



UNIVERSITY
OF TWENTE.

POWER ELECTRONICS FOR ELECTRIC VEHICLE BATTERY CHARGING

Presenter: Thiago Batista Soeiro, t.batistasoeiro@utwente.nl



Outline



About the contributors



The EV market



Power Electronics for EV Charging



Single-Phase Charging



Three-Phase Fast Charging



Wireless EV Charging

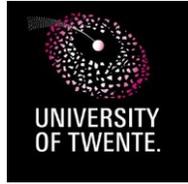


Summary

About the Contributors



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2022 Power Conditioning Engineer at European Space Agency, Noordwijk, Netherlands
2018-2021 Associate Professor at Delft University of Technology, Netherlands
2013-2018 Senior Scientist at ABB Corporate Research Center, Baden-Dattwil, Switzerland
2012 Ph.D., Swiss Federal Institute of Technology - ETH Zurich, Switzerland
2007 M.Sc., Federal University of Santa Catarina, Florianopolis, Brazil
2004 B.Sc.(Hons.), Federal University of Santa Catarina, Florianopolis, Brazil



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2021 Ph.D., Shanghai Jiao Tong University, China
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2018 B.Sc., National Institute of Technology Srinagar



Yang Wu



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2017 B.Sc., Southeast University, China



Dr. Francesca Grazian



2023, Ph.D., DCES Group, Delft University of Technology
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2016 B.Sc., University of Bologna, Italy

The EV Market

Driving towards a greener future



The EV Market

Battery Powered Electric Transportation - on the rise... All forms of transportation becoming more electric!



▲ Electric hoverboards (Source: www.razor.com)



▲ Electric scooters (Source: www.pinterest.ch)



▲ Electric bicycles (Source: www.stromerbike.com)



▲ Hyperloop (Source: www.ocregister.com/)



▲ Electric trucks (Source: www.daimler.com)



▲ Electric buses (Source: www.abb.com)



▲ Electric motorbikes (Source: www.supersoco.eu)



▲ eVTOL (Source: eveairmobility.com)



▲ Electric ferry boats (Source: www.siemens.com)



▲ Electric planes (Source: www.pipistrel.si)



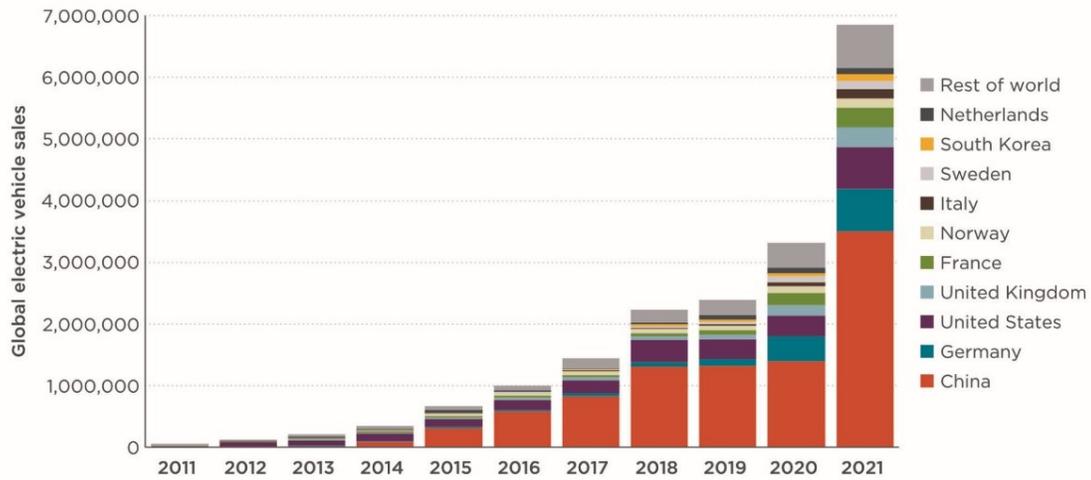
▲ EVs (Source: www.greenliving4live.com)



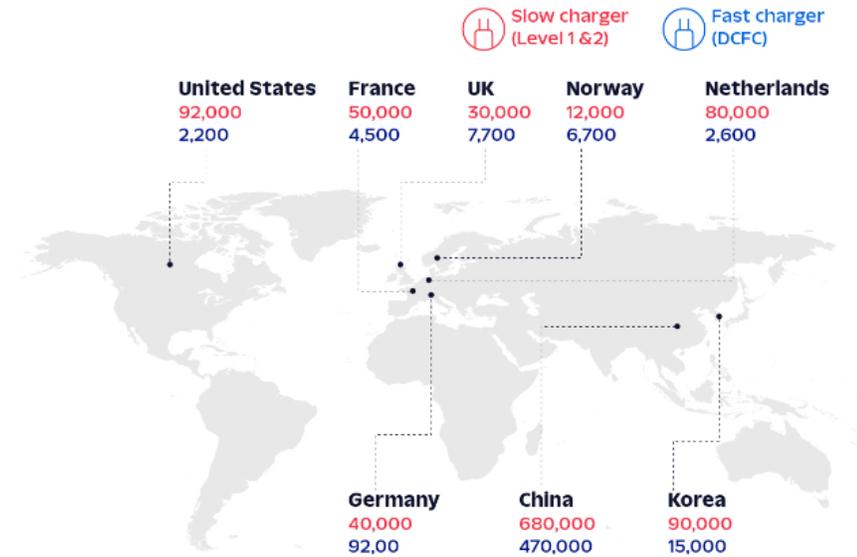
▲ Train (Source: www.railjournal.com)

The EV Market

Numbers of EV Worldwide



▲ Annual Electric sales share globally by market. 2011-2021, (Source: <https://theicct.org/publication/global-ev-update-2021-jun22/>)



▲ Publicly accessible EV chargers. 2021, (Source: <https://interactive.twilio.com/ev-charging-statistics>)

The EV Market

EV Standards & Technologies

Mode1 charging



▲ AC only

Numbers

- ▶ Charging time: 7 - 17 hrs
- ▶ Supply line: 120/230 V, 1-phase AC
- ▶ Amps: 12 - 16 A
- ▶ Charge power: up to 3.7 kW
- ▶ Range added: 5 - 8 km/hour

Mode2 charging



▲ AC only

Numbers

- ▶ Charging time: 0.4 - 7 hrs
- ▶ Supply line: 208 - 240 V, 1-phase AC
- ▶ Amps: 12 - 80 A
- ▶ Charge power: 3.7 - 22 kW
- ▶ Range added: 16 - 32 km/hour

Mode3/4 charging



▲ AC or DC

Numbers

- ▶ Charging time: 0.1 - 0.4 hrs
- ▶ Supply line: 208 - 480 V, 3-phase AC
- ▶ Amps: max 400 A
- ▶ Charge power: 22 - 150 (350) kW
- ▶ Range added: 80% charge in (10)-20-30 minutes

The EV Market

EV Standards & Technologies

IEC 62196 - Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles

Source: Netherlands Enterprise Agency, *The Electric vehicle charging – Definitions and explanations*, version January 2019, 2019

Standard	CHAdeMO	GB/T	CCS Type 1	CCS Type 2	Tesla	ChaoJi	ChaoJi
Compliant Standards	IEEE 2030.1.1 IEC 62916-3	IEC 62916-3	SAE J1772 IEC 62916-3	IEC 62916-3	No related items	CHAdeMO and GB/T (IEC and CCS not yet but is ongoing)	OSHA/ADA
Connector Inlet							
Maximum Voltage (V)	1000	750	600	900	410	1500	1250
Maximum Current (A)	400	250	400	400	330	600	3000
Maximum Power (kW)	400	185	200	350	135	900	3750
Maximum Market Power (kW)	150	125	150	350	120	N.A.	N.A.
Communication Protocol	CAN		PLC		CAN	CAN	PLC+ISO/IEC
V2X Function	Yes		No		Unknown	Yes	Yes
Start year	2009	2013	2014	2013	2012	2020	2023 (Planned)

The EV Market

EV Standards & Technologies

TABLE IV: Technical specifications of some of the best-selling EVs.

