University of Manitoba

RTDS North American ATC 2026, Irwindale CA

# Multi-Port Impedance Measurement Tool in RTDS for Analysis of Wideband Oscillations in Networks With Embedded Power Electronic Converters

Ajinkya Sinkar, Ph.D., P.Eng.
Power Systems Engineer, Nayak Corporation Inc.

on behalf of

Prof. Aniruddha M. Gole, Ph.D., P.Eng., FIEEE, FCAE
Distinguished Professor, University of Manitoba

May 21, 2026

# Project Collaborators

- Dr. Hao Xiao, Research Associate, University of Manitoba
- Dr. Yi Zhang, R&D VP, CTO, RTDS Technologies Inc.
- Dr. Yi Qi, R&D Manager, RTDS Technologies Inc.
- Siwen Sun, Software Developer, RTDS Technologies Inc.

# Presentation Outline

01 Background and Challenge

02 Multi-Port Impedance Measurement Tool

03 Application for SSCI Analysis in RTDS

04 Comparisons With PSCAD/EMTDC

# 1.1 Background

☐ **Wideband oscillations are threatening the stability of networks with numerous embedded power electronic converters due to their interactions with the ac grid**

**Recent real-world wideband oscillation incidents**

| Year | Location | Oscillatory Freq. | System |
|---|---|---|---|
| 2021 | Virginia U.S. | 22/38/82 Hz | Solar Farm |
| 2021 | Scotland | 8 Hz | Wind Farm |
| 2020 | South Australia | 17~19 Hz | Wind Farm |
| 2020 | North China | 2~6 Hz | Wind Farm |
| 2019 | Ontario Canada | 3.5 Hz | Wind Farm |
| 2018 | Central China | 1810 Hz | MMC-HVDC |
| 2013 | Germany | 250~350 Hz | VSC-HVDC |

**Networks with embedded power electronic converters**

# 1.2 Overview and Challenge

Comparison of the different state of the art approaches for analysis of stability

| Approach | Time-Domain | Frequency-Domain | |
|---|---|---|---|
| Mathematical model | State-Space equation | Multi-Port closed-loop impedance matrix | Multi-Port open-loop transfer function matrix |
| Stability criterion | Dominant modes in the LHP | Dominant poles in the LHP | Nyquist/Bode criteria by measured impedances |
| Margin index | Damping ratio of dominant modes | Damping ratio of dominant poles | Magnitude/Phase margins from Bode plots |
| Identification of critical component | Participation factor in time-domain | Participation factor in frequency-domain | A reliable method is lacking |
| CHIL/Black-Box implementation in RTDS | Inapplicable | Inapplicable | Applicable but not existing yet on RTDS |

- ☐ Till now, the frequency-domain stability analysis in RTDS based on the multi-port impedance measurement has been difficult due to real-time algorithm constraints.

# 1.3 Proposed Project

☐ **Project Title:** **Development of Stability Assessment Tools in RTDS Simulator for Multi-Converter Power Systems**

☐ **Project PI:** **Ani Gole, Distinguished Professor, Univ. Manitoba**

☐ **Research Objective:**

1) **Development of multi-port impedance measurement tool in RTDS**
2) **Application of developed tool for analysis of wideband oscillations**

# Presentation Outline

01 Background and Challenge

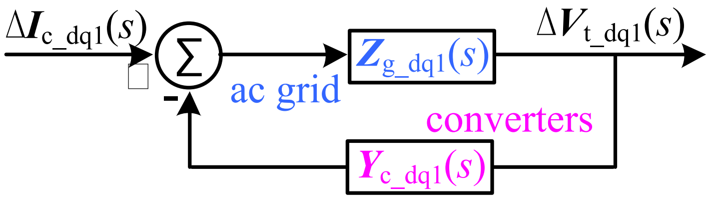
02 Multi-Port Impedance Measurement Tool

03 Application for SSCI Analysis in RTDS

04 Comparisons With PSCAD/EMTDC

# 2.1 Principle of Impedance Based Stability Analysis

## Feedback Diagram of Networks



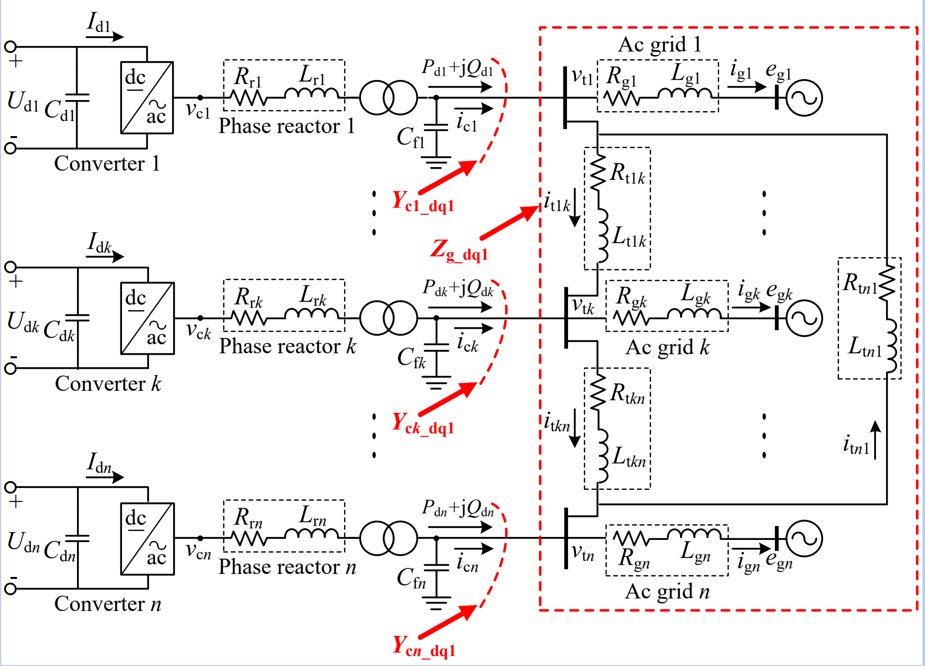
$\boldsymbol{Z}_{\mathrm{g\_dq1}}(s)$: $2n$-order ac grid impedance matrix
$\boldsymbol{Y}_{\mathrm{c\_dq1}}(s)$: $2n$-order converter admittance matrix
$\boldsymbol{Y}_{\mathrm{c\_dq1}}(s)=\mathrm{diag}\{\boldsymbol{Y}_{\mathrm{c1\_dq1}}(s),\ldots,\boldsymbol{Y}_{ck\mathrm{\_dq1}}(s),\ldots,\boldsymbol{Y}_{cn\mathrm{\_dq1}}(s)\}$
dq1: dq-frame aligned with the voltage at bus 1

**closed-loop characteristic equation**

$$\boldsymbol{H}_{\mathrm{cl\_dq1}}(s)=\boldsymbol{I}+\boldsymbol{Z}_{\mathrm{g\_dq1}}(s)\cdot\boldsymbol{Y}_{\mathrm{c\_dq1}}(s)=0$$

- Networks are ***stable*** if all zeros are in LHP
- Zeros calculation is however ***challenging***

## Linearized circuit of networks with power electronic converters



☐ **The network stability can be inferred by looking at the zeros of the closed-loop characteristic equation formed by the converter admittances and grid impedance**

# 2.2 Stability Analysis using Open-Loop Transfer Function Matrix

## Closed-Loop to Open-Loop

$$\boldsymbol{H}_{\mathrm{cl\_dq1}}(s) = \boldsymbol{I} + \boldsymbol{Z}_{\mathrm{g\_dq1}}(s)\cdot \boldsymbol{Y}_{\mathrm{c\_dq1}}(s)$$

- closed-loop transfer function matrix

**stable: zeros in LHP**

$$\boldsymbol{H}_{\mathrm{ol\_dq1}}(s) = \boldsymbol{Z}_{\mathrm{g\_dq1}}(s)\cdot \boldsymbol{Y}_{\mathrm{c\_dq1}}(s)$$

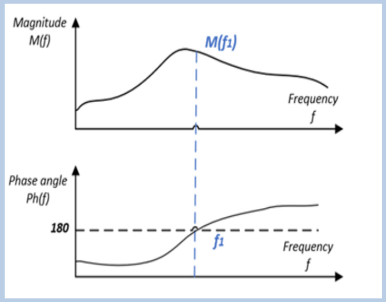
- open-loop transfer function matrix

**modal analysis**

$$\boldsymbol{H}_{\mathrm{ol\_dq1}}(s) = \boldsymbol{R}(s)\cdot\boldsymbol{\varLambda}(s)\cdot\boldsymbol{L}(s)$$

- Eigvalue matrix $\boldsymbol{\varLambda}(s)=\mathrm{diag}\{\lambda_1(s),\ldots,\lambda_k(s),\ldots\lambda_{2n}(s)\}$
- $PF_{jk}(s) = \left|L_{kj}^{\mathrm{T}}(s)\cdot R_{jk}(s)\right| \Big/ \left|\sum_{i=1}^{2n} L_{ki}^{\mathrm{T}}(s)\cdot R_{ik}(s)\right|$

## Stability Margin by Bode Plots



☐ At $f_1$ where the phase crosses 180º, $1/|\lambda_1|$ is the magnitude margin $M_1$ (stable if $M_1 > 1.0$)

