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

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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

Server Power Supply

80 PLUS BRONZE → 80 PLUS SILVER → 80 PLUS GOLD → 80 PLUS PLATINUM → 80 PLUS TITANIUM ☺

% of Rated Load	10%	20%	50%	100%
BRONZE	N/A	80%	85%	81%
SILVER	N/A	85%	89%	85%
GOLD	N/A	88%	92%	88%
PLANTINUM	N/A	90%	94%	91%
TITANIUM	90%	94%	96%	91%

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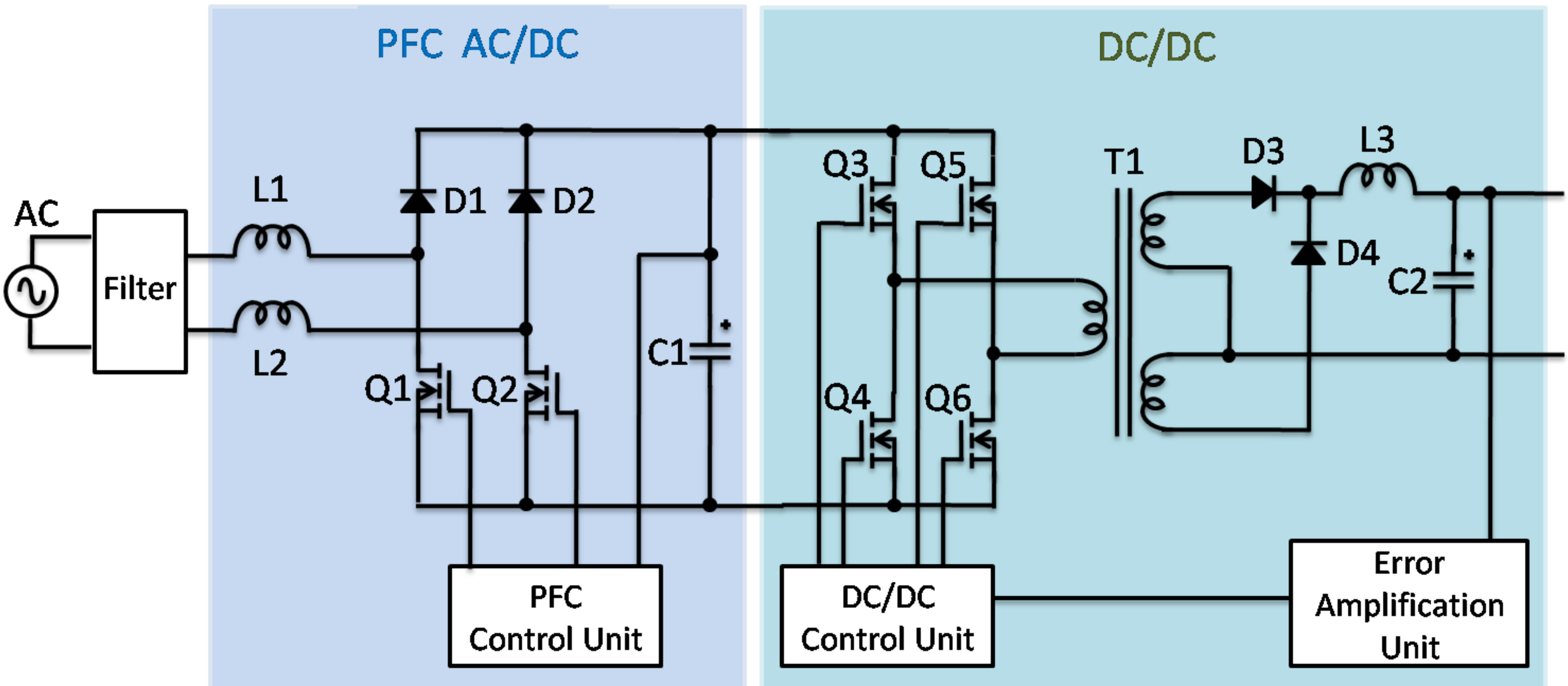
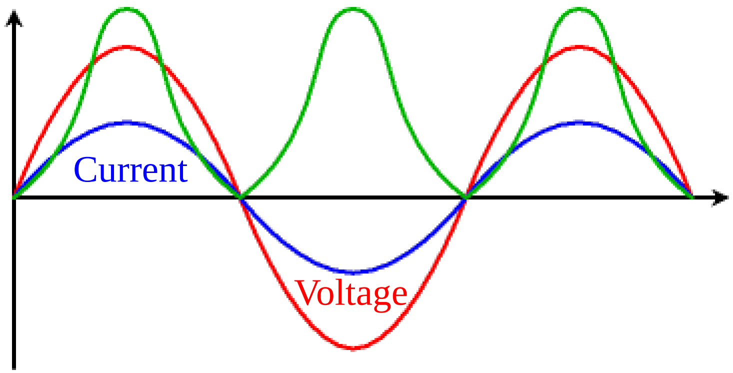
Two parts of Server Power Supply

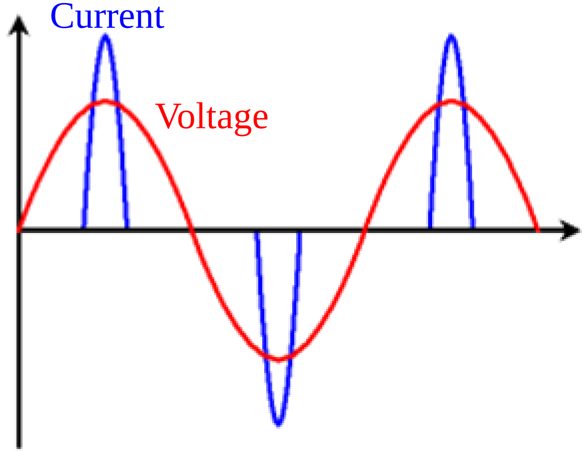
AC/DC part + DC/DC part



Power Factor Correction (PFC) Circuit



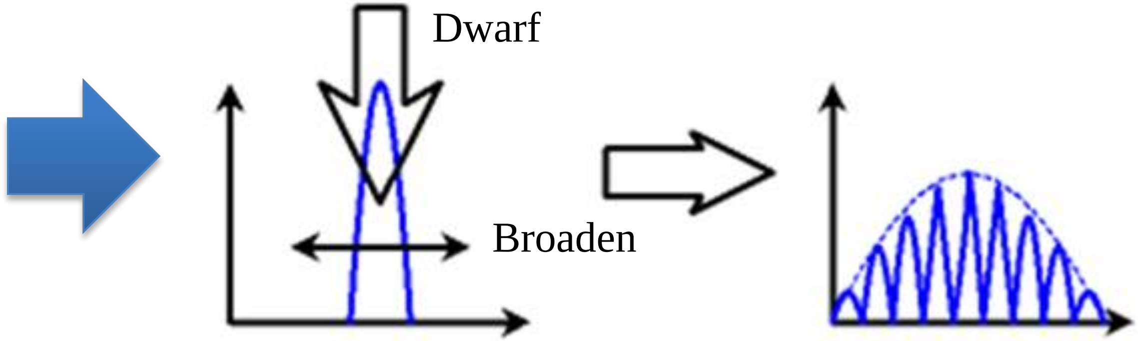
Ideal Input Voltage and Current



Actual Input Voltage and Current

Risk of damage to power transmission and distribution appliances

What PFC does



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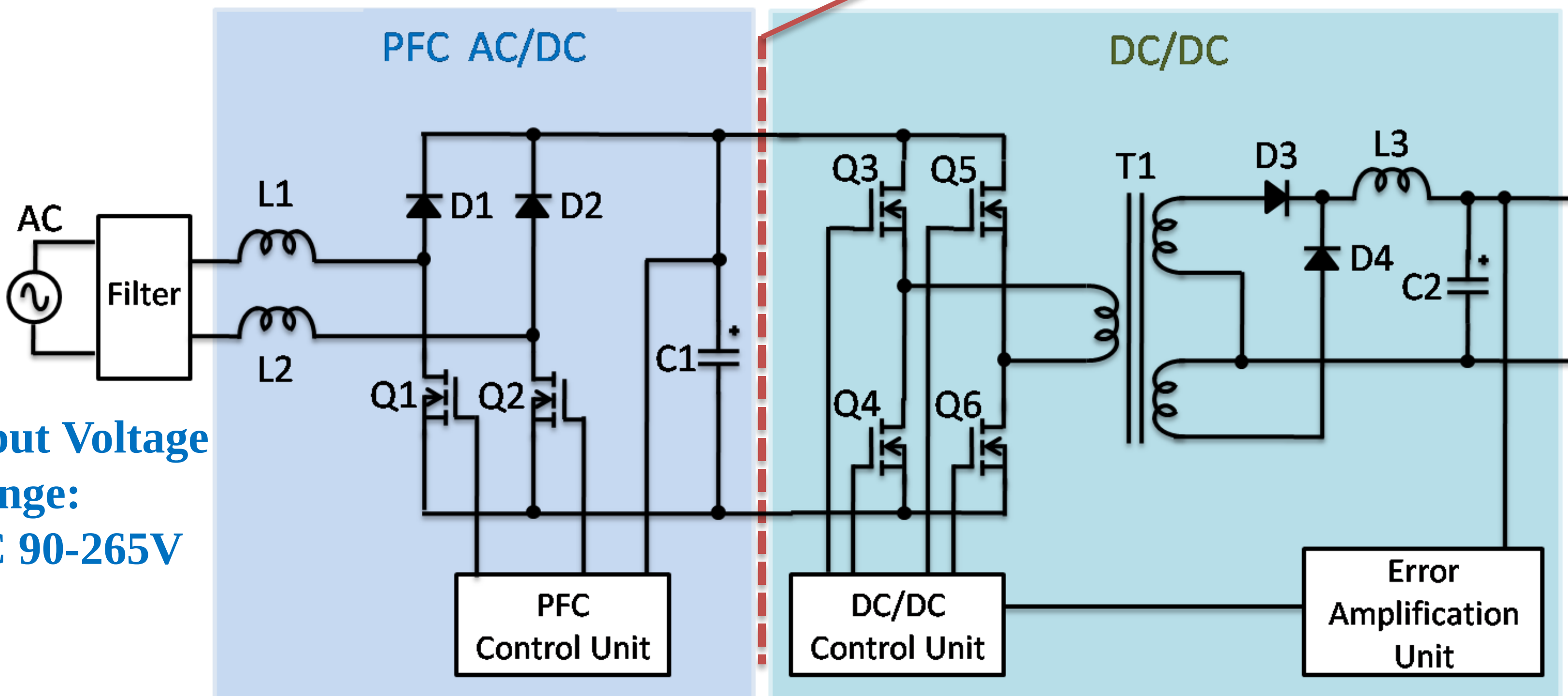
Loss Mechanisms of Server Power Supply ①

