Development of 20 kW SiC-Based Dual Active Bridge Converter for EV Charger

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6	Conclusion

1. Introduction

❖ Overview of Electric Vehicle Chargers[1]

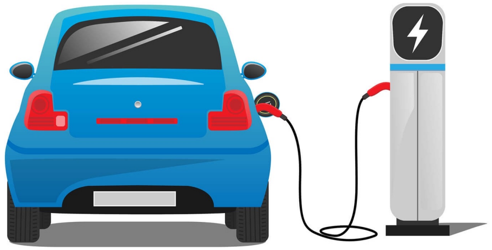
Charger Type	Level 1	Level 2	DC Fast Charging
Connector Type	J1772	J1772	CCS CHAdeMO Tesla
Voltage	120 VAC	208-240 VAC	400-1000 VDC
Typical Power Output	1 kW	7-19 kW	50-350 kW
Estimated BEV Charge Time from Empty	40-50 hrs	4-10 hrs	20 min.-1 hr
Estimated Electric Range per Hour of Charging	2-5 miles	10-20 miles	180-240 miles
Typical Locations	Home	Home, Workplace, and Public	Public


J1772


CCS


CHAdeMO


Tesla



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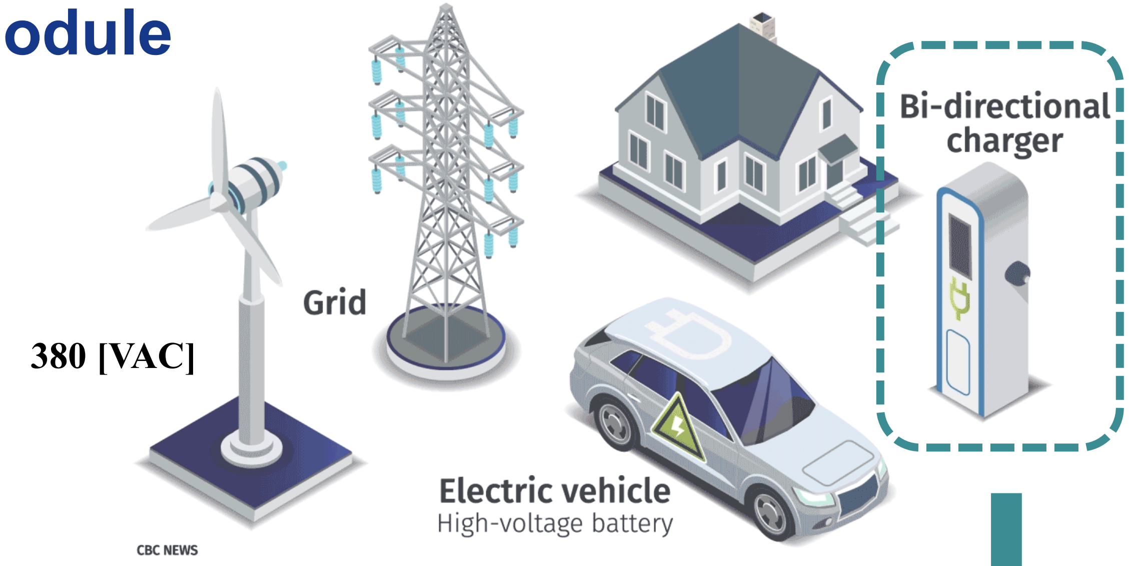
[1] U.S. Department of Transportation https://www.transportation.gov/rural/ev/toolkit/ev-basics/charging-speeds
[Image] https://evocharge.com/resources/how-does-ev-charging-work/

1 Introduction

❖ Specification of DC Fast Charger (DCFC) Module

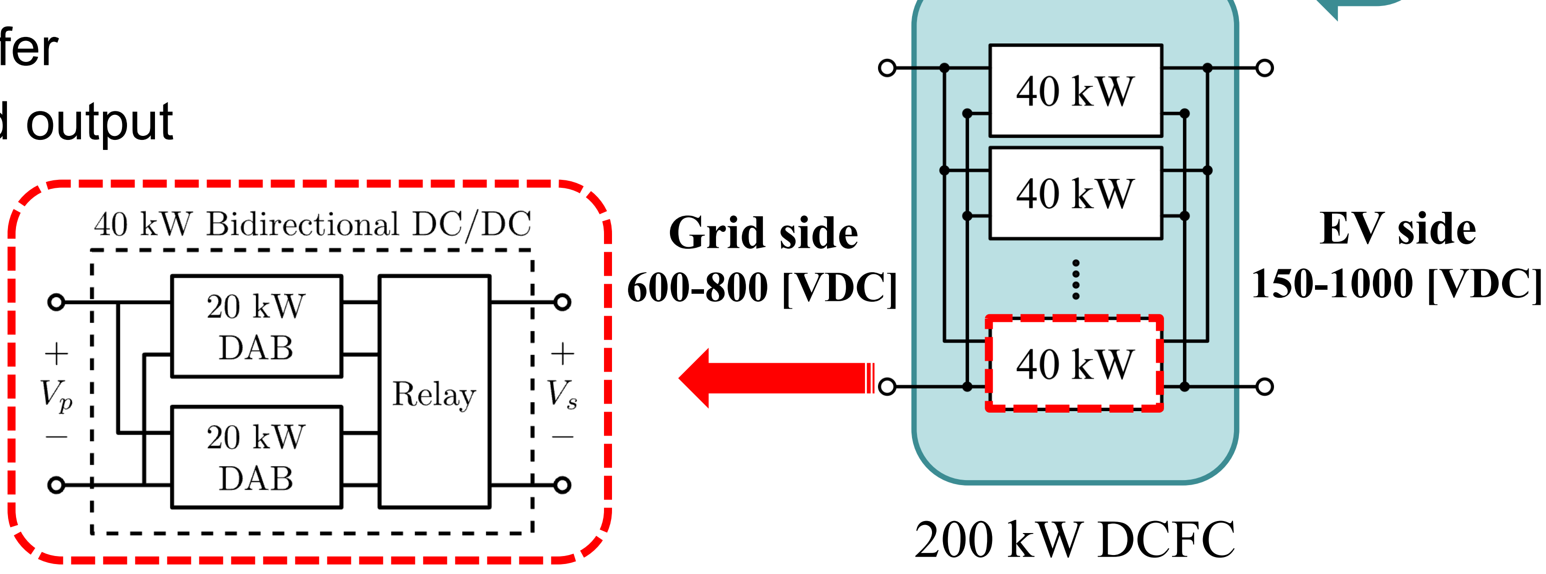
- ▶ Bidirectional power flow
- ▶ Operating condition
  - ✓ Rated output: 40 [kW]
  - ✓ Input voltage: 600 to 800 [V]*
  - ✓ Output voltage: 150 to 1000 [V]*

