An Isolated Bidirectional DC-DC Converter with High Voltage Conversion Ratio and Reduced Output Current Ripple

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Outline

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2. **Proposed Circuit and Its Control Scheme**
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    b) Proposed Circuit Topology Control Method

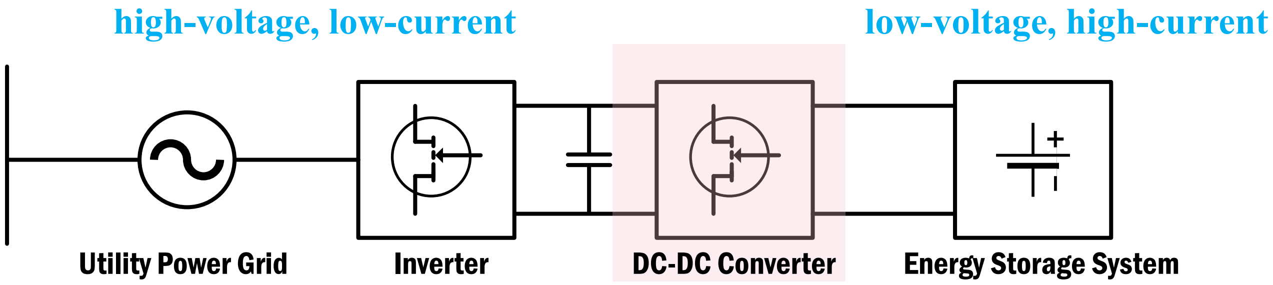
3. **Prototype and Experimental Results**
    a) 400-V/24-V 1-kW Prototype
    b) Prototype Charging and Discharging Test Results
    c) Prototype Efficiency Evaluation

4. **Conclusions and Impact of the Project**

Introduction

Energy storage system interface

- A high voltage gain dc-dc converter to interface utility power grid and energy storage system



Energy storage system interface structure to utility power grid

Basic requirements for the dc-dc converter

- High voltage-step-down ratio from the power grid to the energy storage system
- Galvanic isolation
- Bidirectional power transfer
- Variable voltage range to ensure battery working properly at different battery (state of charge) SOC

Challenges on Bidirectional Dc-dc Converter

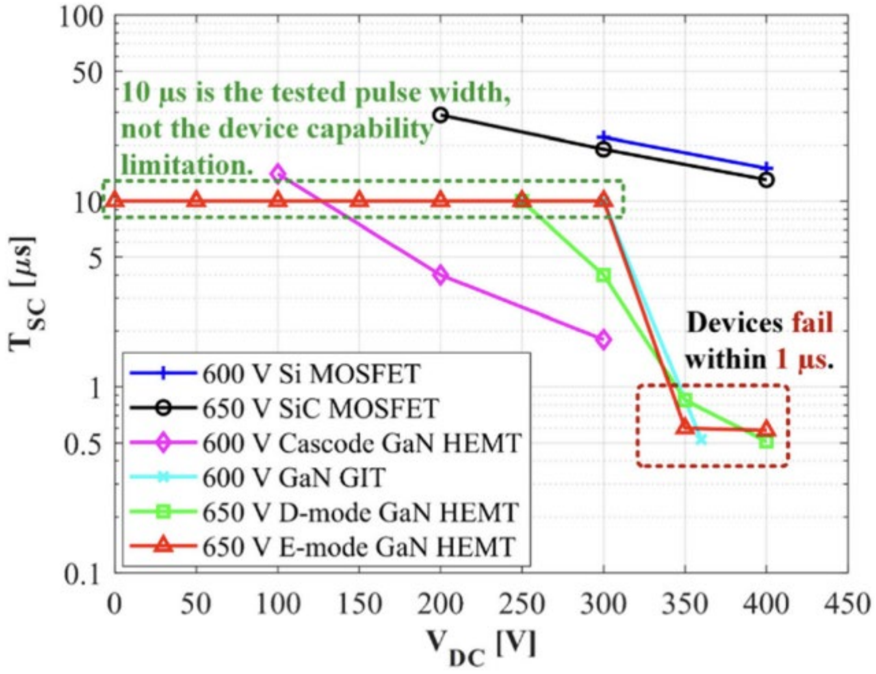
Challenges for isolated bidirectional dc-dc converters

- Small current ripple to improve the durability of the energy storage system
- Reduced voltage stress of power semiconductor devices to enhance the reliability of converter system
- High efficiency to mitigate the heating and energy dissipation of the converter system

Traditional solutions for the challenges and restrictions

- Larger output capacitor bank required for ripple reduction
  Lower power density and higher cost
- Device voltage stress same as dc bus voltage
  Reduced device reliability
- Voltage conversion ratio achieved by transformer turns ratio only
  Lower efficiency and larger size for higher conversion ratio

