SMART SWITCHING POWER ELECTRONICS

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ABOUT ME

- From New Delhi, India
- B.E. (Hons), Birla Institute of Technology and Science – Pilani, India
  - Intern, Tarapur Atomic Power Station, Maharashtra
- Researcher, University of Wisconsin – Madison
  - M.S. & Ph.D.
  - Teaching Assistant (9 semesters)
  - Visiting Scholar, Technische Universität Graz, Austria (Fall 2017)
  - Design Engineer (Intern), SolarEdge Technologies, California (Spring 2019)
- Researcher, Ford Motor Company
  - With Research & Advanced Engineering for 1 year
EXAMPLE PE BASED SYSTEM

Highly power dense
Highly efficient
Inexpensive
Reliable
Safe
COMPONENTS OF PE CONVERTER

Energy Transfer = 1 unit

1 unit = Power × T_s = \frac{\text{Power}}{f_s}

→ 1 unit of energy is power transfer per switching cycle

Energy Storage
≈ 100s - 1000s units
SOLID STATE SWITCHES

1958

Advancements in ICs

1972

Advancements in PE

- Thyristor devices
- IGBTs
- MOSFETs

→ Several kV (up-to 6.5kV)
→ Several kA (up-to 1.5kA)
ENERGY STORAGE ELEMENTS

Capacitors

Electrolytic capacitors → Bulk ES
Film capacitors → Decoupling

[4]
My objective: Lean PE by eliminating bulky ES elements!
EXAMPLE DC-DC PE CONVERTER

Switches:
- voltage and current ratings of the source/load
- New devices (ex. SiC MOSFETS) Compact thermal design

Source/Load Filter:
- total harmonic distortion (THD) specifications
- electromagnetic interference (EMI)
- Increase switching frequency

Energy Storage Element:
- Presumed to be big for robust circuit operation

Background ➔ Benchmarking Bulky PE ➔ Lean PE ➔ AC PE ➔ Results ➔ Lean² PE ➔ Conclusion
TYPICAL OPERATION

\[ S_i = \{0, 1\} \]
\[ S_o = \{0, 1\} \]

By using the concept of averaging [5]:

\[ d_1 = \frac{V_i}{V_{\text{Cap}}} \]
\[ d_2 = \frac{V_o}{V_{\text{Cap}}} \]

Rate of flow = \( f_S \)

Energy Storage element

Source \( f_{\text{Source}}^S \)

Load \( f_{\text{Load}}^S \)

\[ f_{\text{Source}}^S = f_{\text{Load}}^S = f_S \]
2. Selecting the regulation technique
   - Hierarchical Implementation of Proportional Integral Regulator (P-I)
     - Outer DC Link Voltage regulation $\rightarrow$ P-I ($K_p$ & $K_i$)
     - Inner Input Current regulation $\rightarrow$ P ($K_w$)
   - Simplifies output duty ratio control

3. Design must ensure adequate overall system regulation

Background $\rightarrow$ Benchmarking Bulky PE $\rightarrow$ Lean PE $\rightarrow$ AC PE $\rightarrow$ Results $\rightarrow$ Lean² PE $\rightarrow$ Conclusion
**Dynamic Model of Regulator**

Using State-Space equations [6]:

\[
L_i \frac{d i_i}{dt} = V_i - d_1 v_{Cap}^* \\
L_o \frac{d i_o}{dt} = d_2 v_{Cap}^* - i_o R \\
i_{Cap} = C \frac{d v_{Cap}}{dt} = d_1 i_i - d_2 i_o
\]

where,

\[
d_1 = \left\{K_p + \frac{K_i}{s}\right\} \left\{V_{Cap} - V_{Cap}^*\right\} - i_i K_w \\
d_2 = \frac{V_{2}^*}{V_{Cap}^*}
\]

\[
d\lambda = \int (v_{Cap} - V_{Cap}^*) dt
\]

Benchmarked the state-of-the-art approach with the objective of optimized capacitor size
**MODEL FOR CAPACITOR SIZING**

**B) Small Signal Linearized Model**

*Small Signal Linearized Analysis: Superimposition of a load variation*

\[ r_L = R_L + \hat{r}_L \]

\[ \Rightarrow x = X + \hat{x} \]