Manufacturer	Model	Battery Specifications				Driving range per charge (Miles)	Maximum charging power (kW)
		Chemistry	Capacity (kWh)	Energy density (kWh/L)	Weight (kg)		
Volkswagen	e-golf	NCM-333	35.8	103	349	186	40
Nissan	leaf	NCM-523	62	151	410	186	50
Peugeot	e-208		50	140	356	225	100
Audi	e-torn	NCM-622	95	136	700	274	265
BMW	i3/i3s		42.2	152	278	246	50
Hyundai	Kona electric	NCM-622	67.5	149	258	484	75
Jaguar	i-pace		90	149	603	292	350
Kia	e-soul	NCA	64	148	457	280	77
Mercedes	EQC		85	130	652	259	110
Porsche	Taycan	NCA	93.4	148	630	280	270
Skoda	Citigo E iv		36.8	148	248	160	40
Chevrolet	Bolt EV	NCM-712	68	158	410	259	50
Renault	ZOE		54.66	168	326	239	50
Tesla	III	NCA	102.4	162	630	315	150



ABB Terra HP
Max. charging power
350kW



EVBox Ultroniq
Max. charging power
350kW



Project Ultra-E:
2 x 350kW CCS chargers
in Leiderdrop

High-end EV Charging Power is Increasing

The EV Market

EV Standards & Technologies

High-end EV Charging **Voltage** is Increasing

Year of launch	Manufacturer	Model	Battery voltage (latest model)
2018	Audi	e-tron	396 V
2020	FIAT	new 500e	364 V
2019	Mercedes-Benz	EQC	405 V
2021		EQA	420 V
2022		EQB	420 V
2013	Nissan	Leaf S	350 V
2010		Leaf SV	360 V
		Leaf SL	
2012	Tesla	Model S	400 V
		Model X	350 V
2017		Model 3	360 V
2010	Volkswagen	e-up!	374 V
214		e-Golf	323 V
2019		ID.3	408 V
2019	Aston Martin	Rapide E	800 V
2021	Hyundai	IONIQ 5	800 V
2021	KIA	EV6	697 V
2019	Porsche	Taycan	800 V
2023	Lucid Motors	Lucid Air	900 V

400 V Battery

800 V Battery

900+ V Battery



ABB Terra HP
Max. charging power
350kW



EVBox Ultronic
Max. charging power
350kW



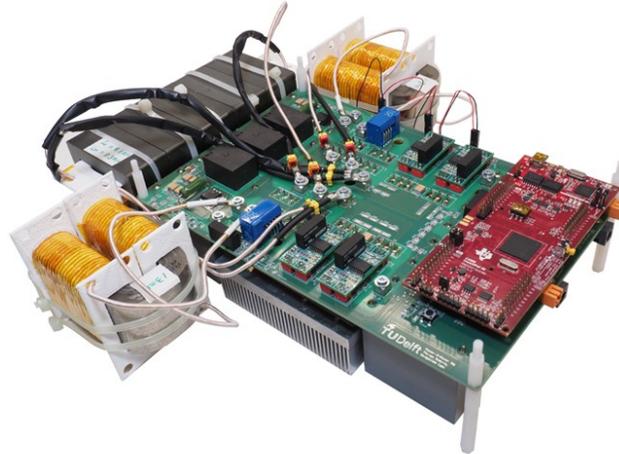
Project Ultra-E:
2 x 350kW CCS chargers
in Leiderdrop



- **Wide Battery Voltage Range Complicates Public Chargers Design & Charging Performance**

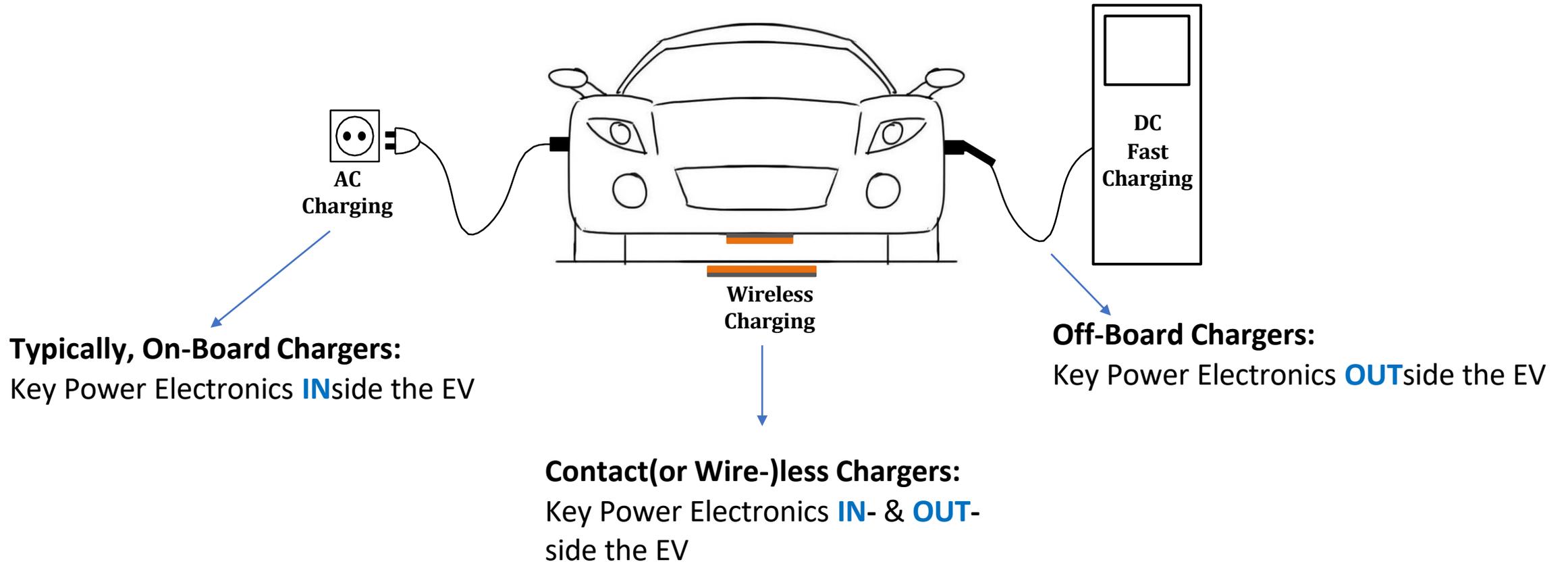
Power Electronics for EV Charging

Empowering the vehicles efficiently



Power Electronics for EV Charging

Typical Solutions

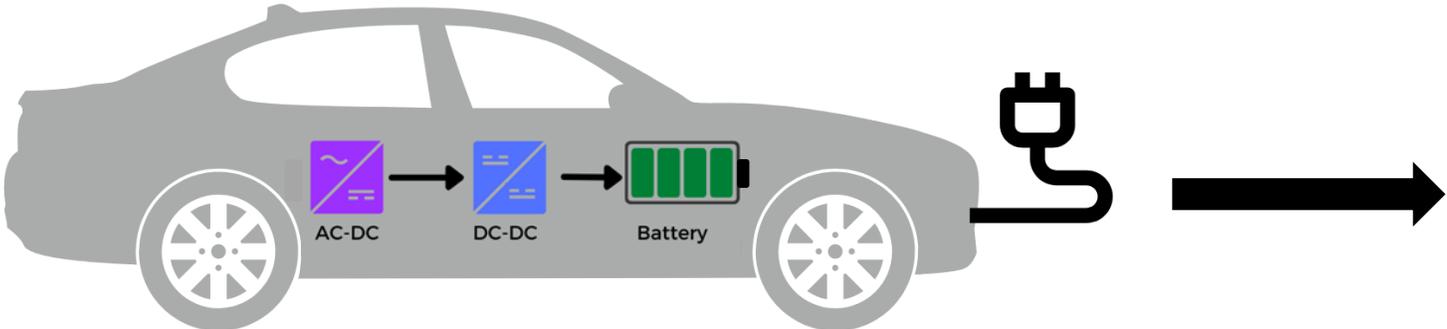


Single-Phase Chargers

Refuel in the comfort of your home



Single-phase Chargers



Onboard charging mechanism



Duosida Level 1 charging cordset
(16 A, SAE J1772 to 62196-2)



