# Identification of IBR-driven Subsynchronous Oscillations

## CIGRE UK C4 Technical Liaison Meeting


**Dr Diptargha Chakravorty**

Principal Consultant

Siemens Energy


Jan 21, 2025

cigre

For power system expertise

# Topics covered

- Project overview
- CIGRE C4 publications
- Frequency domain analysis methods
- Impedance measurement methods
  - Phase to sequence transformation
  - Phase to $\alpha\beta$ transformation
- Test network
  - Method 1 and 2 comparison
  - Sequence Vs $\alpha\beta$ comparison

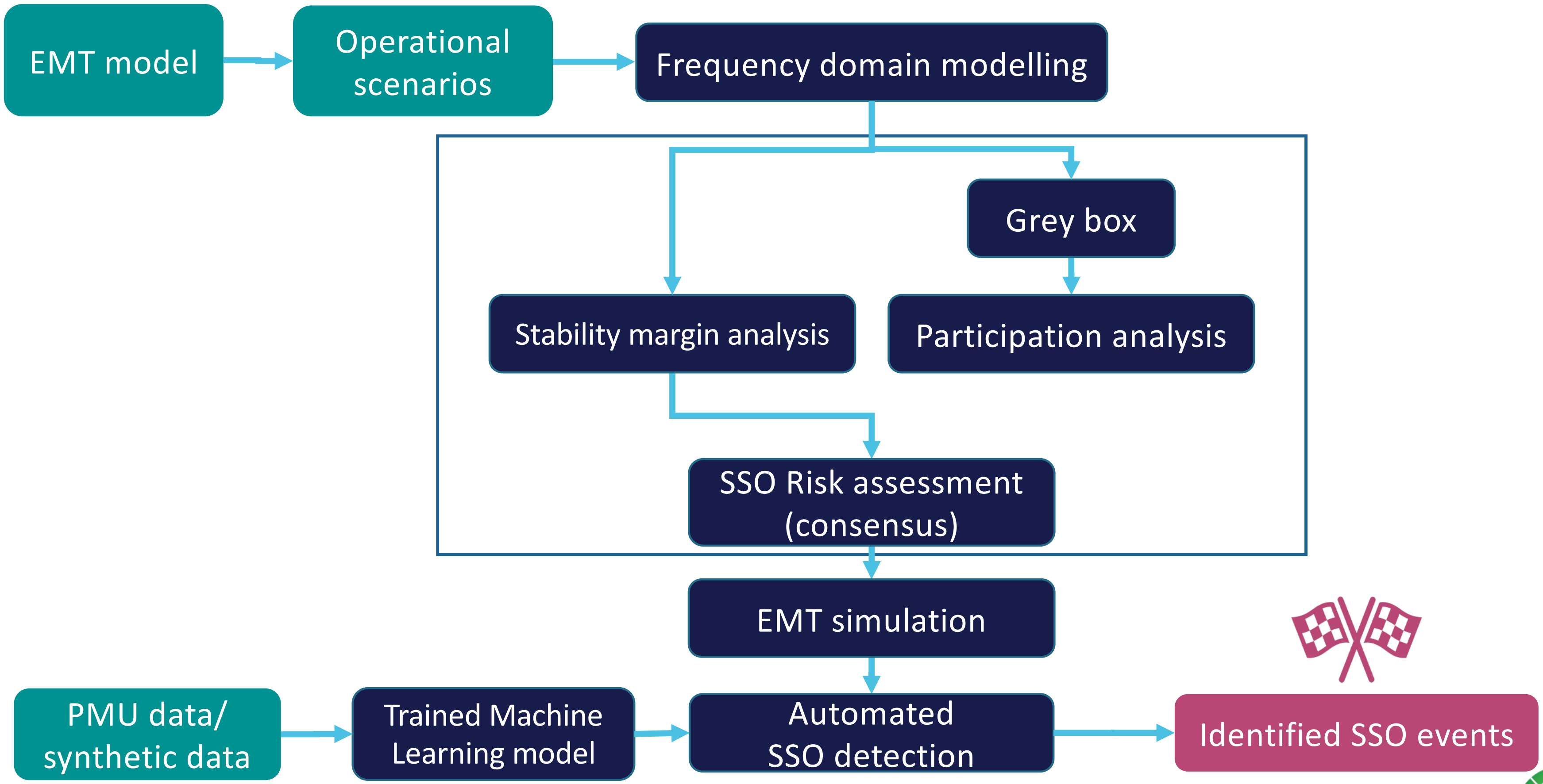
# Project reference and publications

## Project Reference

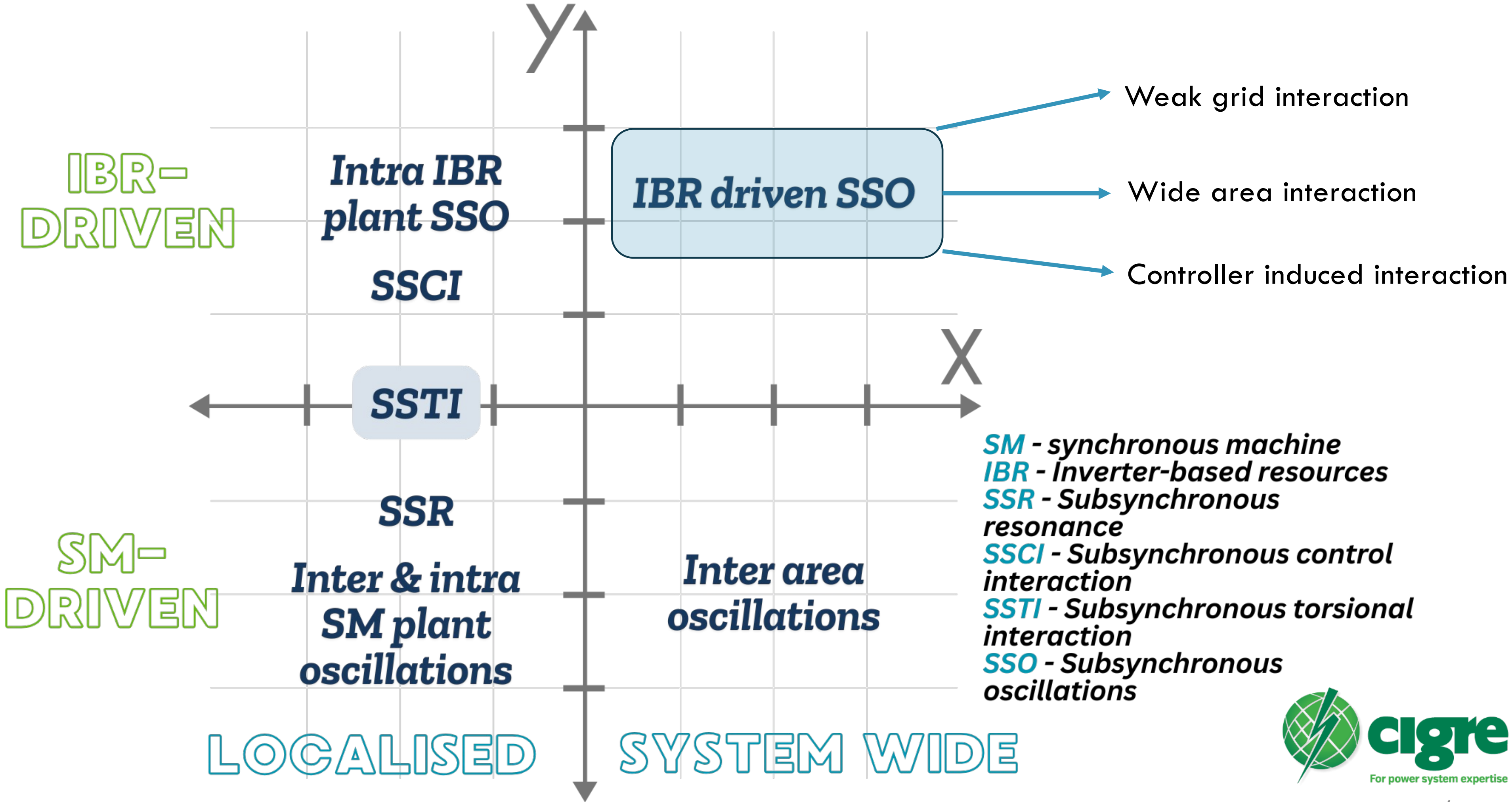
# Automated Identification of SSO events

