Recent Developments in On-board Charging Approaches for Electric Vehicles

FREEDM Symposium 2023

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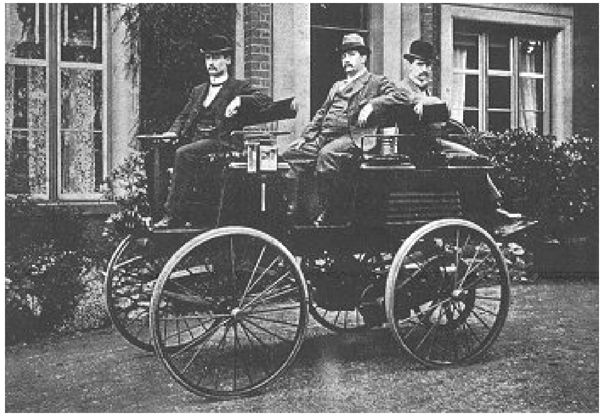
| **Milan M. Jovanović Power Electronics Lab. (MPEL)**
| 2/21/2023

Outline

- ❑ **History of EV**
- ❑ **EV Structure & OBC Architectures**
  - AC-DC Approaches
  - DC-DC Approaches
- ❑ **Summary**

Acknowledgements: Peter Barbosa
Misha Kumar
Boyi Zhang
Nidhi Haryani

A Brief History of Electric Vehicles



1832 – First Crude Electric Vehicle is Developed

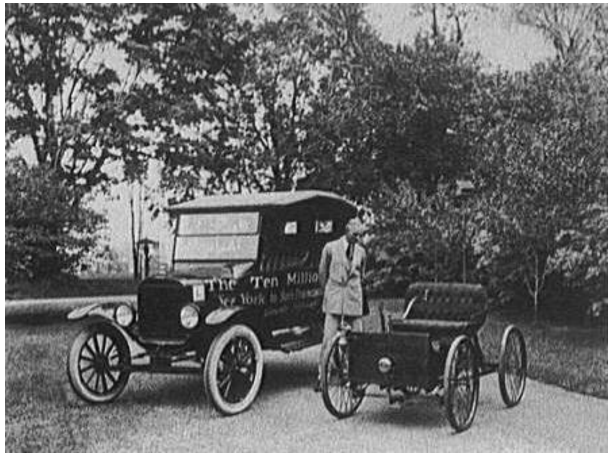
Not practical until 1870s

Picture – 1884 prototype in England

1900s – Electric Cars Reach Their Heyday

By the turn of the century, electric vehicles are all the rage in the US, accounting for ~ a 1/3 of all vehicles on the road

5th Avenue, Manhattan



1910 – Model T Deals a Blow to Electric Vehicles

The mass-produces Model T makes gas-powered cars widely available and affordable.

In 1912, the electric starter is introduced.

Model T : $650
Electric cars: $1,750

1920-1935 – Decline in Electric Vehicles

Better roads and discovery of cheap Texas crude oil help contribute to the decline in electric vehicles. By 1935, they have all but disappeared.

Picture of gasoline filling station that popped up across the US

https://archive.curbed.com/2017/9/22/16346892/electric-car-history-fritchle https://www.energy.gov/articles/history-electric-car

A Brief History of Electric Vehicles

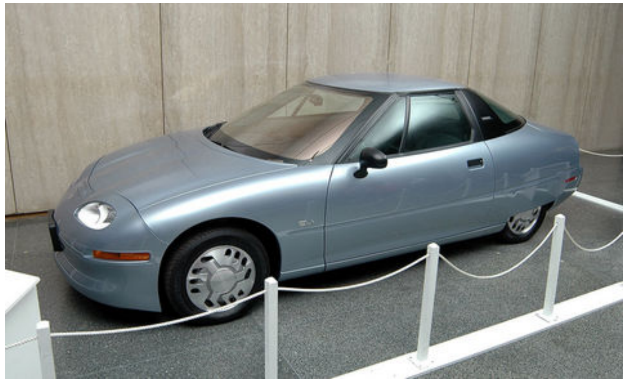
1968 - 1973 – Gas Prices Soar

Over the next 30 years, cheap and abundant gasoline and improvements in ICE created little need for alternatives. In the 60’s and 70’s, soaring gas prices stirred interest in EVs again

1974 - 1977 – Leader in Electric Vehicle Sales

Sebring-Vanguard’s CitiCar – a wedge-shaped compact car that had a range of 50-60 miles. 4,000 cars produced.

6-HP motor!



1996 – EV1 Gains a Cult Following

GM releases the EV1. Range 100 miles. 137 HP electric motor. IGBT inverter!

1997 – First Mass-Produced Hybrid

Toyota introduces the first mass-produced hybrid. Instant success!

2006 – Silicon Valley Startup Takes on Electric Cars

Tesla Motors, a Silicon Valley startup, announces it will produce a luxury electric sports car with a range of 200+ miles. Other automakers takes note…

A Brief History of Electric Vehicles


No. 1: Tesla Model Y


No. 2: Tesla Model 3


No. 3: Ford Mustang Mach-E


No. 4: Tesla Model S


No. 5: Chevy Bolt EV


No. 6: Tesla Model X


No. 7: Hyundai IONIQ 5


No. 8: Kia EV6


No. 9: Volkswagen ID.4



No. 10: Ford F-150 Lightning/Rivian R1T

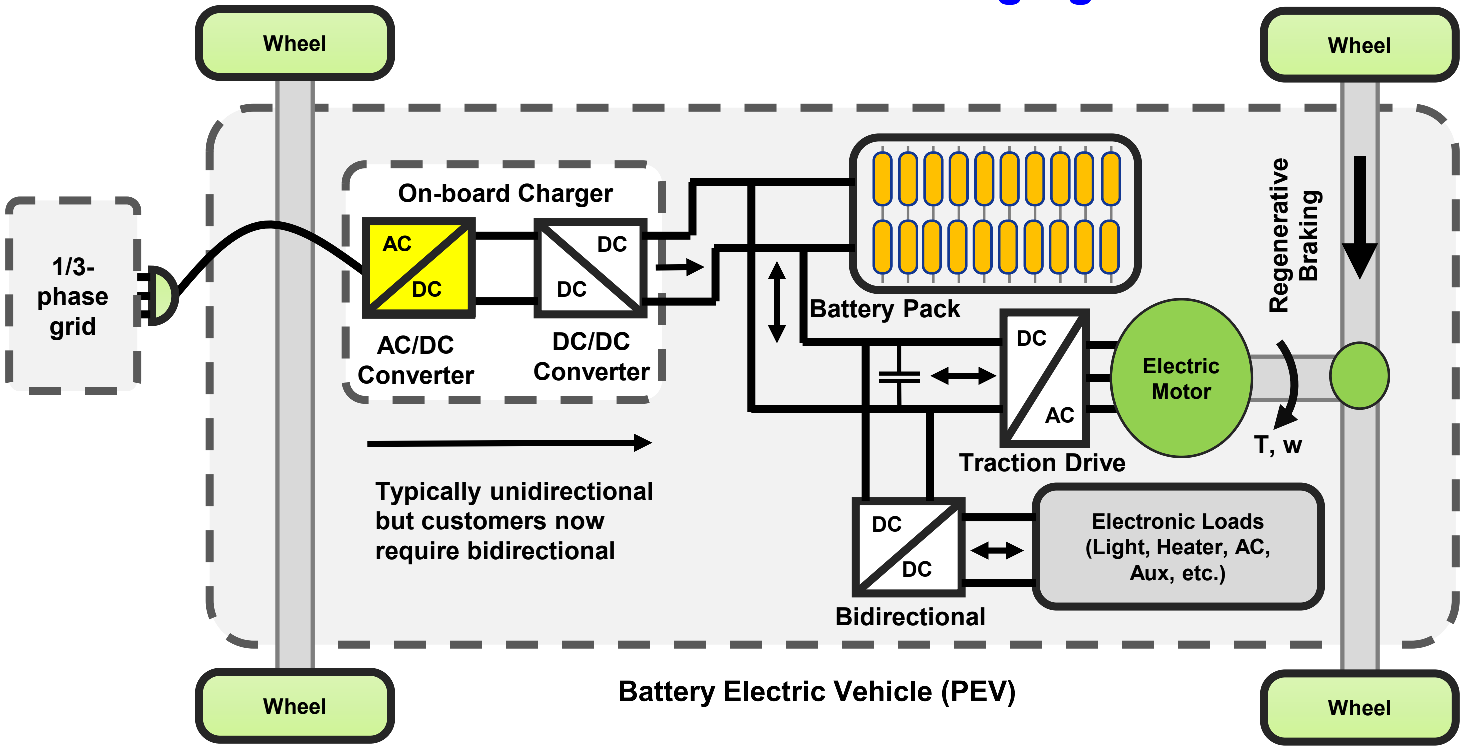
2022 EV sales: 800,000 – 6% of market share, doubling YoY!

