Online Monitoring and Control of Power Converters Using Digital Network Analyzer Techniques

Dissertation Defense

Adam Barkley

Advisor: Enrico Santi
Acknowledgements

Committee Members:
Dr. Enrico Santi (Electrical Engineering)
Dr. Roger Dougal (Electrical Engineering)
Dr. Yong-June Shin (Electrical Engineering)
Dr. Edward Gatzke (Chemical Engineering)

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Outline

1. Major Contributions
2. Introduction and Problem Statement
3. Correlation Method of System ID, State of the Art
4. Improvements and Extensions
5. Verification of Improvements and Extensions
6. Adaptive Control
7. Verification of Adaptive Control
8. Future Work
Major Contributions (1)

Tool Development:

• Improvements to the standard cross-correlation method of system identification which improve estimation accuracy, particularly at high frequencies near the desired closed-loop system bandwidth.

• Extension to the converter-centric method to include measurement of the control loop gain without ever opening the feedback loop.

• Extension to the method to include measurement of Thévenin equivalent impedances looking outward from the converter.

• Software and hardware implementation of the previously described techniques and algorithms to provide simulation and experimental verification.
Major Contributions (2)

Application of Tools to Practical Problems:

• Development of **parameter extraction** techniques to fit non-parametric frequency response estimation data to a parametric model.

• Development of a **detection algorithm** to identify changes in the system, particularly the “problem cases” requiring control adjustment to maintain specified performance margins.

• Introduction of a **control synthesis algorithm** which targets a range of common converter and system level problems.

• Simulation testbed development to provide **verification** with a comprehensive set of realistic scenarios.
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Smart-Grid Concept
Notional Ship DC Distribution System
Introduction and Problem Statement

• Power Distribution Systems increasingly complex
• Recent interest in DC power distribution, Smart-Grids and Renewable Sources
• More power electronic converters + controls
• Large operating point variations (power sources, loads, mission)
• Need to ensure system robustness, stability, reconfigurability
• Online Monitoring is an enabling technology
Importance of Wide-Bandwidth Online Monitoring

- Converter-based systems exhibit salient features across a wide frequency range.
- Power distribution systems are “stiff”, hard to measure using conventional tools.
- Time-varying converter parameters, source system, and load system.
- Each affect converter frequency response uniquely, may reduce performance/stability margins.
- Enables health monitoring, load estimation, adaptive control, and system-level coordination.
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Converter Small Signal Modeling

Boost Converter

Two states: $i_L(t)$ and $v_C(t)$

\[
\begin{align*}
    v_L(t) &= L \frac{di_L(t)}{dt} \quad \rightarrow \quad i_L(t) = \frac{1}{L} \int v_L(t) \, dt \\
    i_C(t) &= C \frac{dv_C(t)}{dt} \quad \rightarrow \quad v_C(t) = \frac{1}{C} \int i_L(t) \, dt
\end{align*}
\]

Steady-State: $\langle v_L \rangle = \langle i_C \rangle = 0$

Nonlinear Averaged Model (one state)

\[
\langle v_L \rangle = V_g - V (1 - D) + \hat{v}_g + V \hat{d} - (1 - D) \hat{v} + \hat{v} \hat{d}
\]

Duty Cycle Variation

\[
M(D) = \frac{1}{1 - D}
\]
State of the Art, Identification

1976: R. D. Middlebrook, “Input filter considerations in design and application of switching regulators”
1989: Girgis, Adly A. McManis, R. Brent, "Frequency Domain Techniques for Modeling Distribution or Transmission Networks Using Capacitor Switching Induced Transients"
2000: B. Johansson, M. Lenells, "Possibilities of obtaining small-signal models of DC-to-DC power converters by means of system identification”
2003: Jinjun Liu; Xiaogang Feng; Lee, F.C.; Borojevich, D., "Stability margin monitoring for DC distributed power systems via perturbation approaches"
2004: Maksimovic, D.; Zane, R.; Erickson, R., "Impact of digital control in power electronics”
2005: M. Allain, P. Viarouge, F.Tourkhami, "The use of pseudo-random binary sequences to predict a DC-DC converter's control-to-output transfer function in continuous conduction mode”
2005: Miao, B.; Zane, R.; Maksimovic, D., "System identification of power converters with digital control through cross-correlation methods”
2006: B. Miao, R. Zane, D. Maksimovic, "FPGA-Based Digital Network Analyzer for Digitally Controlled SMPS”
State of the Art, Application & Control