Improvements can be achieved with the proposed circuit topology



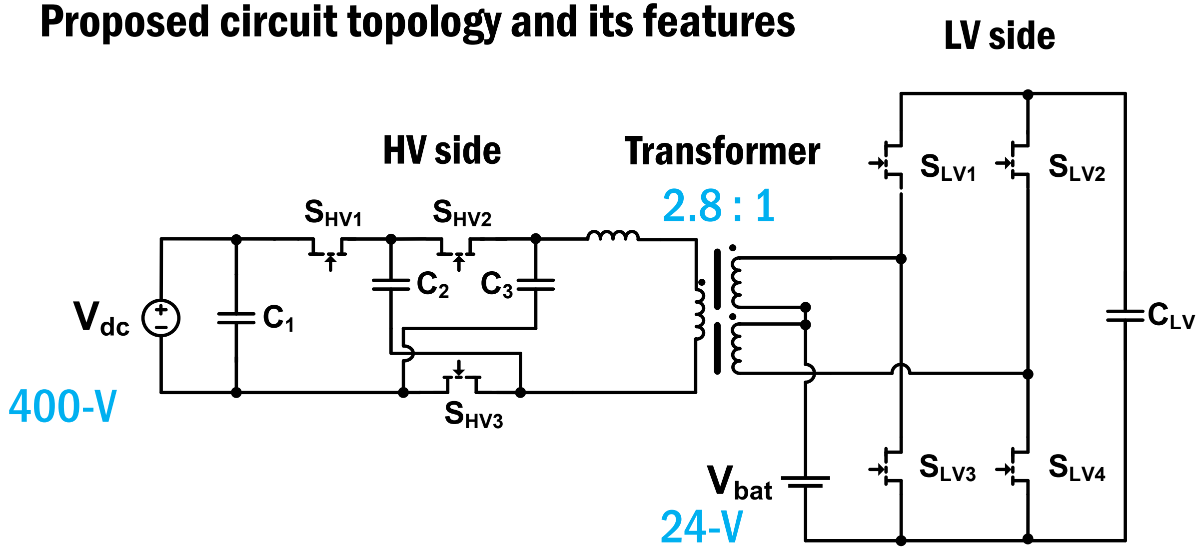
600-V/650-V class power transistor short-circuit capability [1]

[1]X. Lyu et al., "A Reliable Ultrafast Short-Circuit Protection Method for E-Mode GaN HEMT," in IEEE Transactions on Power Electronics, vol. 35, no. 9, pp. 8926-8933, Sept. 2020, doi: 10.1109/TPEL.2020.2968865.

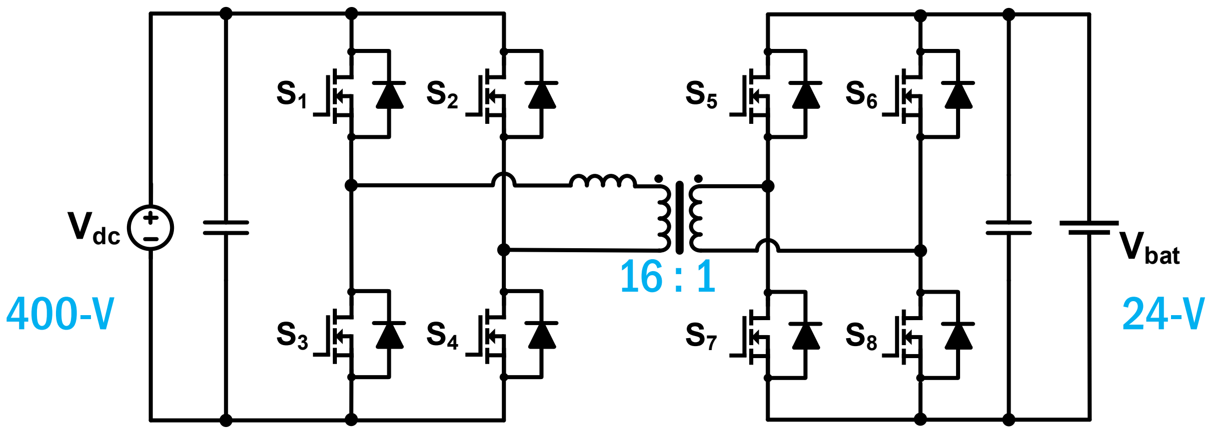
[2] Bala, S., Tengner, T., Rosenfeld, P., & Delince, F. (2012). The effect of low frequency current ripple on the performance of a Lithium Iron Phosphate (LFP) battery energy storage system. 2012 IEEE Energy Conversion Congress and Exposition (ECCE). doi:10.1109/ecce.2012.6342318

