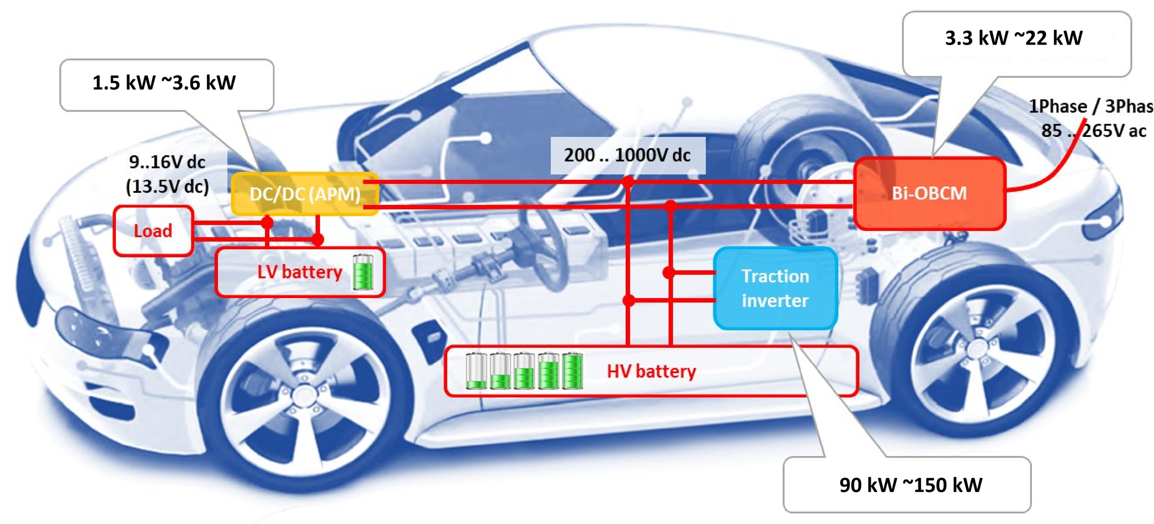
GaN-based High Frequency and High-power Density 2-in-1 Bidirectional OBCM Design for EV Application

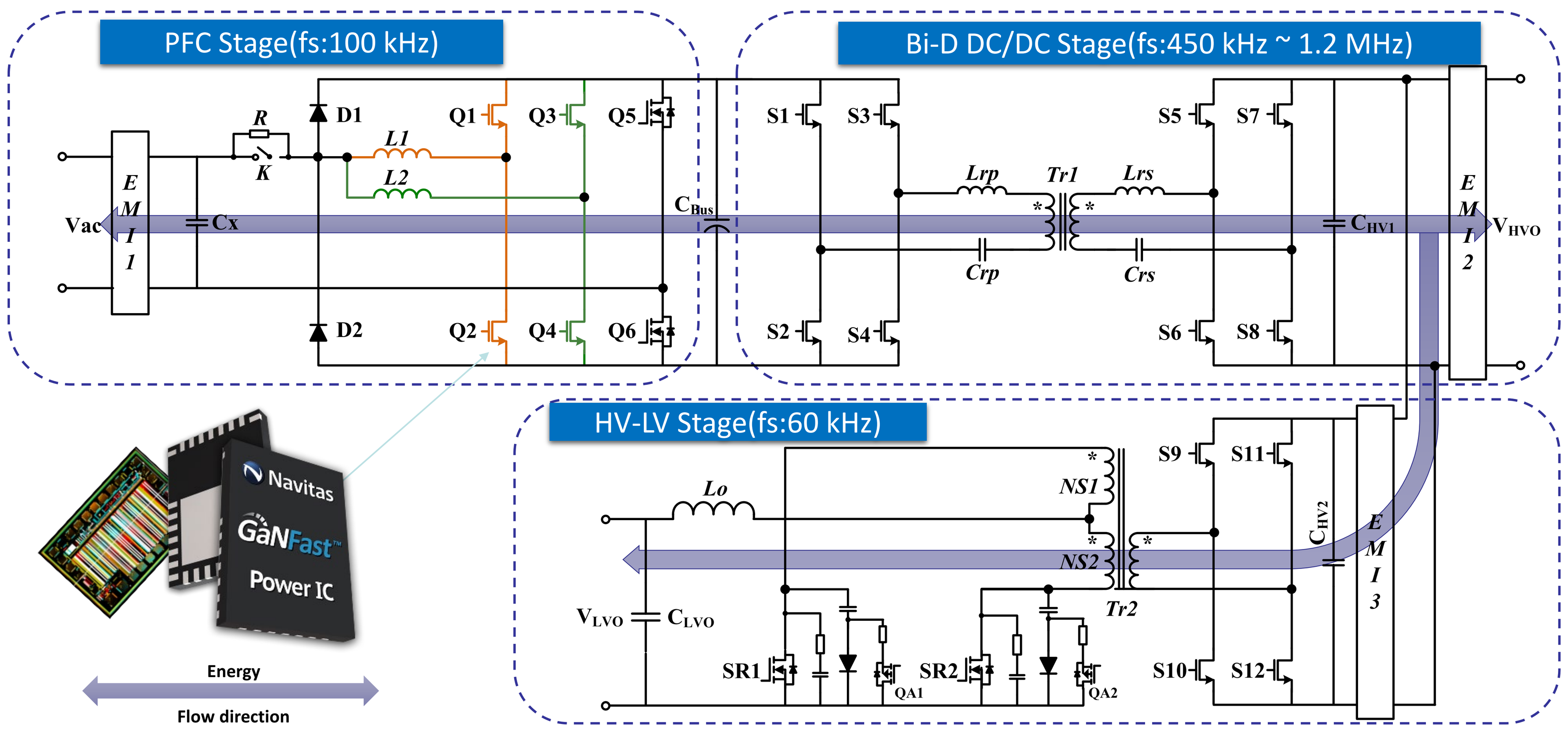
Minli Jia, Hao Sun
Navitas Semiconductor Shanghai EV Design Center, Shanghai, China