1989: Girgis, Adly A. McManis, R. Brent, "Frequency Domain Techniques for Modeling Distribution or Transmission Networks Using Capacitor Switching Induced Transients”


2000: Palethorpe, B.; Sumner, M.; Thomas, D.W.P., "System impedance measurement for use with active filter control”

2002: Sumner, M.; Palethorpe, B.; Thomas, D.W.P.; Zanchetta, P.; Di Piazza, M.C., "A technique for power supply harmonic impedance estimation using a controlled voltage disturbance“

2003: Jinjun Liu; Xiaogang Feng; Lee, F.C.; Borojevich, D., "Stability margin monitoring for DC distributed power systems via perturbation approaches“

2005: M. Allain, P. Viarouge, F.Tourkhani, "The use of pseudo-random binary sequences to predict a DC-DC converter’s control-to-output transfer function in continuous conduction mode”


2007: Zhenyu Zhao; Prodic, A., "Limit-Cycle Oscillations Based Auto-Tuning System for Digitally Controlled DC–DC Power Supplies”

2008: J. Morroni, R. Zane, D. Maksimovic, “Adaptive tuning of digitally controlled switched mode power supplies based on desired phase margin”

Converter-centric Identification and Control

• Each converter can be used as a wide-band perturbation source for identification
  – \( f_{\text{max}} = \text{switching frequency} / 2 \)
  – \( f_{\text{min}} = 1 / \text{perturbation length} \)

• Existing digital control platform used to do online identification

• Measure small-signal converter transfer functions, loop-gain, impedances

• Enables converter health monitoring, load estimation, adaptive control, etc.
Digital Network Analyzer: Correlation Analysis

- Switching converter modeled as a LTI system:

\[ y(n) = \sum_{k=1}^{\infty} h(k)u(n - k) + v(n) \]

- The input-to-output cross-correlation is:

\[ R_{uy}(m) \equiv \sum_{n=1}^{\infty} u(n)y(n + m) = \sum_{n=1}^{\infty} h(n)R_{uu}(m - n) + R_{uv}(m) \]

- White noise input:

\[ R_{uu}(m) = \delta(m) \]
\[ R_{uv}(m) = 0 \]

\[ R_{uv}(m) = h(m) \]
\[ G_{uv}(s) = DFT\{h(m)\} \]
State of the Art

9/2005 *Miao, Zane, Maksimovic

After my proposed improvements...

Simulation results of a forward converter with an undamped input filter using my improvements.


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Shortcomings in the State of the Art

- Finite-length PRBS is not an ideal approximation to white noise
- Zero Order Hold sampling causes undesired effects near the Nyquist frequency
- Converters may feature discontinuous input/output voltage/current waveforms
- White noise may not be the best excitation sequence for low-pass filtered converters

Window $R_{uy}$  
Midpoint Sampling
Oversample and Average  
Blue Noise Excitation
Non-ideal Test Sequence

\[ R_{\text{uu}}(m) = R_{\text{uu, ideal}}(m) + R_{\text{uu}}'(m) = \delta(m) + R_{\text{uu}}'(m) \]

\[ R_{\text{uy}}(m) = R_{\text{uy, ideal}}(m) + R_{\text{uy}}'(m) = h(m) + R_{\text{uy}}'(m) \]

\[ R_{\text{uy}}'(m) = \sum_{n=1}^{\infty} h(n)R_{\text{uu}}'(m-n) \]
Windowing the Cross-correlation

