# Performance Evaluation of SiC-based Isolated Bidirectional DC/DC Converters for Electric Vehicle Charging

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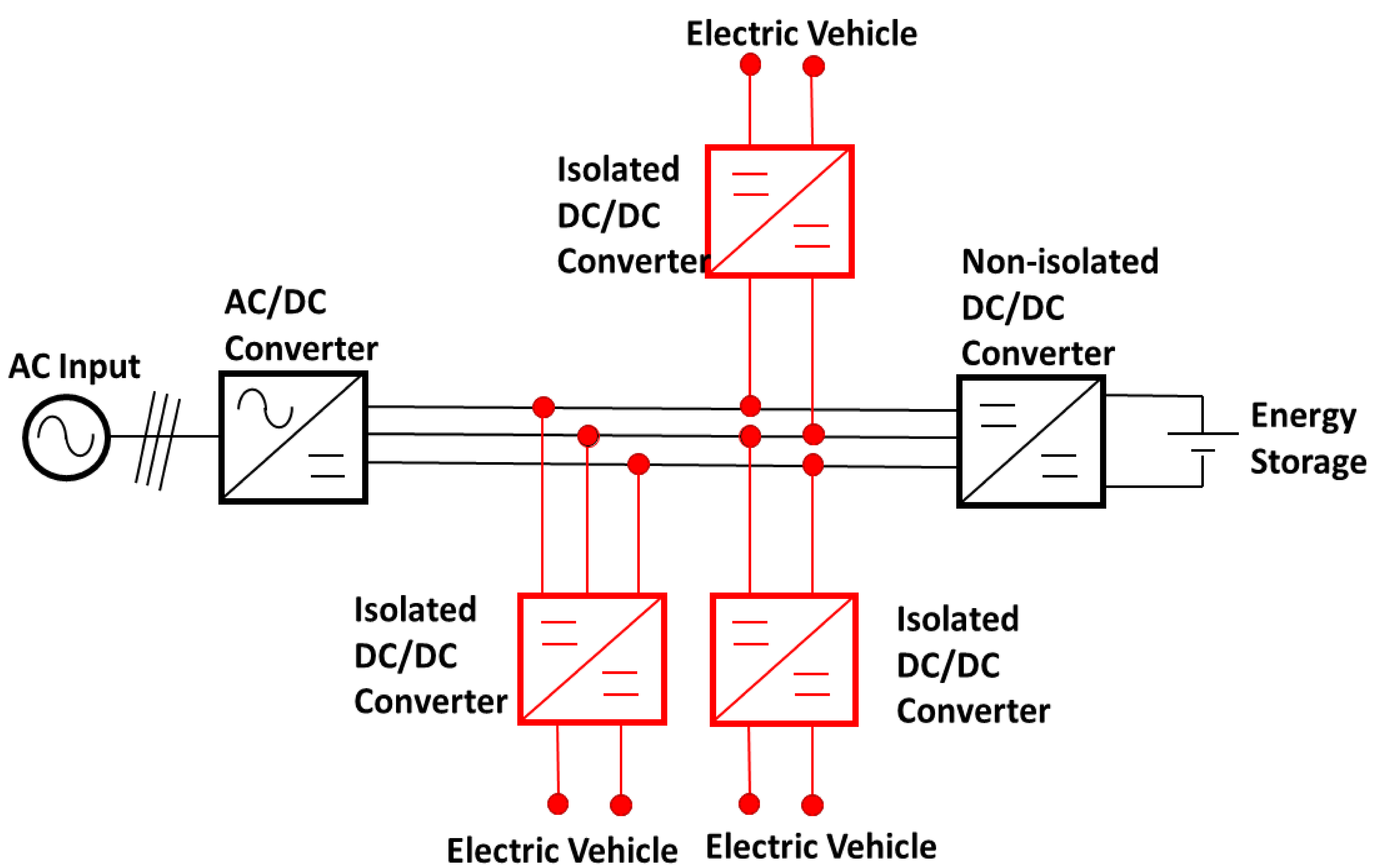
# Content overview

- Background
- Considered topologies
- Converter design considerations
- Performance evaluation – criteria and methods
- Simulation and theoretical analyses results
- Evaluation summary
- Experimental validation
- Conclusions

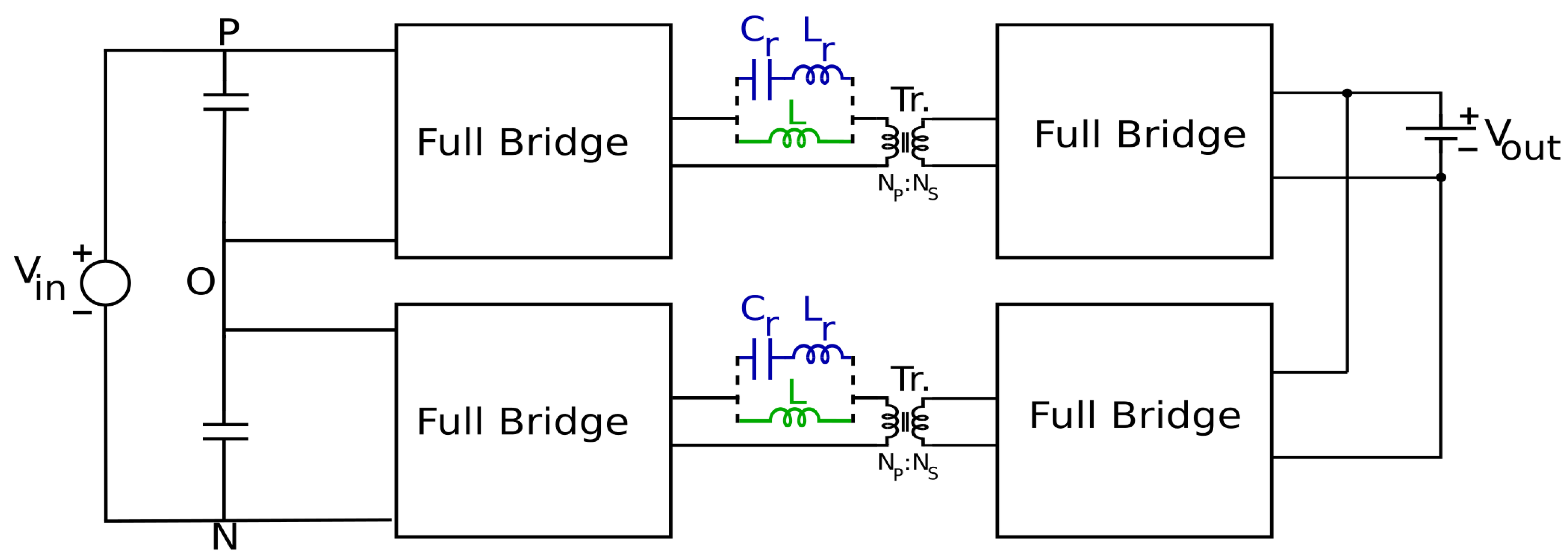
# Background

- The installation of advanced electric vehicles (EVs) fast charging infrastructure with bidirectional capability is paramount considering challenges like EVs demand flexibility, power grid support (V2G), etc.
- The isolated bidirectional DC/DC converter (IBDC) is one of the key components of an EV charging system.
- The first step for its design is the choice and performance evaluation of the utilized power electronics converter topology.

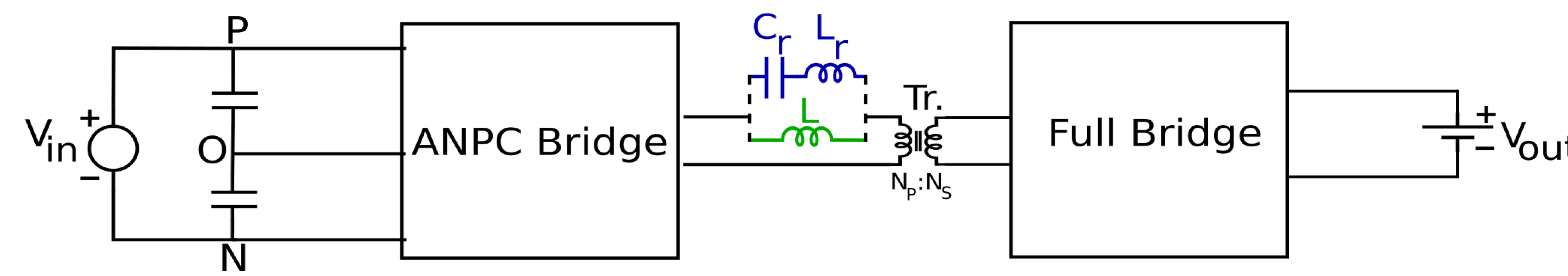



Schematic of the considered EV charging system based on +750/0/-750V three-wire DC bus

