

# Development of Charging Modules for Railway Vehicle Batteries

JUSW 2026

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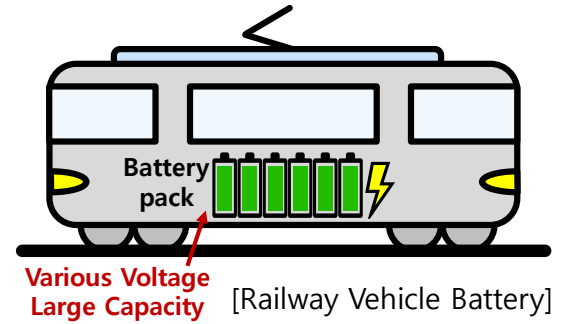
## Contents

1. **Charger Requirements and Topologies**
2. **Hardware Design and Control Technique**
3. **Prototype Experiments**
4. **Conclusion**



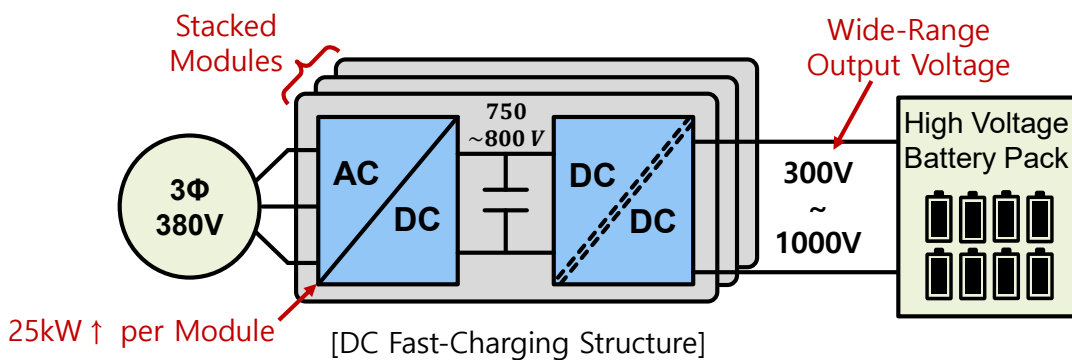
## □ Railway Battery

- Railway battery voltage varies depending on vehicle type, battery configuration and state of charge (SOC)
- A wide output voltage range is required for charging various battery packs
- High-power charging is required to reduce charging time for large-capacity batteries



## □ Structure of DC Fast Charging Modules

- 2-stage structure with a 3-phase AC/DC converter and an isolated DC/DC converter
  - AC/DC : Rectification, Voltage boosting, Power factor correction
  - DC/DC : Galvanic isolation, CC/CV charging control



# AC/DC Converter Topology

## □ AC/DC PFC Topology Comparison

	2-Level	3-Level NPC	3-Level Vienna	3-Level TNPC	3-Level ANPC
Current THD	High	Low	Low	Low	Low
Voltage stress	High	Low	Low	Low	Lowest
Power density	Low	Higher	High	High	Higher
Bidirectional	Yes	Yes	No	Yes	Yes
Efficiency	Low	High	High	High	Highest
Cost	Low	High	Mid	Mid	High
Control	Easy	Mid	Mid	Mid	Mild
Input inductor size	Large	Low	Low	Low	Low

[Topology comparison of AC/DC PFC]

- Compare with 2-level, the 3-level topology has lower THD and reduced voltage stress
- Considering the unidirectional power flow and cost, the 3-level Vienna topology was selected

## □ Isolated DC/DC Converter Topology Comparison

	LLC Converter	Phase-shifted Full Bridge (PSFB)	Dual Active Bridge (DAB)	DAB in CLLC Mode
Device stress	High	Mild Low	Lowest	High
Transformer KVA rating	High	Medium	Low	High
capacitor RMS currents	High	Medium	Low	High
Bidirectional	No	No	Yes	Yes
Conduction losses	High	Medium	Lowest	Medium
Turn ON switching loss	ZVS	ZVS	ZVS	ZVS
Turn OFF switching loss	Low	High	High	Low
Control complexity	Moderate	Very simple	Simple to complex	Moderate
Wide Battery Voltage Fixed Bus Voltage	No	Yes	Yes	No
Paralleling Modules	Intensive	Easy	Easy	Intensive
Switching Frequency	High	High	High	High