Tesla – 65% market share

https://electrek.co/2023/01/09/the-top-10-best-selling-electric-vehicles-in-the-us-of-2022/

Electric Vehicle – Power Train and Charging Structure

On-board charging

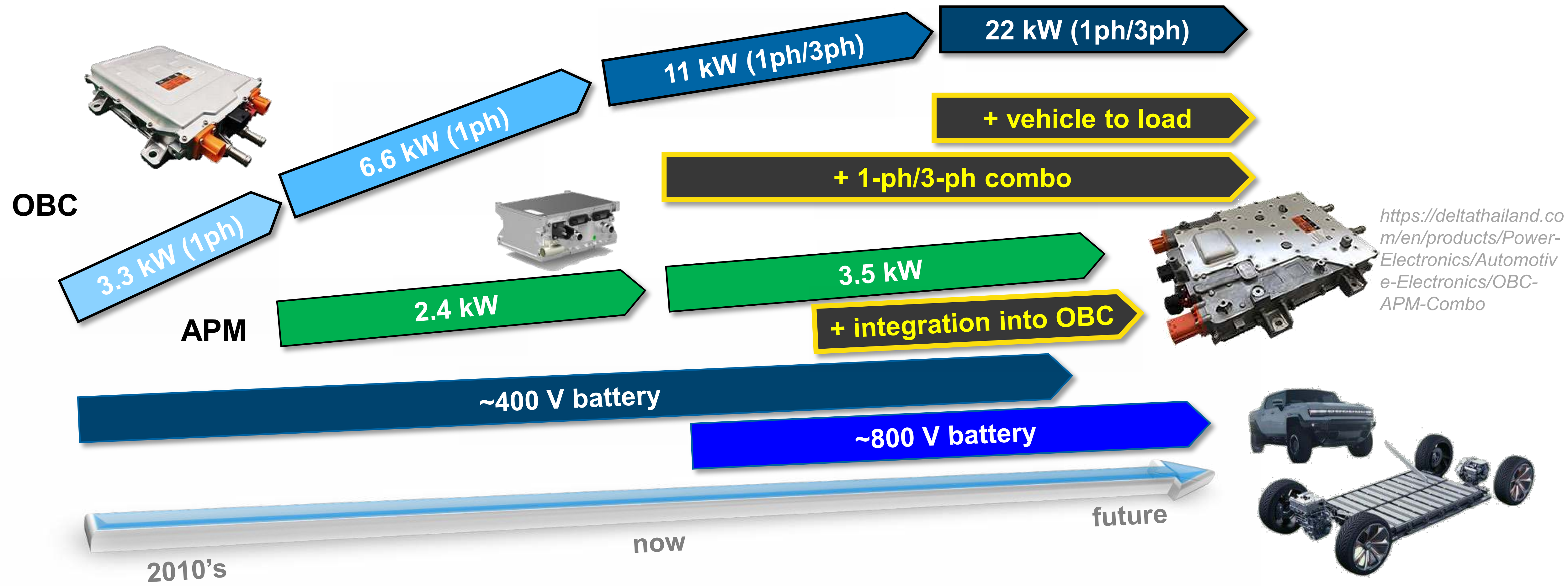


https://www.willbyers.com/blog/history-of-electric-cars

https://www.mouser.com/applications/building-ev-infrastructure/

- Charging of early EVs (1900s) : dangerous business at home (mercury-arc valve)
- Major components over ICE vehicles: **OBC** (AC-DC + DC-DC), **battery pack**, **traction drive**, **electric motor**, **APM DC/DC** (auxiliary power module)
- Universal voltage input, wide battery voltage range, variable power, regenerative power

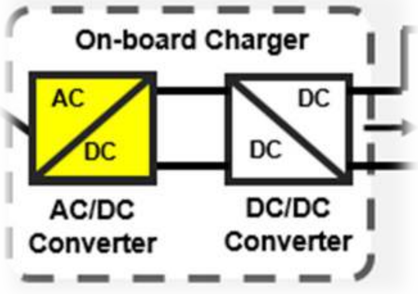
Evolution of On-board Chargers and Auxiliary Power Modules



- Takeaway: increased power and power density, integration of functions, new capabilities
- DOE stretch-goal for 2025: OBC 98% efficient

https://www.freep.com/story/money/cars/mark-phelan/2021/04/05/2024-gmc-electric-hummer-suv/7093724002/

OBC Structure Classification

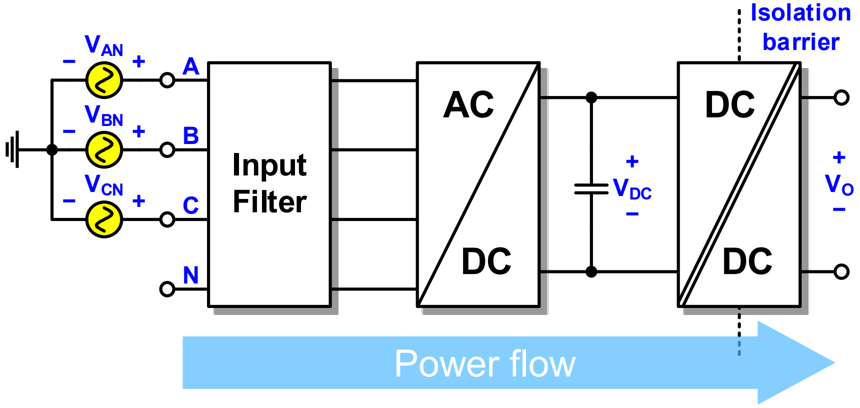


Stock image (Credit: Shutterstock)

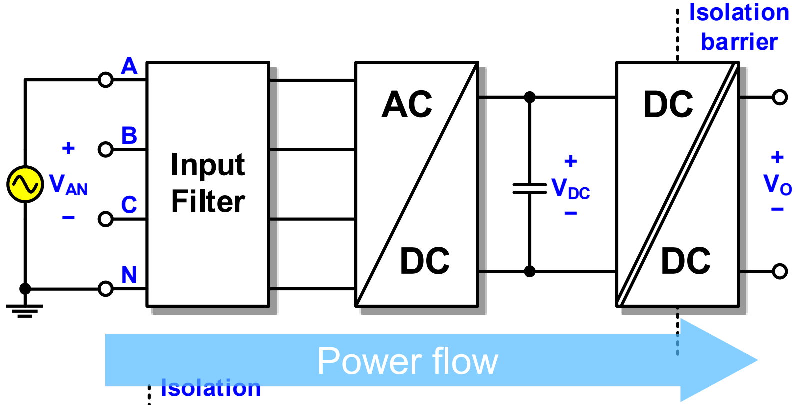
- **2-stage** or **1-stage**
  - **2-stage** approach: DC link to decouple dynamics of AC-DC and DC-DC stages
  - **1-stage** approach: unified control, no or soft DC link
- **Modular** or **integrated** architecture
  - **Modular** approach: each grid phase has its own converter (independent control)
  - **Integrated** approach: treat grid as a true 3-ph source → 3-ph PFC
- **Mechanical** or **magnetic** integration of OBC and APM
  - **Mechanical** integration: same enclosure, PCB, controller but switches/magnetics independent
  - **Magnetic** integration: combine functions into a single multi-port converter to save on switches/magnetics
- Hard-switching vs. soft-switching, battery voltage range, PFC input current conduction mode, …
- Many, many approaches → very active research area

OBC = Universal Power Converter (2-Stage Approach)

