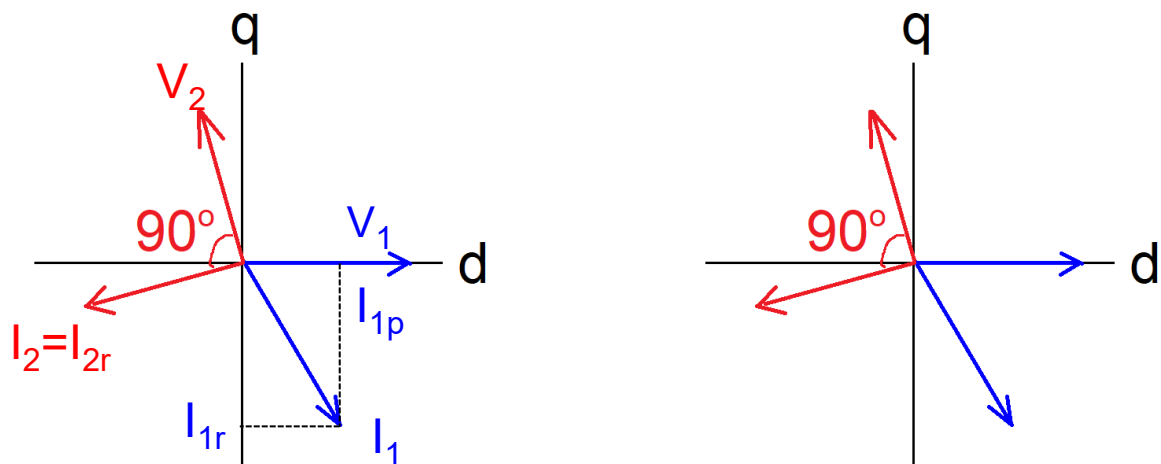
- To account for the coupling between I1 and I2, a joint table is needed.
- What is the format (what quantities does I2 depend on)?
  - V1, I1, angle(I1/V1)
  - V2, I2, angle(I2/V2)
  - angle(V2/V1)
  - etc?

What quantities need to be included in the table for adequate representation of I1 and I2?

|         |         | Time since initiation of a fault (cycles) |                           |         |                           |
|---------|---------|-------------------------------------------|---------------------------|---------|---------------------------|
| V1 (pu) | V2 (pu) | 3 cycles                                  |                           |         |                           |
|         |         | I1 (pu)                                   | Angle(I1/V1)<br>(Degrees) | I2 (pu) | Angle(I2/V2)<br>(Degrees) |
| 0.9     | 0.0     |                                           |                           |         |                           |
|         | 0.1     |                                           |                           |         |                           |
|         | 0.2     |                                           |                           |         |                           |
|         | 0.3     |                                           |                           |         |                           |
|         | 0.4     |                                           |                           |         |                           |
|         | 0.5     |                                           |                           |         |                           |
| 0.8     | 0.0     |                                           |                           |         |                           |
|         | 0.1     |                                           |                           |         |                           |
|         | 0.2     |                                           |                           |         |                           |
|         | 0.3     |                                           |                           |         |                           |
|         | 0.4     |                                           |                           |         |                           |
|         | 0.5     |                                           |                           |         |                           |
| 0.7     | 0.0     |                                           |                           |         |                           |
|         | 0.1     |                                           |                           |         |                           |
|         | 0.2     |                                           |                           |         |                           |
|         | 0.3     |                                           |                           |         |                           |
|         | 0.4     |                                           |                           |         |                           |
|         | 0.5     |                                           |                           |         |                           |
| .....   | .....   | .....                                     | .....                     | .....   | .....                     |