Introduction to the Proposed Circuit Topology

Proposed circuit topology and its features



Proposed Quasi-switched-capacitor Transformer-Interleaved circuit



Traditional dual-active-bridge (DAB) circuit

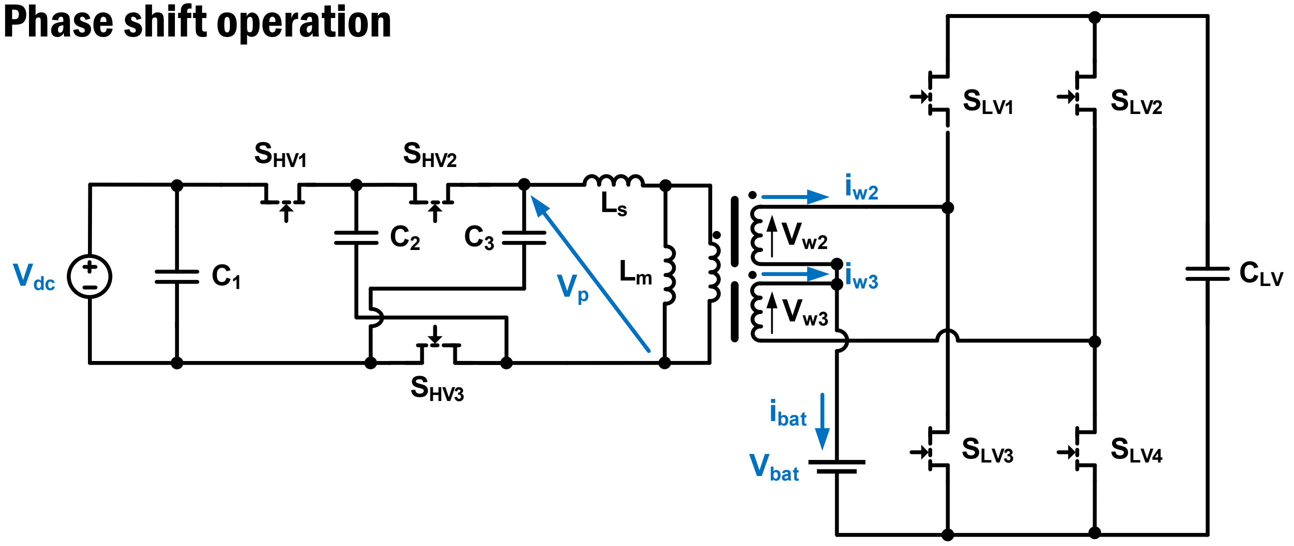
Benefits of the proposed circuit topology

- Reduced HV side switches' voltage stress: $\frac{2}{3}V_{dc}$ (V_{dc} for DAB) – Reliability enhancement
- Reduced current ripple on battery: ideally cancelled (No cancellation for DAB) – Size reduction
- Reduced turns ratio on transformer: 2.8 : 1 turns ratio (16.7 : 1 for DAB) – Manufacturability improvement

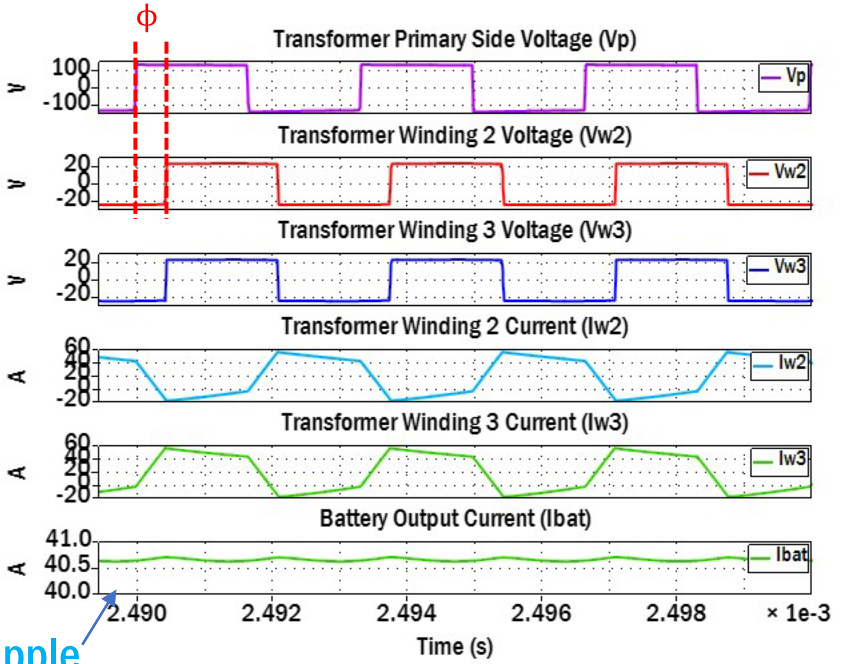
Proposed circuit topology provides cost-effective solution to the energy storage application dc-dc converter

