Adaptive Model Following Control of Switching Regulators
Authors

Mike Elmore
E&M Power
6 Emma Street
Binghamton, NY USA
elmore@EandMpower.com

Victor Skormin
Electrical and Computer Engineering Department
Watson School, Binghamton University
Binghamton, NY USA
Presentation Outline

- Problem Definition
- Previous Work
- Adaptive Model Following Control
  - Analytical Development
  - Simulation Studies
- Hardware Implementation
  - Test Circuit
  - Experimental Results
- Future Work
- Conclusions
Problem Definition

- Parametric uncertainty in switching power supplies and their loads can result in unstable operation or failure to meet performance specifications.

These uncertainties include:

- Power supply component initial tolerance and variations with age, temperature, the manufacturing process, and electrical loading

- Load variations due to distribution impedances in cabling, distributed capacitance, and the nature of the application load itself
Previous Work


Stability of a system can be assured, if the system can be split into two blocks, as shown:

The linear time invariant block must be strictly positive real:
1. $h(s)$ must be real for real $s$.
2. The poles of $h(s)$ must lie in $\text{Re}[s] < 0$.
3. For all real $\omega$, $\text{Re}[h(j\omega)] > 0$, for $-\infty < \omega < \infty$.

The feedback block must satisfy the Popov integral inequality:

$$\int_{t}^{t_1} v^T \cdot w \cdot dt \geq -\gamma^2_0 \text{ for all } t_1 \geq 0$$
Model Reference Adaptive System

Reference Model: \[ \dot{z} = A_m \cdot z + B_m \cdot u \]
Real System: \[ \dot{x} = A(t) \cdot x + B(t) \cdot u \]
State Generalized Error: \[ e = z - x \]

If \( A(t) = A(0) + F(e,t,\tau) \) and \( B(t) = B(0) + G(e,t,\tau) \), then
\[
\begin{align*}
\dot{e} &= \dot{z} - \dot{x} = A_m \cdot z + B_m \cdot u - [A(t) \cdot x + B(t) \cdot u], \\
\dot{e} &= A_m \cdot e - [A(0) - A_m + F(e,t,\tau)] \cdot x - [B(0) - B_m + G(e,t,\tau)] \cdot u, \text{ and} \\
\dot{e} &= A_m \cdot e - [\Delta A(0) + F(e,t,\tau)] \cdot u - [\Delta B(0) + G(e,t,\tau)] \cdot x.
\end{align*}
\]

The goal is to drive \( \Delta A(0) + F(e,t,\tau) \rightarrow 0 \) and \( \Delta B(0) + G(e,t,\tau) \rightarrow 0 \).
Equivalent Representation of a Model Reference System

\[
\begin{align*}
\tau_{v,t} & \quad F(v,t,\tau) \\
\Delta A(0) & \quad G(v,t,\tau) \\
\Delta B(0) & \quad A_m
\end{align*}
\]
To insure the LTI part is flexible we introduce a linear filter $D$, so that $v = D \cdot e$.

The NLTV part is achieved by selecting

$$F(v, t, \tau) = \int_0^t \Phi_1(v, t, \tau) \cdot d\tau + \Phi_2(v, t) + A(0) \quad \text{and}$$

$$G(v, t, \tau) = \int_0^t \Psi_1(v, t, \tau) \cdot d\tau + \Psi_2(v, t) + B(0),$$

where the Popov integral inequality is satisfied if

$\Phi_1(v, t, \tau) = F \cdot v(\tau) \cdot x(\tau)^T \cdot G^T, \quad F > 0 \quad \text{and} \quad G > 0,$

$\Phi_2(v, t) = \overline{F} \cdot v(t) \cdot x(t)^T \cdot \overline{G}^T, \quad \overline{F} \geq 0 \quad \text{and} \quad \overline{G} \geq 0,$

$\Psi_1(v, t, \tau) = M \cdot v(\tau) \cdot u(\tau)^T \cdot N^T, \quad M > 0 \quad \text{and} \quad N > 0,$

$\Psi_2(v, t) = \overline{M} \cdot v(t) \cdot u(t)^T \cdot \overline{N}^T, \quad \overline{M} \geq 0 \quad \text{and} \quad \overline{N} \geq 0.$
However, the adaptive system requires a control law implementation. This is done by adding an additional control signal to the real converter.

\[
\dot{x} = A \cdot x + B \cdot (u + \Delta u) = A \cdot x + B \cdot [K_u(e,t) \cdot u - K(e,t) \cdot x],
\]

where \( K_u(e,t) = K_u - \Delta K_u(e,t) \) and \( K_u(e,t) = K - \Delta K(e,t) \).

This can be shown to be equivalent to

\[
\dot{x} = A(e,t) \cdot x + B(e,t) \cdot u,
\]

if certain system structural conditions are satisfied.