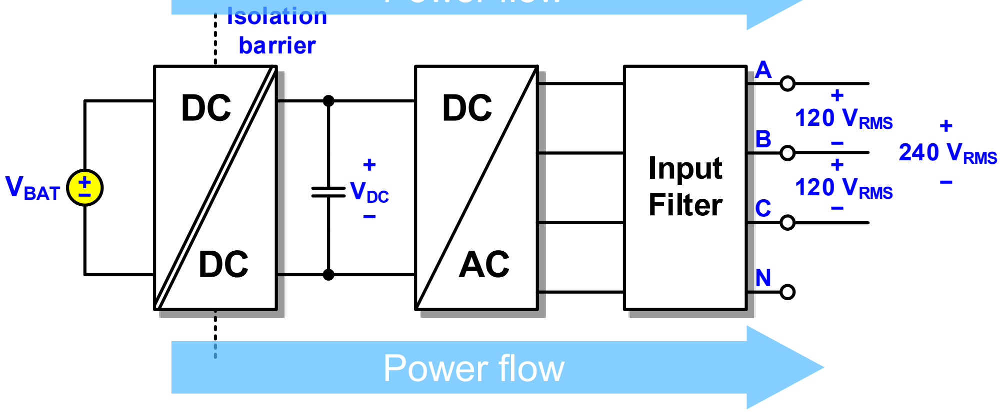
3-ph input



1-ph input

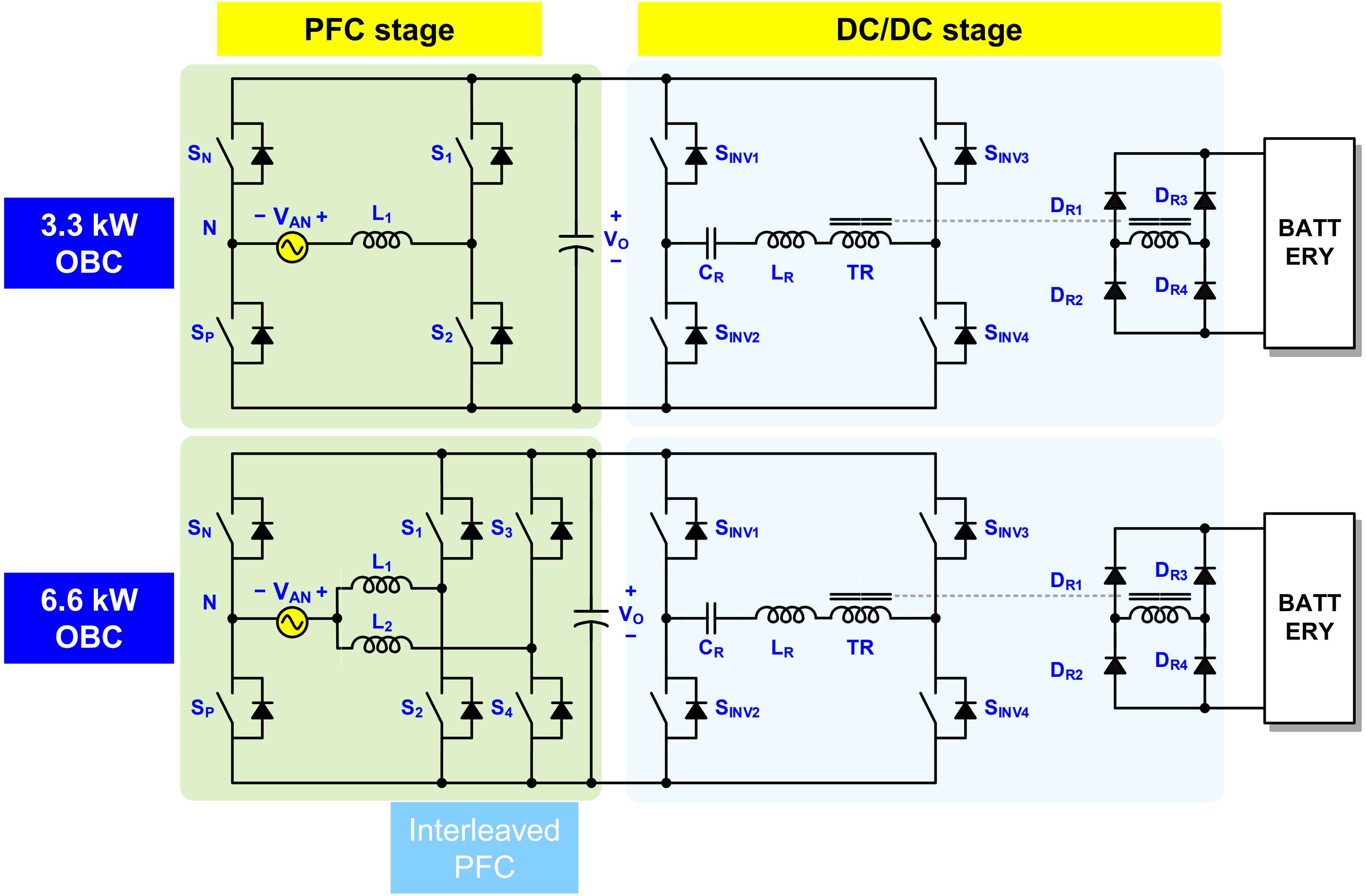


Split-phase output



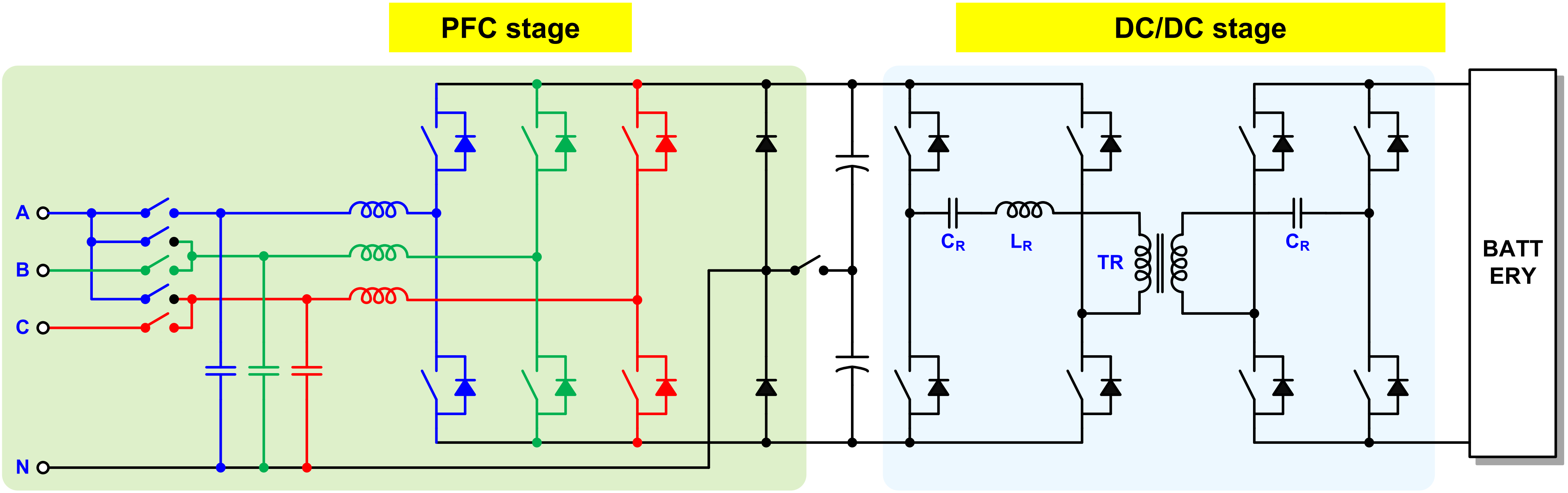
- **AC-DC PFC**:
  - 1-ph grid connections: 85 – 264 V_{RMS}
  - 3-ph connections: 350 – 535 V_{RMS}
- **DC-DC output:**
  - 150 – 500 V (low-voltage battery)
  - 500 – 950 V (high-voltage battery)
- **DC-AC V2L mode:**
  - Split-phase output (2 x 120 V_{RMS})
- Constant DC link beneficial for 1-ph/3-ph (to optimize DC-DC)
- Extremely demanding requirements – power density, efficiency, cost, software features
- Compare to typical converters: server power supply, laptop charger

Integrated OBC – 1-ph (2-Stage Approach)