This project explored, developed, and tested a combination of novel **frequency domain methodologies and machine learning** techniques to **identify potential system operating conditions** that can lead to Sub-Synchronous Oscillations (SSOs) through an **automated control interaction studies framework**.

# Overall Approach



# Types of Subsynchronous Oscillations




***SM** - synchronous machine*
***IBR** - Inverter-based resources*
***SSR** - Subsynchronous resonance*
***SSCI** - Subsynchronous control interaction*
***SSTI** - Subsynchronous torsional interaction*
***SSO** - Subsynchronous oscillations*

Source: Inspired by Dr Balarko Chaudhuri's ppt on IBR-driven SSO, ESIG Webinar, 21st Nov 2024

# CIGRE Publications 1

2024 Paris Session

**Paper ID – 11099**
C4 Power system technical performance
PS1 Power system dynamic analysis in the energy transition: challenges, opportunities and advances

**Framework for Identification of Subsynchronous Oscillations Risks**

**Diptargha CHAKRAVORTY***
**TNEI Services Ltd**
**United Kingdom**
**diptargha@ tneigroup.com**

**Jaime TRIVINO**
**TNEI Services Ltd**
**United Kingdom**
**jaime.trivino@ tneigroup.com**

**Sami ABDELRAHMAN**
**National Grid ESO**
**United Kingdom**
**sami.abdelrahman@ nationalgrideso.com**

This paper discusses the developed framework and the associated tool for SSO identification along with an example case study

# CIGRE Publications 2

2024 Paris Session

**Paper ID – 11096**
C4 Power system technical performance
PS1 Power system dynamic analysis in the energy transition: challenges, opportunities and advances

**Automatic Detection of Subsynchronous Oscillations**

**Diptargha CHAKRAVORTY***
**TNEI Services Ltd**
**United Kingdom**
**diptargha@tneigroup.com**

**Alexandru Christian NEAGU**
**Delft University of Technology**
**The Netherlands**
**a.c.neagu@tudelft.nl**

**Jochen L. CREMER**
**Delft University of Technology**
**The Netherlands**
**j.l.cremer@tudelft.nl**

This paper discusses the developed machine learning-based tool for detection of oscillations in measurement data either from PMU or EMT simulations.

# Frequency domain analysis methods

For power system expertise

# Frequency domain analysis

**Small signal analysis**

## Impedance-based analysis

### Calculated Impedance Types

#### SISO
- Single input single output transfer functions
- Normal sequence impedance calculation without any sequence coupling

#### MIMO
- Multi input multi output impedance matrix in modified sequence domain
- Takes into account the coupling between sequence components

#### SISO with coupling
- Representation by four scalar transfer functions
- Standard positive and sequence impedances

#### Grid-dependent SISO
- SISO equivalent impedance of an IBR considering the grid impedance without any coupling between the sequence components

### Impedance Analysis Methods

#### Impedance Intersection
- Open loop analysis by scanning the impedance of the grid and the plant separately
- Gain and phase margin from bode plots

#### Nyquist analysis
- Open loop analysis in the Nyquist plane using the SISO impedance
- Also possible to use MIMO impedance by using Generalised Nyquist Criteria

#### Eigenvalue analysis
- Closed loop analysis using whole system impedance
- Based on the theory of ‘Grey-box’ analysis
- Uses MIMO impedance matrix

# SISO Form

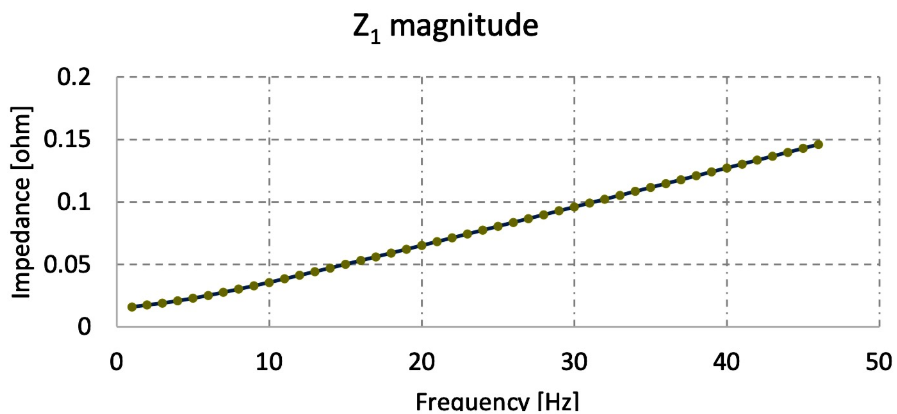
## Grid-independent

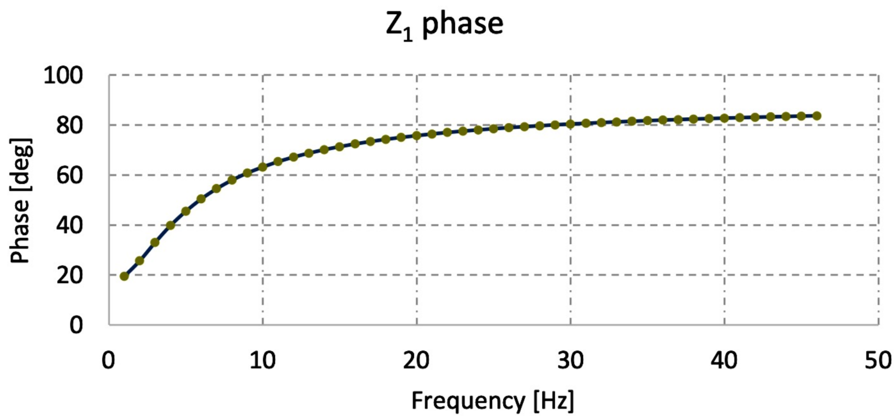
- If the positive and negative sequence impedances are decoupled, then the standard sequence domain impedance can be used.
- Active devices like Inverter-based resources (IBRs) have a frequency-coupled response due to the configuration of controller.
- Mirror Frequency Coupling (MFC) is dominant at low frequencies (Sub-synchronous range) and has an impact on stability performance.