Proposed Topology Control Method

Phase shift operation



Circuit topology



reduced current ripple

Circuit simulation waveforms

Circuit control method

- Phase shift angle ϕ controlled to regulate the transferred power
- Piece-wise linear transformer current similar to DAB

simple and easy-to-achieve control method with low-cost implementation

Parameter	Variables	Value
DC input/battery voltages	V_{dc}/V_{bat}	400 V/24 V
Switching frequency	f_{sw}	300 kHz
Transformer turns ratio	N	6:1:1
Inductance	L_m/Ls	64 μH/6 μH
Switched capacitance	C_2/C_3	5 μF

Circuit simulation parameters

400-V/24-V 1-kW Dc-dc Converter Prototype

1-kW prototype and its features

1-kW 400-V/24-V QSC transformer-interleaved converter

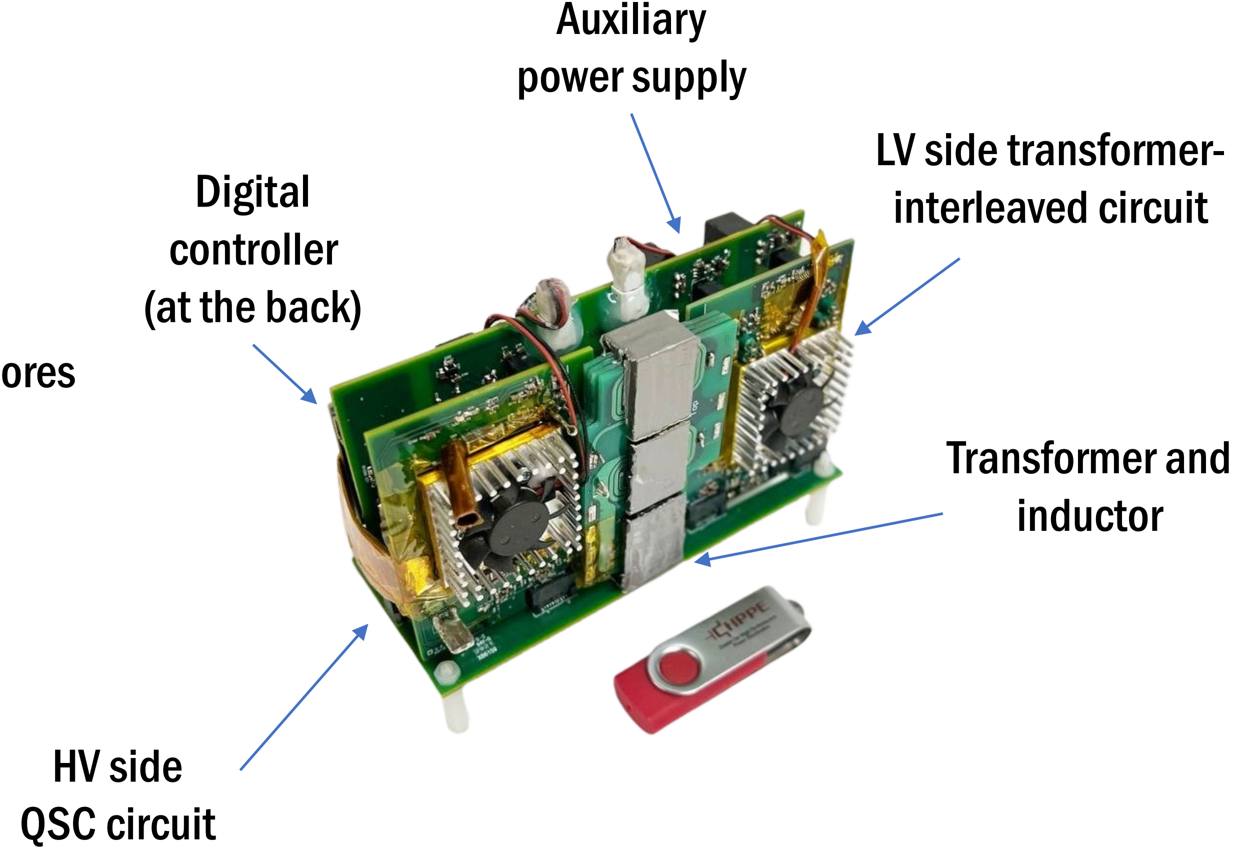
- 650-V GaN device (GS66506T) on the HV side
- 100-V GaN device (EPC2022) on the LV side
- Dual transformer design built with E22/6/16 planar E cores

