Impact of Inverter-based Resources on Impedance-based Protection Functions

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Introduction

- Fault current characteristic of IBRs depends on
  - Its control logic
  - Control settings
  - Pre-fault condition
- For unbalanced faults, IBR may inject
  - only positive sequence current
  - positive sequence and undesired negative sequence
  - positive sequence and desired negative sequence
- Latest German code mandates negative sequence current injection

Introduction

- Phase selection and direction based on negative sequence may be impacted
- Relay vendors use different techniques to implement 21
  - Phase comparator
  - Different methods to estimate X and R
- Analyze the impact by
  - Theory
  - Simulation
  - Hardware Test

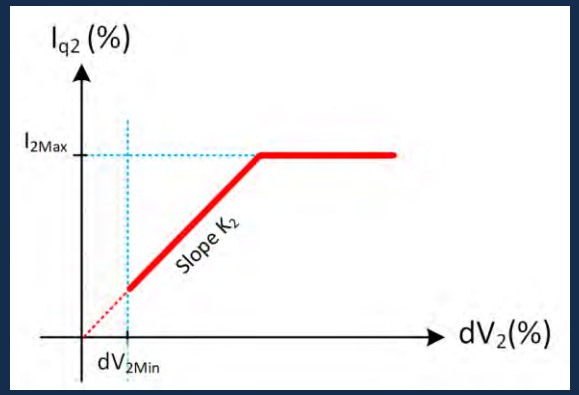
FRT Requirements

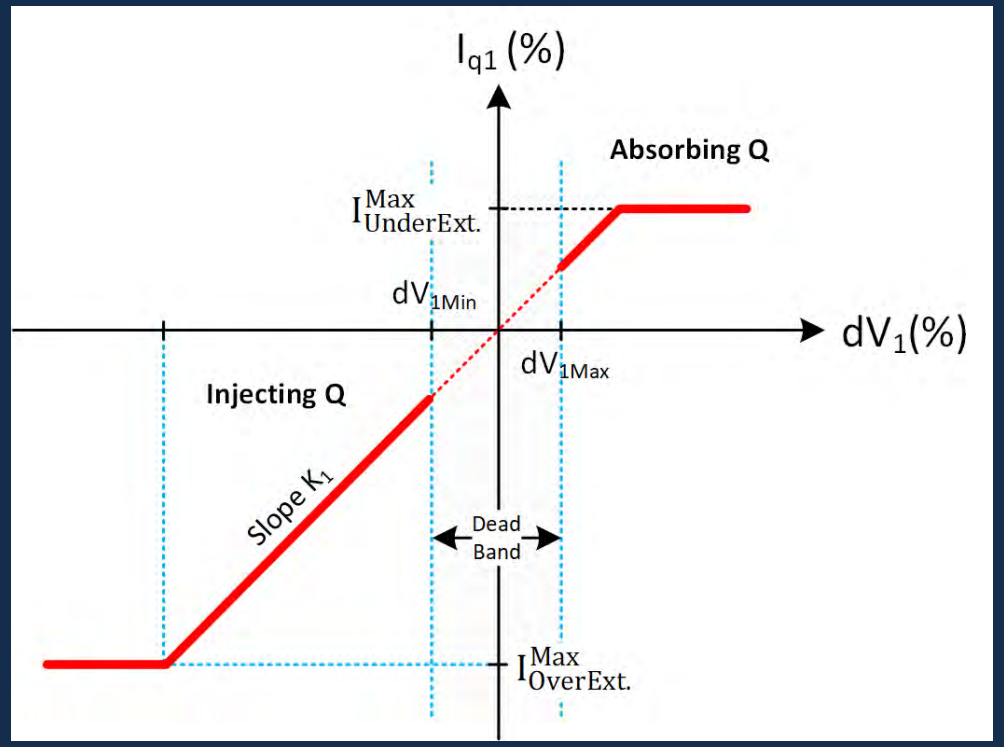
- Dynamic Positive Sequence (DPS) injection

$$I_{1q} = jK_1 \times (|V_{1fault}| - |V_{1pre\text{-}fault}|) \qquad \angle V_1 \text{ is reference}$$