Typical wallbox charging setup

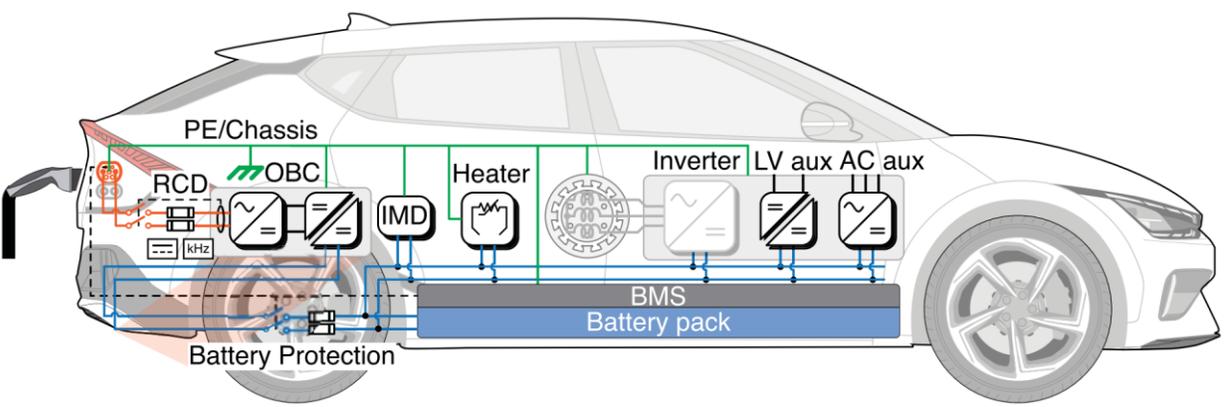


Greenmotion wall charger
(7.4 kW single-phase)

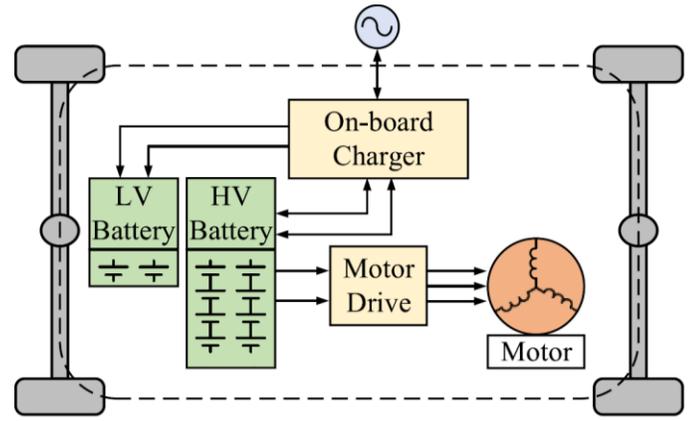
Single-phase Chargers

Recommended Reading

On-Board Chargers: General Knowledge, Challenges, Trends, and Technologies:



S. Rivera, et.al, "Charging Infrastructure and Grid Integration for Electromobility", 2023, *Proceedings of the IEEE*



A. Khaligh, et.al, "Global Trends in High-Power On-Board Chargers for Electric Vehicles", 2019, *IEEE Trans. On Vehicular Tech.*

Single-phase Chargers

Research in single-phase chargers, why?

How to fit more energy (larger batteries) into the same car?
Higher power density of PE → more room for other stuff

How to charge the larger batteries faster?
More charging power → more current and voltage

How to deliver more power without losing efficiency?
New devices and topologies → PE research



- R&D Focus**
- Design Optimization tradeoffs (Efficiency, Reliability, Size, Cost,..)
 - New devices and circuits
 - Soft-Switching Techniques

Challenges & Trends (The Influence of Semiconductor Technology on Power Density)

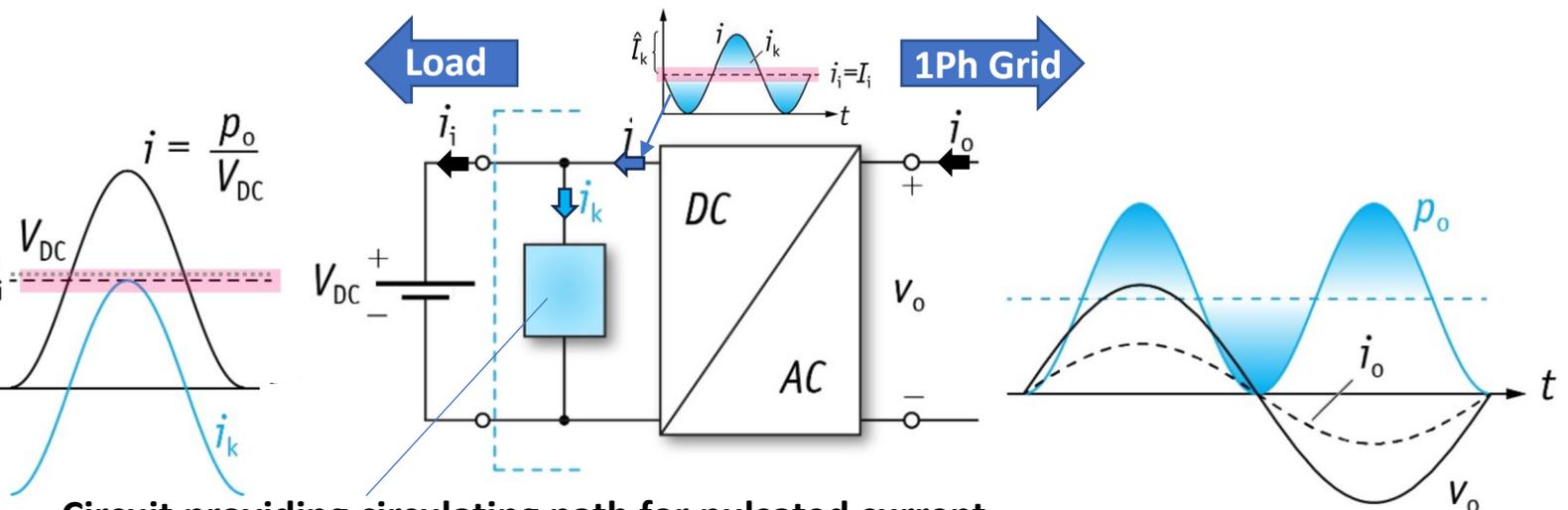


Single-phase Chargers

Front-end: AC/DC Conversion for OBC, FC or Wireless Solutions

Single-Phase Chargers: Active Power Buffer (APB)

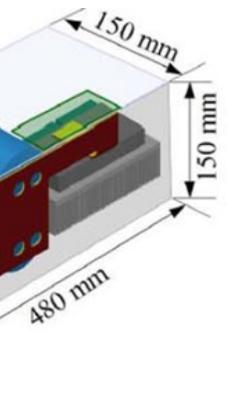
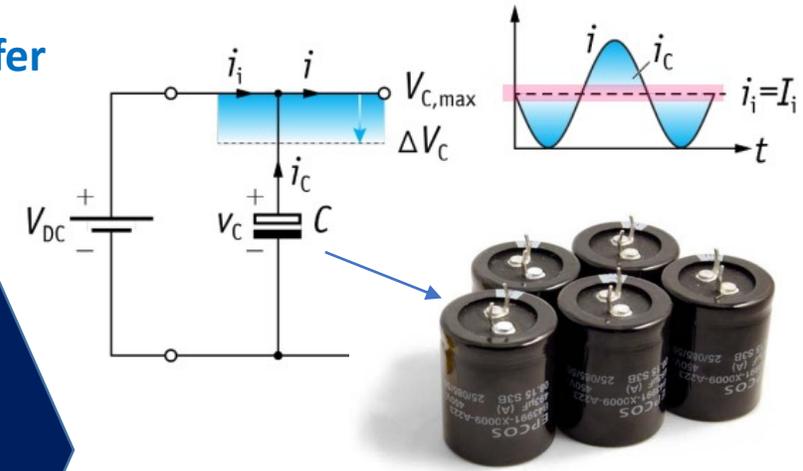
Motivation: Increasing power density and reliability; eliminating the bulky passive buffer



Circuit providing circulating path for pulsated current

Source: ETHZ/PES @SCAPE 2019

Passive Buffer



Takes up large volume!