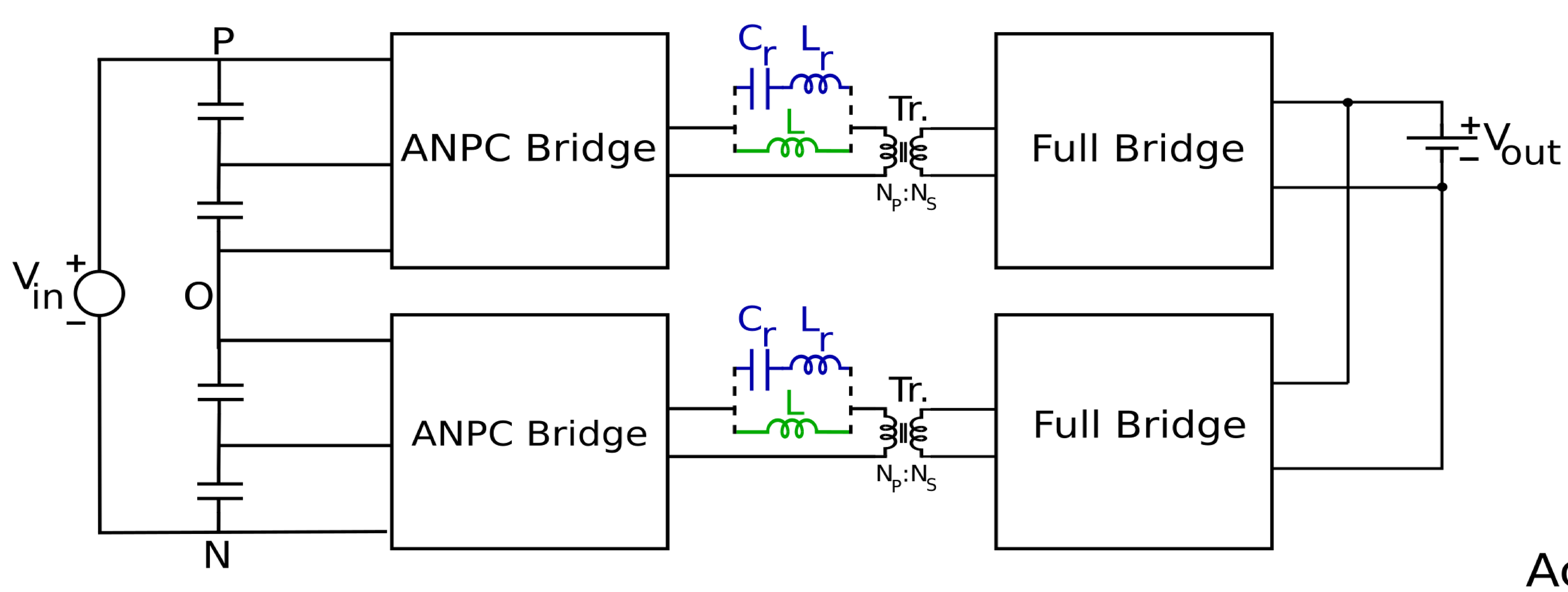
# Considered topologies



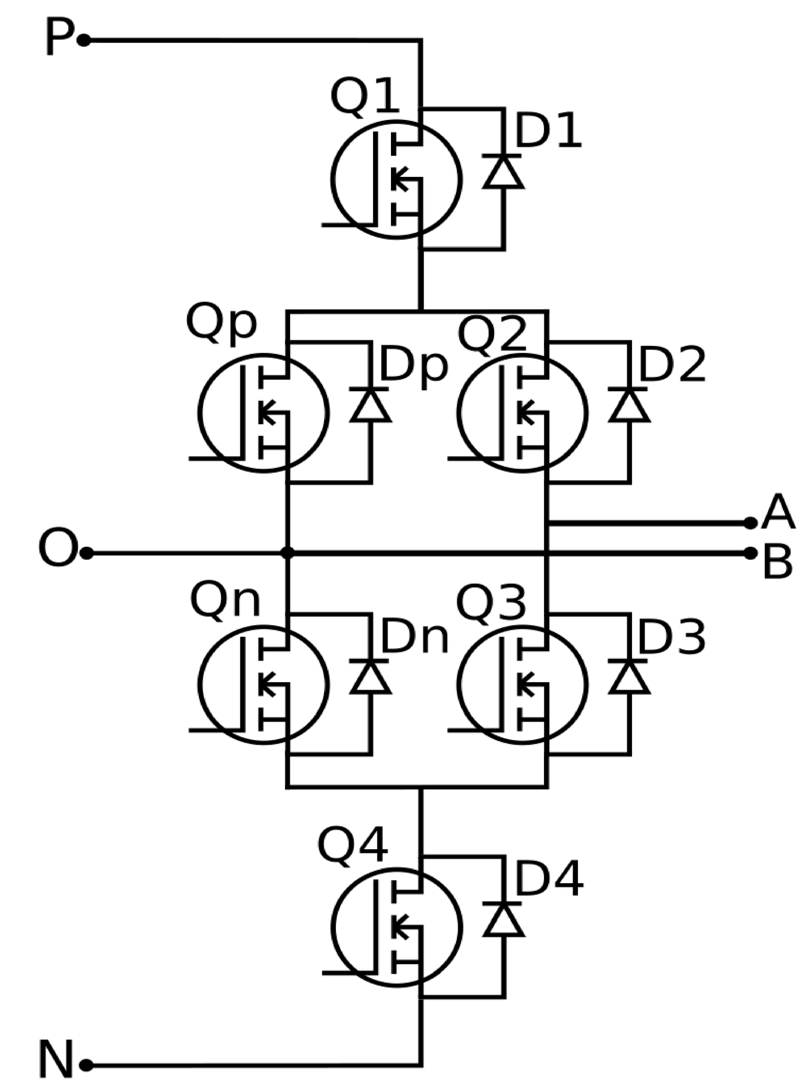

Input-series output-parallel (ISOP) FB DAB



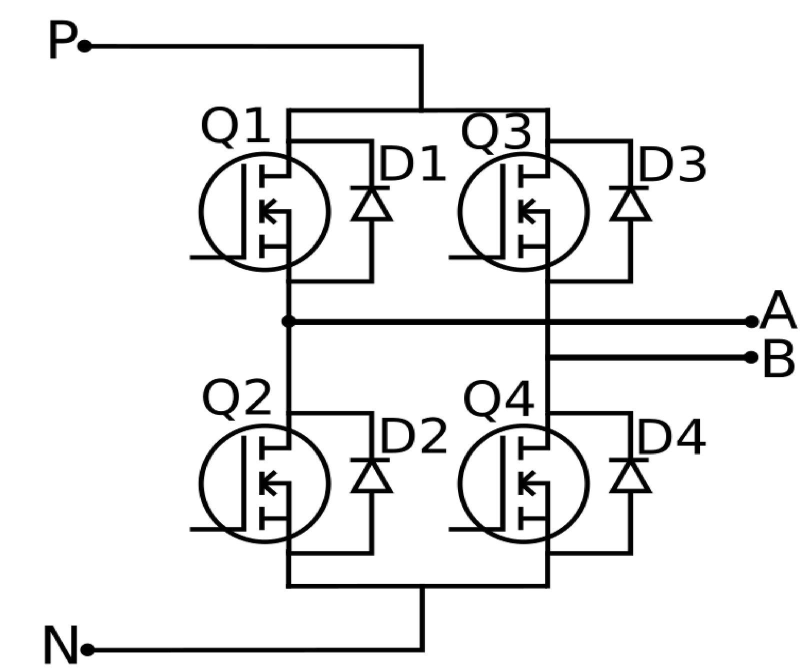

ANPC DAB




ISOP ANPC DAB




Active neutral point clamped (ANPC) bridge


Full-bridge (FB)

Topologies are chosen for evaluation based on following considerations:
1) Bipolar (three-wire) nature of input DC bus
2) Two-terminal nature of EV battery load
3) Bidirectional power flow
3) Voltage flexibility
4) Power scalability

# Converter design considerations

**Design parameters for the converters**

| DAB type | Non-resonant DAB | Series-resonant DAB |
|---|---|---|
| $V_{in}$ | 1500 V | |
| $V_{out}$ | 400 V | |
| $P_{out}$ | 10 kW | |
| $f_{sw}$ | 100 kHz | |
| $L/L_r$ | 17 µH – 70 µH* | 100 µH |
| $C_r$ | - | 28 nF |
| N | Vprimary_pk/Vsecondary_pk | |

**SiC MOSFETs utilized in each topology**

| Topology | MOSFET used in primary bridge | MOSFET used in secondary bridge |
|---|---|---|
| ISOP FB DAB | NTH4L040N120SC1[1] | C3M0015065K[2] |
| ISOP ANPC DAB | IMZA65R039M1HXKSA1[3] | C3M0015065K[2] |
| ANPC DAB | NTH4L040N120SC1[1] | C3M0015065K[2] |

[1]1200V, 40mΩ, 58A SiC MOSFET from ON semiconductor
[2]650V, 15mΩ,120A SiC MOSFET from CREE
[3]650V, 39mΩ, 50A SiC MOSFET from Infineon

Vin -> dc input voltage
Vout-> dc output voltage
Pout-> output power
fsw-> switching frequency
L/Lr -> non-resonant/resonant series-inductance
Cr -> resonant capacitance
N -> transformer turns ratio
Vprimary_pk -> peak transformer primary voltage
Vsecondary_pk -> peak transformer secondary voltage.

*The series-inductance values depend on the converter topology.

# Converter design considerations (cont.)

- Switching frequency selection -> trade-off between the heat sink size, the size of magnetics and the switching losses.

- The selection of SiC MOSFETs was made considering:
  1) Type of bridge circuit (i.e., ANPC or FB)
  2) Considered voltage and power levels,
  3) Better switching performance in terms of faster switching transients due to lower stray inductance in the gate loop (four-pin devices with Kelvin connection)
  4) Availability in the market.

- N= Vprimary_pk/Vsecondary_pk -> to minimize circulating currents.

- Design of L -> to reduce reflow power.