  Magnetizing inductance Lm : 15 µH × 2
- A planar inductor built with EQ25/LP

  Resonant inductance L_s : 5.8 µH

Prototype specifications

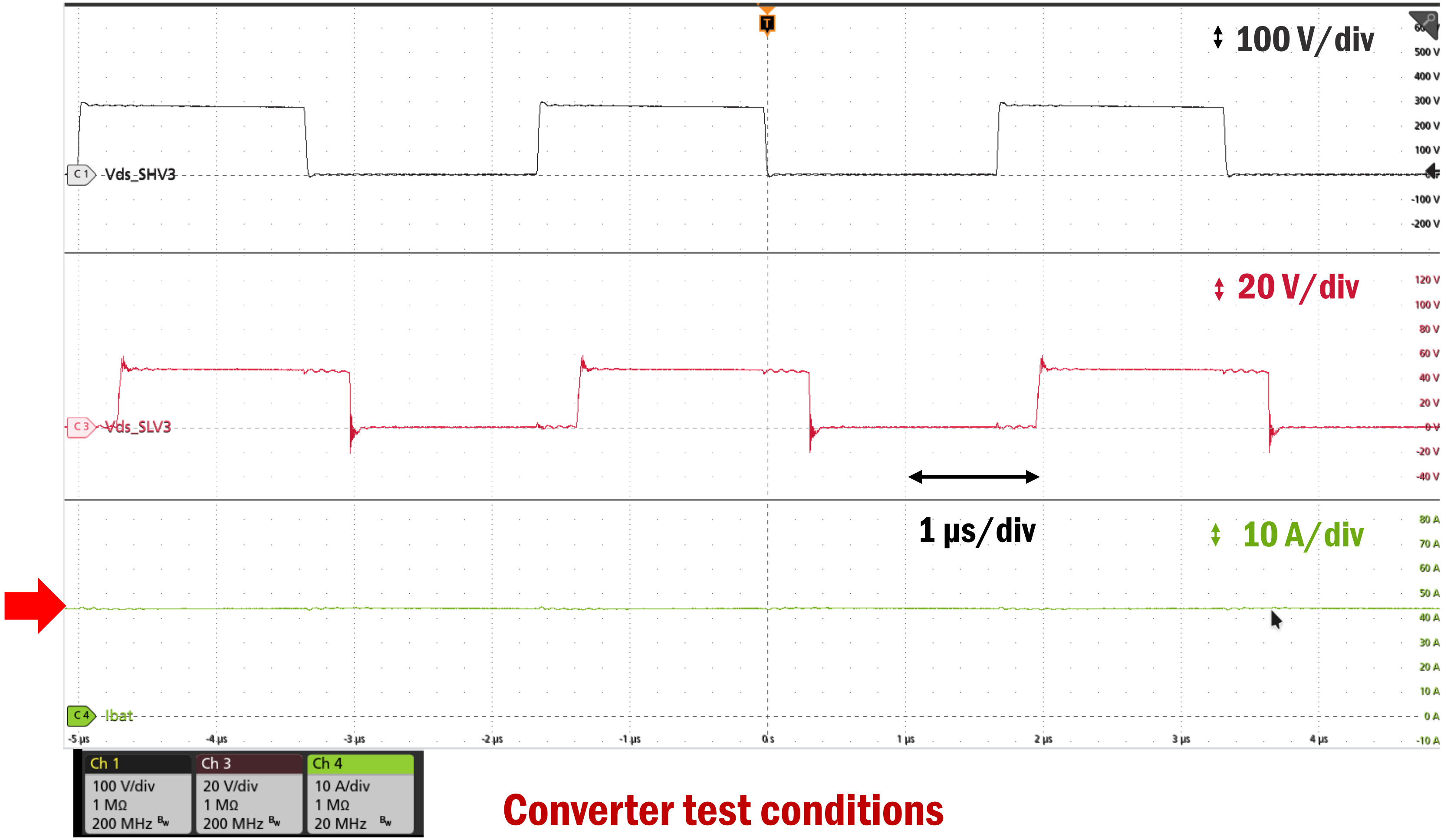
Parameter	Variables	Value
DC input/output voltages	V_{dc}/V_{bat}	400 V/24 V
Switching frequency	f_{sw}	300 kHz
Transformer turns ratio	N	6:2 and 6:2
Inductance	$L_{m\_total}\ /Ls$	30 µH/5.8 µH
Switched capacitance	C_2/C_3	4.4 µF



1-kW, 400 V/24 V, 300 kHz prototype
Dimensions: 13.0 cm × 7.4 cm × 5.6 cm
Power density: 30.42 W/in^3
Main power loop density: 9.45 W/cm^3

Maximum Input Voltage Charging Test

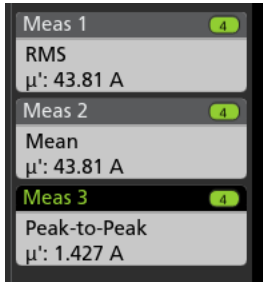
Converter test waveforms (420-V input voltage, R-Load, 1041-W)



Ch 1	Ch 3	Ch 4
100 V/div 1 MΩ 200 MHz Bw	20 V/div 1 MΩ 200 MHz Bw	10 A/div 1 MΩ 20 MHz Bw

V_{ds_SHV3}: 283 V
(HV side switches)

