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D5.4 Undergraduate/Master Curricula Implemented

Title of Course

Power Converters

Title of the presentation

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

др Саша Штаткић

Partnership for Promotion and Popularization of Electrical Mobility through Transformation and Modernization of WB HEIs Study Programs/PELMOB

Call: ERASMUS-EDU-2022-CBHE-STRAND-2

Project Number: 101082860

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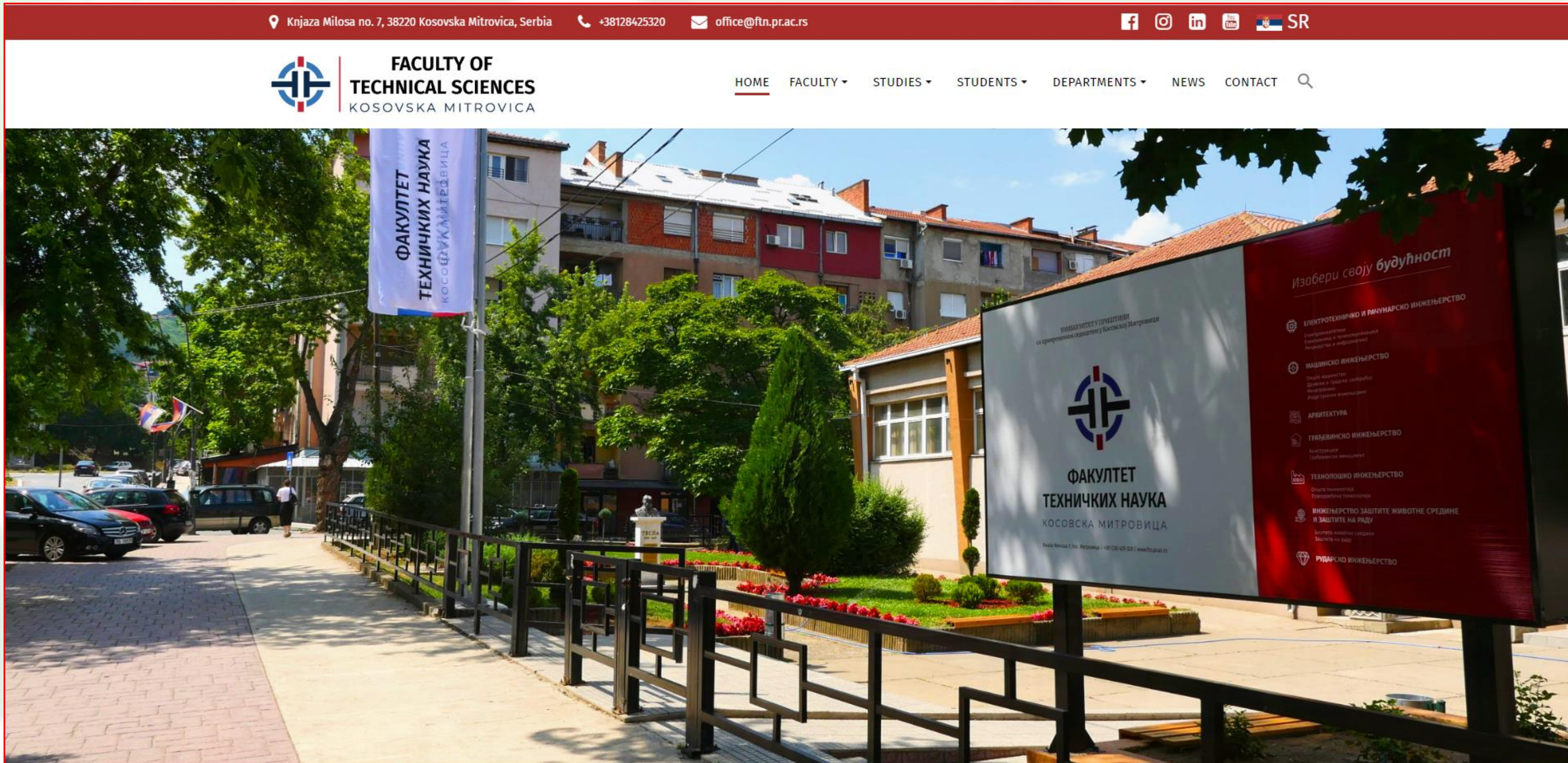

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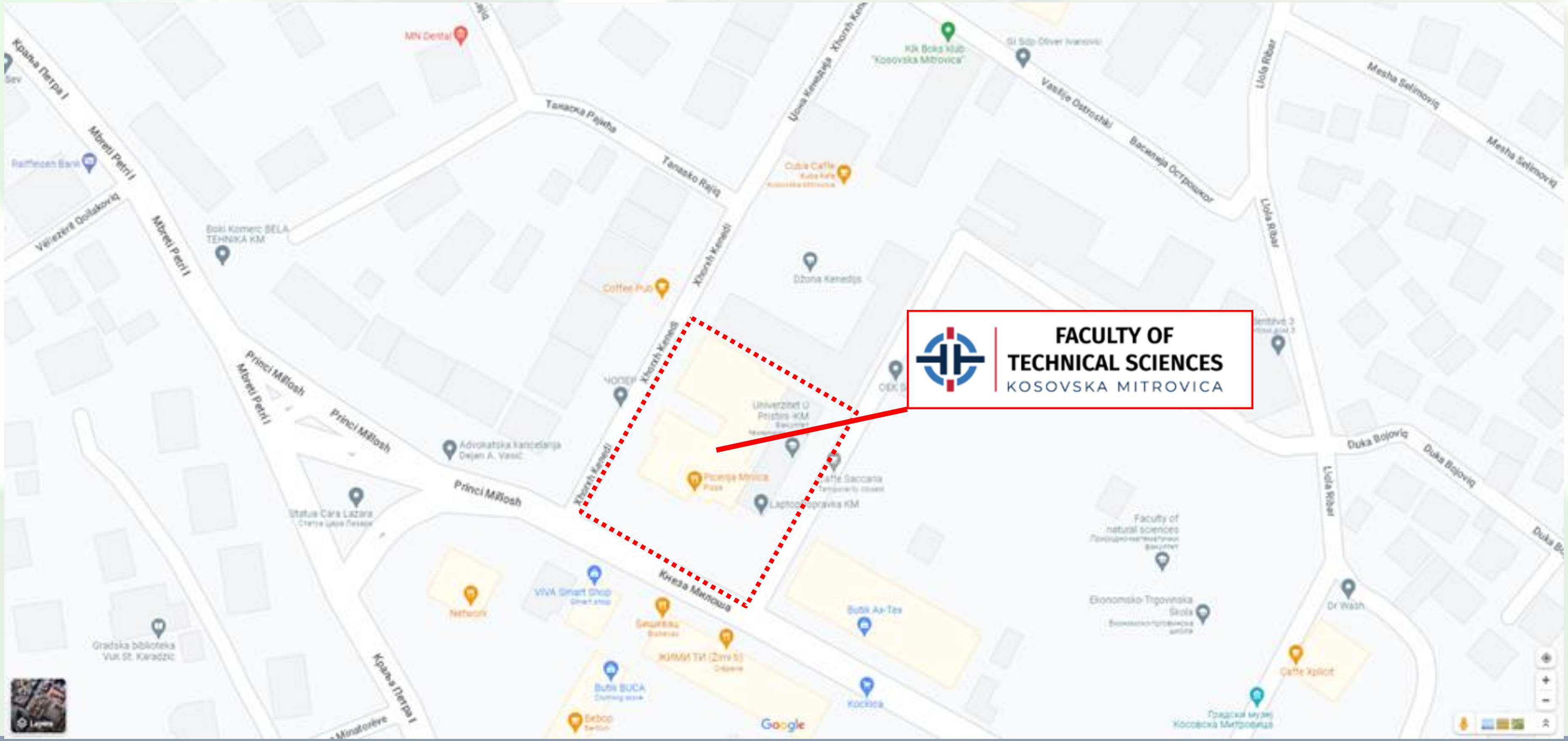

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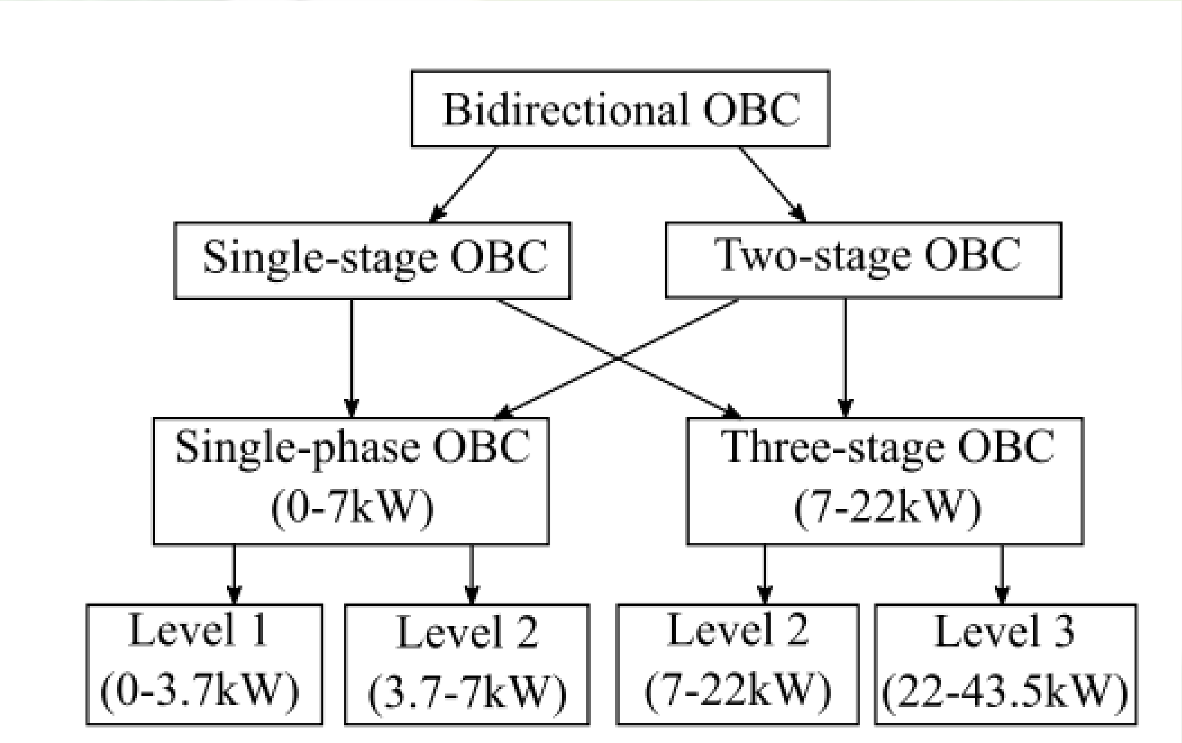
Partnership for Promotion and Popularization of Electrical Mobility through Transformation and Modernization of WB HEIs Study Programs / PELMOB

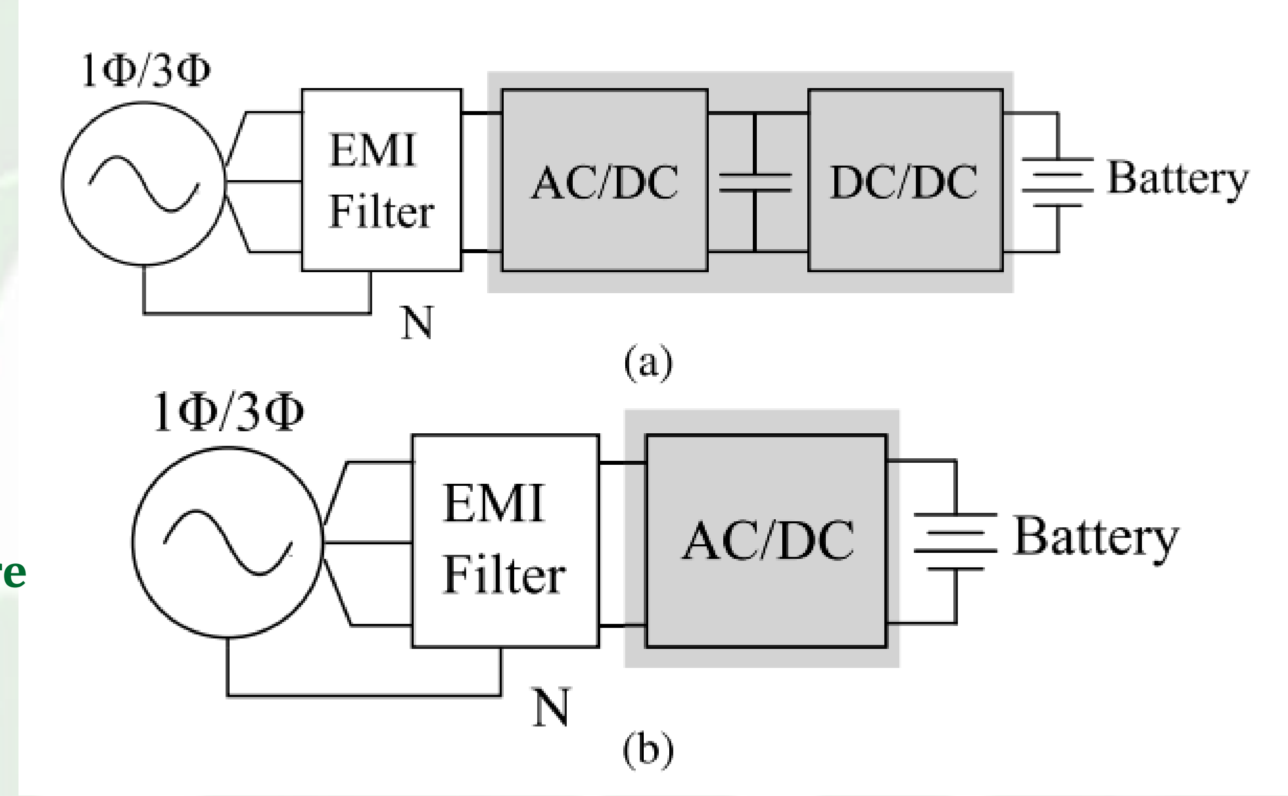
Bidirectional OBC classification On-board Chargers