*charge mode



❖ Dual Active Bridge (DAB) Converter for DCFC Module

- ▶ Insulated bidirectional power transfer
- ▶ Series/parallel connection for rated output
  - ✓ Rated output: 20 [kW]
  - ✓ Input voltage: 600 to 800 [V]*
  - ✓ Output voltage: 300 to 500 [V]*



200 kW DCFC

[Image] https://www.cbc.ca/news/science/ev-to-grid-1.6100454

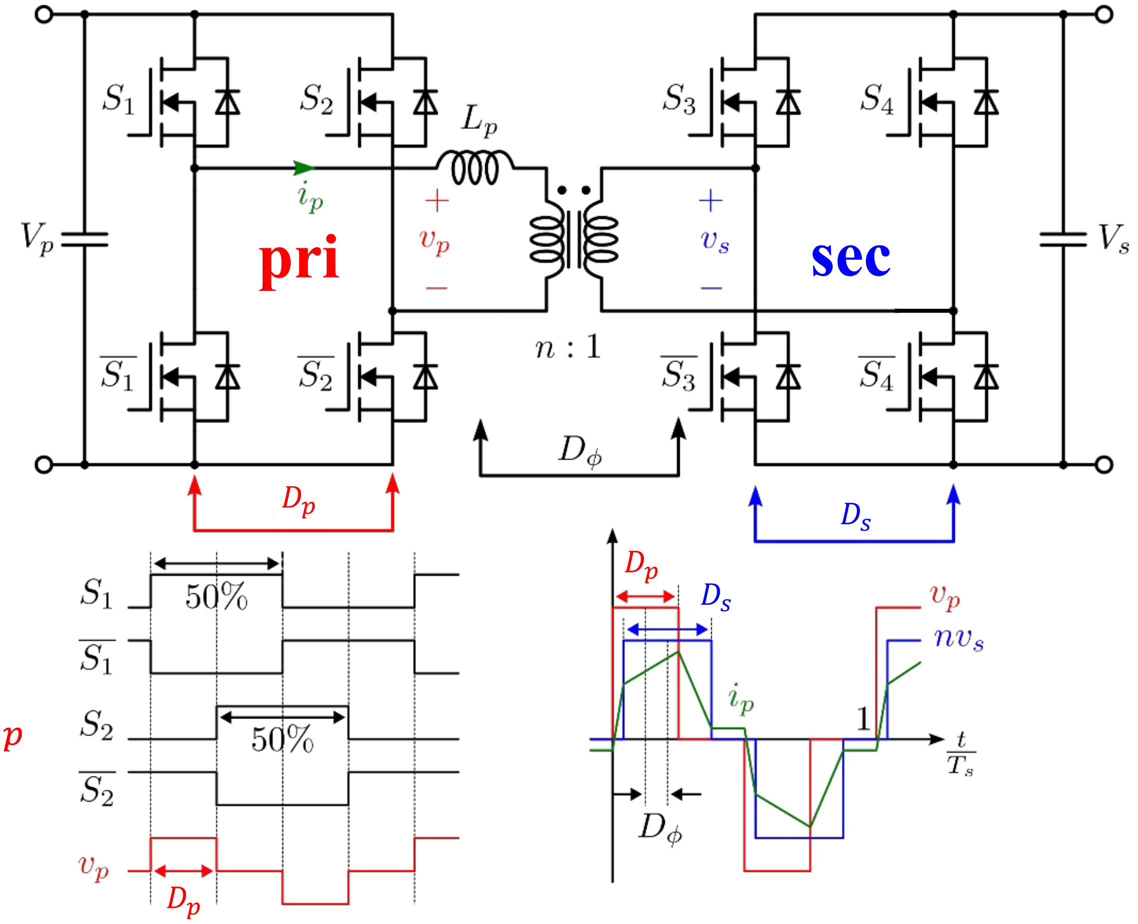
1 Introduction

❖ Concept of DAB Converter

- ▶ 2x H-bridges + 1x high-frequency (HF) transformer
  - ✓ Insulated with HF transformer
  - ✓ Zero-voltage switching (ZVS) → high efficiency
  - ✓ Wide voltage modulation ratio

❖ Parameters of DAB

- ▶ Physical parameters
  - ✓ DC-link voltages: V_p, V_s
  - ✓ HF transformer turn ratio and leakage inductance: n, L_p
- ▶ Control parameters
  - ✓ Duty ratio of ac voltage of each H-bridge: D_p, D_s
  - ✓ Phase shift angle between two H-bridges: D_ϕ



Three degree-of-freedom (3-DOF)

➔ Waveforms of ac voltages and current are determined by $(V_p, V_s, n, L_p, \boxed{D_p, D_s, D_\phi})$