[Topology comparison of DC/DC converter]

- PSFB and DAB can achieve a wide output voltage range through simple phase-shift control
- The PSFB was selected because it is a unidirectional topology and suitable for paralleling multiple modules

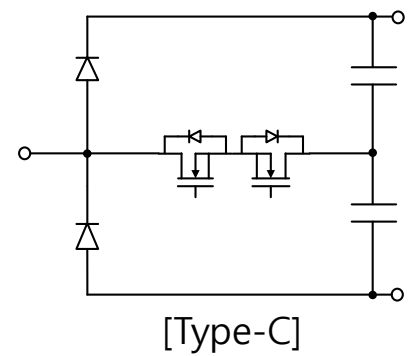
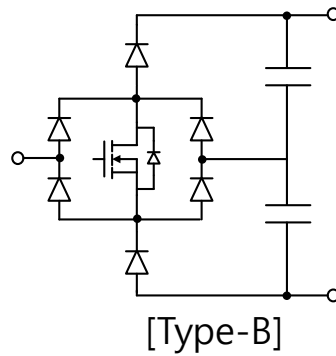
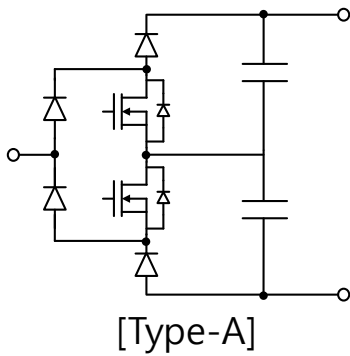


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## Types of 3-Level Vienna (1-Phase)



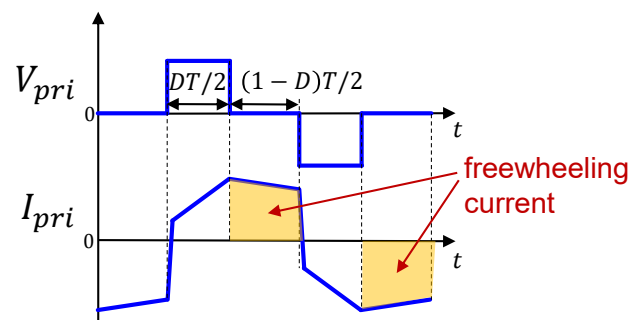
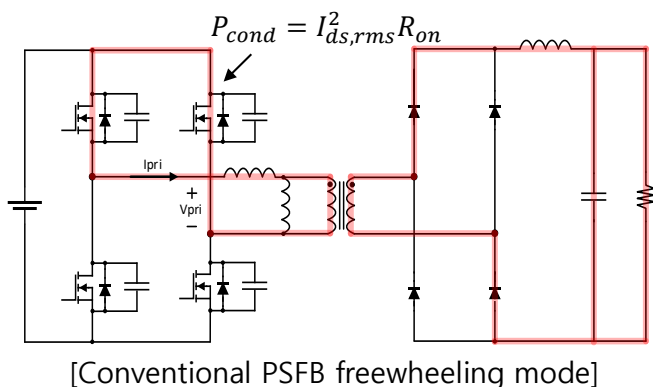
	Type-A	Type-B	Type-C
# of diode	4	6	2
# of MOSFET	2	1	2
for 800V dc-link			
Diode maximum voltage	400	400	800
MOSFET maximum voltage	400	400	400

- Type-C achieves the highest efficiency due to the lowest diode conduction loss
  - Efficiency : C > A > B
  - Cost : C > A > B

# Hardware Design of DC/DC PSFB Converter

## Conduction Loss Issue Caused by Primary-Side Circulating Current

- For low output voltage operation, a small duty ratio ( $D$ ) is required, which increases conduction loss due to the large circulating current.