- Single operating point -> unidirectional power flow considered

# Performance evaluation – criteria and methods

Performance evaluation criteria:

1) Efficiency
2) Loss distribution
3) Volt-Ampere ratings
4) Normalized cost

Considering only the SiC MOSFETs

Evaluation Methods:

- Simulations

(Estimation of SiC MOSFET switching energies)

(Calculation of converter efficiency and loss distribution)

- Theoretical analyses
  - Calculation of normalized cost and volt-ampere semiconductor ratings



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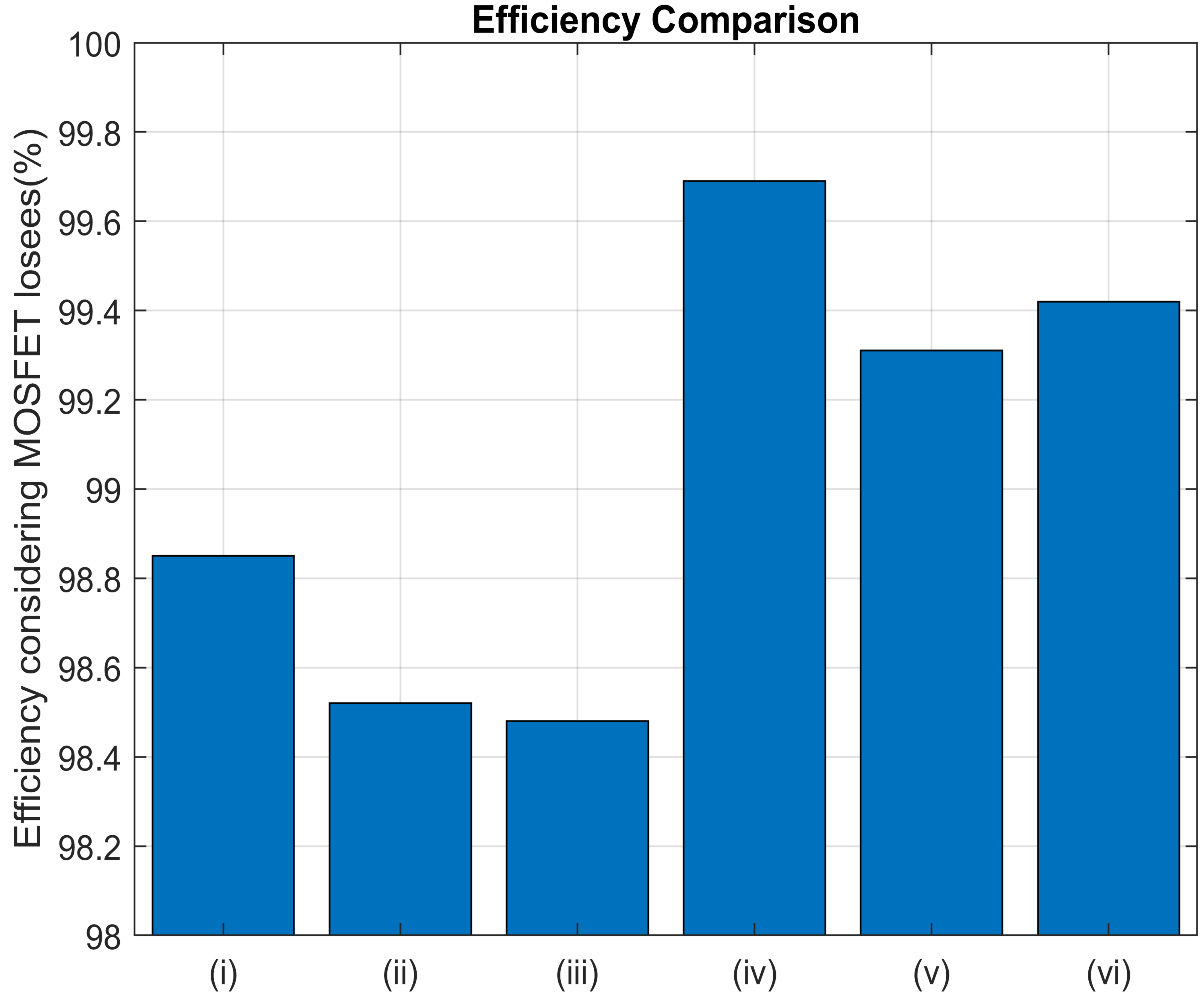
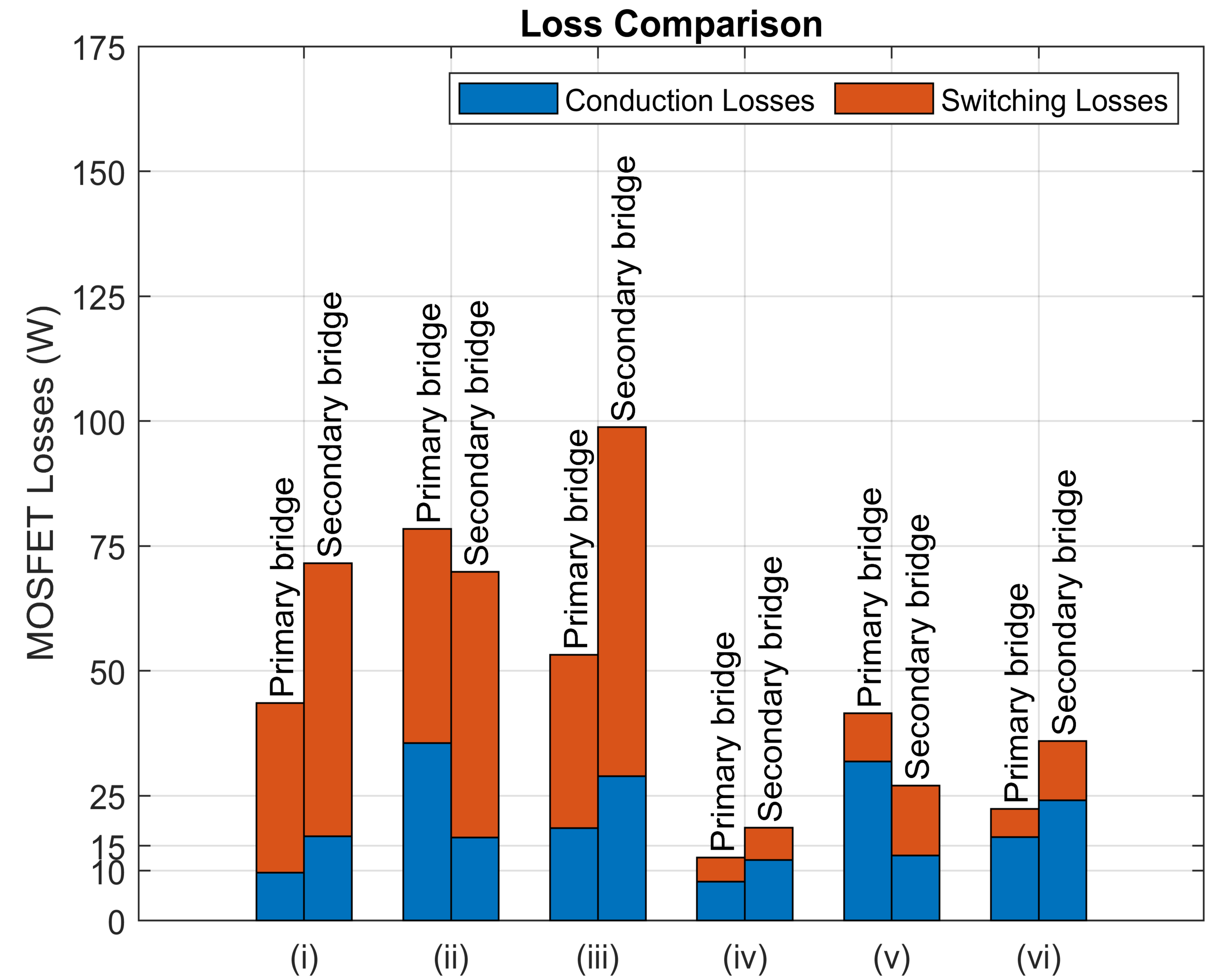
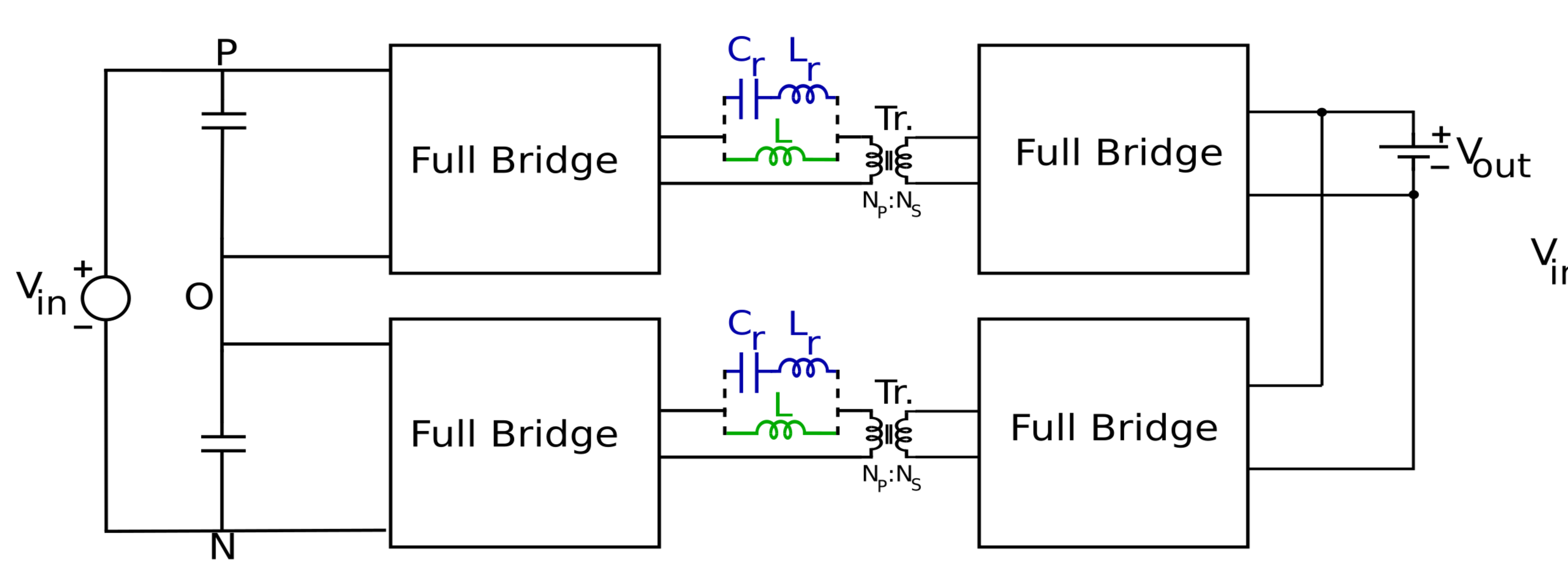
# Simulation results – Efficiency and loss data