V_{ds_SLV3}: 48.5 V
(LV side switches)



Meas 1
RMS
µ': 43.81 A

Meas 2
Mean
µ': 43.81 A

Meas 3
Peak-to-Peak
µ': 1.427 A

I_{bat}: 43.81 A

I_{bat_pp}: 1.43 A
3.26% peak to peak

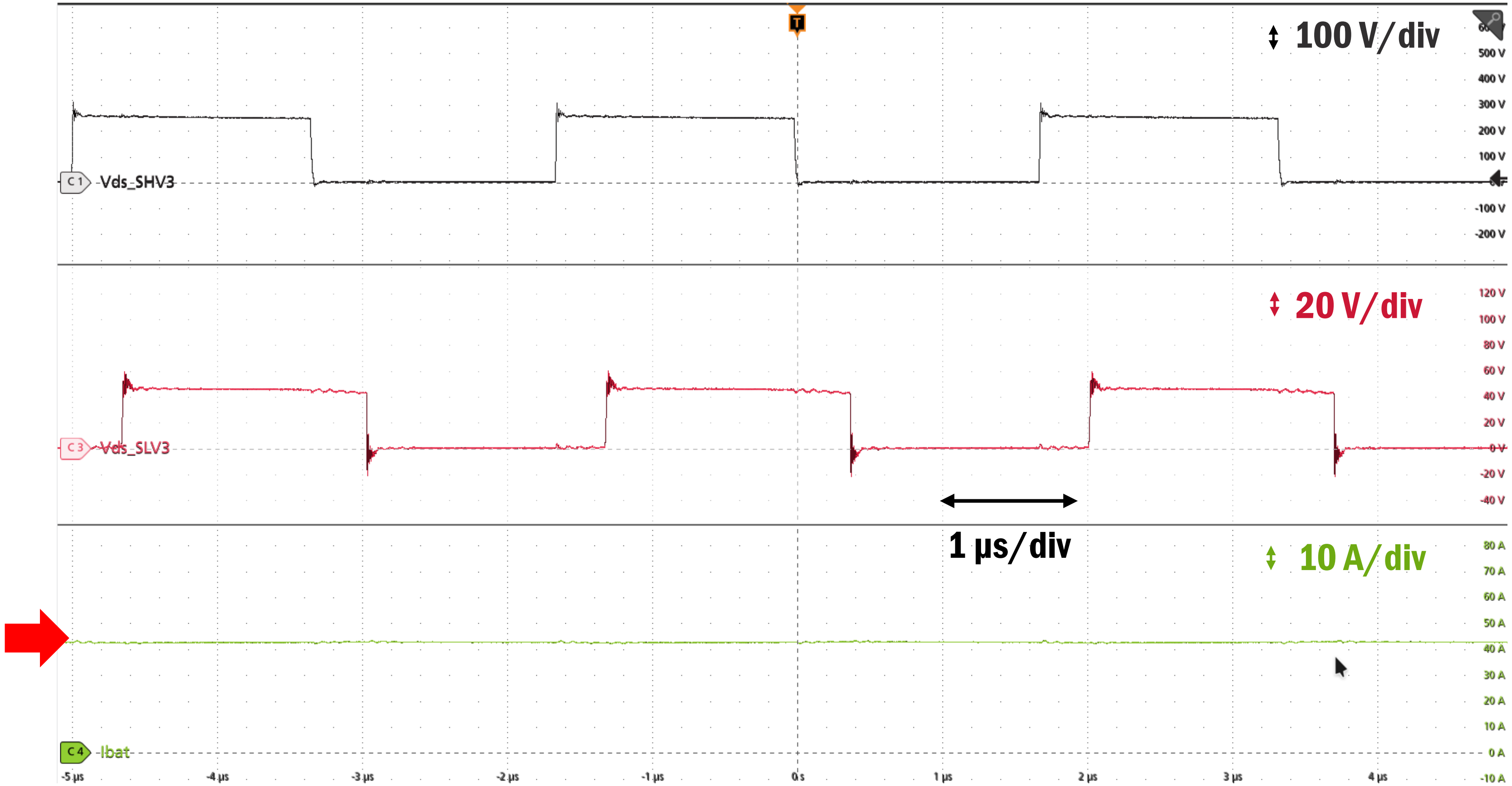
Converter test conditions

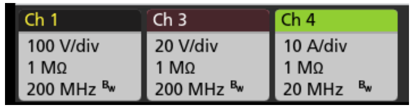
- Input condition: 420 V/2.48 A
- Output voltage: 24.3 V/43.81 A

Reduced voltage stress on HV side GaN devices
Low ripple in LV side output current

Minimum Input Voltage Charging Test

Converter test waveforms (380-V input voltage, R-Load, 1017-W)