Standard sequence domain impedances

$$Y_p = \frac{I_p}{V_p}$$

$$Y_n = \frac{I_n}{V_n}$$



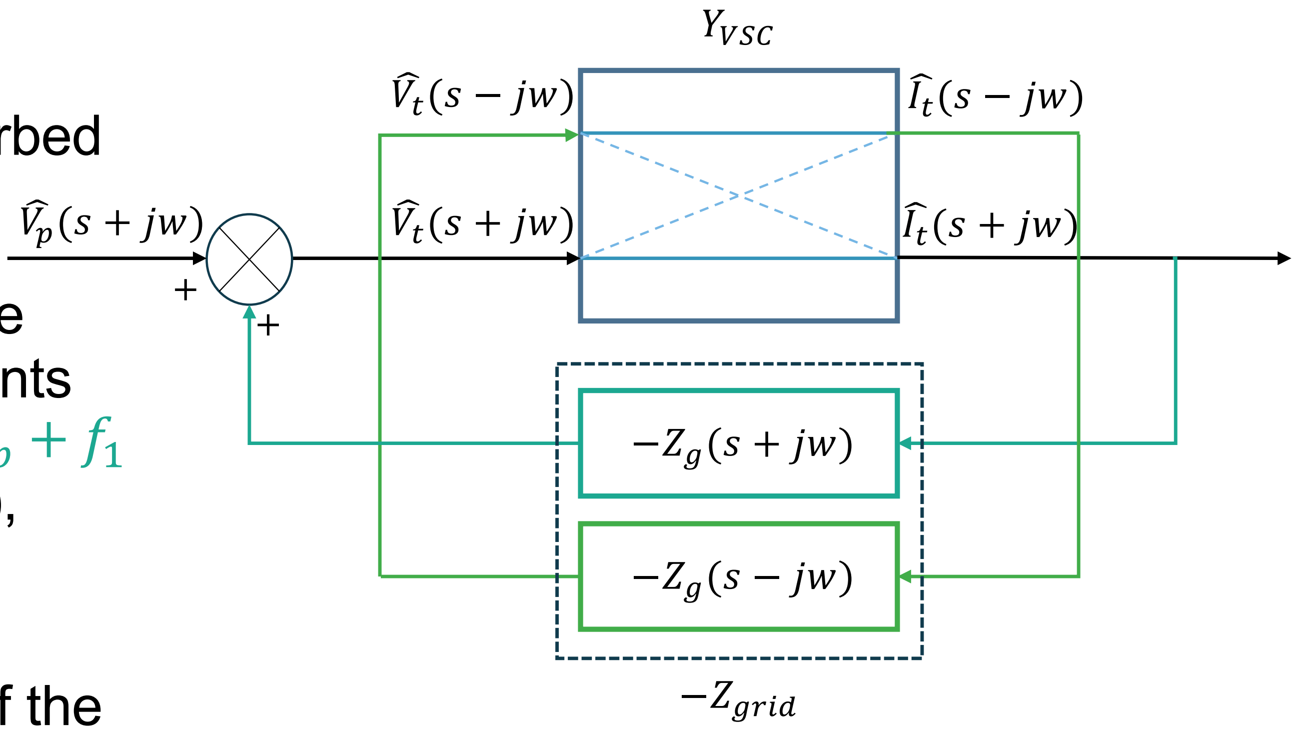



# MIMO Form

**Full matrix with sequence coupling**

- When a 3-phase VSC is disturbed from its nominal operation by injecting a perturbation at an arbitrary frequency $f_p$, then the dominant frequency components in three phase variables are $f_p + f_1$ (+ve seq) and $f_p - f_1$(-ve seq), where $f_1$ is the fundamental frequency.
- Voltages at the ac terminals of the

$$v_a = \overbrace{V_1 \cos(2\pi f_1 t + \phi_{v1}) + \hat{V}_p \cos[2\pi(f_p + f_1)t + \phi_{\mathrm{vp}}]}^{\text{Positive Sequence}} + \underbrace{\hat{V}_n \cos[2\pi(f_p - f_1)t + \phi_{\mathrm{vn}}]}_{\text{Negative Sequence}}$$




S. Shah and L. Parsa, "Impedance Modeling of Three-Phase Voltage Source Converters in DQ, Sequence, and Phasor Domains," in IEEE Transactions on Energy Conversion, vol. 32, no. 3, pp. 1139-1150, Sept. 2017, doi: 10.1109/TEC.2017.2698202.

# MIMO Form - continued

## Full matrix with sequence coupling

- The small signal behaviour of the 3-phase VSC from its ac terminals can be described as

$$\begin{bmatrix} \hat{I}_p(s+j\omega_1) \\ \hat{I}_n(s-j\omega_1) \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{\mathrm{pp}}(s) & Y_{\mathrm{pn}}(s) \\ Y_{\mathrm{np}}(s) & Y_{\mathrm{nn}}(s) \end{bmatrix}}_{Y_{PN}} \begin{bmatrix} \hat{V}_p(s+j\omega_1) \\ \hat{V}_n(s-j\omega_1) \end{bmatrix}$$

- Conventional +ve and –ve seq impedances are related to the diagonal elements of the $Y_{PN}$ as

$$Z_p(s) = \frac{\hat{V}_p(s)}{\hat{I}_p(s)} = \frac{1}{Y_{\mathrm{pp}}(s-j\omega_1)}$$

$$Z_n(s) = \frac{\hat{V}_n(s)}{\hat{I}_n(s)} = \frac{1}{Y_{\mathrm{nn}}(s+j\omega_1)}$$

S. Shah and L. Parsa, "Impedance Modeling of Three-Phase Voltage Source Converters in DQ, Sequence, and Phasor Domains," in IEEE Transactions on Energy Conversion, vol. 32, no. 3, pp. 1139-1150, Sept. 2017, doi: 10.1109/TEC.2017.2698202.