**Results from simulations using PLECS (considering only the SiC MOSFET losses)**

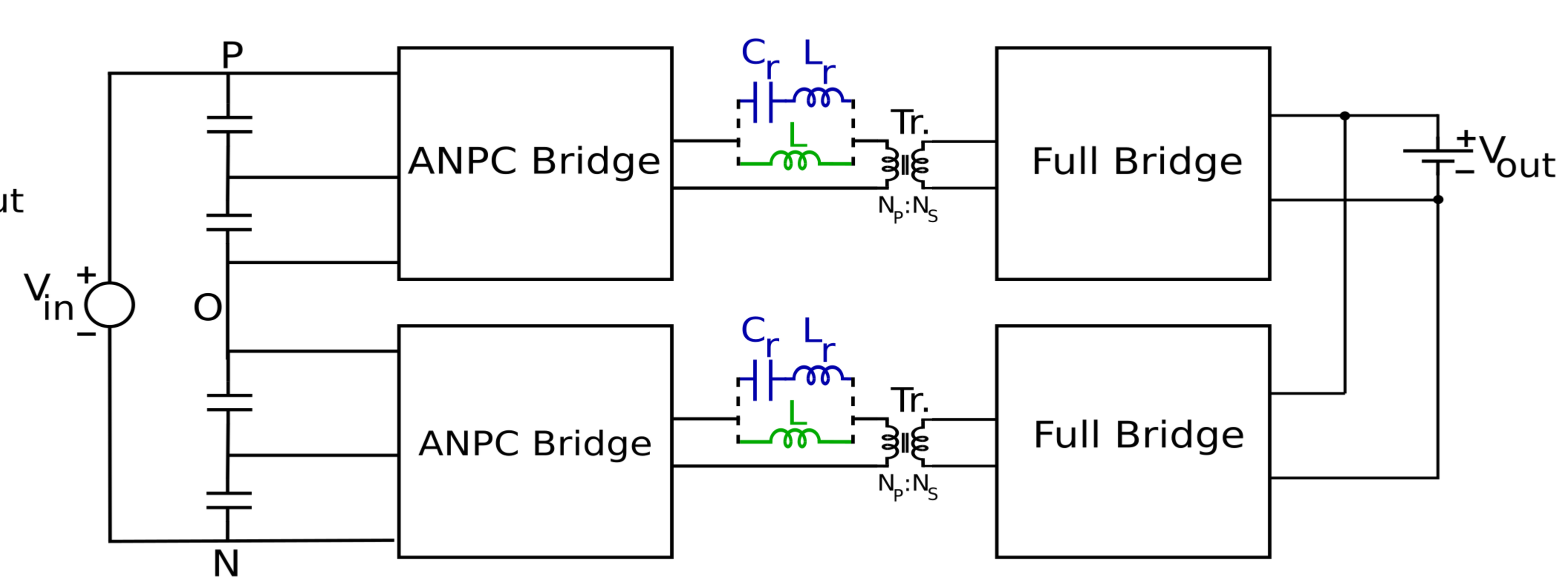


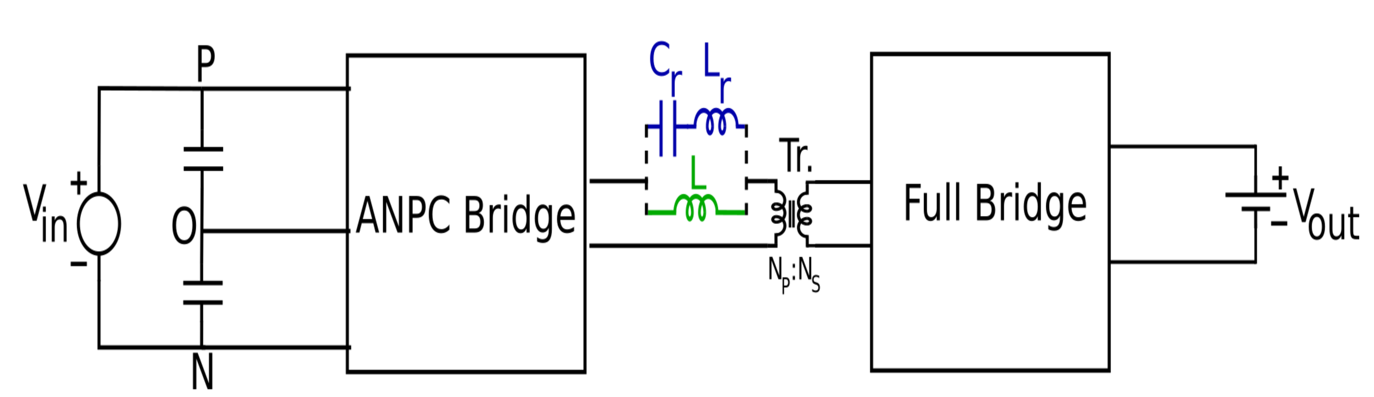

(i) ISOP FB DAB (ii) ISOP ANPC DAB (iii) ANPC DAB (iv) SR ISOP FB DAB (v) SR ISOP ANPC DAB (vi) SR ANPC DAB




Input-series output-parallel (ISOP) FB DAB




ISOP ANPC DAB




ANPC DAB



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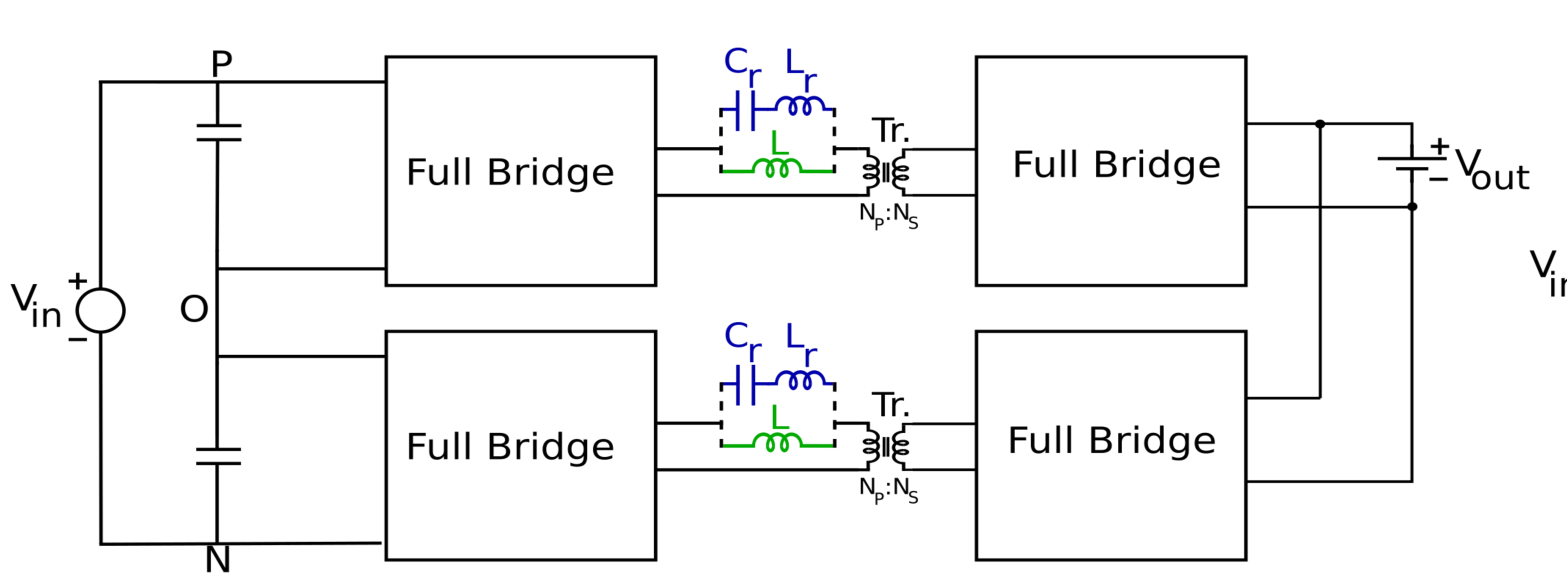
# VA ratings and normalized cost