☐ If $M_k$ for $\lambda_k$ is the lowest from $\lambda_1$ to $\lambda_{2n}$, $f_k$ for the 180º phase is dominant oscillatory freq

## Identification of critical converter

☐ Calculate participation factors $PF_{jk}(f_k)$ at $f_k$ for $j = \{1,\ldots,2n\}$ and identify the critical converter with the highest $PF_{jk}(f_k)$

☐ The stability margin is assessed using Bode plots from the open-loop transfer function

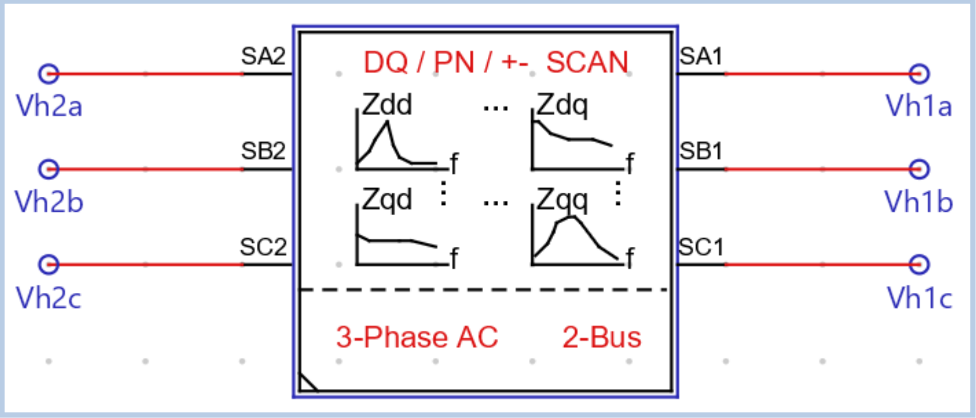
☐ Critical converter is identified using frequency domain participation factor

# 2.3 Design of Multi-Port Impedance Measurement Tool

## Designed Measurement Scheme

- multi-port multi-sine injection, *V*/*I* sampling and processing
- computing DFT of filtered *V*/*I* under real-time considerations
- optimizing inversion of high-order complex *V*/*I* matrix
- calculating impedance matrix and communication with GUI
- assessing stability margin and critical converter in GUI

## Multi-Port Impedance Measurement Tool in RTDS

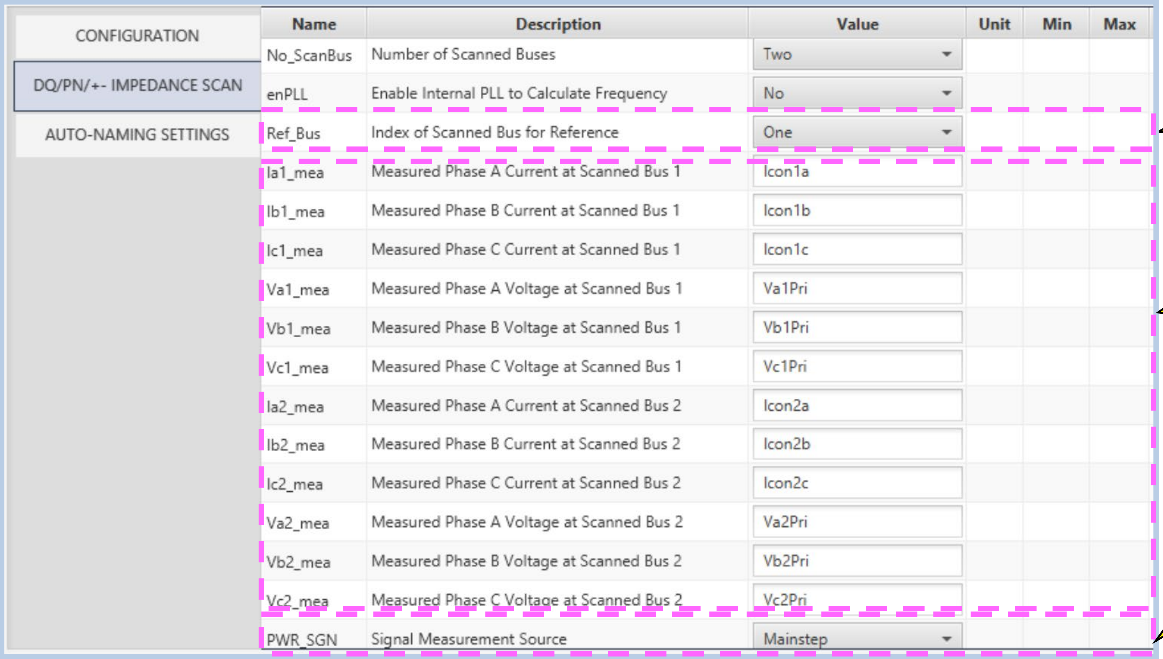


The developed multi-port impedance measurement tool can be implemented in RTDS with a mainstep of 50 us

# 2.4 Functions of Multi-Port Impedance Measurement Tool

- ☐ **The multi-port impedance measurement tool in RTDS provides flexible functions such as selection of reference bus, measured voltages and currents, signal source**

**Functions of Developed Multi-Port Impedance Measurement Tool in RTDS**



| Name | Description | Value | Unit | Min | Max |
|---|---|---|---|---|---|
| No_ScanBus | Number of Scanned Buses | Two | | | |
| enPLL | Enable Internal PLL to Calculate Frequency | No | | | |
| Ref_Bus | Index of Scanned Bus for Reference | One | | | |
| Ia1_mea | Measured Phase A Current at Scanned Bus 1 | Icon1a | | | |
| Ib1_mea | Measured Phase B Current at Scanned Bus 1 | Icon1b | | | |
| Ic1_mea | Measured Phase C Current at Scanned Bus 1 | Icon1c | | | |
| Va1_mea | Measured Phase A Voltage at Scanned Bus 1 | Va1Pri | | | |
| Vb1_mea | Measured Phase B Voltage at Scanned Bus 1 | Vb1Pri | | | |
| Vc1_mea | Measured Phase C Voltage at Scanned Bus 1 | Vc1Pri | | | |
| Ia2_mea | Measured Phase A Current at Scanned Bus 2 | Icon2a | | | |
| Ib2_mea | Measured Phase B Current at Scanned Bus 2 | Icon2b | | | |
| Ic2_mea | Measured Phase C Current at Scanned Bus 2 | Icon2c | | | |
| Va2_mea | Measured Phase A Voltage at Scanned Bus 2 | Va2Pri | | | |
| Vb2_mea | Measured Phase B Voltage at Scanned Bus 2 | Vb2Pri | | | |
| Vc2_mea | Measured Phase C Voltage at Scanned Bus 2 | Vc2Pri | | | |
| PWR_SGN | Signal Measurement Source | Mainstep | | | |

**selection of reference bus for alignment of measurement**

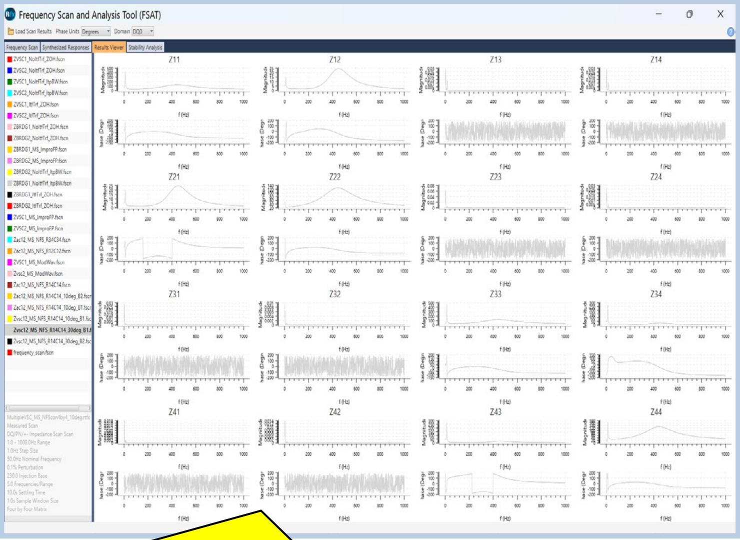
**selection of measured voltages and current in real-time at the concerned converter ac buses**

**selection of signal measurement source from mainstep, substep, or smallstep**

# 2.5 Enhanced GUI for Impedance Display and Oscillation Analysis

- ☐ **The previous graphical user interface (GUI) has been enhanced for higher-order measured impedance display and system-level wideband oscillation analysis**

## Measured Impedance Display


Frequency Scan and Analysis Tool (FSAT)