## Improvement Method

- Current sharing using a primary-side parallel structure

- The total switch conduction loss is reduced to approximately half

$$\begin{array}{ccc}
 \text{[Conventional]} & & \text{[Parallel structure]} \\
 P_{cond} = 4 \times I_{ds,rms}^2 R_{on} & \xrightarrow{\times 1/2} & P_{cond} = 8 \times \left( \frac{I_{ds,rms}}{2} \right)^2 R_{on}
 \end{array}$$

## High Voltage Stress Issue on Secondary-Side Diodes

High peak voltage occurs due to resonance between the transformer leakage inductance and the junction capacitance of the rectifier diodes

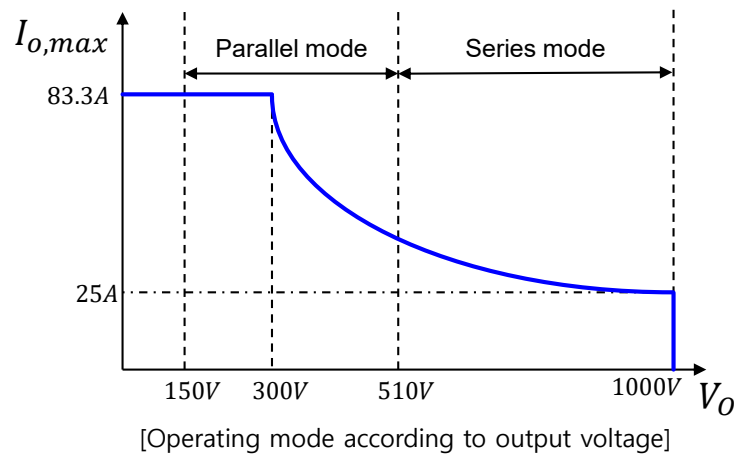
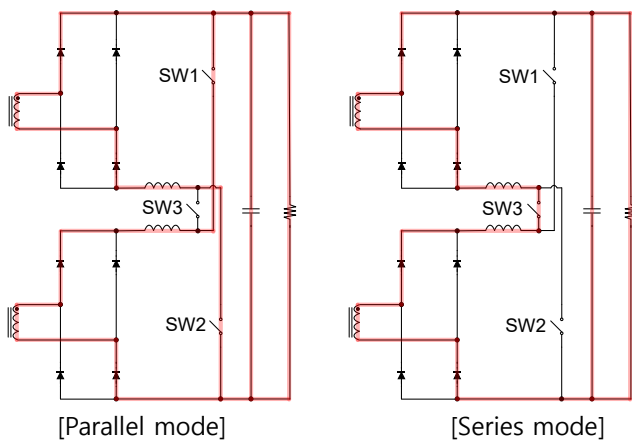
- Peak voltage:  $V_{DR,peak} = 2 \times \frac{N_s}{N_p} \times V_{dc}$

- Ex.)  $V_{dc} = 800[V]$ ,  $\frac{N_s}{N_p} = \frac{10}{7}$  (for maximum 1000V output)  $\rightarrow V_{DR,peak} = 2286[V]$

## Improvement Method

Wide output voltage operation is achieved through secondary-side series/parallel mode change

Redesign the transformer turns ratio:  $\frac{N_s}{N_p} = \frac{5}{7} \rightarrow V_{DR,peak} = 1143[V]$ , 1200V diodes can be used