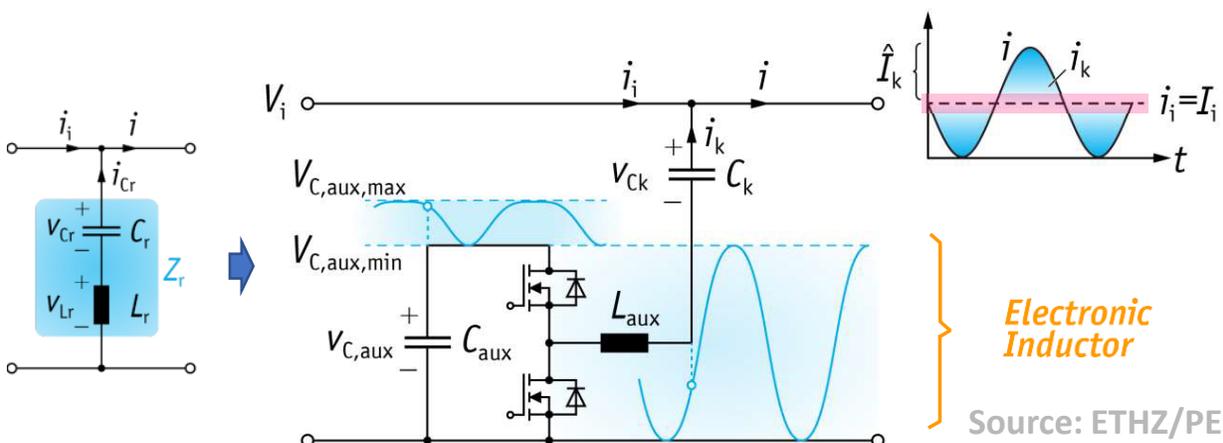
- ◆ Large current will flow at 2x the grid frequency, requiring bulky passive buffer
- ◆ Passive buffer may become limiting factor for target high power density/lifetime
- ◆ Some active power decoupling circuits have been proposed in literature

Single-phase Chargers

Front-end: AC/DC Conversion for OBC, FC or Wireless Solutions

Single-Phase Chargers: Active Power Buffer (APB)

In Literature: Types of Active Power Buffer Circuits

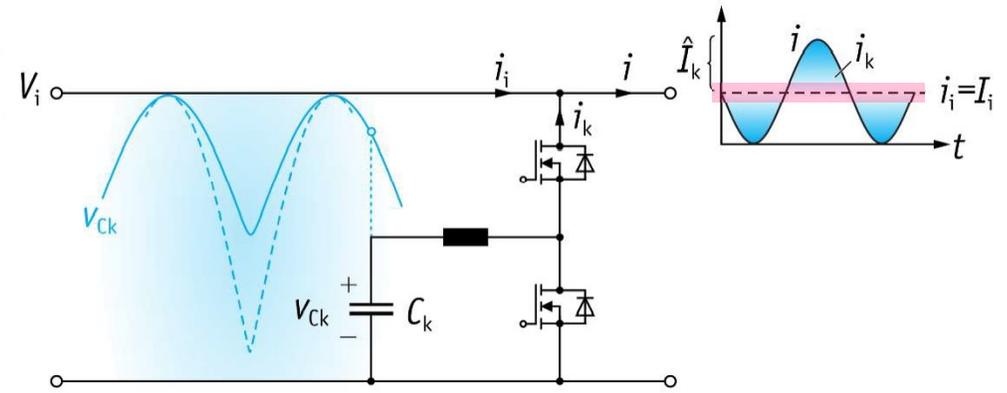


◆ Partial Active Power Pulsation Buffer

Low $U_{C,aux}$ Low Converter Losses
 High Values of C_{kr} , C_{aux} Required for Low $U_{C,aux}$
 Full-Bridge Aux. Converter Allows Lower $U_{C,aux}$

Electronic Inductor

Source: ETHZ/PES @SCAPE 2019



◆ Full Active Power Pulsation Buffer

Large Voltage Fluctuation Foil or Ceramic Capacitor
 Buck- or Boost-Type DC/DC Interface Converter
 Buck-Type allows Utilizing 600V Technology
 Lower Overall Volume Compared to Electrolytic Capacitor

S. Qin, Y. Lei, C. Barth, W. Liu, R. C. N. Pilawa-Podgurski, "Architecture and control of a high energy density buffer for power pulsation decoupling in grid-interfaced applications", in Proc. COMPEL, 2021

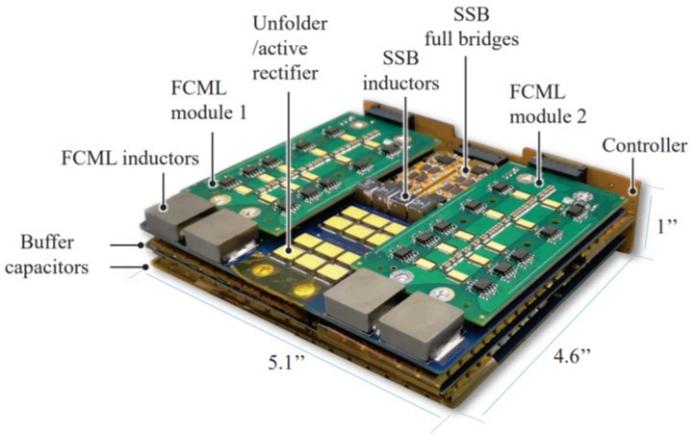
A. C. Kyritsis, N. P. Papanikolaou, and E. C. Tatakis, "A novel parallel active filter for current pulsation smoothing on single stage grid connected AC-PV modules," in Proc. ECPE, 2007.

Single-phase Chargers

Front-end: AC/DC Conversion for OBC, FC or Wireless Solutions

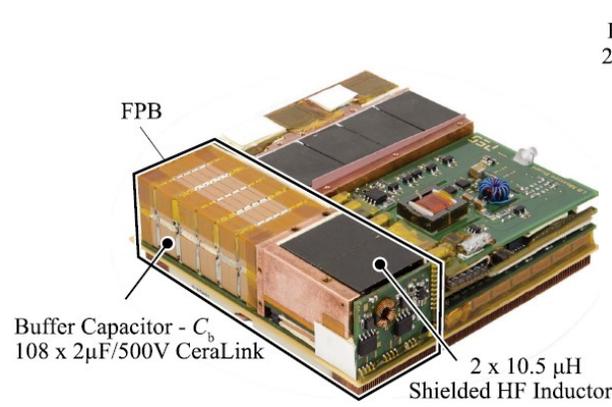
Single Phase Chargers: Active Power Buffers (APB)

Further Reading: Pushing Power Density Limits



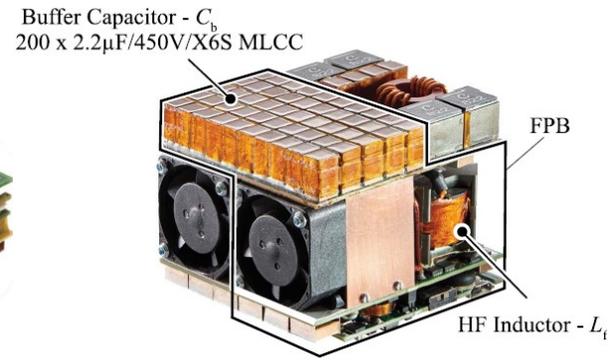
6-level Flying Capacitor Multilevel PFC stage employing GaN devices and Series-Stacked Buffer

Z. Liao, D. Chou, K. Fernandez, Y. Syu, R. Pilawa-Podgurski "An Interleaved 6-Level GaN Bidirectional Converter With an **Active Energy Buffer** for Level II Electric Vehicle Charging", IEEE Energy Conversion Congress and Exposition, 2020