Link Voltage: 265*√2≒**390V**



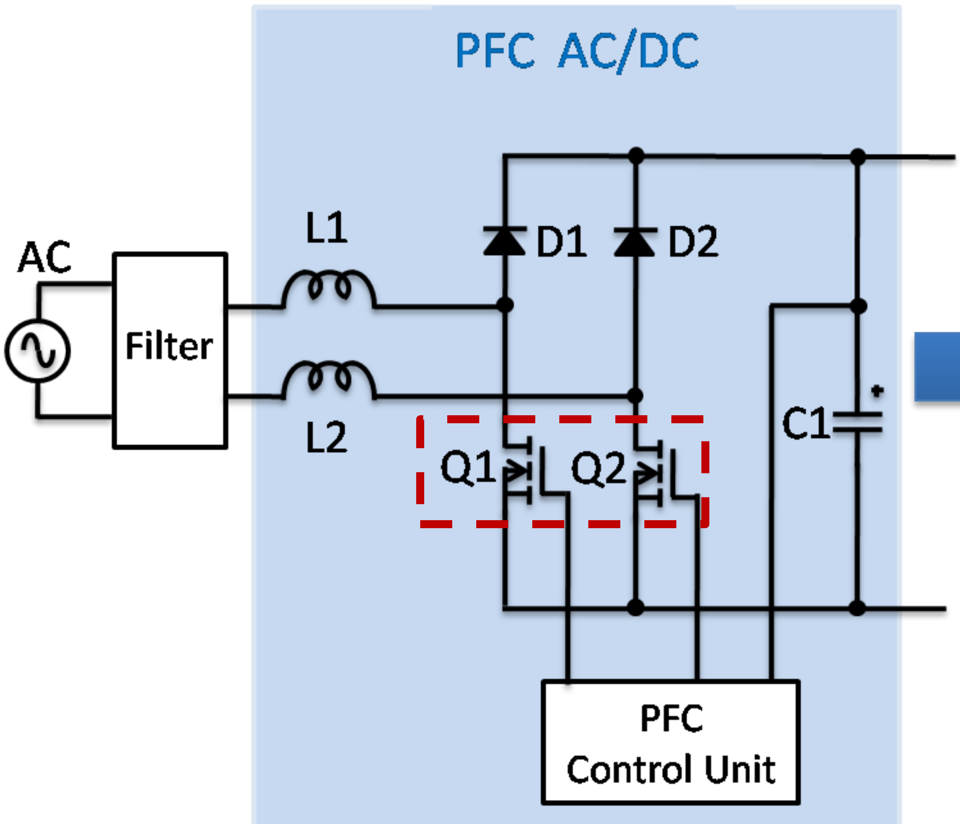
Input Voltage Range: AC 90-265V

Output Voltage: DC 12V

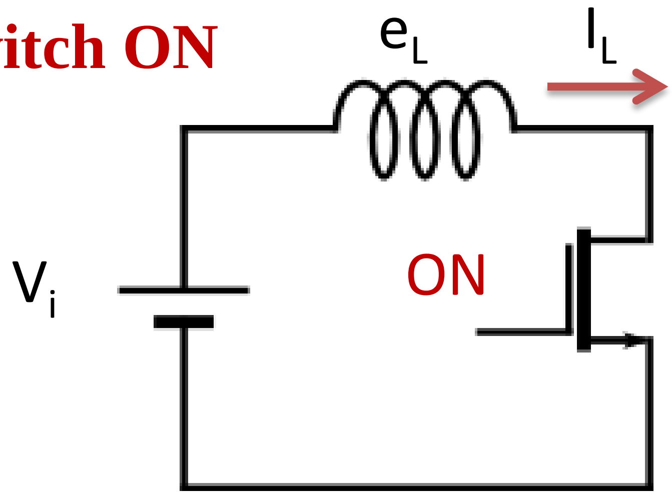
Server Power Supply Circuit

High Link Voltage → **Lower energy efficiency**

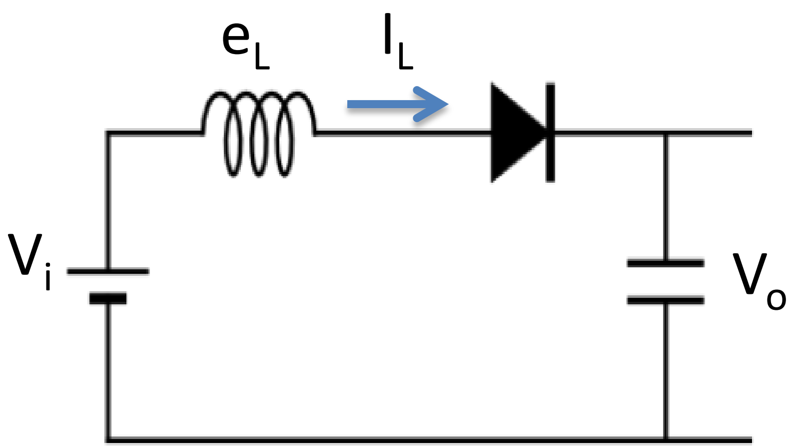
Principle of PFC AC/DC ②: Boost



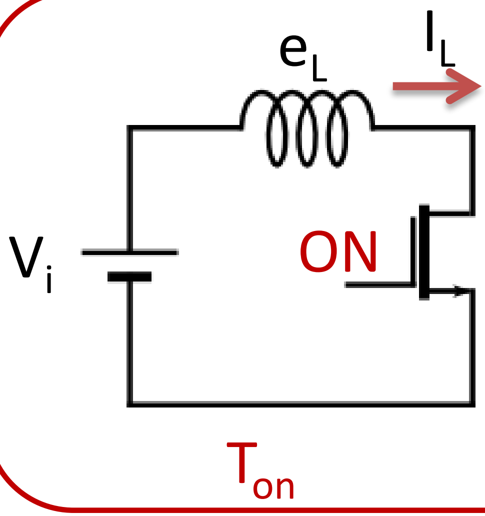
Switch ON



Switch OFF



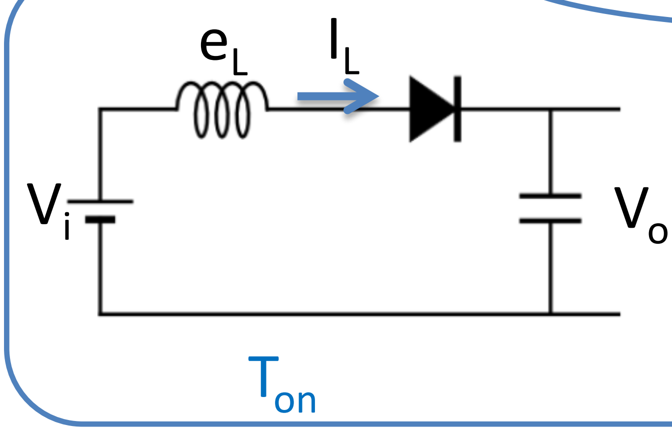
Energy Charging



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

Steady state: $e_L = V_i$ $\quad i_u = \frac{V_i}{L} \cdot T_{on}$

Energy Releasing



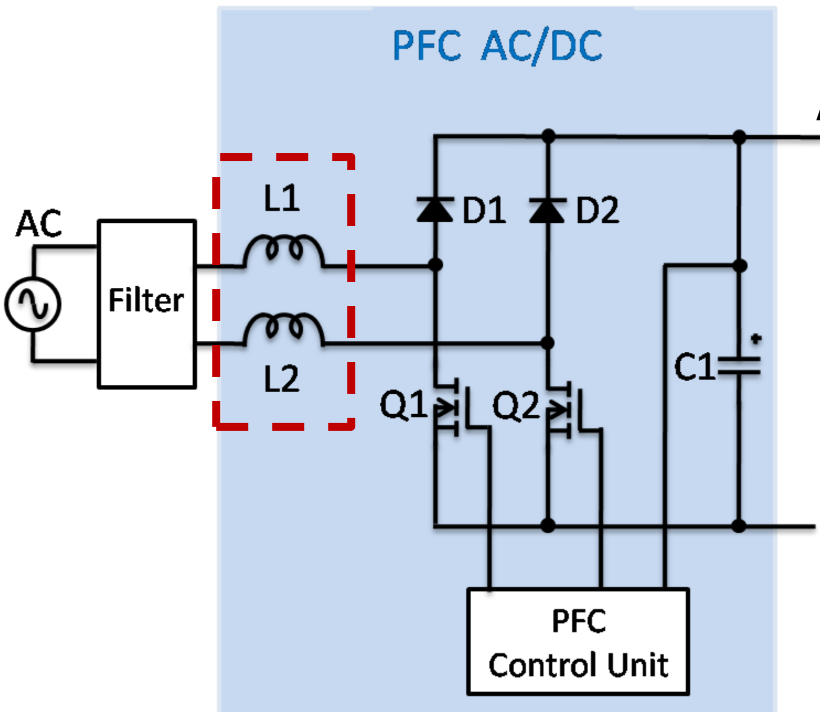
$$e_L = V_o - V_i$$

V_i 、V_o remain the same → e_L remains the same

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

Steady State $\boxed{i_d = i_u}$ ⇒ $V_o = (1 + \frac{T_{on}}{T_{off}}) \cdot V_i$

Loss derived from High Link Voltage



● **Reactor Loss / Iron Loss** $P_i = P_h + P_e = K(B_m^{2.77}, f^{1.55})$

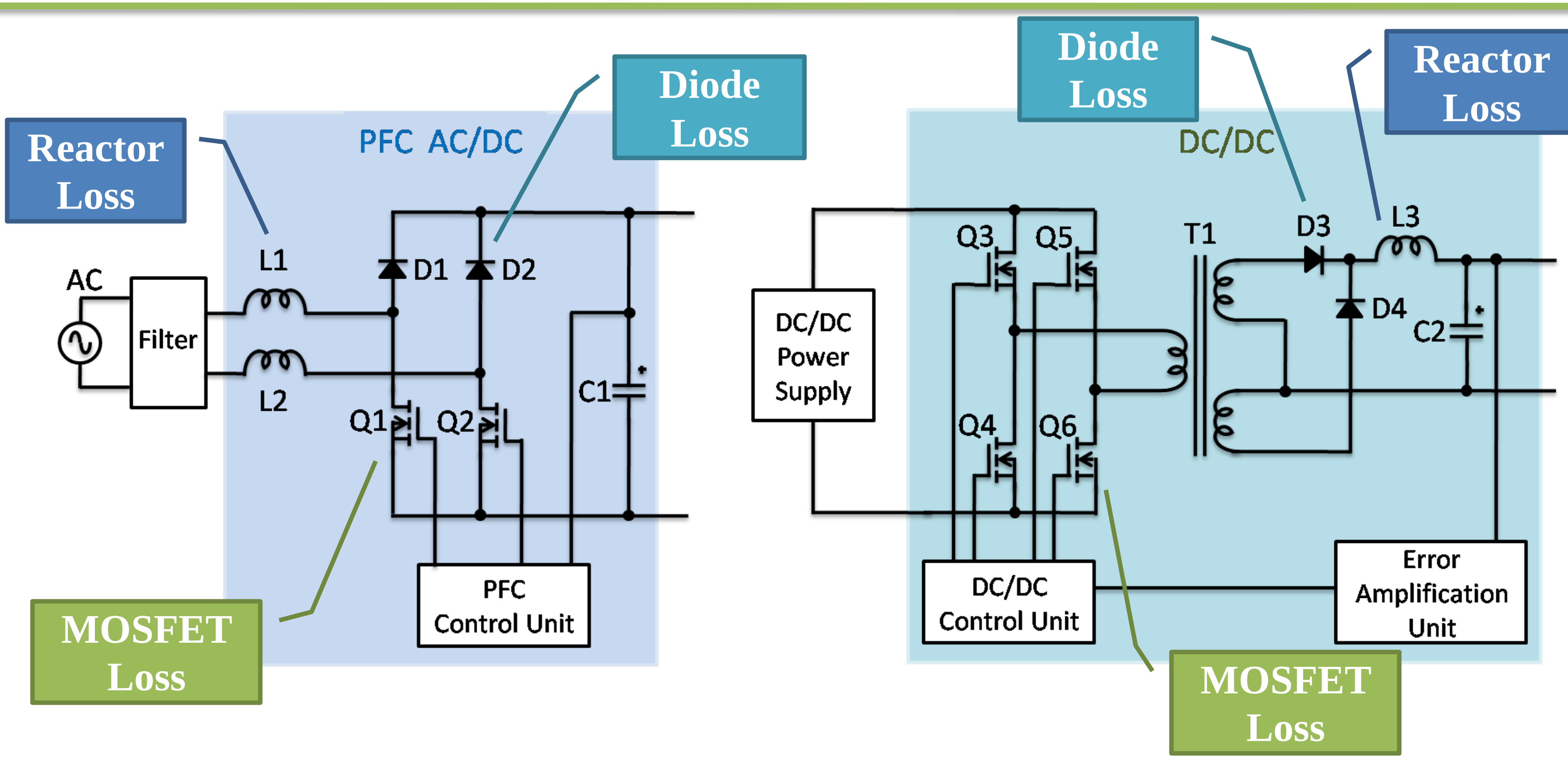
● Hysteresis Loss $P_h = k_h^{`} \dfrac{e_L^{1.6}}{f^{0.6}}$