- Dynamic Positive and Negative Sequence (DPNS) injection

$$I_2 = jK_2 \times (|V_{2fault}| - |V_{2pre\text{-}fault}|) \angle V_2$$

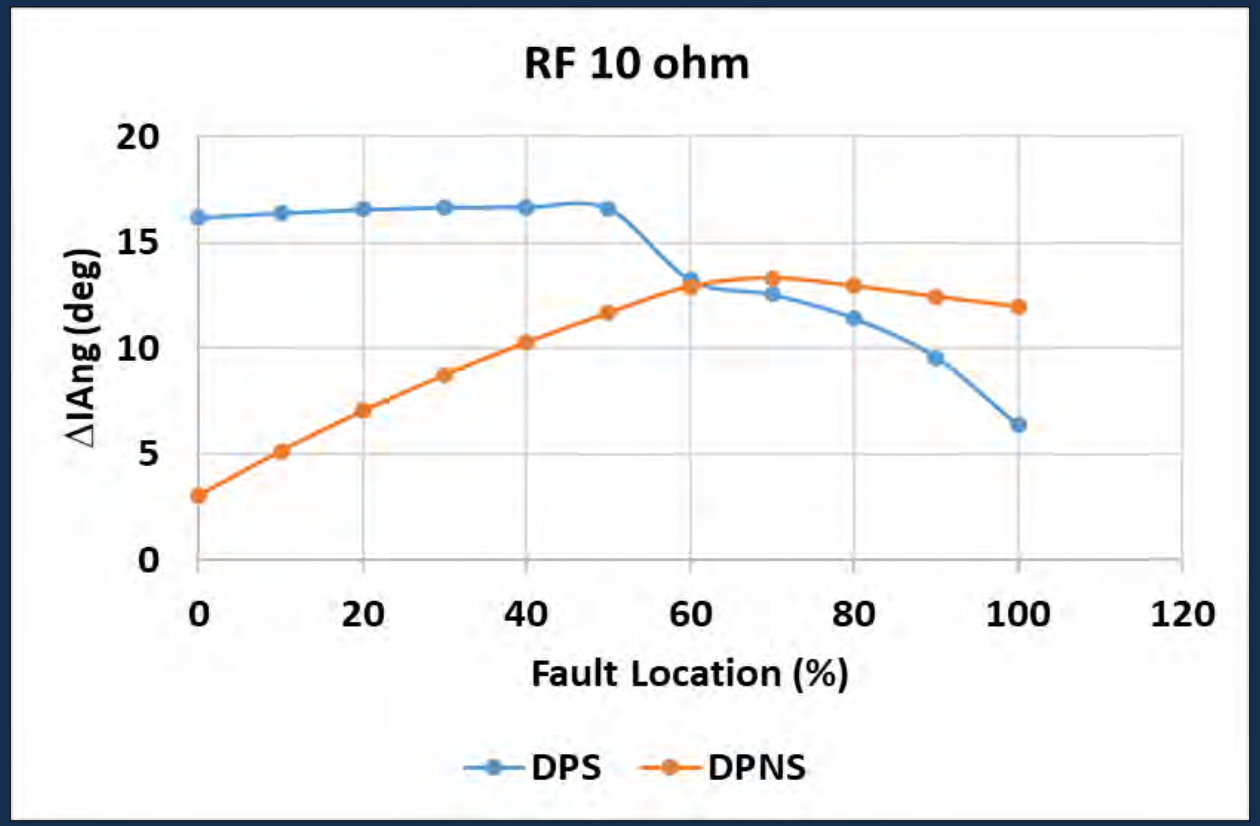




- Rest of the capacity may be used for I_{1d}

