Real-time Small Signal Stability Assessment of the Power Electronic-based Components in Distribution Systems

Presented by:
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Principal Eng., SDG&E
Professional Experiences

San Diego Gas & Electric – Distributed Energy Resources

Principal Engineer - Technical Project Lead  May 2017 – Present

- Work as the Technical Project Lead for EPIC Program.

- Apply a high level of technical expertise to solve problems in DER integration in SDG&E.

- Effectively work in project teams comprised of either or both of SDG&E staff and contractors.

- Coordinate input from various departments within the Company to meet project objectives.

- Work as the technical resource at the SDG&E Integrated Test Facility (ITF) to manage/run the RTDS activities and develop PHIL/CHIL testbeds (e.g. Advanced Energy Storage).
Professional Experiences

Varentec - Advanced Research and Applications

Senior Power System Engineer  Feb. 2016 – May 2017

• Power systems modeling and simulation: utilizing various T&D software/tools (i.e. CYME, Synergi, Milsoft, Python, and Open-DSS) to model and study utility power grids in integration with our unique Volt-VAR Control solution and calculate model-based metrics (e.g., voltage margin).

• Data analysis: using Tableau and MATLAB to
  • Analyze power system field data, gathered from deployed devices in the feeders as well as AMI and/or SCADA data;
  • Calculate field data-based metrics (such as, voltage margin, CVR factor for power and energy, watt loss reduction, and volt loss recovery) and analyze the systems after deployment of our VVC solution.

• Research and development:
  • Development of M&V techniques/methods.
  • Conducting a research with Open-DSS to validate the developed M&V methods and metrics.
Professional Experiences

Pacific Gas and Electric Company - Smart Grid Applications at Applied Technology Services (ATS)

Senior Electrical Engineer


Provided engineering and technical support to ensure successful deployment of pilot smart grid projects at PG&E, such as:

• Volt-VAR Optimization (VVO):
  implementation of PHIL experiment via RTDS, Grid Simulator, smart inverters, and programmable loads.
• Distributed Energy Resource Management System (DERMS)
• Fault Detection and Location (FDL)
Outline

• Introduction
  – Motivation
  – Contribution

• Stability analysis in AC systems
  – General requirements
  – Different small-signal stability analysis techniques

• Proposed small-signal stability method

• Experimental results and sample stability analysis

• Conclusion and future work
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Introduction

- FREEDM

Energy Cell
Introduction

- Power Electronic-based Distribution Systems (PEDS)
Introduction

- Solid State Transformer (SST)
- Generally, Power Electronic-based Components (PECs)
  - Power quality, voltage regulation, and power factor
  - Regulated output power → Constant power load
Introduction

- **Constant Power Load (CPL)**
  - Electrical load with a regulated-output power converter
- **Nature of stability investigation is considerably changed**
  - CPLs are prone to operate as negative impedances
  - Input voltage drops: load current increases
  - Nonlinear I-V characteristics can cause instability

\[ v_{in}(i) = \frac{1}{i_{in}} \]

Linear approximation shows negative slope (impedance) for a CPL connected to PEC
• Does integration of the PECs into the distribution system affect its small-signal stability?

Motivation
Contribution

• Novel real-time stability analysis criterion and technique, to assess small-signal stability of the PEDS
  – New real-time small-signal stability criterion
    – Developed based on impedance measurement and Nyquist criterion
    – Capable to be developed for real-time applications
  – Captures some part of system’s nonlinearities
    – Perturbs systems in a range of frequencies

• Hardware development and experimental implementation
  – Implementation of the proposed stability criterion in a real-time platform
  – Small-signal stability analysis of a test system through Power Hardware-In-the-Loop (PHIL) experiment
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Nyquist Theorem

- Could be utilized to describe the stability of the systems
- General feedback system

\[ \frac{y(s)}{u(s)} = [I + G(s)K(s)]^{-1}G(s) \]

- System is stable IFF the number of RHP zeros of the G and K is equal to the CCW encirclements around point (-1+0j) of the Nyquist contour of

\[ L(s) = G(s)K(s) \]
Nyquist Immittance Criterion

• Interconnected (source-load) PEDS

\[ v = \frac{v_{ST} - Z_S I_L}{1 + Z_S Y_L} \]

By analogy source-load system is stable IFF the Nyquist evaluation of return ratio \((Z_S Y_L)\) does not encircle \((-1+j0)\)

Nyquist Evaluation-based

- If the Nyquist evaluation of \((Z_S Y_L)\) doesn’t cross this boundary, then -1 cannot be encircled.