**C) Sensitivity Analysis**

\[
\begin{bmatrix}
\frac{\dot{i}_i}{\hat{i}_i} & \frac{\dot{i}_o}{\hat{i}_o} & \frac{\dot{v}_{Cap}}{\hat{v}_{Cap}} \\
\frac{\hat{i}_i}{\dot{i}_i} & \frac{\hat{i}_o}{\dot{i}_o} & \frac{\hat{v}_{Cap}}{\dot{v}_{Cap}} \\
\frac{\hat{v}_{Cap}}{\dot{v}_{Cap}} & \frac{\hat{\lambda}}{\dot{\lambda}} & \frac{\hat{\lambda}}{\dot{\lambda}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{\dot{i}_i}{\hat{i}_i} & \frac{\dot{i}_o}{\hat{i}_o} & \frac{\dot{v}_{Cap}}{\hat{v}_{Cap}} \\
\frac{\hat{i}_i}{\dot{i}_i} & \frac{\hat{i}_o}{\dot{i}_o} & \frac{\hat{v}_{Cap}}{\dot{v}_{Cap}} \\
\frac{\hat{v}_{Cap}}{\dot{v}_{Cap}} & \frac{\hat{\lambda}}{\dot{\lambda}} & \frac{\hat{\lambda}}{\dot{\lambda}}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{\dot{r}_L}{\hat{r}_L} & \frac{\dot{r}_L}{\hat{r}_L} & \frac{\dot{r}_L}{\hat{r}_L}
\end{bmatrix}
\]
How will the dc link capacitor voltage behave during load transients?

\[
\frac{[\tilde{V}_\text{Cap}]}{\tilde{I}} = k_o s \left( \frac{s}{\omega_z} + 1 \right) \frac{s^4}{\omega_\alpha^4} + \frac{s^3}{\omega_\beta^3} + \frac{s^2}{\omega_\gamma^2} + \frac{s}{\omega_\delta} + 1
\]

\[
k_o = \frac{D_2 I_o}{D_1 K_i R}
\]

\[
\omega_z = \frac{K_w V^*_\text{Cap}}{L_i}
\]

\[
\omega_\alpha^4 = \frac{D_1 K_w K_i V^*_\text{Cap} R}{L_i L_o C L_i}
\]

Uncovering the secrets → Making model useful

Model Objectives

- Stable system
- Optimized transient peaks
- Develop design guidelines

» System is dominated by a single pole transfer function!
**SYSTEM STABILITY**

\[
\frac{[v_{\text{Cap}}]}{f} = \frac{ks\left(\frac{s}{w_z} + 1\right)}{s^4 + \frac{s^3}{\omega^3} + \frac{s^2}{\omega^2} + \frac{s}{\omega} + 1}
\]

\[
\omega^3_\beta \approx \frac{D_1K_w^*K_iV_{Cap}^*R}{K_w^*V_{Cap}^*C_{L_o} - K_pK_wI_iL_iL_o} > 0 \quad \text{For Stability!}
\]

\[
K_p < \frac{CV_{Cap}^*}{L_i|I_i|}
\]

\[
\Delta \text{Safety Margin} = \frac{0.8C \times 0.8V_{Cap}^*}{1.2L_i \times 1.2|I_i|}
\]

\[\Delta \text{Can depend on design specifications}\]

\[K_p \text{ has an upper bound} \rightarrow \text{Low Capacitance systems require lower } K_p\]
**OPTIMIZED TRANSIENT PEAK**

E) Characterizing system performance

How does \( V_{Cap} \) respond to load change?

\[
\frac{\bar{V}_{Cap}}{f} = \frac{ks \left( \frac{s}{\omega_z} + 1 \right)}{\omega_\alpha^4 + \frac{\omega_\beta^3}{\omega_\gamma} + \frac{\omega_\gamma^2}{\omega_\delta} + \frac{s}{\omega_\delta} + 1} \approx \frac{ks}{\omega_\delta} + 1
\]

Time Domain Translation (step change in load):

\[
L^{-1} \left\{ \frac{\bar{V}_{Cap}}{s^2f} \right\} = k_\delta e^{-\omega_\delta t}
\]

\( \Rightarrow \) Voltage overshoot \( \approx \frac{D_2I_0}{2D_2^2 + RK_pD_1} \)

Converter dynamics are dominated by single pole transfer function \( \rightarrow \) a result of asymptotic stability analysis

Assumptions for the regulator:

- Current regulator with good regulation accuracy
- Reduced transient peaks during transient conditions

Background \( \rightarrow \) Benchmarking Bulky PE \( \rightarrow \) Lean PE \( \rightarrow \) AC PE \( \rightarrow \) Results \( \rightarrow \) Lean\(^2\) PE \( \rightarrow \) Conclusion
TRADE-OFF

1. Ensure System Stability:

\[ K_p < \frac{CV_{Cap}^+}{L_i|I_i|} \]

- \( C \downarrow \) \( K_p \downarrow \)

2. Limit Transient Peaks:

Voltage overshoot \( \approx \frac{D_2I_0}{2D_2^2 + RK_pD_1} \)

- \( K_p \downarrow \) \( \text{Transient Peak} \uparrow \)

Conflicting requirements \( \rightarrow \) Classical approach theoretically limits C-size reduction
TIME DOMAIN SIMULATIONS

State-of-the-art approach, without abundant energy storage, leads to poor performance!