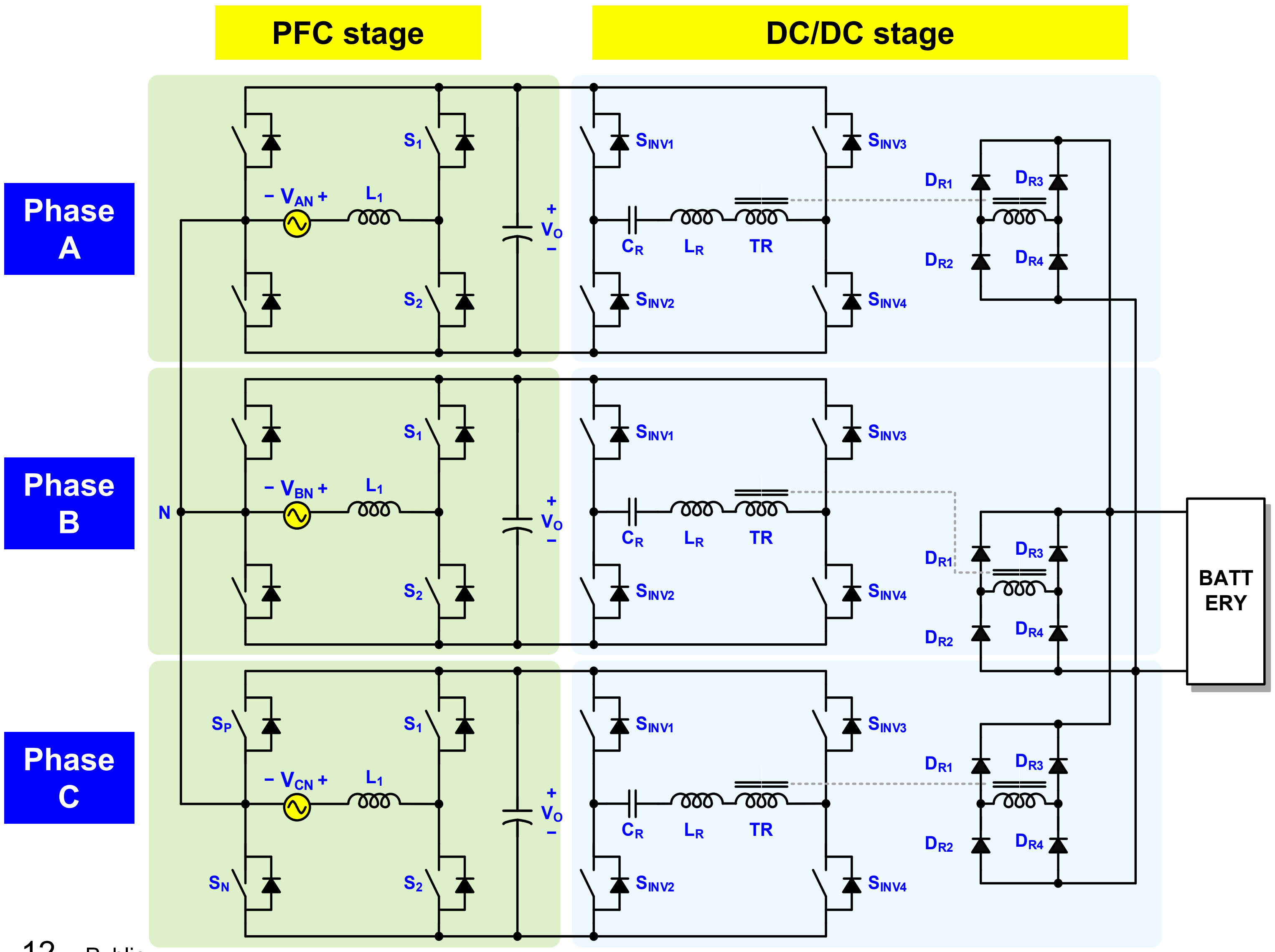
- Industry-standard 2-stage, unidirectional solution
- DC link filters 120-Hz ripple
- PFC:
  - CCM hard-switching PFC
  - Duty-cycle control
- DC-DC:
  - Typically full-bridge soft-switching LLC
  - Variable-frequency control
  - Burst mode at light load

Integrated OBC – 1-ph/3-ph Combo (2-Stage Approach)



- Relay reconfiguration between 1-ph and 3-ph AC input
- 3-ph: 6-switch PFC
- 1-ph: 3x interleaved totem-pole PFC
- Hard-switching CCM
- Constant PFC output at 800 V
- DC-DC:
  - Full-bridge soft-switching LLC
  - Variable-frequency control
  - Burst mode at light load
- Total OBC efficiency: 95-96%

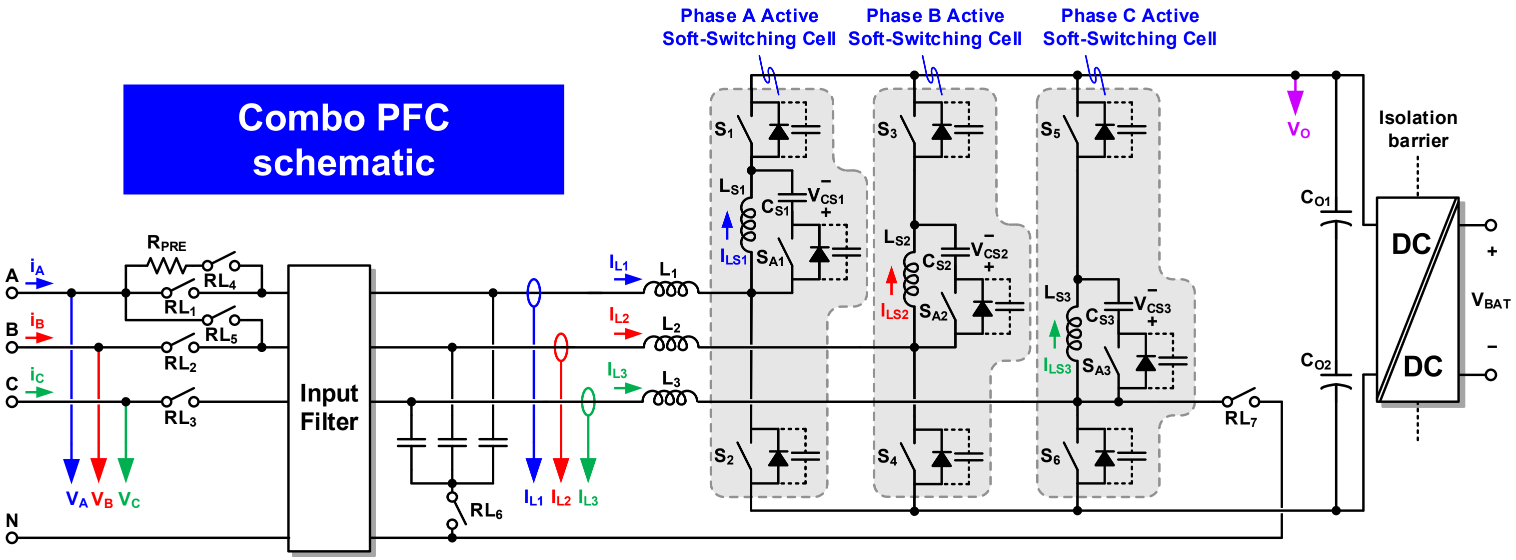
Modular 1-ph/3-ph Combo OBC (2-Stage Approach)



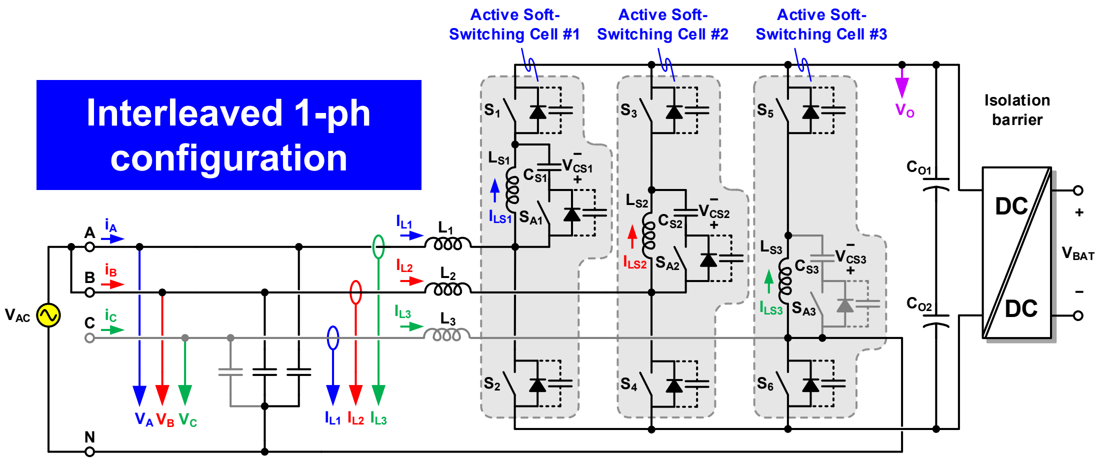
- **PFC**:
  - CCM hard-switching PFC
  - Duty-cycle control
- **DC-DC**:
  - Full-bridge soft-switching LLC
  - Variable-frequency control
  - Burst mode at light load
- Simple and robust control, fault tolerance
- Higher cost (devices, DC links, DSPs, transformers, …) → upcoming EV price war?