Load Scan Results Phase Units Degrees Domain DQ0

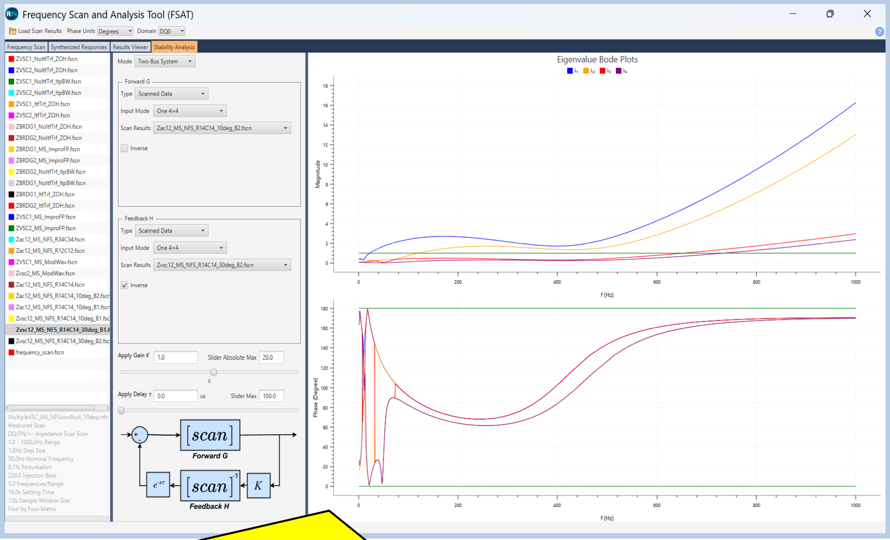
Frequency Scan | Synthesized Responses | Results Viewer | Stability Analysis

ZVSC1_NoltfTrf_ZOH.fscn
ZVSC2_NoltfTrf_ZOH.fscn
ZVSC1_NoltfTrf_ltpBW.fscn
ZVSC2_NoltfTrf_ltpBW.fscn
ZVSC1_ltfTrf_ZOH.fscn
ZVSC2_ltfTrf_ZOH.fscn
ZBRDG1_NoltfTrf_ZOH.fscn
ZBRDG2_NoltfTrf_ZOH.fscn
ZBRDG1_MS_ImproFP.fscn
ZBRDG2_MS_ImproFP.fscn
ZBRDG2_NoltfTrf_ltpBW.fscn
ZBRDG1_NoltfTrf_ltpBW.fscn
ZBRDG1_ltfTrf_ZOH.fscn
ZBRDG2_ltfTrf_ZOH.fscn
ZVSC1_MS_ImproFP.fscn
ZVSC2_MS_ImproFP.fscn
Zac12_MS_NFS_R34C34.fscn
Zac12_MS_NFS_R12C12.fscn
ZVSC1_MS_ModWav.fscn
Zvsc2_MS_ModWav.fscn
Zac12_MS_NFS_R14C14.fscn
Zac12_MS_NFS_R14C14_10deg_B2.fscn
Zac12_MS_NFS_R14C14_10deg_B1.fscn
Zvsc12_MS_NFS_R14C14_10deg_B1.fsc
**Zvsc12_MS_NFS_R14C14_30deg_B1.f**
Zvsc12_MS_NFS_R14C14_30deg_B2.fsc
frequency_scan.fscn

MultipleVSC_MS_NFScon4by4_10deg.rtfx
Measured Scan
DQ/PN/+- Impedance Scan Scan
1.0 - 1000.0Hz Range
1.0Hz Step Size
50.0Hz Nominal Frequency
0.1% Perturbation
230.0 Injection Base
5.0 Frequencies/Range
10.0s Settling Time
1.0s Sample Window Size
Four by Four Matrix

**Full picture of the measured impedance magnitudes and angles is clearly shown**

## System-Level Wideband Oscillation Analysis


Frequency Scan and Analysis Tool (FSAT)

Load Scan Results Phase Units Degrees Domain DQ0

Frequency Scan | Synthesized Responses | Results Viewer | Stability Analysis

ZVSC1_NoltfTrf_ZOH.fscn
ZVSC2_NoltfTrf_ZOH.fscn
ZVSC1_NoltfTrf_ltpBW.fscn
ZVSC2_NoltfTrf_ltpBW.fscn
ZVSC1_ltfTrf_ZOH.fscn
ZVSC2_ltfTrf_ZOH.fscn
ZBRDG1_NoltfTrf_ZOH.fscn
ZBRDG2_NoltfTrf_ZOH.fscn
ZBRDG1_MS_ImproFP.fscn
ZBRDG2_MS_ImproFP.fscn
ZBRDG2_NoltfTrf_ltpBW.fscn
ZBRDG1_NoltfTrf_ltpBW.fscn
ZBRDG1_ltfTrf_ZOH.fscn
ZBRDG2_ltfTrf_ZOH.fscn
ZVSC1_MS_ImproFP.fscn
ZVSC2_MS_ImproFP.fscn
Zac12_MS_NFS_R34C34.fscn
Zac12_MS_NFS_R12C12.fscn
ZVSC1_MS_ModWav.fscn
Zvsc2_MS_ModWav.fscn
Zac12_MS_NFS_R14C14.fscn
Zac12_MS_NFS_R14C14_10deg_B2.fscn
Zac12_MS_NFS_R14C14_10deg_B1.fscn
Zvsc12_MS_NFS_R14C14_10deg_B1.fsc
**Zvsc12_MS_NFS_R14C14_30deg_B1.f**
Zvsc12_MS_NFS_R14C14_30deg_B2.fsc
frequency_scan.fscn

MultipleVSC_MS_NFScon4by4_10deg.rtfx
Measured Scan
DQ/PN/+- Impedance Scan Scan
1.0 - 1000.0Hz Range
1.0Hz Step Size
50.0Hz Nominal Frequency
0.1% Perturbation
230.0 Injection Base
5.0 Frequencies/Range
10.0s Settling Time
1.0s Sample Window Size
Four by Four Matrix

Mode: Two-Bus System

Forward G
Type: Scanned Data
Input Mode: One 4×4
Scan Results: Zac12_MS_NFS_R14C14_10deg_B2.fscn
☐ Inverse

Feedback H
Type: Scanned Data
Input Mode: One 4×4
Scan Results: Zvsc12_MS_NFS_R14C14_30deg_B2.fscn
☑ Inverse

Apply Gain $K$: 1.0 Slider Absolute Max: 20.0

Apply Delay $\tau$: 0.0 us Slider Max: 100.0

**Dominant freq., stability margin, critical converter are shown in a straightforward manner in graphs**

# Presentation Outline

01 Background and Challenge

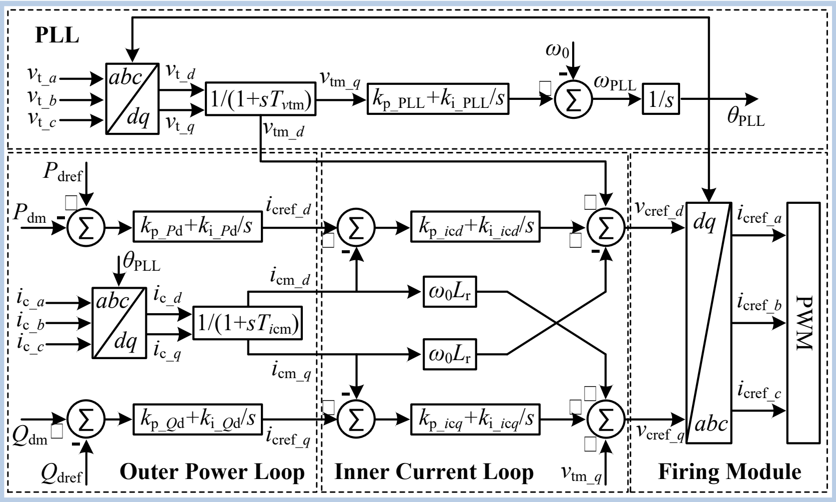
02 Multi-Port Impedance Measurement Tool

03 Application for SSCI Analysis in RTDS

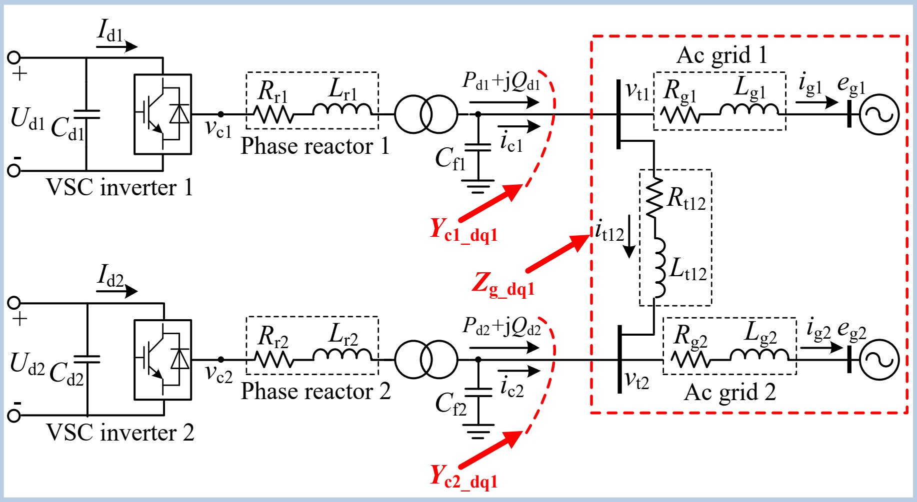
04 Comparisons With PSCAD/EMTDC

# 3.1 The Test System

- **Test System**: The dual-infeed VSC-HVDC inverter network with ac bus tie-line
- **Control Mode**: VSC inverter 1 in constant $P_1Q_1$ and 2 in constant $P_2V_2$ control
- **Control Bandwidth**: PLL 1 and 2, 17 Hz; $P_1Q_1$, 8/8 Hz; $P_2V_2$, 10/4 Hz; $i_{cdq}$, 200 Hz