Introduction

- The integrated design of OBC and LV DC/DC can reduce the system size, improve the power density and reduce the cost.
- Wide-band gap semiconductor device GaN brings an opportunity to further improve the power density of Power-Supply-Unit in EV.



System Topology



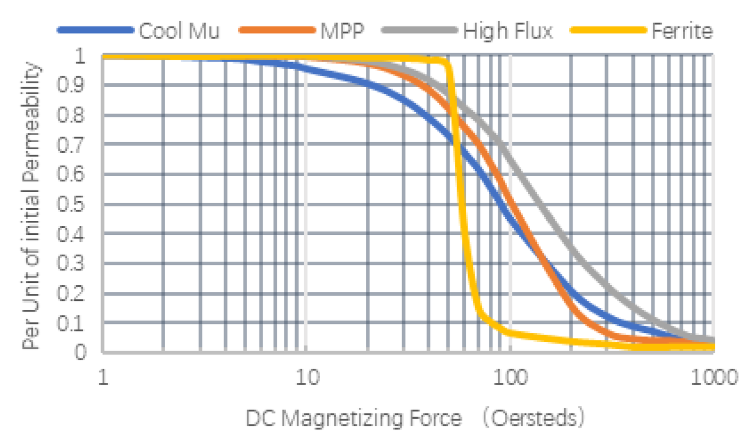
- Interleaved CCM Totem-pole PFC for Bi-AC/DC Stage.
- Bi-directional CLLC with delay-time control of wide voltage range output ,ZVS and high switching frequency (***450 kHz~1.2 MHz***) range for Bi-DC/DC Stage.
- Hard switching full bridge for LV DC/DC.
- All 650V GaN devices for high voltage side.

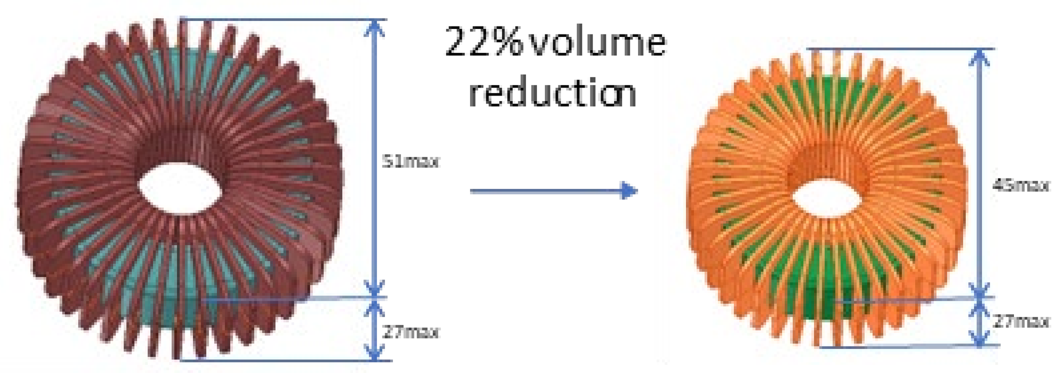
Bi-AC/DC Stage

Table 1

Totem-pole PFC per phase parameter	
Vac	220 V
Iac_RMS	16 A
Vbus	400 V
f_Line/f_s	50 Hz / 100 kHz

$$L_{PFC\_min} = \frac{V_{Bus}/2}{k_{Ripple}\cdot\sqrt{2}\cdot I_{Ac\_rms}\cdot 2\cdot f_s}$$