1-ph/3-ph Combo CCM Soft-switching PFC (2-Stage Approach)

Combo PFC schematic



Interleaved 1-ph configuration



- 3-ph / interleaved 1-ph PFC combo (relays)
- Increase power density → reduce the size of boost chokes → increase switching frequency
- Increase efficiency → decrease R_{DSON} → increase switching loss
- **Solution: soft-switching**
- CCM preferred due to control simplicity and filter design
- Target switching frequency: ~150 kHz (EMI starts at 150 kHz), 5.6 kW/L
- DC link: ~ 800V
- V2L mode – split-phase output voltage

T. Sadilek, L. Huber, Y. Jang, P. Barbosa and I. Husain, "Analysis, Design, and Performance Evaluation of SiC Active Soft-Switching Cell for 1-ph/3-ph Universal Voltage Input PFC for On-Board Charger Applications," in IEEE Transactions on Power Electronics, vol. 38, no. 1, pp. 1204-1217, Jan. 2023, doi: 10.1109/TPEL.2022.3199204.

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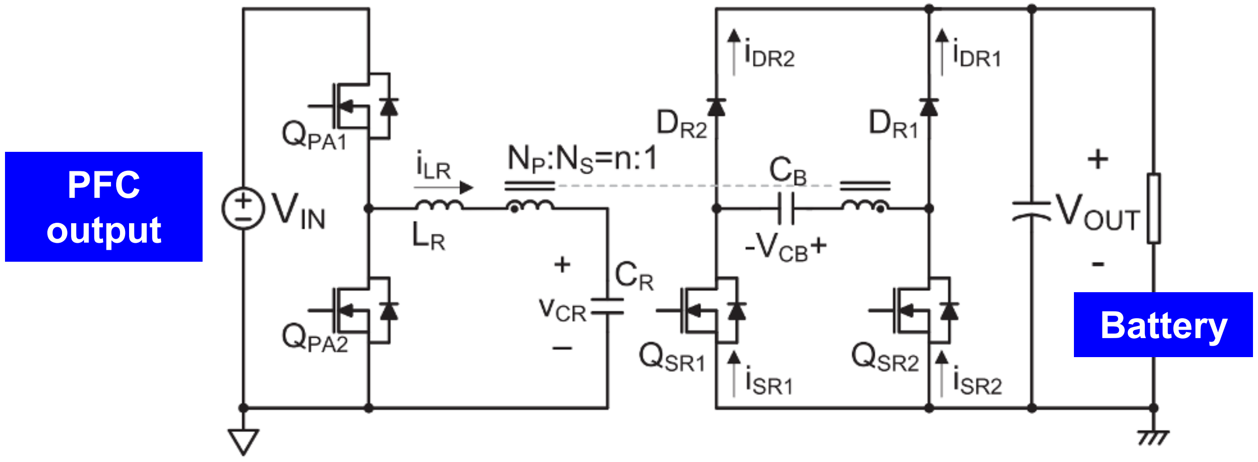
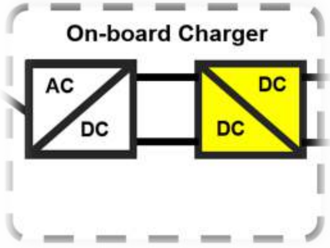
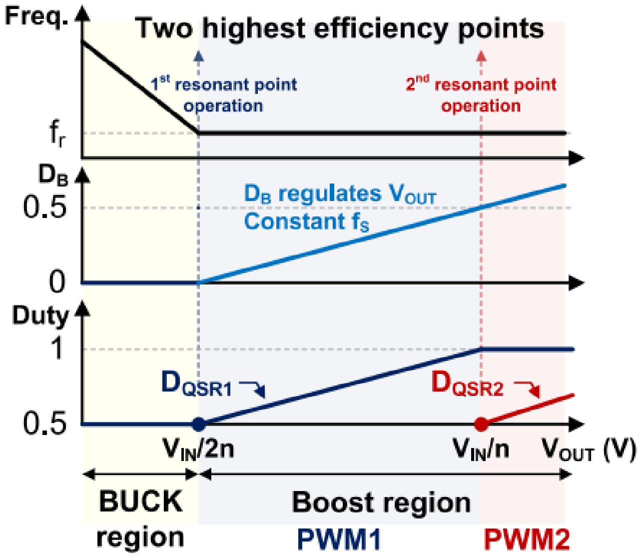
PWM-controlled Series Resonant Converter (2-Stage Approach)



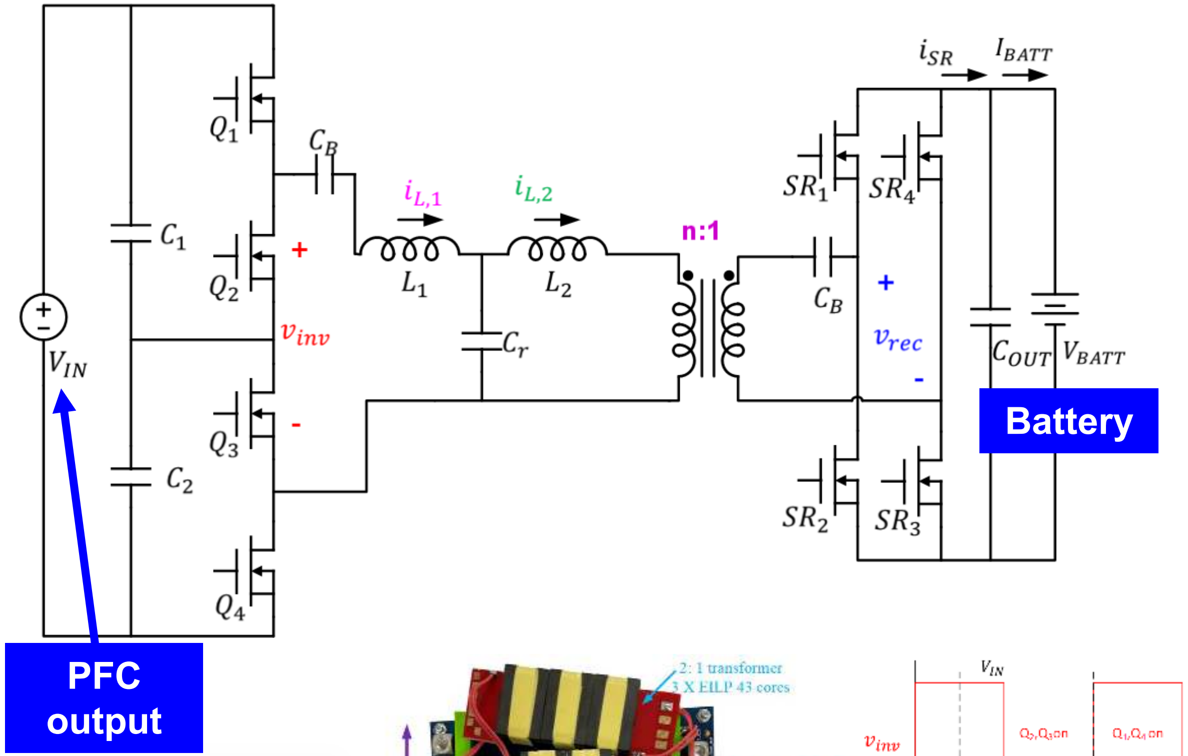


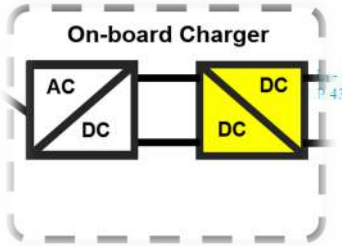


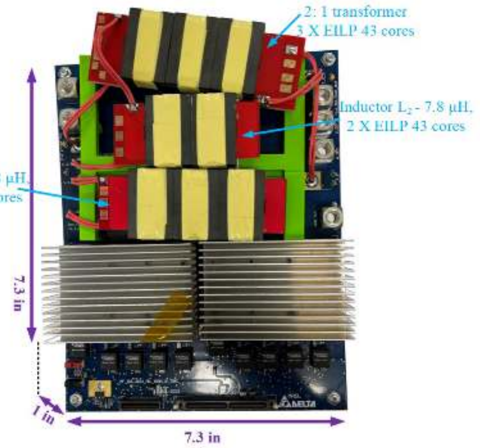
- Series-Resonant Converter (SRC) vs. LLC: magnetizing inductance L_M in high (100x larger than L_R)
- Resonant converters can operate at fixed switching frequency
- **PWM-controlled Series Resonant Converter** with wide output voltage range
- Duty-cycle control on the secondary side
- **Resonant point A**: D_{QSR1} = D_{QSR2} = 50% (full-bridge rectifier)
- **Resonant point B**: D_{QSR1} = 100%, D_{QSR2} = 50% (half-bridge rectifier)

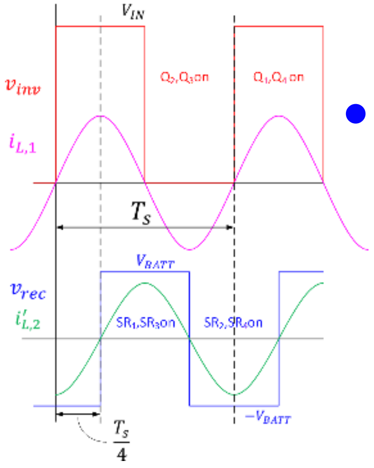
J. -W. Kim and P. Barbosa, "PWM-Controlled Series Resonant Converter for Universal Electric Vehicle Charger," in IEEE Transactions on Power Electronics, vol. 36, no. 12, pp. 13578-13588, Dec. 2021, doi: 10.1109/TPEL.2021.3072991.