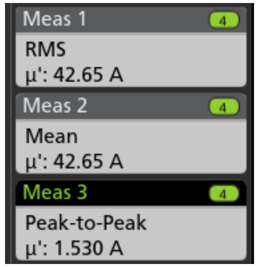




Ch 1	Ch 3	Ch 4
100 V/div 1 MΩ 200 MHz Bw	20 V/div 1 MΩ 200 MHz Bw	10 A/div 1 MΩ 20 MHz Bw

V_{ds_SHV3}: 256 V
(HV side switches)

V_{ds_SLV3}: 52.1 V
(LV side switches)



Meas 1 4
RMS
μ': 42.65 A
Meas 2 4
Mean
μ': 42.65 A
Meas 3 4
Peak-to-Peak
μ': 1.530 A

I_{bat}: 42.65 A

I_{bat_pp}: 1.53 A
3.58% peak to peak

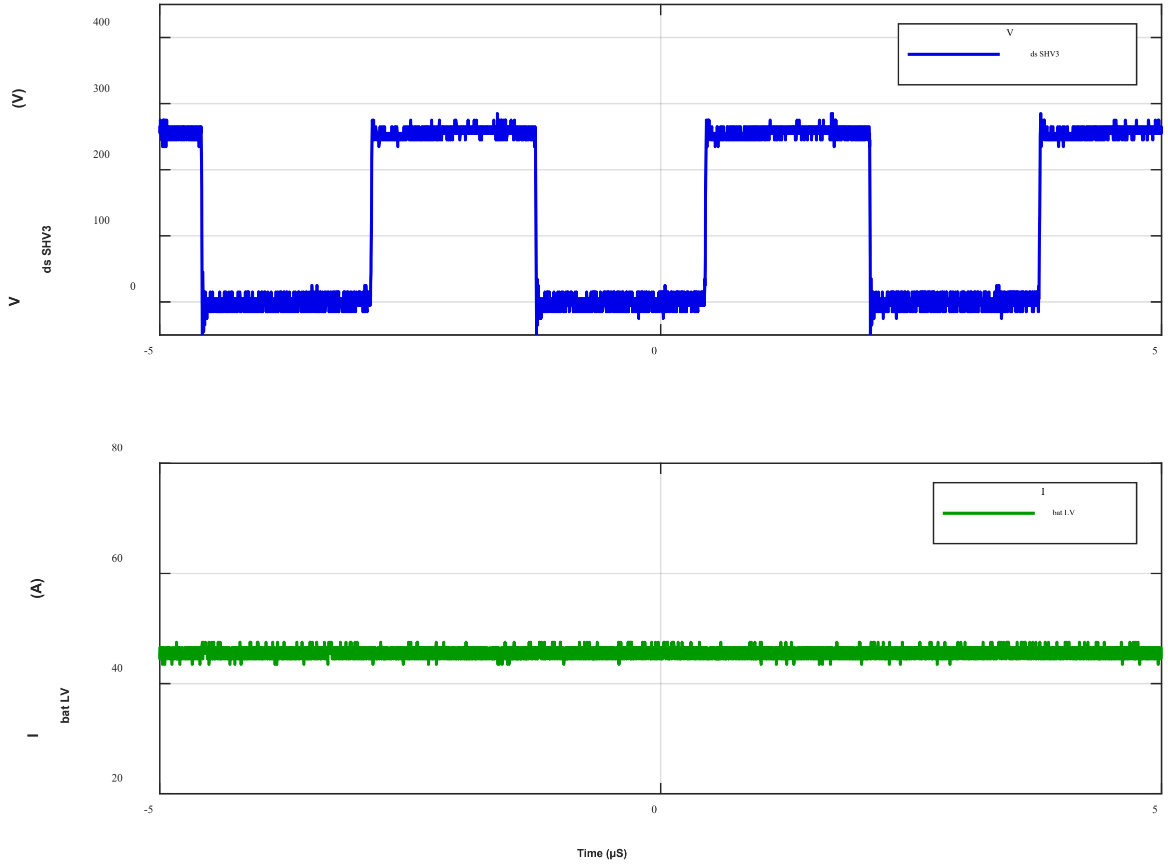
Converter test conditions

- Input condition: 380 V/2.69 A
- Output voltage: 26 V/42.65 A

Capable of operating at different operation points with low current ripple

Nominal Voltage Full Power Discharging Test

Converter test waveforms at 1094-W discharging



V_{ds_SLV3}: 265 V (HV side switches)