- The desired information, \( R_{\text{ideal}} \), is time-localized.
- Windowing can be used to suppress \( R_{\text{ideal}} \).
- A smooth window is needed to avoid creating artificial high-frequency edges.
- Width must be chosen to avoid smearing low-frequencies.

\[
w_{\text{gauss}}(t) = e^{-\alpha t^2}\]

\[
W_{\text{gauss}}(\omega) = \sqrt{\frac{\pi}{\alpha}} e^{-\frac{\omega^2}{4\alpha}}
\]
Midpoint Sampling / Oversampling

\[ DFT\{R_{uy}(m)\} = G_{uy}(j\omega) \cdot G_{ZOH}(j\omega) = G_{uy}(j\omega) \cdot \frac{1-e^{-j\omega T}}{j\omega T} \]

Midpoint Sampling:

\[ DFT\{R_{uy}(m)\} = G_{uy}(j\omega) \cdot \frac{1-e^{-j\omega T}}{j\omega T} \cdot e^{\frac{j\omega T}{2}} = G_{uy}(j\omega) \cdot e^{\frac{j\omega T}{2}} - e^{-\frac{j\omega T}{2}} \]

\[ = G_{uy}(j\omega) \cdot \frac{\sin(\omega T/2)}{(\omega T/2)} \]
Simulation Verification of Improvements

12-bit, single-period, 100 kHz PRBS, no improvements

Windowing

Midpoint Sampling

All Improvements
Loop Gain Measurement

\[ G_{xu}(s) \equiv \frac{\hat{x}(s)}{\hat{u}(s)} = \frac{1}{1 + T_{\text{loop}}(s)} \]

\[ G_{yu}(s) \equiv \frac{\hat{y}(s)}{\hat{u}(s)} = -\frac{T_{\text{loop}}(s)}{1 + T_{\text{loop}}(s)} \]

\[ T_{\text{loop}}(s) \equiv G_{vd}(s) \cdot G_{\text{controller}}(s) = \frac{T_{\text{loop}}(s)}{1 + T_{\text{loop}}(s)} = -\frac{G_{yu}(s)}{G_{xu}(s)} \]

Colors: correlation analysis
Black: network analyzer
Impedance Measurement Using Network Analyzer

Converter must establish the operating point

50Ω output impedance
Output is not isolated
Expensive ($10,000+)

Large DC blocking capacitor
Or wide-band current transformer + amplifier
Impedance Measurement

Source Impedance Measurement

\[ G_{vd}(s) \equiv \frac{\hat{v}(s)}{\hat{d}(s)} \]

\[ G_{id}(s) \equiv \frac{\hat{i}(s)}{\hat{d}(s)} \]

Load Impedance Measurement

\[ Z(s) \equiv \frac{\hat{v}(s)}{\hat{i}(s)} = \frac{\hat{v}(s)}{\hat{d}(s)} \cdot \frac{G_{vd}(s)}{G_{id}(s)} \]
Blue Noise Excitation

\[ \frac{Y(s)}{X(s)} = (k_1 + k_2) - \frac{k_1}{e^{s\tau}} \]
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Experimental Testbed

- 300W Buck converter
- Loads:
  - Wire-wound Resistive
  - LRC filter
  - Constant power load
- LC input filter
- FPGA controller and test signal generator
Experimental Testbed

- FPGA Controller
- DC/DC Sync. Buck Converter
Typical Time-domain Waveforms
Power Resistive Load

- 3Ω wire-wound ceramic
- \( L_{\text{self}} = 23.8 \ \mu \text{H} \)
- Matching with Network Analyzer to 30 kHz
- \( f_{\text{nyquist}} = 50 \ \text{kHz} \)
- Blue noise perturbation
LRC Load