2. Loss Analysis of DAB Converter

2 Loss Analysis of DAB Converter

❖ Operation Example

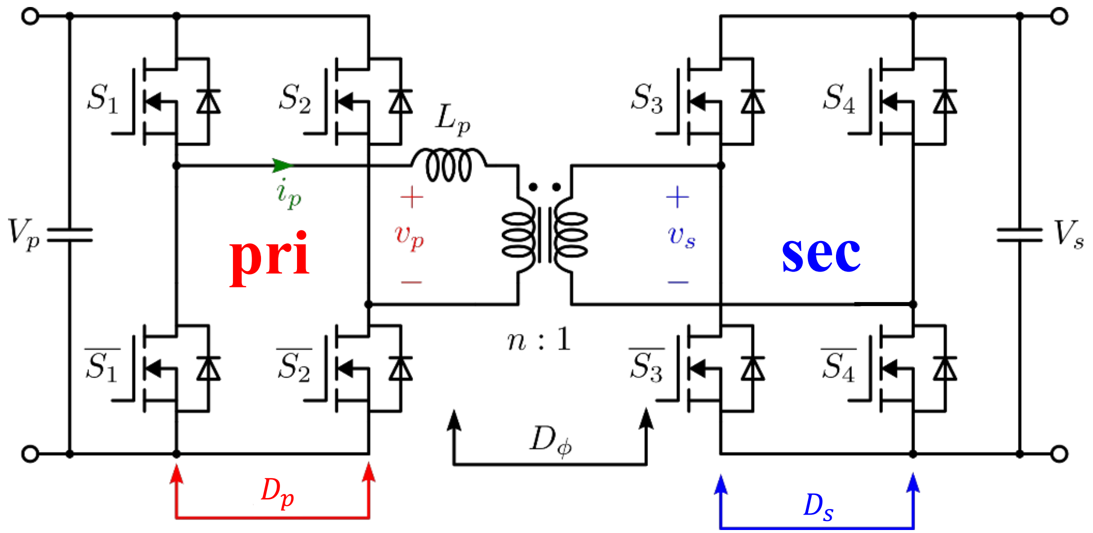
▶ Physical parameters

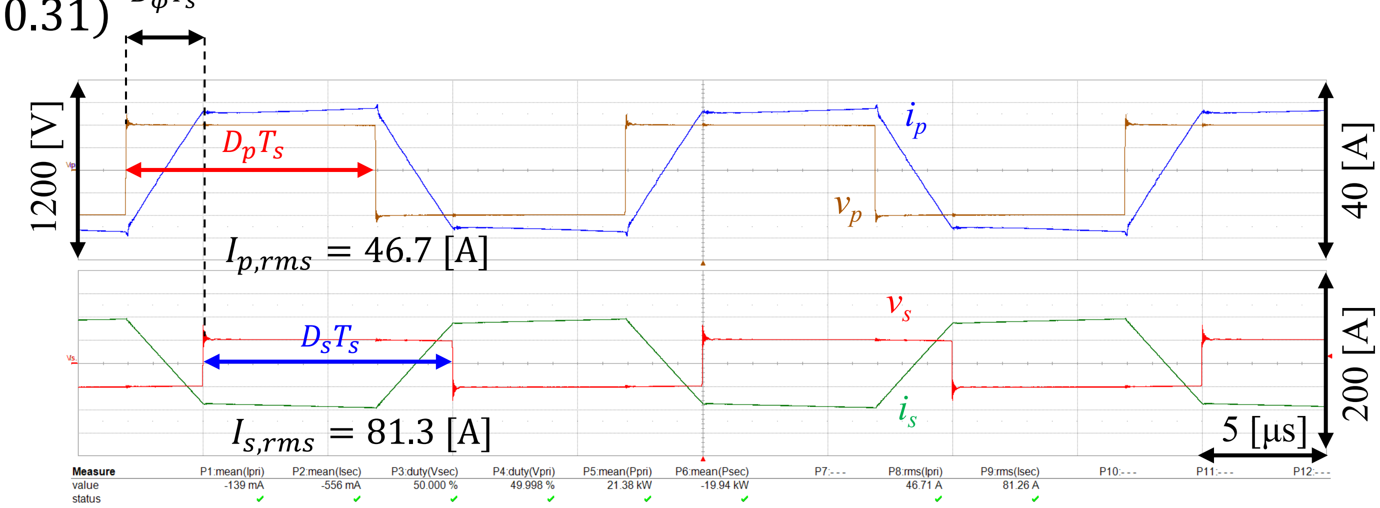
- ✓ DC-link voltages $(V_p, V_s) = (600\ [\text{V}], 300\ [\text{V}])$
- ✓ Transformer values $(n, L_p) = (1.82, 35\ [\mu\text{H}])$

▶ Control parameters

- ✓ Switching frequency $f_{sw} = 50\ [\text{kHz}]$
- ✓ Modulation values $(D_p, D_s, D_\phi) = (0.5, 0.5, 0.31)$

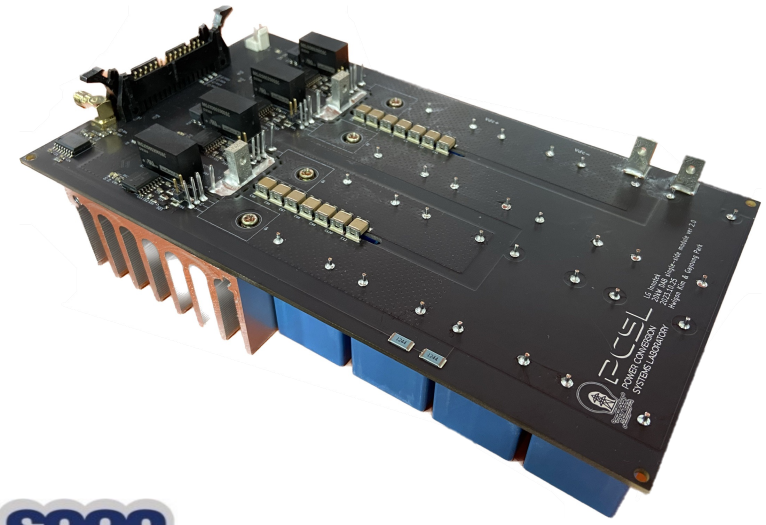
V_p: 600~800 [V]
V_s: 300~500 [V]





Measure	P1:mean(Ipri)	P2:mean(Isec)	P3:duty(Vsec)	P4:duty(Vpri)	P5:mean(Ppri)	P6:mean(Psec)	P7:---	P8:rms(Ipri)	P9:rms(Isec)	P10:---	P11:---	P12:---
value	-139 mA	-556 mA	50.000 %	49.998 %	21.38 kW	-19.94 kW		46.71 A	81.26 A			
status	✓	✓	✓	✓	✓	✓		✓	✓			