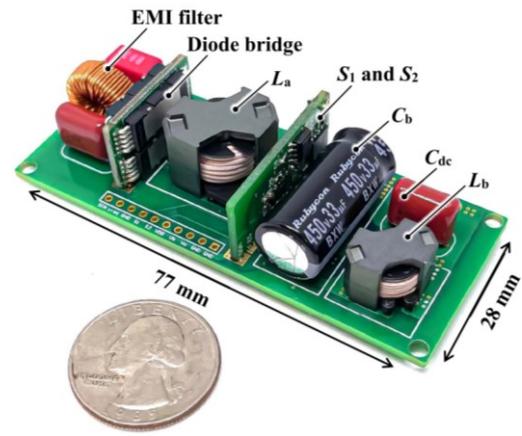


Full-power processing buck-type converter active buffer approach

D. Neumayr, G. C. Knabben, E. Varescon, D. Bortis, J. W. Kolar, "Comparative Evaluation of a Full- and Partial-Power Processing **Active Power Buffer** for Ultracompact Single-Phase DC/AC Converter Systems", IEEE Journal of Emerging and Selected Topics in Power Electronics, 2021



Partial-power processing type using auxiliary series-connected converter



Modified Boost PFC Front-End Topology to Reduce L, C Size

Huan Li, Sinan Li, Weidong Xiao, "A New PFC Front End With Constant DC-Link Voltage, **Reduced Buffer Capacitance**, and Soft Switching", IEEE Transactions on Power Electronics, 2023

Single-phase Chargers

Front-end: AC/DC Conversion for OBC, FC or Wireless Solutions

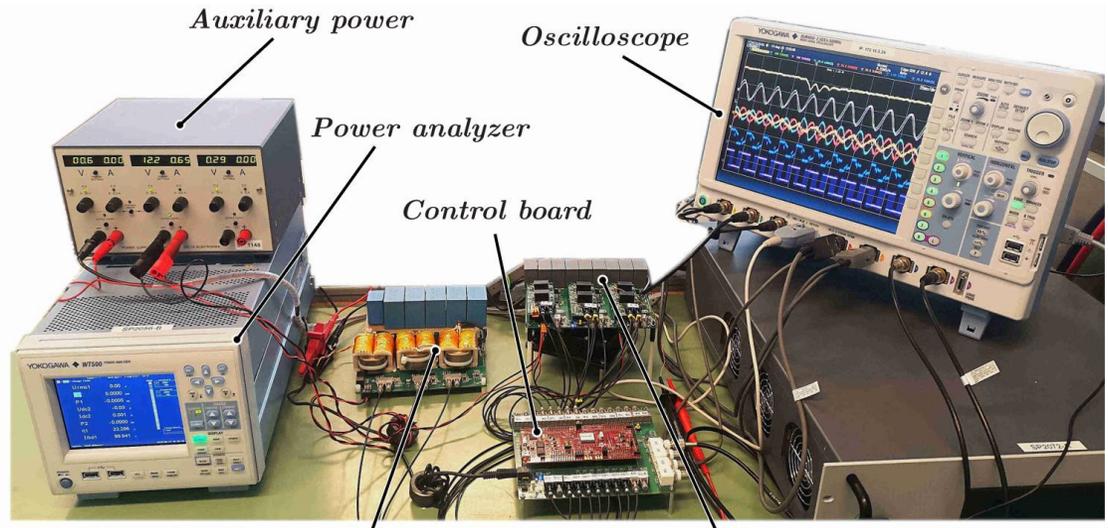
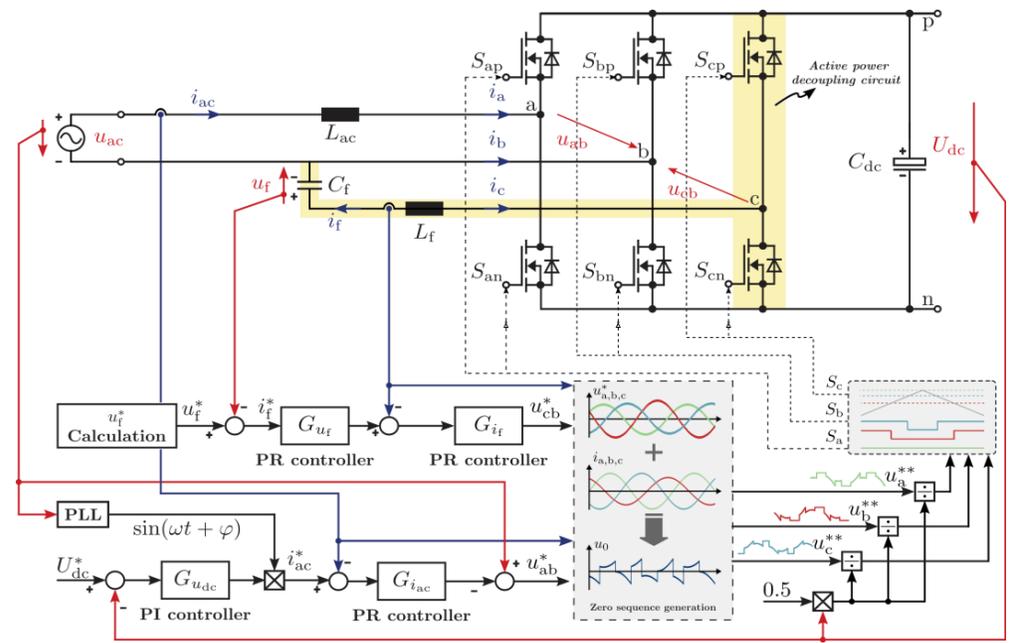
Dr. Junzhong Xu



Single-Phase Chargers: Active Power Buffer (APB)

In Literature: DPWM in Active Power Buffer for Improved Efficiency

Source: Junzhong Xu, Thiago B. Soeiro, Fei Gao, Houjun Tang, and Pavol Bauer, "Minimum Switching Losses Discontinuous PWM Strategy For Bidirectional Single-phase AC-DC Converter With Active Power Decoupling Circuit," IEEE Transactions on Power Electronics, 2021.



Main Contributions of this work:

- ◆ New Minimum switching loss modulation (The lowest from any know APB)
- ◆ Further improve the power efficiency by 0.8% (96.8%→97.6%)
- ◆ Heatsink-less Design and increased power density