- Commonly used as an output filter
- \( R_{\text{load}_2} = 10 \, \Omega \)
- \( f_0 = 920 \, \text{Hz} \)
- Matching with Network Analyzer up to 5kHz (White), and 20 kHz (Blue)
- \( f_{\text{nyquist}} = 50 \, \text{kHz} \)
Constant Power Load

- $Z_{\text{load}} \approx -20 \, \Omega$
- Negative impedance (180° phase)
- Matching with analytic up to $f_{\text{nyquist}} = 50 \, \text{kHz}$
- Network Analyzer measurement is not usable at low frequency
LC Input Filter

- Undamped LC input filter
- Good matching of corner frequency, capacitor ESR, inductor ESR
- Low-frequency discrepancy due to limitation of Network Analyzer current probe
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Model Fitting

• Nonparametric frequency response data $\rightarrow$ transfer function

• Candidate transfer function of user-specified order

$$G_{\text{candidate}}(s) = \frac{A_N s^N + A_{N-1} s^{N-1} + \cdots + A_0}{B_M s^M + B_{M-1} s^{M-1} + \cdots + B_0}$$

• Weighted Least Squares Fitting

• Optional weighting function to emphasize certain frequencies

$$J = \sum_k W(j \omega_k) \cdot \left( G_{\text{candidate}}(s) \bigg|_{s=j\omega_k} - G_{\text{wy}}(j\omega_k) \right)^2$$

• Solve using numerical methods such as Gauss-Newton
Adaptive Control Structure
Timing Overview

![Diagram of timing overview]

- **Startup**
- **Steady State Under Control**
- **Perturb**
- **Post Process**
- **Perturb**
- **Post Process**
- **Perturb**
- **Post Process**
- **Detect**
- **Synthesize Control**
- **Perturb**
- **Post Process**

Timeline:
- **$v_{out}(t)$**
- **$i_{out}(t)$**
- **$T_{TOTAL}$**
- **$T_{IDENT}$**

- **Parameter Change**
- **Success**

Components:
- **Test Signal**
- **Digital Controller**
- **Embedded Controller**
- **System Identification**
- **Control Adaptation**
- **PWM**
- **$V_{ref}$**
- **$V_{out}$**
- **$L_{out}$**
- **$R_{load}$**
- **$C_{out}$**
- **$R_{C_ESR}$**
- **$Z_{source}$**
Adaptive Control Synthesis

• With a fitted parametric model estimate, many classical control design tools are usable

• Model estimate is updated regularly, use the latest available estimate only

• Two synthesis options are considered here:
  — PID controller design via loop shaping
  — Internal Model Control (IMC)
Adaptive PID design via Loop Shaping

PID compensator of the form:

\[
G_{PID}(s) = G_{mid} \left( \frac{2\pi f_{z1}}{s} + 1 \right) \left( \frac{s}{2\pi f_{z2}} + 1 \right) \left( \frac{2\pi f_{p1}}{s} + 1 \right) \left( \frac{s}{2\pi f_{p2}} + 1 \right)
\]

The design problem is to find zero/pole locations and gain to satisfy the user constraints:

**Step 1:** Evaluate the estimated magnitude and phase at the desired crossover frequency

\[
f_{c\_goal} = \frac{f_{sw}}{10} \quad \text{and} \quad \phi_{m\_goal} = 60^\circ
\]

\[
G_{est\_mag} = |G_{vd}(s)|_{s = j2\pi f_{c\_goal}}
\]

\[
G_{est\_phase} = \angle G_{vd}(s)_{s = j2\pi f_{c\_goal}}
\]

**Step 2:** Choose \( f_{z2} \) and \( f_{p1} \) to give the required phase lead at the desired crossover frequency

\[
f_{z2} = f_{c\_goal} \left( \frac{1 - \sin(\phi_{m\_goal} - G_{est\_phase} - \pi)}{1 + \sin(\phi_{m\_goal} - G_{est\_phase} - \pi)} \right)
\]

\[
f_{p1} = f_{c\_goal} \left( \frac{1 - \sin(\phi_{m\_goal} - G_{est\_phase} - \pi)}{1 + \sin(\phi_{m\_goal} - G_{est\_phase} - \pi)} \right)
\]