● Eddy Current Loss $P_e = k_e^{`} \dfrac{(t e_L)^2}{f^{0.6}}$

$$e_L = V_o - V_i$$

Link Voltage

Loss Mechanisms of Server Power Supply ②



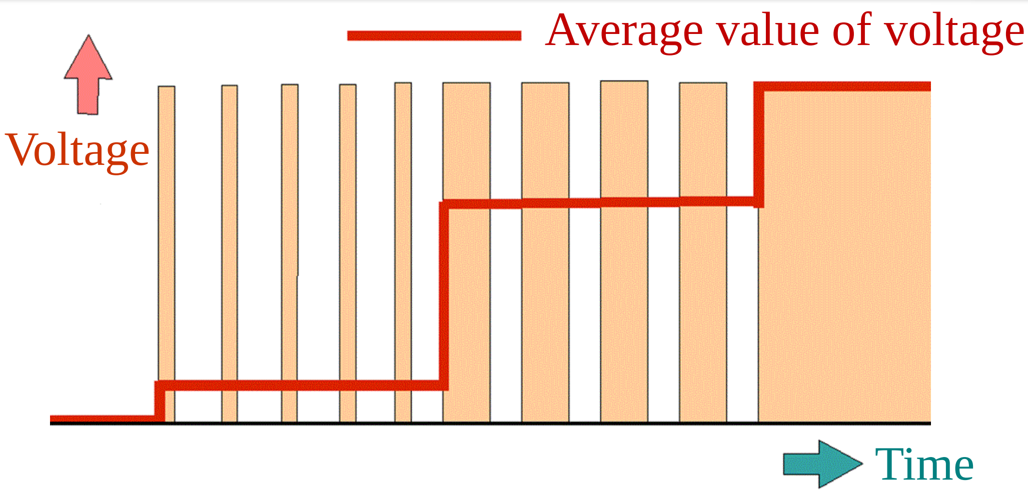
Diode Loss →

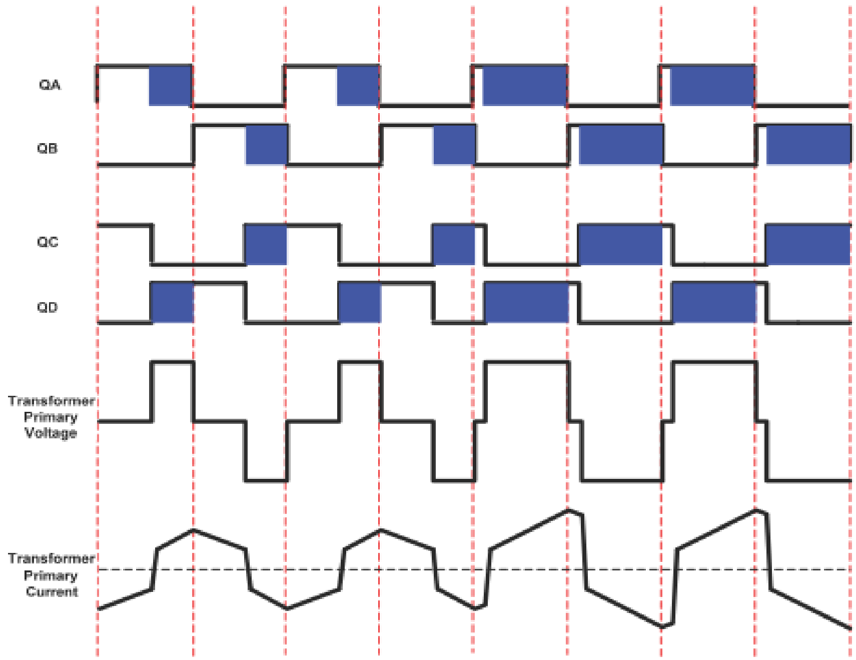
$$P_{SW(DIODE)} = 0.5 \times V_{REVERSE} \times I_{RR(PEAK)} \times t_{RR} \times f_S$$

MOSFET Loss →

$$P_{SW(MOSFET)} = 0.5 \times V_D \times I_D \times (t_{SW(ON)} + t_{SW(OFF)}) \times f_S$$