Bidirectional On-board Chargers (OBC) configurations

(a) Two-stage architecture

(b) Single-stage architecture

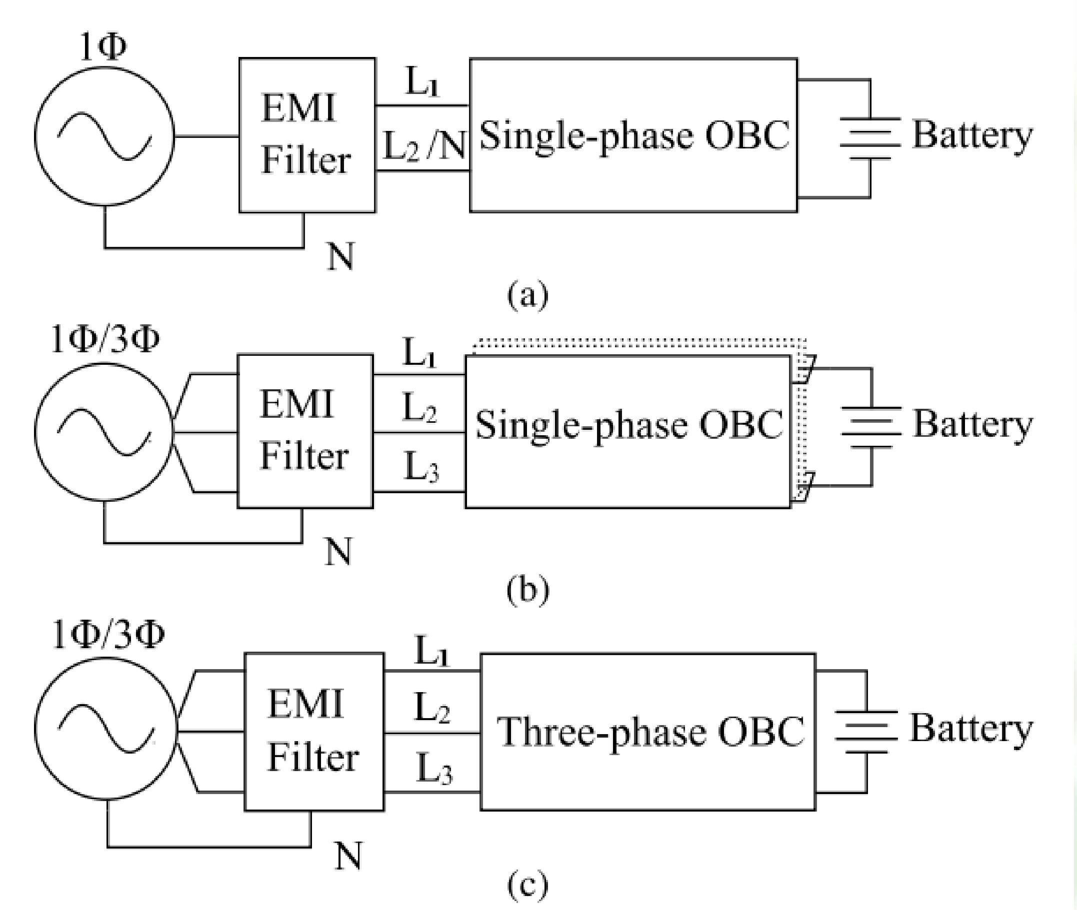


Bidirectional On-board Chargers (OBC) power architectures

(a) Single-phase input architecture

(b) Modular single-phase input architecture

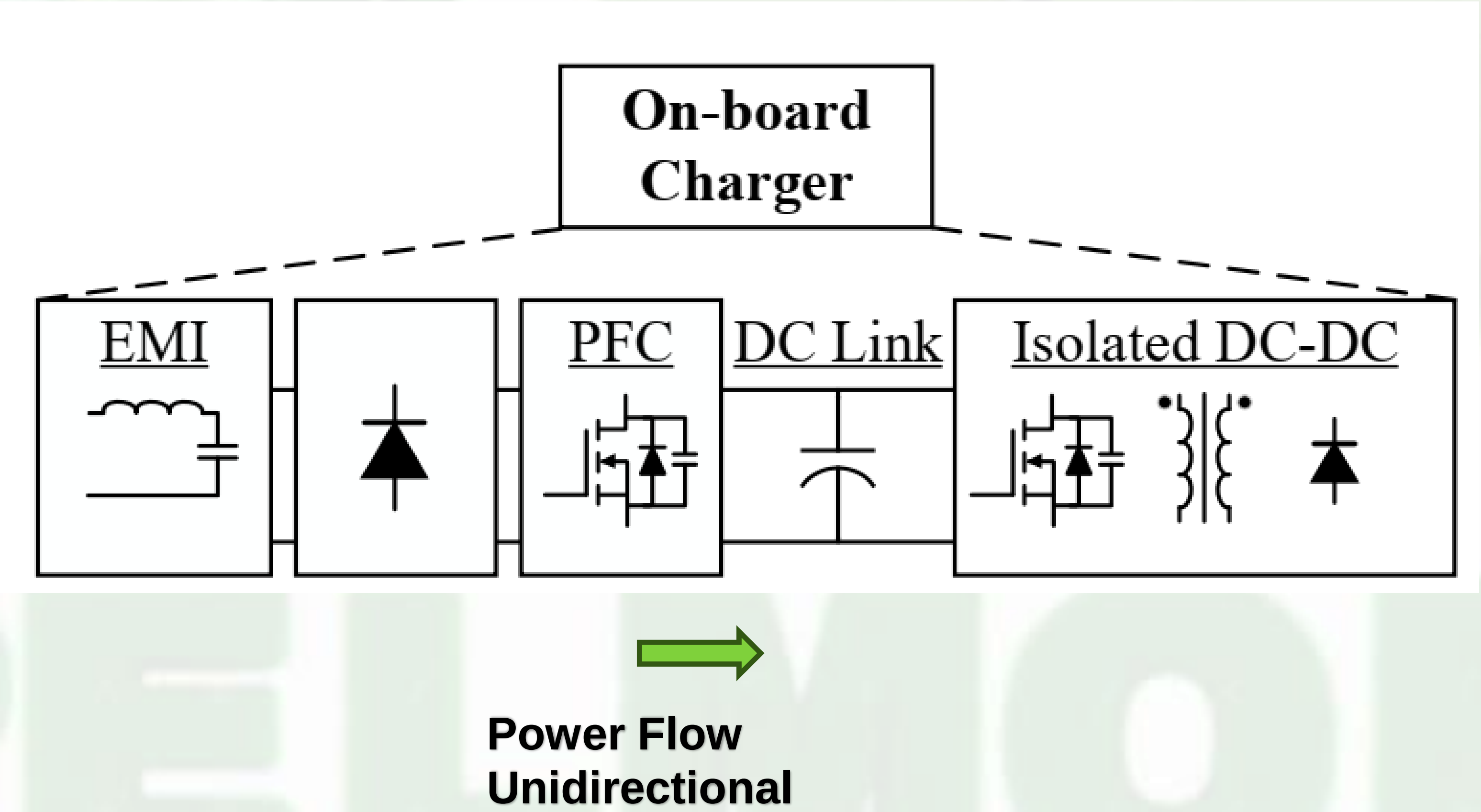
(c) Direct three-phase input architecture



The US Drive OBC targets

OBC Target	PFC	DC/DC	OBC
Specific Power (kW/kg)	4	4	4
Power density (kW/L)	4.6	4.6	4.6
Efficiency (%)	>99	>98	98

Block diagram for unidirectional On-board Charger



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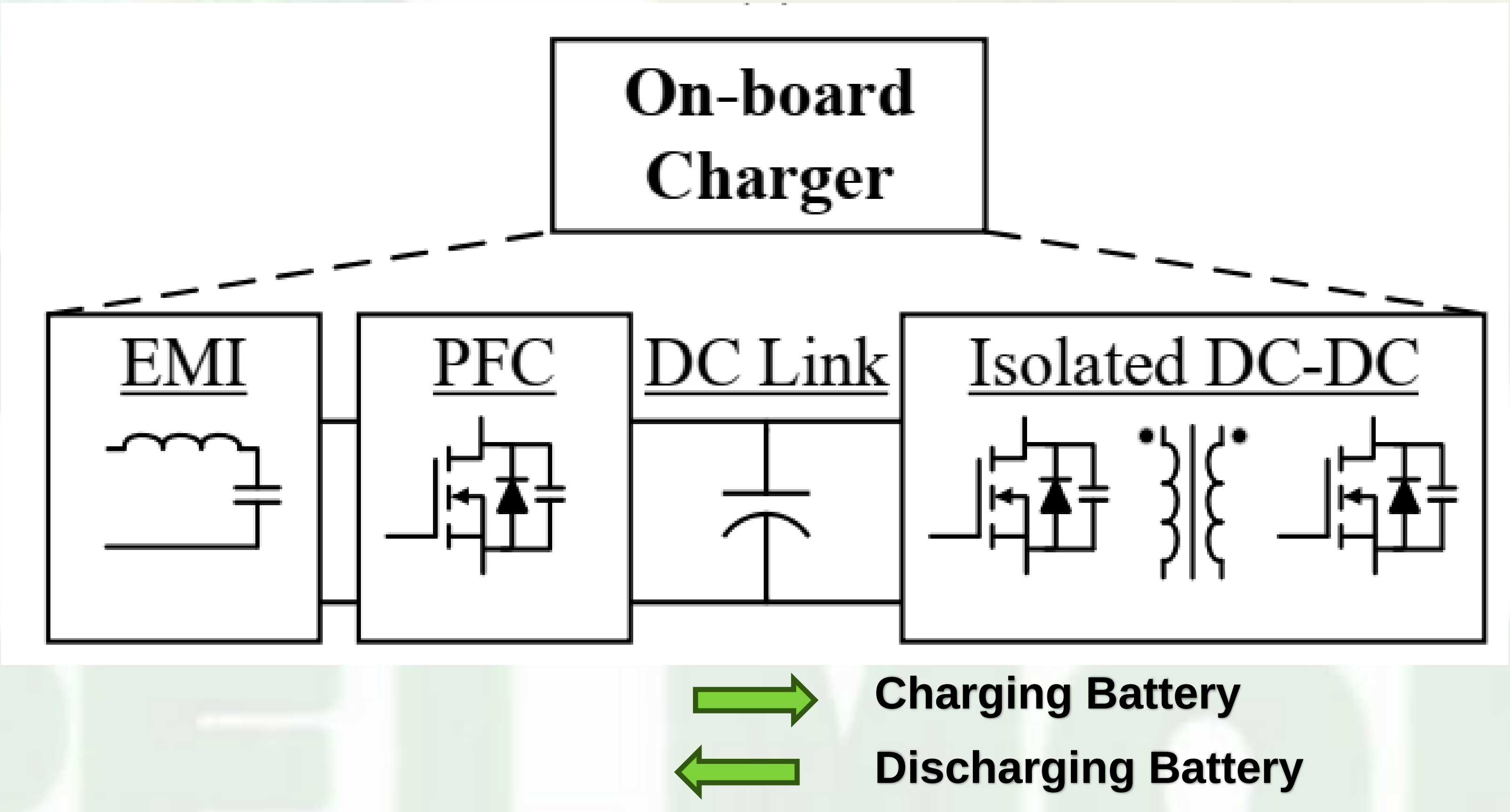
Block diagram for bidirectional On-board Charger



Power Flow Bidirectional

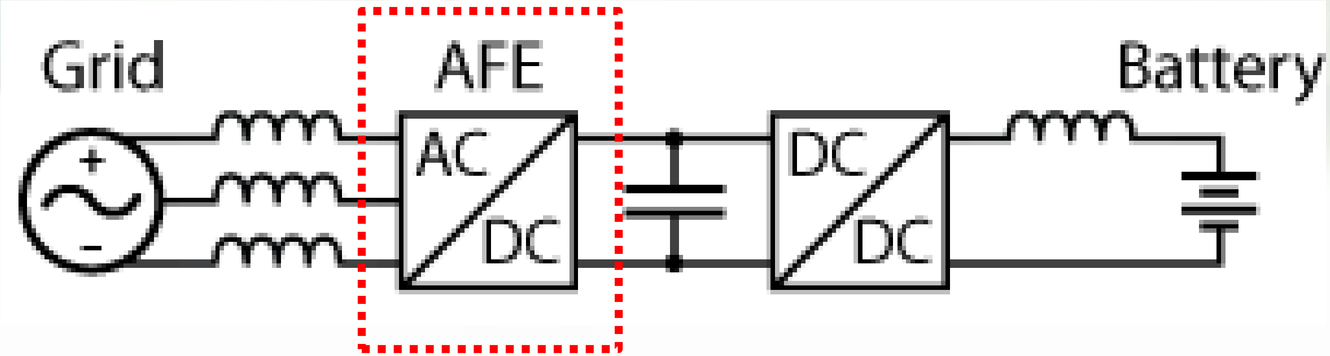
Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

Electric Vehicle (EV) fast charger

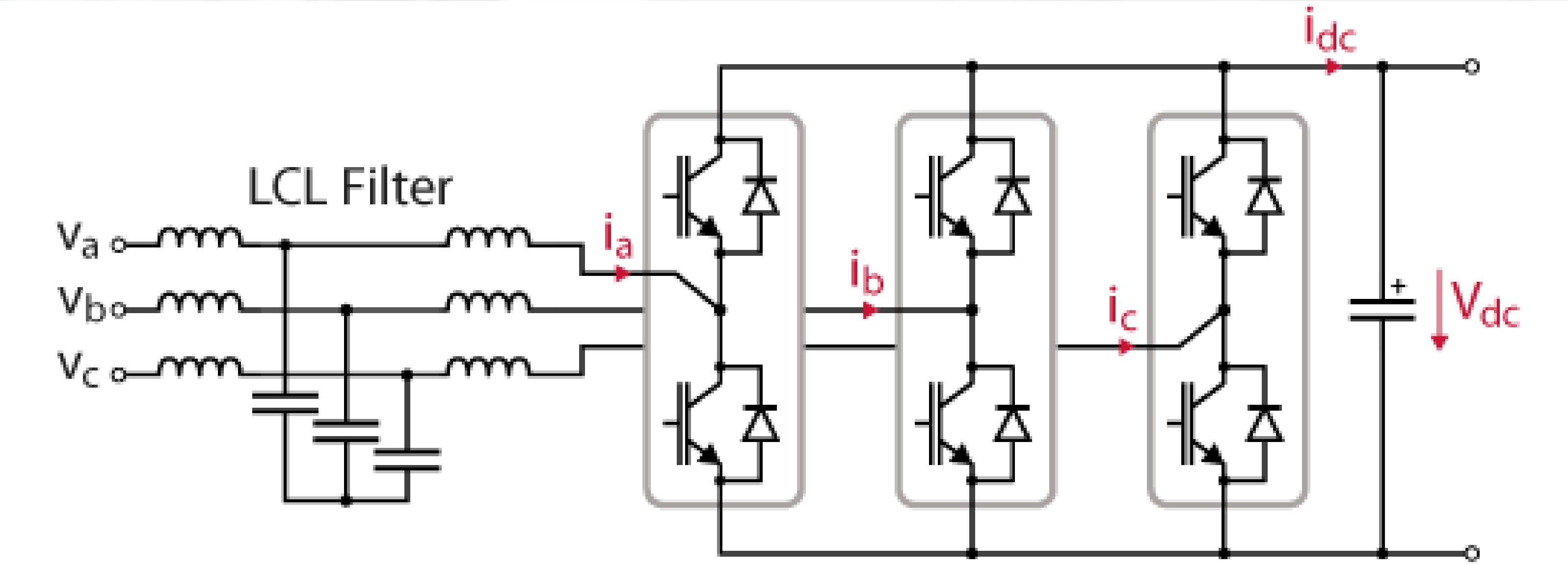
Active Front End (AFE) is a family of controllable rectifiers



Controllable Rectifiers (AC – DC)

Bi-directional converter topologies for the OBC

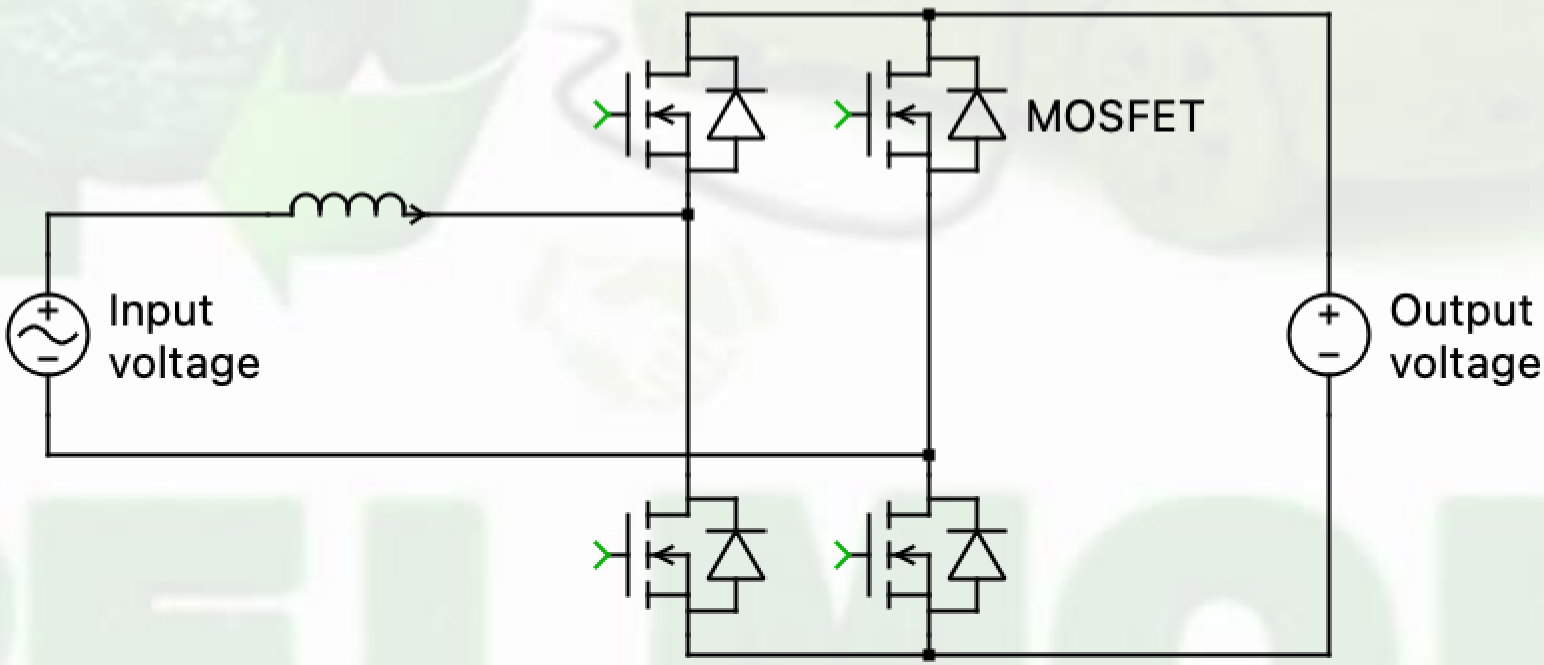
Typical topology of an Active Front End



The Active Front End (AFE) is a family of controllable rectifiers that serve as AC to DC converters. Compared with the traditional diode rectifiers, the **Active Front End allows for bidirectional power flow** (i.e., regenerative power injection to the grid) and also actively shapes the current waveform to achieve low total harmonic distortion (THD) and high power factor. In practice, the Active Front End is usually used together with an LCL filter for further harmonic attenuation.

