Soft Switching in Switched Inertance Hydraulic Circuits

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Agenda

• Background
• Motivations
• Soft Switching Sequence
• Modeling
• Results
• Conclusion
Fundamental Boost Converter

DC-DC pressure boost circuit
Fundamental Boost Converter

DC-DC pressure boost circuit

Duty Ratio:
\[ D = \frac{t_{\text{tank}}}{T_{\text{switch}}} \]

\[ 0 < D < 1 \]

Load Pressure:
\[ p_{\text{load}} = \frac{p_{\text{rail}}}{1 - D} \]
Motivations

• Throttling losses are as high as 44%
Background

• “Soft switching”
  – Mitigate pressure gradients across the switching valve during transition

• Methods
  – Transition overlap
  – Bypass check valves
  – Buffering accumulators
Soft Switched Boost Converter I

\[ Q_L = \frac{Q_0}{(1 - D)T} \]

\[ p_{\text{rail}} = Q_L \]

\[ p_1 = p_{\text{tank}} \]

\[ p_1 = p_{\text{tank}} \]
Soft Switched Boost Converter II

\[ Q_L \]

\[ (1 - D)T \]

\[ T \]

\[ p_{load} \]

\[ p_{rail} \]

\[ p_1 \]

\[ p_{tank} \]

\[ p_1 \rightarrow p_{load} \]
Soft Switched Boost Converter III

\[ p_1 = p_{load} \]
Soft Switched Boost Converter IV

\[ Q_L \]

\[ (1 - D)T \]

\[ T \]

\[ p_{\text{rail}} \rightarrow Q_L \]

\[ p_{1} = p_{\text{load}} \]

\[ p_{\text{tank}} \]

\[ p_{\text{load}} \]
Soft Switched Boost Converter V

\[ p \rightarrow p_{\text{tank}} \]

\[ p_{\text{rail}} \rightarrow Q_L \]

\[ Q_L \rightarrow (1-D)T \]

\[ Q_L \rightarrow T \]

\[ (1-D)T \]

\[ T \]

\[ p_{\text{load}} \]
Soft Switched Boost Converter VI

\[ \begin{align*}
Q_L & \geq Q_0 \\
0 & \leq (1 - D)T
\end{align*} \]

\[ p_1 = p_{tank} \]
Model Summary

• Inertance tube
  – Lumped parameter
  – Requires relatively short inertance tube
  – Wave propagation effects are negligible
    • $L_{tube} < 0.05 \lambda_{switch}$
  – Non-optimal

• Check valves
  – Instantaneous

\[
q_c = \begin{cases} 
0 & \text{if } p_1 - p_2 < p\text{crack} \\
C_d A_c \sqrt{\frac{2(p_1-p_2)}{\rho}} & \text{if } p_1 - p_2 > p\text{crack}
\end{cases}
\]
Simulation Boundary Conditions

- Rail Pressure
  - 6 MPa
- Tank Pressure
  - 0.101 MPa
- Load Flow
  - 0.1 L/s
Simulation Methods

1. Initialize system, begin valve operation
2. Run simulation to cyclic steady state
   - 20 cycles of constant mean load pressure
3. Analyze final simulated cycle
Steady State Simulation Results

Fundamental

Soft Switched
Steady State Simulation Results II

Soft Switched Boost Converter, D = 0.70

Power Losses

Power Losses (kW)

Orifice Area (m²)

Time (s)

0 0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.009 0.01

0 10 20 30 40

0 \times 10^{-5}

P_{\text{loss,SS}}

P_{\text{loss,Base}}

A_{\text{tank}}

A_{\text{load}}
Steady State Simulation Results III

Load Pressure vs. Duty Cycle

- Fundamental
- Soft Switched
- Rail Pressure

Load Pressure (MPa) vs. Duty Cycle
Steady State Simulation Results IV
Conclusions

• Efficiency Improvement: 42%
• Power delivery improvement: 76%
• Spring accumulators can be replaced with the fluid compliance of an optimally sized inertance tube
Future Work

• Include non-ideal check valve model
  – Optimize physical valve parameters

• Include optimal inertance tube length
  – Requires wave propagation models
Thank You!
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