▲ Voltage and current waveforms for 20 kW output



◀ 20 kW DAB converter prototype

2 Loss Analysis of DAB Converter

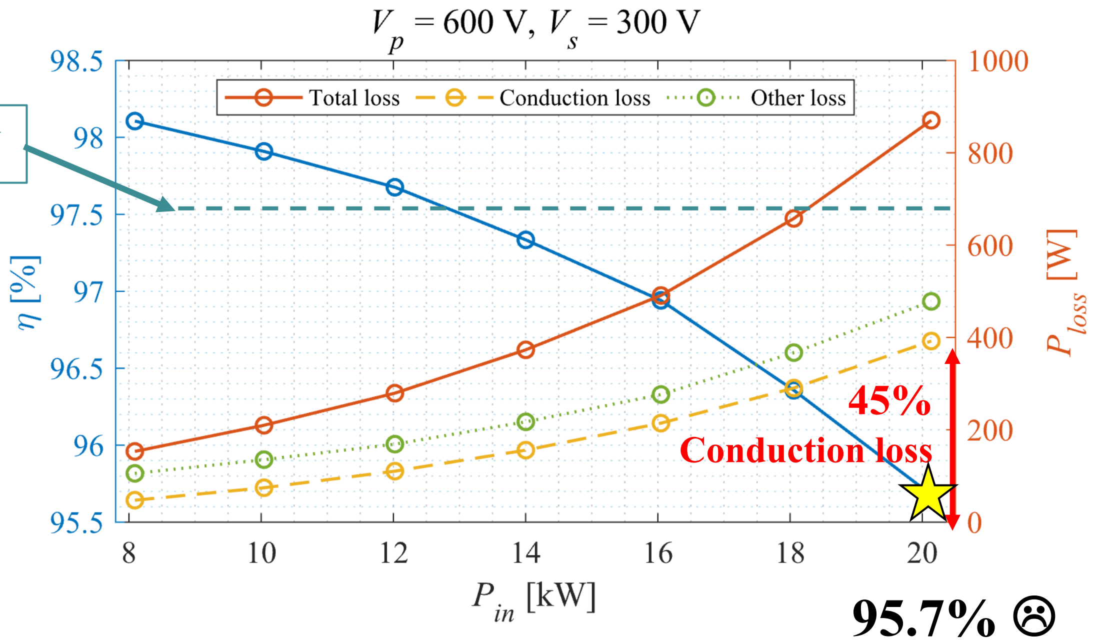
❖ Composition of Loss

- ▶ Core loss
- ▶ Conduction loss
- ▶ Switching loss

❖ Factors that Influence Efficiency

- ▶ Operating point of DAB converter
  - ✓ Physical/control parameters $(V_p, V_s, n, L_p, D_p, D_s, D_\phi)$
  - ✓ Voltage and current waveforms ★ flux linkage (volt-sec) ★ RMS current ☆ hard/soft switching
    ★ peak current → trf saturation
- ▶ HF Transformer parameters
  - ✓ Number of turns ★ flux linkage (volt-sec) ★ winding resistance
  - ✓ Core material / effective volume ★ core characteristic
- ▶ Switching device characteristics: MOSFFET ★ on resistance ★ switching-on/off loss

Goal efficiency: 97.7% @ 20 kW



95.7% ☹

3. Core Loss: Experimental Approach

3 Core Loss: Experimental Approach

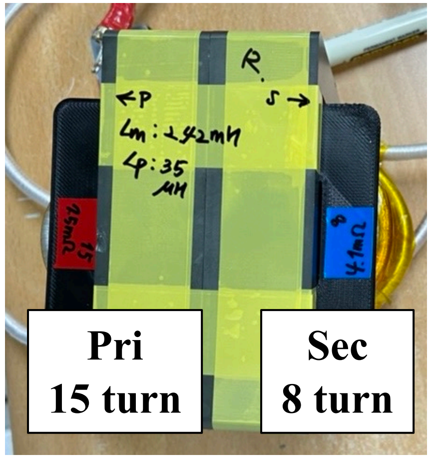
❖ Experimental Setup

- ▶ DAB parameters
  - ✓ Physical values: $(V_p, V_s, n, L_p) = (600\ [\mathrm{V}], 300\ [\mathrm{V}], 1.85, 35\ [\mu\mathrm{H}])$
  - ✓ Leakage inductance: fixed to $35\ [\mu\mathrm{H}]$
  - ✓ Control values: $(D_p, D_s) = (0.5, 0.5)$ fixed, D_ϕ varied

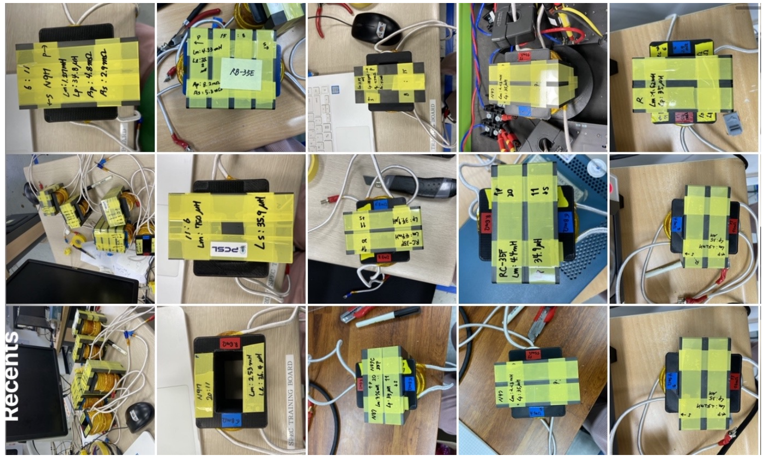
- ▶ Transformer labeling
  - ✓ Ferrite core material: N87 vs. N97 vs. R material
  - ✓ Number of turns: integer combination for $N_p/N_s = 1.85$ (fixed)
    - A (20:11) vs. B (15:8) vs. C (11:6)
  - ✓ Core area: number of ferrite E cores used
    - D (2 cores) vs. F (4 cores) vs. E (8 cores)
  - ✓ Example: RB-35F
    - Four R material cores used
    - # of turns is 15:8 and $L_p = 35\ [\mu\mathrm{H}]$

		35uH		
N87		D	E	F
	A	N87A-35D	N87A-35E	N87A-35F
	B	N87B-35D	N87B-35E	N87B-35F
	C	N87C-35D	N87C-35E	N87C-35F
N97		D	E	F
	A	N97A-35D	N97A-35E	N97A-35F
	B	N97B-35D	N97B-35E	N97B-35F
	C	N97C-35D	N97C-35E	N97C-35F
R		E	E	F
	A	RA-35D	RA-35E	RA-35F
	B	RB-35D	RB-35E	RB-35F
	C	RC-35D	RC-35E	RC-35F