Detrimental to:
- Lifetime
- Output quality
- Reliability
- Cost

Requires derating of capacitors, switches, etc.

Predicted by our analytical model
RESULTS

Load rejection (%)

Overshoot (%)

Capacitance (µF)

1000 100 10

400 units 40 units 4 units

Boost Operation with conventional approach

<table>
<thead>
<tr>
<th>Source Parameters</th>
<th>P</th>
<th>20 kW</th>
<th>1 unit (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_i</td>
<td>200 V</td>
<td>1 unit (V)</td>
<td></td>
</tr>
<tr>
<td>I_i</td>
<td>100 A</td>
<td>1 unit (A)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_o</td>
</tr>
<tr>
<td>I_o</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Link Voltage</th>
<th>V_Cap</th>
<th>400 V</th>
<th>2 unit (V)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Switching Frequency</th>
<th>f_S</th>
<th>100 kHz</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Reactive Elements &amp; Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% Ripple</td>
</tr>
<tr>
<td>5% Ripple</td>
</tr>
</tbody>
</table>

| C | 1000 µF | 400 unit (J) |
|   | 100 µF  | 40 unit (J)  |
|   | 10 µF   | 4 unit (J)   |

Lower energy storage traditionally leads to poor system performance!
Tiny Energy Storage

~2-10 units of energy transfer

Rate of flow = $f_s$

Source $f_s$

Load $f_s$

Advantage
Absence of bulk energy storage (ES) → High power density system

Tradeoff
Careful transfer of energy is a must between the source and the load

Replace a big reservoir by a lean reservoir!
THREE NEW ASPECTS

Careful energy transfer between source and load = How do we regulate the energy level of a tiny ES element?

1. Synchronized transfer of energy to/from the ES element
2. Accurate calculation of time periods of energy transfer
3. Regulation required during uncertain model parameters and transient conditions

Averaging may not work!

\[ d_1 = \frac{V_i}{V_{\text{Cap}}} \]
SWITCHING STATES

Background → Benchmarking Bulky PE → Lean PE → AC PE → Results → Lean² PE → Conclusion

Diagram showing the switching states of a circuit with inductors and capacitors.
SEQUENCED SWITCHING

Example:
voltage step-up (boost)

Charge interval $\sigma_1$

Discharge interval $\sigma_2$

Idle interval $\sigma_0$

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**Accurate Duty Ratio Calculation**

\[ d_j = \frac{2E_j f_S}{V_{ci} i_j} \left[ 1 - \sqrt{1 - \frac{e_j}{E_j}} \right] \]

During the \( j \)th interval,
- \( v_j \): voltage across \( C \)
- \( i_j \): current into \( C \)
- \( e_j \): Energy transfer to \( C \)
- \( E_j \): Energy stored in \( C \)

\( e_j = 0.2J \)

A) if \( C = 5\mu F, E_j = 0.4J \)
B) if \( C = 25\mu F, E_j = 2J \)

**Conventional**

\[ \left[ \frac{e_j}{E_j} \right] \ll 1 \]

**Taylor Series**

**Averaged duty ratio**

\[ d_j \approx \frac{2E_j f_S}{V_{ci} i_j} \left[ \frac{e_j}{2E_j} \right] \]

\[ d_j \approx \frac{v_j}{V_N} \]
SEQUENCED SWITCHING REGULATION

Conventional Approach: Averaged $\rightarrow$ Dynamics are $10x$ slower than $f_s$

Big bucket can work with slower dynamics

Lean Power Conversion:

Need faster dynamics for lean PE

Could we add regulation to control the flow rate at source/load to manage the lean bucket?

Conventional Approach: Averaged $\rightarrow$ Dynamics are $10x$ slower than $f_s$

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CAPACITOR CHARGE RESTORATION

Boost operation

Ideal case

Real world cases

δ → residue

δ → residue
CAPACITOR CHARGE RESTORATION

Example load interval tuning

Example source interval tuning
Stability Analysis: Variable Structure Systems [7], [8]

Residue $\delta$ → $\delta = v_{Cap} - V_N \Rightarrow \dot{\delta} = v_{Cap}$

Corrective action (switching) → $u_\delta = sign(\delta)$

$$\frac{dv_{Cap}}{dt} = v_{Cap} = \dot{\delta} = \frac{dS_i - dL_i}{C}$$

Case 1: Tuning the load interval:

$$\dot{\delta} = \frac{-d_i i_i - d_o i_o}{C} = \frac{-d_i i_i - [d_o + sign(\delta)] i_o}{C}$$

$\Rightarrow \delta \dot{\delta} < 0$ Stable operation!