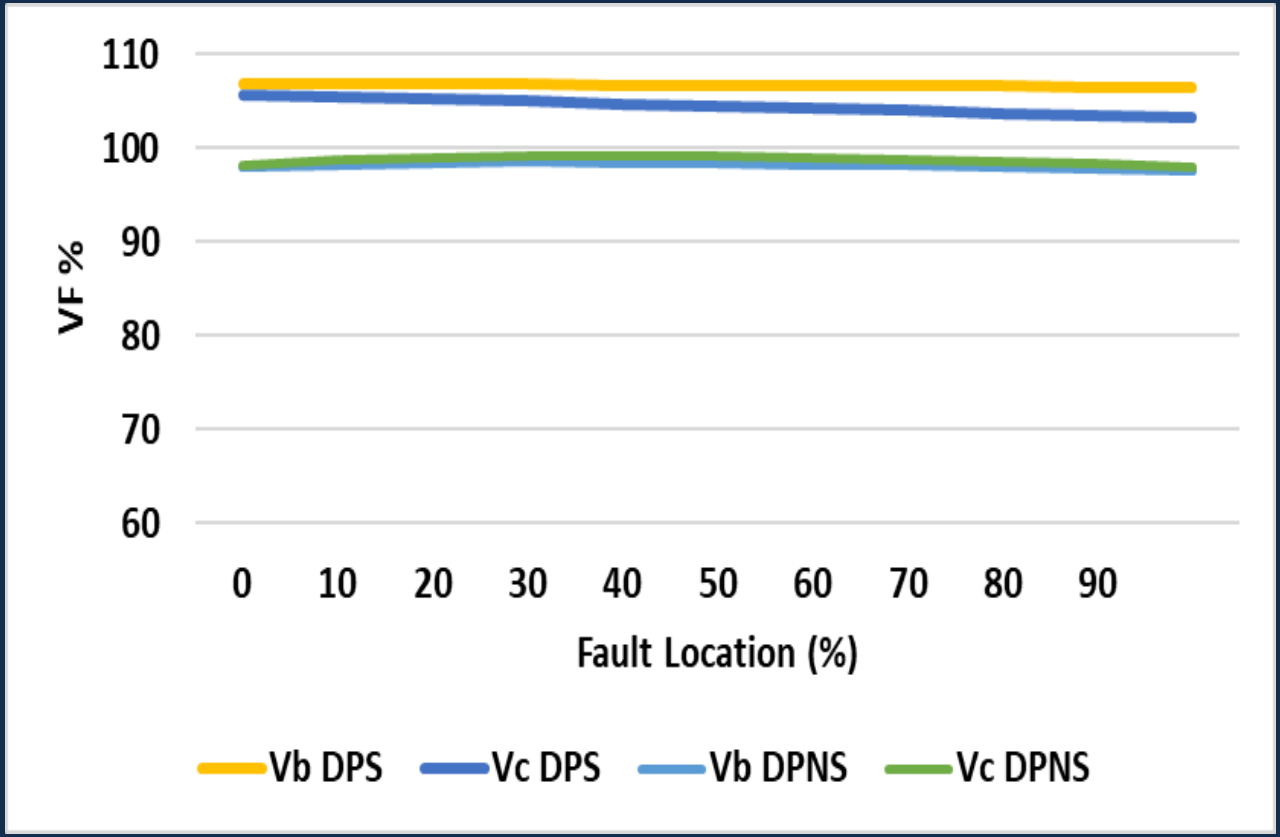
Test System and High-Level Evaluation

- Unknown non-homogeneity in DPS and DPNS



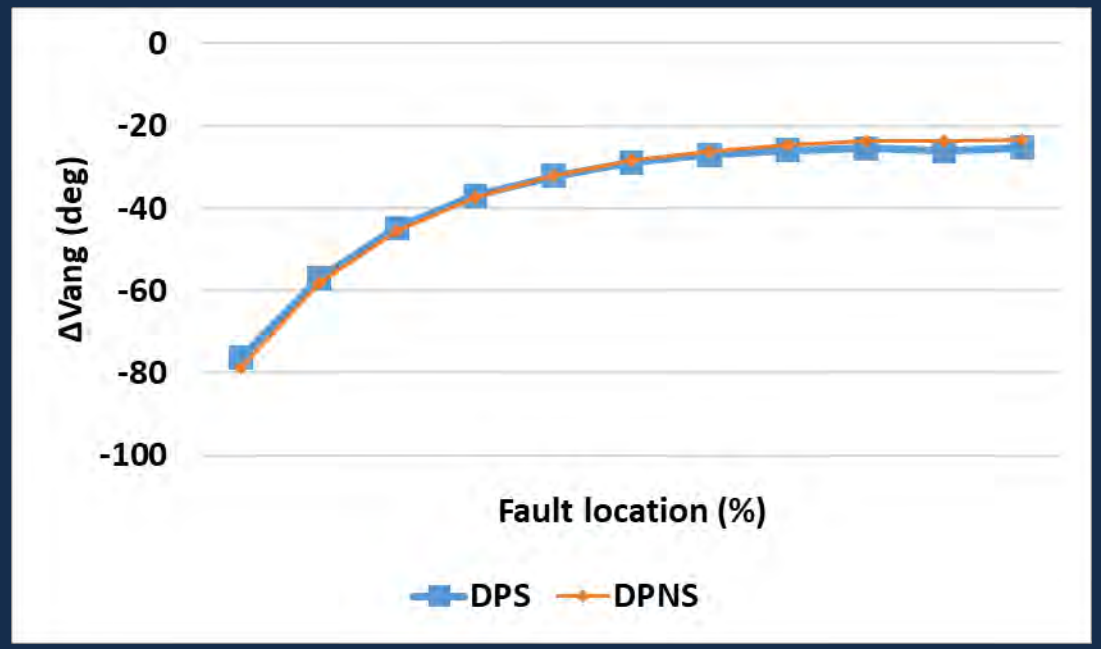
Test System and High-Level Evaluation

- Voltage profile of healthy phases (AG fault)