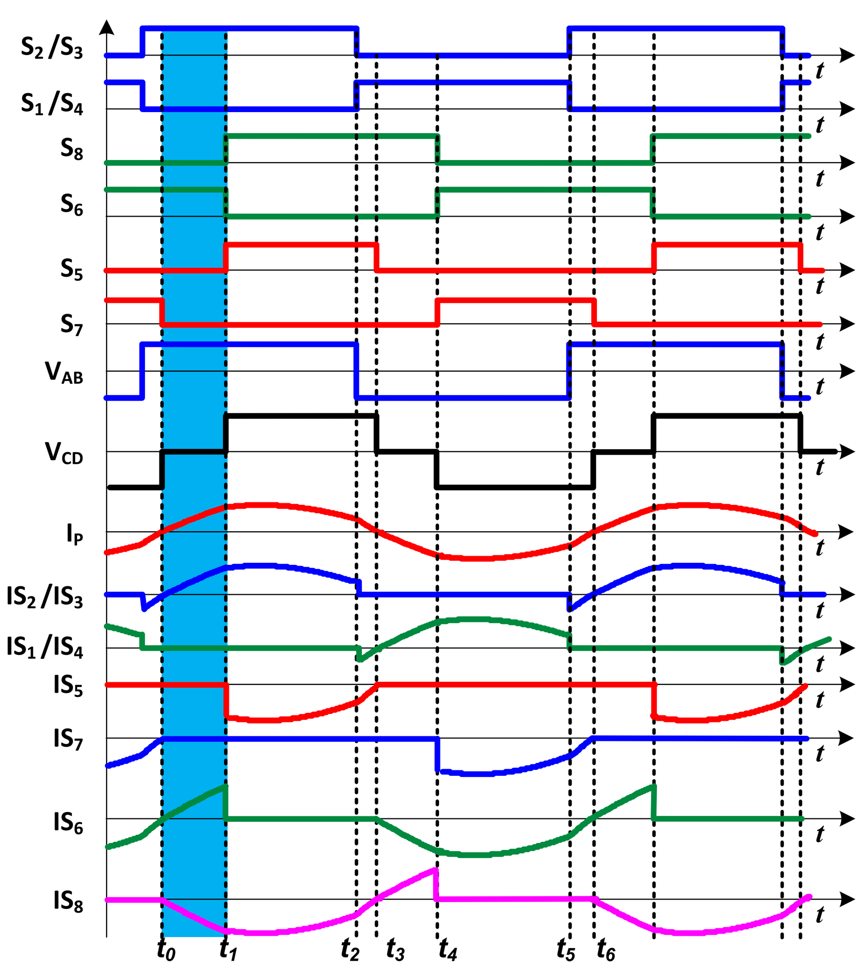




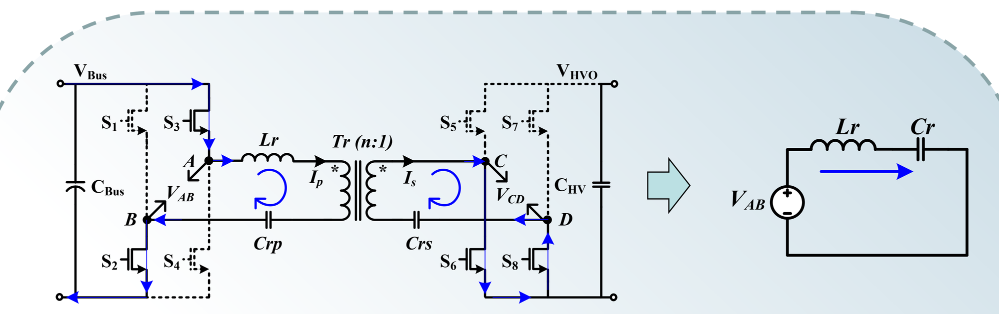
50 kHz design   100 kHz design

- Usually, the value of k_{Ripple} is set to 1 for per-phase current. Based on the parameters in Table 1, minimum inductance satisfying the demand is 45 uH.
- High-flux core, low loss for high frequency applications, volume is reduced by about 20% compared with the traditional 50 kHz PFC inductor design.

Bi-DC/DC Stage



Modulation Strategy



Working Mode 1: [t_0~t_1]