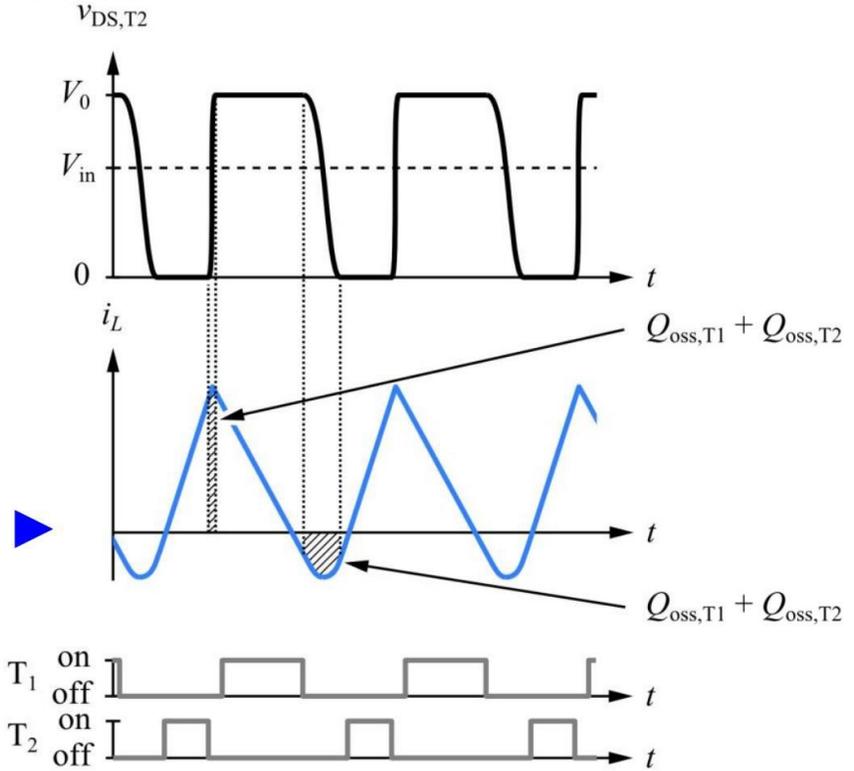
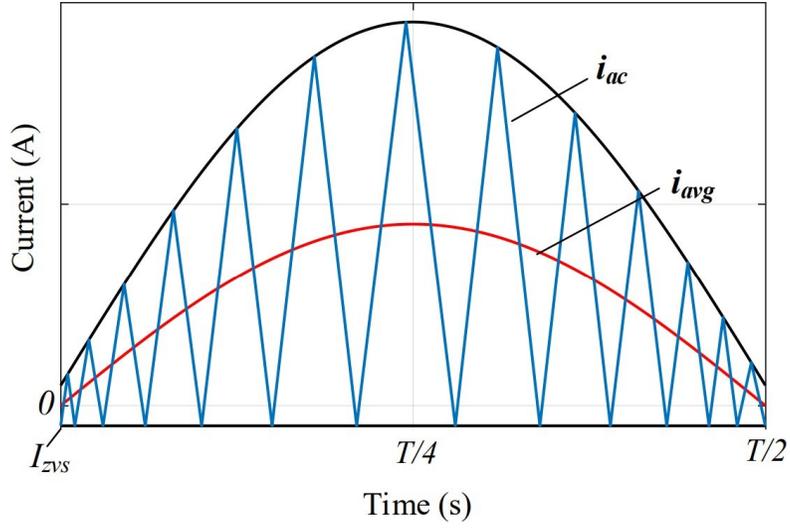
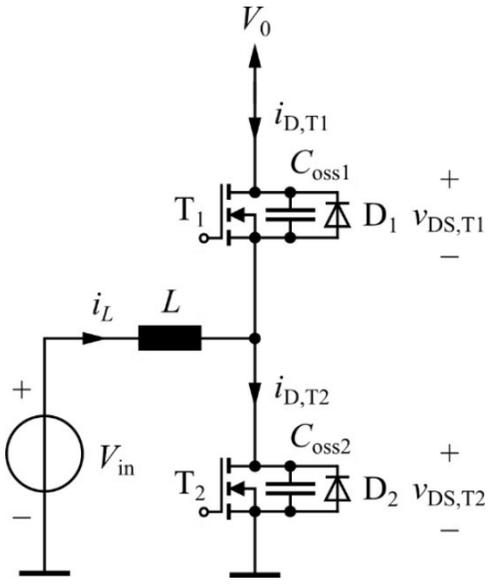


Single-phase Chargers

Front-end: AC/DC Conversion for OBC, FC or Wireless Solutions

Single-Phase Chargers: Zero Voltage Switching (ZVS) – Triangular Current Mode (TCM) Operation

In Literature: Using small source-side inductance to achieve ZVS with a high ripple current



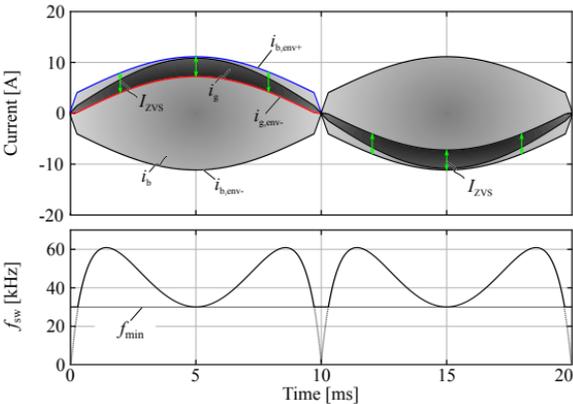
- ◆ Synchronous Rectification → Less Conduction Losses
- ◆ Negative Current → Guarantee ZVS Turn-On, but variable frequency
- ◆ ZVS limits EMI, and switching losses caused by diode charge recovery

Single-phase Chargers

Front-end: AC/DC Conversion for OBC, FC or Wireless Solutions

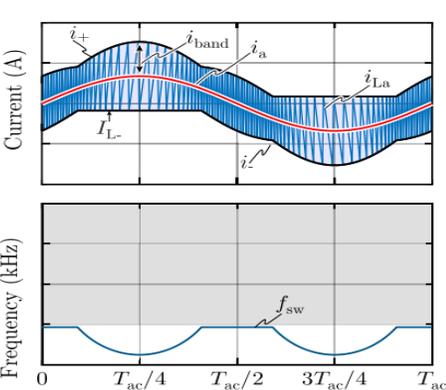
Single-Phase Chargers: Zero Voltage Switching (ZVS) – Triangular Current Mode (TCM) Operation

Further Reading: Minimizing Frequency Variation, Analytical Loss Calculation



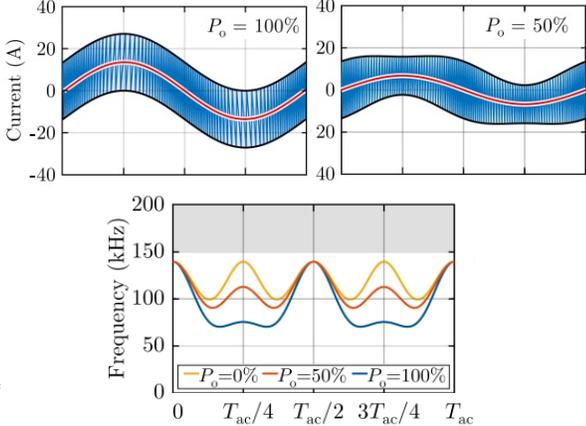
In Integrated TCM, the switching frequency is adapted in such a way that a constant turn-off current I_{ZVS} is achieved

Daniel Rothmund, Dominik Bortis, Jonas Huber, Davide Badienez, Johann W. Kolar "10kV SiC-Based Bidirectional **Soft-Switching Single-Phase AC/DC Converter** Concept for Medium-Voltage Solid-State Transformers", IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems, 2017

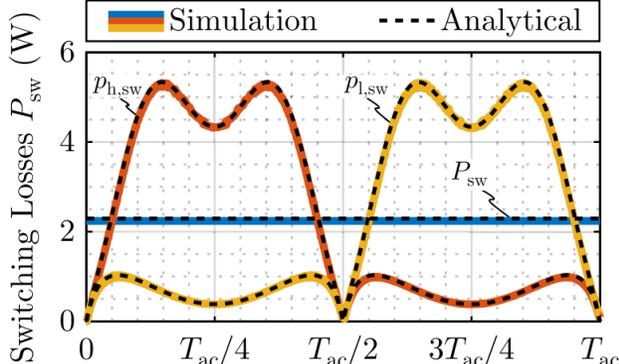


Bounded TCM approach narrows fundamental switching frequency within the restricted spectrum

Michael Haider, Jon Azurza Anderson, Neha Nain, Grayson Zulauf, Johann W. Kolar, Dehong Xu, And Gerald Deboy "Novel **ZVS S-TCM Modulation** of Three-Phase AC/DC Converters", IEEE Open Journal of Power Electronics, 2020



Sinusoidal TCM modulation approach maintains ZVS and is implemented with very low frequency variation bands



Analytical loss modelling with residual ZVS losses are more accurate in TCM-modulated converters

Michael Haider, Jon Azurza Anderson, Neha Nain, Grayson Zulauf, Johann W. Kolar, Dehong Xu, And Gerald Deboy, "Analytical Calculation of the **Residual ZVS Losses** of TCM-Operated Single-Phase PFC Rectifiers", IEEE Open Journal of Power Electronics, 2021

