Efficiency Improvement for Switching Power Supply at Light Load Using DSP Control

Chuan Gao, Guanglei Jin, Richen Jiang, Murong Li
Yasunori Kobori, Haruo Kobayashi
Masashi Ochiai, Shinji Aso

Gunma University
Sanken Electric Co., Ltd.
Outline

• Research Background
• Two Parts of Server Power Supply
• Loss Mechanisms of PFC AC/DC Converter and DC/DC Converter
• Experimental Environment
• Experiment Results A:
  *Link Voltage Optimization of BLPFC AC/DC at a Half-Load*
• Experiment Results B:
  *Optimization of PWM Frequency of BLPFC AC/DC at a Load Rate of 5% to 20%*
• Experiment Results C:
  *Optimization of PWM Frequency of PSFB DC/DC at a Load Rate of 5% to 20%*
• Conclusion
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Research Background

● The **energy efficiency** of server power supply is gaining attention.

● Low energy efficiency at light load of 20%~30% 😞

● 80 PLUS Certified Power Supplies and Manufacturers

<table>
<thead>
<tr>
<th>80 PLUS: BRONZE</th>
<th>80 PLUS: SILVER</th>
<th>80 PLUS: GOLD</th>
<th>80 PLUS: PLATINUM</th>
<th>80 PLUS: TITANIUM</th>
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</thead>
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<table>
<thead>
<tr>
<th>% of Rated Load</th>
<th>10%</th>
<th>20%</th>
<th>50%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRONZE</td>
<td>N/A</td>
<td>80%</td>
<td>85%</td>
<td>81%</td>
</tr>
<tr>
<td>SILVER</td>
<td>N/A</td>
<td>85%</td>
<td>89%</td>
<td>85%</td>
</tr>
<tr>
<td>GOLD</td>
<td>N/A</td>
<td>88%</td>
<td>92%</td>
<td>88%</td>
</tr>
<tr>
<td>PLANTINUM</td>
<td>N/A</td>
<td>90%</td>
<td>94%</td>
<td>91%</td>
</tr>
<tr>
<td>TITANIUM</td>
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Two parts of Server Power Supply

AC/DC part + DC/DC part
Power Factor Correction (PFC) Circuit

Ideal Input Voltage and Current

Actual Input Voltage and Current

Risk of damage to power transmission and distribution appliances

What PFC does
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Loss Mechanisms of Server Power Supply

Link Voltage: $265\times\sqrt{2} \approx 390V$

Input Voltage Range: AC 90-265V

Output Voltage: DC 12V

High Link Voltage → Lower energy efficiency
Principle of PFC AC/DC ②: Boost

Switch ON

Switch OFF
Energy Charging

Current through L: \[ i_u = \frac{1}{L} \int_0^{T_1} e_L dt \]

Steady state: \[ e_L = V_i \]
\[ i_u = \frac{V_i}{L} \cdot T_{on} \]

Energy Releasing

\[ e_L = V_o - V_i \]

\( V_i, V_o \) remain the same \( \rightarrow e_L \) remains the same

Current through L: \[ i_d = \frac{V_o - V_i}{L} \cdot T_{off} \]

Steady State \[ i_d = i_u \]
\[ V_o = (1 + \frac{T_{on}}{T_{off}}) \cdot V_i \]
Loss derived from High Link Voltage

- **Reactor Loss / Iron Loss**
  \[ P_i = P_h + P_e = K(B_m^{2.77}f^{1.55}) \]

- **Hysteresis Loss**
  \[ P_h = k_h \frac{e_L^{1.6}}{f^{0.6}} \]

- **Eddy Current Loss**
  \[ P_e = k_e \frac{(t e_L)^2}{f^{0.6}} \]

\[ e_L = V_o - V_i \]
Loss Mechanisms of Server Power Supply

\[ P_{SW(DIODE)} = 0.5 \times V_{REVERSE} \times I_{RR(PEAK)} \times t_{RR} \times f_S \]

\[ P_{SW(MOSFET)} = 0.5 \times V_D \times I_D \times (t_{SW(ON)} + t_{SW(OFF)}) \times f_S \]
PWM (Pulse-width Modulation) Control