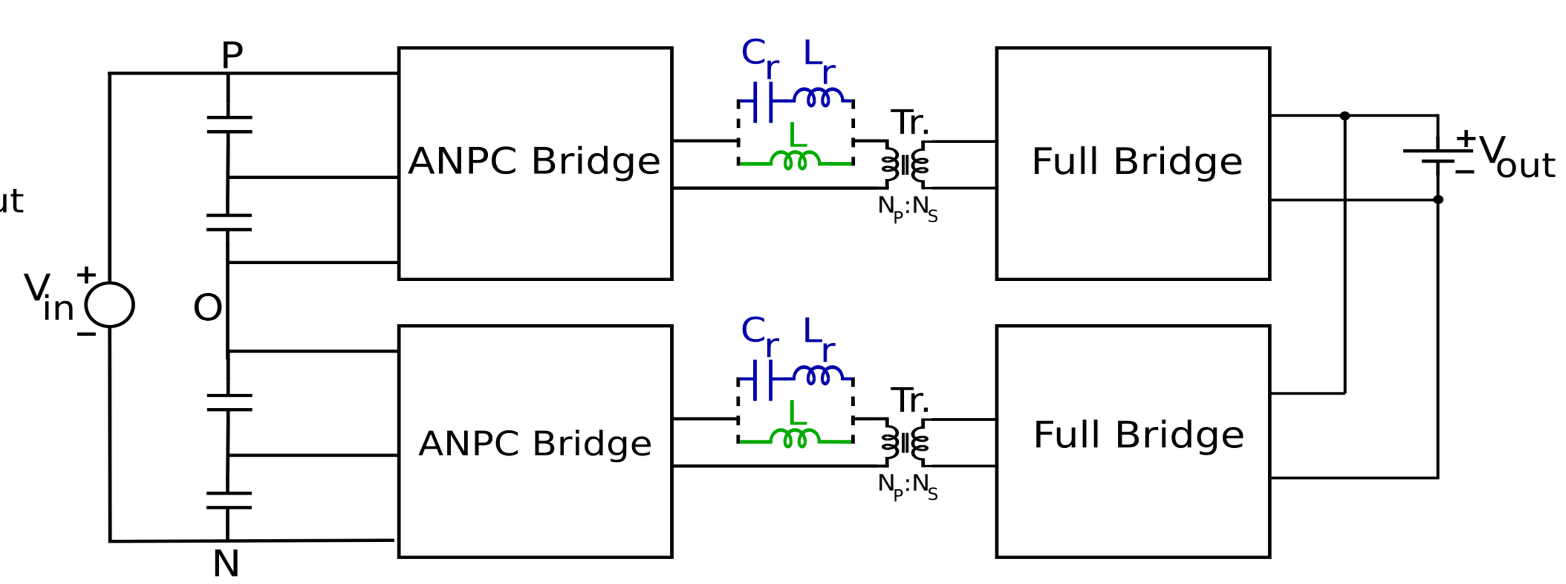
| Topology | VA rating of SiC MOSFETs (kVA) | | | Normalized total cost of MOSFETs* |
|---|---|---|---|---|
| | Primary bridge | Secondary bridge | Total | |
| ISOP FB DAB | 556.8 (8 * 1200V * 58A) | 624 (8 * 650V * 120A) | 1180.8 | 2.34 |
| ISOP ANPC DAB | 390 (12 * 650V * 50A) | 624 (8 * 650V * 120A) | 1014 | 2.32 |
| ANPC DAB | 417.6 (6 * 1200V * 58A) | 312 (4 * 650V* 120A) | 729.6 | 1.44 |

*Cost normalized per 200 USD

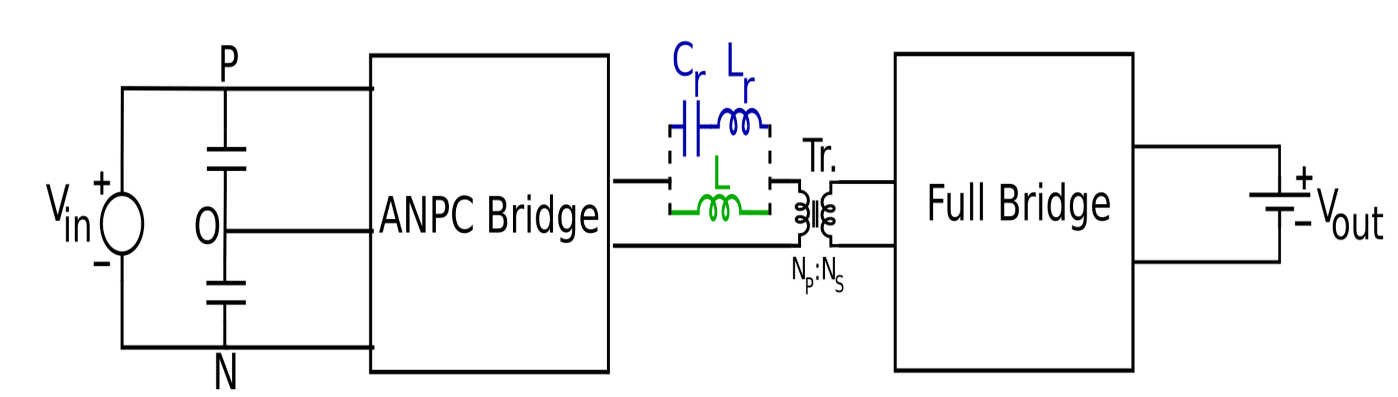
ANPC DAB is the most cost-effective configuration and requires the lowest VA ratings of SiC MOSFETs compared to the ISOP DAB topologies for the considered operating conditions.