As with \( A(e,t) \) and \( B(e,t) \) before,

\[
\Delta K(e,t) = \int_0^t \Phi_1(v,t,\tau) \cdot d\tau + \Phi_2(v,t) + \Delta K(0) \quad \text{and}
\]

\[
\Delta K_u(e,t) = \int_0^t \Psi_1(v,t,\tau) \cdot d\tau + \Psi_2(v,t) + \Delta K_u(0).
\]

The model reference system with signal adaptation now has a similar structure to the model reference system with parametric adaptation.
Adaptive Model Following Control

AMFC Plant

Reference Model (RM)

Adaptation Mechanism (AM)

Real Switching Converter

$\Delta u$

$u$

$e$

$z$

$x$

$\Delta u$

$r$

$\Delta u$

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Simulation Studies

- Simulation studies were conducted in Vissim and Matlab.
- Simulations of buck, boost, and buck-boost converters were performed.
- The simulations showed that certain simplifications in the implementation of AMFC could be achieved:
  - All three converter types can control inductor current with only inductor current feedback in the AMFC plant.
  - The buck converter can control output voltage with only output voltage feedback in the AMFC plant.
  - The boost and buck-boost converters are unstable with only output voltage feedback in the AMFC plant.
Simulation Studies: Boost Output Voltage with Inductor Variation

Without Adaptation

With Adaptation

\[ L_m = 1.33 \mu\text{H} \quad \text{duty cycle stepped} \]

\[ L = 0.67 \mu\text{H} \quad 0.6 \rightarrow 0.55 \]
Simulation Studies: Boost Inductor Current with Inductor Variation

Without Adaptation

\[ L_m = 1.33 \mu \text{H} \]
\[ L = 0.67 \mu \text{H} \]

With Adaptation

\[ V_g \text{ stepped} \]
\[ 5V \rightarrow 5.5V \]
Simulation Studies: Buck-Boost Inductor Current with Output Capacitor Variation

Without Adaptation

\[ C_m = 1700 \mu F \]

\[ C = 3400 \mu F \]

With Adaptation

Duty cycle stepped

0.30 → 0.29
Buck and PWM Circuit Implementation

Compensation and AM Error Voltages Summing Junction

$u$ \quad R_{38}$

$e$ \quad R_{37}$

$R_{36}$ \quad R_{35}

$U_6$ \quad UC2823AD (PWM Controller)

$U_7$ \quad TPS2832 (Synchronous Buck MOSFET Drivers)

$Q_1, Q_2$ \quad ITF86130SK8T (7.8m$\Omega$, 30V)
Reference Model (RM) Circuit Implementation

Component values are Calculated in Matlab

Component values are

\[ U_2 \quad MC34074A \]
\[ U_5 \quad AD633JR \]
Adaptation Mechanism (AM) and Difference Circuit Implementation

Buck Output Voltage

\[ v_o \]
\[ v_{om} \]
\[ R_1 \]
\[ R_2 \]
\[ R_3 \]
\[ R_4 \]
\[ U_1 \]
\[ e \]

RM Output Voltage

\[ Y_1 \]
\[ W \]
\[ X_1 \]
\[ Z \]

\[ U_3 \]
\[ C_1 \]
\[ R_7 \]
\[ R_8 \]
\[ R_9 \]
\[ U_1 \]

AM Error Voltage

\[ U_1 \]
\[ U_4 \]
\[ Y_1 \]
\[ W \]
\[ X_1 \]
\[ Z \]

Adaptation gains are:

\[ k_i = \frac{1}{R_7 \cdot C_1} \]
\[ k_p = \frac{R_9}{R_8 \cdot k_i} \]

\[ U_1 \text{ MC34074A} \]
\[ U_3, U_4 \text{ AD633JR} \]
Blue is RM and Red is Real Buck Plant
Buck Total Loop Gain with Output Capacitor Variation

Blue is RM and Red is Real Buck

Buck without AMFC  Buck with AMFC
Buck Plant with Output Inductor Variation

Blue is RM and Red is Real Buck Plant

Buck Plant without AMFC

Buck Plant with AMFC
Buck Total Loop Gain with Output Inductor Variation

Blue is RM and Red is Real Buck

Buck without AMFC

Buck with AMFC
Closed-loop Audiosusceptibility Comparison

Blue is RM and Red is Real Buck

Buck without AMFC

Buck with AMFC
Closed-loop Output Impedance Comparison

Blue is RM and Red is Real Buck

Buck without AMFC  Buck with AMFC
Future Work

• Analytical and experimental studies of the interaction of AMFC and input filters has been completed and will be presented next month at IECNON 2003 in Roanoke, VA, USA.

• Simulation studies and hardware implementation for Digital AMFC has begun. Digital AMFC offers the potential for greater flexibility and performance invariance, than analog AMFC.

• AMFC of switching converters operating in the discontinuous mode needs to be investigated.

• Analytical justification for the implementation simplifications needs to be completed.
Conclusions

- Analytical and simulation studies of switching buck, boost, and buck-boost converters have demonstrated the feasibility of AMFC, based on the principles of hyperstability and positivity.

- These studies have shown that AMFC can mitigate the effects of parameter uncertainty and drift in buck, boost, and buck-boost converters.

- A hardware implementation of a buck converter with voltage feedback AMFC has been shown to significantly reduce the open-loop frequency response variation with changes to the output inductor and capacitor.

- The audiosusceptibility has been shown to be unchanged from conventional voltage mode control with AMFC.

- The output impedance has been shown to be significantly reduced from conventional voltage mode control with AMFC.