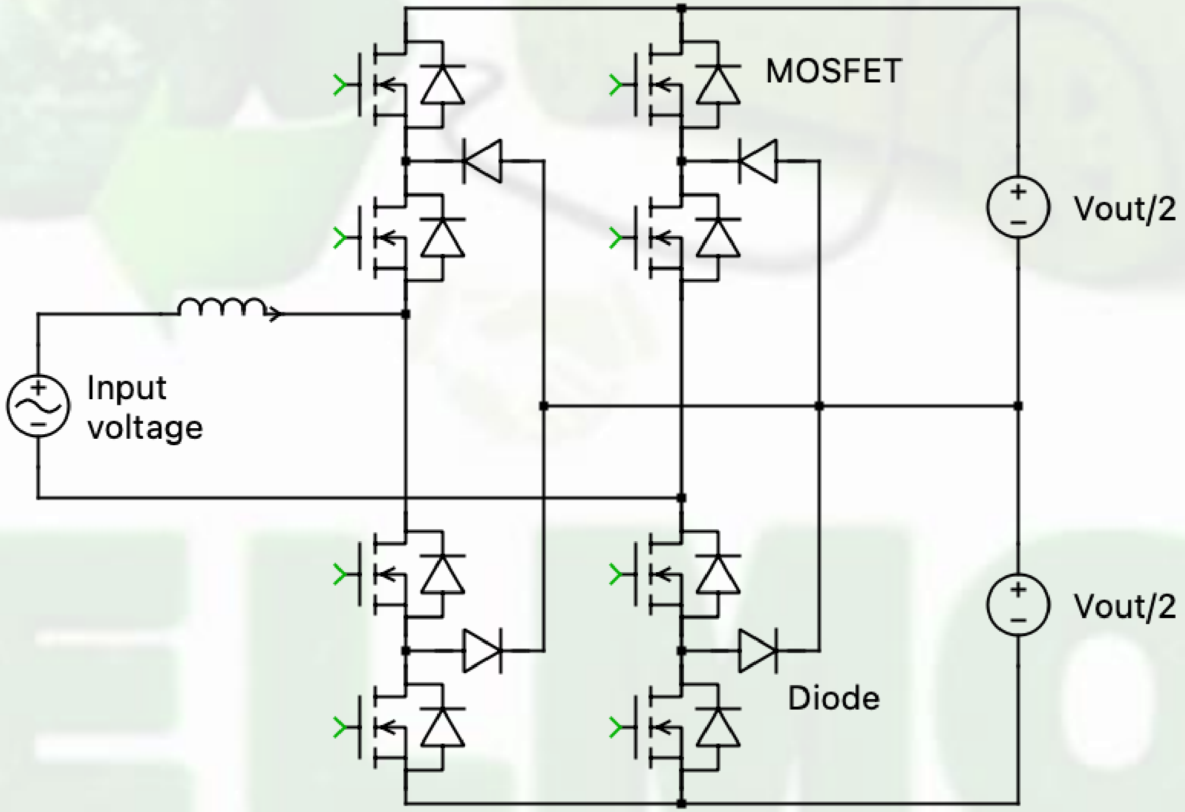
Bi-directional converter topologies for the OBC

Single Phase 2-Level Active Front End (AFE)



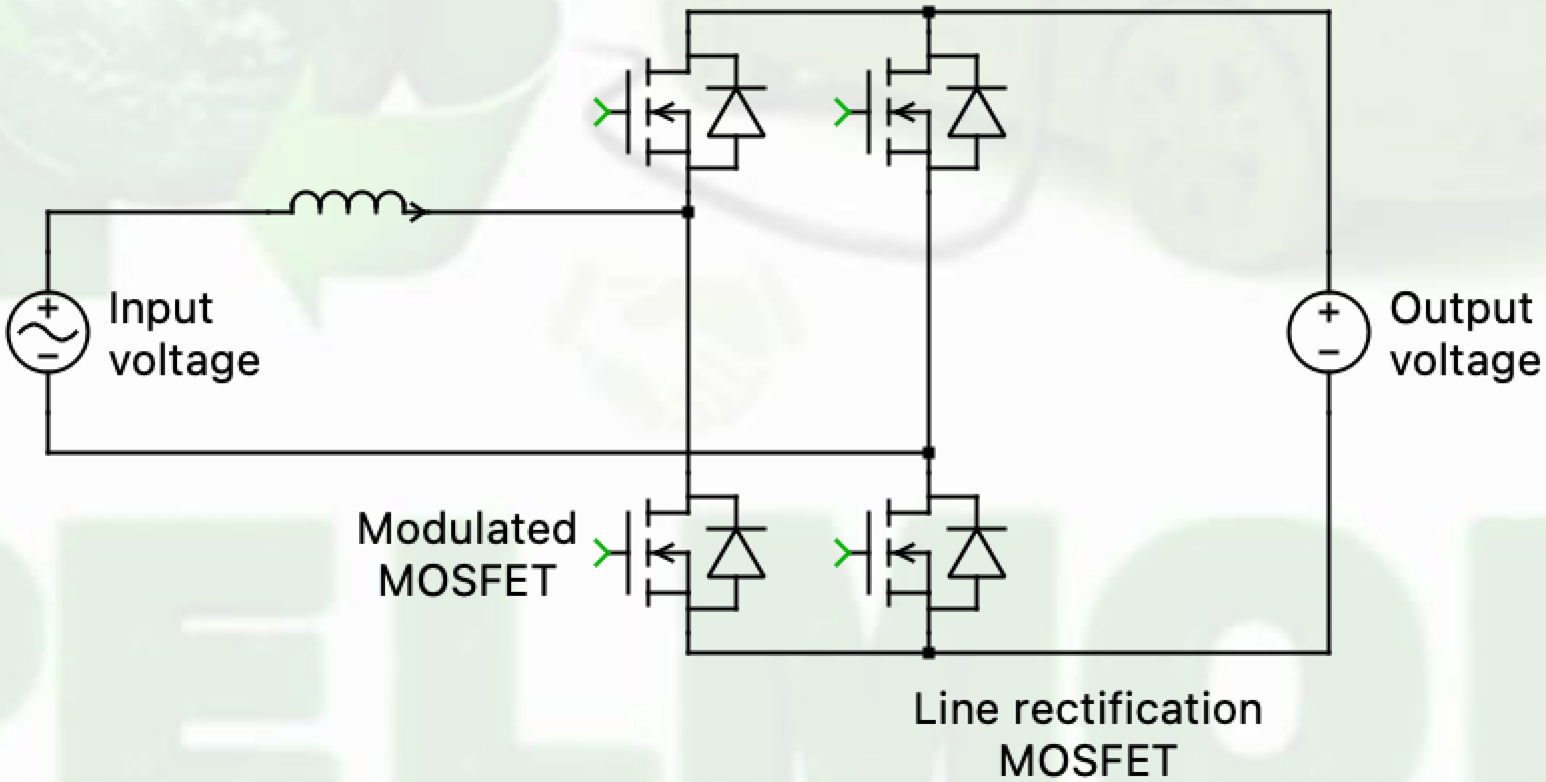
Bi-directional converter topologies for the OBC

Single Phase 3-Level Neutral-Point Clamped (NPC) Active Front End (AFE)



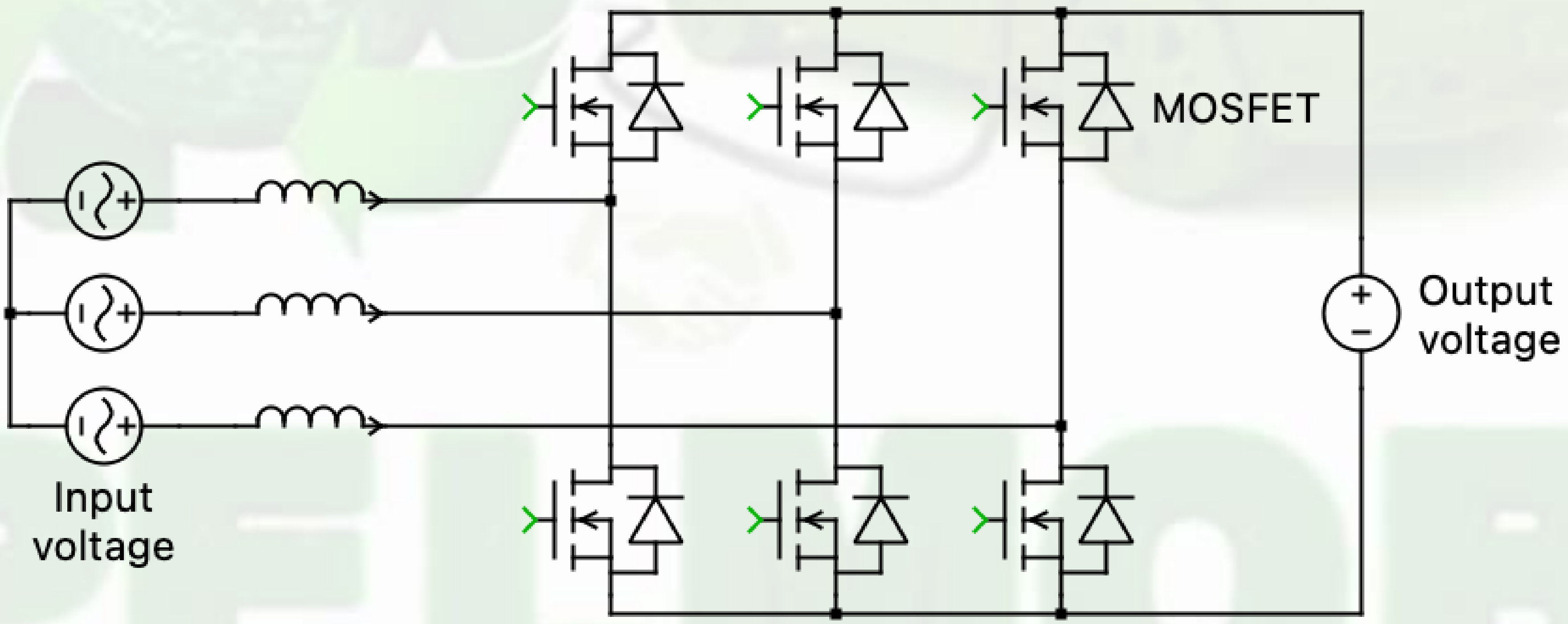
Bi-directional converter topologies for the OBC

Totempole Converter - LF MOSFETs



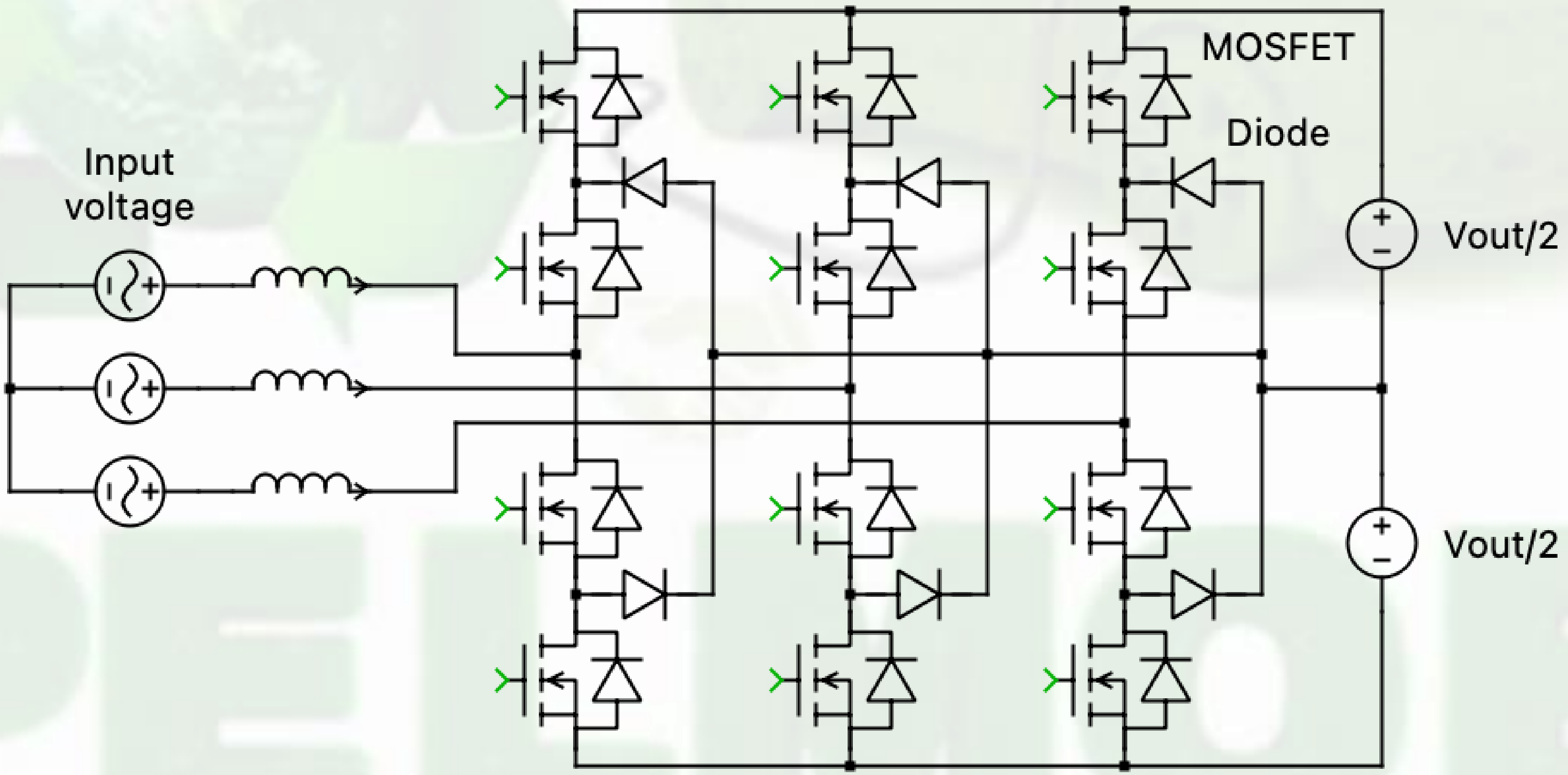
Bi-directional converter topologies for the OBC

Three Phase 2-Level Active Front End (AFE)



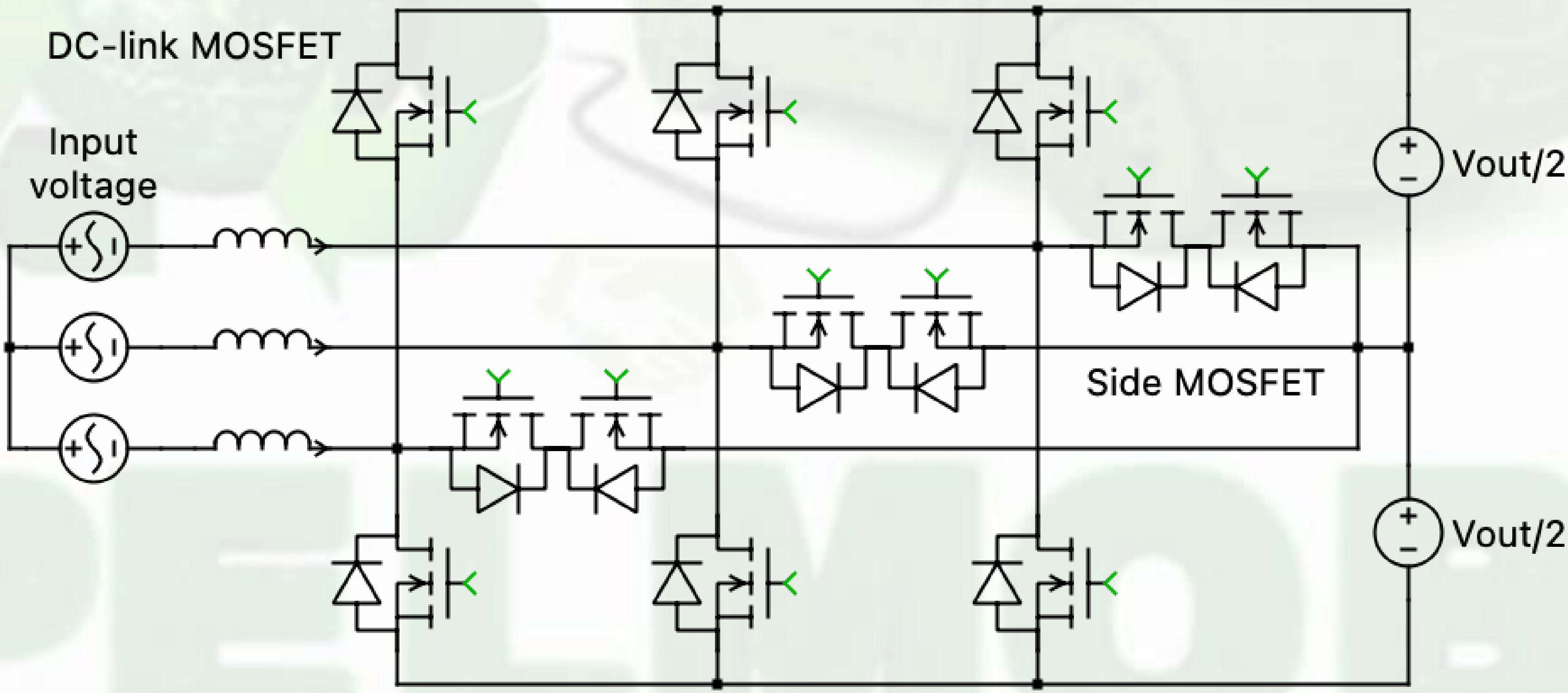
Bi-directional converter topologies for the OBC

Three Phase 3-Level Neutral-Point Clamped (NPC) Active Front End (AFE)



Bi-directional converter topologies for the OBC

Three Phase 3-Level T-Type Active Front End (AFE)



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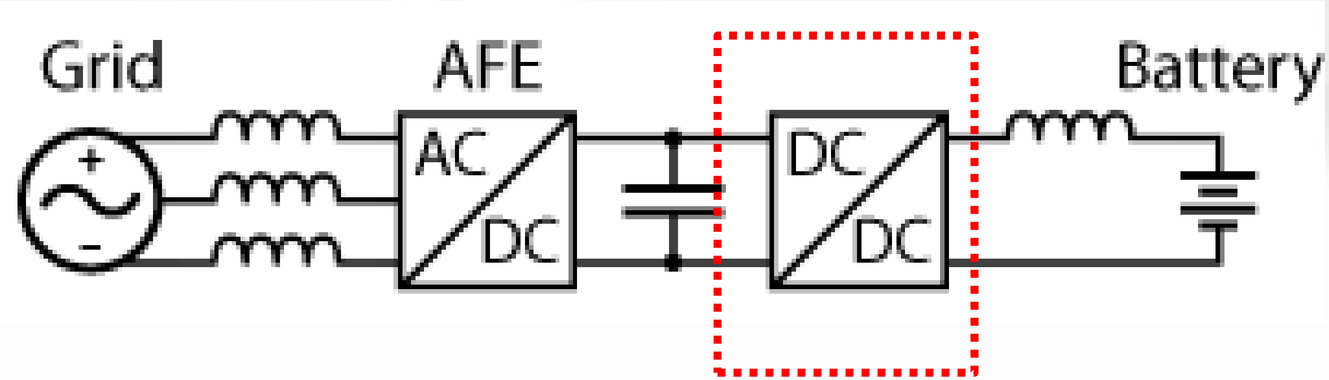
Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