**Step 3:** Set the low-frequency inverted zero (integrator) and high frequency pole one decade away to avoid phase interaction

\[
f_{z1} = \frac{f_{z2}}{10} \quad f_{p2} = 10 f_{p1}
\]

**Step 4:** Find the required midband gain, \( G_{mid} \)

\[
G_{mid} = \frac{f_{z2}}{G_{est\_mag} f_{c\_goal}}
\]
Internal Model Control (IMC)

Internal Model Control Structure

- Internal model estimate, \( \tilde{g}(s) \), runs inside of the controller
- No feedback signal for perfect estimation, when \( \tilde{g}(s) = g(s) \)
- Stable if and only if \( c(s) \) and \( g(s) \) individually stable

IMC Design Procedure:

**Step 1:** Factor the model estimate into invertible (-) and non-invertible (+) parts

\[
\tilde{g}(s) = \tilde{g}(s)_+ \tilde{g}(s)_- 
\]

**Step 2:** Compensator, \( c(s) \) inverts the invertible part of the plant

\[
c(s) = \frac{1}{\tilde{g}(s)_-} f(s)
\]

**Step 3:** Choose a filter, \( f(s) \), of order \( n \) to make \( c(s) \) semi-proper

\[
f(s) = \frac{1}{(\lambda s + 1)^n}
\]
Internal Model Control (IMC)

To implement, the IMC structure can be transformed into a conventional negative feedback form

\[ g_c(s) = \frac{c(s)}{1 - c(s)\tilde{g}(s)} \]

\[ = \frac{c(s)}{1 - f(s)\tilde{g}(s)_+} \]

For most low-order plants, the resulting controller, \( g_c(s) \), is a PI / PID compensator.

With IMC, the design decision is reduced to choosing a single parameter: the filter pole location, \( \lambda \).
IMC Compensator Implementation

- Generic 4\textsuperscript{th} order transfer function for the worst test case
- Integrators (gray), coefficients (yellow), sum block (blue)
- Coefficients can be changed without disturbing output
- Smooth enable/disable
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Adaptive Control Test Cases

Case 0: Nominal Parameters
Case 1: Step Output Capacitance
Case 2: Step Output Capacitor ESR
Case 3: Constant Power Load Step
Case 4: Switch in an Undamped LC Input Filter
Adaptive Control Simulation Testbed
Adaptive PID Results via Loop Shaping

\[ |G_{PID}(s)|_{db} \]

\[ \frac{1}{G_{est \_mag}} \]

\[ G_{mid} \]

\[ f_{C \_goal} \]

\[ f_{21}, f_{22}, f_{p1}, f_{p2} \]

\[ f_{log} \]

Constraint, \( f_{bw} \)

Constraint, \( \phi_m \)
IMC Test Case 0: Nominal Parameters
IMC Test Case 0: Nominal Parameters

Magnitude $G_{vd}$ - Case 0 (after Fitting)

Phase of $G_{vd}$ - Case 0 (after Fitting)

Before Control Adaptation

After Control Adaptation
IMC Test Case 1: Step Output Capacitance
IMC Test Case 1: Step Output Capacitance

Magnitude $G_{vd}$ - Case 1 (after fitting)

Phase of $G_{vd}$ - Case 1 (after fitting)

Nominal Converter vs. Test Case 1 - Before Control Adaptation

Nominal Converter vs. Test Case 1 - After Control Adaptation

Before

After
IMC Test Case 2: Step Output Capacitor ESR

Overview of Case 2 Simulation

- Perturbation
- Inductor Current [A]
- Output Voltage [V]
- Time [s]

Step Output Capacitor ESR
IMC Test Case 2: Step Output Capacitor ESR

Magnitude of Gvd - Case2 (after Fitting)