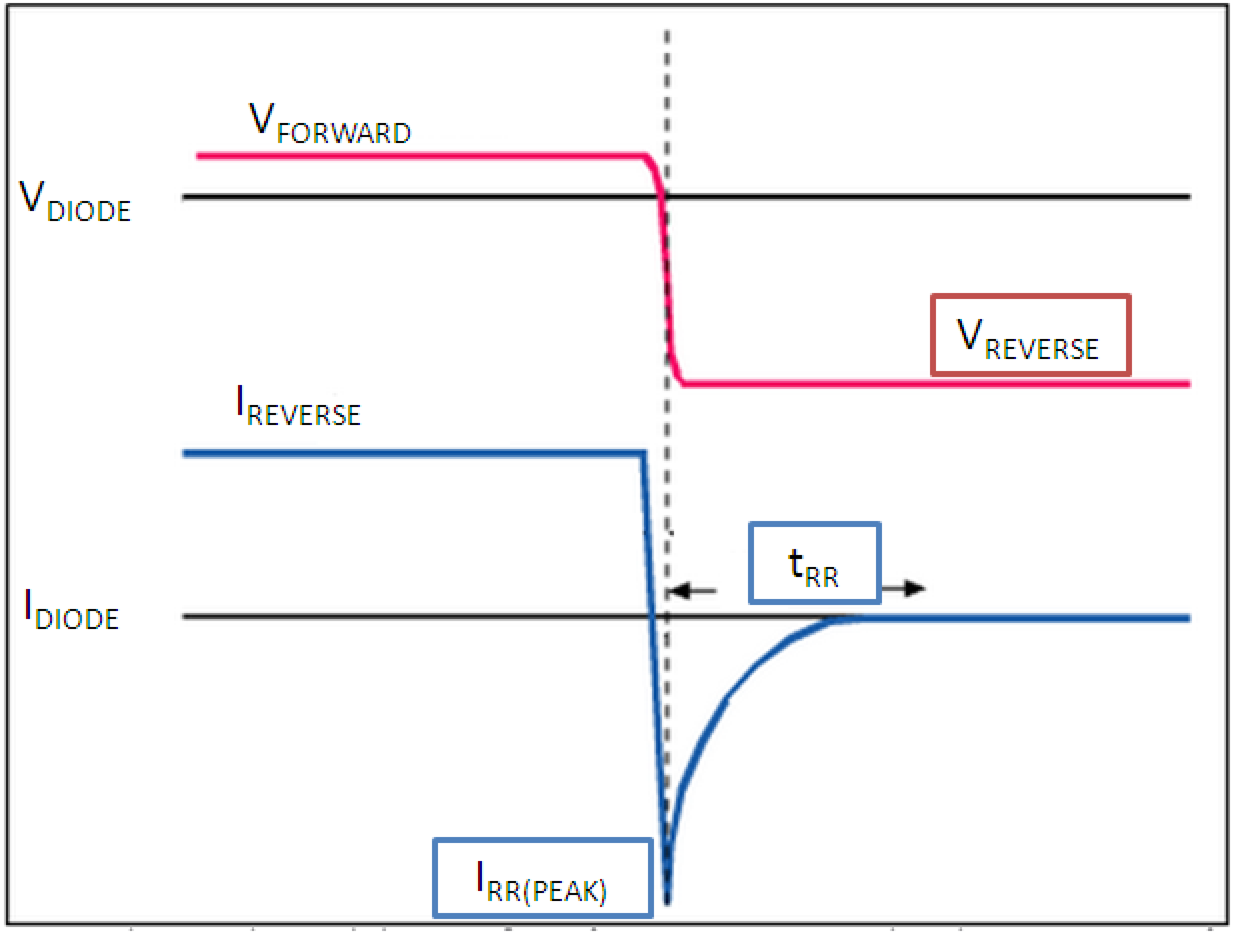
PWM(Pulse-width Modulation) Control





PSFB (Phase Shifted Full Bridge)
PWM waveform

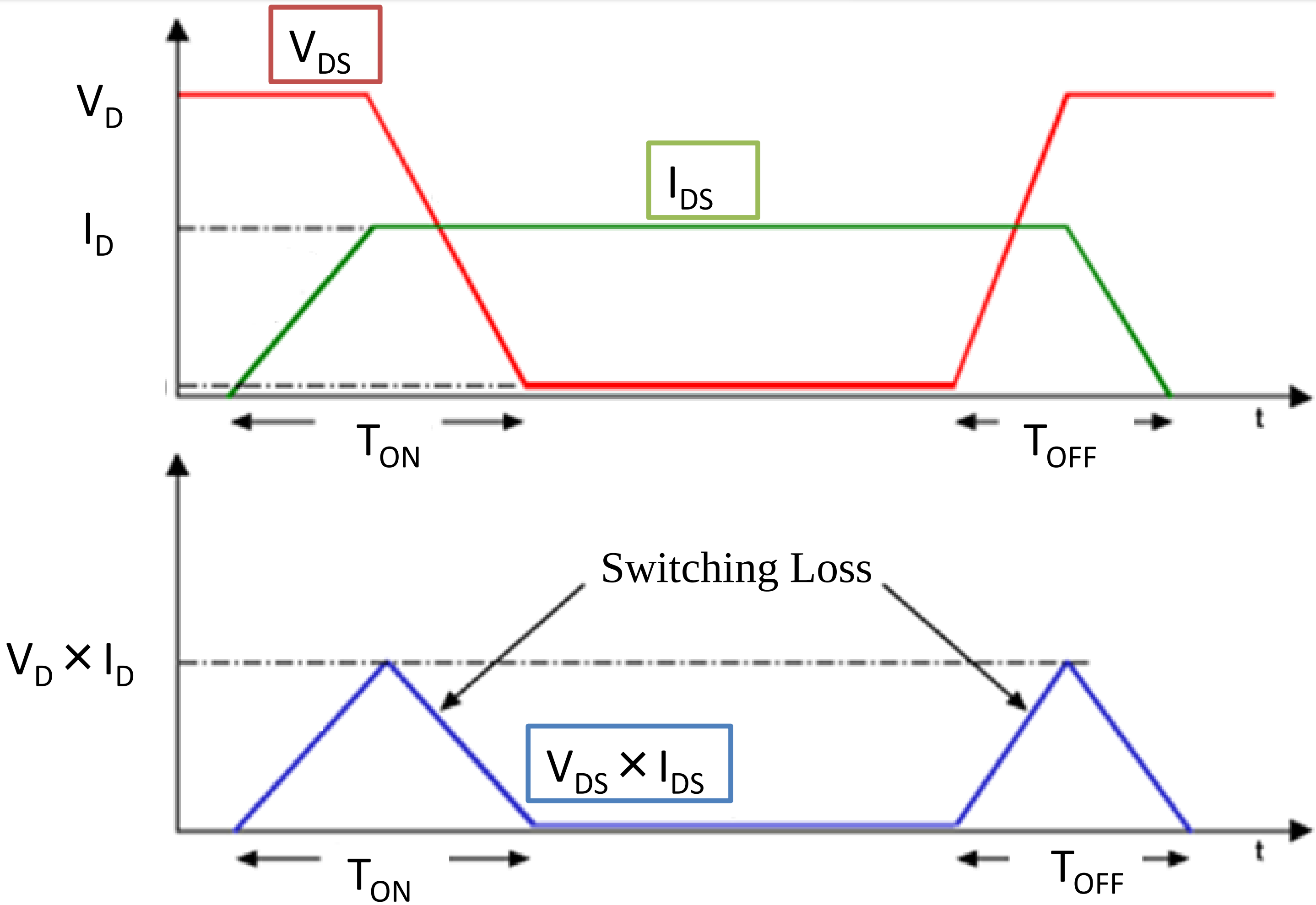
Diode Loss



Power Loss＝Reverse Voltage × Spike Current × Time Span × Frequency

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

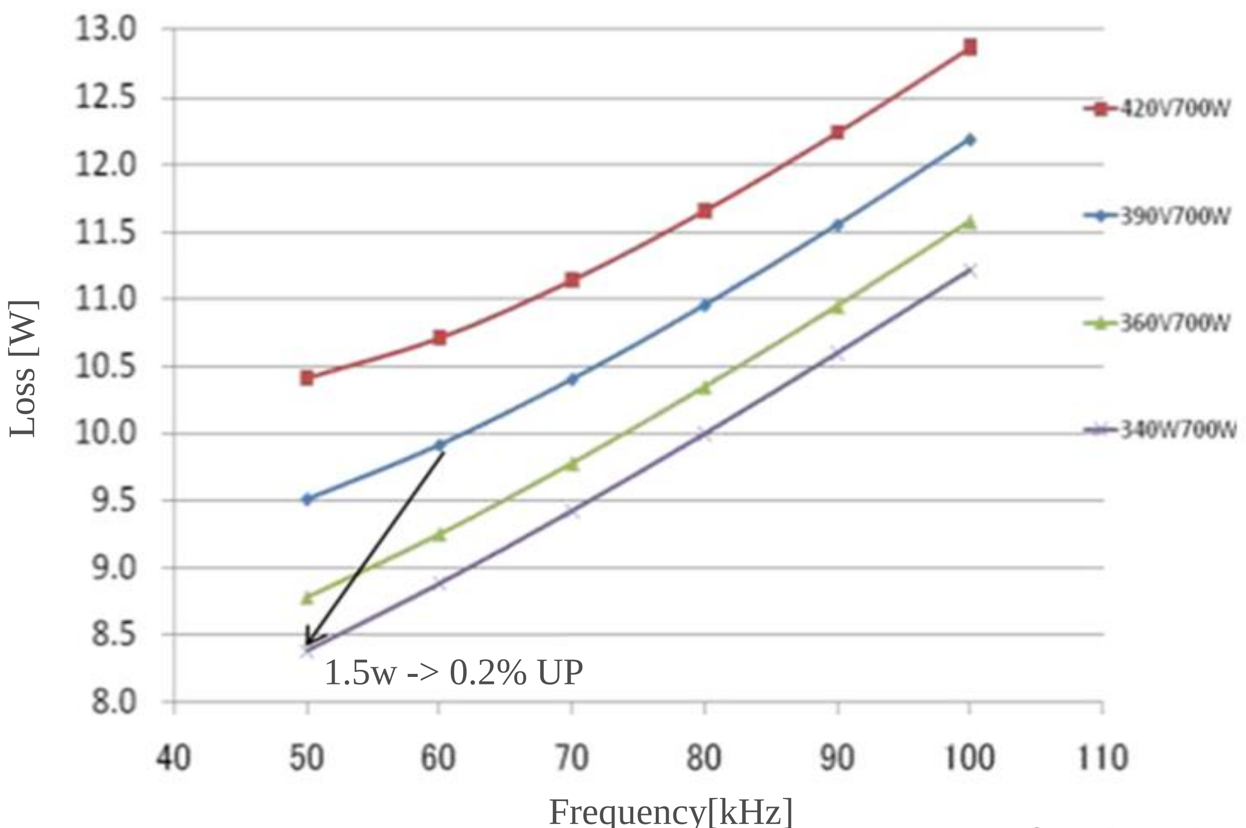
MOSFET Loss



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

$$P_{SW(MOSFET)} = 0.5 \times V_{DS} \times I_D \times (t_{SW(ON)} + t_{SW(0FF)}) \times f_S$$

Total Effect of Loss Mechanism ①+②



Courtesy of *Sanken Electric Co., Ltd.*

Energy efficiency downgrade of the PFC
on the account of these two main loss mechanism
(Reactor Loss + Diode Loss + MOSFET Loss).

Proposed Method

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)

Efficiency degradation

Proposed Method

[PFC]
- ●Variable link voltage
- ●PWM(variable frequency)

[DC/DC]
- ●PWM(variable frequency)

Circuit topology
Hardware

DSP digital control
Software

Research Approach

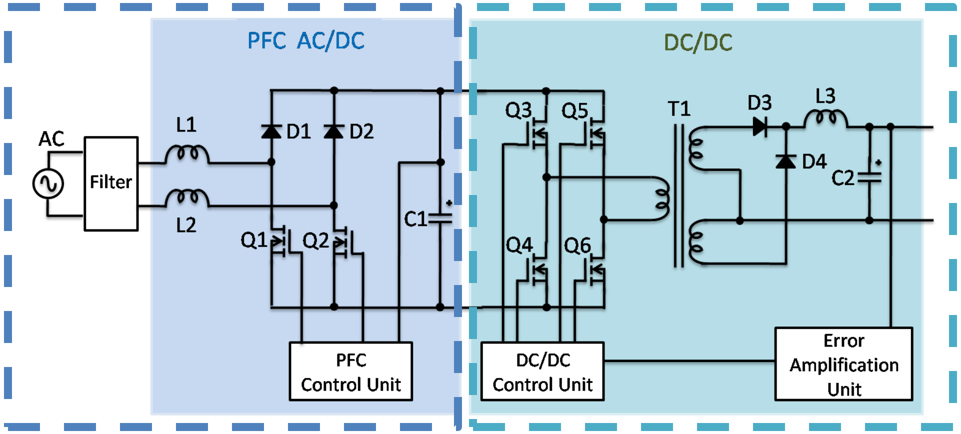
The experiment is conducted by a mean of two parts and three steps.

BLPFC AC/DC part (Bridgeless Power Factor Correction AC/DC)

- Step A: Load rate50% → Deal with **Link Voltage**
- Step B: Load rate10%~20% → Deal with **PWM Frequency**

PSFB DC/DC part (Phase Shift Full Bridge DC/DC)

- Step C: Load rate10%~20% → Deal with **PWM Frequency**



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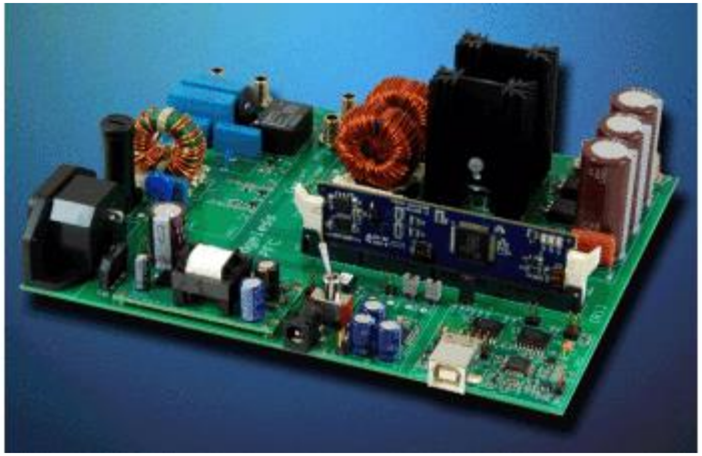
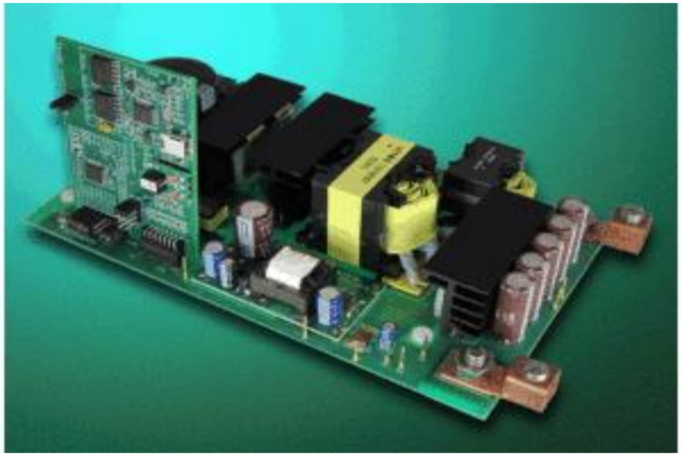
Experimental Environment

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



- 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.



- 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.