*Shaded area is where experiment was conducted on



▲ RB-35F



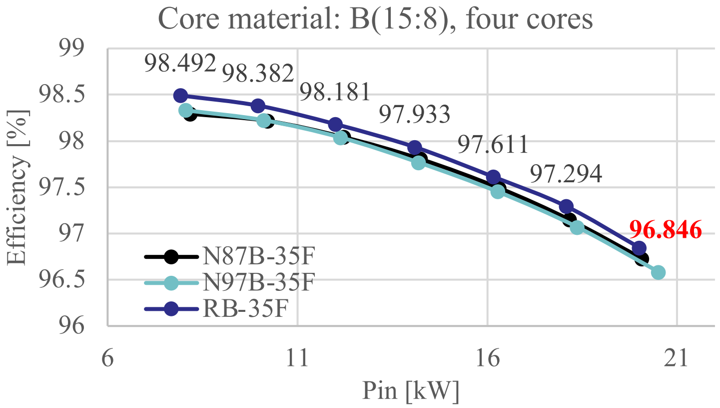
▲ Labeled transformers

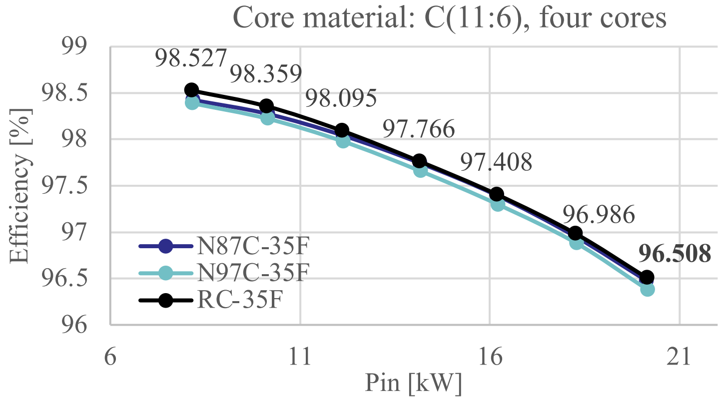
3 Core Loss: Experimental Approach

❖ Experimental Results

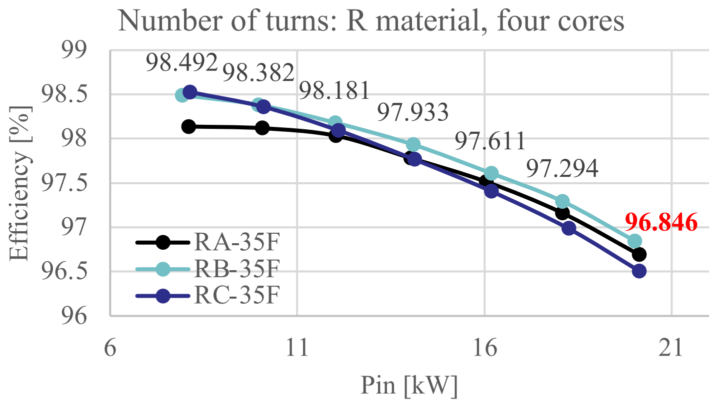
- ▶ Effect of core material
  - ✓ Efficiency*: N97 < N87 < R

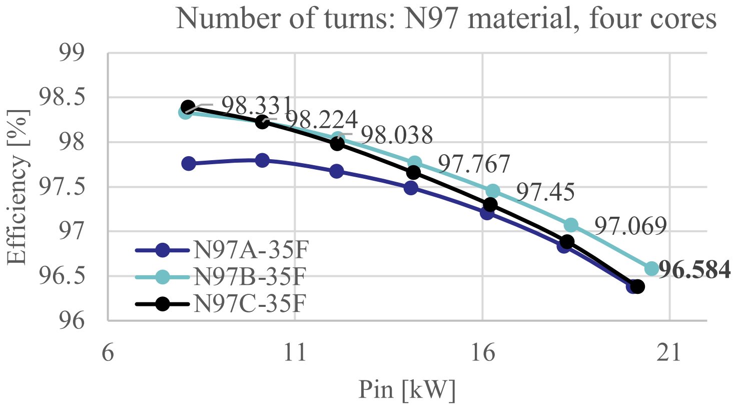
*20 kW power output


Core material: B(15:8), four cores

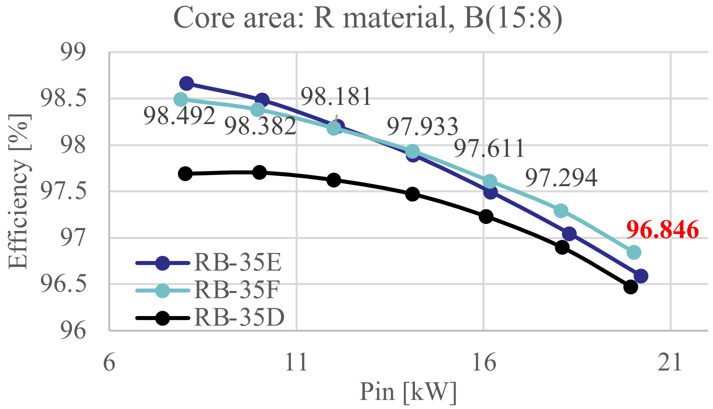

Core material: C(11:6), four cores

- ▶ Effect of number of turns
  - ✓ Efficiency*: A, C < B (15:8)
  - ✓ As # of turns increases,
    - Core loss ▼
    - Conduction loss ▲


Number of turns: R material, four cores


Number of turns: N97 material, four cores

- ▶ Effect of core area
  - ✓ Efficiency*: D, E (2, 8 cores) < F (4 cores)
  - ✓ As core area increases,
    - Core loss ▼
    - Conduction loss ▲


Core area: R material, B(15:8)

4. Conduction Loss:

RMS Current Minimization

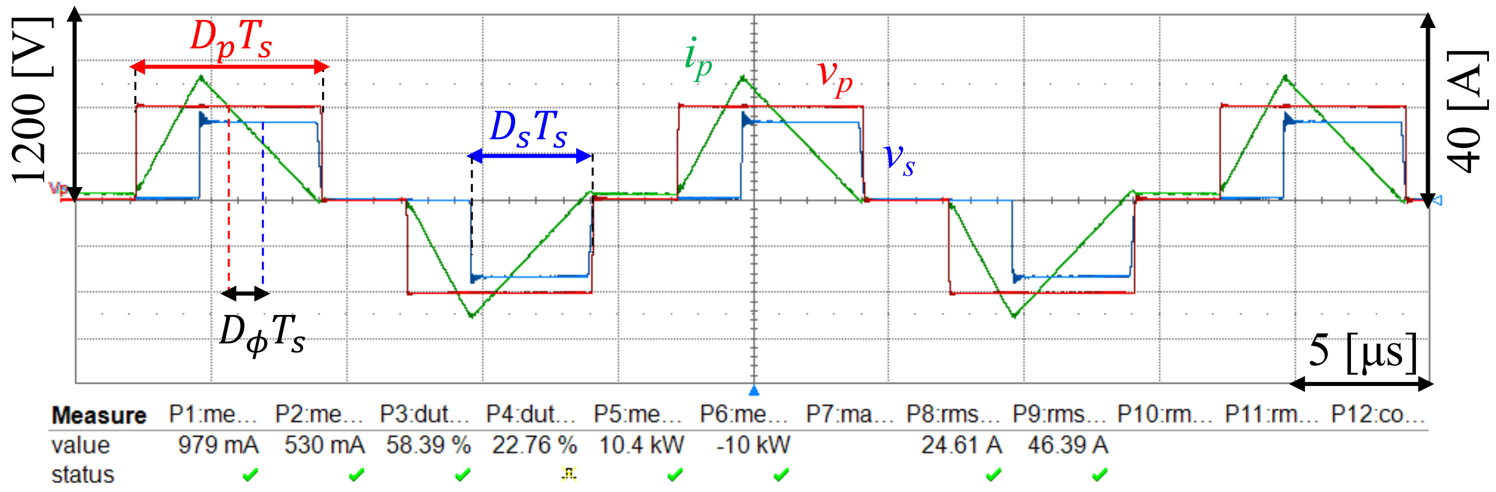
Conduction Loss: RMS Current Minimization

❖ Conduction Loss

- ▶ $P_{cond} = \boxed{I_{p,rms}^2} R_{tot}$

To be minimized!