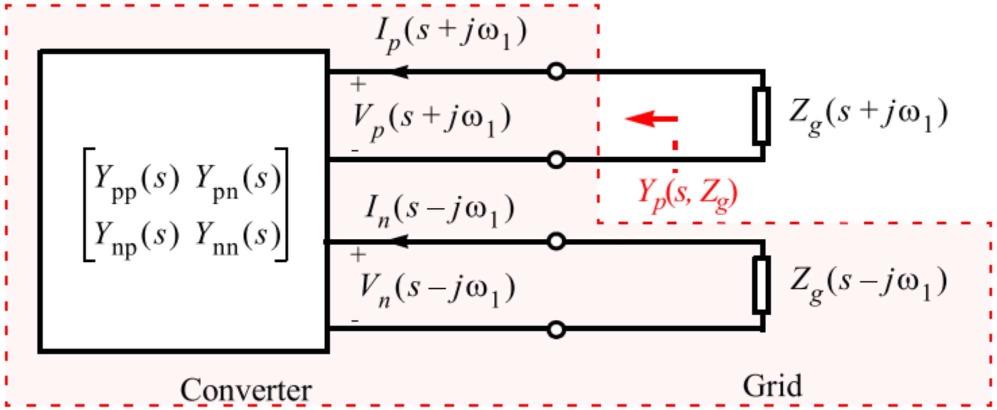
# SISO Form

**Grid-dependent**

- The sequence admittance with frequency coupling of the equipment can be represented using two SISO transfer functions that are dependent on the grid impedance $Z_g(s)$

$$Y_p(s, Z_g) = Y_{pp}(s - j\omega_1) - \frac{Y_{pn}(s - j\omega_1)Y_{np}(s - j\omega_1) \cdot Z_g(s - j2\omega_1)}{1 + Y_{nn}(s - j\omega_1) \cdot Z_g(s - j2\omega_1)}$$

$$Y_n(s, Z_g) = Y_{nn}(s + j\omega_1) - \frac{Y_{pn}(s + j\omega_1)Y_{np}(s + j\omega_1) \cdot Z_g(s + j2\omega_1)}{1 + Y_{nn}(s + j\omega_1) \cdot Z_g(s + j2\omega_1)}$$




- This SISO representation is valid only when the grid (equivalent source) does not exhibit sequence coupling in its sequence impedance.
- This representation is not suitable for aggregating the sequence admittance of different components in a network.

S. Shah and L. Parsa, "Impedance Modeling of Three-Phase Voltage Source Converters in DQ, Sequence, and Phasor Domains," in IEEE Transactions on Energy Conversion, vol. 32, no. 3, pp. 1139-1150, Sept. 2017, doi: 10.1109/TEC.2017.2698202.

# SISO Form

**4 scalar transfer functions**

- The sequence admittance with frequency coupling can also be represented using four scalar transfer functions.
- Here $Y_p$ and $Y_n$ are standard positive and negative sequence admittances
- And $Y_{cp}$ and $Y_{cn}$ are the admittances at coupling frequencies

$$\left.\begin{aligned} Y_p(s) &= \frac{I_p(s)}{V_p(s)} \\ Y_{\text{cp}}(s) &= \frac{I_n(s-j2\omega_1)}{V_p(s)} \end{aligned}\right\} \text{where} V_n(s-j2\omega_1)=0$$

$$\left.\begin{aligned} Y_n(s) &= \frac{I_n(s)}{V_n(s)} \\ Y_{\text{cn}}(s) &= \frac{I_p(s+j2\omega_1)}{V_n(s)} \end{aligned}\right\} \text{where} V_p(s+j2\omega_1)=0$$

- These transfer functions are related to the elements of the sequence admittance matrix by

$$Y_p(s) = Y_{pp}(s - jw)$$
$$Y_{cp}(s) = Y_{np}(s - jw)$$

$$Y_n(s) = Y_{nn}(s + jw)$$
$$Y_{cn}(s) = Y_{pn}(s + jw)$$

S. Shah and L. Parsa, "Impedance Modeling of Three-Phase Voltage Source Converters in DQ, Sequence, and Phasor Domains," in IEEE Transactions on Energy Conversion, vol. 32, no. 3, pp. 1139-1150, Sept. 2017, doi: 10.1109/TEC.2017.2698202.

For power system expertise

# Impedance measurement approaches

For power system expertise

# MIMO Form - measurement approaches

$$\begin{bmatrix} \hat{i}_p(s + jw_1) \\ \hat{i}_n(s - jw_1) \end{bmatrix} = \overbrace{\begin{bmatrix} Y_{pp}(s) & Y_{pn}(s) \\ Y_{np}(s) & Y_{nn}(s) \end{bmatrix}}^{\boldsymbol{Y_{PN}}} \begin{bmatrix} \hat{v}_p(s + jw_1) \\ \hat{v}_n(s - jw_1) \end{bmatrix}$$