Input-series output-parallel (ISOP) FB DAB

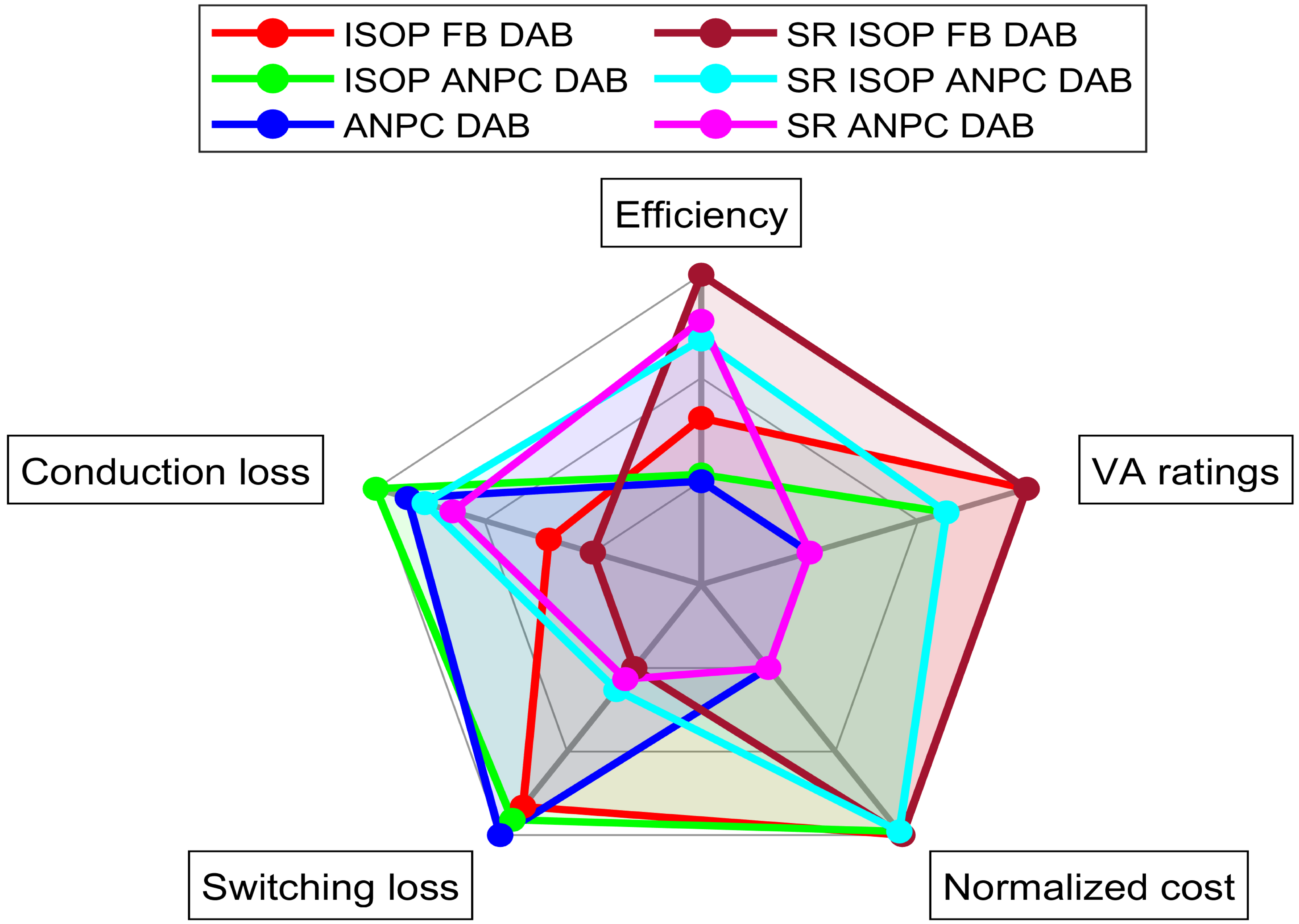


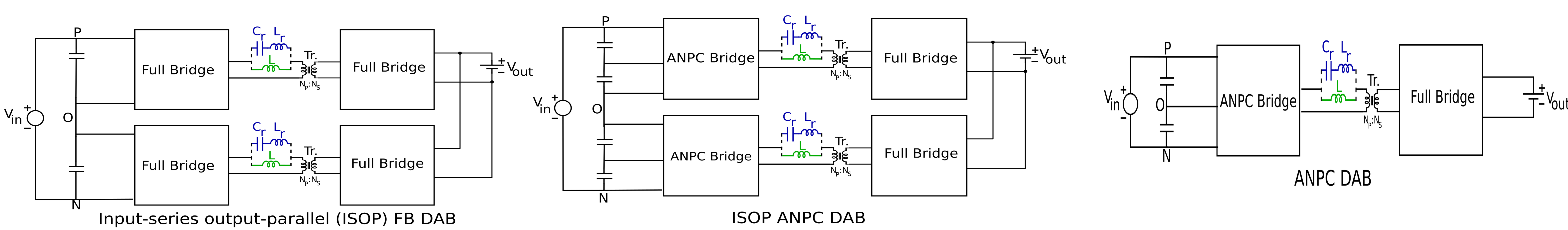

ISOP ANPC DAB




ANPC DAB

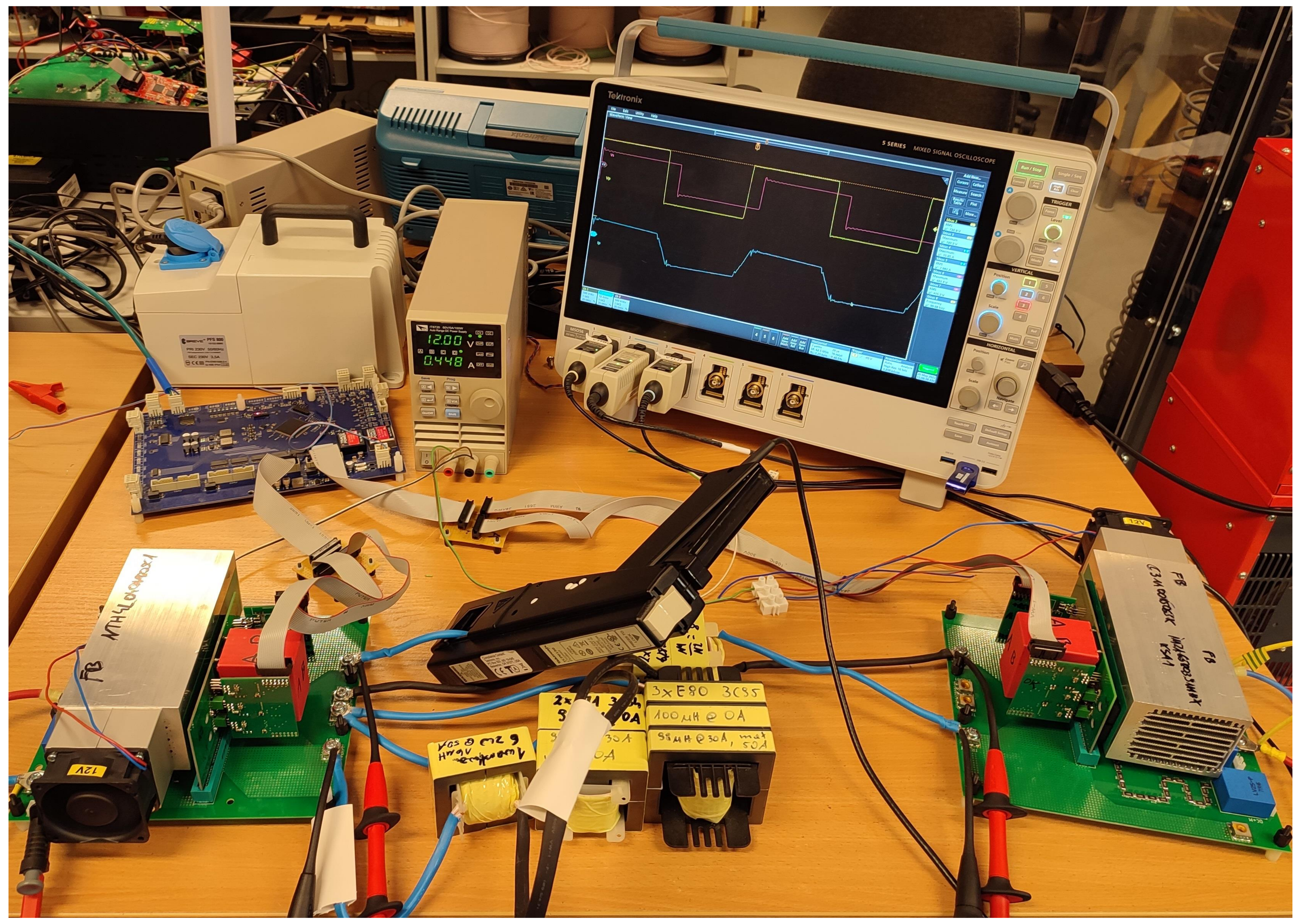
# Evaluation summary



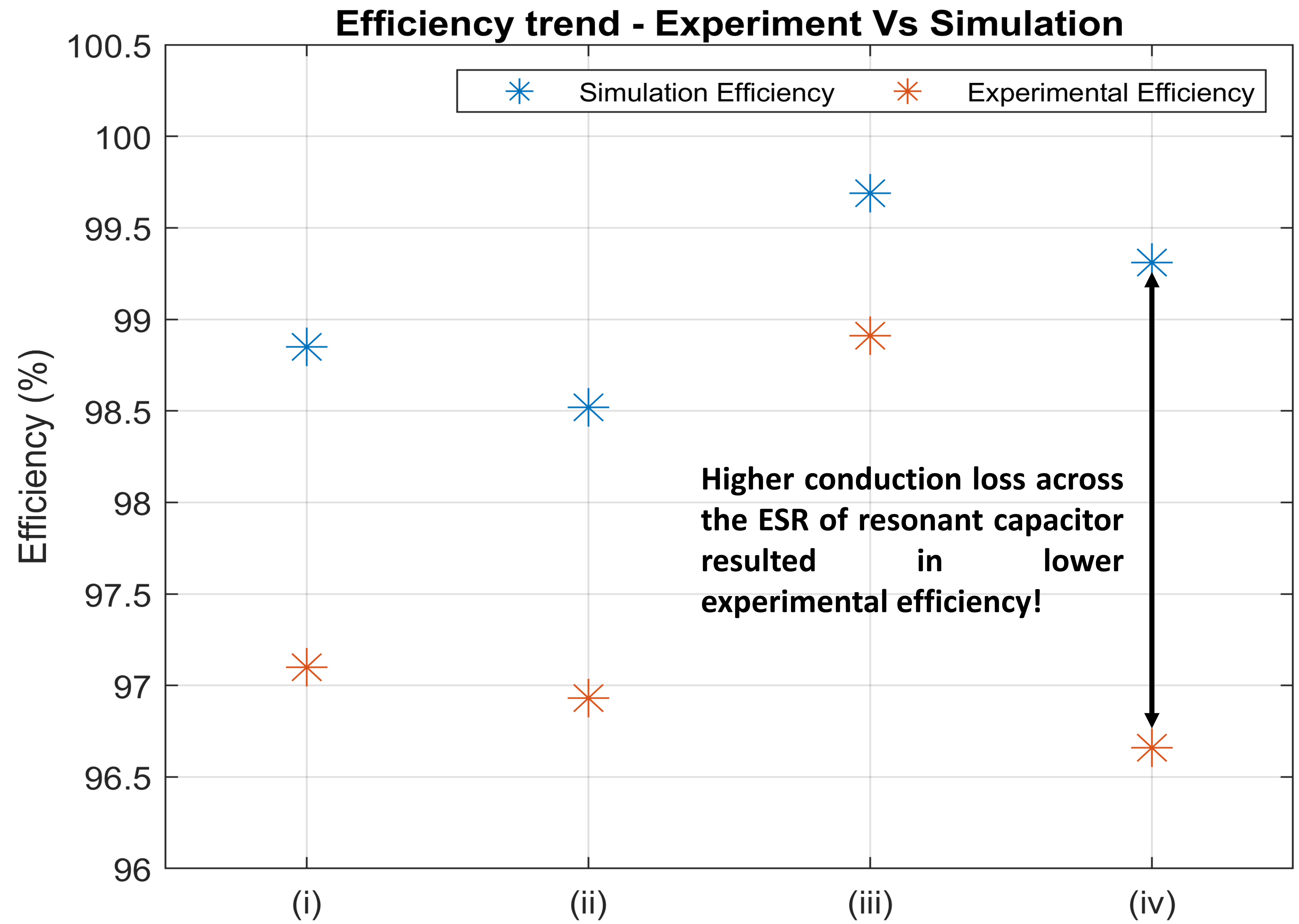



# Experimental validation

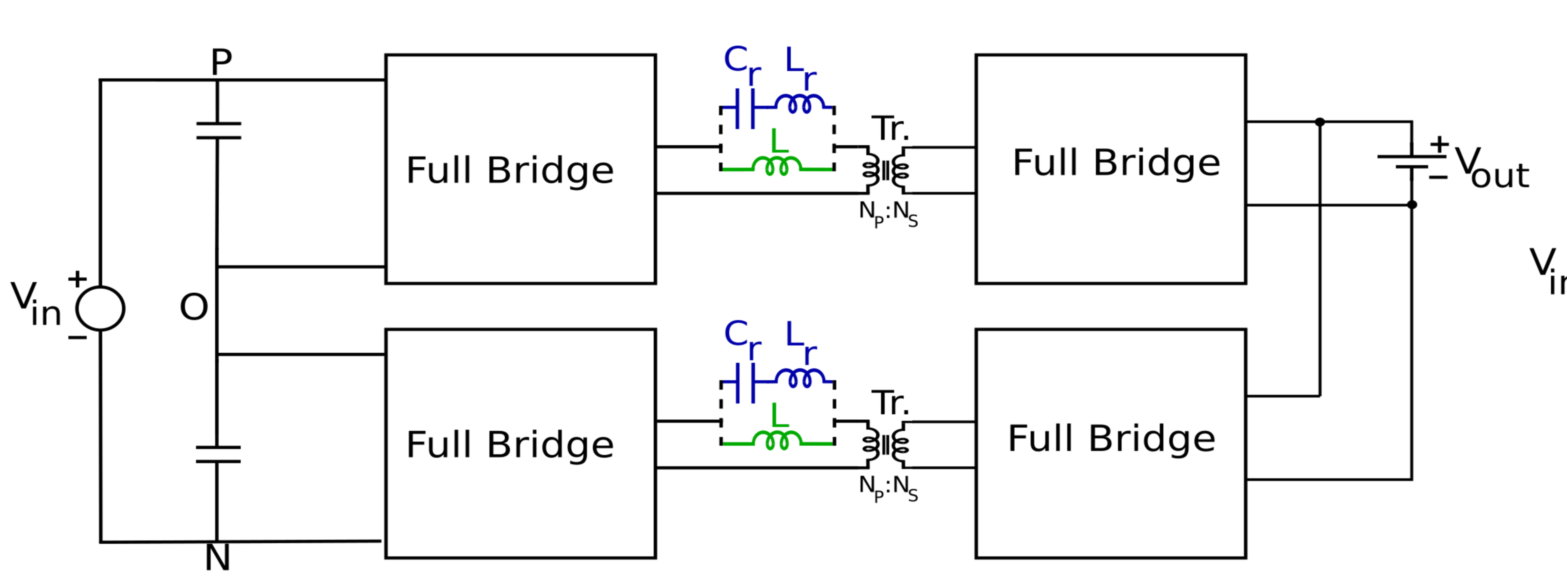
ISOP DAB -> two parallel-connected DAB modules sharing the total power transferred -> validation of a single module is sufficient in terms of efficiency comparison.