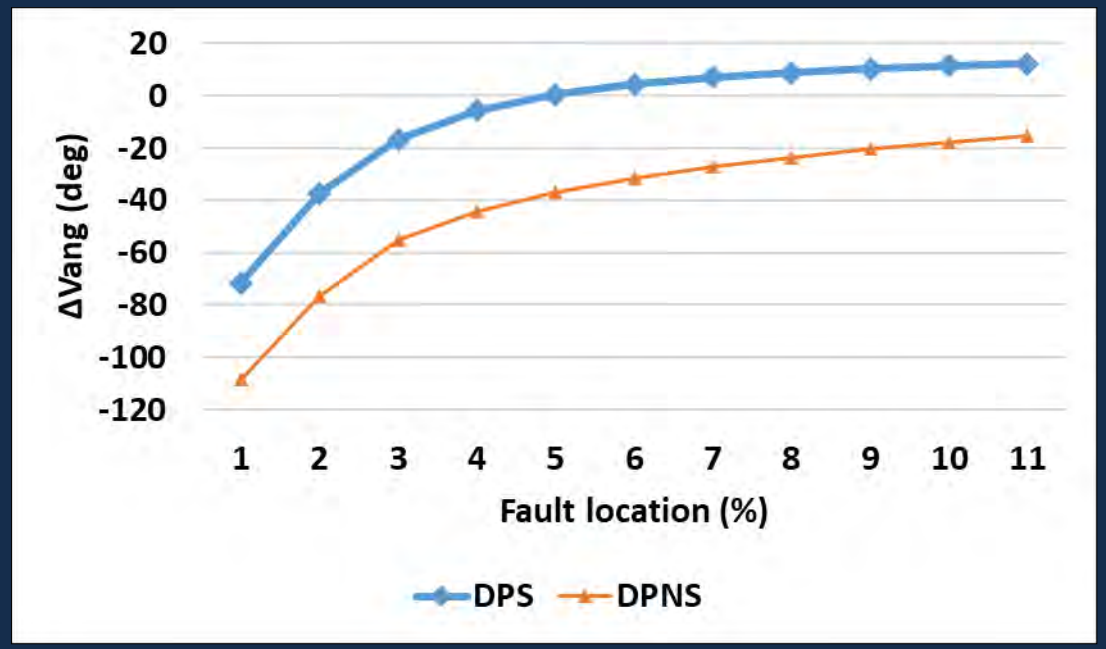


Test System and High-Level Evaluation

- Change in positive sequence voltage angle



Strong System



Weak System

Impedance-based Protection Function

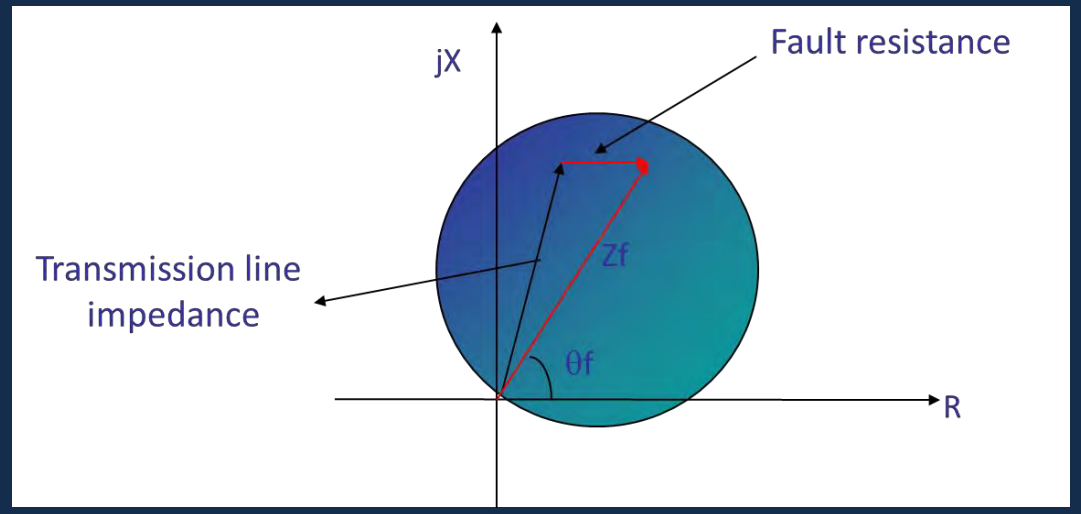
- Phase comparator
  - Mho Characteristic

$$S_{Pol} = V_{mem1}$$
$$S_{Opr} = -V_a + Z_{Set}(I_a + K_0 I_0)$$

Ground

$$S_{Pol} = V_{mem1\,(bc)} = -j\,V_{mem1}$$
$$S_{Opr} = -V_{bc} + Z_{Set}\,I_{bc}$$

Phase



  - In DPS, susceptible to
    - Smaller expansion
    - Larger non-homogeneity

Impedance-based Protection Function

- Quadrilateral (Ground)

Characteristic	Polarizing signal	Operating signal
Reactance	jI_0 or jI_2	$Z\ (I + K_0\ I_0) - V$
Reverse reactance	jI_0 or jI_2	$Z_{Rev}\ (I + K_0\ I_0) - V$
Right blinder	$Z_R\ (I_a + K_0\ I_0)$	$-V + Z_R\ (I_a + K_0\ I_0)$
Left blinder	$Z_L\ (I_a + K_0\ I_0)$	$-V + Z_L\ (I_a + K_0\ I_0)$

- In DPS,
  - Use of I_2 results in mal-operation
  - Higher Non-homogeneity

Impedance-based Protection Function

- Impedance Measurement
  - Method I

$$mZ_1 = V_a /(I_a + K_0 I_0)$$

  - Error is introduced in estimated resistance and reactance
  - Method II

$$R_{Seen} = \frac{Im\{V_a\}\, Im\{I_X\} + Re\{V_a\}\, Re\{I_X\}}{Re\{I_X\}\, Re\{I_R\} + Im\{I_X\}\, Im\{I_R\}} \qquad mX_1 = \frac{Im\{V_a\}\, Re\{I_R\} - Re\{V_a\}\, Im\{I_R\}}{Re\{I_X\}\, Re\{I_R\} + Im\{I_X\}\, Im\{I_R\}}$$

$$I_R = I_a + (R_0/R_1 - 1)I_0 \text{ and } I_X = I_a + (X_0/X_1 - 1)I_0$$

  - Error is introduced in estimated resistance

Impedance Measurement

- Method III

$$mX_1 = \mathrm{Im}\{V_a I_F^*\} / \mathrm{Im}\{(R_1/X_1 + j)(I_a + K_0 I_0)\, I_F^*\}$$

$$R_F = \mathrm{Im}\{V_a (Z_1^* (I + K_0 I_0))^*\} / \mathrm{Im}\{I_F (Z_1^* (I + K_0 I_0))^*\}$$

- I_F is estimated by $3I_0$, $3I_2$, $1.5I_2 + 1.5I_0$
- In DPS,
  - $3I_2$ shall be avoided.
  - R_F estimation is adversely impacted when $1.5I_2 + 1.5I_0$ is used
  - $3I_0$ may be not be a good choice if there is a mutual coupling

Impedance Measurement

- Method III Phase loop

$$mX_1 = Im\{V_{bc} \times I_{comp}^*\}\sin\varphi / Im\{(R_1/X_1 + j) I_{bc}\, I_{comp}^*\}$$

$$0.5R_F = Im\{V_{bc}\,(Z_1\, I_{bc}))^*\} / Im\{2\, I_{comp}\,(Z_1 I_{bc}))^*\}$$

  - Icomp = j1.73 I_2 for BC
  - This method will not work correctly for DPS injection.