Current-source Battery Charger (2-Stage Approach)





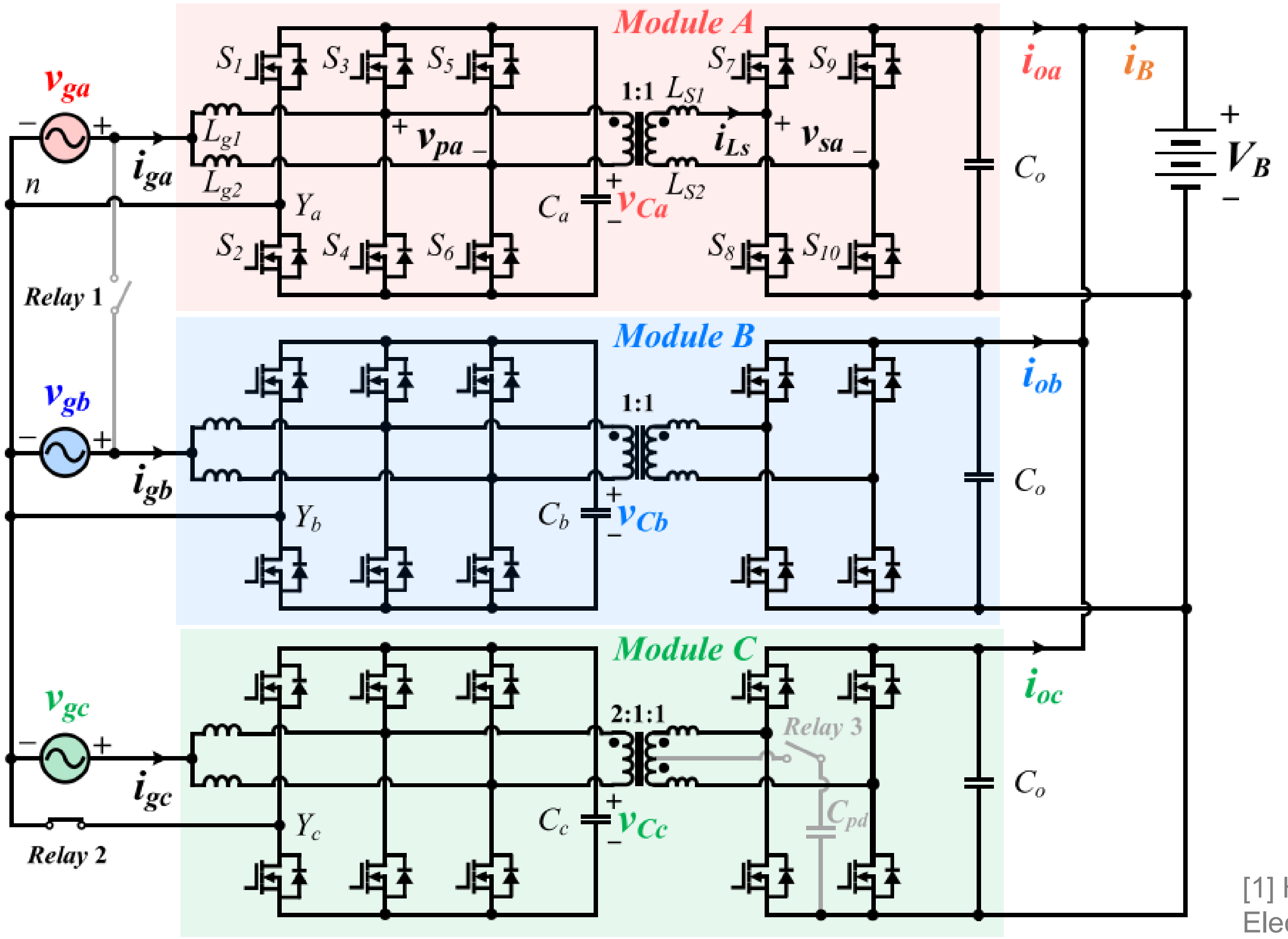




- LCL immitance network (L_1 = L_2)
- **Single-resonant frequency** and **single operating frequency**
- Constant phase-shift between primary and secondary sides
- Current source property – output voltage does not affect output current
- Constant PFC output link at 800 V: vary resonant tank voltage excitation by phase-shifting primary-side SHBs to control output current
- ZVS of all devices (GaN), planar magnetics at 500 kHz (7.3 kW/L)

S. Mukherjee, J. M. Ruiz and P. Barbosa, "A High Power Density Wide Range DC–DC Converter for Universal Electric Vehicle Charging," in IEEE Transactions on Power Electronics, vol. 38, no. 2, pp. 1998-2012, Feb. 2023, doi: 10.1109/TPEL.2022.3217092.

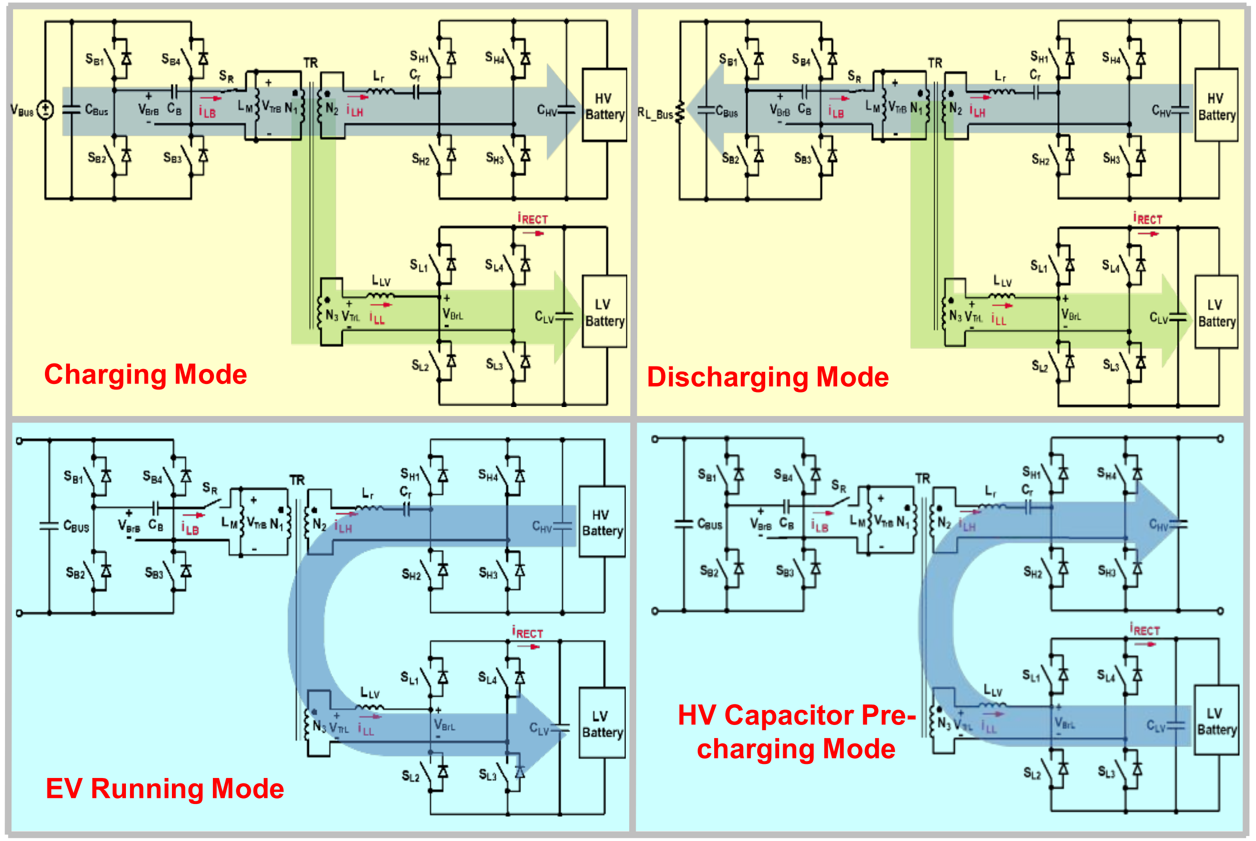
1-Stage Approach Example



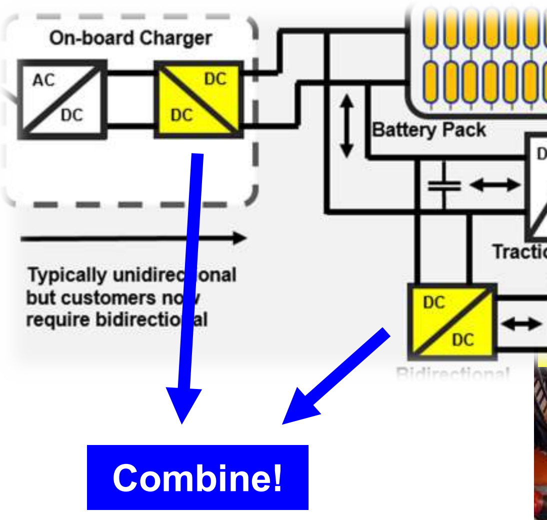
- Constant-frequency, constant duty cycle approach (phase shift-control)
- 3-ph → no power flow fluctuation
- 1-ph → module C is used as active power filter
- Soft-switching, 150 kHz
- No DC link (CB = several uF)
- Single-stage approach: effectively more or the same number of devices, strong performance coupling between input and output voltage since there is no decoupling stage