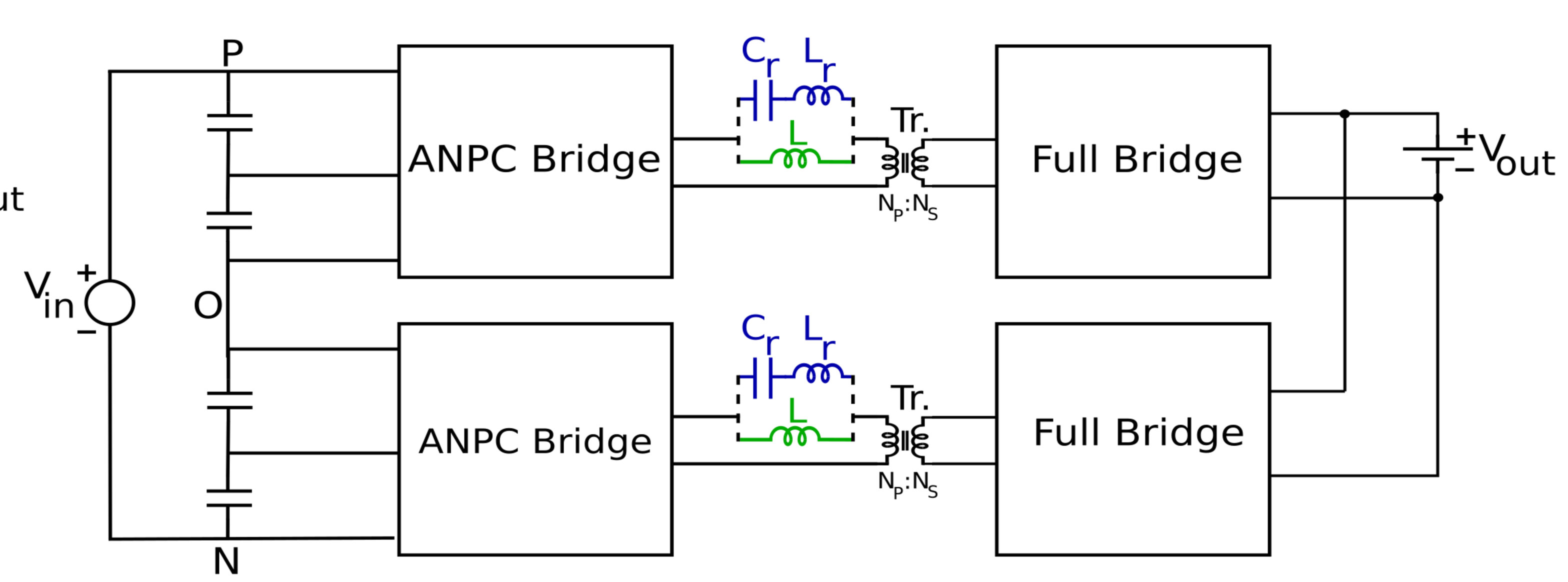
5-kW non-resonant FB DAB prototype




(i) ISOP FB DAB (single module) (ii) ISOP ANPC DAB (single module)
(iii) SR ISOP FB DAB (single module) (iv) SR ISOP ANPC DAB (single module)



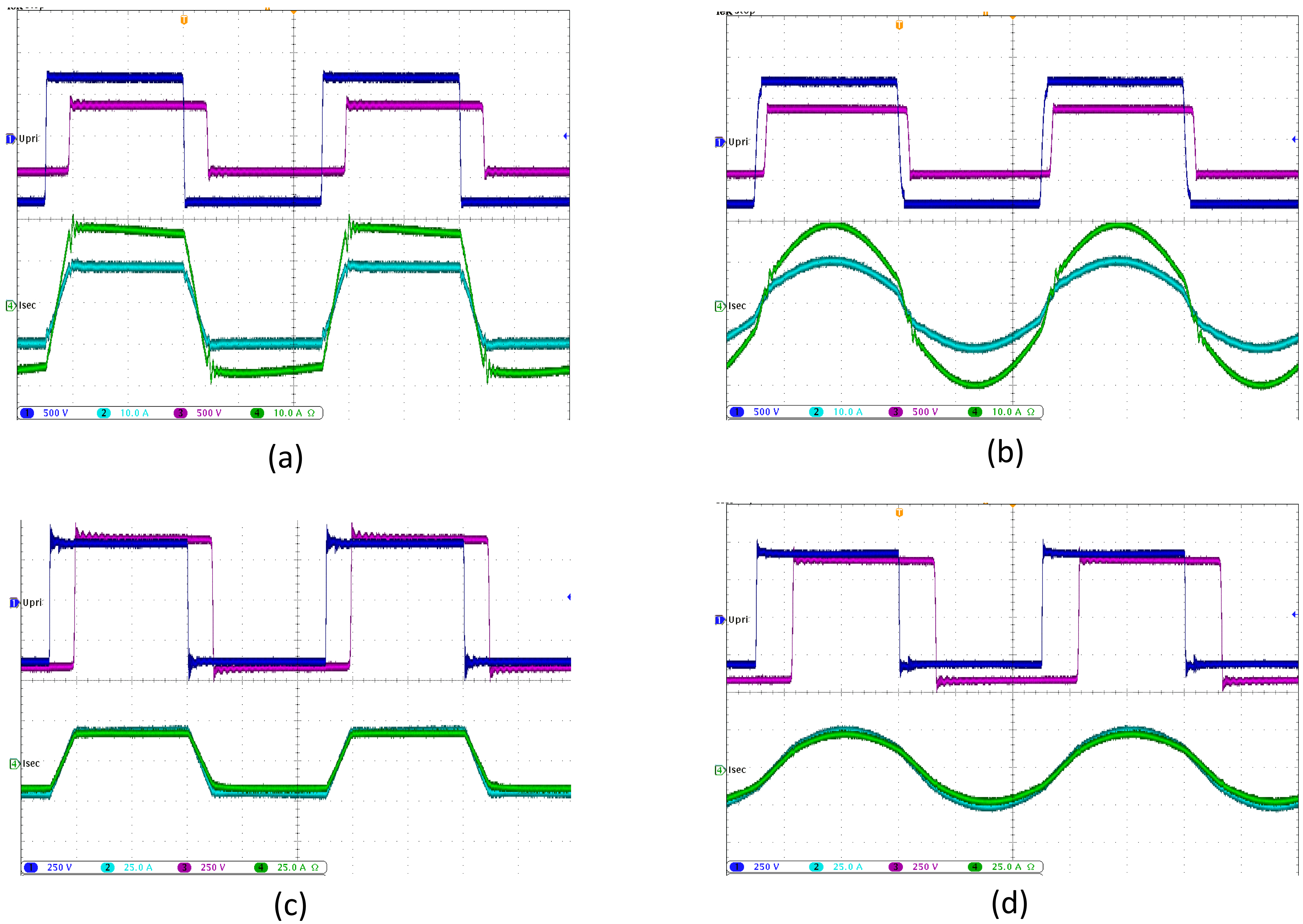

Input-series output-parallel (ISOP) FB DAB

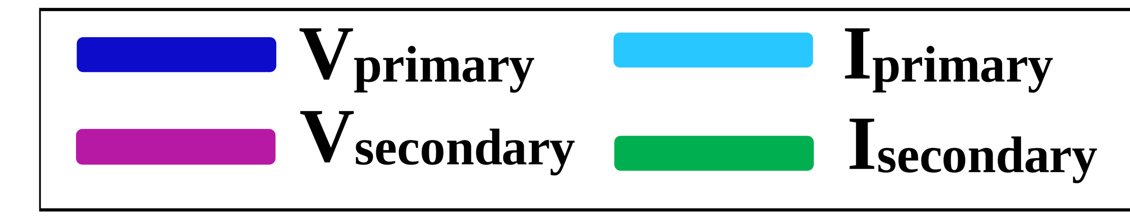



ISOP ANPC DAB

Note: Simulation results are based on only MOSFET losses whereas experimental results correspond to overall efficiency!

# Experimental validation - Waveforms




- SR DABs have a near sinusoidal transformer current waveform compared to their non-resonant counterparts, resulting in lower RMS bridge currents.
- ANPC DABs carry almost double the current in the primary bridge and reflects half of the DC input voltage on transformer primary compared to FB DABs for the same power transferred.
- The SR ANPC DAB has a primary RMS current of about 17A compared to 8A in SR FB DAB, the losses due to the ESR of Cr is about 68W and 15W, respectively. This is one of the major contributors to higher losses in the SR ANPC DAB.