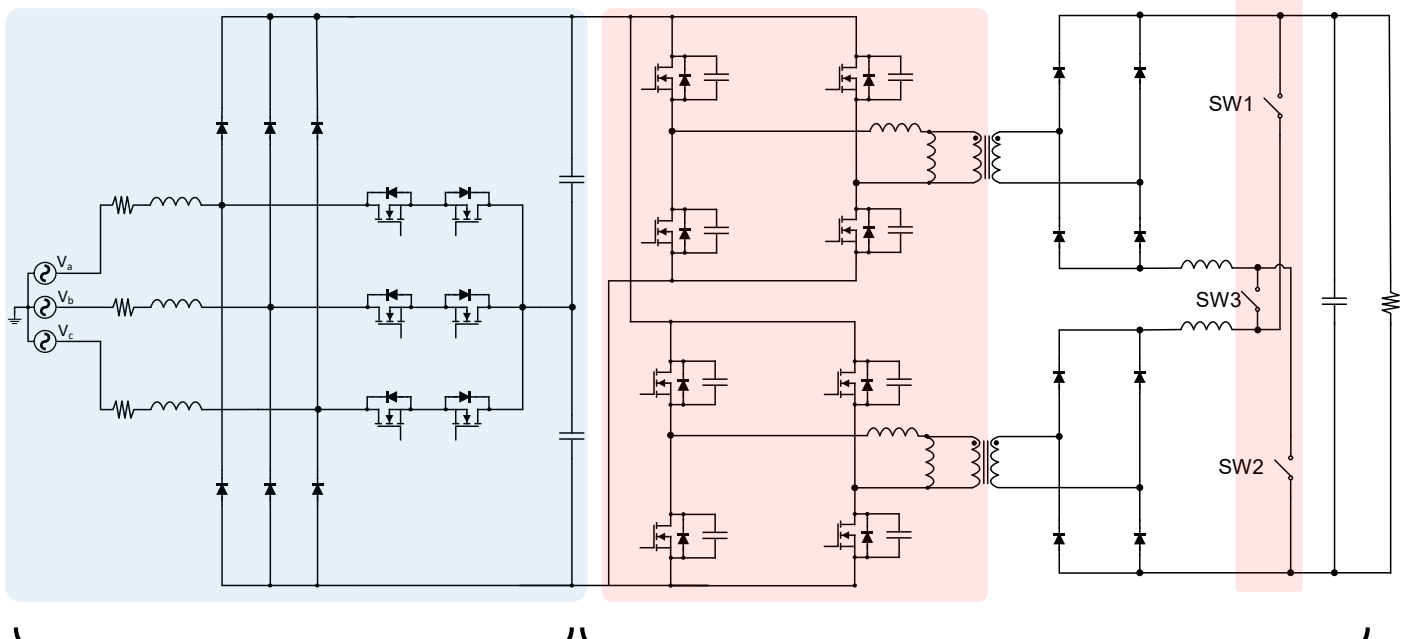
# Hardware Design

## Proposed Circuit of 25kW Charging Module

3-phase 3-level Vienna rectifier

Primary-side parallel structure

Switches for secondary-side series/parallel mode change

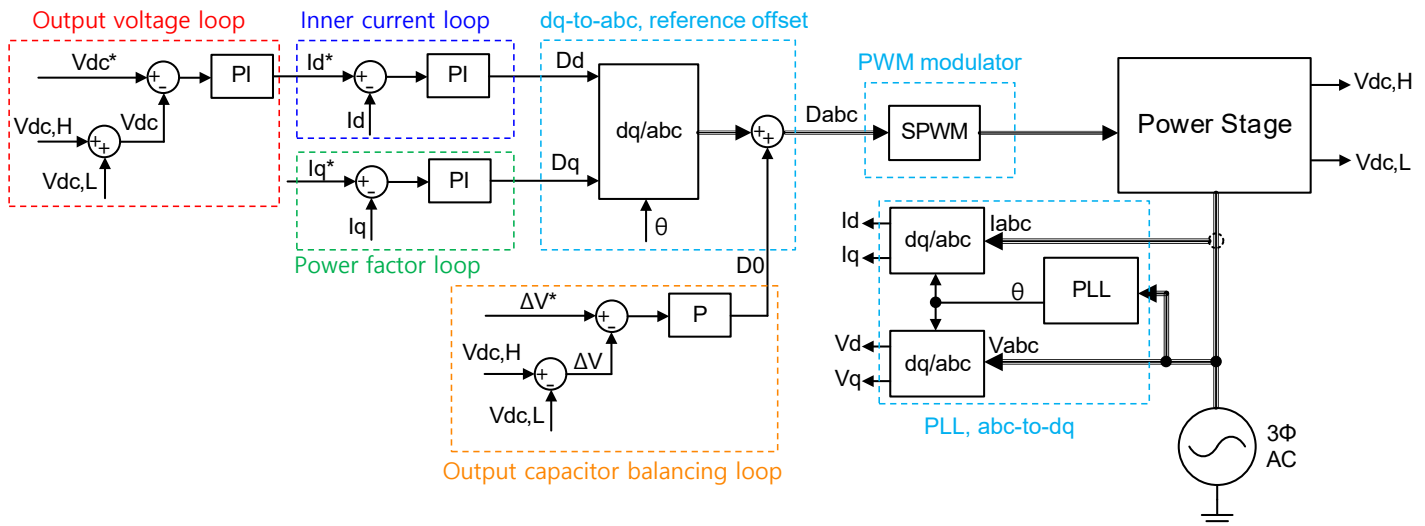


AC/DC side  
3ph 3-level Vienna Rectifier

DC/DC side  
Input parallel, output series/parallel PSFB

## 3-Phase Vienna Rectifier Control Structure

- DQ synchronous reference frame control