Phase of Gvd - Case2 (after Fitting)

Nominal Converter vs Test Case 2 - Before Control Adaptation

Before

Nominal Converter vs Test Case 2 - After Control Adaptation

After
IMC Test Case 3:
Constant Power Load Step

Overview of Case 3 Simulation

- **Perturbation**
- **Inductor Current [A]**
- **Output Voltage [V]**

Time [s]

CPL Step
0W → 175W

CPL Step
175W → 0W
IMC Test Case 3: Constant Power Load Step

Before

After

Magnitude of Gvd - Case3 (after Fitting)

Phase of Gvd - Case3 (after Fitting)

Nominal Converter vs. Test Case 3 - Before Control Adaptation

Nominal Converter vs. Test Case 3 - After Control Adaptation
IMC Test Case 4: Connect Undamped LC Input Filter

Switch in LC Input Filter
IMC Test Case 4: Connect Undamped LC Input Filter
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Future Work

• Extension to Three-Phase Systems
• Experimental Validation of Adaptive Control
• Formalization of IMC Filter Parameter Selection
• Comparison with Other Control Structures
• Comparison with Robust Control
• Stabilization of Open-Loop Unstable Plants
• System Level Studies, Multiple Converters
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Publications

Journal


Conference


Expected Publications

Journal

• Barkley, A., Santi, E. “Online Impedance Monitoring Applying Perturbation Techniques to Switching Converters” *(submitted to Transactions on Power Electronics, awaiting review)*

• Barkley, A., Santi, E. “Adaptive Control of Power Converters using Digital Network Analyzer Techniques”

• Martin, D., Barkley, A., Santi, E. “Wide Bandwidth System Identification of Three-Phase System Impedances by Applying Perturbations to an Existing Converter”

• Barkley, A.; Michaud, D.; Santi, E.; Monti, A.; Patterson, D.; “Single Active Stage Brushless DC Motor Drive with High Input Power Factor for Single Phase Applications”

Conference

Major Contributions (1)

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- Improvements to the standard cross-correlation method of system identification which improve estimation accuracy, particularly at high frequencies near the desired closed-loop system bandwidth.
- Extension to the converter-centric method to include measurement of the control loop gain without ever opening the feedback loop.
- Extension to the method to include measurement of Thévenin equivalent impedances looking outward from the converter.
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- Introduction of a **control synthesis algorithm** which targets a range of common converter and system level problems.
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Questions?
Derivation of Ruy \( \Rightarrow h(n) \)

Given: \( y(n) = \sum_{k=1}^{\infty} h(k)u(n-k) + v(n) \)

\[
\begin{align*}
R_{uy}(m) &\equiv \sum_{n=1}^{\infty} u(n)y(n+m), \\
R_{uu}(m) &\equiv \sum_{n=1}^{\infty} u(n)u(n+m), \\
R_{uv}(m) &\equiv \sum_{n=1}^{\infty} u(n)v(n+m)
\end{align*}
\]

Prove that: \( R_{uy}(m) \equiv \sum_{n=1}^{\infty} u(n)y(n+m) = \sum_{n=1}^{\infty} h(n)R_{uu}(m-n) + R_{uv}(m) \)

\[
\begin{align*}
\sum_{n=1}^{\infty} u(n)y(n+m) &= \sum_{n=1}^{\infty} u(n) \cdot \left( \sum_{k=1}^{\infty} h(k)u(n+m-k) + v(n+m) \right) \\
\sum_{n=1}^{\infty} u(n)y(n+m) &= \sum_{n=1}^{\infty} \sum_{k=1}^{\infty} h(k)u(n)u(n+m-k) + \sum_{n=1}^{\infty} u(n)v(n+m)
\end{align*}
\]

swap n,k indices (no Order of Operation problem)

\[
\begin{align*}
\sum_{n=1}^{\infty} u(n)y(n+m) &= \sum_{n=1}^{\infty} \sum_{k=1}^{\infty} u(n)u(k)u(k+m-n) + R_{uv}(m) \\
\sum_{n=1}^{\infty} u(n)y(n+m) &= \sum_{n=1}^{\infty} h(n)R_{uu}(m-n) + R_{uv}(m)
\end{align*}
\]
Test Equipment