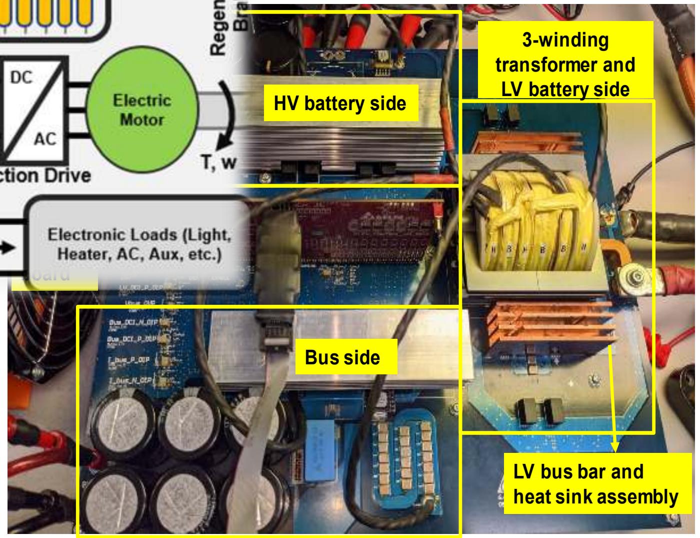
[1] H. Kim, J. Park, S. Kim, R. M. Hakim, H. Belkamel, and S. Choi, "A Single-Stage Electrolytic Capacitor-less EV Charger with Single- and Three-Phase Compatibility," IEEE Trans. Power Electron., vol. 8993, no. c, pp. 1–1, 2021, doi: 10.1109/TPEL.2021.3127010.

Magnetic Integration of DC-DC and APM (2-Stage Approach)



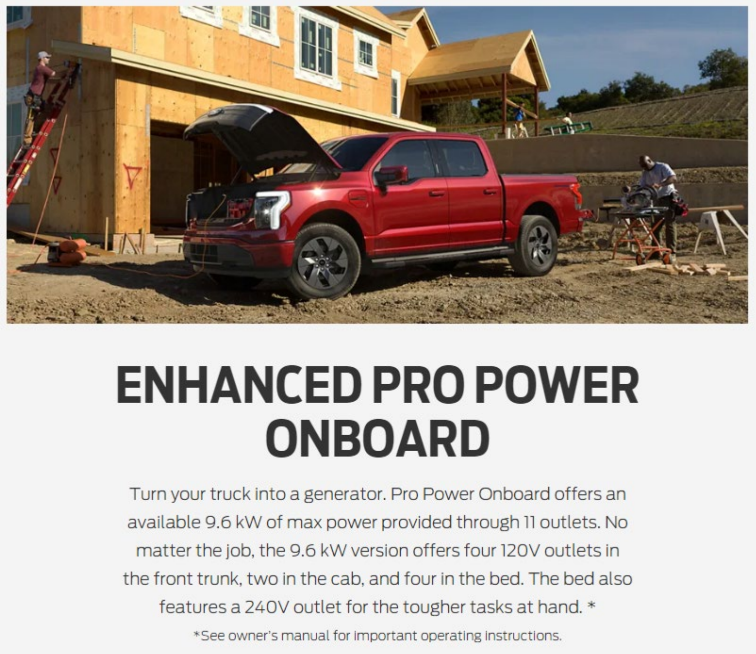
M. Kumar, P. M. Barbosa, J. M. Ruiz, J. Minli and S. Hao, "Isolated Three-Port Bidirectional DC-DC Converter for Electric Vehicle Applications," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), Houston, TX, USA, 2022, pp. 2000-2007, doi: 10.1109/APEC43599.2022.9773690.

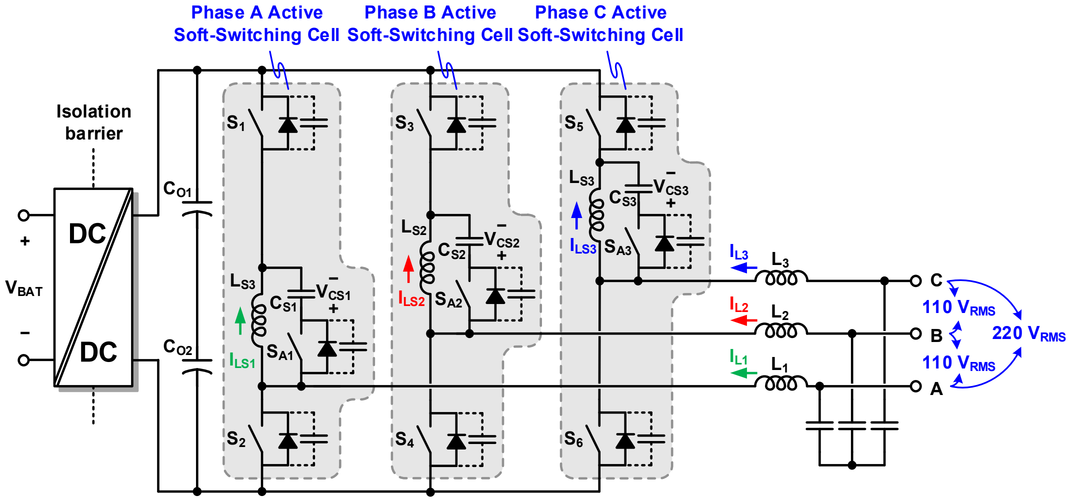


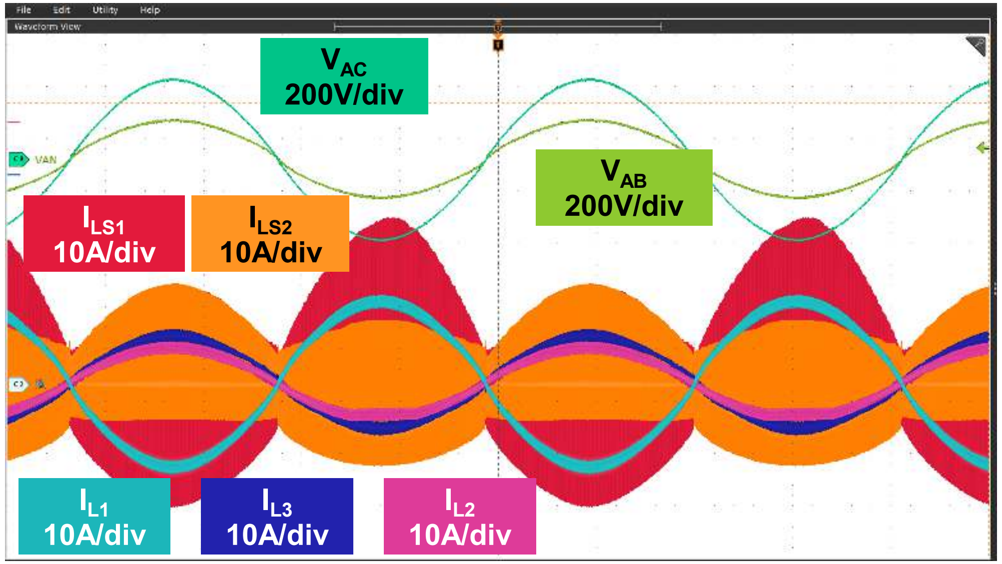


- Combine OBC DC-DC and APM into a single multi-port network → **single magnetic component** + fewer bridges!
- Many different ways to do so, suitable way: SRC + DAB
- V_{BUS} = PFC output (400 V)
- HV battery 270 V – 430 V
- LV battery 9 V – 15 V (high current!)