Reduced voltage stress

I_{bat}: 45.6 A

24-V input voltage, 1094-W input power
Full voltage, full power discharging

Converter test conditions

- **Input condition: 24 V/45.6 A**
- **Output voltage: 395 V**

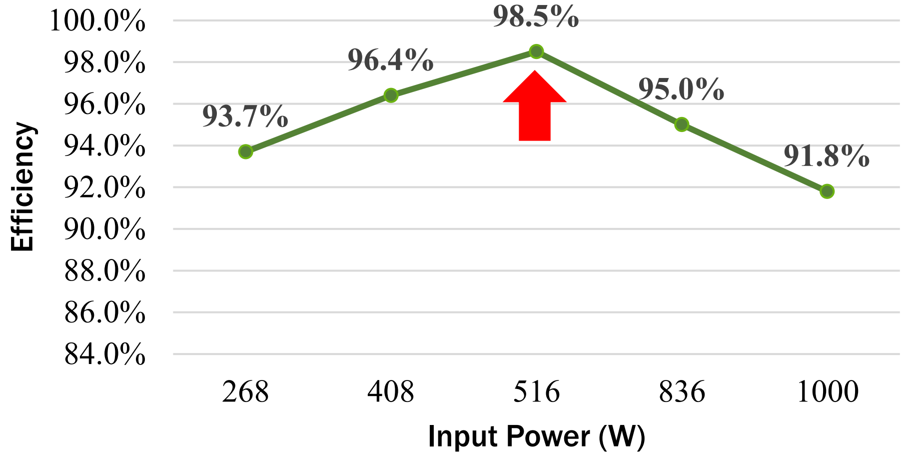
Converter Efficiency Evaluation

Converter efficiency summary for charging and discharging

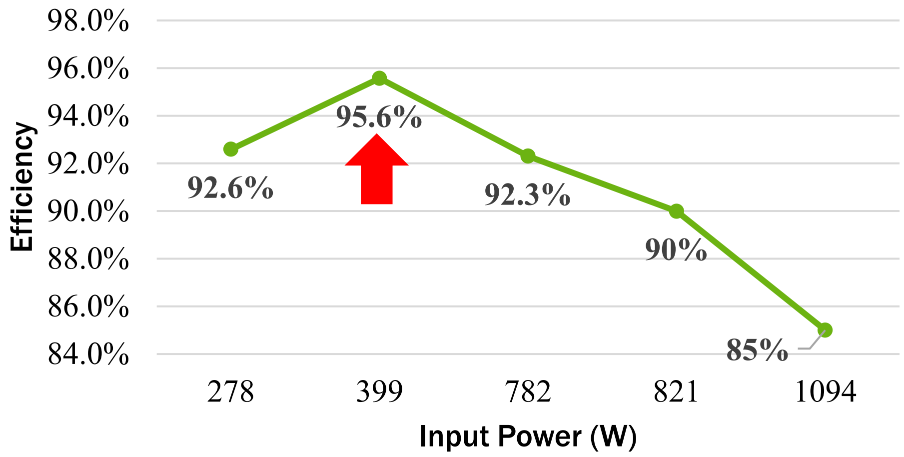
Converter efficiency charts for charging and discharging

Efficiency measurement conditions

- Input voltage: 400 V
- Output voltage: 24 V



Converter Charging Efficiency



Converter Discharging Efficiency

Efficiency measurement summary

- Charging stage highest efficiency is 98.5%, discharging stage highest efficiency is 95.6%

Impact of the Project

- High efficiency and high power density design for reduction on the installation and operation cost
- Reduced current ripple for reduced heat generation and longer lifetime
- Reduced voltage stress for GaN device reliability enhancement
- Reduced turns ratio for transformer manufacturability improvement

Peak efficiency is about 98.5% in charging which is comparable to its bidirectional resonant converter counterparts with additional ripple reduction, and a 9.45 W/cm^3 (155 W/in^3) main power loop density surpasses similar rating bidirectional isolated dc-dc converters [1][2][3]

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[1] 97.8%, 130W/in^3: B. Li, Q. Li, F. C. Lee and Y. Yang, "A symmetrical resonant converter and PCB transformer structure for common mode noise reduction," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA, 2017.

[2] 96%, 37W/in^3: B. Li, Q. Li, F. C. Lee, Z. Liu and Y. Yang, "A High-Efficiency High-Density Wide-Bandgap Device-Based Bidirectional On-Board Charger," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 3, pp. 1627-1636, Sept. 2018, doi: 10.1109/JESTPE.2018.2845846.

[3] 94.61%, 5.6W/in^3: Y. -C. Liu, C. Chen, K. -D. Chen, Y. -L. Syu and N. A. Dung, "High-Frequency and High-Efficiency Isolated Two-Stage Bidirectional DC–DC Converter for Residential Energy Storage Systems," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 3, pp. 1994-2006, Sept. 2020, doi: 10.1109/JESTPE.2019.2953117.

Conclusions and Future Work

- An isolated high voltage conversion ratio bidirectional dc-dc converter is proposed and validated
- The voltage stress reduction and current ripple cancellation features fit well for energy storage application
- The 1-kW, 300-kHz, 400-V/24-V circuit prototype performance has been evaluated with cutting-edge counter-parts
- Working on demonstrating dc-dc converter with state-of-art GaN devices

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Thank You!

Questions?