Electric Vehicle (EV) fast charger

Active Front End (AFE) is a family of controllable rectifiers



Controllable DC – DC Converters

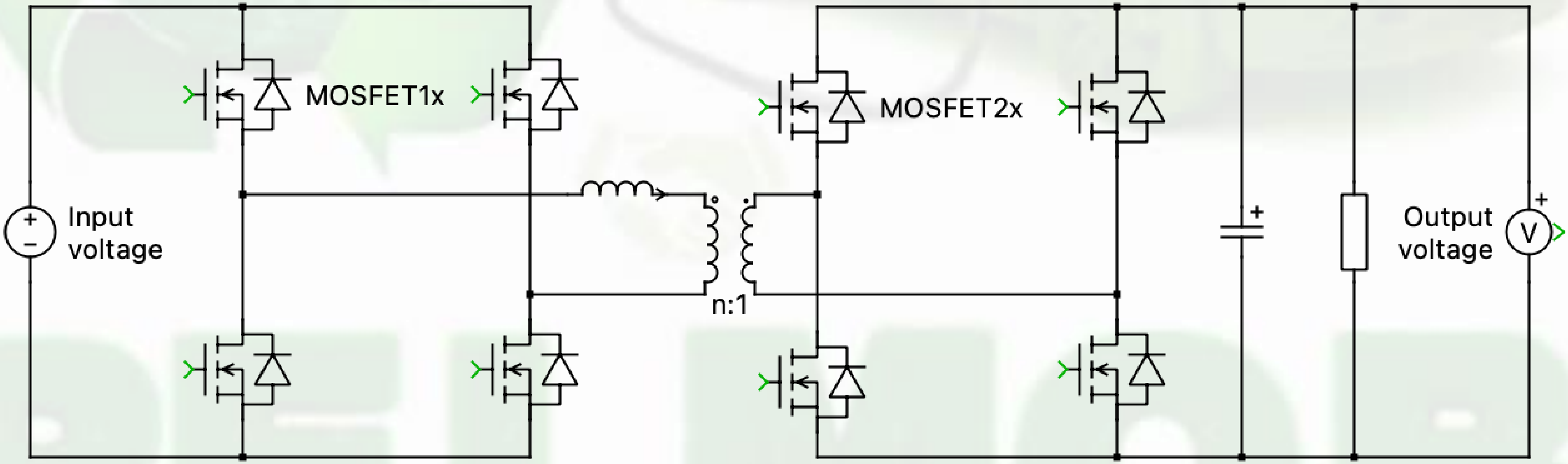
Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

Controllable DC – DC Converters

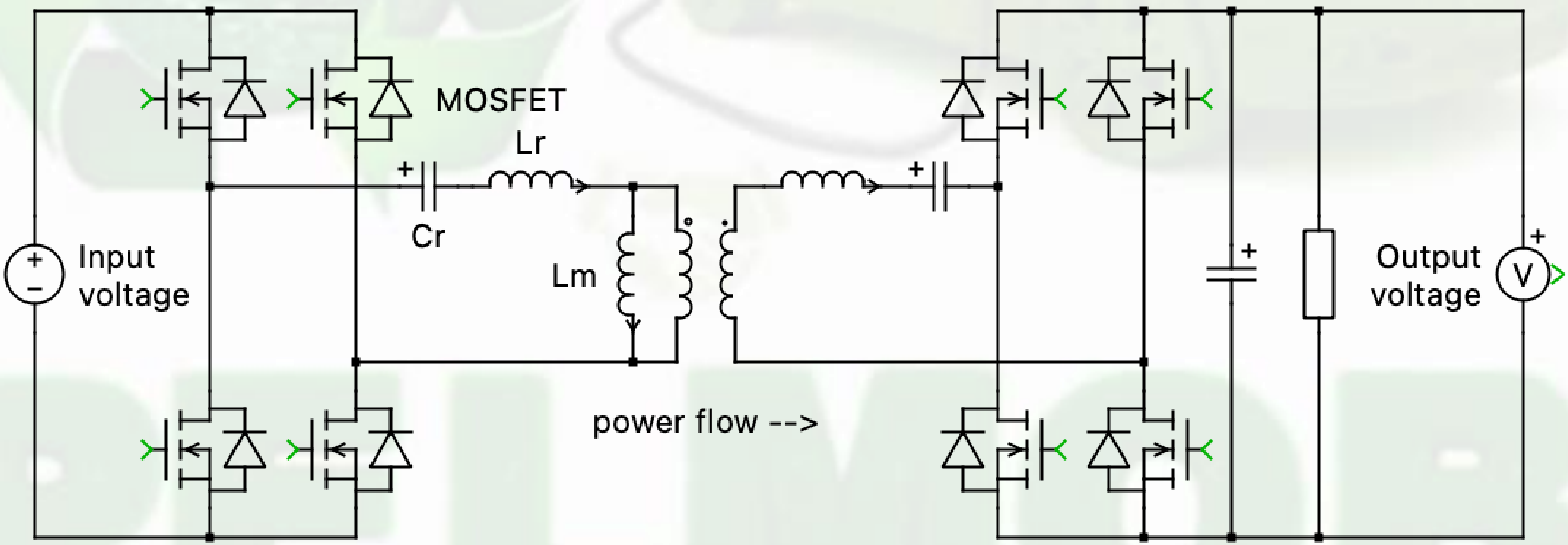
Dual Active Bridge Converter



Bi-directional converter topologies for the OBC

Controllable DC – DC Converters

CLLC Resonant Converter (Charging Mode)

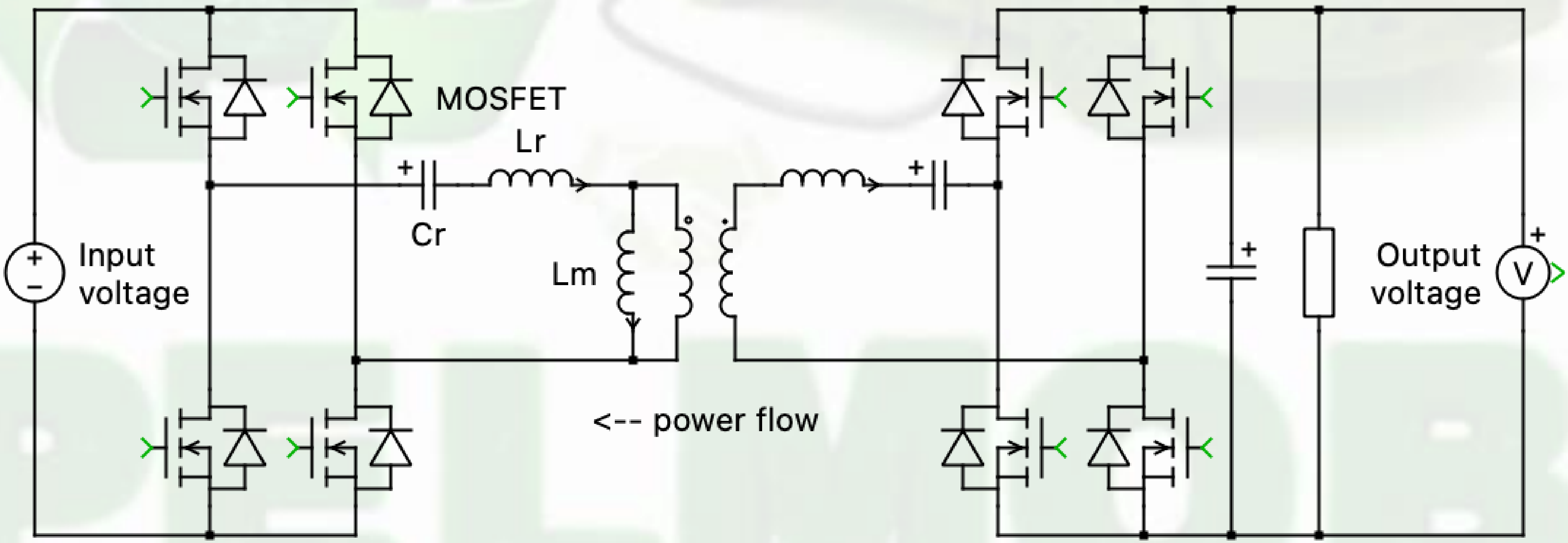


Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

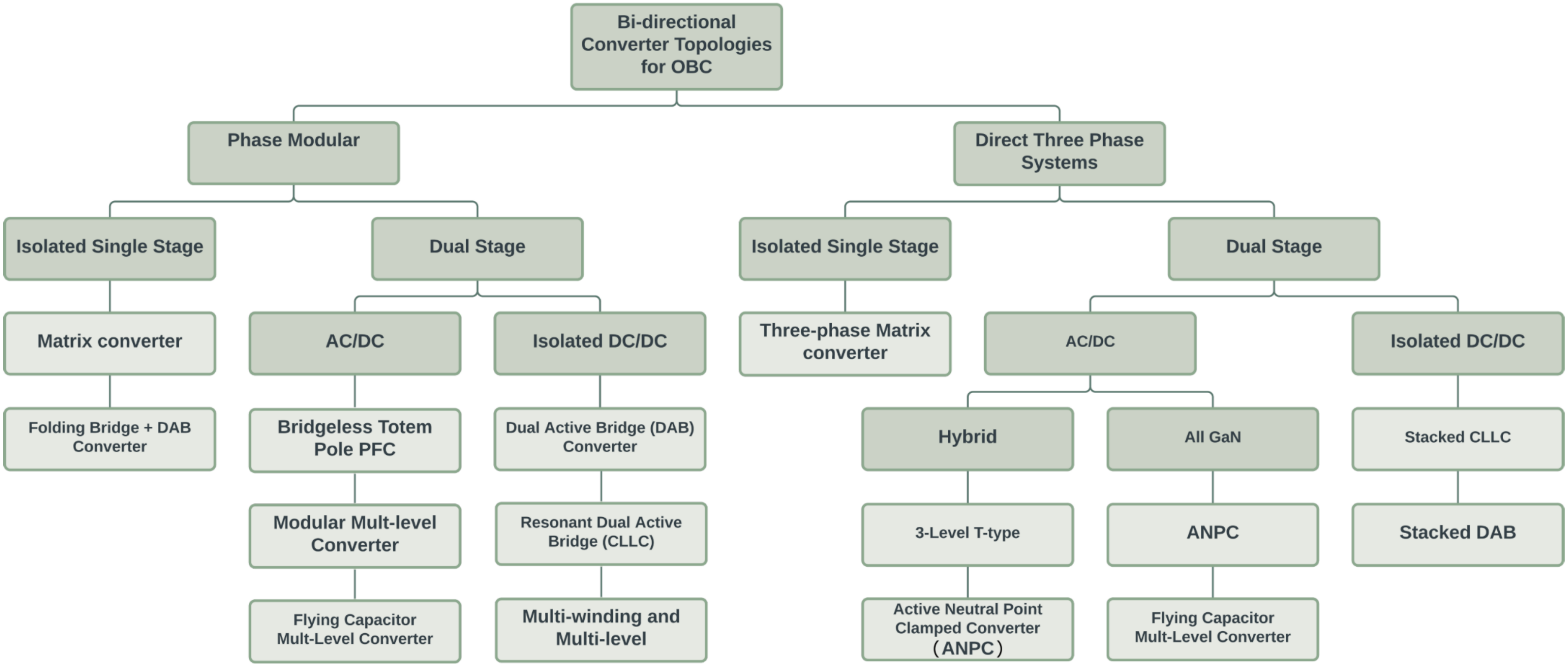
Controllable DC – DC Converters

CLLC Resonant Converter (Discharging Mode)



Classification of bi-directional converter topologies for the OBC

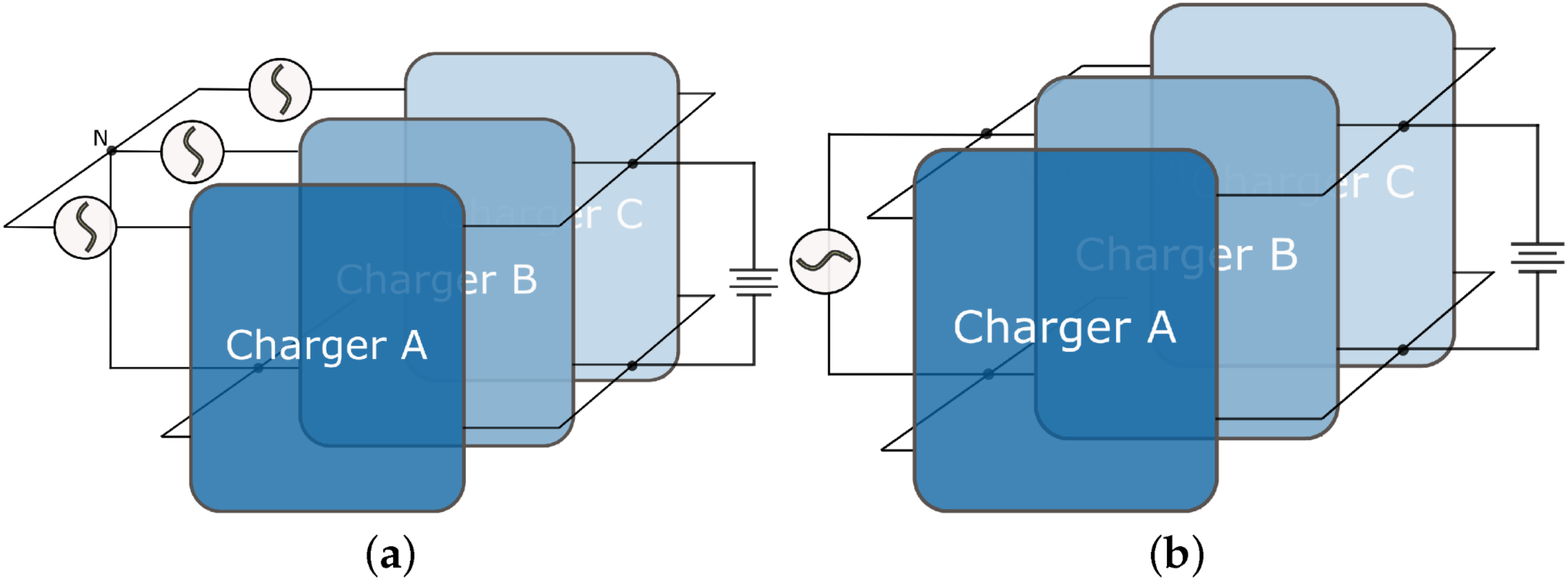
On-Board Battery Chargers - OBC



Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Phase modular charger architecture



(a) three-phase

(b) single-phase application

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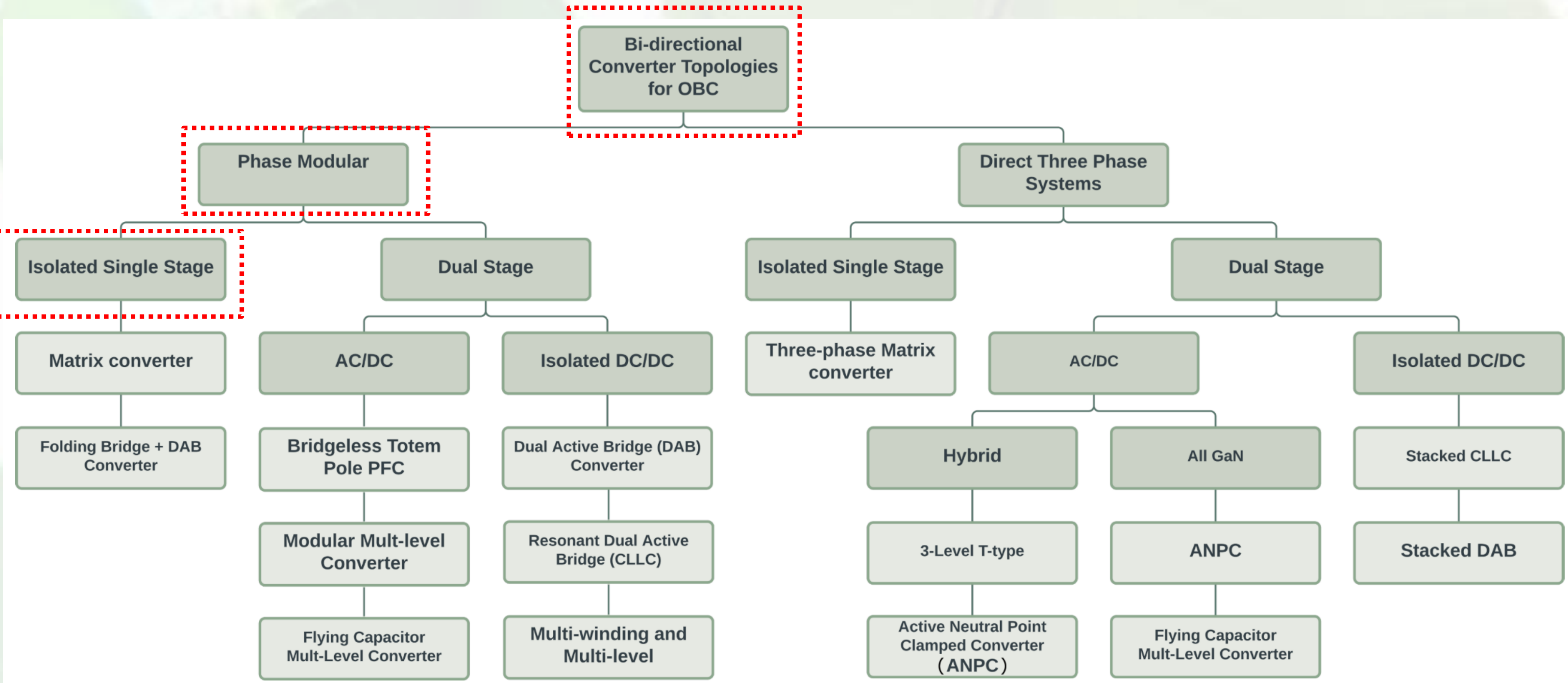
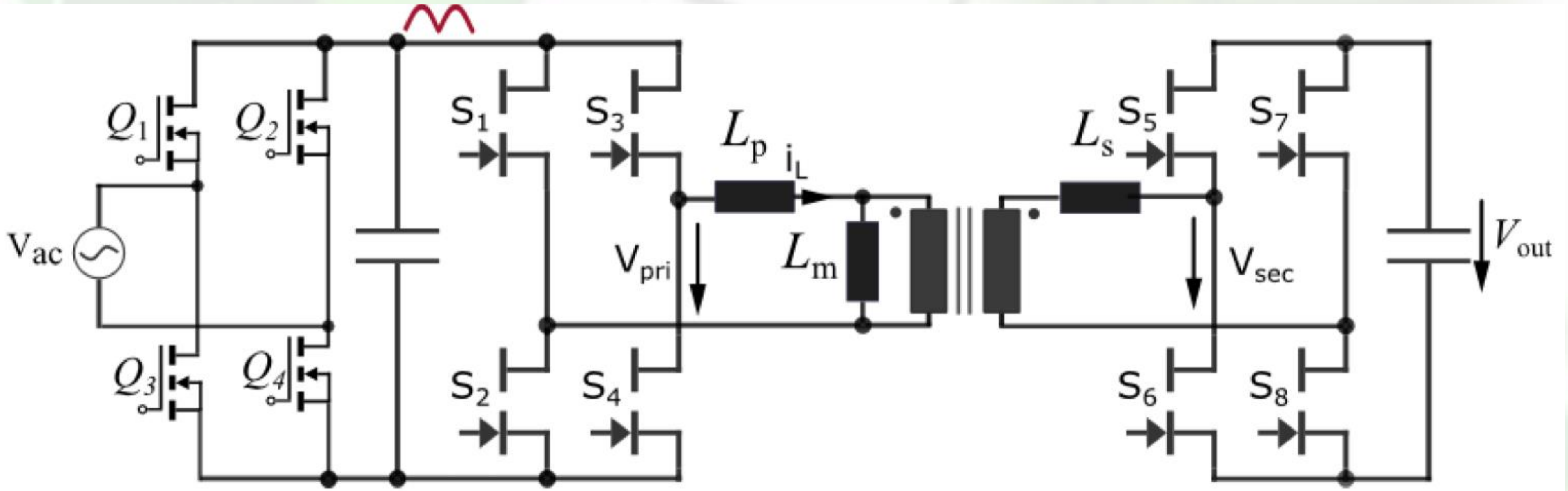
Classification of bi-directional converter topologies for the OBC