Impedance Measurement

- Method IV

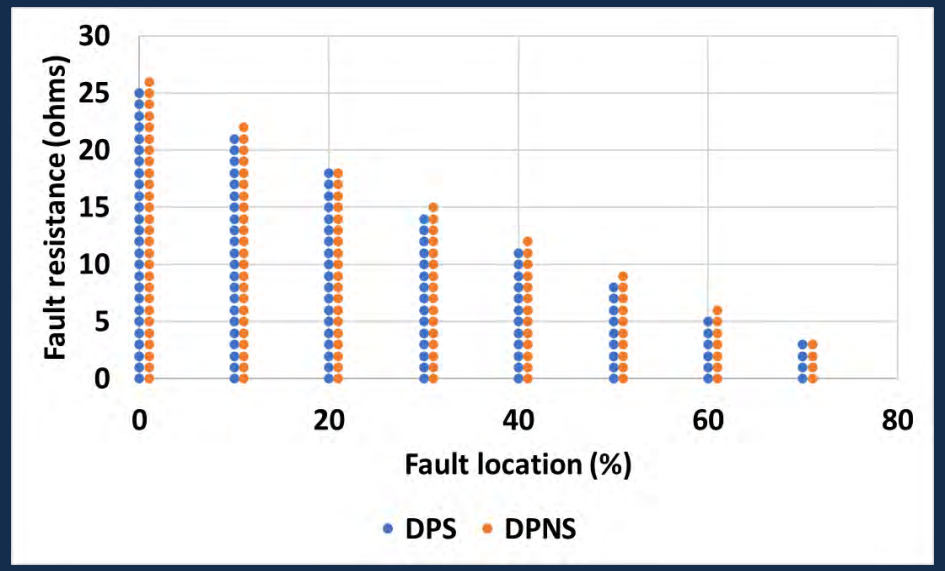
Characteristic	Polarizing signal	Operating signal
Reactance	jI_0 or jI_2	$Z\,(I + K_0\,I_0) - V$
Reverse reactance	jI_0 or jI_2	$Z_{Rev}\,(I + K_0\,I_0) - V$

$$R_F = \mathrm{Im}\{\, V_a\,(Z_1^*\,(I + K_0\,I_0))^*\}/\mathrm{Im}\{I_F\,(Z_1^*\,(I + K_0\,I_0))^*\}$$

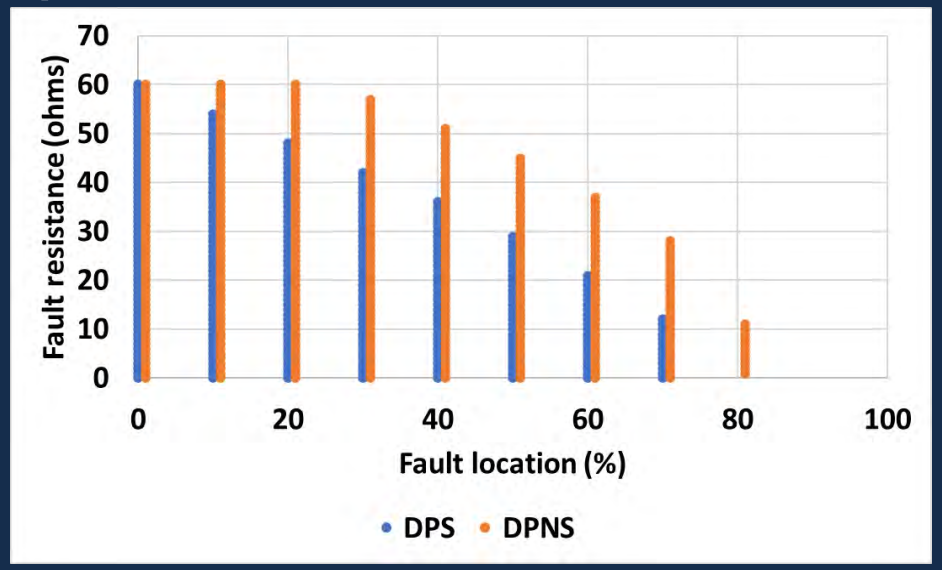
- In DPS,
  - $3I_2$ shall be avoided.
  - R_F estimation is adversely impacted when $1.5I_2 + 1.5I_0$ is used
  - $3I_0$ may be not be a good choice if there is a mutual coupling

Simulation and Test Results

- Phase Comparator (Mho)



Expected trip for LG fault in a strong system



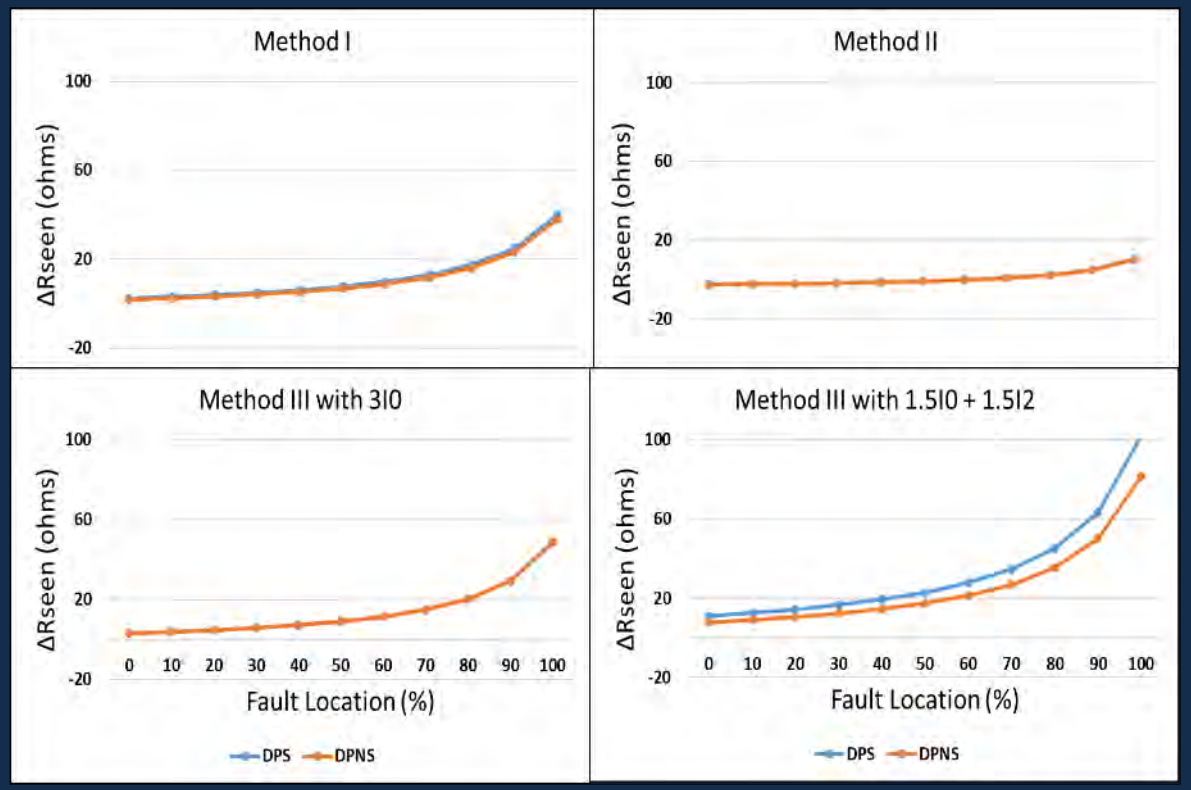
Expected trip for LG fault in a weak system