**Power and current loop control and PLL of VSC inverter**

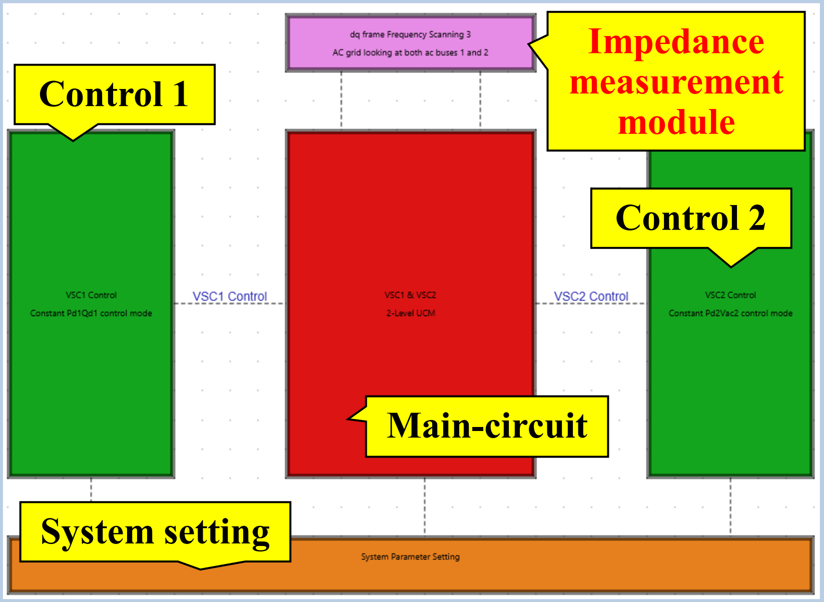


**Schematic diagram of dual-infeed VSC-HVDC inverter network**

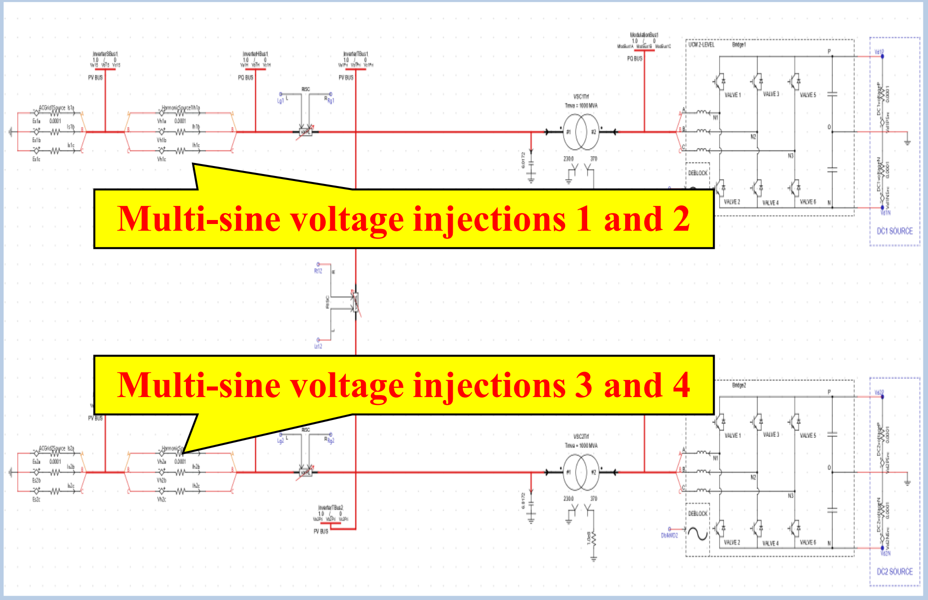
# 3.2 Arrangement of Test System Setup in RSCAD

- ☐ **Main-circuit with the multi-sine series voltage injection; converter control blocks, parameter setting block and impedance measurement module**

Entire layout of the test system setup in RSCAD



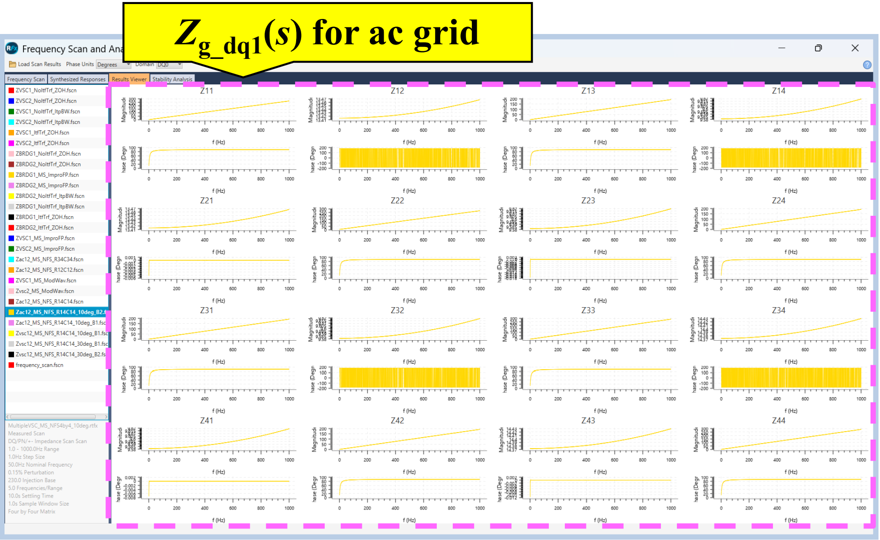
Schematic diagram of main-circuit with multi-sine voltage injection



**Project Source: "Example Cases\14 Impedance Scan\Harmonic Scan (Measured)\Two-Port Scan"**

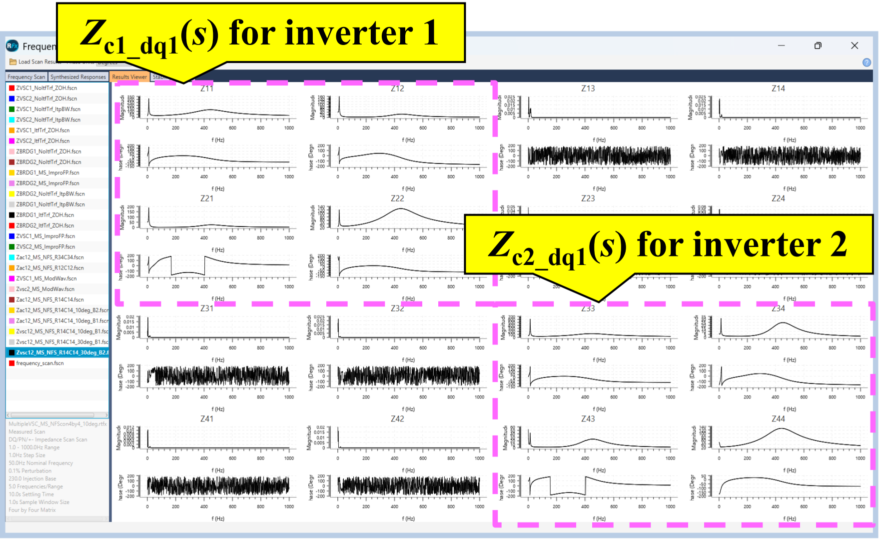
# 3.3 Two-Port Impedance Measurement Results

- ☐ **Ac Grid**: The 4th order $Z_{g\_dq1}(s)$ includes 16 measured complex impedances
- ☐ **Inverters 1 and 2**: 2nd order $Z_{c1\_dq1}(s)$ for inverter 1, 2nd order $Z_{c2\_dq1}(s)$ for inverter 2


$Z_{g\_dq1}(s)$ for ac grid

MultipleVSC_MS_NFS4by4_10deg.rtfx
Measured Scan
DQ/PN/+- Impedance Scan Scan
1.0 - 1000.0Hz Range
1.0Hz Step Size
50.0Hz Nominal Frequency
0.15% Perturbation
230.0 Injection Base
5.0 Frequencies/Range
10.0s Settling Time
1.0s Sample Window Size
Four by Four Matrix

Magnitudes and angles of ac grid impedance matrix elements


$Z_{c1\_dq1}(s)$ for inverter 1

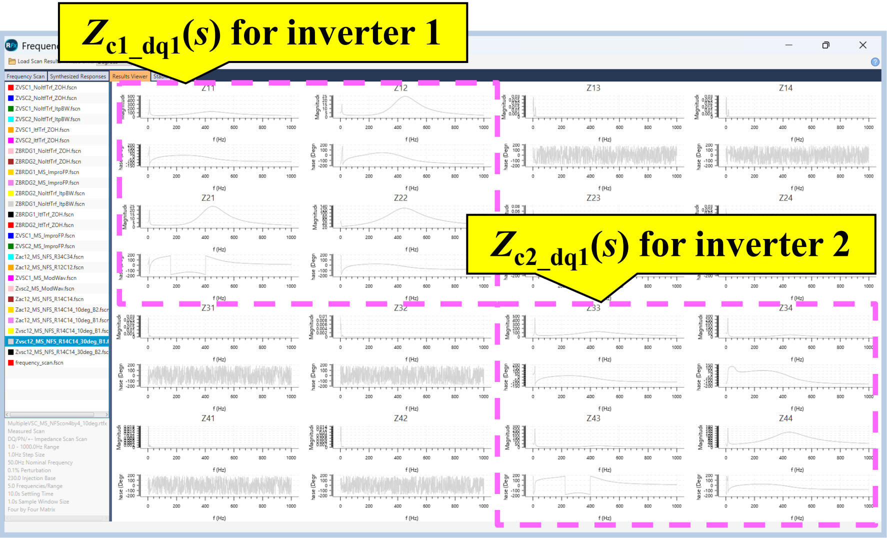
$Z_{c2\_dq1}(s)$ for inverter 2

MultipleVSC_MS_NFScon4by4_10deg.rtfx
Measured Scan
DQ/PN/+- Impedance Scan Scan
1.0 - 1000.0Hz Range
1.0Hz Step Size
50.0Hz Nominal Frequency
0.1% Perturbation
230.0 Injection Base
5.0 Frequencies/Range
10.0s Settling Time
1.0s Sample Window Size
Four by Four Matrix