Average value of voltage

Voltage

Time

QA
QB
QC
QD

PSFB (Phase Shifted Full Bridge)
PWM waveform
Diode Loss

\[
P_{SW(DIODE)} = 0.5 \times V_{REVERSE} \times I_{RR(PEAK)} \times t_{RR} \times f_s
\]

Power Loss = Reverse Voltage \times Spike Current \times Time Span \times Frequency
MOSFET Loss

Power Loss = Drain-Source Voltage × Channel Current × Time Span × Frequency

\[ P_{SW(MOSFET)} = 0.5 \times V_{DS} \times I_D \times (t_{SW(ON)} + t_{SW(0FF)}) \times f_S \]
Energy efficiency downgrade of the PFC on the account of these two main loss mechanism (Reactor Loss + Diode Loss + MOSFET Loss).
This paper discussed how to improve the efficiency of power supplies at half-load and light load under 20% using digital control.

**Conventional Method**
- [PFC]
  - Fixed link voltage
  - PWM(fixed frequency)
- [DC/DC]
  - PWM(fixed frequency)

**Proposed Method**
- [PFC]
  - Variable link voltage
  - PWM(variable frequency)
- [DC/DC]
  - PWM(variable frequency)

Circuit topology Hardware
DSP digital control Software

Efficiency degradation
Research Approach

The experiment is conducted by a mean of two parts and three steps.

BLPFC AC/DC part (Bridgeless Power Factor Correction AC/DC)
- Step A: Load rate 50% → Deal with Link Voltage
- Step B: Load rate 10%~20% → Deal with PWM Frequency

PSFB DC/DC part (Phase Shift Full Bridge DC/DC)
- Step C: Load rate 10%~20% → Deal with PWM Frequency
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Experimental Environment

Specifications of experiment boards controlled by **C2000 Series DSP**
(Texas Instruments Inc.)

**BL PFC (Bridgeless PFC) AC/DC Kit**
- Input Voltage (AC line): 85V(Min) to 265V(Max), 47~63Hz
- 400Vdc Output
- 300 Watts Output Power
- Full Load efficiency greater than 93%
- Power factor at 50% or greater load – 0.98(Min)
- PWM frequency 200kHz.

**PSFB (Phase shifted Full Bridge) DC/DC Kit**
- 400V DC input (370Vdc to 410Vdc operation)
- 12V DC output
- Peak efficiency greater than 95%
- 50A (600Watt) rated output.
- Phase Shifted Full Bridge Circuit topology
- 100kHz switching frequency.

- **Link voltage**
- **400Vdc Output**
- **PWM frequency 200kHz**
- **400V dc Input (370Vdc to 410Vdc)**
- **100kHz switching frequency**
Experimental Environment

Code Composer Studio (CCStudio or CCS) is an integrated development environment (IDE) to develop applications for Texas Instruments (TI) embedded processors.

BL PFC (Bridgeless PFC) AC/DC Kit
- Appropriate Link Voltage
- Appropriate PWM Switching Frequency

PSFB (Phase shifted Full Bridge) DC/DC Kit
- Appropriate PWM Switching Frequency

These characteristics can be achieved by modifying the main program.
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Loss Mechanisms of Server Power Supply

Input Voltage < Link Voltage (85 ~ 265V) (390 ~ 400V)

- By monitoring the effective value of input voltage and adjust the link voltage in a real-time way.

Monitor the input voltage Vin_N, Vin_L

Read into DSP

Evaluation of effective value $V_{\text{rms}}$

Link voltage: $V_{\text{out}} = \text{Optimum boost ratio} \times V_{\text{rms}}$
Experiment Results A: 

**Link Voltage Optimization of BLPFC AC/DC at a Half-Load**

**Experiment environment**
- AC input voltage $V_{in}=100V$
- Switching frequency is fixed at 200kHz
- Load rate 50% (150W output)

**Graph**

![Graph showing link voltage optimization](image)

**Key Points**
- Unexpected problem occurs when link voltage is set down below 190V.
- Appropriate link voltage is 200V if possible.
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Loss Mechanisms of Server Power Supply

(Diode loss & MOSFET loss $\propto f$)

Therefore, a variable PWM switching frequency by digital control has been tested.