BL PFC (Bridgeless PFC) AC/DC Kit

- 400Vdc Output
- PWM frequency 200kHz

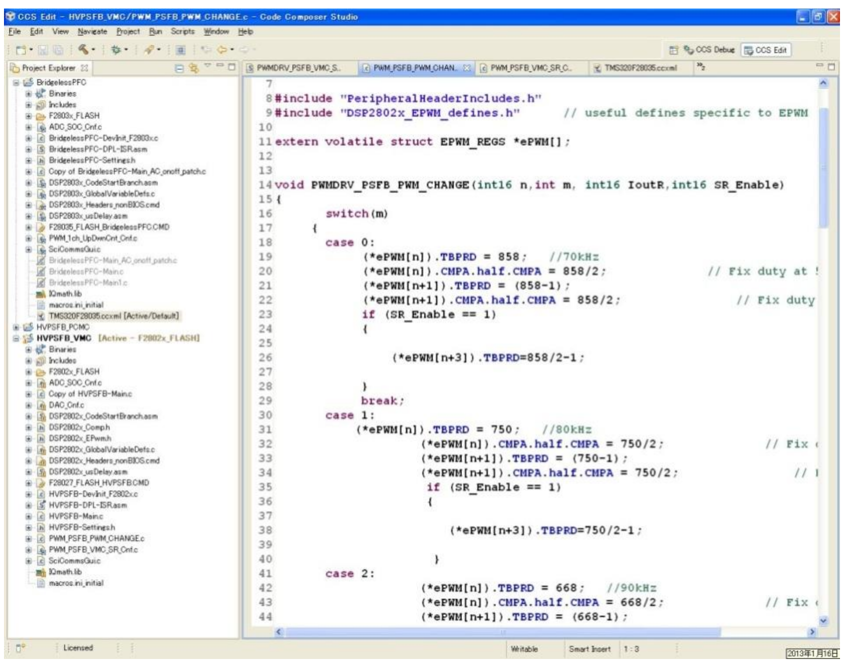
Link voltage

PSFB (Phase shifted Full Bridge) DC/DC Kit

- 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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Analysis of BLPFC AC/DC part ①

- Loss Mechanisms of Server Power Supply ①

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

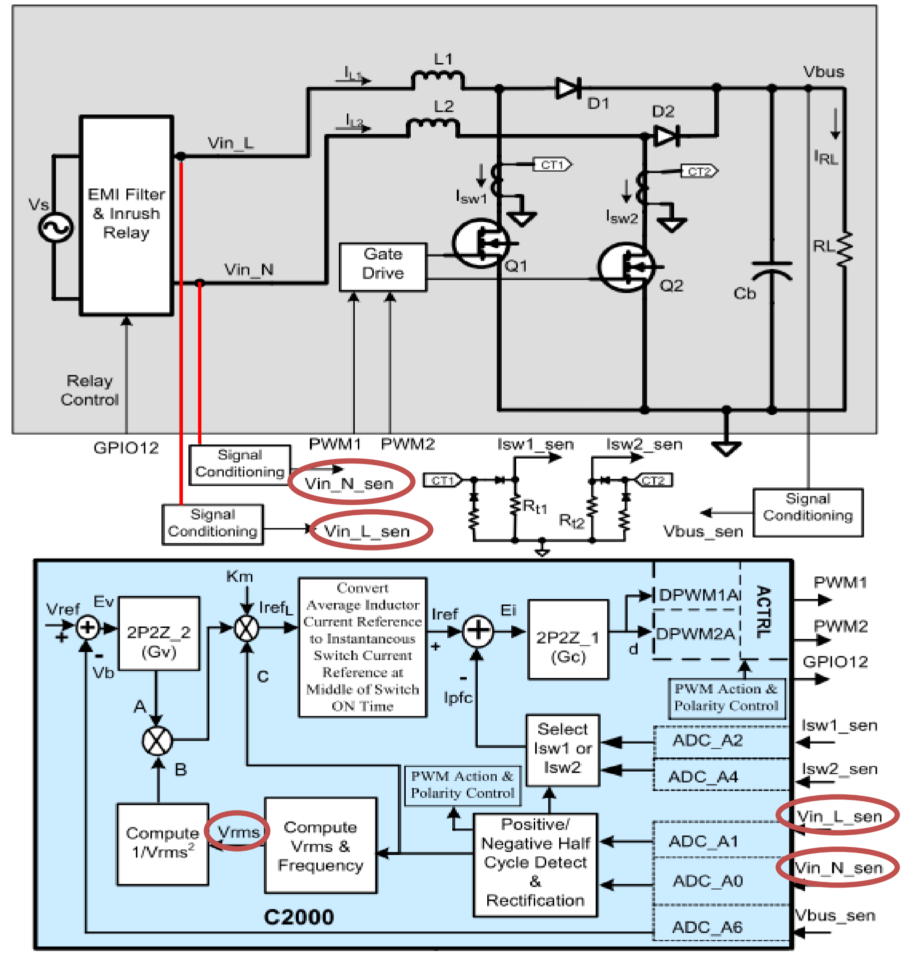
●By monitoring the **effective value of** input voltage and adjust the link voltage in a real-ti way.

Monitor the input voltage Vin_N ,Vin_L

Read into DSP

Evaluation of effective value V_{rms}

Link voltage: V_{out}= Optimum boost ratio × V_{rms}

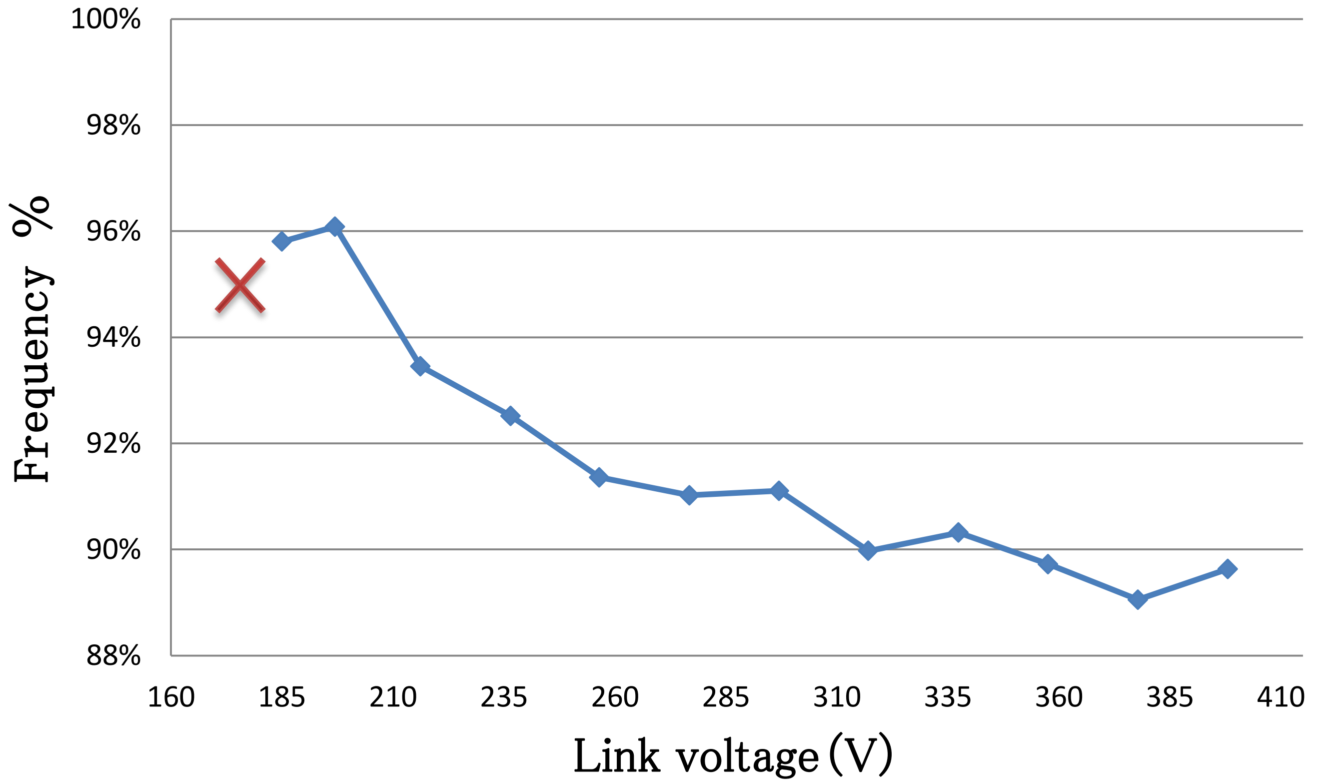


Experiment Results A:

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

Experiment environment

- AC input voltage Vin=100V
- Switching frequency is fixed at 200kHz
- Load rate 50% (150W output)



Unexpected problem occurs when link voltage is set down below 190V.

Appropriate link voltage is 200V if possible.

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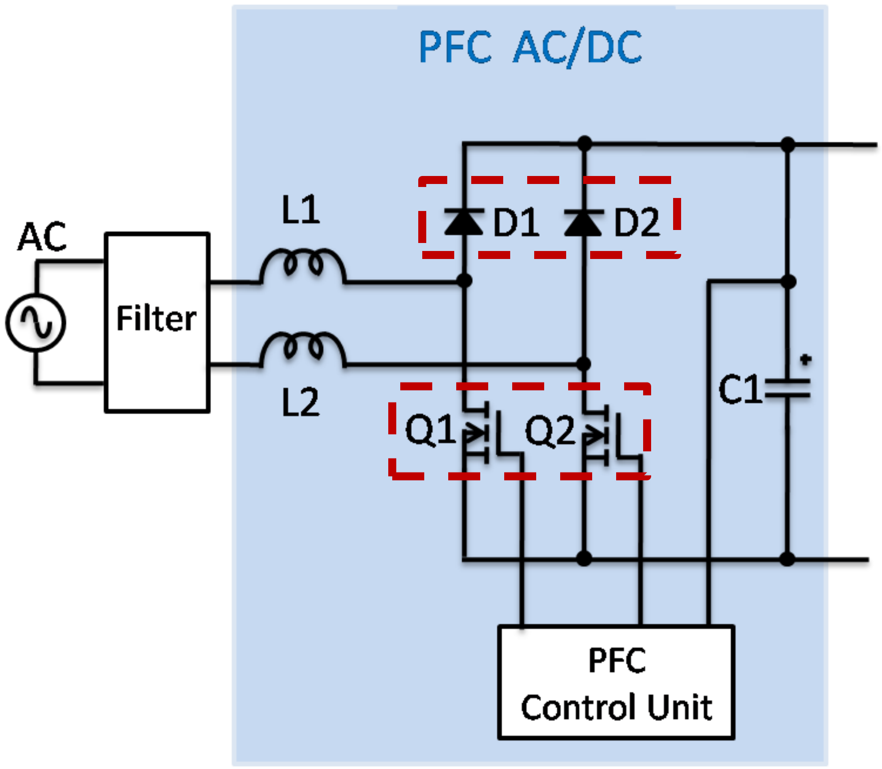


- Loss Mechanisms of Server Power Supply ②
  (Diode loss & MOSFET loss ∝ f)