Magnitudes and angles of converter impedance matrix elements

# 3.4 Impact of Reference Bus for Alignment of Measurement

- ☐ Voltage Angle Difference Between Ac Bus 1 and 2: 30 deg
- ☐ The measured converter impedances referred at bus 1 and 2 differ below 250 Hz
- ☐ The impact on converter impedances vanishes beyond current control bandwidth

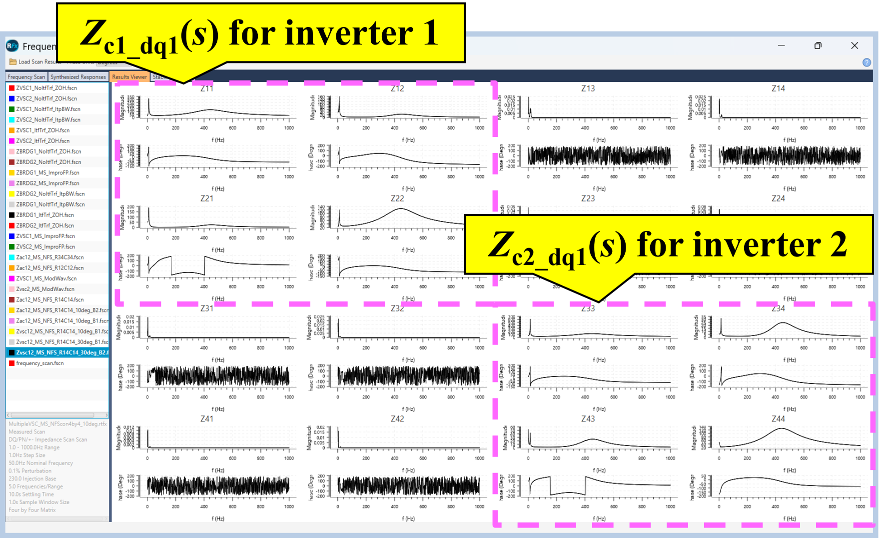


MultipleVSC_MS_NFScon4by4_10deg.rtfx
Measured Scan
DQ/PN/+- Impedance Scan Scan
1.0 - 1000.0Hz Range
1.0Hz Step Size
50.0Hz Nominal Frequency
0.1% Perturbation
230.0 Injection Base
5.0 Frequencies/Range
10.0s Settling Time
1.0s Sample Window Size
Four by Four Matrix

**$Z_{c1\_dq1}(s)$ for inverter 1**

**$Z_{c2\_dq1}(s)$ for inverter 2**

Converter impedance matrix elements referred at ac bus 1



MultipleVSC_MS_NFScon4by4_10deg.rtfx
Measured Scan
DQ/PN/+- Impedance Scan Scan
1.0 - 1000.0Hz Range
1.0Hz Step Size
50.0Hz Nominal Frequency
0.1% Perturbation
230.0 Injection Base
5.0 Frequencies/Range
10.0s Settling Time
1.0s Sample Window Size
Four by Four Matrix

**$Z_{c1\_dq1}(s)$ for inverter 1**

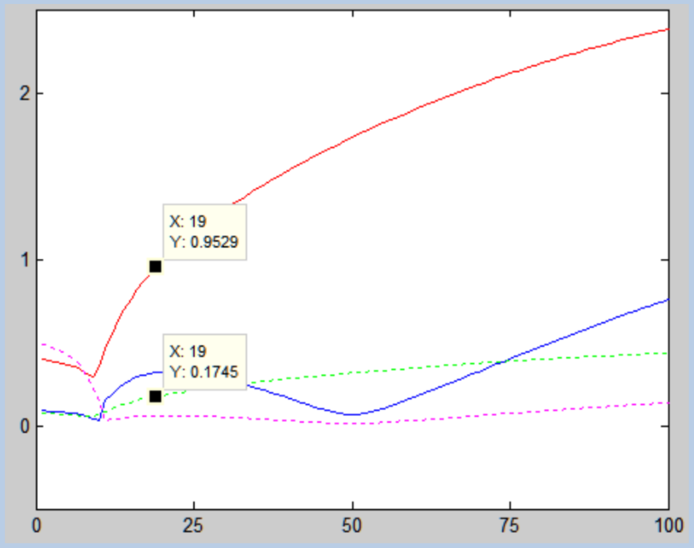
**$Z_{c2\_dq1}(s)$ for inverter 2**

Converter impedance matrix elements referred at ac bus 2

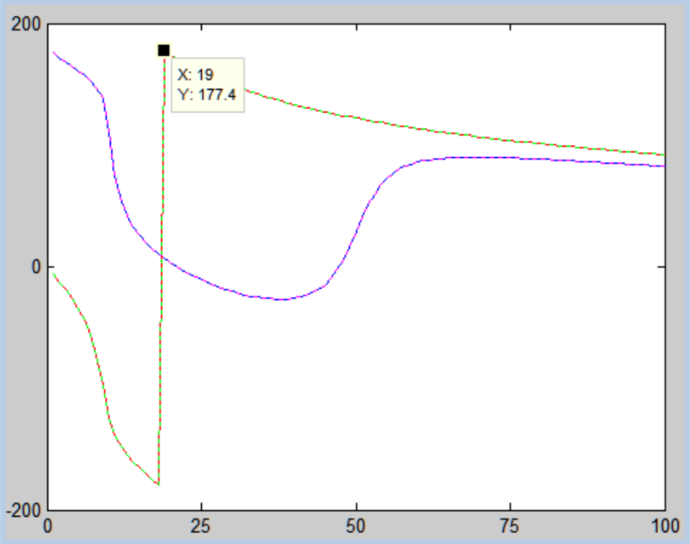
# 3.5 Identification of Dominant Frequency and Stability Margin

- ☐ **Open-Loop:** $H_{ol\_dq1}(s) = Z_{g\_dq1}(s) \cdot \mathrm{diag}\{Z^{-1}_{c1\_dq1}(s), Z^{-1}_{c2\_dq1}(s)\} \Rightarrow \mathrm{diag}\{\lambda_1, \lambda_2, \lambda_3, \lambda_4\}$
- ☐ **Dominant Freq.:** At 19 Hz, $\lambda_1$ cross negative real-axis from phase plot
- ☐ **Magnitude Margin:** $M_1 = 1/|\lambda_1| = 1/0.9529 = 1.05$ (marginally stable)

Magnitude of 4 eigenvalues of open-loop $H_{ol\_dq1}(s)$



Phase of 4 eigenvalues of open-loop $H_{ol\_dq1}(s)$



# 3.6 Validation of Identified Results by Step Response

- ☐ **Dc power and ac voltage responses with 5 % power order step in VSC inverter 1**
- ☐ **Simulated oscillatory period: 0.05278 s (18.9 Hz) validating the predicted 19 Hz**
- ☐ **Responses are oscillatory but stable agree perfectly with the small signal model**

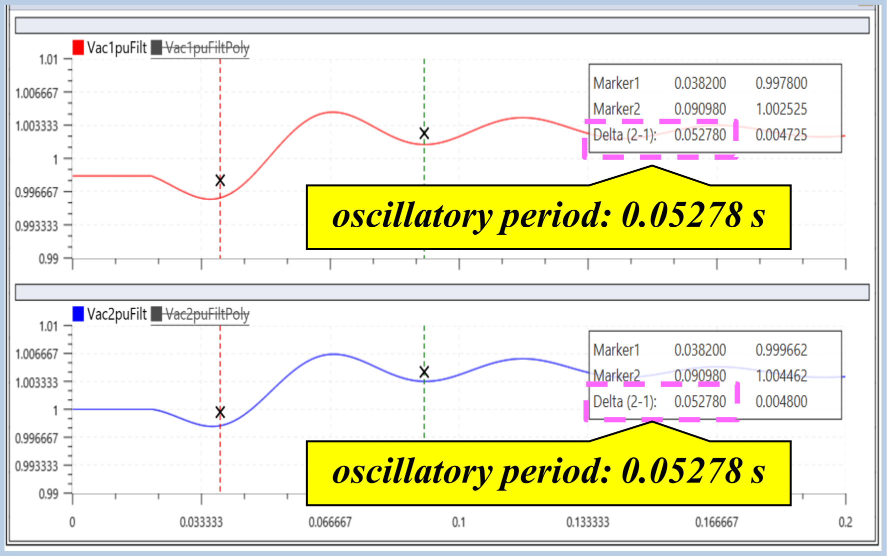
| | | |
|---|---|---|
| Marker1 | 0.067100 | 0.964941 |
| Marker2 | 0.119880 | 0.953450 |
| Delta (2-1): | 0.052780 | -0.011491 |