- ▶ RMS current determined by DAB parameters



Measure	P1:me...	P2:me...	P3:dut...	P4:dut...	P5:me...	P6:me...	P7:ma...	P8:rms...	P9:rms...	P10:rm...	P11:rm...	P12:co...
value	979 mA	530 mA	58.39 %	22.76 %	10.4 kW	-10 kW		24.61 A	46.39 A			
status	✓	✓	✓		✓	✓		✓	✓			

▲ **TPS modulation waveforms for 10 kW output**

$(V_p = 600\ [\text{V}], V_s = 500\ [\text{V}], n = 1.875, L_p = 28\ [\mu\text{H}],$

$D_p = 0.35, D_s = 0.23, D_\phi = 0.06)$

(0~0.5) (0~0.5) (0~0.25)

❖ DAB Modulation Schemes

- ▶ Triple-phase-shift (TPS) modulation
  - ✓ 3-DOF: D_p, D_s, D_ϕ
  - ✓ Various optimization objectives
    - Ex) peak current, circulating power, etc.

4 Conduction Loss: RMS Current Minimization

❖ TPS Modulation for Minimizing RMS Current[2]

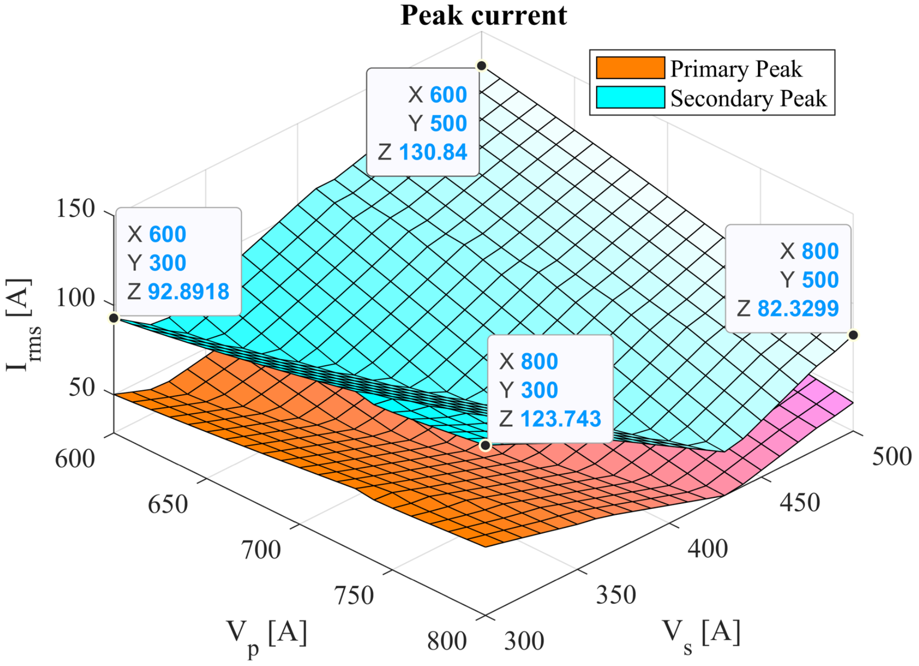
- ▶ Optimization variable: (D_p, D_s, D_ϕ)
- ▶ Objective: to minimize RMS current
- ▶ Constraint: to output desired power

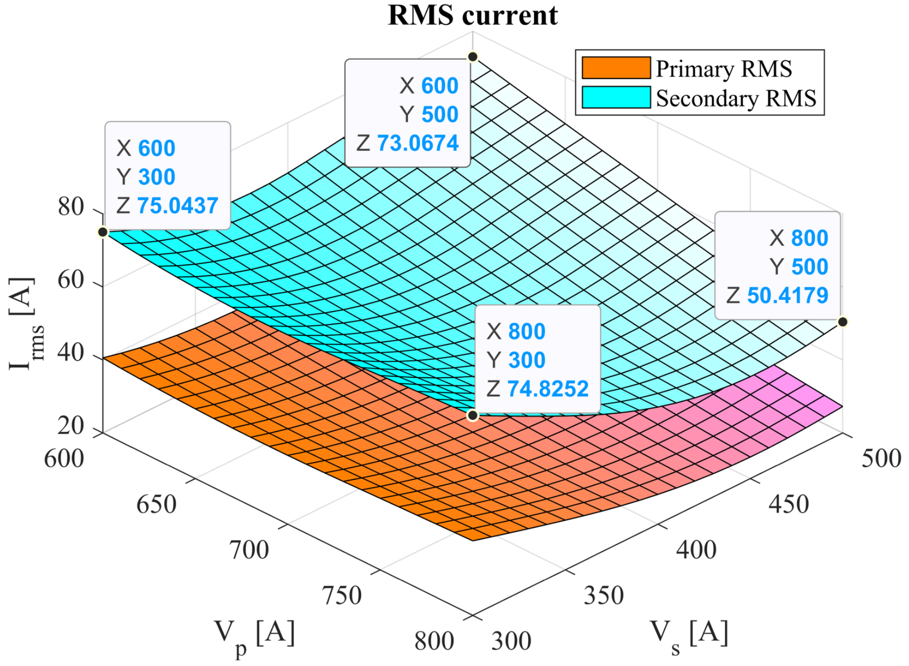
$$\min_{x} f(x) \ \ such\ that \begin{cases} c(x) \le 0 \\ c_{eq}(x) = 0 \\ Ax \le b \\ A_{eq}x = b_{eq} \\ lb \le x \le ub \end{cases}$$

- $x := [D_p \quad D_s \quad D_\phi]$
- $f(x) = I_{rms}^2(x)$
- $c_{eq}(x) = P - P_{ref} = 0$
- $Lb = [0.01 \quad 0.01 \quad 0.01]$
  $Ub = [0.5 \quad 0.5 \quad 0.25]$

▲ Nonlinear optimization problem for RMS current minimization

- ▶ Peak and RMS current calculated with optimal (D_p^*, D_s^*, D_ϕ^*) for each operating point