- Phase Locked Loop (PLL) : Detects the phase angle of the three-phase grid voltage
- Output voltage and input current control loops
- Power factor control loop ( $I_q^*=0$ )
- Output capacitor voltage balancing loop ( $\Delta V^*=0$ )
- PWM modulator: Converts duty references into switch gate signals

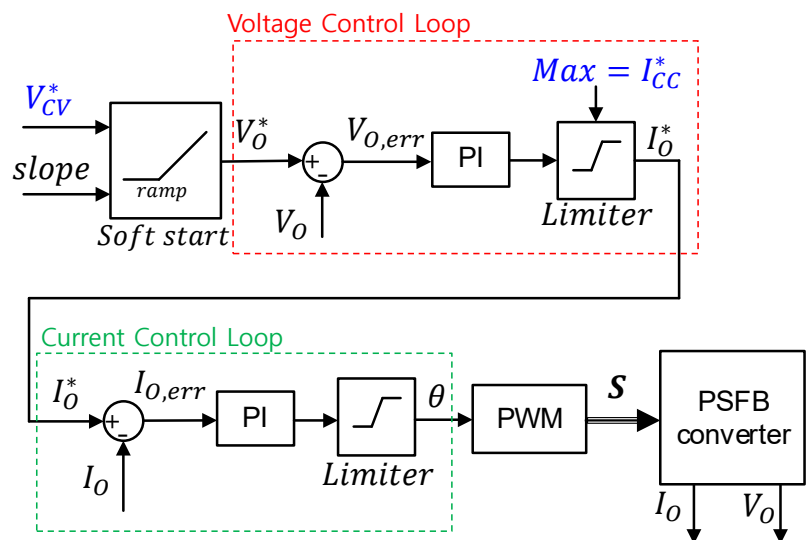
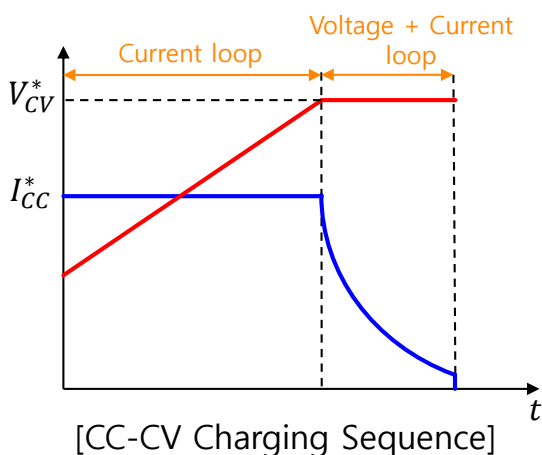