On-Board Battery Chargers - OBC



Bi-directional converter topologies for the OBC

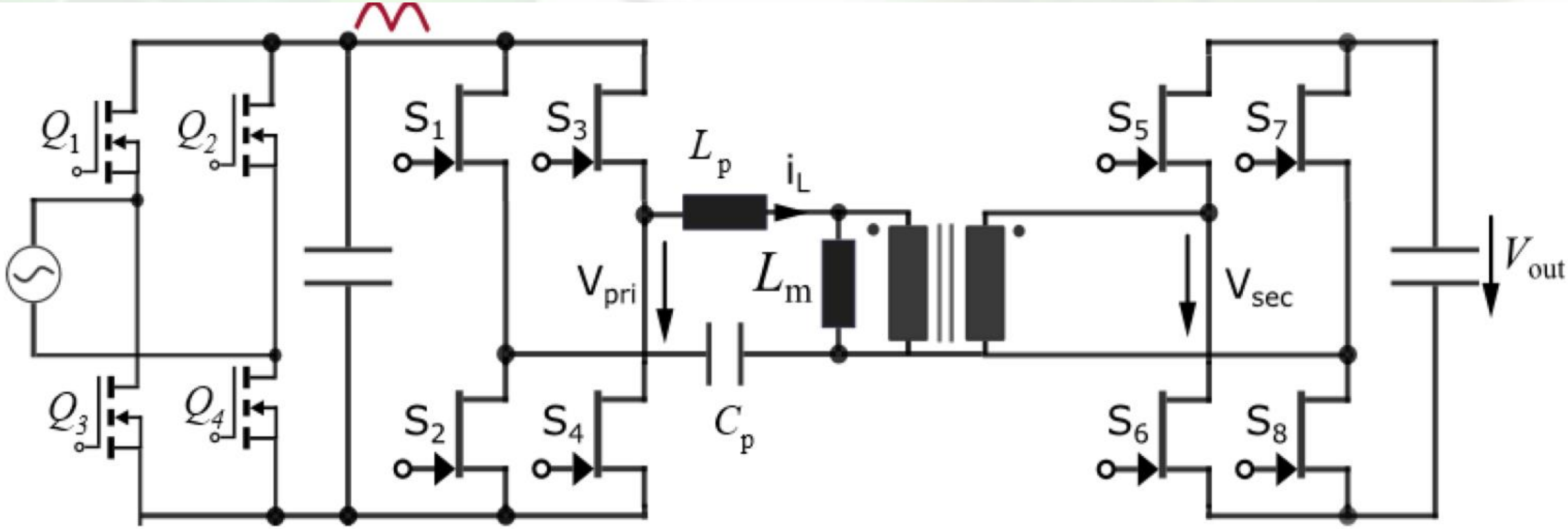
Single-phase single-stage - dual active bridge (DAB) AC/DC converter



Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

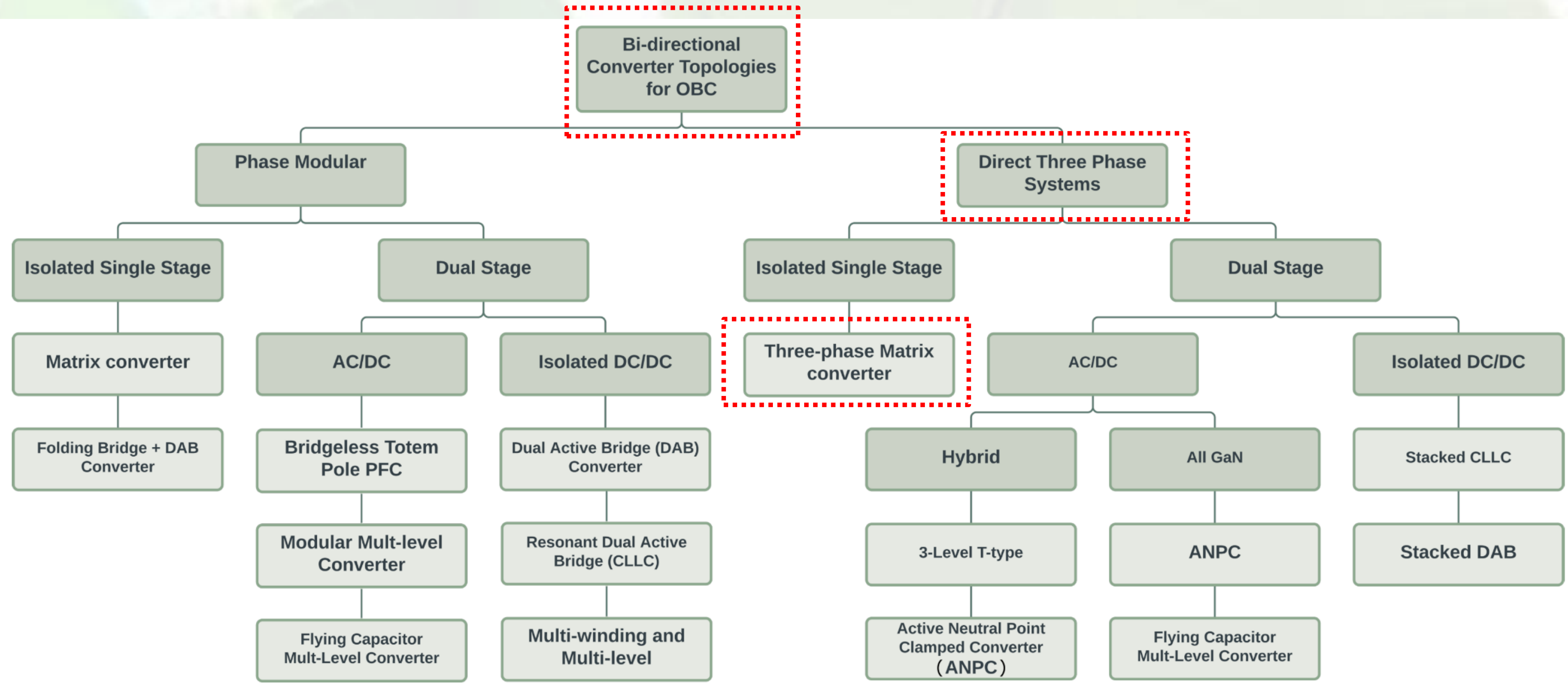
Bi-directional converter topologies for the OBC

Single-phase single-stage Series-resonant DAB AC/DC converter



Classification of bi-directional converter topologies for the OBC

On-Board Battery Chargers - OBC



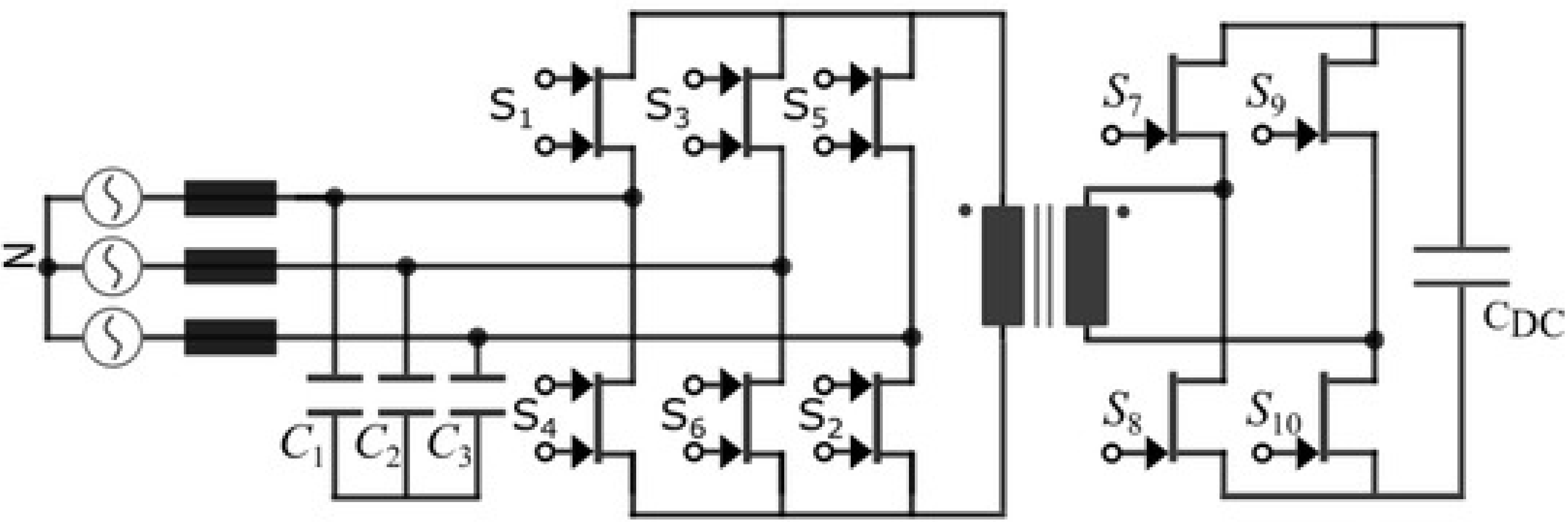
Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

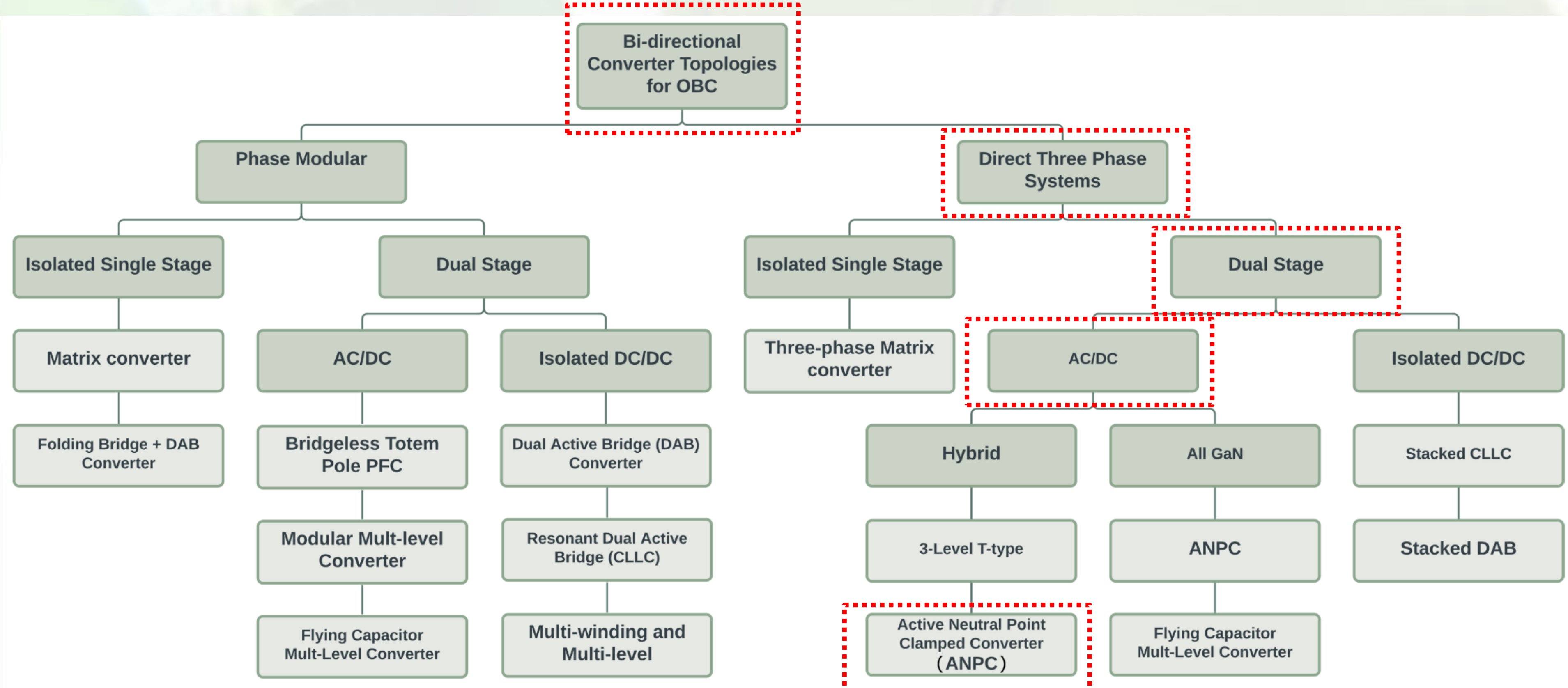
Single-Stage Three-Phase AC/DC Converters

Matrix-type bi-directional three-phase AC/DC converter



Classification of bi-directional converter topologies for the OBC

On-Board Battery Chargers - OBC



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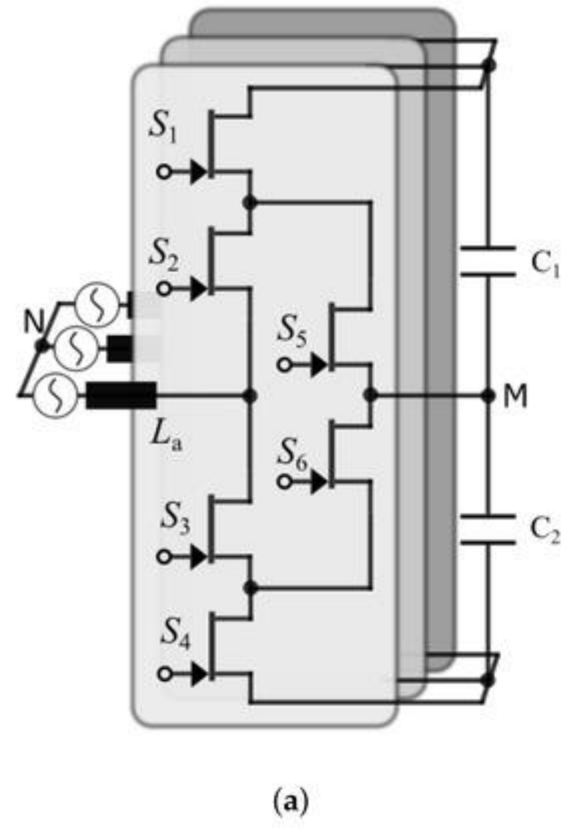
Bi-directional converter topologies for the OBC