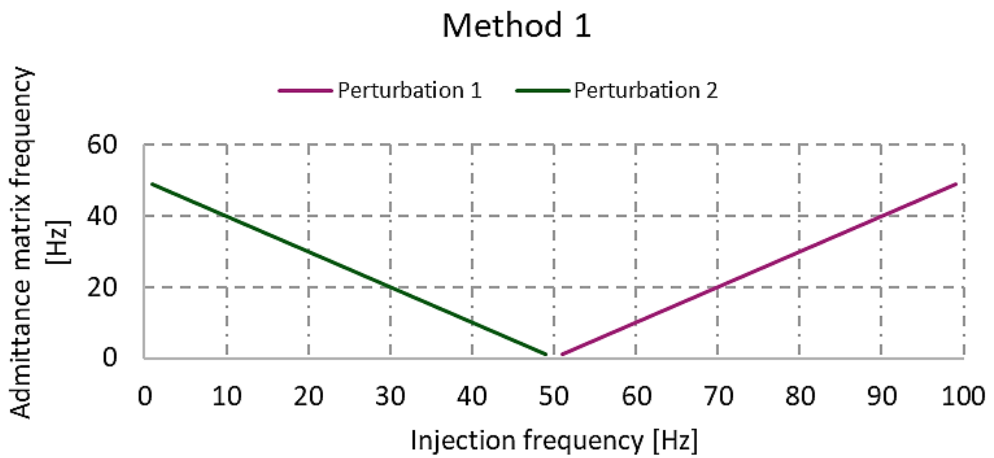
Method 1

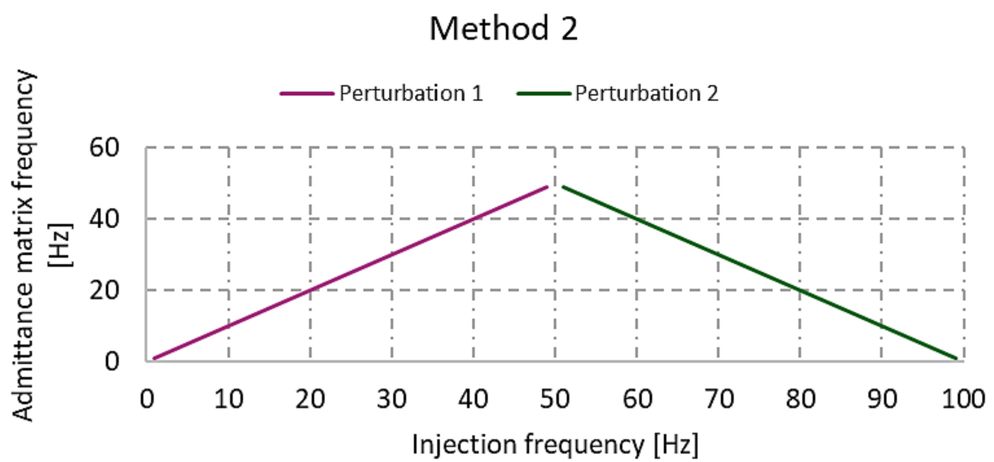
$$\begin{bmatrix} \hat{i}_{\alpha\beta}(s) \\ \hat{i}^*_{\alpha\beta}(s - 2jw) \end{bmatrix} = \overbrace{\begin{bmatrix} Y_{\alpha\beta 11}(s) & Y_{\alpha\beta 12}(s) \\ Y_{\alpha\beta 21}(s) & Y_{\alpha\beta 22}(s) \end{bmatrix}}^{\boldsymbol{Y_{\alpha\beta}}} \begin{bmatrix} \hat{v}_{\alpha\beta}(s) \\ \hat{v}^*_{\alpha\beta}(s - 2jw) \end{bmatrix}$$

Method 2

# MIMO Form – Methods comparison

**Injection frequency**




- No major differences except Method 1 starts from the fundamental and approaches the ends while Method 2 starts from the ends and approaches the fundamental.
- Also, Perturbation 1 measures the positive sequence impedance between the 50-100Hz range in Method 1 while the same perturbation measures the impedance between 1-50Hz range in Method 2.

# MIMO Form – Sequence domain

**Self and mutual impedance terms**

## Symmetrical, coupled, linear, three-phase system

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} L_S & M & M \\ M & L_S & M \\ M & M & L_S \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

## Conversion to sequence domain

$$A^{-1}\mathrm{A} \begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix} = A^{-1} \begin{bmatrix} L_S & M & M \\ M & L_S & M \\ M & M & L_S \end{bmatrix} A \frac{d}{dt} \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix}$$

$$\mathrm{A} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

$$where\ a = -0.5 + j0.86$$

$$\begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} L_S + 2M & 0 & 0 \\ 0 & L_S - M & 0 \\ 0 & 0 & L_S - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix}$$

cigre
For power system expertise

Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications, Amirnaser Yazdani; Reza Iravani

# MIMO Form – Sequence domain

**Self and mutual impedance terms**

$$\begin{bmatrix} v_0 \\ v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} L_S + 2M & 0 & \overset{Z_{13}}{0} \\ 0 & L_S - M & 0 \\ \underset{Z_{31}}{0} & 0 & L_S - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_0 \\ i_1 \\ i_2 \end{bmatrix}$$

If the mutual couplings across phases are not equal (asymmetrical three phase system), then the off-diagonal terms will be non-zero and

$$Z_{12} = Z_{21}^* \; Z_{13} = Z_{31}^*, Z_{23} = Z_{32}^* \; \& \; Z_{22} = Z_{33}$$

# MIMO Form – $\alpha\beta$ frame

**Self and mutual impedance terms**

Space phasor representation of three phase quantities

$$\vec{f}(t) = \frac{2}{3}\left[e^{j0} f_a(t) + e^{j\frac{2\pi}{3}} f_b(t) + e^{j\frac{4\pi}{3}} f_c(t)\right]$$

Space phasor projection on cartesian coordinates

$$\vec{f}(t) = f_\alpha(t) + j f_\beta(t)$$

Phase quantities to $\alpha\beta$ quantities

$$\mathbf{C} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

$$\begin{bmatrix} f_\alpha(t) \\ f_\beta(t) \end{bmatrix} = \frac{2}{3}\mathbf{C}\begin{bmatrix} f_a(t) \\ f_b(t) \\ f_c(t) \end{bmatrix}$$

# MIMO Form – $\alpha\beta$ frame

**Self and mutual impedance terms**

Symmetrical, coupled, linear, three-phase system

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} L_S & M & M \\ M & L_S & M \\ M & M & L_S \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Phase quantities to $\alpha\beta$ quantities

$$\frac{2}{3} C C^T \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3} C \begin{bmatrix} L_S & M & M \\ M & L_S & M \\ M & M & L_S \end{bmatrix} C^T \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

Self and mutual inductance in $\alpha\beta$ frame

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} L_s - M & \overset{\alpha\beta_{12}}{0} \\ \underset{\alpha\beta_{21}}{0} & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

If the mutual couplings across phases are not equal (asymmetrical three phase system), then the off-diagonal terms will be non-zero and