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

Light load＋Fixed frequency

Light load＋Variable frequency

Proposed

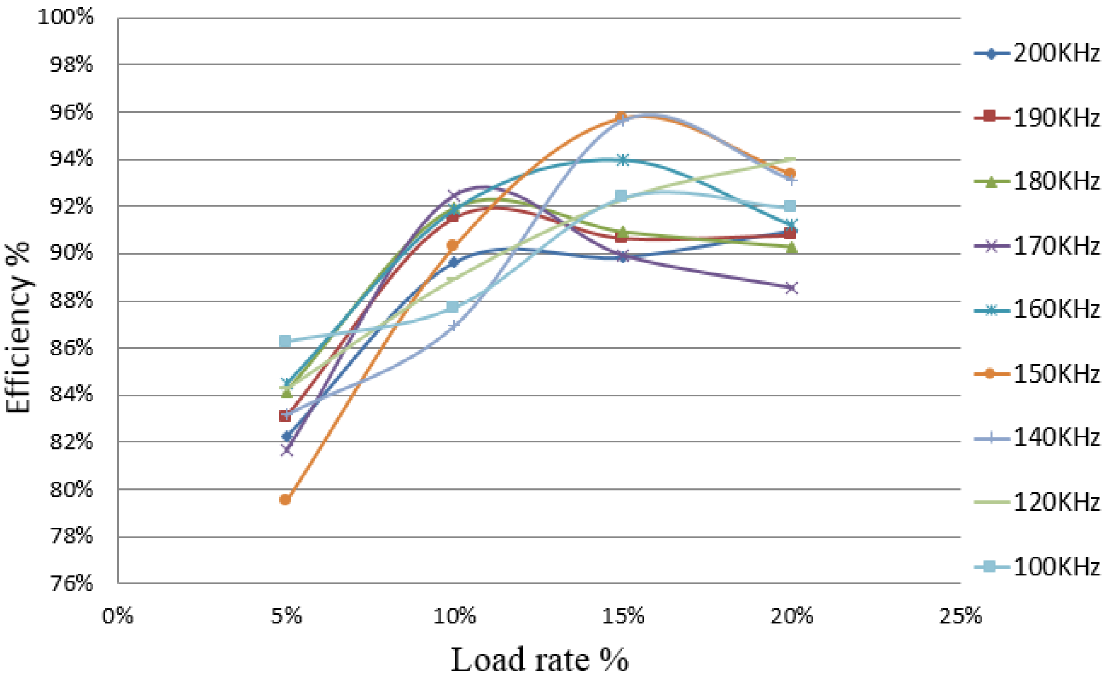
Experiment Results B:

Optimization of PWM Frequency of BLPFC AC/DC

at a Load Rate of 5% to 20%

Experiment environment

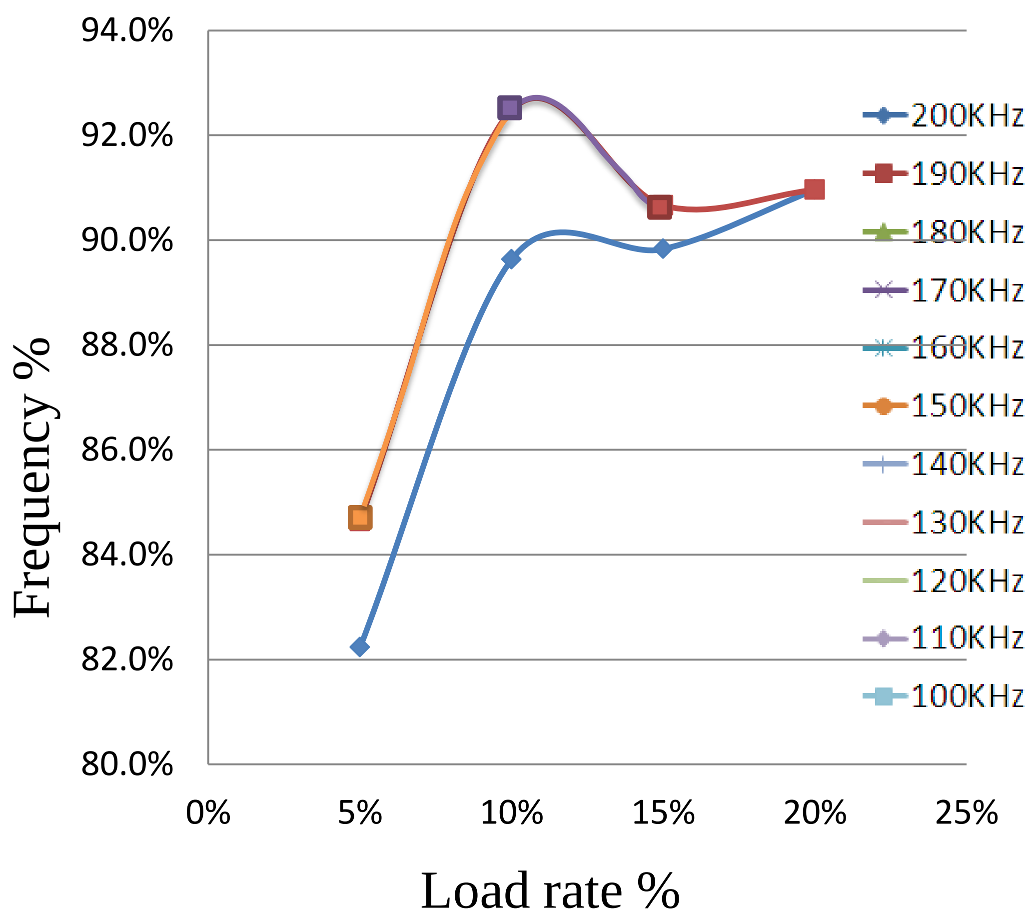
- AC input voltage Vin=100V
- Link voltage（PFC output voltage）is fixed at 400V



(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%



(b) Comparison of efficiency between 200kHz and optimum frequency.

Conventional fixed frequency 200kHz is not always efficient.

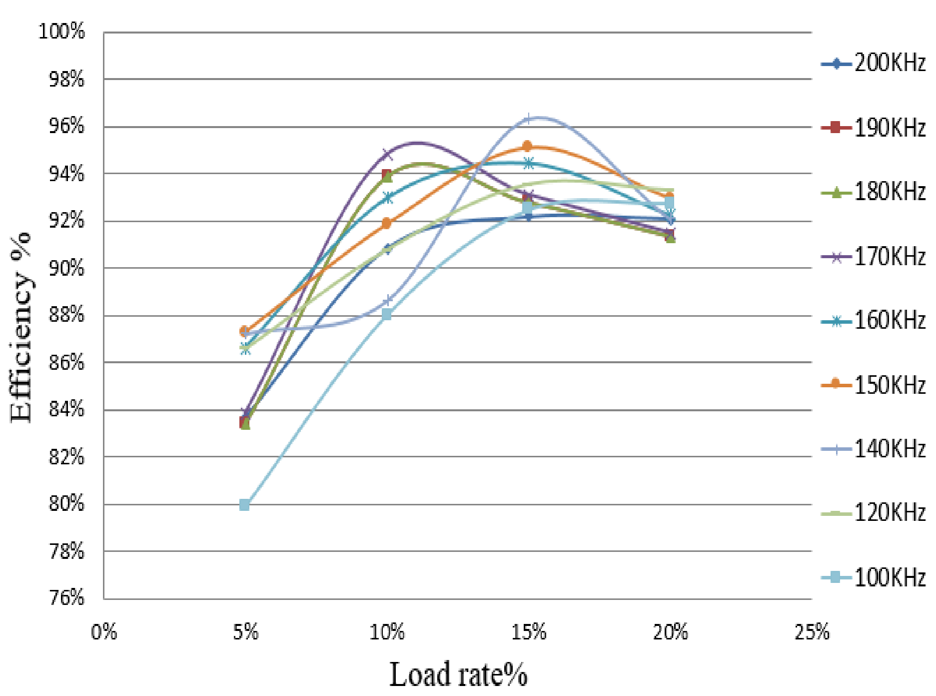
Load	Appropriate frequency
5%-10%	150kHz
10%-15%	170kHz
15%-20%	190kHz
20%～	200kHz

Experiment Results B:

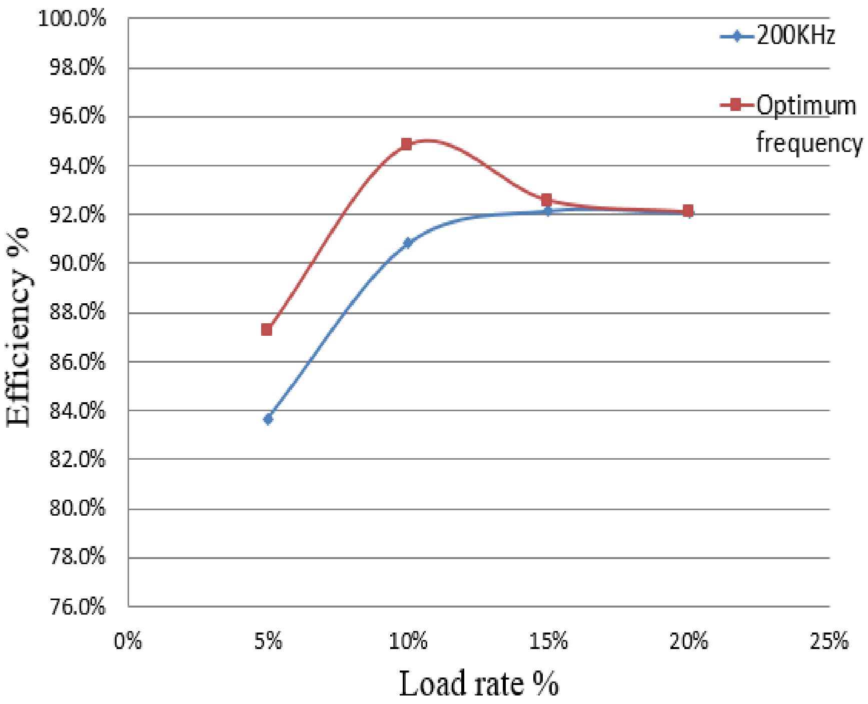
Optimization of PWM Frequency of BLPFC AC/DC at a Load Rate of 5% to 20%

Experiment environment

- AC input voltage Vin=100V
- Link voltage（PFC output voltage）is fixed at 350V



(a) Variation of efficiency according to frequency at 350V link voltage.



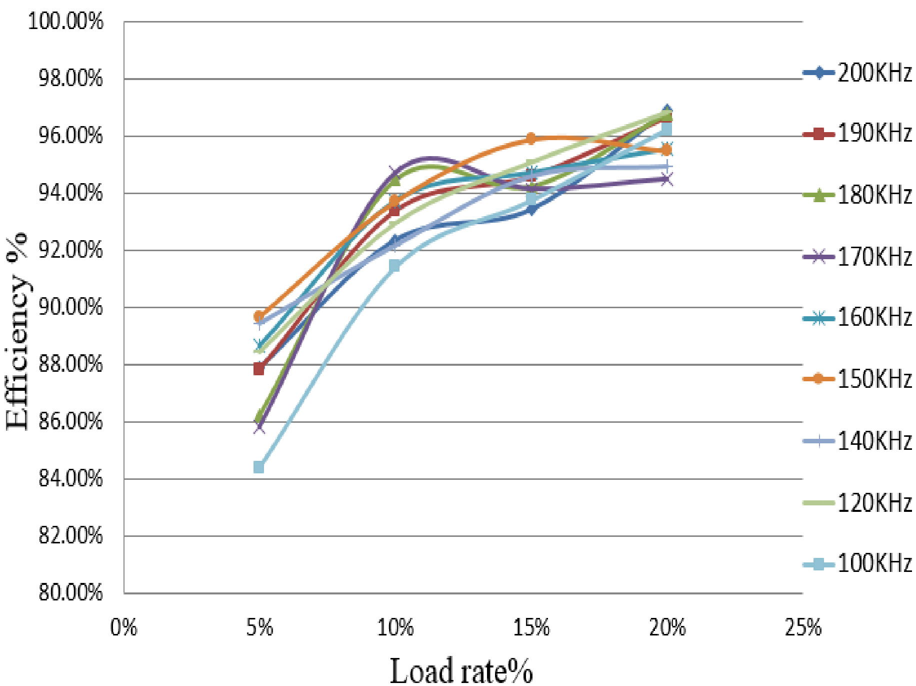
(b) Comparison of efficiency between 200kHz and optimum frequency.