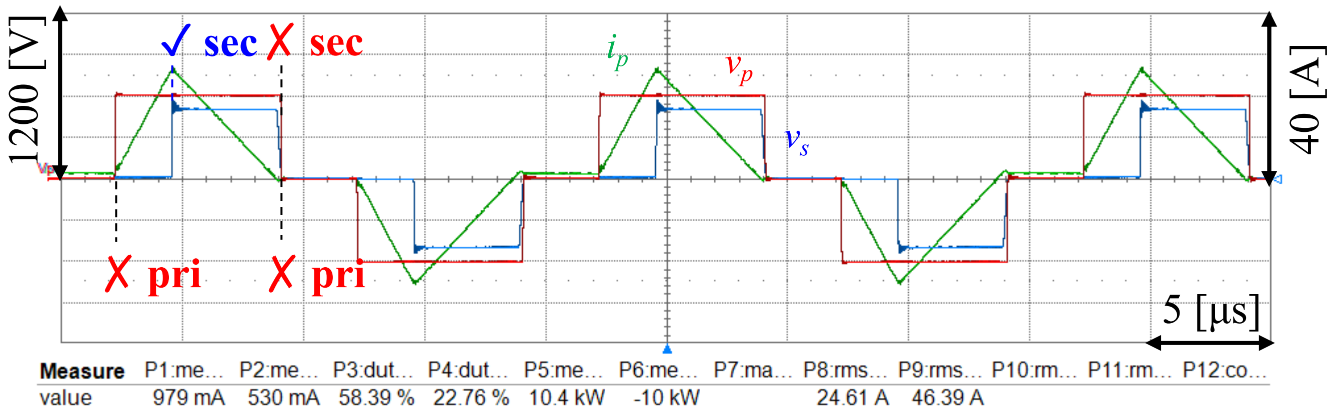
[2] Noroozi et al.. “RMS Current Minimization in a SiC-Based Dual Active Bridge Converter Using Triple-Phase-Shift Modulation.” *IEEE Transactions on Industrial Electronics* 70, no. 7 (July 2023): 7173–82.

4 Conduction Loss: RMS Current Minimization

❖ Limitations of RMS Current Minimization

- ▶ Trade-off: conduction loss ↔ switching loss
  - ✓ Small $R_{ds,on}$, Large E_{on}, E_{off} of SiC MOSFET
- ▶ Zero-voltage switching (ZVS) > zero-current switching (ZCS)
  - ✓ On-loss E_{on} > Off-loss E_{off}

✓ ZVS ✗ ZCS



▲ **TPS modulation waveforms for 10 kW output**

$(V_p = 600\ [\text{V}], V_s = 500\ [\text{V}], n = 1.875, L_p = 28\ [\mu\text{H}],$
$D_p = 0.35, D_s = 0.23, D_\phi = 0.06)$

	IMZA120R014M1H	IMZA120R007M1H
Package	TO247-4-NT3.7	TO247-4-NT3.7
I_{DDC}	127 A	225 A
$R_{ds,on}$	14 mΩ	7 mΩ
$R_{g,int}$	3.7 Ω	1.8 Ω
C_{iss}	4580 pF	9170 pF
C_{oss}	211 pF	420 pF
$t_{d,on}$	48 ns	97 ns
$t_{d,off}$	58 ns	116 ns
E_{on}	560 μJ	1360 μJ
E_{off}	150 μJ	410 μJ

▲ **Comparison between**
1200V SiC MOSFET from Infineon

➔ Solution is to achieve ZVS!

5. Switching Loss:

ZVS Constrained Optimization

5 Switching Loss: ZVS Constrained Optimization

❖ TPS Modulation for Lower Switching Loss

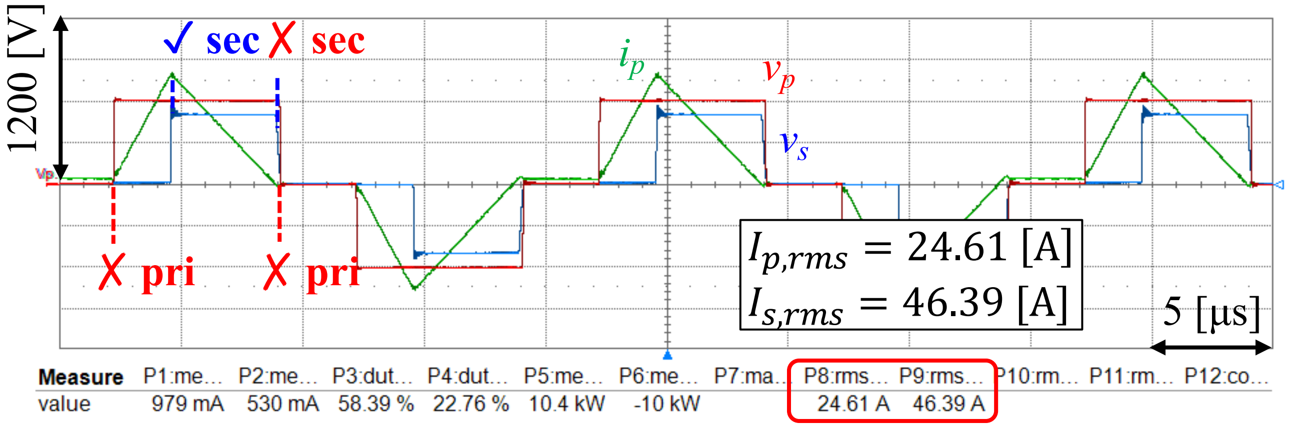
- ▶ **Add ZVS condition as constraints** of optimization problem
- ▶ Optimal solution is satisfies:
  - ✓ ZVS constraint
  - ✓ Desired output power
  - ✓ RMS current minimization

$$\min_{x} f(x) \ \ such\ that \begin{cases} c(x) \le 0 \\ c_{eq}(x) = 0 \\ \boxed{Ax \le b} \\ A_{eq}x = b_{eq} \\ lb \le x \le ub \end{cases}$$

- $x := [D_p \quad D_s \quad D_\phi]$
- $f(x) = I_{rms}^2(x)$
- $c_{eq}(x) = P - P_{ref} = 0$
- $Lb = [0.01 \quad 0.01 \quad 0.01]$
  $Ub = [0.5 \quad 0.5 \quad 0.25]$
- $\boxed{i_{p,s}(x) > I_{ZVS}}$

❖ Experimental Result: TPS Modulation for 10 kW Power Out

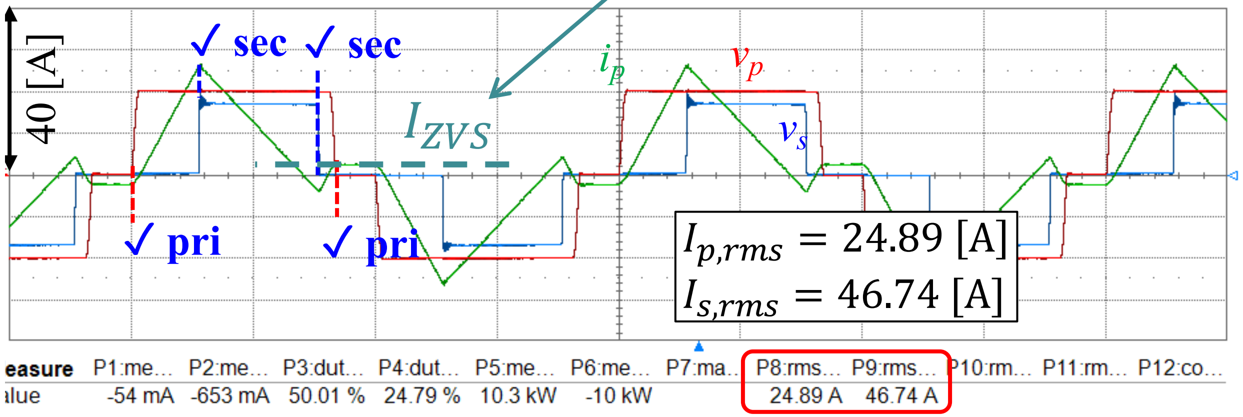
✓ ZVS ✗ ZCS



Measure	P1:me...	P2:me...	P3:dut...	P4:dut...	P5:me...	P6:me...	P7:ma...	P8:rms...	P9:rms...	P10:rm...	P11:rm...	P12:co...
value	979 mA	530 mA	58.39 %	22.76 %	10.4 kW	-10 kW		24.61 A	46.39 A			