# Current Limiter Options 1 & 3 – Tabular Model

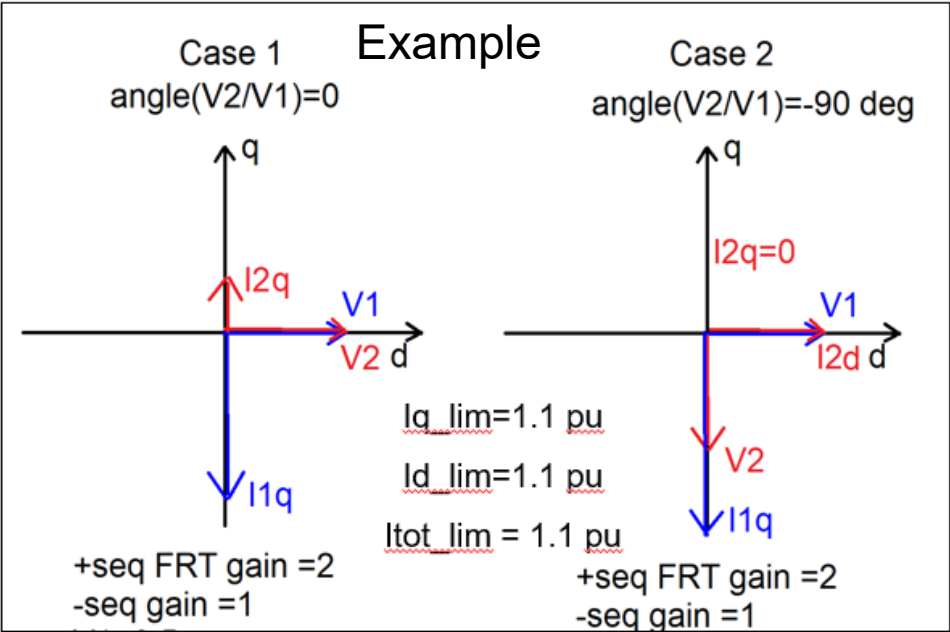


- Current limit is applied to active and reactive currents: ( $I_1 = I_{1p} + j \cdot I_{1r}$ ,  $I_2 = I_{2r}$ )
- $I_2$  depends on  $V_1$ ,  $V_2$

| V1 (pu) | V2 (pu) | Time since initiation of a fault (cycles) |                        |         |                        |
|---------|---------|-------------------------------------------|------------------------|---------|------------------------|
|         |         | 3 cycles                                  |                        |         |                        |
|         |         | I1 (pu)                                   | Angle(I1/V1) (Degrees) | I2 (pu) | Angle(I2/V2) (Degrees) |
| 0.9     | 0.0     |                                           |                        |         |                        |
|         | 0.1     |                                           |                        |         |                        |
|         | 0.2     |                                           |                        |         |                        |
|         | 0.3     |                                           |                        |         |                        |
|         | 0.4     |                                           |                        |         |                        |
|         | 0.5     |                                           |                        |         |                        |
| 0.8     | 0.0     |                                           |                        |         |                        |
|         | 0.1     |                                           |                        |         |                        |
|         | 0.2     |                                           |                        |         |                        |
|         | 0.3     |                                           |                        |         |                        |
|         | 0.4     |                                           |                        |         |                        |
|         | 0.5     |                                           |                        |         |                        |
| 0.7     | 0.0     |                                           |                        |         |                        |
|         | 0.1     |                                           |                        |         |                        |
|         | 0.2     |                                           |                        |         |                        |
|         | 0.3     |                                           |                        |         |                        |
|         | 0.4     |                                           |                        |         |                        |
|         | 0.5     |                                           |                        |         |                        |
| .....   | .....   | .....                                     | .....                  | .....   | .....                  |

# Current Limiter Option 2 – Tabular Model

- Current limit is applied to d- and q-axis current components
- I2 depends on V1, V2, and angle(V2/V1).



|                                   | V1<br>(pu) | V2<br>(pu) | I1q<br>(pu) | I1d<br>(pu) | I2q<br>(pu) | I2d<br>(pu) |
|-----------------------------------|------------|------------|-------------|-------------|-------------|-------------|
| Case 2:<br>angle(V2/V1) = -90 deg | 0.5        | 0.5        | 0.73        | 0           | 0.37        | 0           |
| Case 1:<br>angle(V2/V1)= 0 deg    | 0.5        | 0.5        | 1           | 0           | 0           | 0.47        |