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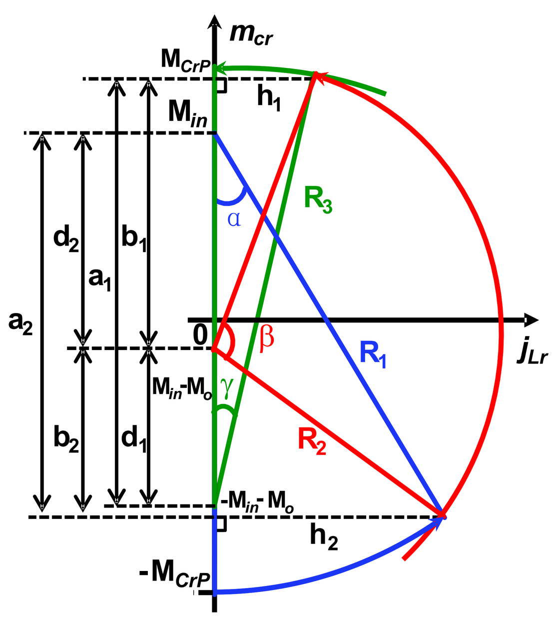
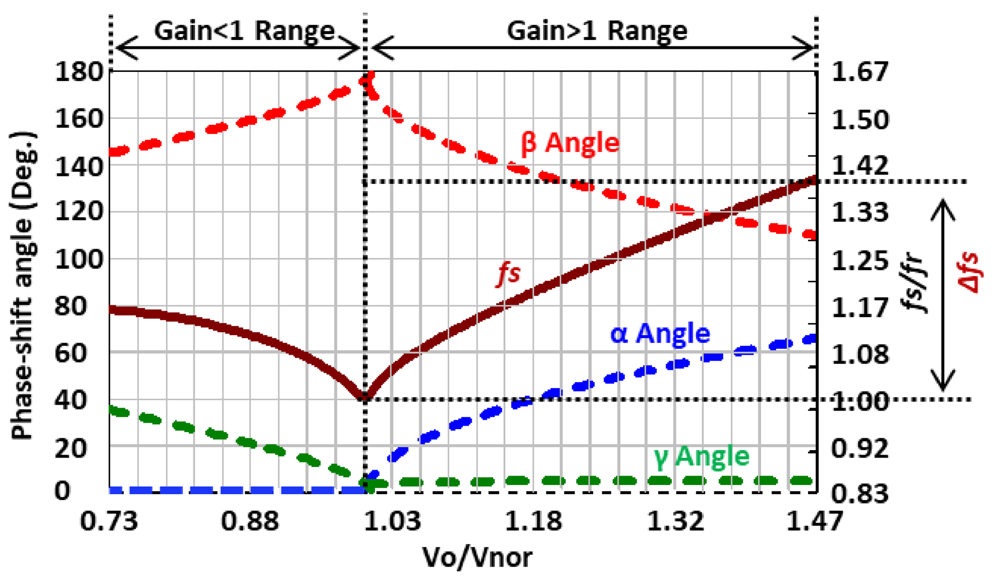


- LC resonant circuit as a second-order system is suitable for phase plane analysis.
- Delay-time control can achieve high gain output adjustment for DC/DC.

$$i_{Lr}(t)=\begin{cases}\frac{V_{in}}{R_o}R_1\sin(\omega_r t) & 0\le t<T_\alpha\\ \frac{V_{in}}{R_o}R_2\sin[\omega_r(t-T_\alpha)+\beta_{start\_angle}] & T_\alpha\le t<T_\alpha+T_\beta\\ \frac{V_{in}}{R_o}R_3\sin[\omega_r(t-T_\alpha-T_\beta)+\pi-\gamma] & T_\alpha+T_\beta\le t<\frac{T_s}{2}\end{cases}$$

Phase plane analysis for half switching cycle

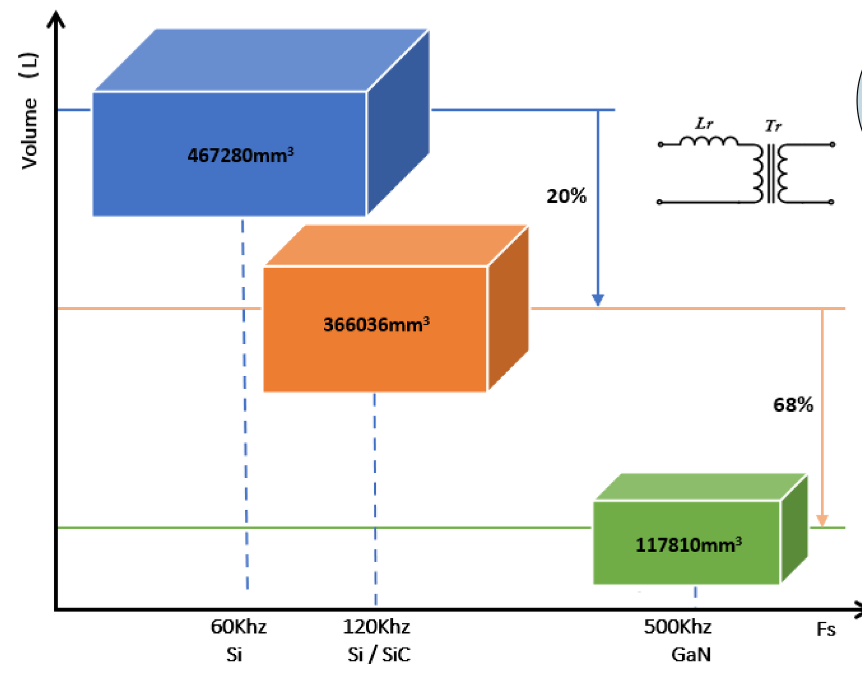
Characters of Bi-DC/DC Stage and Mag. Design

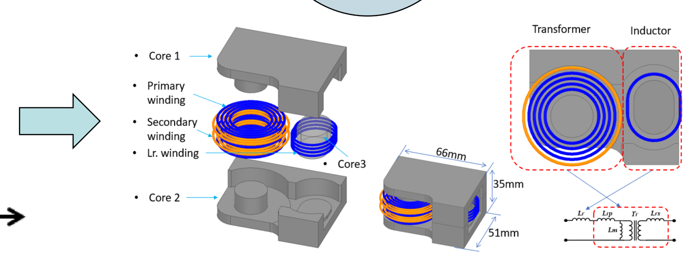


α, β, γ, fs VS Vo

- fs>fr is maintained throughout the output voltage range and keeping "V" shape.
- Larger Angle α means larger system gain.
- Narrow fs range and good for transformer design.