***oscillatory period: 0.05278 s***

| | | |
|---|---|---|
| Marker1 | 0.067100 | 1.005278 |
| Marker2 | 0.119880 | 1.001715 |
| Delta (2-1): | 0.052780 | -0.003563 |

***oscillatory period: 0.05278 s***

**DC power step responses of VSC inverters 1 and 2 in RTDS**



| | | |
|---|---|---|
| Marker1 | 0.038200 | 0.997800 |
| Marker2 | 0.090980 | 1.002525 |
| Delta (2-1): | 0.052780 | 0.004725 |

***oscillatory period: 0.05278 s***

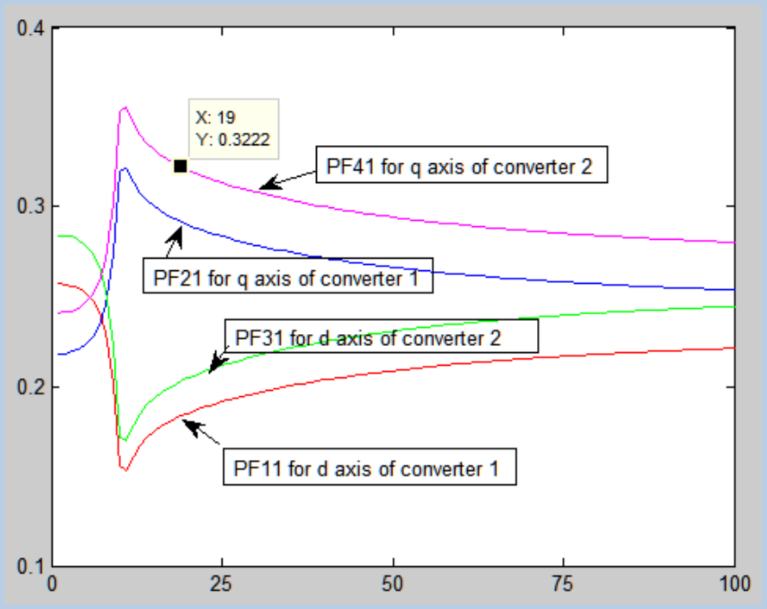
| | | |
|---|---|---|
| Marker1 | 0.038200 | 0.999662 |
| Marker2 | 0.090980 | 1.004462 |
| Delta (2-1): | 0.052780 | 0.004800 |

***oscillatory period: 0.05278 s***

**Bus voltage step responses of VSC inverters 1 and 2 in RTDS**

# 3.7 Assessment of Critical Converter

- ☐ **Critical Participation Factor:** at 19 Hz, is $PF_{41}$ has the highest value of 0.3222
- ☐ **Critical Converter:** VSC converter 2 has largest contribution to the 19 Hz mode $\lambda_1$

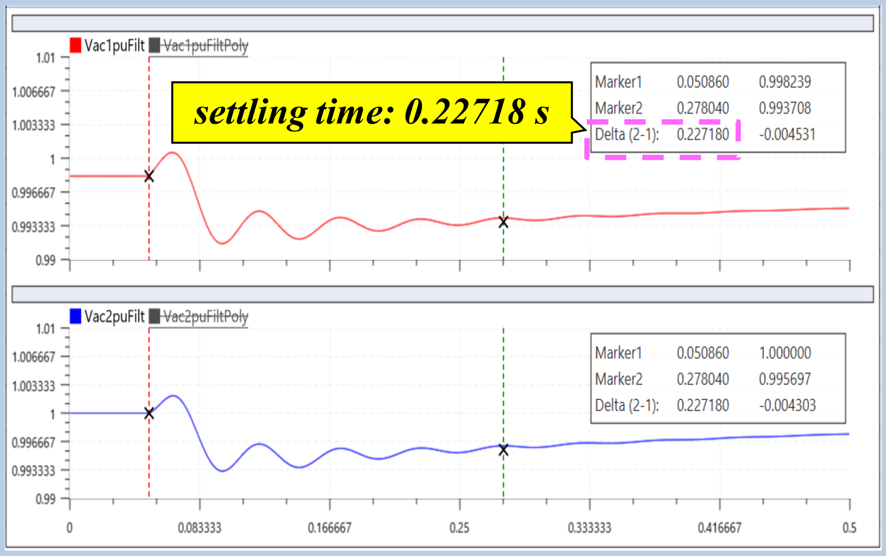


**PF variations versus frequency corresponding to $\lambda_1$**

***Time-Domain state-space equation indicates that: The reported 19 Hz oscillation is sub-synchronous control interactions (SSCI) arising from: Interaction between current control loop and PLL !***

# 3.8 Validation of Assessed Critical Converter

- Comparison of ac voltage curves with 5 % power order step in inverters 1 and 2
- The setting time and peak-valley distance for step change in inverter 2 is longer
- The simulated behaviors in RTDS validate the predicted critical inverter 2 by PF

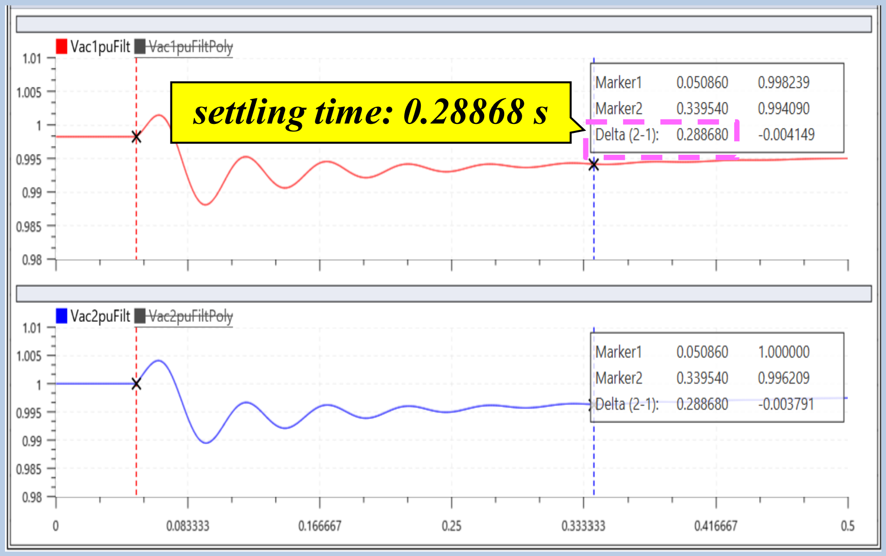


settling time: 0.22718 s

| | | |
|---|---|---|
| Marker1 | 0.050860 | 0.998239 |
| Marker2 | 0.278040 | 0.993708 |
| Delta (2-1): | 0.227180 | -0.004531 |

| | | |
|---|---|---|
| Marker1 | 0.050860 | 1.000000 |
| Marker2 | 0.278040 | 0.995697 |
| Delta (2-1): | 0.227180 | -0.004303 |

Voltage responses with power order step of inverter 1 in RTDS



settling time: 0.28868 s

| | | |
|---|---|---|
| Marker1 | 0.050860 | 0.998239 |
| Marker2 | 0.339540 | 0.994090 |
| Delta (2-1): | 0.288680 | -0.004149 |

| | | |
|---|---|---|
| Marker1 | 0.050860 | 1.000000 |
| Marker2 | 0.339540 | 0.996209 |
| Delta (2-1): | 0.288680 | -0.003791 |

Voltage responses with power order step of inverter 2 in RTDS

# Presentation Outline

01 Background and Challenge

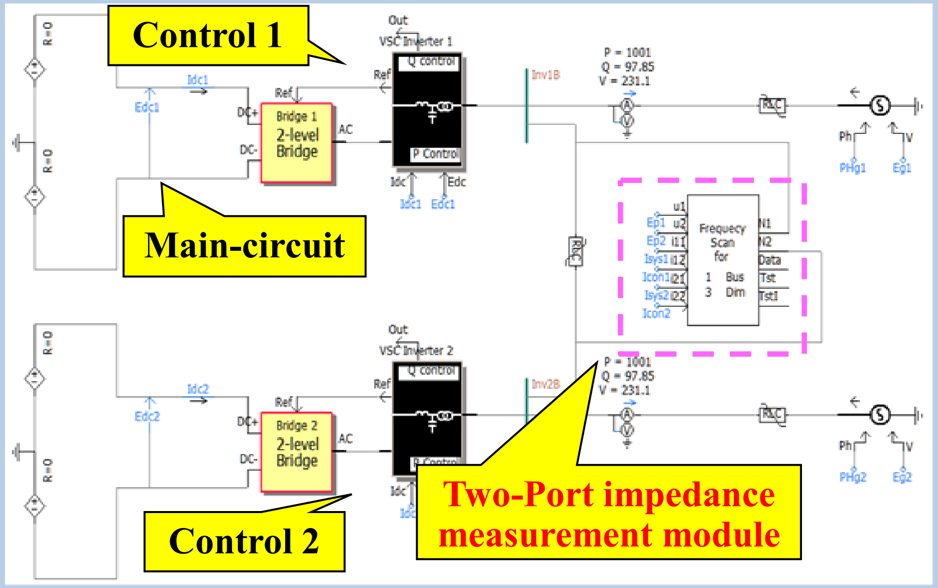
02 Multi-Port Impedance Measurement Tool