$$\alpha\beta_{11} \neq \alpha\beta_{22}, \alpha\beta_{12} = \alpha\beta_{21}$$

# Measurement methods comparison

# MIMO Form – Comparison

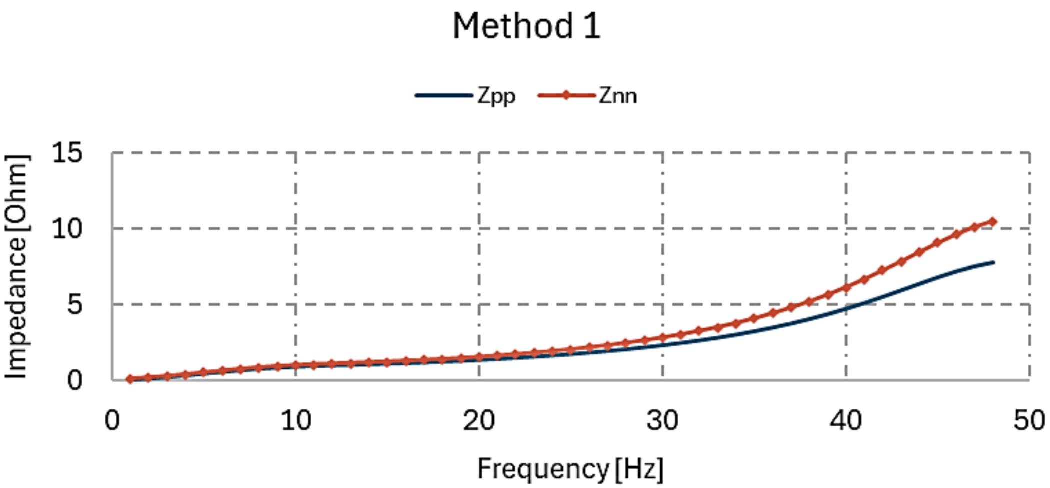
**Test network impedance measurement**

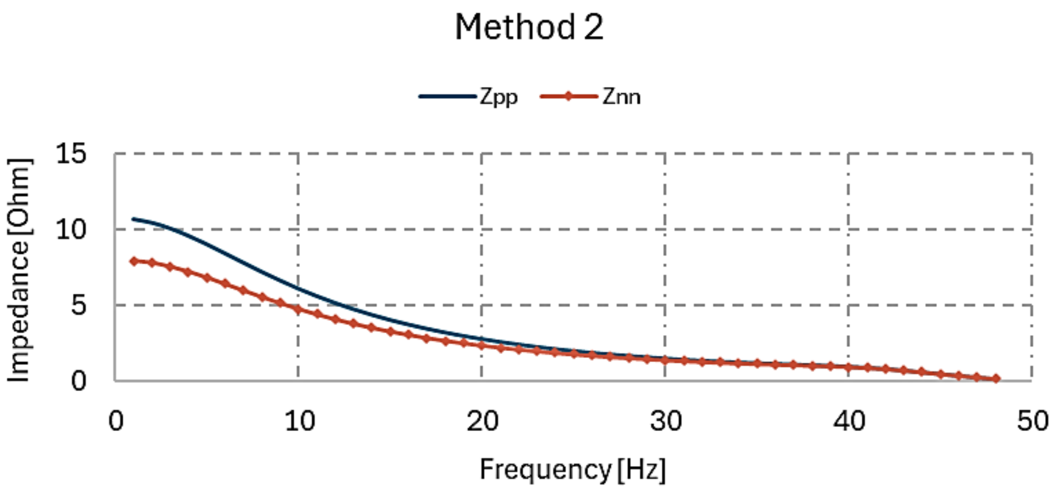
Modelled in PSCAD


- 50 Hz system, VSC in PQ control mode
- Impedance measured in the subsynchronous range
- Method 1 and Method 2 used to estimate the impedance of the converter
- Sequence impedance compared to $\alpha\beta$ impedance