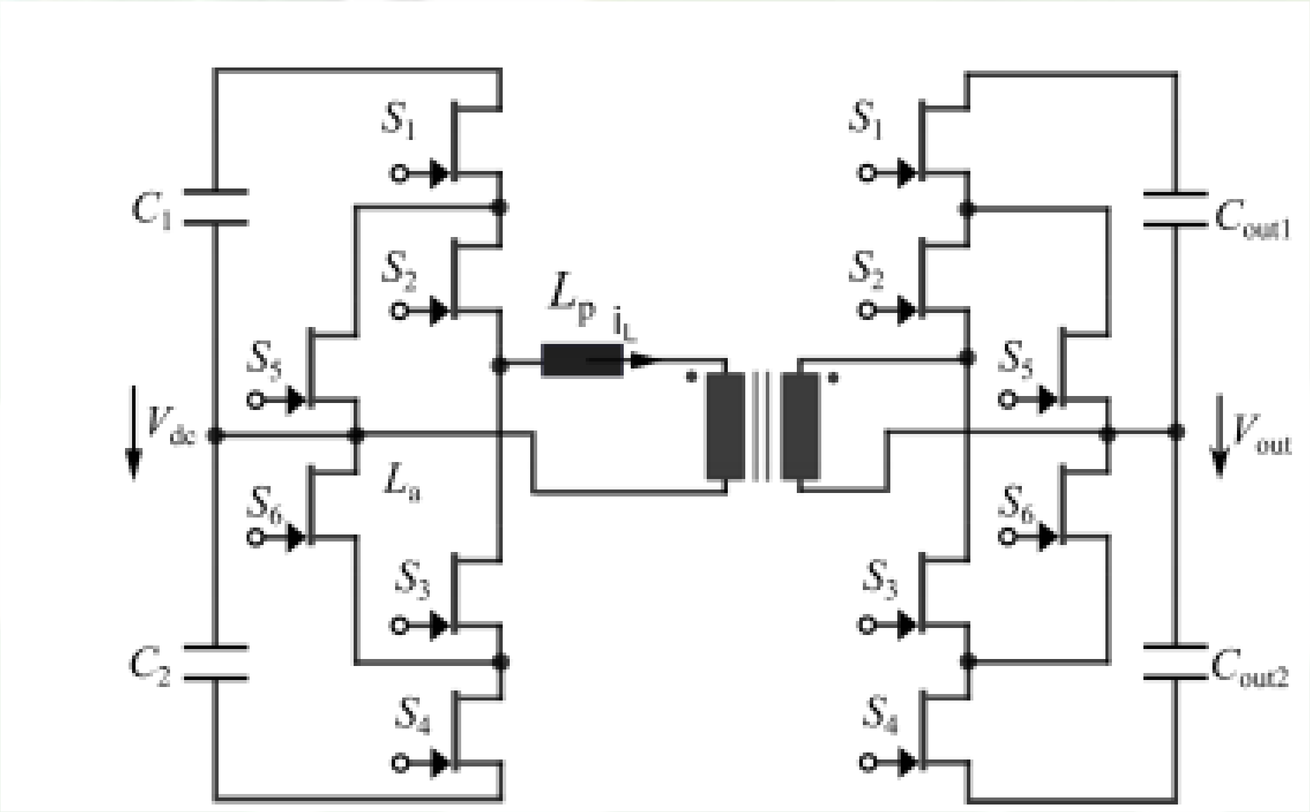
Three-Phase Active Front-End (AFE) Converters for the Dual Stage OBC Applications



(a) Three-phase three-level active neutral point clamped ANPC converter

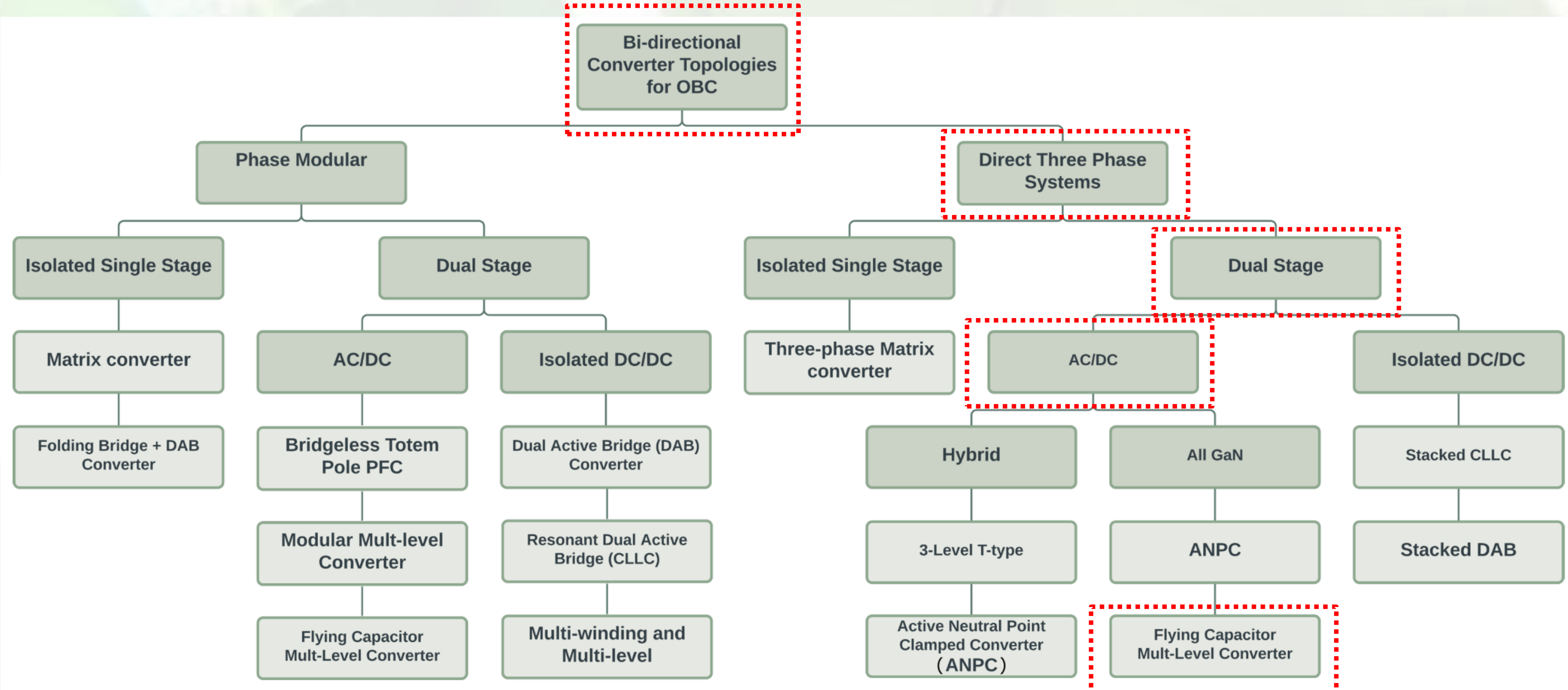
Bi-directional converter topologies for the OBC

Three-level ANPC dual active half-bridge converter



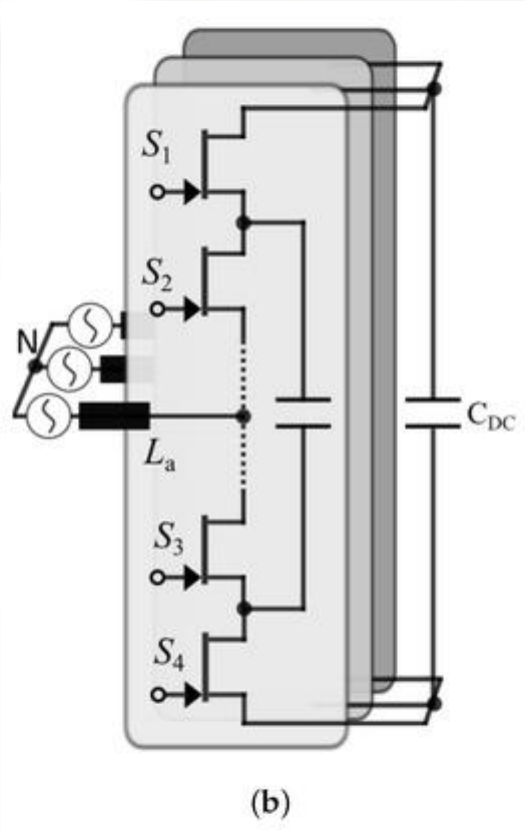
Classification of bi-directional converter topologies for the OBC

On-Board Battery Chargers - OBC



Bi-directional converter topologies for the OBC

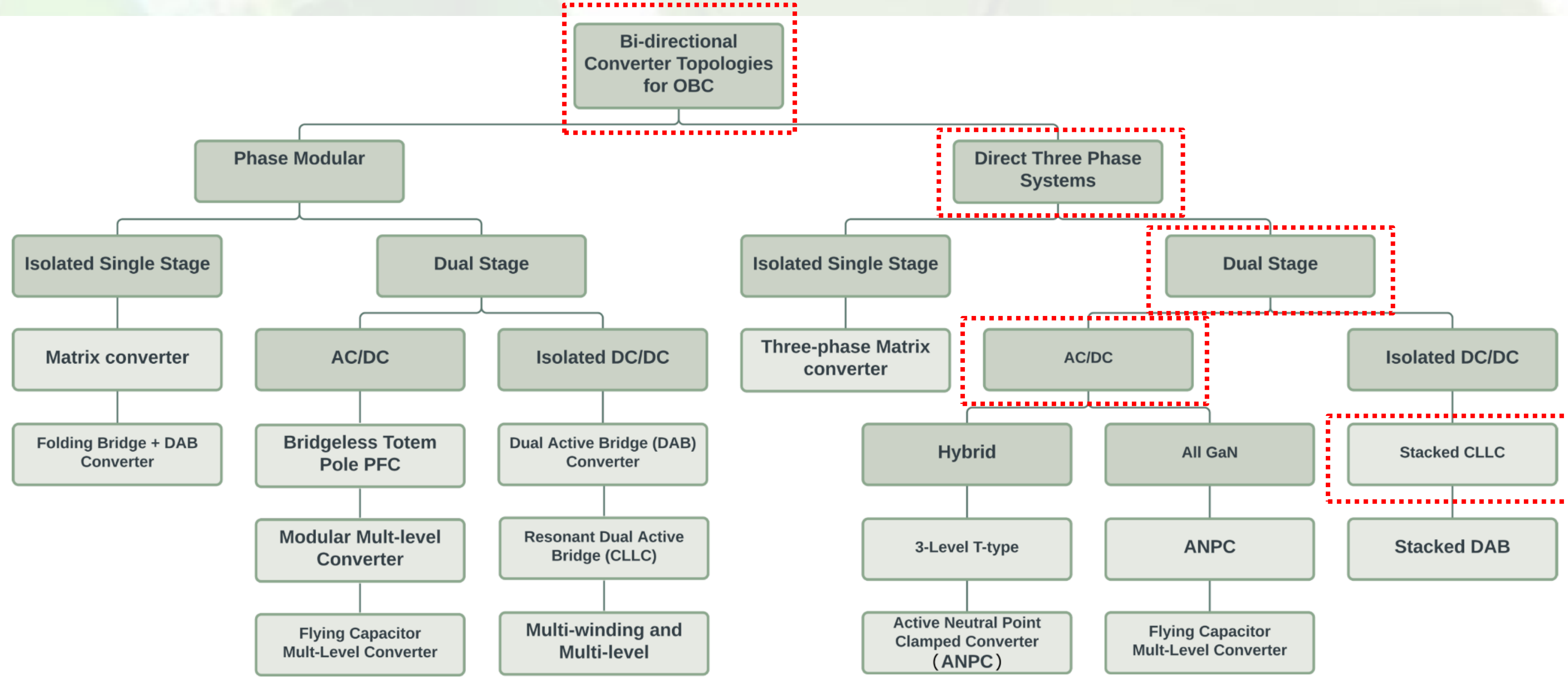
Three-Phase Active Front-End (AFE) Converters for the Dual Stage OBC Applications



(b) Three-phase flying-capacitor multi-level (FCML) converter

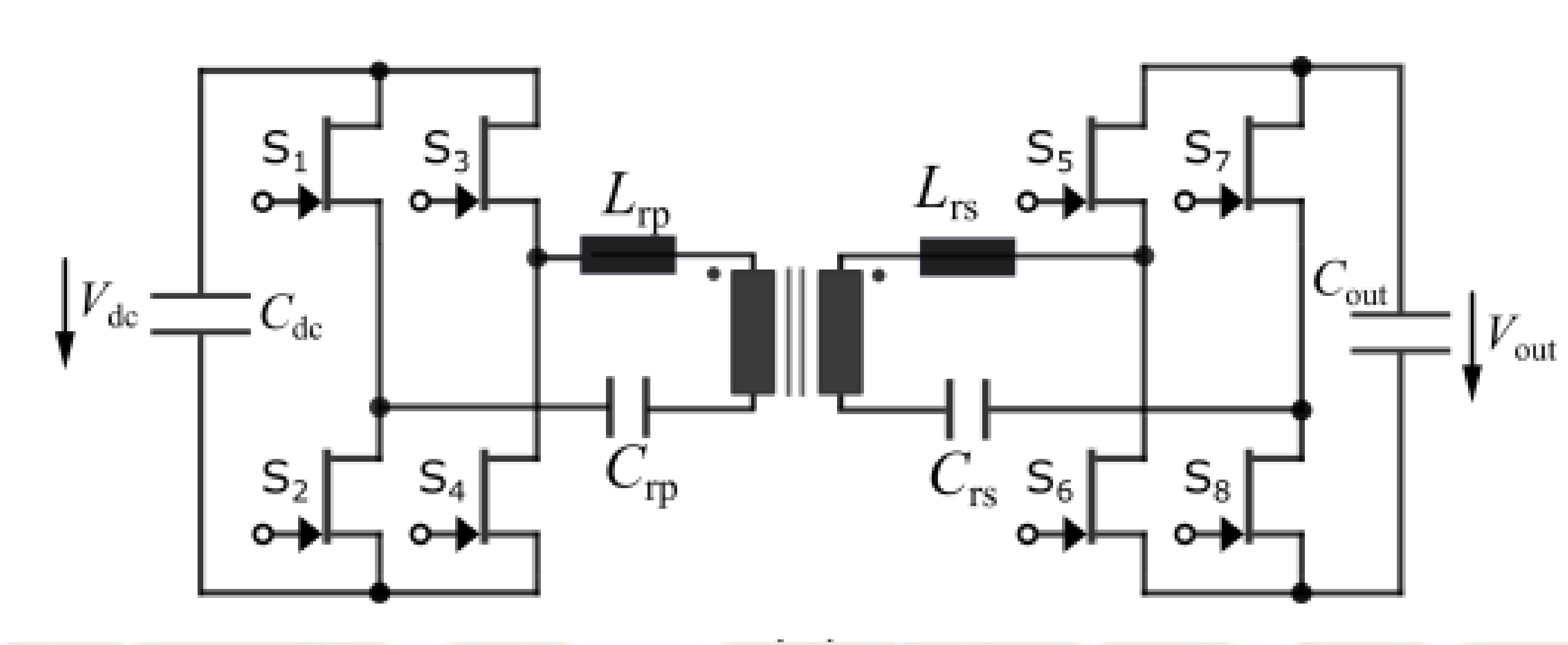
Classification of bi-directional converter topologies for the OBC

On-Board Battery Chargers - OBC



Bi-directional converter topologies for the OBC

Full-bridge CLLC converter topologies



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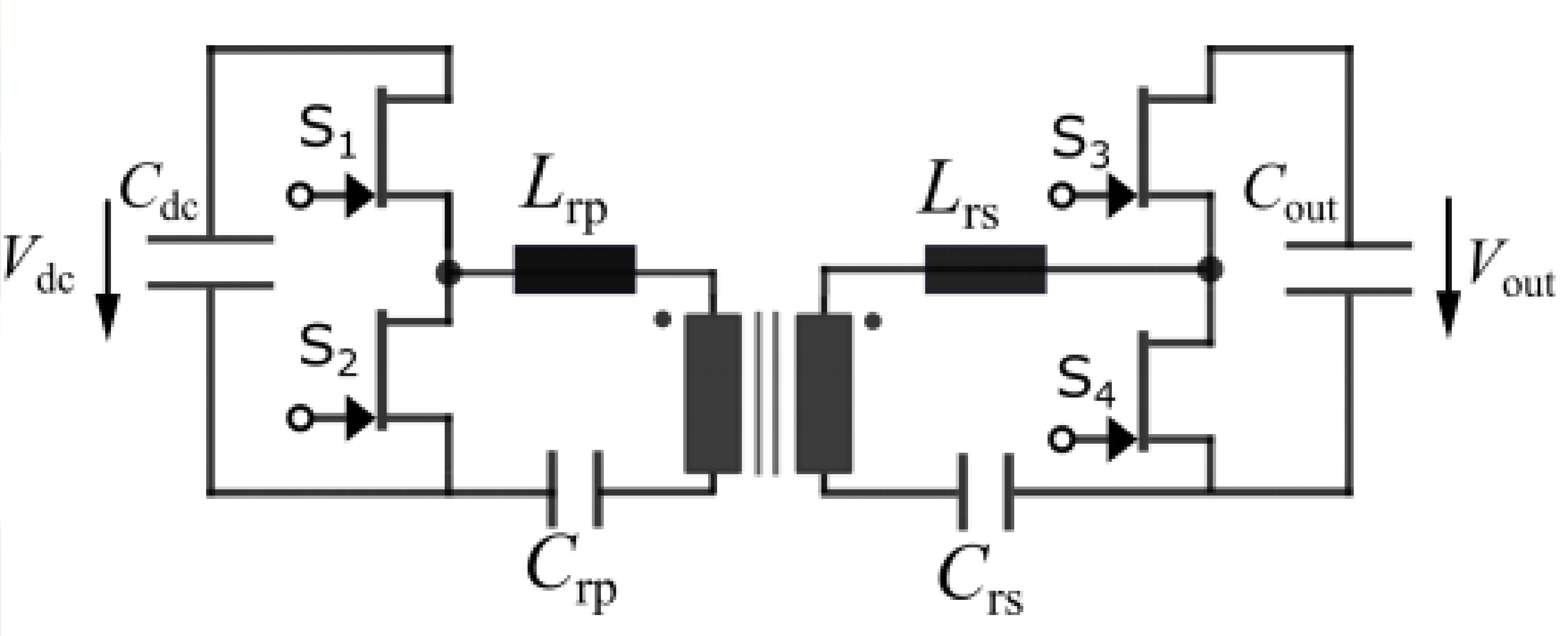
Bi-directional converter topologies for the OBC