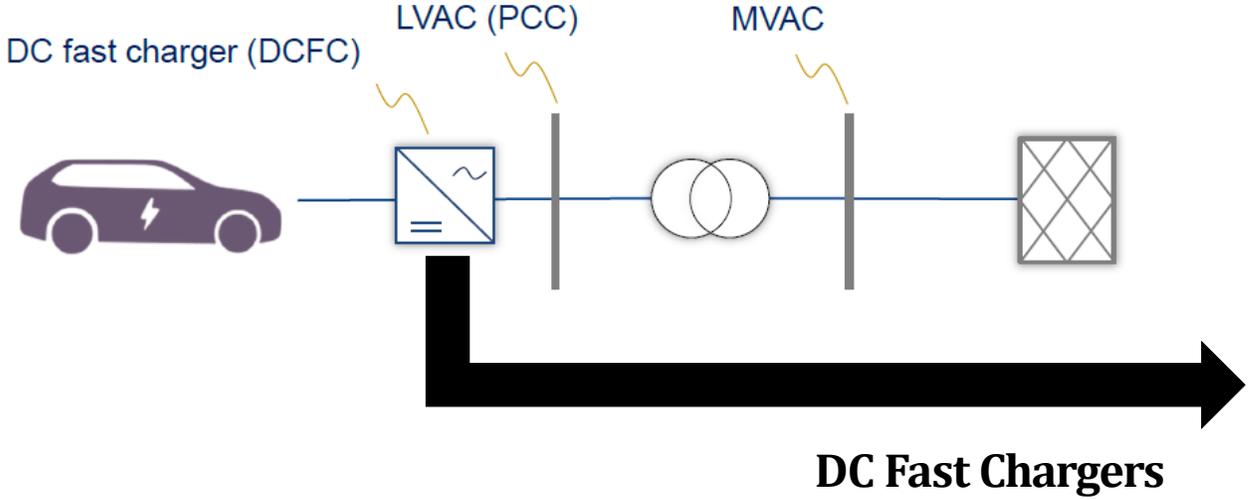
Three Phase Fast Chargers

Power up and get going ...



Three Phase Fast Chargers

Typical fast charging setup



Heliox Mobile
(40 kW, CCS2)



ABB Terra 53CJG
(50kW, CCS & Chademo)

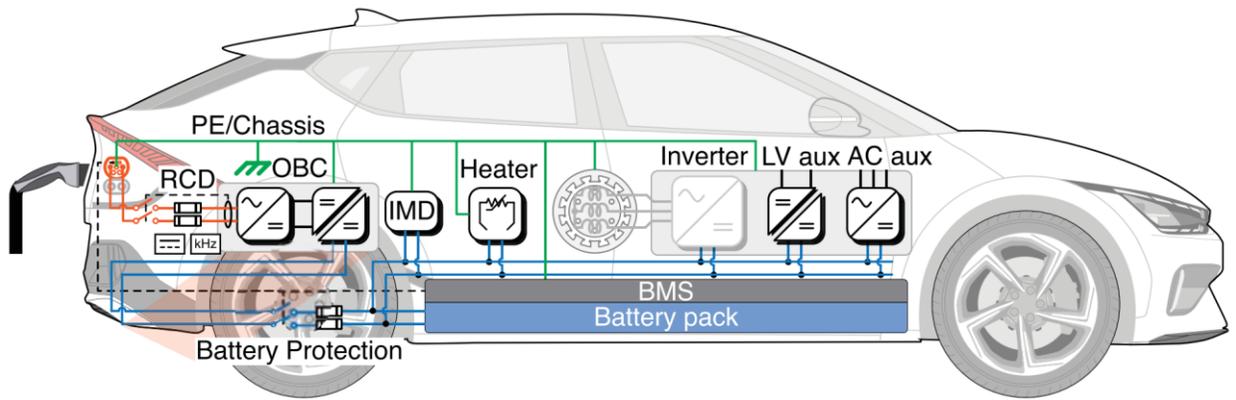
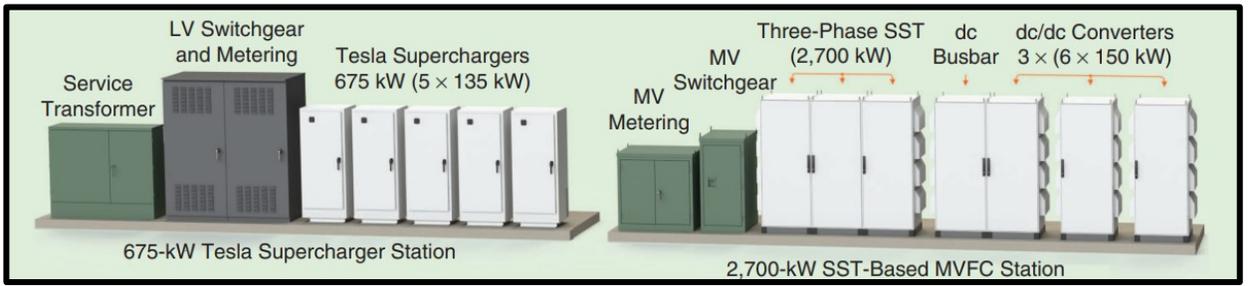


Porsche DCFC
(350kW, CCS)

Three-phase Fast Chargers

Recommended Reading

Off-Board Chargers: General Knowledge, Challenges, Trends, and Technologies:



Srdjan Srdic and Srdjan Lukic, "Toward Extreme Fast Charging Challenges and opportunities in directly connecting to a medium-voltage line" IEEE Electrification Magazine, 2019

S. Rivera, et.al, "Charging Infrastructure and Grid Integration for Electromobility", 2023, Proceedings of the IEEE

Three-phase Fast Chargers

Research in three-phase fast chargers, why?

Where is all the power coming from?

Optimize grid-support BESS → reduce peak power demand

Is this fast charging safe?

MF isolation → safe and compact

Thermal management of all the PE?

Lower losses, easier thermal management

Compatibility with different EVs?

Adaptive topologies → Multifunctional charger

Won't all this PE pollute the ac grid?