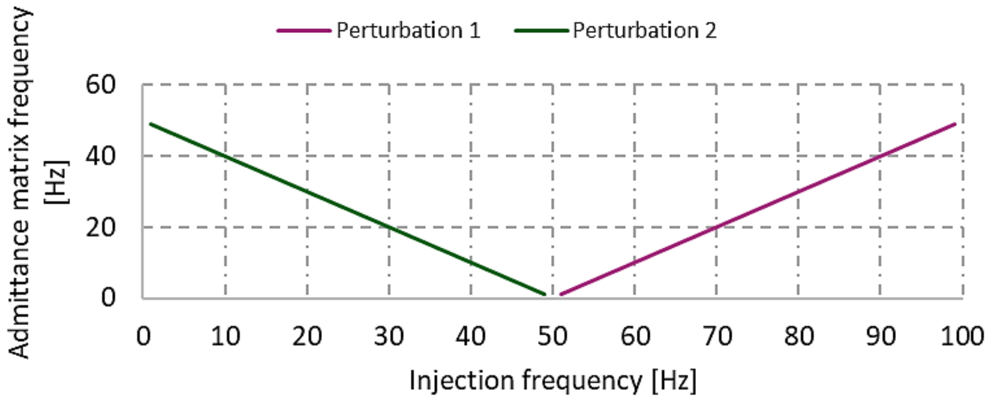
# Modified Seq impedance – Zpp & Znn

## Method 1 & Method 2

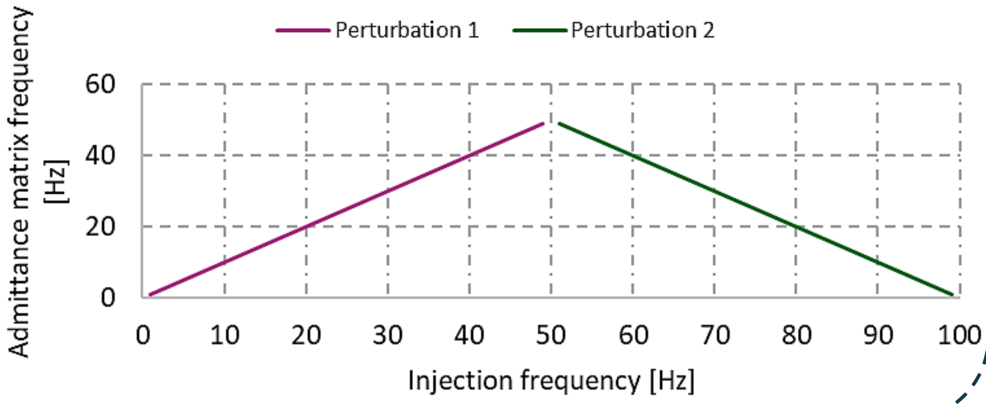



Method 1 $(s + jw)$ & $(s - jw)$

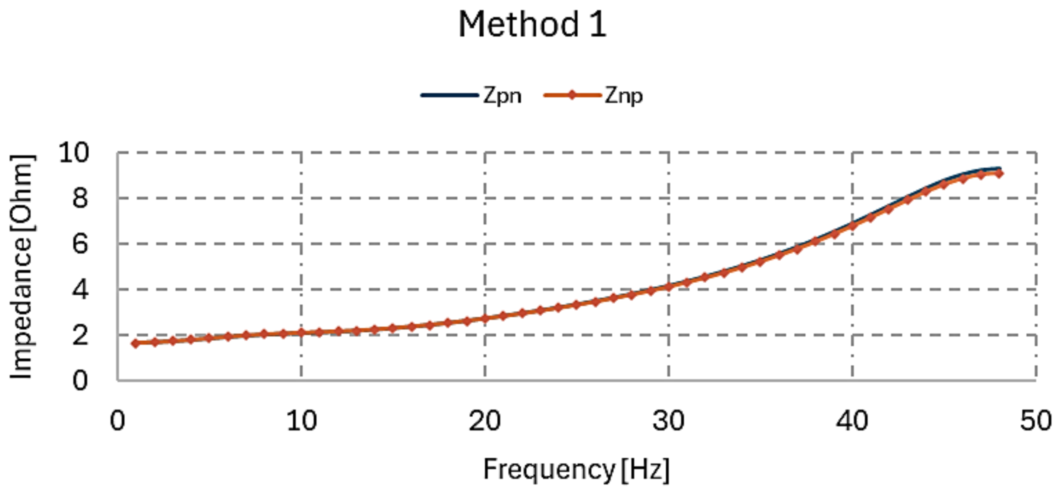


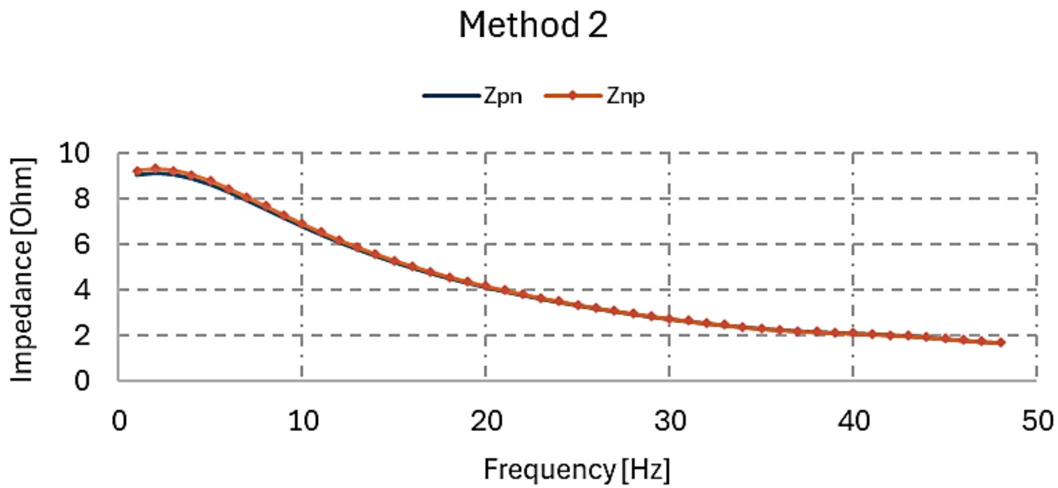

Method 2 $(s)$ & $(s - 2jw)$

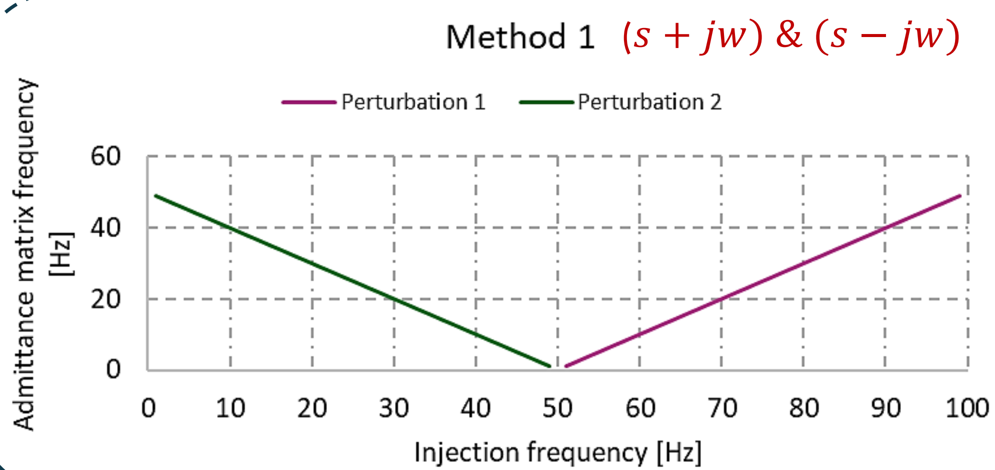


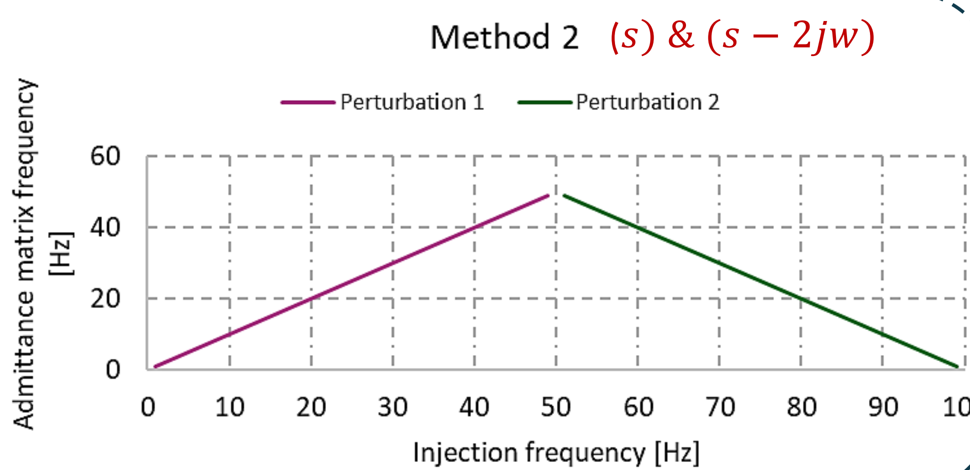
# Modified Seq impedance – Zpn & Znp

## Method 1 & Method 2



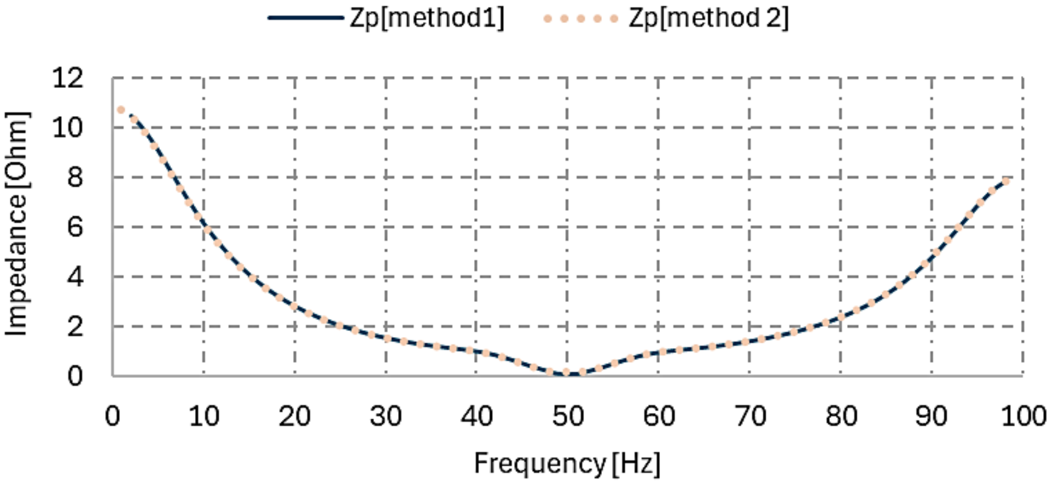



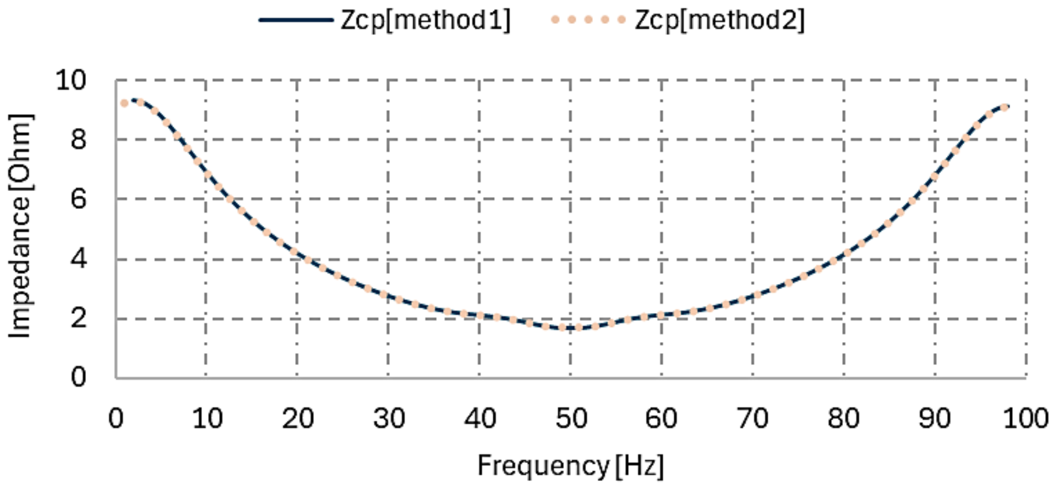



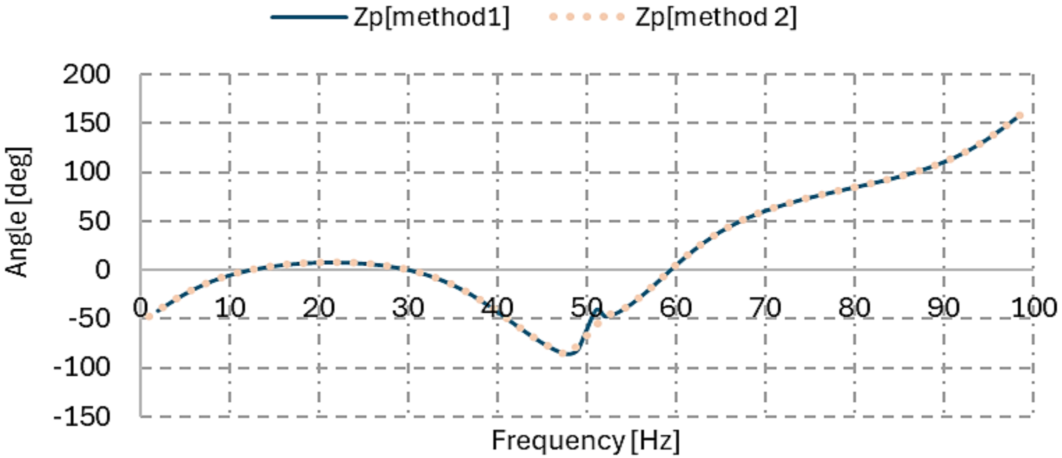



# Seq impedance comparison

**Method 1 & Method 2**



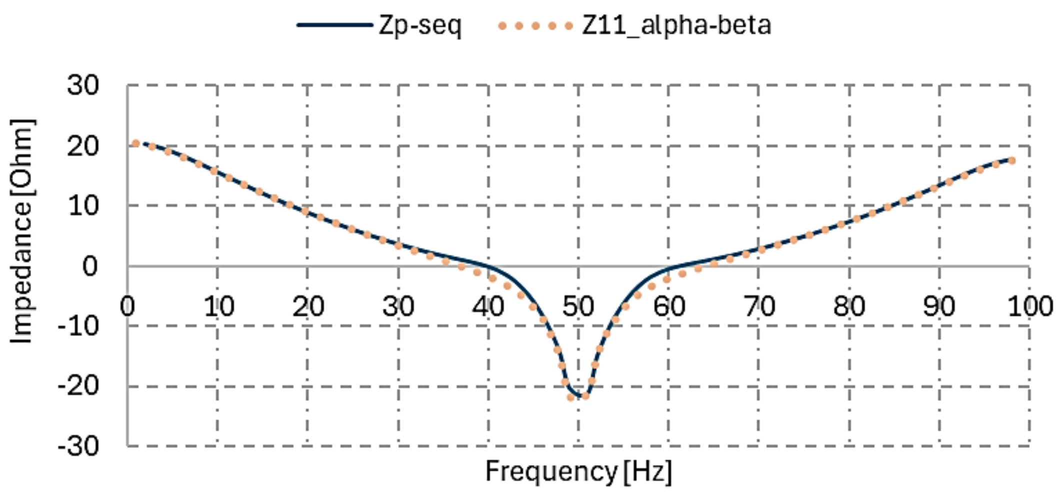