[Control Block Diagram of Three-Phase Vienna Rectifier]

# Control of DC/DC PSFB Converter

## PSFB Converter Control Structure

- Dual-loop PI control structure for output voltage and current control
- Voltage reference ( $V_{cv}^*$ ) is set to the target battery voltage for CV charging
- Inrush current is minimized through soft-start during initial startup
- During CC charging, the voltage controller output is limited by the limiter  $\rightarrow I_o^* = I_{cc}^*$
- When the battery voltage ( $V_o$ ) reaches the voltage reference ( $V_o^*$ ), CV charging is performed
- The controller output is the phase-shift angle ( $\theta$ )



[Control Block Diagram of PSFB Converter]

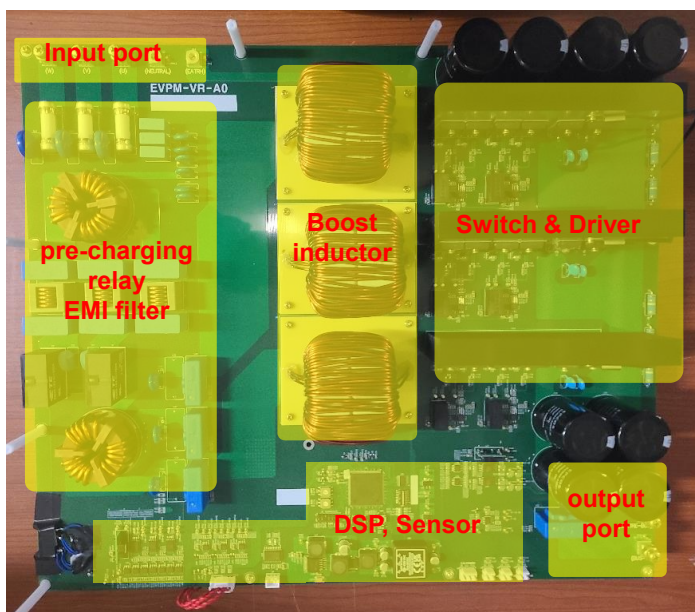
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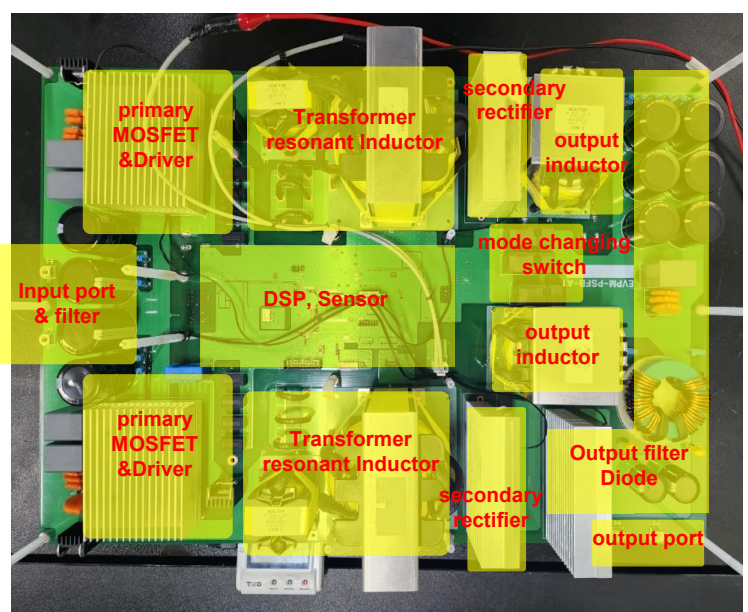