03 Application for SSCI Analysis in RTDS

04 Comparisons With PSCAD/EMTDC

# 4.1 Arrangement of Test System Setup in PSCAD/EMTDC

- **The PSCAD/EMTDC program is used for validating results in RTDS including two-port impedance measurement tool without real-time algorithm constraints**



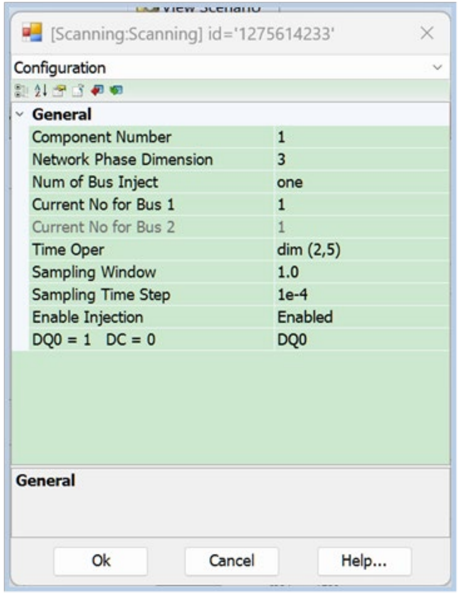
Control 1

Main-circuit

Control 2

Two-Port impedance measurement module

Entire layout of the test system setup in PSCAD



[Scanning:Scanning] id='1275614233'

Configuration

**General**

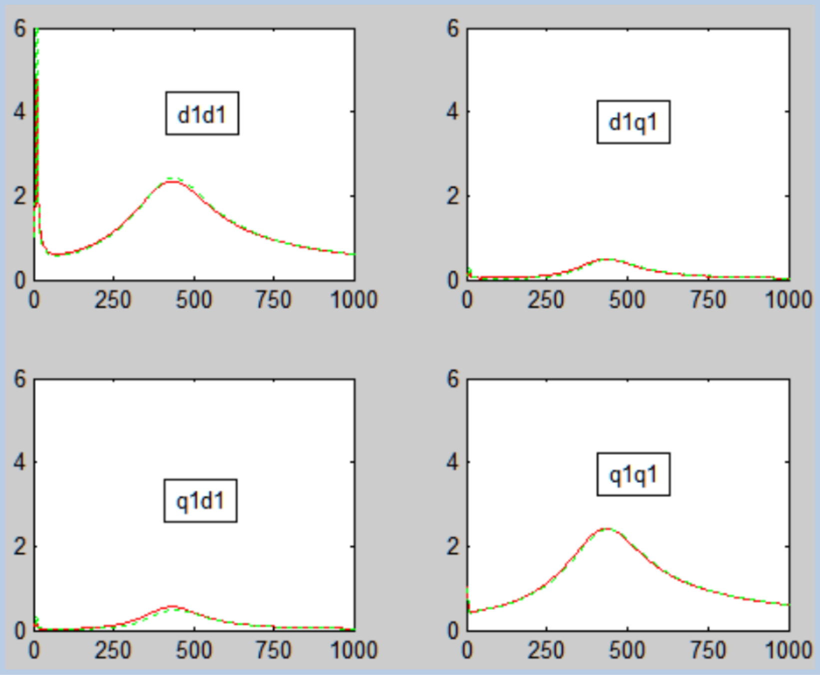
| | |
|---|---|
| Component Number | 1 |
| Network Phase Dimension | 3 |
| Num of Bus Inject | one |
| Current No for Bus 1 | 1 |
| Current No for Bus 2 | 1 |
| Time Oper | dim (2,5) |
| Sampling Window | 1.0 |
| Sampling Time Step | 1e-4 |
| Enable Injection | Enabled |
| DQ0 = 1 DC = 0 | DQ0 |

**General**

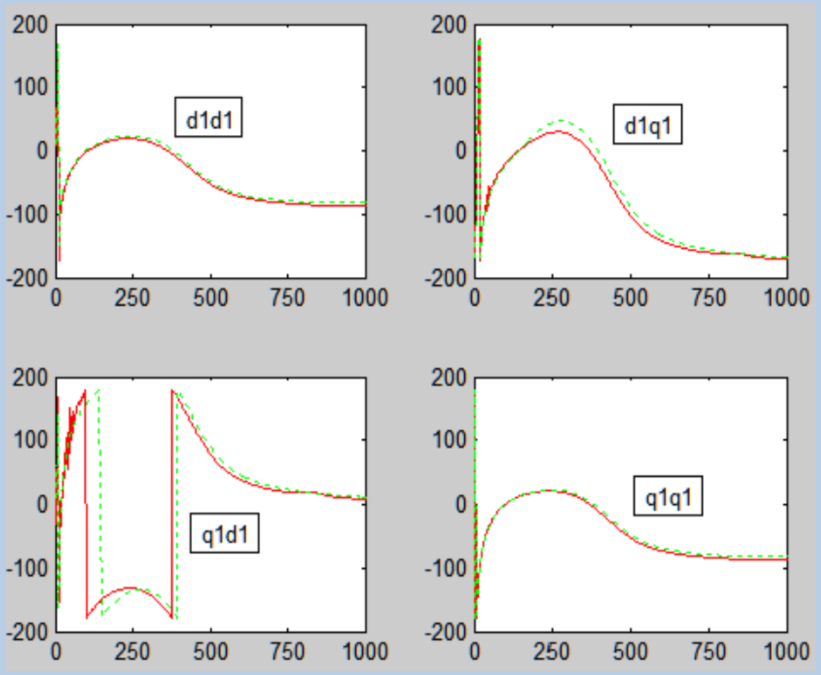
Parameter configuration setting

# 4.2 Comparison of Impedance Measurement for Inverter 1

**Magnitudes of measured impedance for inverter 1**



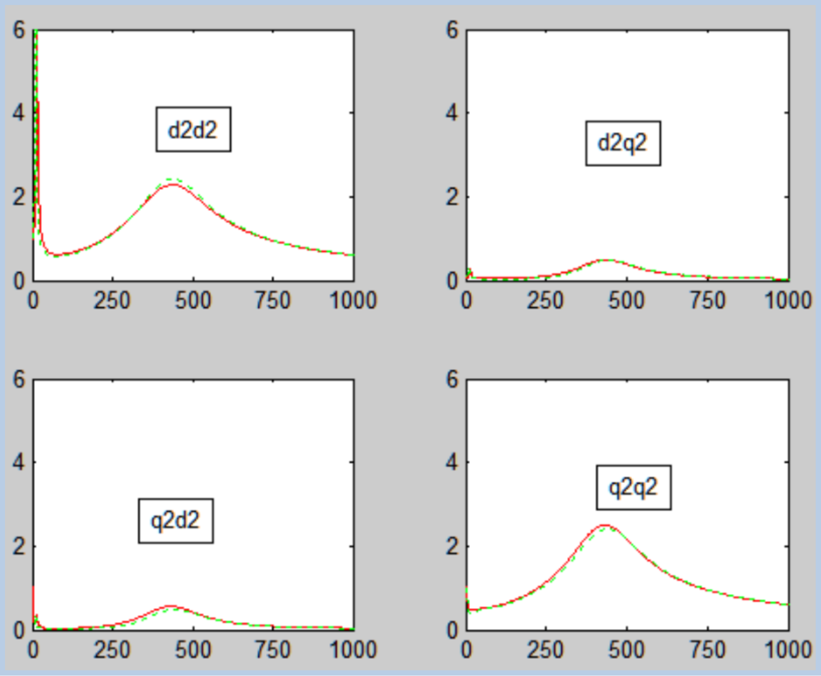
**Phases of measured impedance for inverter 1**



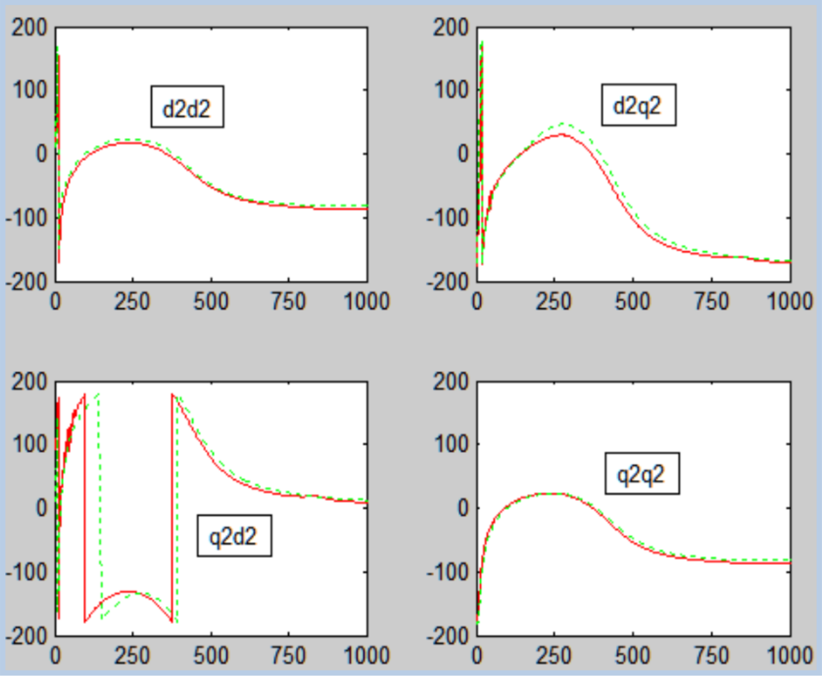
- **The magnitudes and phases of the two-port measured impedance for inverter 1 obtained from PSCAD (red curve) are matching well with those obtained from RTDS (green curve)**