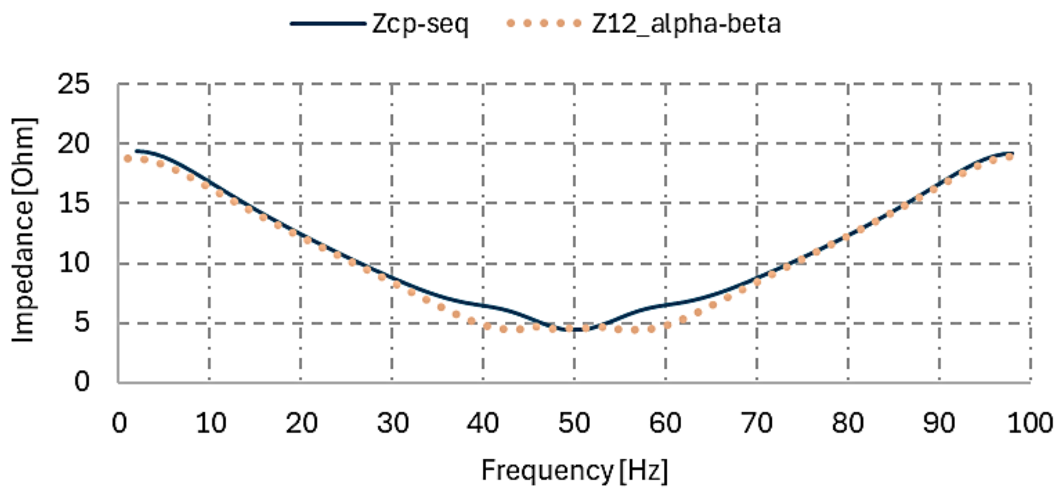

$$Z_{p-method2}(s) = Z^*_{p-method1}(s)$$
$$Z_{cp-method2}(s) = Z^*_{cp-method1}(s)$$

cigre
For power system expertise

# MIMO Form – Comparison

**Sequence vs $\alpha\beta$ impedance**




- Impedances calculated in the $\alpha\beta$ frame corresponds to the sequence impedance calculated by Method 1
- There could be differences between the two domain if there are unequal mutual inductances between the phases
- Finite coupling impedance observed in both methods, which is expected for a converter system

# Thank You for listening!

For power system expertise