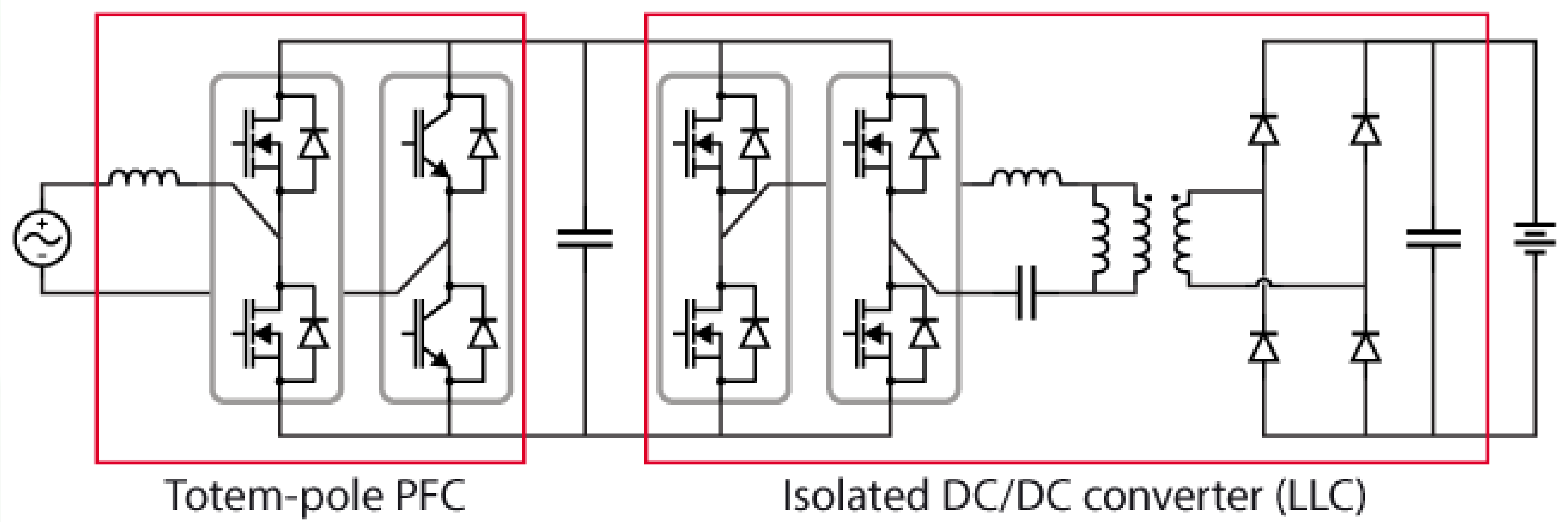
Half-bridge CLLC converter topologies



Bi-directional converter topologies for the OBC

Dual stage On-board charger

First stage **Second stage**



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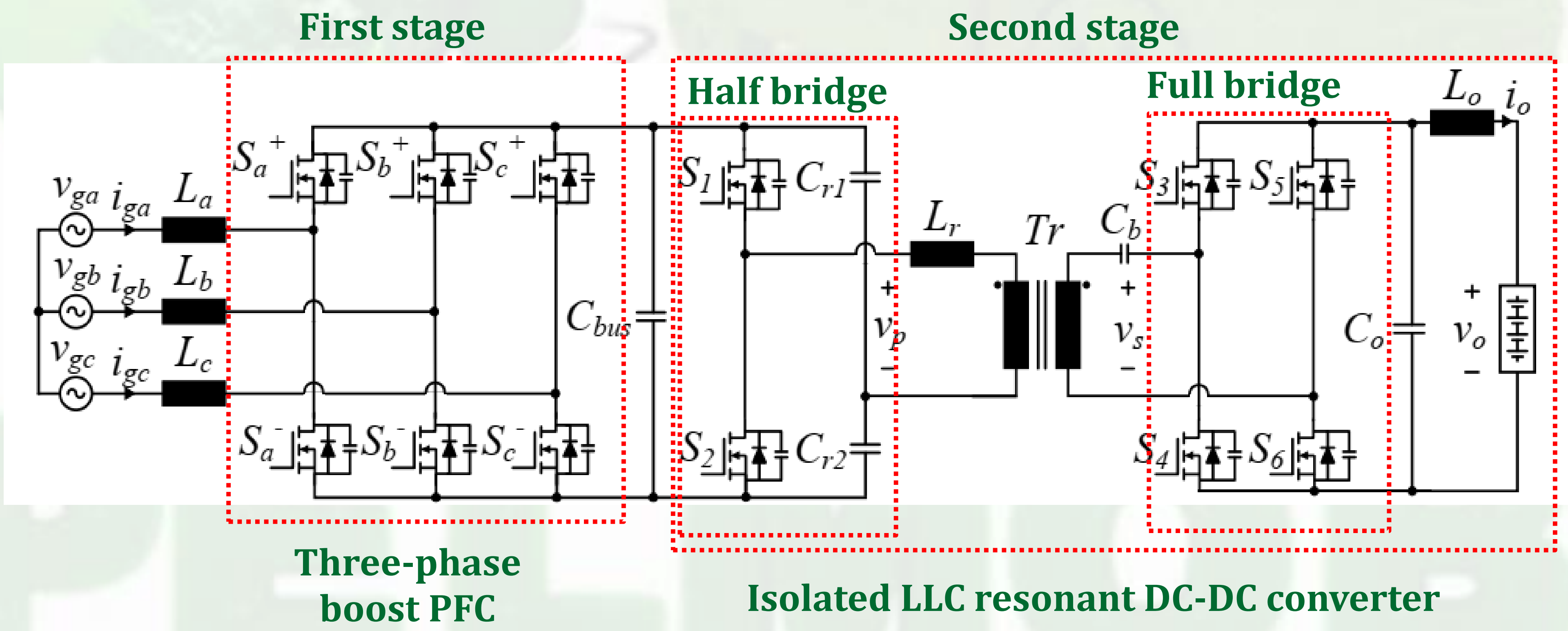
Bi-directional converter topologies for the OBC

Dual stage On-board charger



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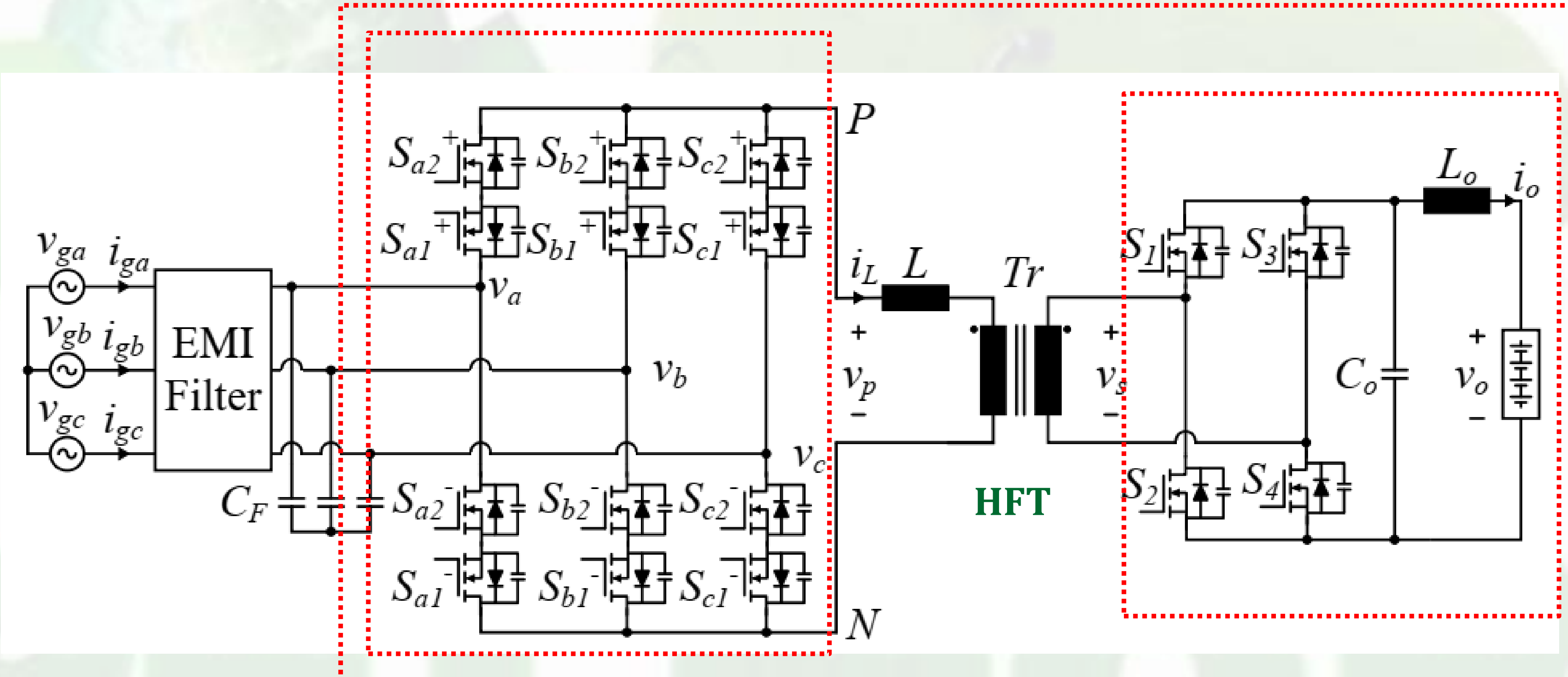
Bi-directional converter topologies for the OBC

Single stage On-board charger



3-phase matrix converter with back-to-back switches

Full bridge active converter

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Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

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25 kW High Efficiency High Power Density Bi-directional T-type Inverter

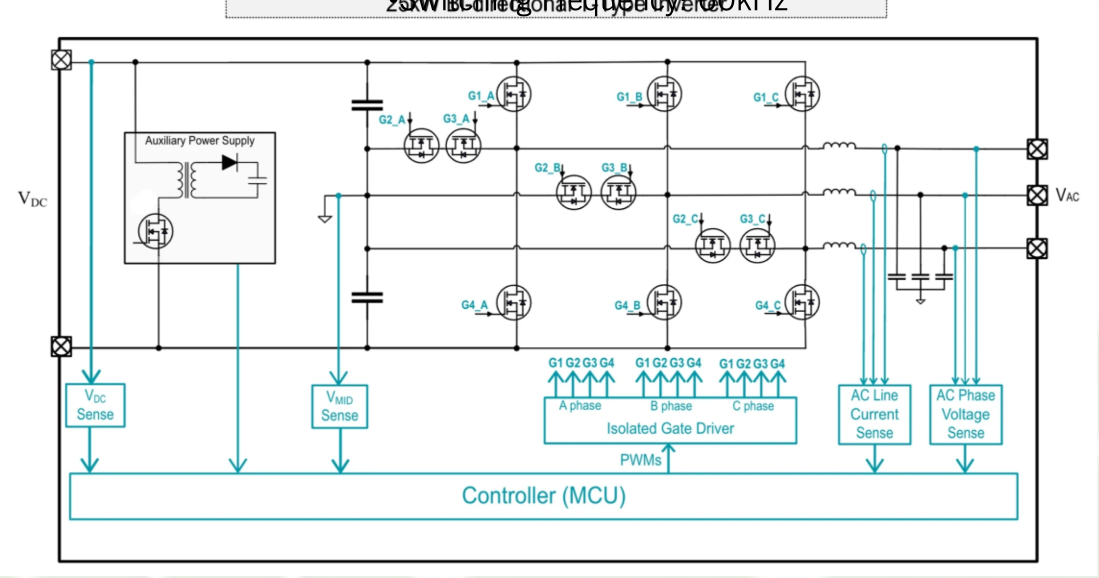
AC/DC DC/AC Convertor

Inverter Mode Specifications:

- DC Input Voltage: 800V DC
- Max current: 36A
- AC Output Voltage: 380-480V$_{line-line}$ 50/60Hz
- Max power: 25kW
- Switching Frequency: 60kHz

PFC Mode Specifications:

- Three Phase Input Voltage 380-480V$_{line-line}$ 50/60Hz
- Max current: 36A
- Output DC Voltage: 650V → 900V; Max power 25kW
- Max current: 36A
- Switching Frequency: 60kHz



Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

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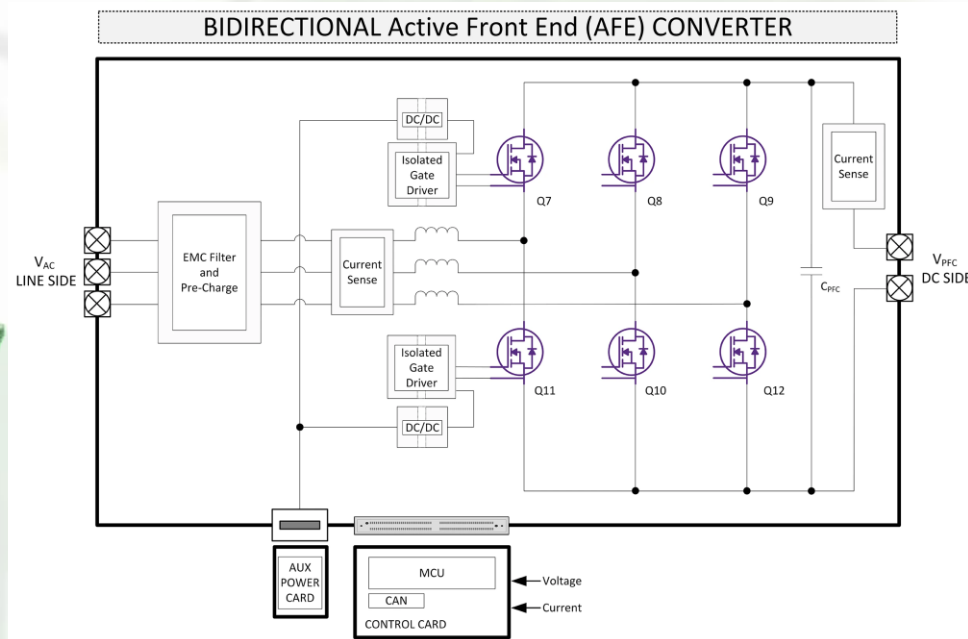
AC/DC DC/AC Convertor

22 kW Bi-Directional Active Front End (AFE)

1200V C3M™ SiC MOSFETs to create a 22kW three phase bidirectional active front end (AFE) converter for electric vehicle (EV) on-board charger (OBC).



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Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

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Bi-directional converter topologies for the OBC

22 kW Bi-Directional Active Front End (AFE)

AC/DC DC/AC Convertor

1200V C3M™ SiC MOSFETs to create a 22kW three phase bidirectional active front end (AFE) converter for electric vehicle (EV) on-board charger (OBC).

Power density of 4.6kW/L

PFC Mode

Three Phase Input Voltage: 305Vrms → 450Vrms line-line 50/60Hz
Max current: 32A
Output DC Voltage: 650V → 900V; Max power 22kW

•Single Phase Input Voltage: 180Vrms → 264Vrms 50/60Hz
Max current: 32A
Output DC Voltage: 380V → 900V; Max power 6.6kW

Inverter Mode

•DC Input Voltage: 350V → 760V DC
Max current: 20A

•AC Output Voltage: 230Vrms 50Hz single phase
Max power: 6.6kW

•Switching Frequency: 45kHz

•Tooled heatsink to simulate cooling plate

•CAN interface

Power Converters

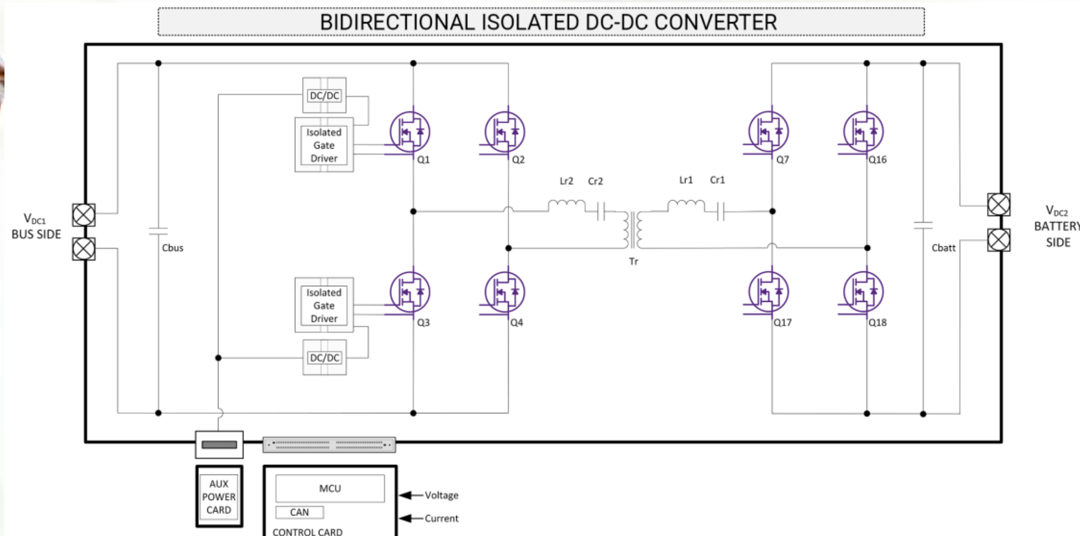
Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

DC/DC Convertor

22 kW Bi-Directional CLLC

1200V SiC MOSFETs to create a 22kW Bi-directional High Efficiency DC/DC Converter for electric vehicle (EV) on-board (OBC) and off-board fast charging applications.



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Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

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DC/DC Convertor

22 kW Bi-Directional CLLC

1200V SiC MOSFETs to create a 22kW Bi-directional High Efficiency DC/DC Converter for electric vehicle (EV) on-board (OBC) and off-board fast charging applications.