## Prototype Hardware

### □ Implemented Prototype Hardware

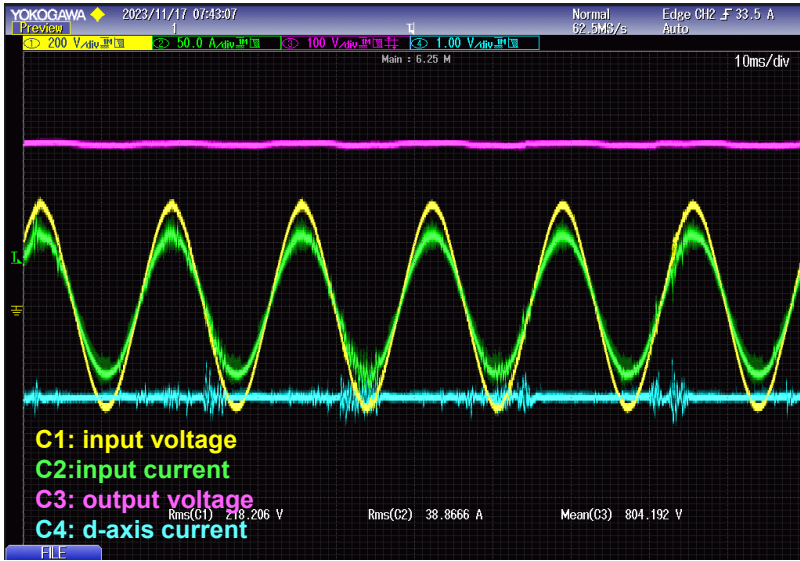


[25kW AC/DC Vienna Rectifier]



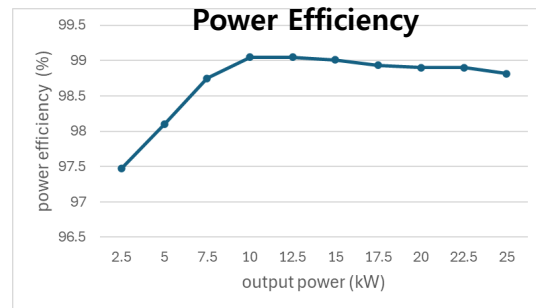
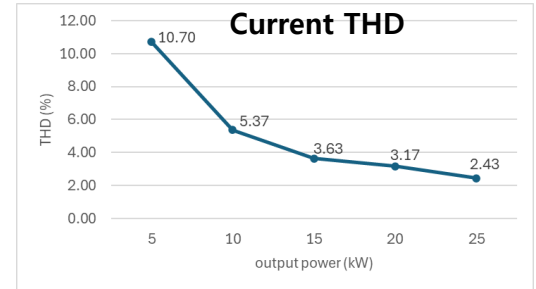
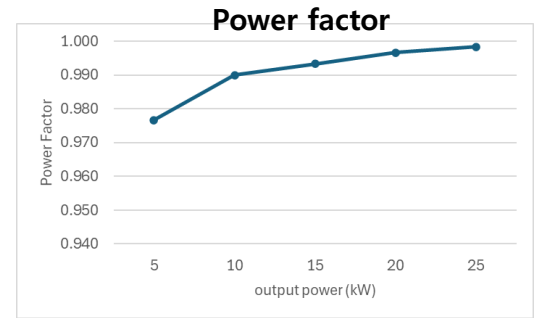
[25kW DC/DC PSFB Converter]

## Operation Test of 3-Phase Vienna Rectifier



[25kW operating waveforms]

- Power factor: Over 0.99 at loads above 10 kW
- Current THD: 2.43% at 25 kW
- Efficiency: Maximum efficiency over 99%

