Modeling and Characterizing a Power Hardware-in-the-Loop Amplifier

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Motivation

Power Hardware-in-the-Loop Testing
Amplifier interfaces with device under test

Experiment design
Predict stability and accuracy

Need to know response characteristics
Project objective

System identification
Model building and validation

Real time simulation
Power amplifier
Device under Test

Interfaces
Operating modes
AC (90kVA) and DC (60kW) voltage source
With and w/o transformer coupling
Choice of voltage levels
4-quadrant

Three independent amplifier stages
One amplifier per phase
To be characterized
Example Test Setup

**RTS**

- **Protection**: Simulation of setup with model of device under test
- **Monitoring, Trend Data Logging, Data capture**
- **Experiment Controls**: Analog and digital I/O, Output status

**Voltage and current Measurements (AC or DC setup)**

- **Load Bank**
- **OS**: I_{a,b,c,n} V_{a,b,c}
- **EUT**: A, B, C, N, PE

**Voltage and current References**

- **DC Real Time Model(s)**: V_{dc}
- **AC Real Time Model(s)**: V_{a,b,c}

**Experiment Controls**

- **DAQ**
- **Voltage References**: DC voltage function generator
- **LAN Configuration Interface**: Status, trigger, communication

**Voltage measurement(s)**

- **Current measurements**
- **References**
- **Status, trigger, communication**
Project Tasks

Select operating conditions

Test sets
- Voltage oscillations
- Voltage ramps (steps)
- Load steps
- Regeneration mode

Circuit models
- Switching
- Average value

Transfer functions
- Instantaneous
- Envelop

Selected operating conditions and test sets

Validating
(current project phase)

Experiments
Response quantities/Metrics

PHIL Design

Apply model and determine stability

PHIL example
Example Test Sets with Resistive Loads

Disturbance type:
- ♦ oscillations
- ✔ step response

Operating mode:
- Yellow square: AC 150 V
- Green square: AC 300 V

R … base resistor component, 3.4 ohm, 80 A, twelve available

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### Model structure

- **Core power components** with information from AMETEK
- **Sub-power stages and connections**
- **Filter**
- **Controls**
  - Outer voltage loop
  - Inner current loop

### Model implementation

- Offline and real time parameterized models
  - Physics based
  - Transfer function

### Simulating

- Selected operating conditions and test sets
  - **Validating** (current project phase)
  - Evaluate metrics that allow compare measured and simulated
    - **PHIL Design**
  - Experiment: Apply model and determine stability

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**Modeling and Simulation**

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Example Response: DC Ramp

DC ramps

Same voltage reference for laboratory testing and simulation

Real time simulator analog reference voltage signal (scaled)

Measured and simulated responses
Example Response: DC with Oscillations

Added oscillations to DC offset

Comparing measured FFT with simulated
Example Response AC

AC fundamental + harmonics

Time (ms)

0 5 10 15 20 25

Voltage (V)

-400 -300 -200 -100

0 100 200 300 400

ref
sim
mea
Example Response AC

![Graph showing voltage (V) over time (ms) with reference, simulation, and measurement lines.]

![Graph showing frequency (Hz) on the x-axis and voltage (V) on the y-axis, with a peak at 50 Hz.]

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Transfer Function Identification

\[ \frac{V_{out}}{V_{ref}} = \frac{G}{s} \frac{e^{-sT_{del}}}{\frac{s}{2\pi f_p} + 1} \]

DC 200 V Mode
5.1 Ohm, Y-connected Load
0.8 pu Voltage Magnitude
(Group 22)

G = 0.998
\( f_p = 1950 \text{ Hz} \)
\( T_{del} = 50 \text{ us} \)
This project: Characterizes amplifier
Model building and validation

Future application: Power Hardware-in-the-Loop Testing
Experiment design: predict stability and accuracy

NREL Energy System Integration Facility
Amplifier is base building block of grid simulator based testing