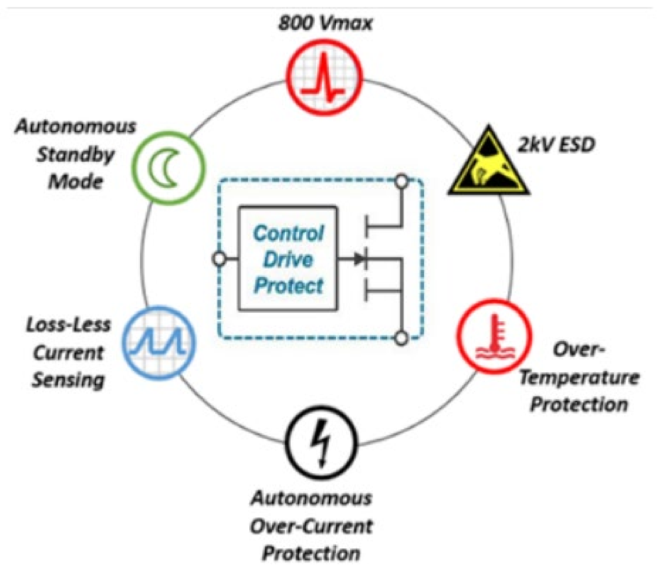
At the same 6.6 kW power, the volume of GaN based high-frequency transformer is more than 50% smaller than that of Si based design



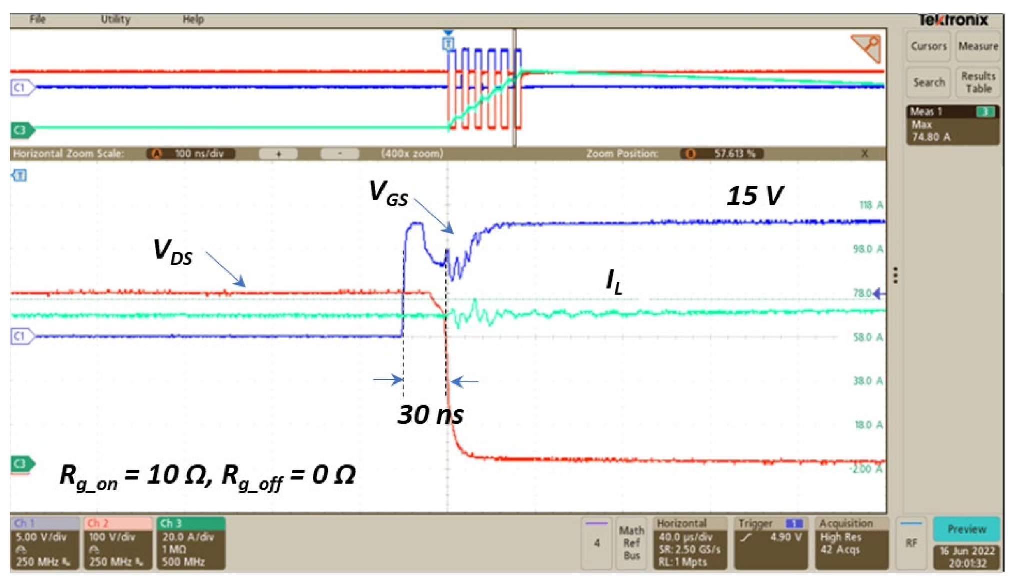


Comparison of transformer volumes at different fs

Functions of Navitas NV651X-series GaN devices



GaNFast functionality



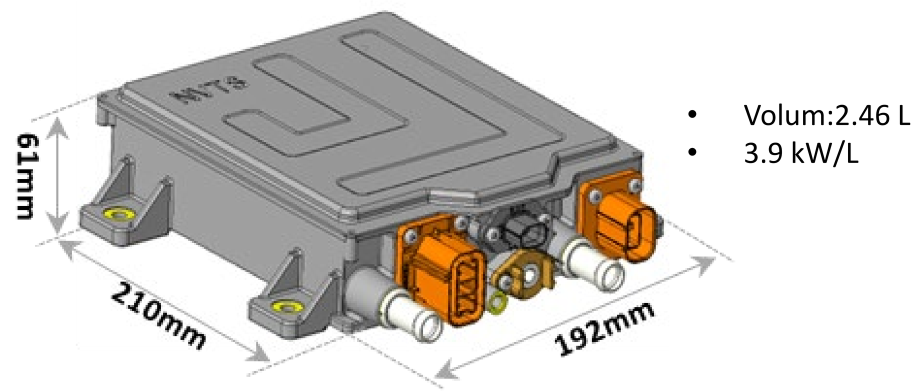
Typical double-pulse test waveform

- 12~18 V for DRIVE to SK.
- Integrated ***level-shift*** and ***deglitch circuit*** for improved ***anti-interference*** performance
- GaNFast power ICs are easy-to-use, highspeed, high-performance ***'digital-in, power-out***' building blocks.
- Monolithic integration of GaN gate drive & GaN power stage enables ~zero loss in turn-off because ***the gate-drive loop has ~zero impedance,*** eliminates parasitic gate-loop inductance and prevents gate ringing and glitching.