Analysis of BLPFC AC/DC part

Light load + Fixed frequency

Light load + Variable frequency

Proposed
Experiment Results B:
Optimization of PWM Frequency of BLPFC AC/DC
at a Load Rate of 5% to 20%

Experiment environment

- AC input voltage $V_{\text{in}}=100\text{V}$
- Link voltage (PFC output voltage) is fixed at $400\text{V}$

(a) Variation of efficiency according to frequency at 400V link voltage.
Experiment Results B: Optimization of PWM Frequency of BLPFC AC/DC at a Load Rate of 5% to 20%

Conventional fixed frequency 200kHz is not always efficient.

Load | Appropriate frequency
--- | ---
5%–10% | 150kHz
10%–15% | 170kHz
15%–20% | 190kHz
20% ~ | 200kHz

(b) Comparison of efficiency between 200kHz and optimum frequency.
Experiment Results B:
Optimization of PWM Frequency of BLPFC AC/DC
at a Load Rate of 5% to 20%

Experiment environment
• AC input voltage $V_{in}=100V$
• Link voltage (PFC output voltage) is fixed at 350V

(a) Variation of efficiency according to frequency at 350V link voltage.
(b) Comparison of efficiency between 200kHz and optimum frequency.
Experiment Results B:
Optimization of PWM Frequency of BLPFC AC/DC
at a Load Rate of 5% to 20%

Experiment environment
- AC input voltage $V_{in} = 100V$
- Link voltage (PFC output voltage) is fixed at 300V

(a) Variation of efficiency according to frequency at 300V link voltage.
(b) Comparison of efficiency between 200kHz and optimum frequency.
Experiment Results B: Optimization of PWM Frequency of BLPFC AC/DC
at a Load Rate of 5% to 20%

Experiment environment
- AC input voltage $V_{in} = 100V$
- Link voltage (PFC output voltage) is fixed at 250V

(a) Variation of efficiency according to frequency at 250V link voltage.

(b) Comparison of efficiency between 200kHz and optimum frequency.
Experiment Results B: Optimization of PWM Frequency of BLPFC AC/DC at a Load Rate of 5% to 20%

Experiment environment
- AC input voltage $V_{in}=100V$
- Link voltage (PFC output voltage) is fixed at 200V

(a) Variation of efficiency according to frequency at 200V link voltage.

(b) Comparison of efficiency between 200kHz and optimum frequency.
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Analysis of PSFB DC/DC part

- Loss Mechanisms of Server Power Supply .EMAIL
  (Diode loss & MOSFET loss $\propto f$)

- A variable PWM switching frequency using digital control can also benefit the efficiency of the PSFB DC/DC circuit.

- [Diagram of DC/DC circuit with components labeled Q3, Q5, Q4, Q6, T1, D3, D4, L3, C2, DC/DC Power Supply, DC/DC Control Unit, Error Amplification Unit.]

  - Light load + Fixed frequency
  - Light load + Variable frequency

- Proposed
Analysis of PSFB DC/DC part

The left feedback part (red) is added to the control unit by the proposed method.
Experiment Results C:
Optimization of PWM Frequency of PSFB DC/DC
at a Load Rate of 5% to 20%

- **Light load**: settled to a working frequency of 70kHz
- **50% load rate**: back to 100kHz

Conventional fixed frequency 200kHz is not always efficient.
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Conclusion

What we have done:

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<th>Proposed</th>
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<tr>
<td><strong>High link voltage</strong></td>
<td><strong>Lower link voltage</strong> (Low boost ratio)</td>
</tr>
<tr>
<td><strong>PWM of fixed frequency</strong></td>
<td><strong>PWM of variable frequency</strong></td>
</tr>
<tr>
<td><strong>efficiency 6% ↑ @50% load rate</strong></td>
<td><strong>efficiency 1~4% ↑ @5%~20% load rate</strong></td>
</tr>
<tr>
<td><strong>efficiency 3~6% ↑ @10%~20% load rate</strong></td>
<td></td>
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Final goal:
Server Power supply (PFC AC/DC+DC/DC)

Problem to be solved:
The efficiency behavior and mechanism when combing the PFC AC/DC board and DC/DC board.
Thank you for your attention!

We would like to contribute to make the Earth green.
Question

• Q: How much does efficiency increase?
• A: By lowering the link voltage from 400V to 200V if possible, there is a nearly 4% efficiency increase. And by adopting appropriate PWM switching frequency, efficiency increases by 1~2% of each part.