- Hardware test

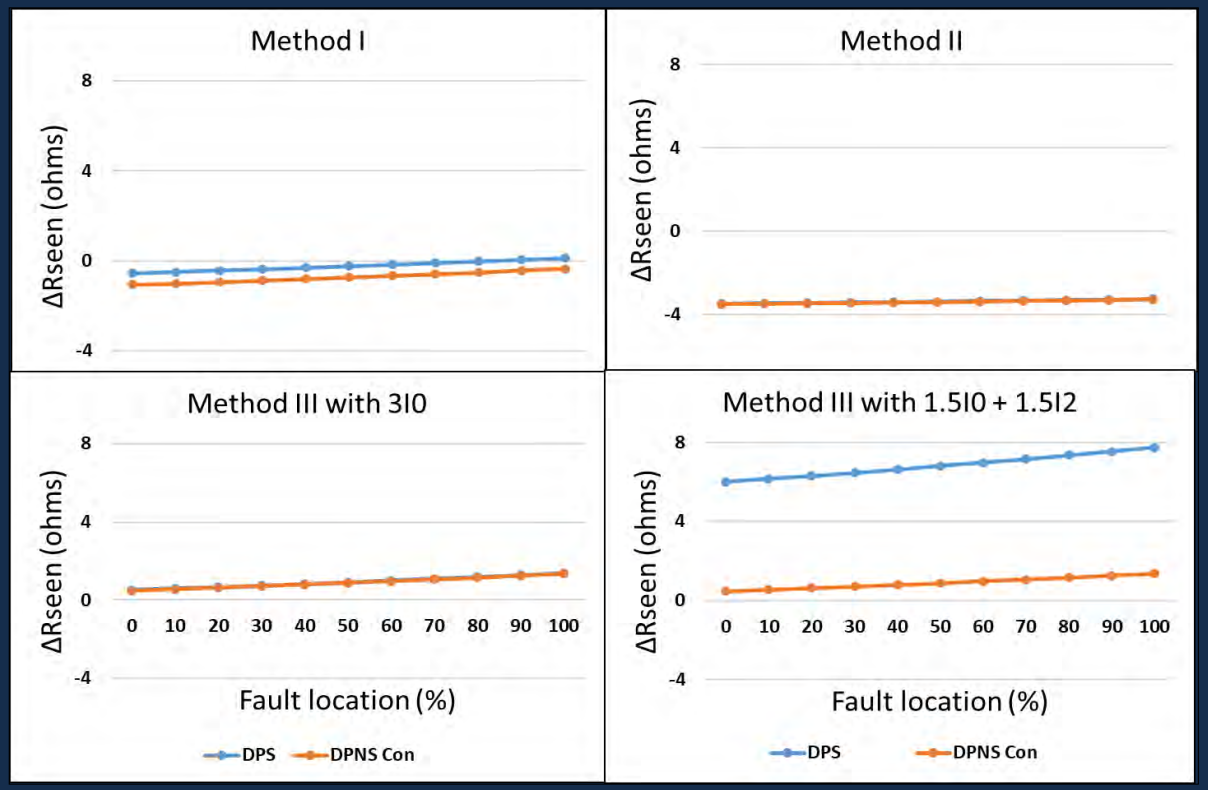
IBR injection	Fault location (from IBR)	RF	Expected Trip (ETAP)	Relay Output (D60)
DPNS	60	35	Yes	Yes
DPNS	60	45	No	No
DPS	60	15	Yes	Yes
DPS	60	25	No	No