Vehicle-to-Load (V2L) Operation







- Some EV manufacturers aim to provide inverter mode to support local loads

Summary

- Automotive power electronics for on-board charging has seen tremendous changes in power level and functional requirements over the past decade
- Academia and industry are exhaustively searching the research space for optimal solution(s)
- For now, 2-stage solution seems a better choice
- Delta Power Electronics is a major player in market… MPEL focuses on EV area

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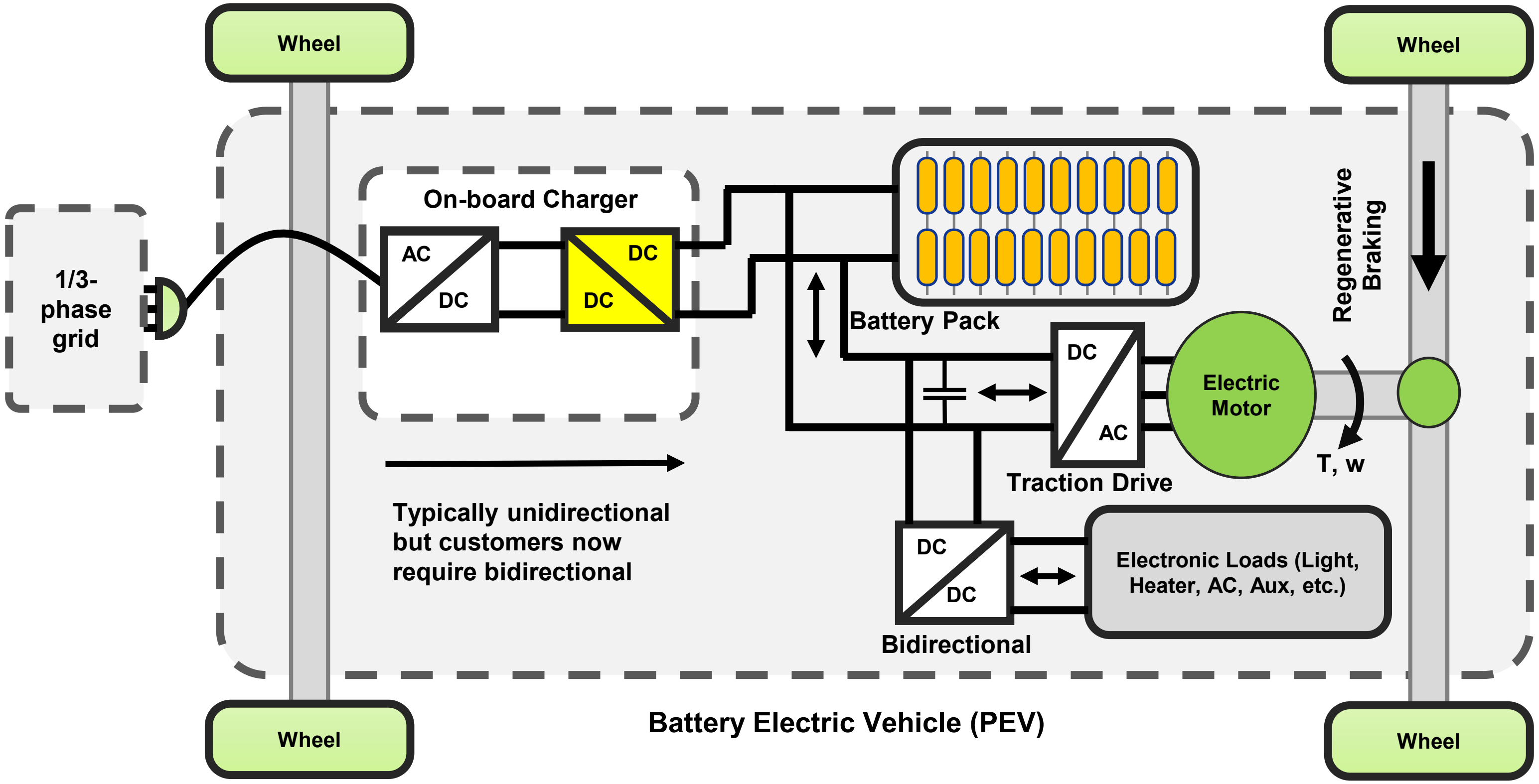
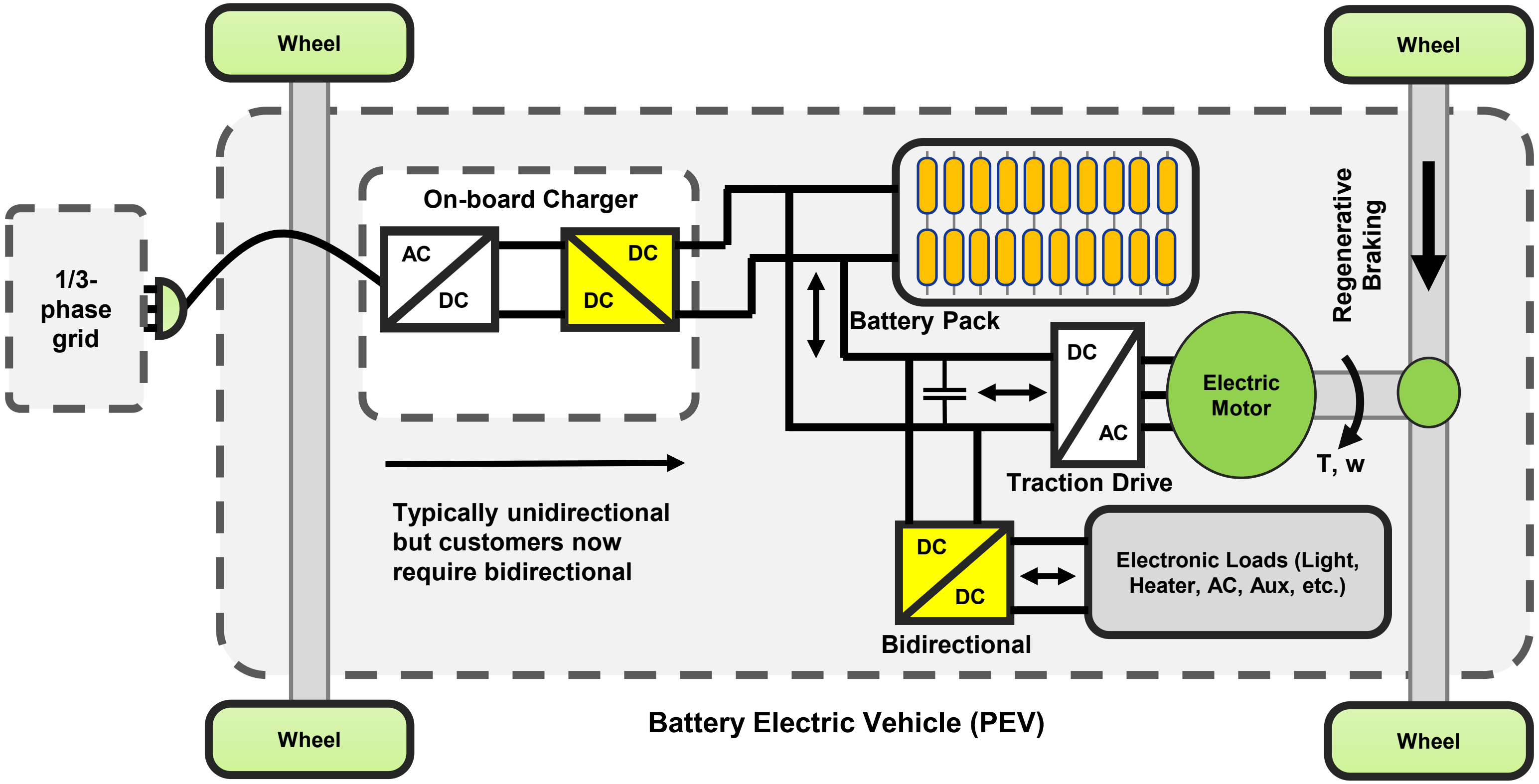


Battery Electric Vehicle (PEV)


Wheel
Wheel
1/3-
phase
grid
On-board Charger
AC
DC
DC
DC
Battery Pack
Regenerative
Braking
DC
AC
Electric
Motor
T, w
Traction Drive
Typically unidirectional
but customers now
require bidirectional
DC
DC
Bidirectional
Electronic Loads (Light,
Heater, AC, Aux, etc.)
Wheel
Wheel
Battery Electric Vehicle (PEV)

Recent Developments in On-board Charging Approaches for Electric Vehicles

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