Case 2: Tuning the source interval:

$$\dot{\delta} = \frac{-d_i i_i - d_o i_o}{C} = \frac{-[d_i + sign(\delta)] i_i - d_o i_o}{C}$$

$\Rightarrow \delta \dot{\delta} > 0$ Unstable operation!
STABILITY - WAVEFORMS

Load interval tuning $\delta\delta < 0$

Source interval tuning $\delta\delta > 0$

Capacitor voltage $V_{Cap}$

Time (ms)

Source current $I_s$, Load current $I_o$
RESULT

Conventional

50% load rejection at 0.1s

Link Voltage $v_{\text{Cap}}$

Currents

$C = 1000\mu F$

$C = 10\mu F$

400 units

4 units

Proposed

Link Voltage $v_{\text{Cap}}$

Currents

$C = 10\mu F$

4 units

Background → Benchmarking Bulky PE → Lean PE → AC PE → Results → Lean² PE → Conclusion
SUMMARY

Background → Benchmarking Bulky PE → Lean PE → AC PE → Results → Lean² PE → Conclusion
EXAMPLE DESIGN
AC CONVERSION SYSTEMS

Coupled Modulation

Conventional

Extension to AC Systems using:

→ Space Vector Diagram
or,
→ 2-Phase Equivalent System Approach
PHOTOVOLTAIC SYSTEM EXAMPLE

<table>
<thead>
<tr>
<th></th>
<th>Conventional PWM [9]</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Inductor ((L_{\text{DC}}))</td>
<td>5mH</td>
<td>5mH</td>
</tr>
<tr>
<td>Link Capacitor ((C))</td>
<td>1000µF</td>
<td>10µF</td>
</tr>
<tr>
<td>Output Inductor ((L_{\text{O}}))*</td>
<td>7.5mH</td>
<td>7.5mH</td>
</tr>
<tr>
<td>Output Capacitor ((C_{\text{O}}))*</td>
<td>0.55µF</td>
<td>0.70µF</td>
</tr>
</tbody>
</table>

* Ripple Current: 3%

- Transformer-less photovoltaic inverters
- L-C output filter meet ripple specifications of 3% ripple current
- 0.33J of energy transfer between source and load in 100µs
- Proposed approach with nominal energy storage of 0.6J at dc link (against 60J with conventional PWM)
PV: SIMULATION WAVEFORMS

Load Resistance

Positive Switch Duty Ratios

Output Currents

Capacitor Voltage VCap

Time (seconds)

100% Δ

1.0

0.5

0.0

2.0

0

-2.0

400

200

0

5.5%

3.2%

2.5%

0.00 0.02 0.04 0.06 0.08 0.10

Sequenced and synchronized connection of source & load

Distinct charge-discharge of ES element

ES element charge restoration

<4% overshoot @ 100% load rejection

High-quality output

<6% ripple @ 2p.u. ES, Rated power

Background → Benchmarking Bulky PE → Lean PE → AC PE → Results → Lean² PE → Conclusion
SiC MOSFET based converter

DC-AC and AC-AC conversion capabilities with up-to 700V dc bus

High common mode immune circuitry
- Negative bias gate driver with isolated bipolar power supplies
- Current sensors
- Mixed signal voltage sensing

8-channel 16-bit Σ-Δ ADC converter

Controller: Xilinx Zedboard

Tested up-to 1.8kW
**Background** → Benchmarking Bulky PE → Lean PE → AC PE → Results → Lean² PE → Conclusion

**Waveforms From Prototype**

- **Low frequency waveforms**
- **High frequency waveforms**

**Laboratory Setup**

Next Step → Lean² PE?
ZERO UNITS ENERGY STORAGE

Rate of flow = $f_s$

![Diagram of energy storage system](image)

- Source $f_s$
- Load $f_s$
- Conventional
- 0 p.u. ES
- ~0.1 µF!

Sets an upper limit of link capacitance!
**Background → Benchmarking Bulky PE → Lean PE → AC PE → Results → Lean² PE → Conclusion**

**ZERO UNITS CONVERTER PROTOTYPE**

100W IM Drive
200V 3 Phase ac 400Hz $f_s = 7.8$kHz, $C = 39\text{nF}$

Motor Line Currents

Link Voltage & Input DC Current

39nF!
HIGHLIGHTS

- Enables two orders of reduction in the energy storage requirements of capacitive/inductive elements (0-10 units vs. 100-1000 units) → Highly dense and Lean Power Conversion
- Energy storage elements can be minimally sized ([nF, few µF] vs. [100s µF, mF])
- PE converters can employ film capacitors (vs. electrolytic capacitors)
  - Higher lifespan
  - Lower losses
- Lays the foundation for new directions towards high density power conversion for several applications including wind energy, traction, industrial drives, etc.
REFERENCES


THANK YOU

Questions/Comments?

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For students: ECE 4/545 Power Electronic Systems Design (Winter term)