Charging Mode

Output Voltage : 480V-800V DC Nominal. System capable of 200V-800V DC
At Vin=650V-900V DC ; Output Power : 22kW ; Output current : 36A
At Vin=380V-900V DC ; Output Power : 6.6kW ; Output current : 26.4A

Discharging Mode

Output Voltage : 360V-750V DC Nominal
Output Power : 6.6kW ; Output current : 19A
Full bridge CLLC resonant converter operating at 135-250kHz
Tooled heatsink to simulate cooling plate
CAN interface

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Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

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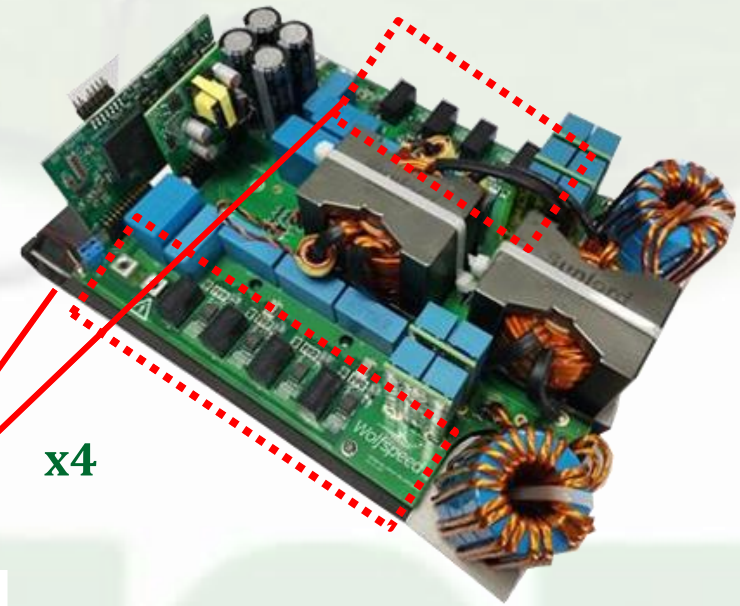
Bi-directional converter topologies for the OBC

1200V C3M™ SiC MOSFETs to create a 22kW three phase bidirectional active front end (AFE) converter for electric vehicle (EV) on-board charger (OBC).

1200V SiC MOSFETs to create a 22kW Bi-directional High Efficiency DC/DC Converter for electric vehicle (EV) on-board (OBC) and off-board fast charging applications.

AC/DC DC/AC Convertor

DC/DC Convertor



+

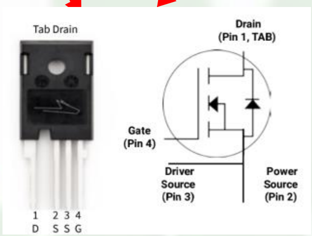
x4

x4

x6

22 kW Bi-Directional Active Front End (AFE)

Power density of 4.6kW/L



22 kW Bi-Directional CLLC

Power densities of 8kW/L

1200V 75mohm Silicon Carbide Power MOSFET

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Power Converters

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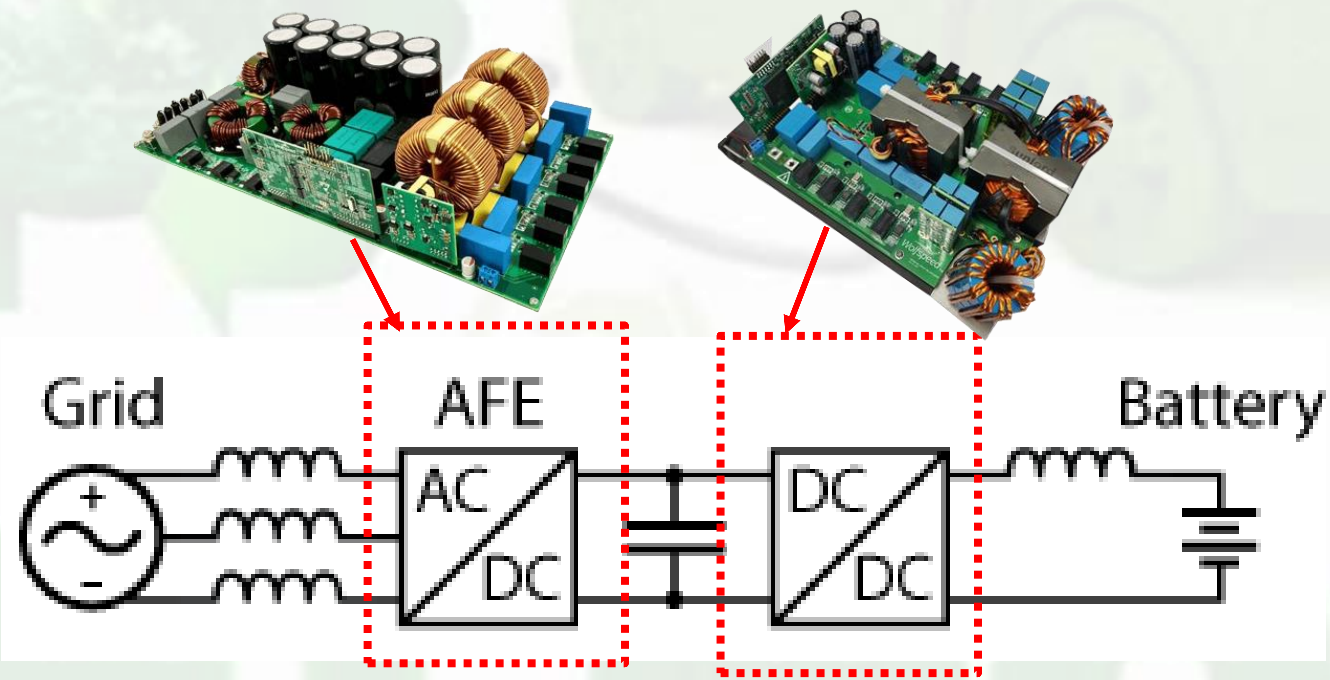
FACULTY OF TECHNICAL SCIENCES KOSOVSKA MITROVICA

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Bi-directional converter topologies for the OBC

Electric Vehicle (EV) fast charger



22 kW Bi-Directional Active Front End (AFE)

22 kW Bi-Directional DC/DC CLLC Convertor

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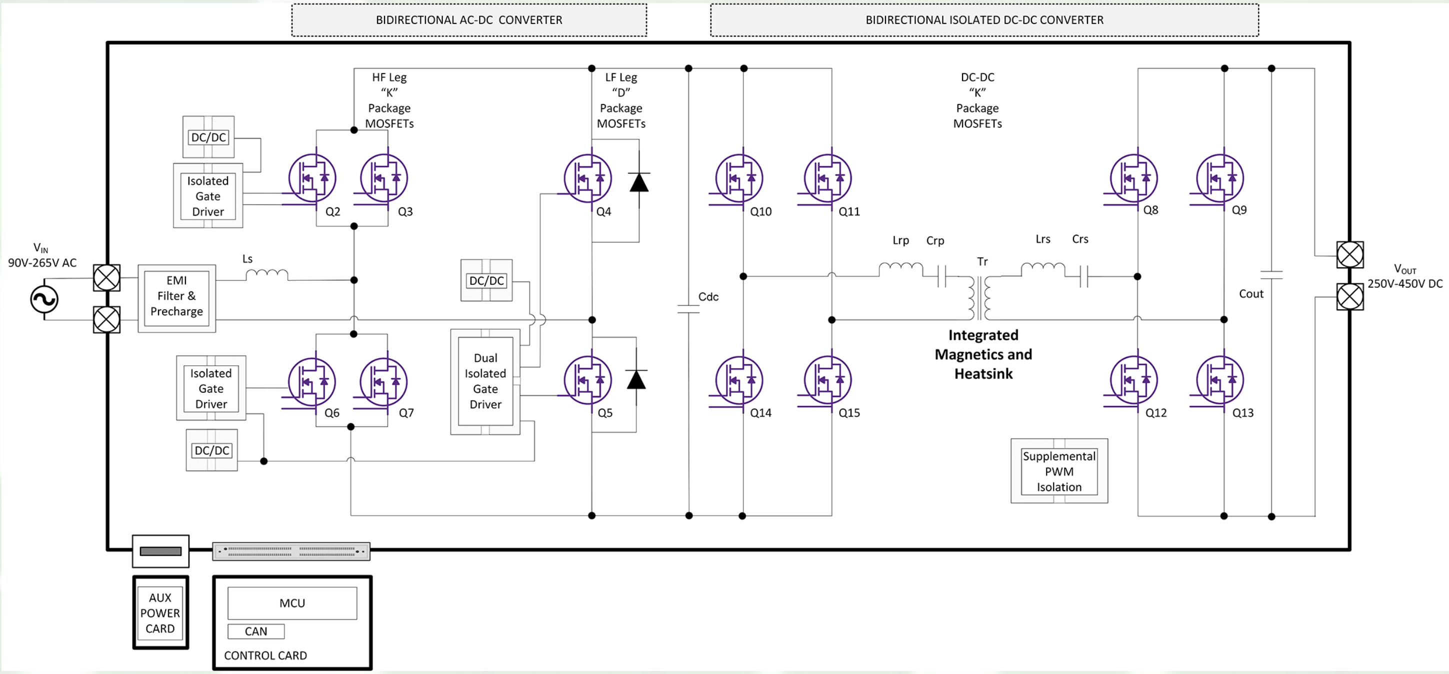
6.6 kW Bi-Directional Totem-Pole PFC and CLLC, High Power Density

With 650V E-Series Silicon Carbide MOSFETs create a high-power density electric vehicle (EV) on-board charger (OBC)



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6.6 kW Bi-Directional Totem-Pole PFC and CLLC, High Power Density

With 650V E-Series Silicon Carbide MOSFETs create a high-power density electric vehicle (EV) on-board charger (OBC).

Specifications

- Universal single phase input voltage between 90V and 265V
- Output Voltage of 250V-450V DC
- 18A Output Current in charging mode
- Front End AC/DC PFC using CCM Totem-Pole Bi-Directional Topology operating at 67Khz
- Bi-Directional DC/DC CLLC resonant converter operating at 148-300KHz
- Constant Current; Constant Voltage or Constant Power Mode
- Unique integrated heatsink design removes heat from MOSFET's; transformer and inductors
- CAN Interface

Power Converters

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DC/DC Convertor

6.6 kW Bi-Directional CLLLC

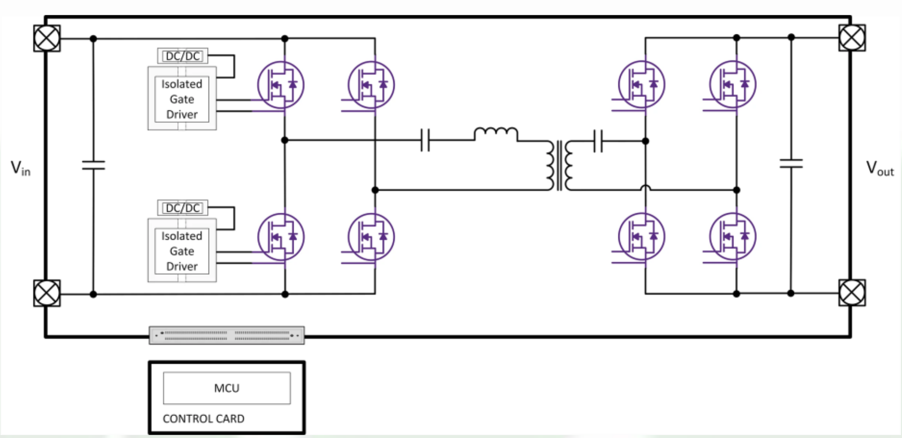
CLLLC resonant DAB with bidirectional power flow capability and soft switching characteristics is an ideal candidate for Hybrid Electric Vehicle/Electric Vehicle on-board chargers and energy storage applications. This design illustrates control of this power topology in closed voltage and closed current-loop mode.

Specifications

- Input Voltage: 380 – 600 V DC
- Output Voltage: 280 – 450 V DC
- Power Max: 6.6 kW
- Peak Efficiency: 98%

Applications

- On-board charger
- Fast charging
- On-board DC/DC converter



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Unit kW/L?

The unit **kW/L** stands for **kilowatts per liter** and is a measure of **power density**.

•**kW (kilowatt)**: A unit of power, representing the rate of energy conversion or transfer (1 kW = 1000 watts).

•**L (liter)**: A unit of volume (1 L = 0.001 m³).

What **6.5 kW/L** Means:

•It indicates that the power converter can deliver **6.5 kilowatts of power for every liter of its volume**.

•A higher **kW/L** value means the converter is more **compact and efficient** in terms of power output relative to its size.

Why It Matters:

•High power density (like **6.5 kW/L**) is crucial in applications where space is limited, such as:

- Electric vehicles (EVs)
- Aerospace systems
- Portable power systems
- Data centers

•It reflects advancements in **thermal management, semiconductor efficiency, and packaging technologies**.

Comparison:

•Traditional power converters might have power densities in the range of **1–3 kW/L**.

•**6.5 kW/L** is considered **very high**, suggesting cutting-edge design and materials.

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Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Power Converter Topologies for EVs & V2G

Topology	Key Features	Efficiency	Power Range	Best For	V2G Ready?
Totempole PFC (SiC/GaN)	Bridgeless, bidirectional, low THD	>98%	3.7–22 kW	Premium EVs (Tesla, Lucid)	✓ Yes
Vienna Rectifier	Cost-effective, 3-level PFC	97%	3.7–11 kW	Mass-market 400V EVs	✗ No
ANPC/3-Level NPC	Neutral-point clamping, 800V+ support	97–99%	22–350 kW	Ultra-fast charging (Porsche Taycan)	✓ Yes
MMC	Modular, scalable, ultra-low THD	98–99%	50 kW–1 MW+	HVDC, fleet charging	✓ Yes
Dual Active Bridge (DAB)	Isolated, bidirectional, soft switching	>98%	11–350 kW	High-power OBCs (V2G/V2L)	✓ Yes
CLLC Resonant	High-frequency, compact, bidirectional	98%	6.6–22 kW	Integrated OBCs (BMW, Hyundai)	✓ Yes
Wireless (Inductive)	Cable-free, automated charging	~90%	3.7–22 kW	Luxury EVs (Mercedes EQ)	✓ (Limited)

Power Converter Topologies for EVs & V2G

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- **Key Applications**
  - ✓ **V2G/V2L:** Totempole PFC + DAB or ANPC.
  - ✓ **Cost-Effective Charging:** Vienna + LLC.
  - ✓ **Ultra-Fast Charging (800V+):** ANPC/MMC.
  - ✓ **Space-Constrained EVs:** CLLC or traction-inverter integration.

- **Power Density Targets:**
  - ✓ **Current:** 4.6 kW/L (e.g., 22 kW SiC AFE).
  - ✓ **Future:** 6.5+ kW/L (GaN, advanced cooling).

Which power converter topology meets the power needs of electric vehicles and V2G capabilities?

- **For Projects Prioritizing V2G/Bidirectional Power Flow:**
  - ✓ **Top Pick: Totempole PFC (SiC/GaN) + DAB**
    - *Why?* >98% efficiency, compact, and full V2G support (e.g., Tesla, Lucid).
    - *Power Range:* 11–22 kW.
  - ✓ **Alternative: ANPC/MMC** for 800V+ ultra-fast charging (e.g., Porsche Taycan).

- **For Cost-Sensitive Projects (No V2G):**
  - ✓ **Top Pick: Vienna Rectifier + LLC**
    - *Why?* Simple, 97% efficiency, ideal for 400V mass-market EVs.
    - *Power Range:* 3.7–11 kW.

Which power converter topology meets the power needs of electric vehicles and V2G capabilities?

- **For Space-Constrained Designs:**
  - ✓ **Top Pick: CLLC Resonant or Traction-Inverter Integration**
    - *Why?* Uses existing motor windings (e.g., Renault ZOE) or high-frequency isolation.
- **For Ultra-High Power (Fleet/Megawatt Charging):**
  - ✓ **Top Pick: Modular Multilevel Converter (MMC)**
    - *Why?* Scalable to MW levels with low THD (e.g., electric buses/trucks).

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Final Considerations & Conclusion

- **Bidirectional Power Flow is Critical for V2G:**
  - ✓ Enables EVs to **feed energy back to the grid** (V2G), homes (V2H), or loads (V2L).
  - ✓ **Topologies like Totempole PFC, ANPC, and DAB** are dominant for efficiency and controllability.

- **Topology Selection Depends on Use Case:**
  - ✓ **Low Power (≤7 kW):** Vienna Rectifier + LLC (cost-effective).
  - ✓ **Mid-Power (11–22 kW):** Totempole PFC (SiC) + DAB (high efficiency, V2G-ready).
  - ✓ **High Power (≥50 kW):** ANPC/MMC (800V+, ultra-fast charging).

Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Final Considerations & Conclusion

- **Integration Trends:**
  - ✓ **Traction-Inverter Reuse:** Saves space/weight (e.g., Hyundai E-GMP).
  - ✓ **Wireless Charging:** Convenient but less efficient (~90%).

- **Performance Targets :**
  - ✓ **Efficiency:** >98% (OBC), >99% (PFC).
  - ✓ **Power Density:** 4.6 kW/L (achievable with SiC/GaN).

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Future Directions

- **Wide Bandgap Semiconductors (SiC/GaN):**
  - ✓ Enable **higher switching frequencies**, reducing size/weight.
  - ✓ Critical for **6.6 kW/L+ power density** (e.g., 22 kW CLLC converters).
- **Modular Architectures:**
  - ✓ **MMC and FCML converters** scale for megawatt charging (trucks, buses).
- **Standardization:**
  - ✓ Harmonizing **V2G protocols** and **topology benchmarks** (e.g., THD <5%).

Power Converters

Electric Vehicle Power Converters for Vehicle-to-Grid (V2G) technology

Conclusion

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Power converters are the **cornerstone of V2G-enabled EVs**, balancing **efficiency, cost, and bidirectional capability**. The industry is shifting toward:

- **Totempole PFC + DAB** for mainstream EVs (11–22 kW).
- **ANPC/MMC** for high-power applications (800V+).
- **SiC/GaN adoption** to meet **6.5 kW/L+ power density** targets.

*"The future of EV charging lies in **deeply integrated, bidirectional systems** that maximize energy flexibility while minimizing footprint. Innovations in topology and semiconductors will drive the next wave of V2G adoption."*