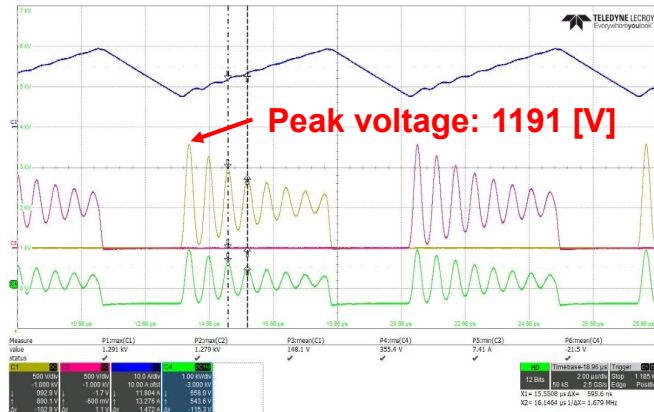


# Experimental Results of DC/DC PSFB Converter

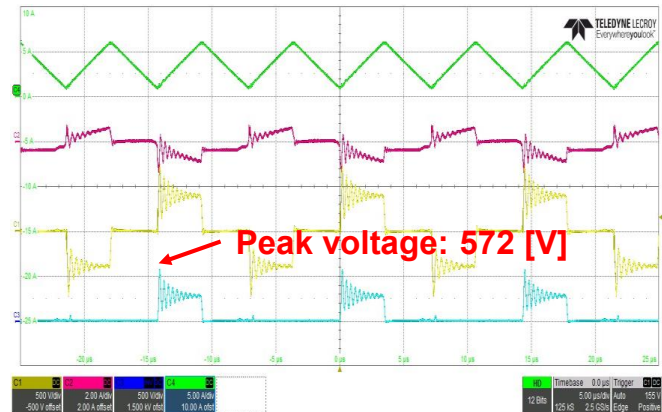
## Comparison of Secondary-Side Rectifier Diode Peak Voltage

- Compared with a conventional PSFB converter under an input voltage of 400 V

[Conventional PSFB]  $\frac{n_s}{n_p} = \frac{10}{7}$

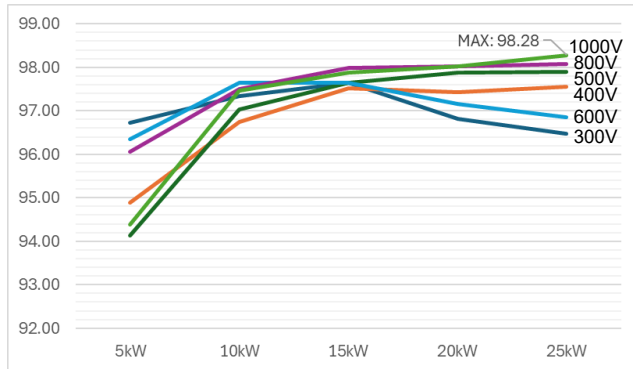


[Proposed PSFB]  $\frac{n_s}{n_p} = \frac{5}{7}$

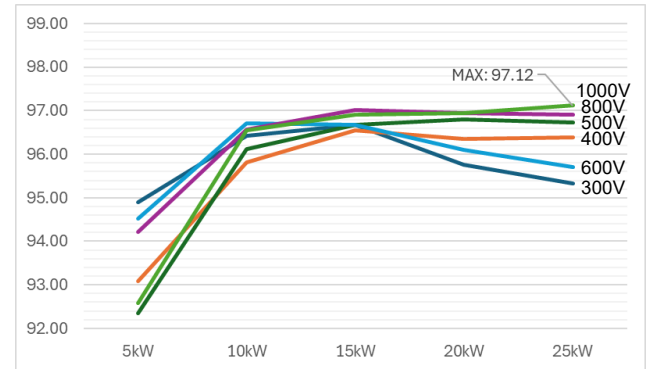


- The peak voltage is reduced by approximately 52% in the proposed PSFB converter

## □ Power Efficiency According to Output Voltage and Output Power



[DC/DC Converter Efficiency]



[Overall Efficiency of AC/DC + DC/DC Converter]

- A maximum overall efficiency of 97.12% was achieved at 1000 V and 25 kW output



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## ❑ Proposed 25 kW Fast-Charging Module

- The primary side of the PSFB converter was designed with a parallel structure to reduce conduction loss caused by circulating current.
- The secondary side of the PSFB converter was designed with a series/parallel mode-change structure to achieve a wide output voltage range efficiently.
- The AC/DC converter achieved a maximum efficiency of over 99%, and the DC/DC converter achieved a maximum efficiency of 98.28%.
  - A maximum overall efficiency of 97.12% was achieved.



# Thank you

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