▲ **Only RMS current minimization considered**

($V_p = 600$ [V], $V_s = 500$ [V], $n = 1.875$, $L_p = 28$ [μH],
$D_p = 0.35$, $D_s = 0.23$, $D_\phi = 0.06$)



easure	P1:me...	P2:me...	P3:dut...	P4:dut...	P5:me...	P6:me...	P7:ma...	P8:rms...	P9:rms...	P10:rm...	P11:rm...	P12:co...
alue	-54 mA	-653 mA	50.01 %	24.79 %	10.3 kW	-10 kW		24.89 A	46.74 A			

▲ **ZVS constrained RMS current minimization**

($V_p = 600$ [V], $V_s = 500$ [V], $n = 1.875$, $L_p = 28$ [μH],
$D_p = 0.425$, $D_s = 0.248$, $D_\phi = 0.05$)

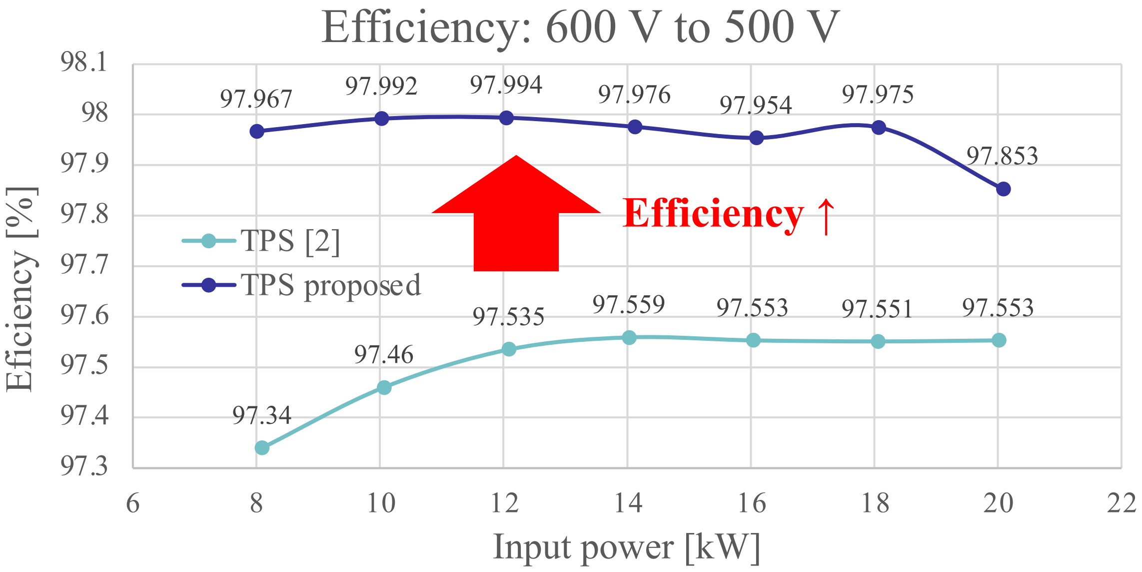
5 Switching Loss: ZVS Constrained Optimization

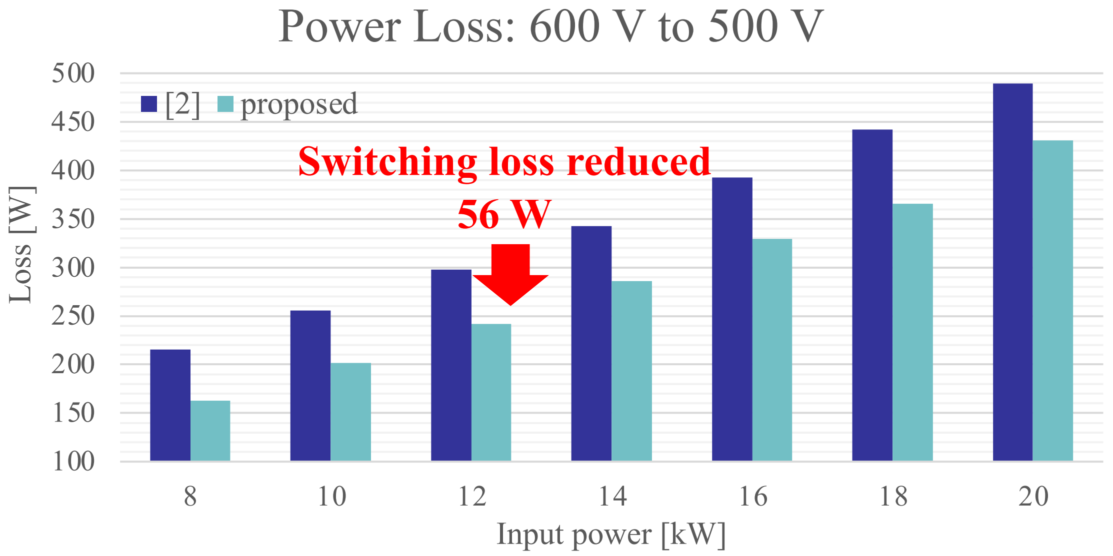
❖ Proposed TPS Modulation Method

- ▶ ZVS constrained RMS current minimization
  - ✓ Extend # of switches that ZVS as many as possible
  - ✓ Aimed for MOSFET-based DAB converter

❖ Experimental Result: Efficiency

- ▶ Switching loss reduced by achieving ZVS





6. Conclusion

6 Conclusion

❖ Development of DAB Converter for DC Fast Charger

- ▶ SiC-based 20 [kW] DAB Converter

❖ Loss Analysis

- ▶ Core loss reduction
  - ✓ Experiments on transformer characteristics
- ▶ Conduction loss reduction
  - ✓ TPS modulation based on optimization
  - ✓ RMS current minimized
- ▶ Switching loss reduction
  - ✓ Proposed TPS modulation based on ZVS constrained optimization
  - ✓ Enabled ZVS of as many switches as possible
  - ✓ Reduced switching loss → Efficiency ↑

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