- Purpose of stability criteria:
  - Design: calculating range of load admittance from source impedance
  - Analysis: stability assessment

Numerical & Computational-based

Eigenvalue-based Stability Techniques

• For any interconnected source-load system (PEDS)
  - Transfer function of the linearized model
    \[ V_{dq}(s) = \left[ I + Z_{sdq}(s) Y_{ldq}(s) \right]^{-1} V_{sdq}(s) \]
  - State-space representation of the linearized model
    \[
    \begin{cases}
    \frac{dX}{dt} \approx Ax + Bu \\
y \approx Cx + Du
    \end{cases}
    \]

\[ \lambda(S) = (SI - A) \]

• The eigenvalues should remain in the **LHP**

\[ [I + Z_{sdq}(s) Y_{ldq}(s)] = 0 \]

OR

\[ |SI - A| = 0 \]
Outline

• Introduction
  – Motivation
  – Contribution

• Stability analysis in AC systems

• Proposed small-signal stability method
  – Proposed stability criterion and technique
  – Practical consideration
  – Real-time approach

• Experimental results and sample stability analysis

• Conclusion and future work
Proposed Stability Criterion

Unit Circle Criterion

- The Nyquist diagram of the \((Z_S Y_l)\) restricted within the unit circle would result in a stable system.

\[
L_{dq}(s) = Z_{Sdq} Y_{Ldq} = \begin{bmatrix} Z_{Sdd}(s) & Z_{Sdq}(s) \\ Z_{Sqd}(s) & Z_{Sqq}(s) \end{bmatrix} \begin{bmatrix} Y_{Ldd}(s) & Y_{Ldq}(s) \\ Y_{Lqd}(s) & Y_{Lqq}(s) \end{bmatrix}
\]
Proposed Stability Criterion

Unit Circle Criterion

- For a PEC in order to be a small-signal stable, the magnitude of $Z_s Y_l$ should not be greater than one. (regardless of phase!)

$$ |L_{dq}(s)| \leq 1 :$$

$$ \begin{bmatrix} Z_{Sdd}(s) & Z_{Sdq}(s) \\ Z_{Sqd}(s) & Z_{Sqq}(s) \end{bmatrix} \begin{bmatrix} Y_{Ldd}(s) & Y_{Ldq}(s) \\ Y_{Lqd}(s) & Y_{Lqq}(s) \end{bmatrix} \leq 1 $$

- In high power factor PEC, all the load dynamics would be reflected on the $d$-$d$ channel

$$ |L_{dq}(s)| \approx \begin{bmatrix} Z_{Sdd}(s) & Z_{Sdq}(s) \\ Z_{Sqd}(s) & Z_{Sqq}(s) \end{bmatrix} \begin{bmatrix} Y_{Ldd}(s) & 0 \\ 0 & 0 \end{bmatrix} \approx \begin{bmatrix} Z_{Sdd}(s)Y_{Ldd}(s) & 0 \\ Z_{Sqd}(s)Y_{Ldq}(s) & 0 \end{bmatrix} \Rightarrow $$

$$ Z_{Sdd}(s)Y_{Ldd}(s) \leq 1 $$
Impedance Measurement

• One of the most significant and well-developed techniques
• Based on Perturb-and-Observe algorithm
• Mainly has been utilized for design purposes
• Capable to be developed for real-time applications
• Widely was utilized for stability study of the PECs from both DC and AC interfaces

\[
Z_S(s) = \frac{V(s)}{I_S(s)}
\]

\[
Z_L(s) = \frac{V(s)}{I_L(s)}
\]

Ideal Balanced Injection

- By current or voltage sources

- Shunt current injection and series voltage injection

- Shunt current injection
  - Source impedance is low → perturbations by current mainly affect the source side → source side is less noisy → better results
  - Load impedance is high →

- Series voltage injection
  - Perturbations by voltage mainly affect the load side → load side is less noisy → better results

Linear Representation of a PEC

- PECs exhibit nonlinear dynamics during operating in various loading conditions
- Linear models of the systems vary in different operating points
- Stability analysis in different loading conditions
- Based on AC impedance measurement techniques on AC link
- Defines source impedance/load admittance (return-ratio) of systems in different operating points
- Investigates small-signal stability of the PECs with different “Stability Criteria” (i.e. Middlebrook, unit circle, and GMPM)