Simulation and Test Results

- Impedance-based Methods



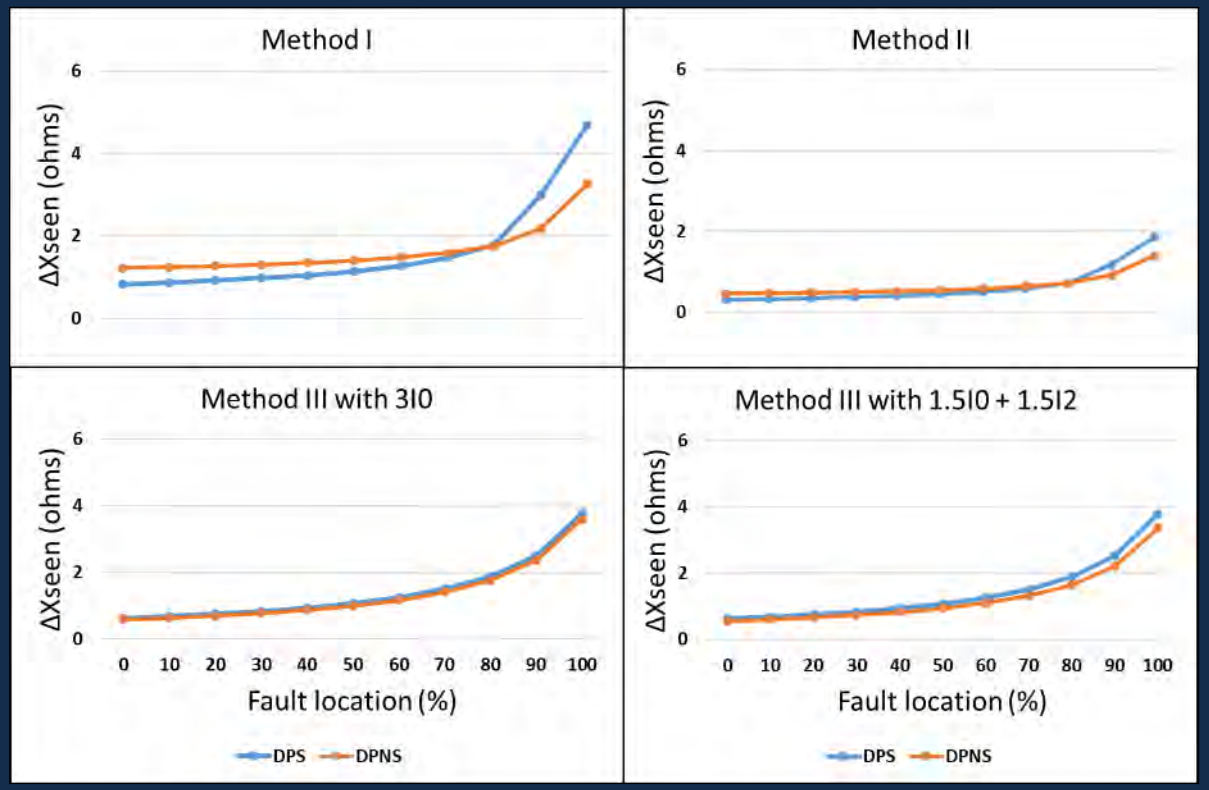
ΔR_{seen} for LG fault in a strong system at R_f = 5 ohms



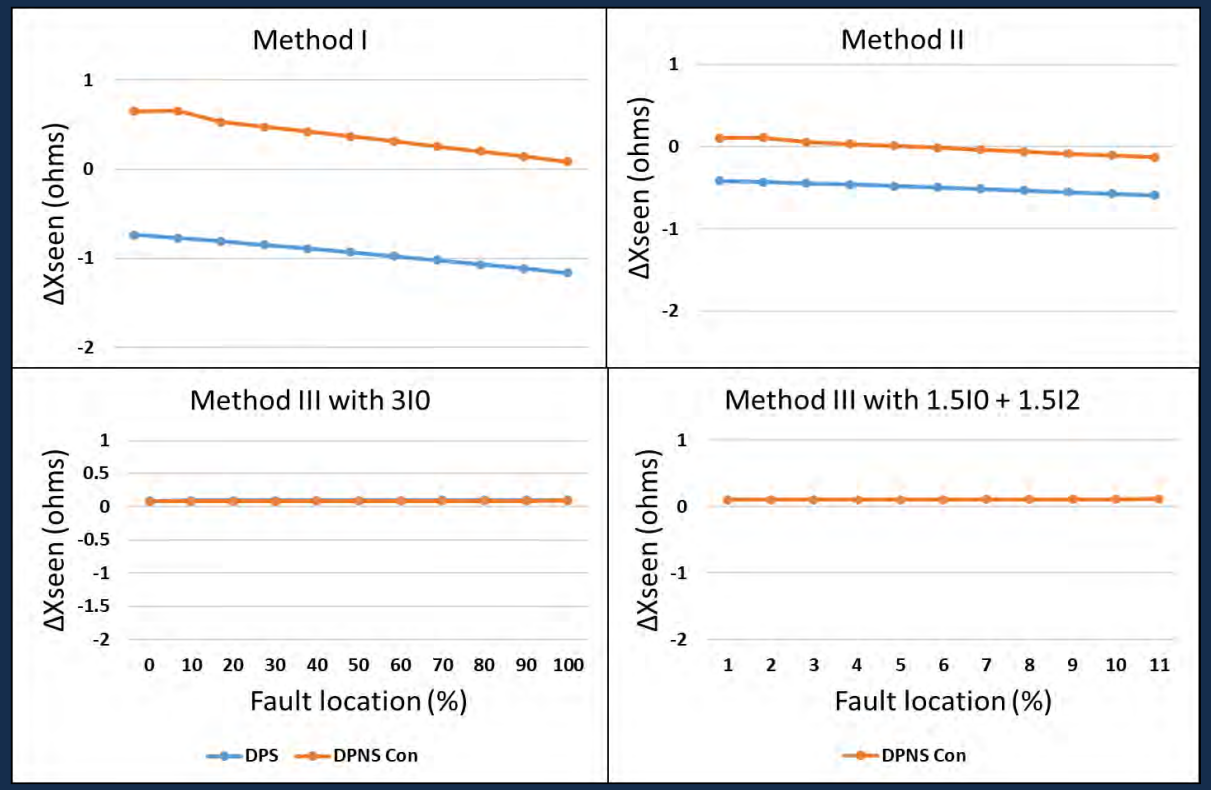
ΔR_{seen} for LG fault in a weak system at R_f = 5 ohms