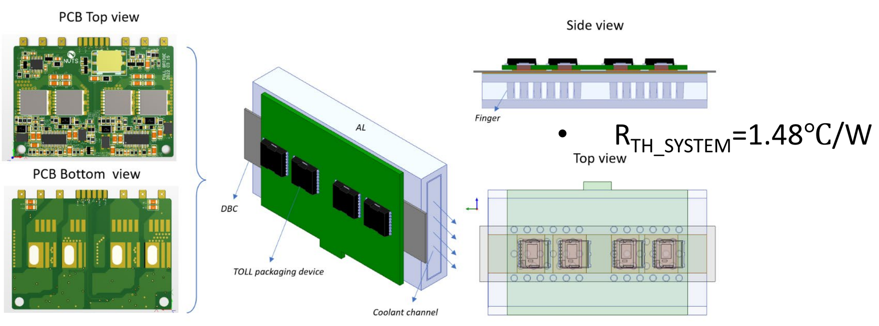
2-in-1 OBC Prototype and key waveforms

Table 2 Main parameters of 2-in-1 OBC

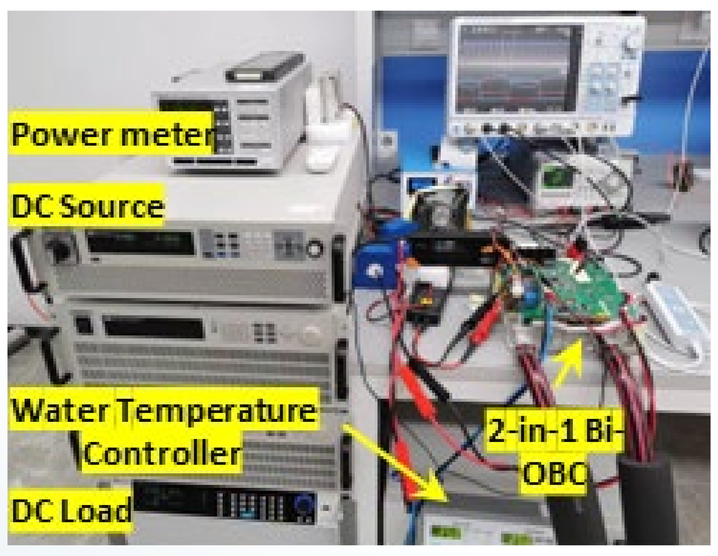
	6.6 kW Bi-directional OBC + 3.0 kW LV DC-DC	
	Parameters	Value
OBC	V_{AC}	85~265 V
	V_{BAT}	250~500 V, 280~460 V full load
	I_{AC_Max}	32 A
	I_{HVo_Max}	23.5 A
	Power	6.6 kW charging, 220 V_{AC}/6.0 kVA discharging
	L_{PFC}	50 uH
	f_{PFC}	100 kHz
	Res. Inductor	4.0 uH
	Res. Cap.	40 nF (equivalent)
	Res. Frequency	400 kHz
	Trans. turns ratio	1.2
LV DC-DC	LV V_{OUT}	9~16 V (nom. 13.5 V)
	LV P_{OUT}	3.0 kW (3.6 kW peak)
	I_{LVo_Max}	222 A
GaN Devices	Q_1~Q_4, S_1~S_8	NV6514 power IC
	S_9~S_{12}	NV6513 power IC