Perturb source by shunt current injection and load by series voltage injection

Run model of the PEC

Capture the system’s responses

Define phase of the system with Phase-Locked-Loop

Transform voltage/current values to $d$-$q$ reference frame

Utilize DFT to transfer time-domain to frequency-domain

Calculate source impedance/load admittance matrices in $d$-$q$

Calculate return-ratio matrix in $d$-$q$

Plot the magnitude of the return-ratio

Evaluate stability with proposed criterion

Stop
Practical Consideration

• Perturbing in a range of frequencies (1 ~ 1000 Hz)
  – “Injection current harmonics” block for non-real-time applications (i.e. models in PSCAD platform)
  – Chirp signal excitation for real-time applications (i.e. RSCAD platform or hardware)

• Perturbation magnitude
  – 0.5% ~ 1% of the systems’ nominal ratings

• Phase-Locked-Loop (PLL) to determine system’s phase
  – $d$-$q$ reference frame transformation

• FFT/DFT to define magnitudes and phases of the system’s responses, subsequently calculate $Z_S$ and $Y_L$
Real-time Approach

• Chirp excitation signals (swept-sine signals)
  – Wide-bandwidth signals
  – Instantaneous frequency is a function of time
    • Enables perturbing systems in real-time throughout a range of frequencies 1 ~ 1000 Hz

\[ x(t) = A \sin(2\pi(f_0 + (f_1 - f_0) t/2 T)t) \]

• Parallel perturbation
  – Shunt current injection
  – To Define real-time
Proposed Stability Criteria

Unit Circle Criterion

• Advantages:
  – Easy to apply
  – Less computationally complex
  – **Real-time** capability
    • Concurrent perturbations in the source and load sides
    • Utilizing chirp signal
  – Perturbing in a range of frequencies
    • Assessing the systems’ stability in different operating points
  – **Precise evaluation of the system’s stability in real-time**
Outline

• Introduction to small-signal stability analysis
  – Motivation
  – Contribution

• Stability analysis in AC systems

• Proposed small-signal stability method

• Experimental results and sample stability analysis
  – PSCAD
  – RTDS
  – Hardware implementation

• Conclusion
PSCAD Model

SST

AC Interface

12 kV DC

400 V DC

7.2 kV AC

Shunt Current Injection

Source Impedance

AC-DC Rectifier

Isolated Bidirectional DC-DC Converter

DC-AC Inverter

Series Voltage Injection

Port 1

120/240 VAC

Port 2

Load Admittance
• **Real-Time Digital Simulator (RTDS)**
  – Has been successfully utilized for PHIL in a wide range of applications
  – Communicates with I/O cards via fiber optic
  – Interfaces: GTAI, GTAO, and GTDI
RTDS Model

IEEE 34-Bus Test System

12/17/2019
Stability Analysis in RTDS under Static Load

SST1 and SST2 in the IEEE-34 bus test system were connected to their nominal/initial load

Unit circle stability criterion
Stability Analysis in RTDS under Dynamic Load

- \( P_a (W) \)
  - \( I_{a-rms} (A) \)
  - \( V_{a-rms} (V) \)
  - \( L_{dd-a} \)

- \( P_b (W) \)
  - \( I_{b-rms} (A) \)
  - \( V_{b-rms} (V) \)
  - \( L_{dd-b} \)
Hardware Implementation

Power Hardware-In-the-Loop (PHIL) experiment

- Reproduce some part of test system in hardware and have the rest of the system in a simulator
- Utilized RTDS
PHIL SST Implementation

- Active Rectifier
- Six-switch, single-phase DC-AC Inverter
- Power Amplifier
- Programmable AC Load

Device Under Test (DUT)

Rectifier
DC-DC Converter
Inverter

SST in RTDS

7.2 kV AC
12 kV DC
400 V DC

208 V, 3Φ feed
12/17/2019

400 V DC
120/240 VAC
PHIL Experiment

PHIL Experiment Schematic in RTDS

Power Amplifier

DSP

V_ref

D

V_DC

HIL

in Hardware

12/17/2019
PHIL Experiment

PHIL Experiment Schematic

SST

in RTDS

AC Interface

12 kV DC

400 V DC

Port 1

Port 2

Load Admittance

Power Amplifier:

DSP

V_{DC, ref}

D_{ref}

V_{DC}

D

in Hardware

HIL

12/17/2019

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PHIL Experiment

PHIL Experiment Schematic

in RTDS

RTDS DAC to DSP ADC for PHIL Control

Power Amplifier

in Hardware
PHIL Experiment

RTDS Analog Outputs to DSP

\[ V_{DC} \text{ (DC voltage reference)} \]

\[ D_a, D_b \]
PHIL Experiment

Isolated Bidirectional DC-DC Converter
Source Impedance
AC-DC Rectifier
DC-AC Inverter

7.2 kV
120/240 VAC
12 kV DC
400 V DC

SST
High Frequency Transformer

Port 1
Port 2
AC Interface
Load Admittance

AC Interface

Shunt Current Injection
Controlled Current Source
Source Impedance

AC-DC Rectifier
Isolated Bidirectional DC-DC Converter
DC-AC Inverter

V_{dc\_ref}, D_{ref}

DSP

3-Phase 208 V

DC-AC Rectifier
3-Phase 400 V DC
DC-AC Inverter

Variable AC Load
Load

in RTDS

in Hardware

12/17/2019
Test Bed Specifications
- 208 V, 3Φ input
- 5 kVA
- TI F28335 DSP
- RTDS interface over GTA0/GTA1
PHIL Experiment, No-load Test

in RTDS

SST

in Hardware
PHIL Experiment, No-load Test

PLECS simulation results: No-load
PHIL Experiment, No-load Test

Hardware results: No-load
PHIL with Constant RL Load

R = 132 Ω
L = 1 mH

in RTDS

3-Phase 209 V

3-Phase AC-DC Rectifier

400 V DC

DC-AC Inverter

120/240 VAC

V_{DC,ref}

D_{ref}

DSP

V_{DC}

D_i

in Hardware
PHIL with **Constant RL Load**

**PLECS model result, open-loop test**

**Vdc**

**Vphase**

**Iphase**
PHIL with **Constant RL Load**

Results from PHIL Experiment, open-loop test

![Graph showing V\textsubscript{DC}, V\textsubscript{an}, V\textsubscript{bn}, and I\textsubscript{a}](image-url)
Dynamic AC Load

Programmable AC Load
NHReaserch 4600 Series

Applications that require the entire range of non-linear loading

NHR 4600 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS Voltage (V)</td>
<td>50-350</td>
</tr>
<tr>
<td>Max Current (A)</td>
<td>30</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>0-3</td>
</tr>
</tbody>
</table>
Dynamic AC Load

- Isolated Bidirectional DC-DC Converter
- Source Impedance
- AC-DC Rectifier
- DC-AC Inverter

- 7.2 kV
- 120/240 VAC
- 12 kV DC
- 400 V DC

- SST
- High Frequency Transformer

- Port 1
- Port 2

- AC Interface

- Load Admittance
- Shunt Current Injection

- AC Interface in RTDS

- Controlled Current Source

- 400 V DC
- 120/240 VAC

- 3-Phase
- 208 V

- DSP

- V

- DC

- in Hardware

- Variable AC Load

- NHResearch

- 4600 AC Load
Dynamic AC Load

Closed-loop test with programmable AC load $P = 1$ kW

This shows the captured results from PHIL experiment are consistent with RTDS results.
Dynamic AC Load

Closed-loop test with programmable AC load $P = 1.5$ kW

This shows the captured results from PHIL experiment are consistent with RTDS results
Dynamic AC Load

Closed-loop test with programmable AC load $P=3 \text{ kW}$

This shows the captured results from PHIL experiment are consistent with RTDS results.
PHIL Experiment Results

$V_{DC}(V)$

$I_{a-rms} (A)$

$V_{ab-rms} (V)$

$L_{dd}$

$P (kW)$

Relative Stability!
Outline

• Introduction to small-signal stability analysis
  – Motivation
  – Contribution

• Experimental results and stability analysis through PHIL

• Conclusion
Conclusion

• Developed novel small-signal stability analysis criterion and technique for the PEDS
  – Based on impedance measurement and Nyquist criterion
  – Applicable for real-time applications

• Enabled Real-time capability
  – Parallel perturbations
  – Perturbing systems in a range of frequencies

• Implemented the proposed stability criterion to the test system in RTDS platform

• Developed a PHIL experiment to study stability of a SST during load variation
Questions?