- Data Logging: LeCroy WaveRunner 6100A 1GHz Digital Storage Oscilloscope
- Network Analyzer: Agilent 4395A 10Hz-500Mhz
- Voltage Probes: Lecroy 10x PP07-WR 500Mhz
- DC Current Probe: Tektronix A6302
- DC Current Probe Amplifier: Tektronix AM503B
- AC Current Probe: Tektronix P6021, low frequency bandwidth = 120 Hz
Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value [units]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vg</td>
<td>40 [V]</td>
</tr>
<tr>
<td>Lfilt</td>
<td>200 [uH]</td>
</tr>
<tr>
<td>Cfilt</td>
<td>69 [uF]</td>
</tr>
<tr>
<td>Lout</td>
<td>70 [uH]</td>
</tr>
<tr>
<td>Cout</td>
<td>69 [uF]</td>
</tr>
<tr>
<td>Rload1</td>
<td>3 [Ω]</td>
</tr>
<tr>
<td>Lload</td>
<td>300 [uH]</td>
</tr>
<tr>
<td>Cload</td>
<td>100 [uF]</td>
</tr>
<tr>
<td>Rload2</td>
<td>12.5 [Ω]</td>
</tr>
<tr>
<td>Rsense</td>
<td>0.6 [Ω]</td>
</tr>
<tr>
<td>Lself</td>
<td>23.8 [uH]</td>
</tr>
</tbody>
</table>
Converter Small Signal Modeling

http://ece.colorado.edu/~pwrelect/book/slides/Ch1slides.pdf
# Adaptive Control Testbed Timing

<table>
<thead>
<tr>
<th>Simulation Interval</th>
<th>Simulation Time [s]</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Initialization, start the simulation</td>
</tr>
<tr>
<td>1</td>
<td>0.03</td>
<td>After initialization, step the voltage reference for startup</td>
</tr>
<tr>
<td>2</td>
<td>0.09</td>
<td>After startup is complete (in steady state), do Load Step 1</td>
</tr>
<tr>
<td>3</td>
<td>0.095</td>
<td>After Load Step 1, do Load Step 2</td>
</tr>
<tr>
<td>4</td>
<td>0.11</td>
<td>After Load Step 2, open the control loop and do Identification 1</td>
</tr>
<tr>
<td>5</td>
<td>0.235</td>
<td>After Identification 1, pause to do post processing, update control gains, then re-enable control</td>
</tr>
<tr>
<td>6</td>
<td>0.245</td>
<td>After control re-enable, change one of the system parameters</td>
</tr>
<tr>
<td>7</td>
<td>0.26</td>
<td>After the parameter change, do Load Step 3</td>
</tr>
<tr>
<td>8</td>
<td>0.29</td>
<td>After Load Step 3, do Load Step 4</td>
</tr>
<tr>
<td>9</td>
<td>0.325</td>
<td>After Load Step 4, open the control loop and do Identification 2</td>
</tr>
<tr>
<td>10</td>
<td>0.4561</td>
<td>After Identification 2, pause to do post processing, update control gains, then re-enable control</td>
</tr>
<tr>
<td>11</td>
<td>0.475</td>
<td>After control re-enable, do Load Step 5</td>
</tr>
<tr>
<td>12</td>
<td>0.50</td>
<td>After Load Step 5, do Load Step 6</td>
</tr>
<tr>
<td>13</td>
<td>0.5502</td>
<td>After Load Step 6, Shut Down (set the output voltage reference to zero)</td>
</tr>
<tr>
<td>14</td>
<td>0.65</td>
<td>Stop simulation</td>
</tr>
</tbody>
</table>
References


References (2)

References (3)