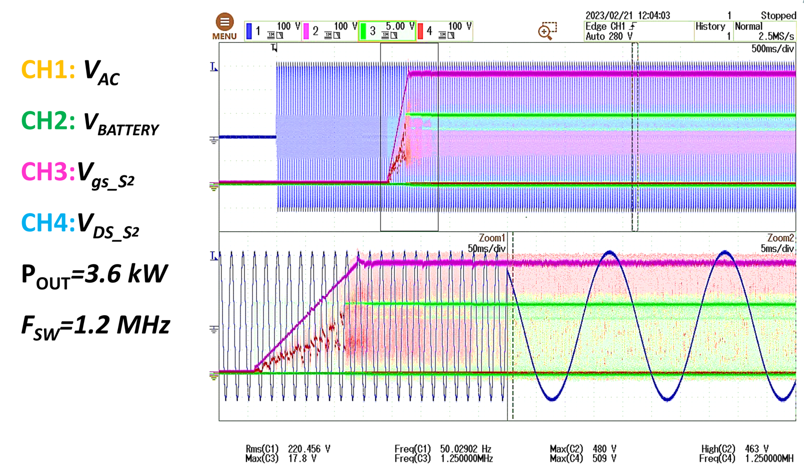
Prototype "2-in-1" OBC dimensions



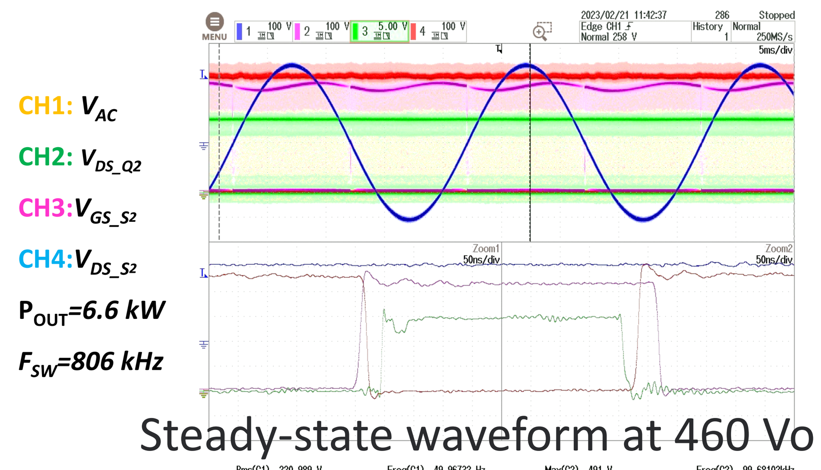
Thermal solution for GaN devices



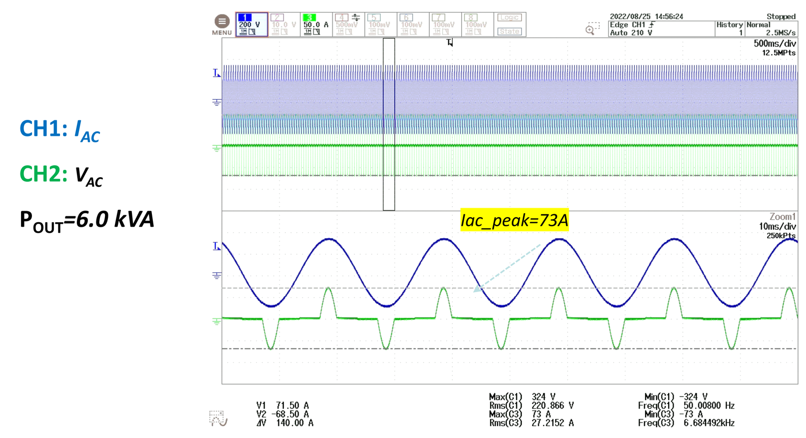
Platform set-up



Soft-start waveform at 460 Vo



Steady-state waveform at 460 Vo

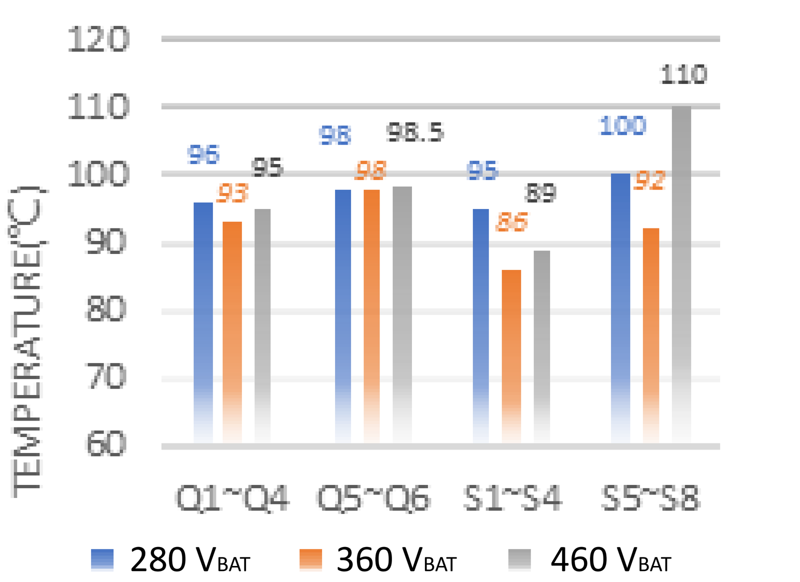


Discharging 6.0 kVA non-linear load

Thermal and Efficiency

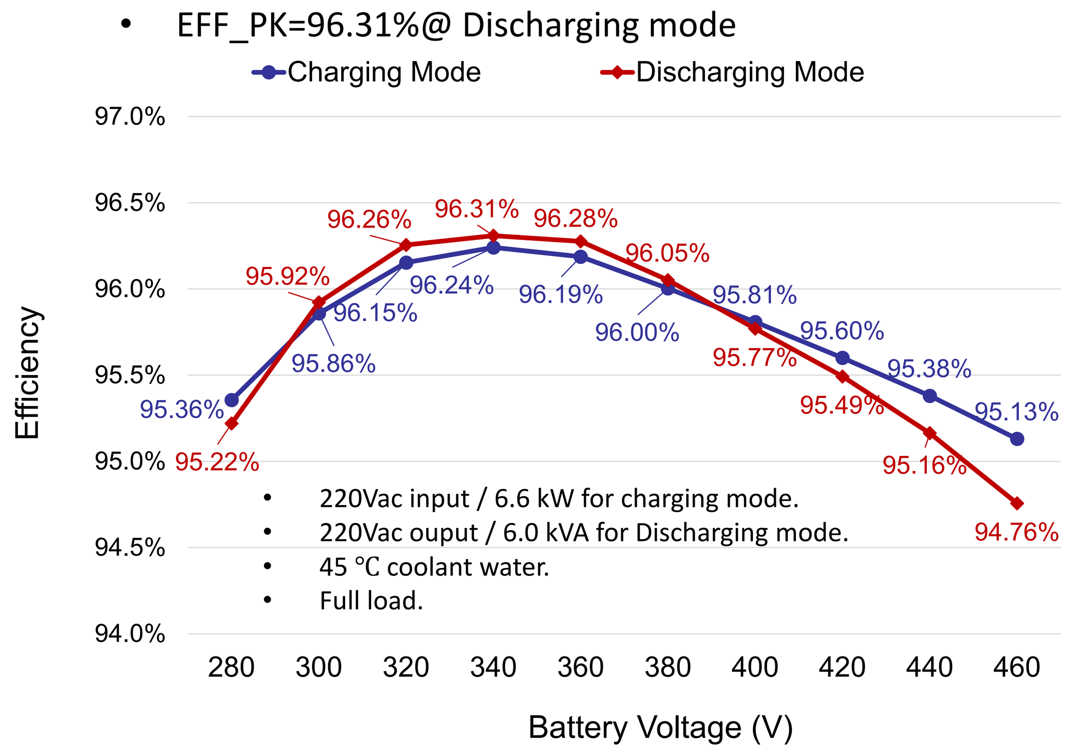