Experiment Results B:

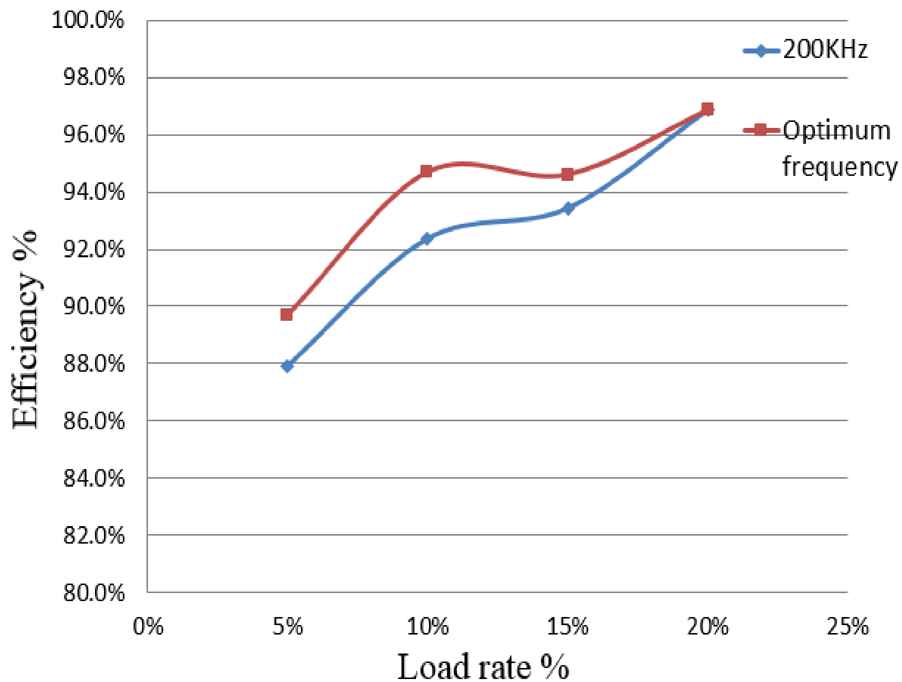
Optimization of PWM Frequency of BLPFC AC/DC at a Load Rate of 5% to 20%

Experiment environment

- AC input voltage Vin=100V
- Link voltage (PFC output voltage) is fixed at 300V



(a) Variation of efficiency according to frequency at 300V link voltage.



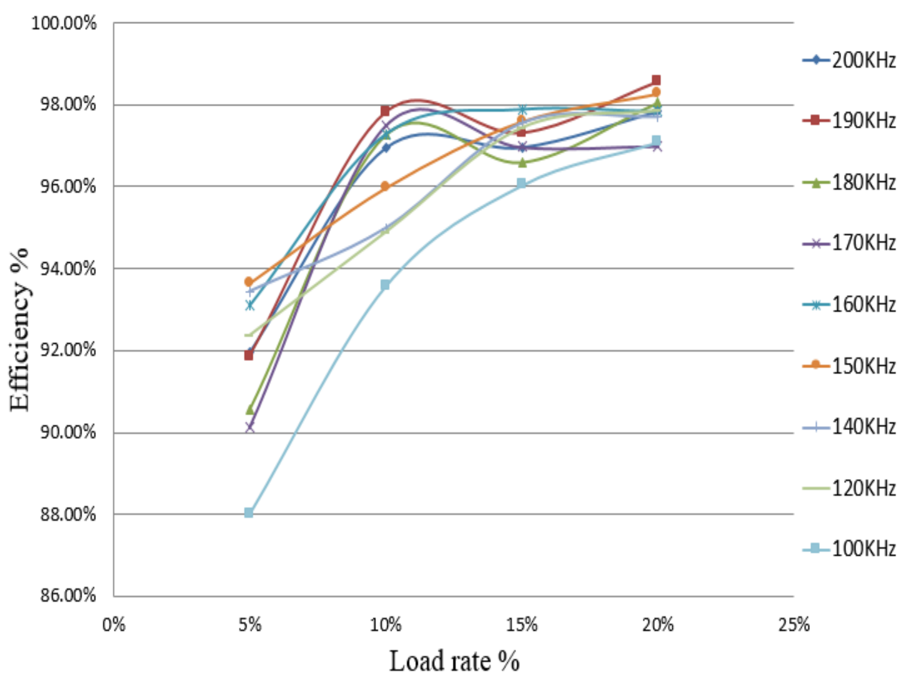
(b) Comparison of efficiency between 200kHz and optimum frequency.

Experiment Results B:

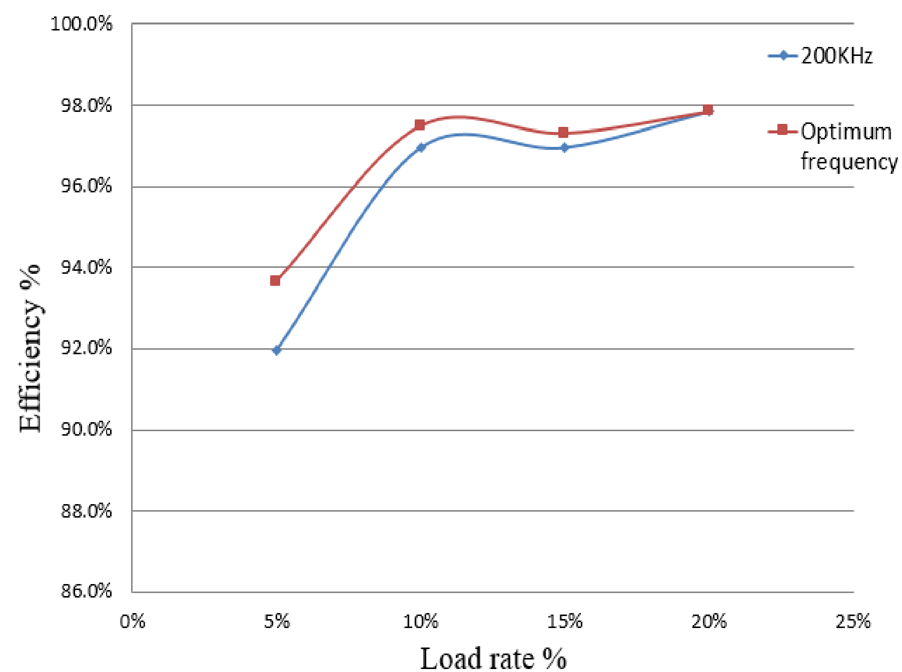
Optimization of PWM Frequency of BLPFC AC/DC at a Load Rate of 5% to 20%

Experiment environment

- AC input voltage Vin=100V
- Link voltage（PFC output voltage）is fixed at 250V



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



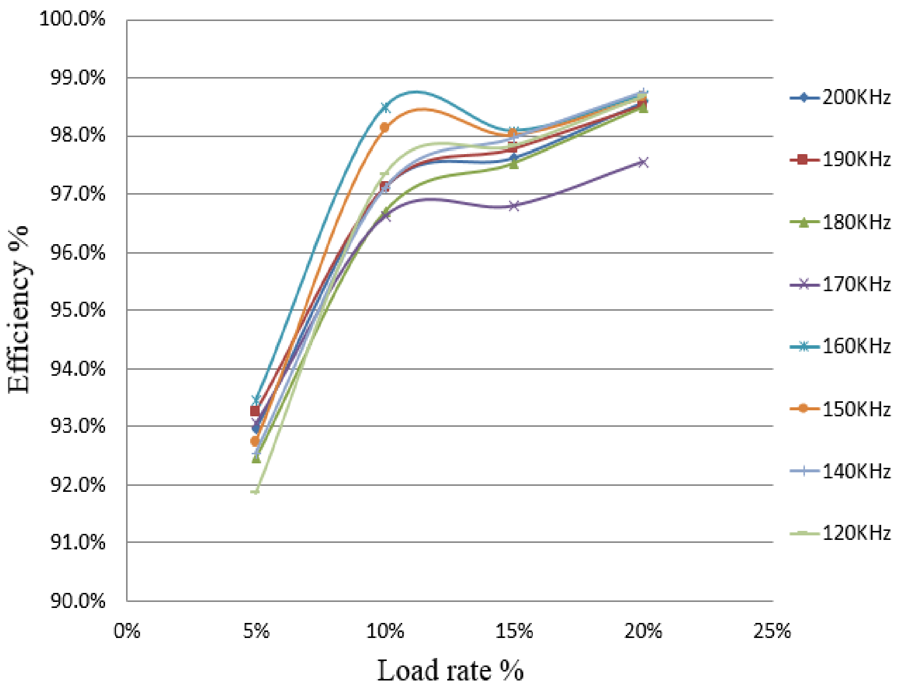
(b) Comparison of efficiency between 200kHz and optimum frequency.