| V1 (pu) | V2 (pu) | Angle(V2/V1) | Time since initiation of a fault (cycles) |                           |         |                           |
|---------|---------|--------------|-------------------------------------------|---------------------------|---------|---------------------------|
|         |         |              | 3 cycles                                  |                           |         |                           |
|         |         |              | I1 (pu)                                   | Angle(I1/V1)<br>(Degrees) | I2 (pu) | Angle(I2/V2)<br>(Degrees) |
| 0.9     | 0.0     | 0            |                                           |                           |         |                           |
|         |         | 60           |                                           |                           |         |                           |
|         |         | 120          |                                           |                           |         |                           |
|         |         | 180          |                                           |                           |         |                           |
|         |         | 240          |                                           |                           |         |                           |
|         |         | 300          |                                           |                           |         |                           |
|         |         | 0            |                                           |                           |         |                           |
|         |         | 60           |                                           |                           |         |                           |
|         |         | 120          |                                           |                           |         |                           |
|         |         | 180          |                                           |                           |         |                           |
|         |         | 240          |                                           |                           |         |                           |
|         |         | 300          |                                           |                           |         |                           |
|         | 0.1     | 0            |                                           |                           |         |                           |
|         |         | 60           |                                           |                           |         |                           |
|         |         | 120          |                                           |                           |         |                           |
|         |         | 180          |                                           |                           |         |                           |
|         |         | 240          |                                           |                           |         |                           |
|         |         | 300          |                                           |                           |         |                           |
|         | 0.2     | 0            |                                           |                           |         |                           |
|         |         | 60           |                                           |                           |         |                           |
|         |         | 120          |                                           |                           |         |                           |
|         |         | 180          |                                           |                           |         |                           |
|         |         | 240          |                                           |                           |         |                           |
|         |         | 300          |                                           |                           |         |                           |
|         | .....   | .....        | .....                                     | .....                     | .....   | .....                     |
|         |         | .....        | .....                                     | .....                     | .....   | .....                     |
|         |         | .....        | .....                                     | .....                     | .....   | .....                     |
|         |         | .....        | .....                                     | .....                     | .....   | .....                     |

# Suggested Table

- Generate a table for V1,V2,I1,I2 only
- Ignore the dependence on angle(V2/V1)
- There might be some error depending on the current limiter logic implementation

| angle(V2/V1)=0 |            |            |                  |            |                  |
|----------------|------------|------------|------------------|------------|------------------|
| V1<br>(pu)     | V2<br>(pu) | I1<br>(pu) | Angle<br>(I1/V1) | I2<br>(pu) | Angle<br>(I2/V2) |
| 0.9            | 0.0        | 1.00       | -10.52           | 0.00       | 0.00             |
|                | 0.1        | 1.04       | -11.09           | 0.20       | 90.00            |
|                | 0.2        | 0.94       | -12.29           | 0.40       | 90.00            |
|                | 0.3        | 0.78       | -14.89           | 0.60       | 90.00            |
|                | 0.4        | 0.50       | -23.66           | 0.80       | 90.00            |
|                | 0.5        | 0.18       | -90.00           | 0.92       | 90.00            |
|                | 0.6        | 0.16       | -90.00           | 0.94       | 90.00            |
|                | 0.7        | 0.14       | -90.00           | 0.96       | 90.00            |
|                | 0.8        | 0.12       | -90.00           | 0.98       | 90.00            |
|                | 0.9        | 0.11       | -90.00           | 0.99       | 90.00            |
| 0.8            | 0.0        | 1.10       | -21.36           | 0.00       | 0.00             |
|                | 0.1        | 1.01       | -23.49           | 0.20       | 90.00            |
|                | 0.2        | 0.85       | -27.96           | 0.40       | 90.00            |
|                | 0.3        | 0.61       | -41.17           | 0.60       | 90.00            |
|                | 0.4        | 0.37       | -90.00           | 0.73       | 90.00            |
|                | 0.5        | 0.32       | -90.00           | 0.79       | 90.00            |
|                | 0.6        | 0.28       | -90.00           | 0.82       | 90.00            |
|                | 0.7        | 0.25       | -90.00           | 0.85       | 90.00            |
|                | 0.8        | 0.22       | -90.00           | 0.88       | 90.00            |
|                | 0.9        | 0.20       | -90.00           | 0.90       | 90.00            |
| 0.6            | 0.0        | 1.10       | -46.68           | 0.00       | 0.00             |
|                | 0.1        | 0.92       | -60.21           | 0.20       | 90.00            |
|                | 0.2        | 0.73       | -90.00           | 0.37       | 90.00            |
|                | 0.3        | 0.63       | -90.00           | 0.47       | 90.00            |
|                | 0.4        | 0.55       | -90.00           | 0.55       | 90.00            |
|                | 0.5        | 0.49       | -90.00           | 0.61       | 90.00            |
|                | 0.6        | 0.44       | -90.00           | 0.66       | 90.00            |
|                | 0.7        | 0.40       | -90.00           | 0.70       | 90.00            |
|                | 0.8        | 0.37       | -90.00           | 0.73       | 90.00            |
|                | 0.9        | 0.34       | -90.00           | 0.76       | 90.00            |
| ...            | ...        | ...        | ...              | ...        | ...              |



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