Transformer voltage and current waveforms for (a) non-resonant FB DAB, (b) series-resonant FB DAB, (c) non-resonant ANPC DAB and (d) series-resonant ANPC DAB

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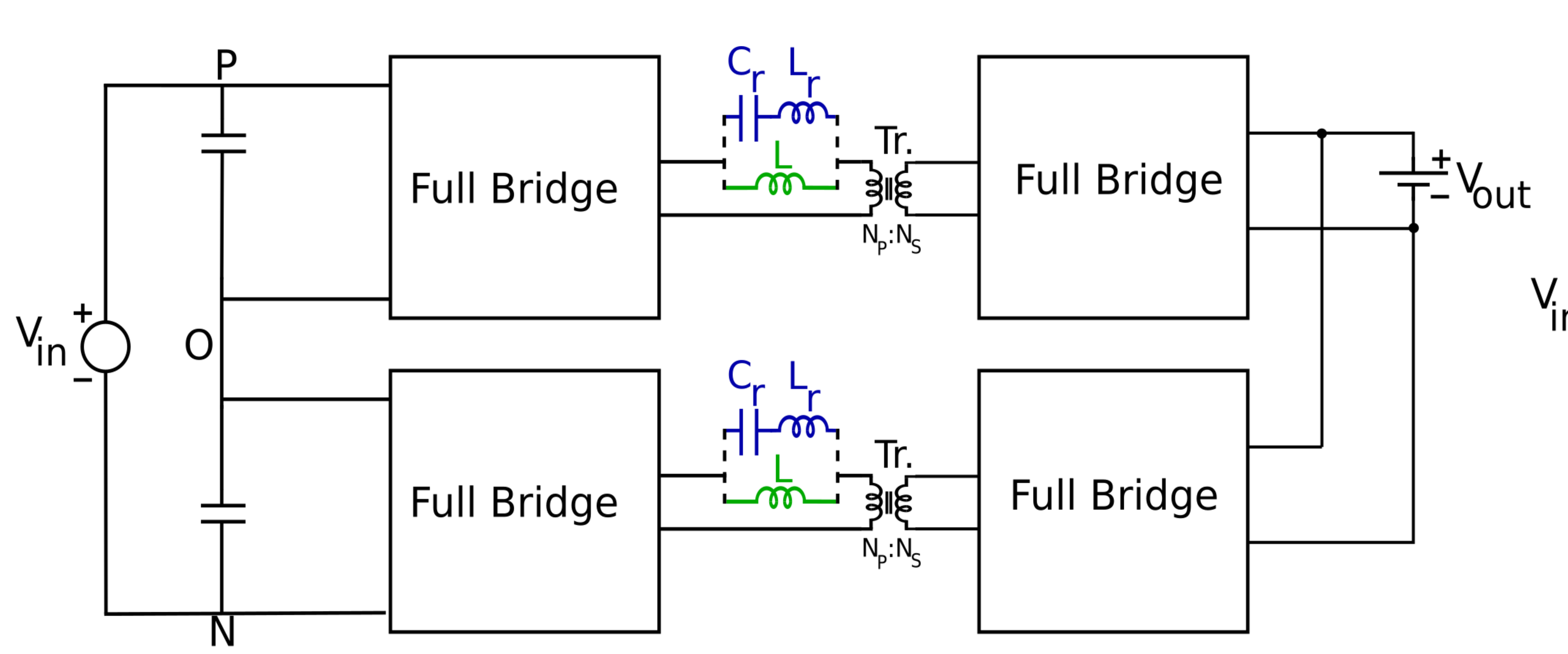
# Conclusions

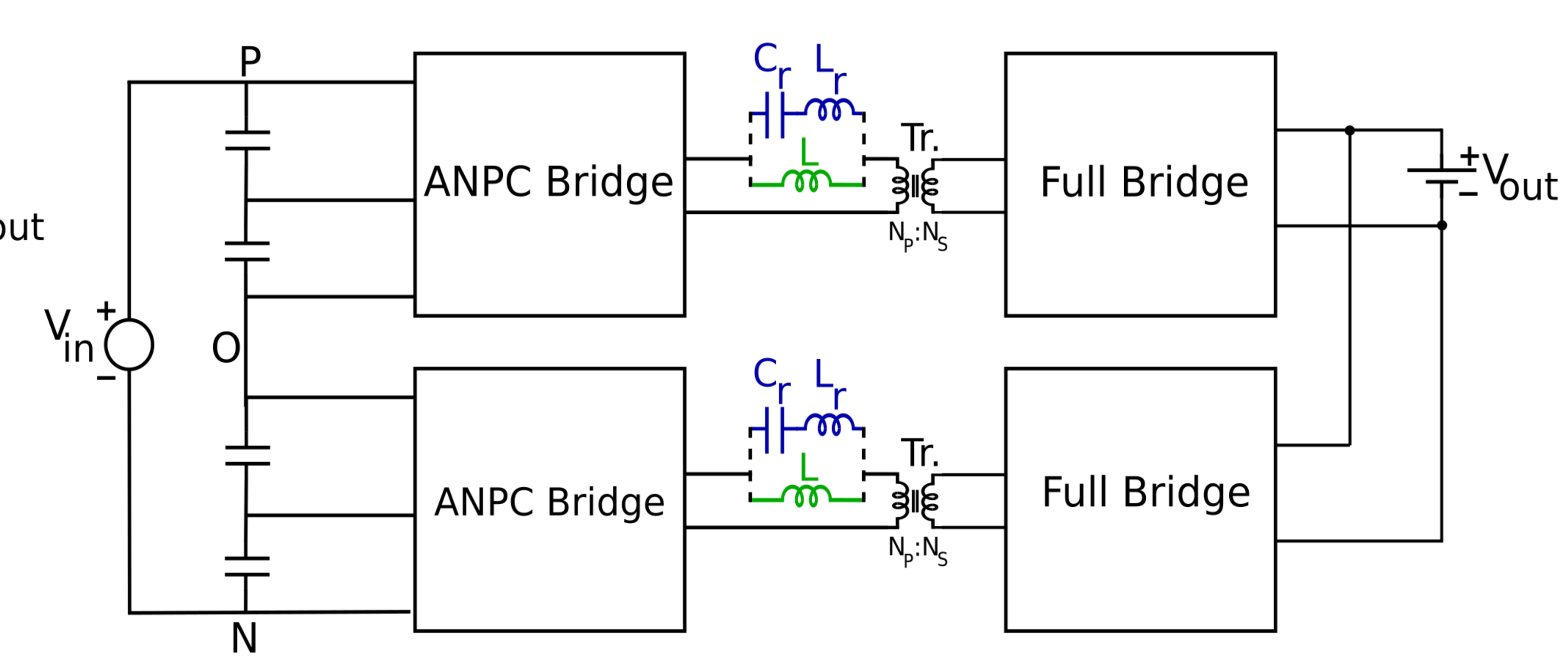
- In terms of **efficiency and SiC MOSFET losses**, the series-resonant variants outperform the non-resonant DABs with the **SR ISOP FB DAB** exhibiting the best performance.

- When the **normalized cost and the VA ratings** of SiC MOSFETs are considered, the **ANPC DAB** configuration seems to be the most promising one.

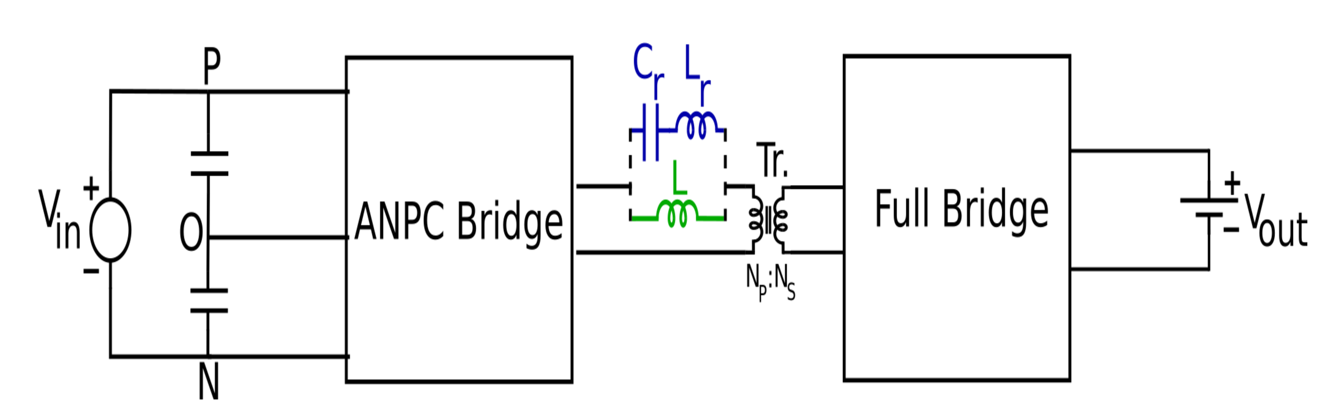
- Considering a fair trade-off between efficiency, loss distribution, VA ratings and the normalized cost, the **SR ANPC DAB** exhibits the **overall** best performance for this application.



Input-series output-parallel (ISOP) FB DAB



ISOP ANPC DAB



ANPC DAB

# Reference

Based on the paper presented at EPE 2022 (will be published soon):

K.Naresh Kumar, R.Miśkiewicz, P.Trochimiuk, J.Rąbkowski and D.Peftitsis, “Performance Evaluation of SiC-based Isolated Bidirectional DC/DC Converters for Electric Vehicle Charging”.

Thank you for your attention!

Any questions?

Contact: kaushik.n.kumar@ntnu.no