Experiment Results B:

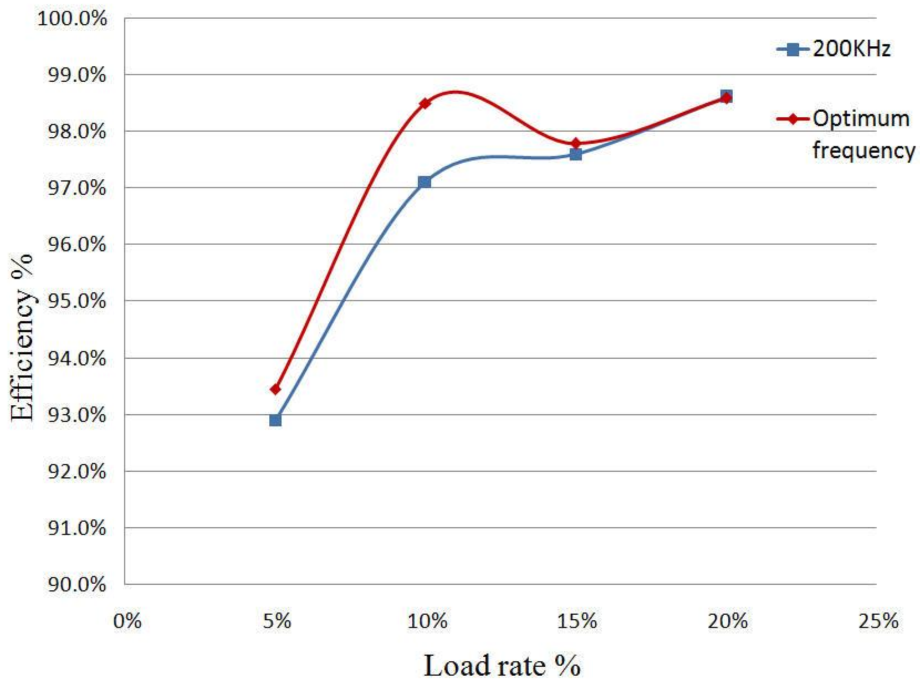
Optimization of PWM Frequency of BLPFC AC/DC at a Load Rate of 5% to 20%

Experiment environment

- AC input voltage Vin=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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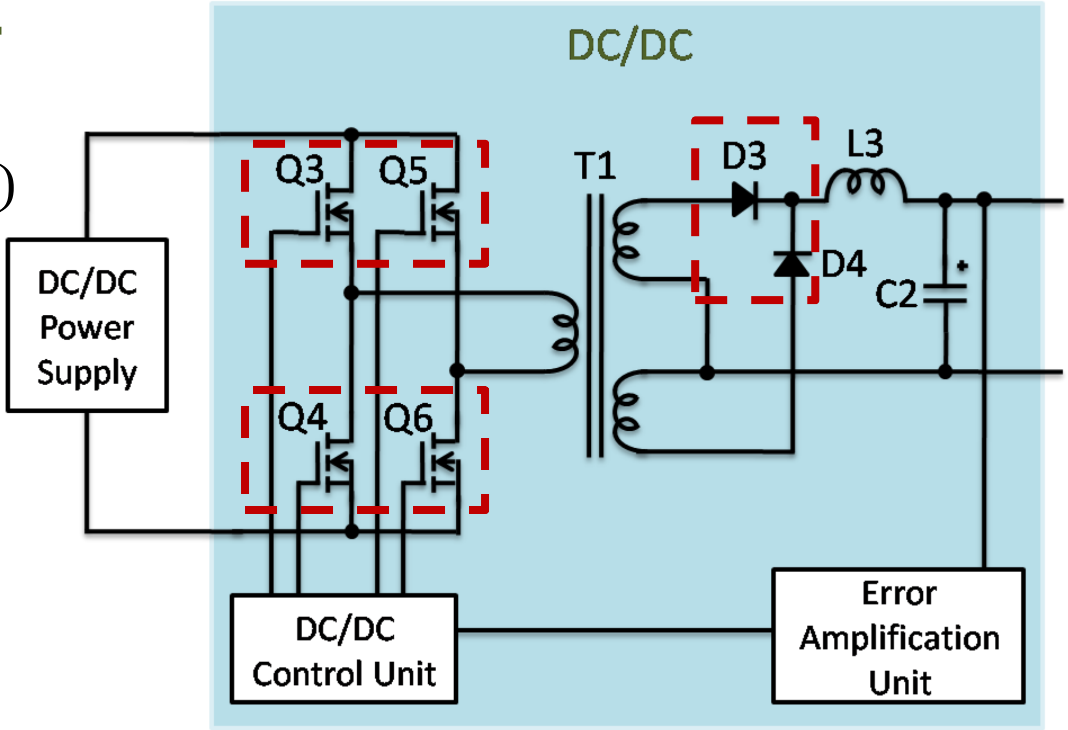
Analysis of PSFB DC/DC part

- Loss Mechanisms of Server Power Supply ②
  (Diode loss & MOSFET loss ∝ f)

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

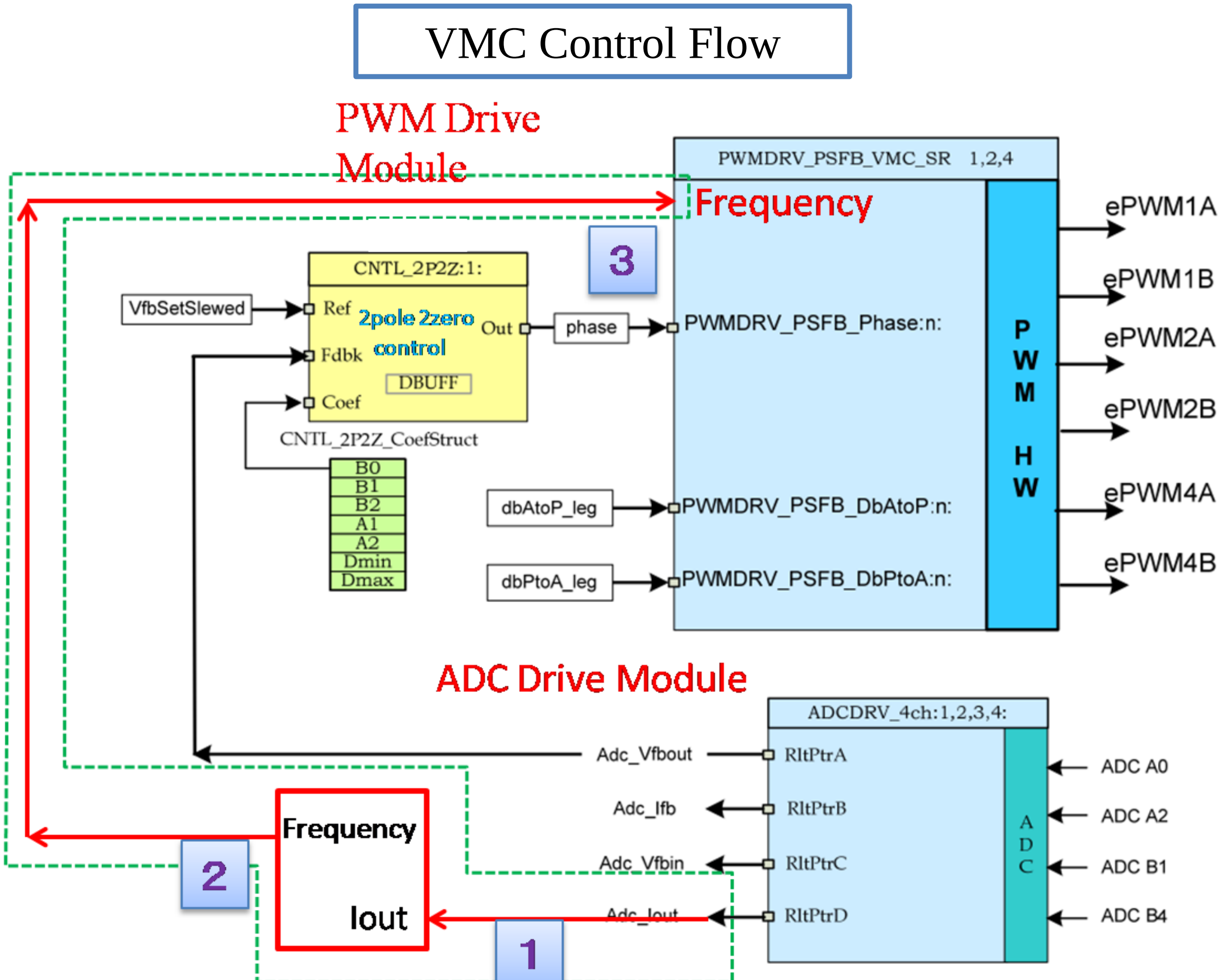


Light load＋Fixed frequency

Light load＋Variable frequency

Proposed

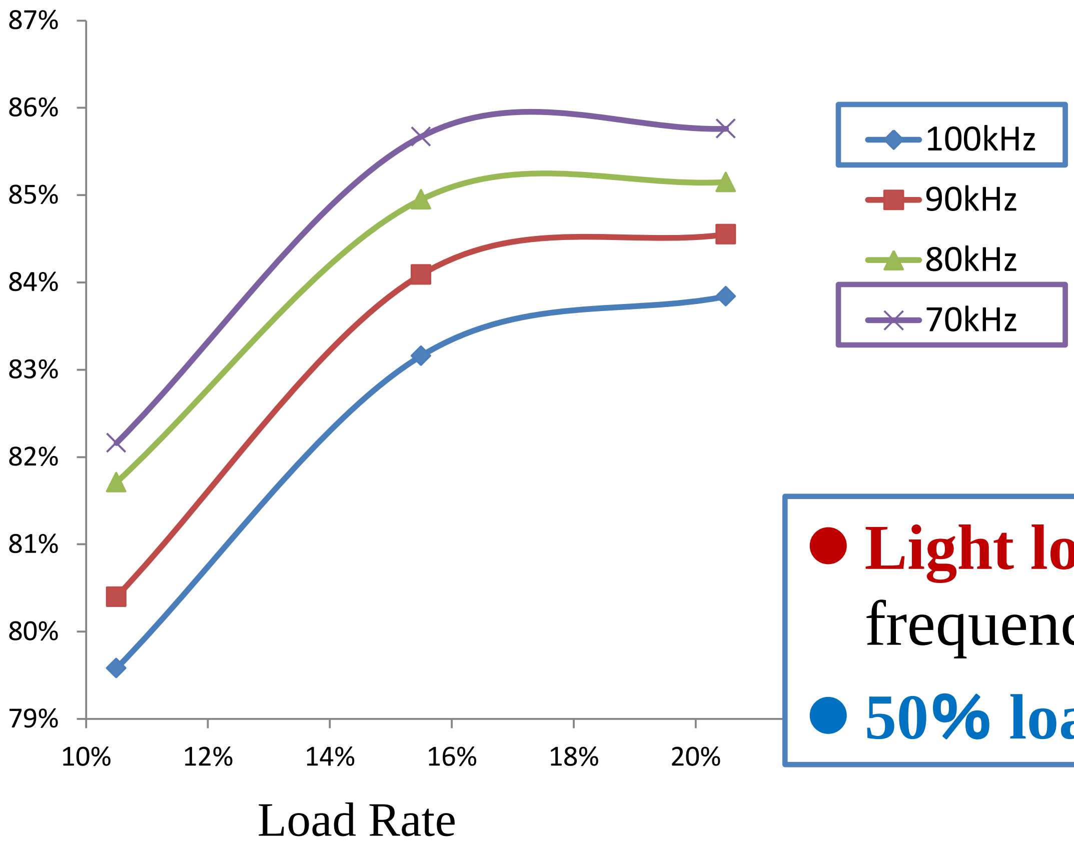
Analysis of PSFB DC/DC part



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%



Conventional fixed frequency 200kHz is not always efficient.

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

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Conclusion

What we have done:

Conventional	Proposed
High link voltage + **PWM of fixed frequency**	**Lower link voltage** (Low boost ratio) + **PWM of variable frequency** with Digital control

- **AC/DC variable link voltage:** **efficiency 6%↑** @50% load rate
- **AC/DC variable PWM frequency:** **efficiency 1~4%↑** @5%~20%load rate
- **DC/DC variable PWM frequency :** **efficiency 3~6%↑** @10%~ 20%load rate

Final goal:

Server Power supply（PFC AC/DC+DC/DC）

80 PLUS TITANIUM

% of Rated Load	10%	20%	50%	100%
TITANIUM	90%	94%	96%	91%

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.

Kobayashi
Laboratory

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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.