Feasibility of GaN in high-power, high-frequency applications is verified

- GaN device are all below 110°C which verifies the feasibility of heat dissipation.



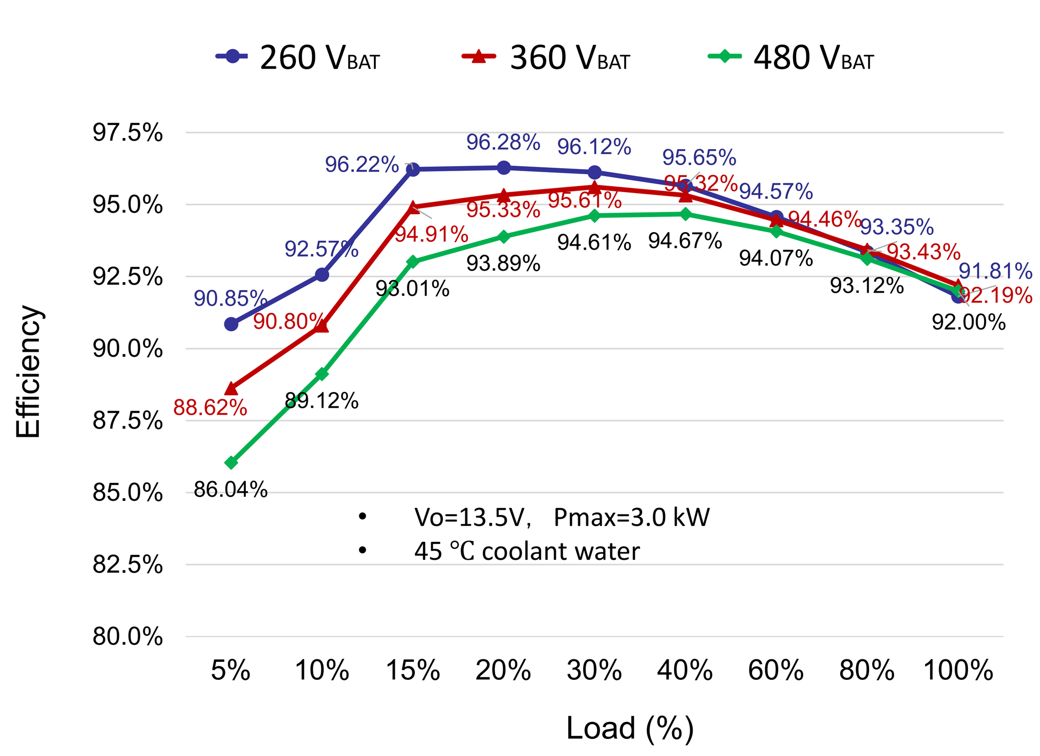
Thermal test results of GaN at 65°C coolant water

- EFF_PK=96.24%@ Charging mode
- EFF_PK=96.31%@ Discharging mode



Efficiency of OBC @ charging and discharging

- EFF_PK=96.28%@ 260V_{BAT}



Efficiency of HV-LV DC-DC