# 4.3 Comparison of Impedance Measurement for Inverter 2

**Magnitudes of measured impedance for inverter 2**



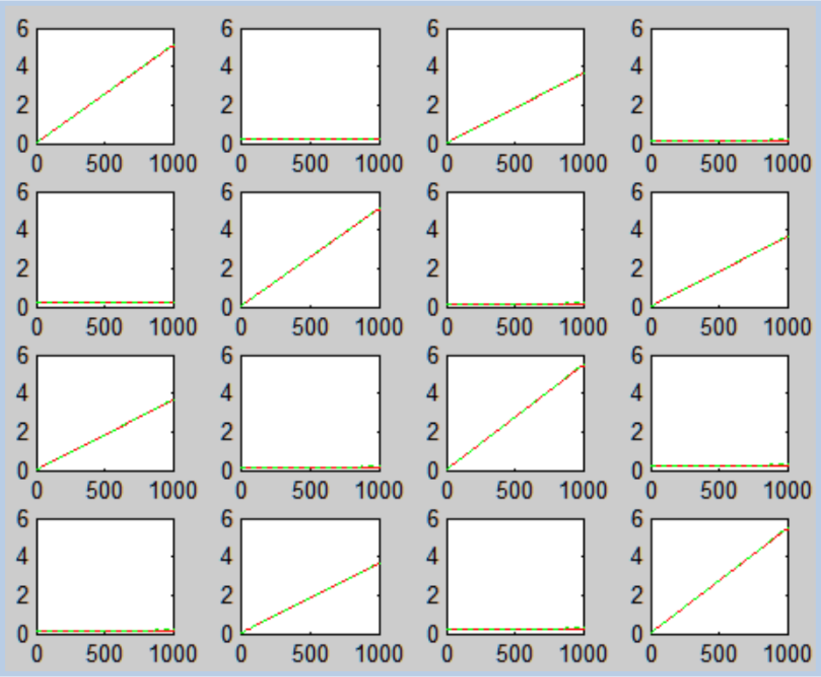
**Phases of measured impedance for inverter 2**



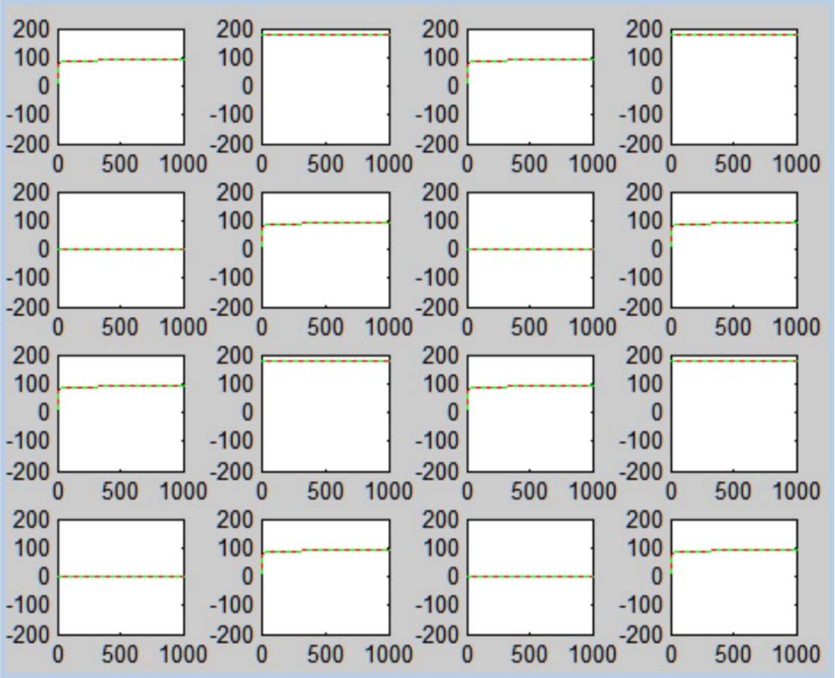
- ☐ **The magnitudes and phases of the two-port measured impedance for inverter 2 obtained from PSCAD (red curve) are matching well with those obtained from RTDS (green curve)**

# 4.4 Comparison of Impedance Measurement for Ac Grid

Magnitudes of measured impedance for ac grid



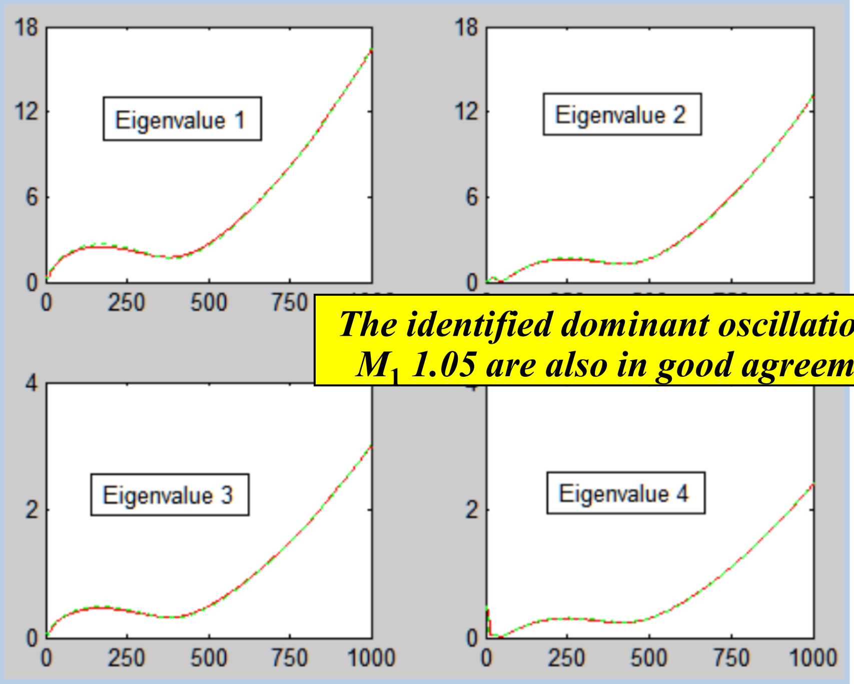
Phases of measured impedance for ac grid



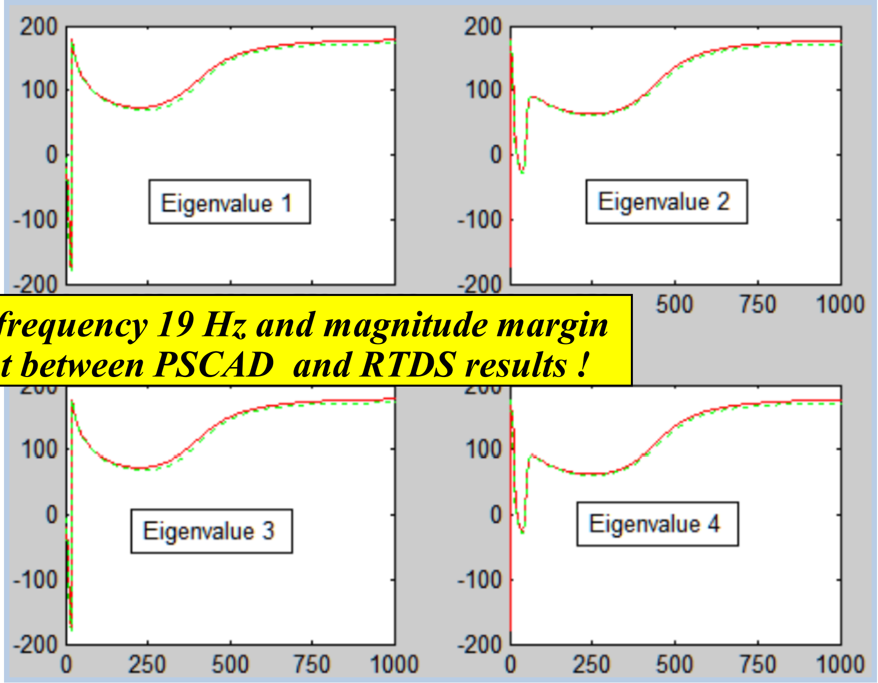
- ☐ **The magnitudes and phases of the two-port measured impedance for ac grid obtained from PSCAD (red curve) are matching well with those obtained from RTDS (green curve)**

# 4.5 Comparison of Bode Plots

**Magnitudes of calculated 4 eigenvalues in Bode plot**



**Phases of calculated 4 eigenvalues in Bode plot**



***The identified dominant oscillation frequency 19 Hz and magnitude margin $M_1$ 1.05 are also in good agreement between PSCAD and RTDS results !***

- ☐ **The magnitudes and phases of eigenvalues from $H_{ol\_dq1}(s)$ obtained from PSCAD (red curve) are matching well with those obtained from RTDS (green curve)**

# Conclusion and Future Work

- ☐ The developed multi-port impedance measurement tool in RTDS suitable for CHIL implementation can be applied for identification of dominant oscillation frequency, stability margin, and critical converter

- ☐ The developed tool in RTDS has been validated by comparing measured impedances and stability analysis with the PSCAD/EMTDC program

- ☐ The further applications of the developed tool will be conducted soon in more practical engineering projects with power electronic converters

# Q & A