Simulation and Test Results

- Impedance-based Methods



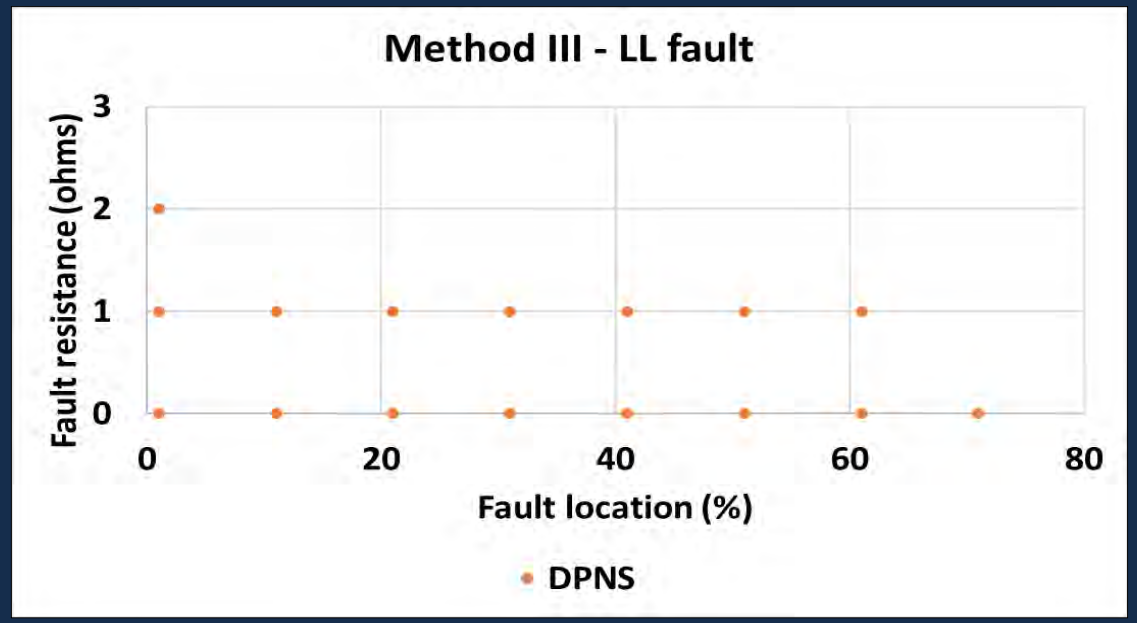
ΔX_{seen} for LG fault in a strong system at R_f = 5 ohms



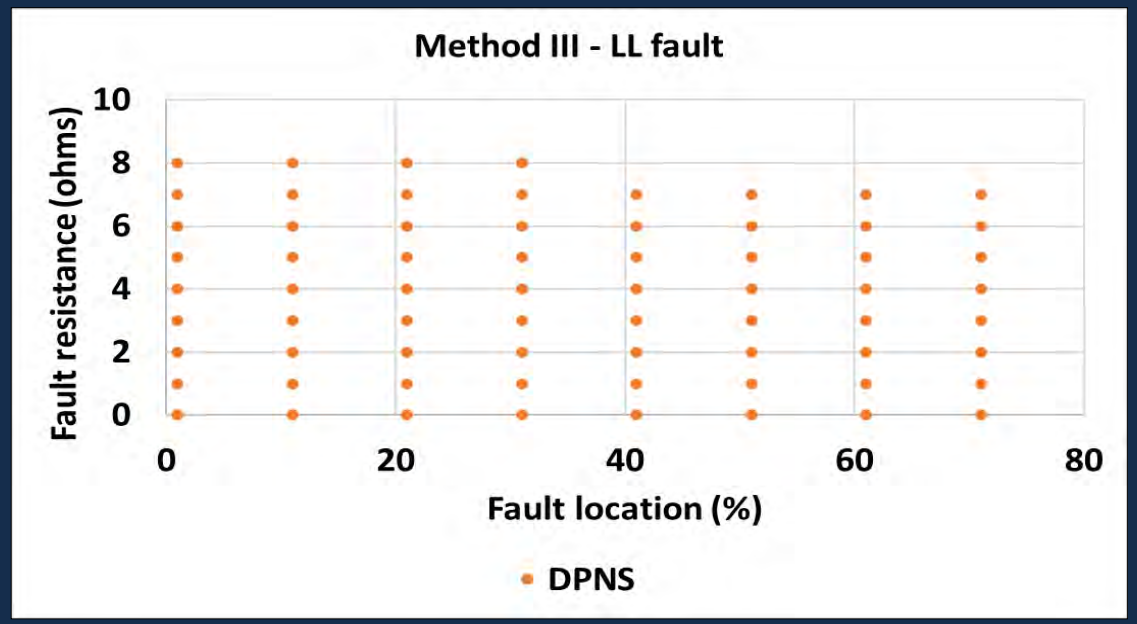
ΔX_{seen} for LG fault in a weak system at R_f = 5 ohms

Simulation and Test Results

- Method 3 set to over R_F = 20 ohm
  - LL Fault, DPNS
  - Adversely impacted by infeed



Strong System



Weak System

Summary

- Lack of negative sequence injection by IBR results in
  - High voltage in healthy phases
  - Smaller voltage angle change (fault and pre-fault)
  - Unknown non-homogeneity effect
- Phase Comparator Method – Smaller resistive coverage for LG, LL faults
- Impedance based for LG faults
  - Method I, II and Method III with 3 I_0 are not affected
  - Method III employing 3 I_2, $1.5I_0+1.5I_2$ should be avoided

Thank You!
Questions?