Advanced modulation methods → Low THD and EMI

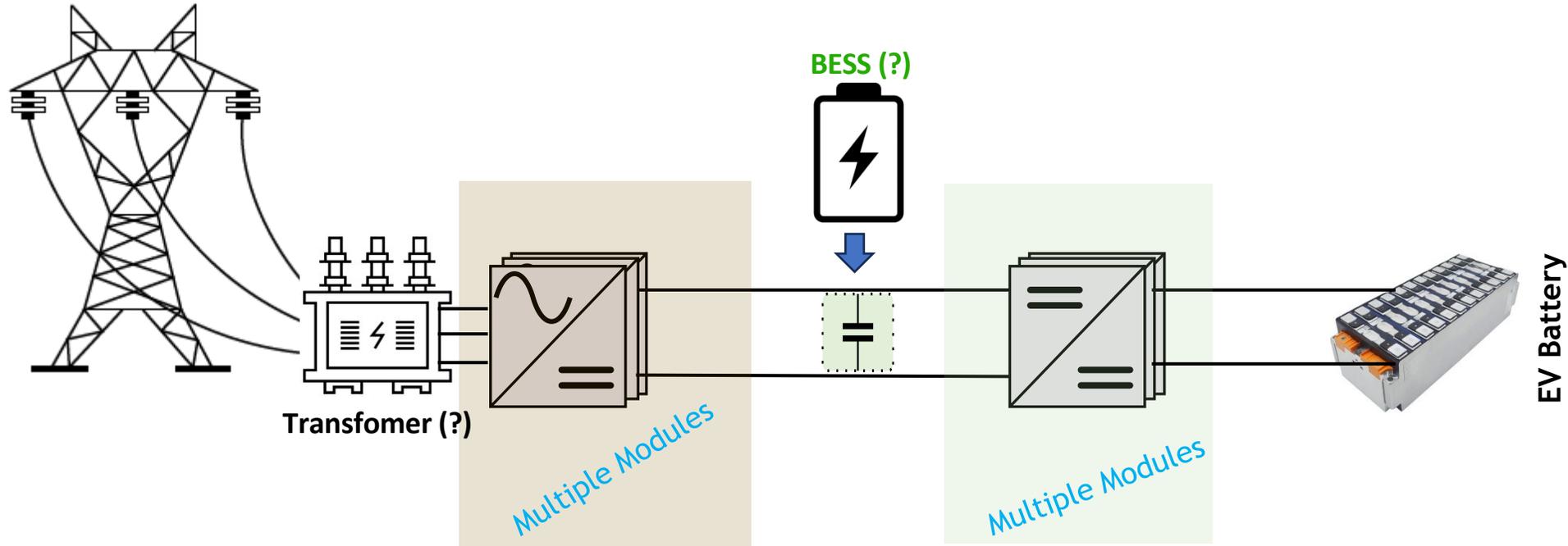


R&D Focus

- Smaller, safer, reliable, cheaper, better

Three-phase Fast Chargers

Topologies for EV Chargers



Duties of AC/DC

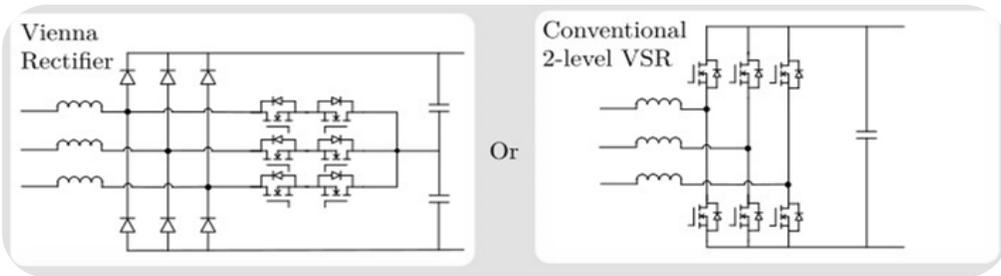
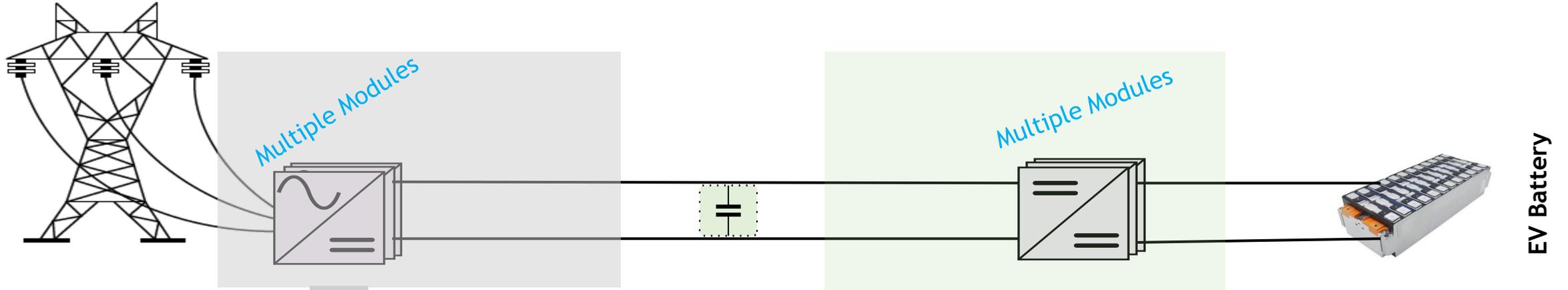
- To ensure grid compliance
- To ensure high power factor
- Grid support (advanced)

Duties of DC/DC

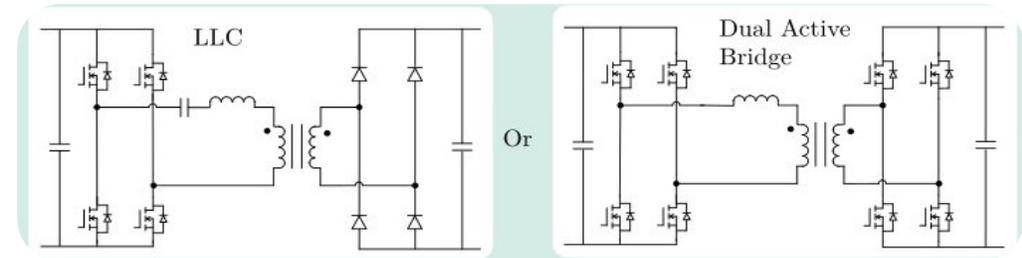
- To control charging current
- To ensure high efficiency for wide output voltage range

Three-phase Fast Chargers

Topologies for EV Chargers



- Medium cost, Low THD (3-level)
 - Unidirectional power flow
- High cost, Medium THD (2-level)
 - Bidirectional power flow
 - High controllability



- ZVS
 - Unidirectional power flow
 - Narrow band voltage gain control
- ZVS
 - Bidirectional power flow
 - Wide band voltage gain control

EV Battery

Three Phase Fast Chargers

Dingsihao Lyu



Back-end: DC/DC Conversion for OBC and FCS Solutions

Fast EV Chargers: Reconfigurable Charger for Wide Battery Voltage Range

Motivation: Maintaining excellent efficiency while charging onboard batteries of different voltage ranges

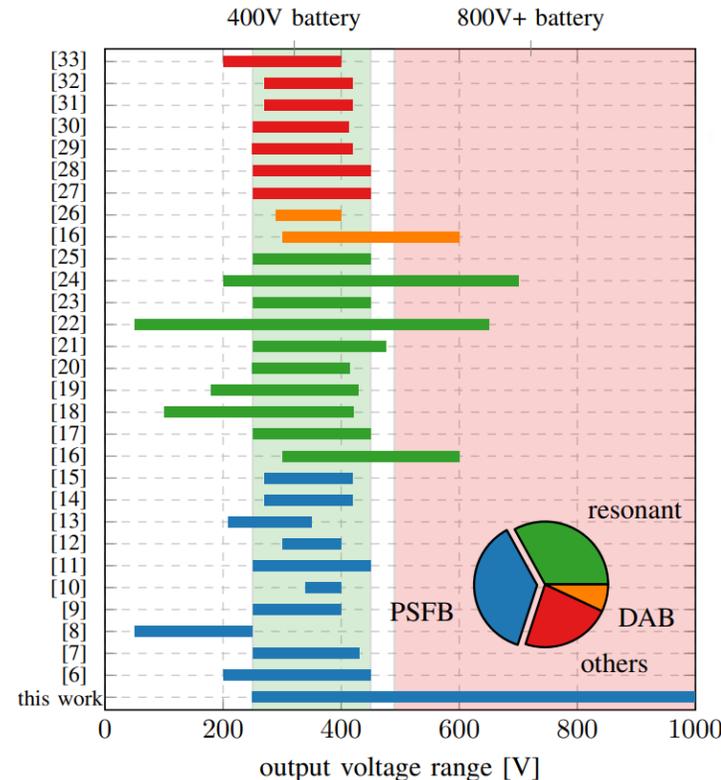
Source: Dingsihao Lyu, Thiago Batista Soeiro, and Pavol Bauer, "Design and Implementation of a Reconfigurable Phase-Shift Full-Bridge Converter for Wide Voltage Range EV Charging Applications," IEEE Transactions on Transportation Electrification, 2022.

DC/DC converters in the literature from 2011-2021

Year of launch	Manufacturer	Model	Battery voltage (latest model)
2018	Audi	e-tron	396 V
2020	FIAT	new 500e	364 V
2019	Mercedes-Benz	EQC	405 V
2021		EQA	420 V
2022		EQB	420 V
2013	Nissan	Leaf S	350 V
2010		Leaf SV	360 V
		Leaf SL	
2012	Tesla	Model S	400 V
2017		Model X	350 V
2010		Model 3	360 V
2010	Volkswagen	e-up!	374 V
214		e-Golf	323 V
2019		ID.3	408 V
2019	Aston Martin	Rapide E	800 V
2021	Hyundai	IONIQ 5	800 V
2021	KIA	EV6	697 V
2019	Porsche	Taycan	800 V

400 V Battery

800 V Battery



The phase-shift full-bridge (PSFB) converter and the resonant converter are the most used DC/DC converters

Three Phase Fast Chargers

Dingsihao Lyu



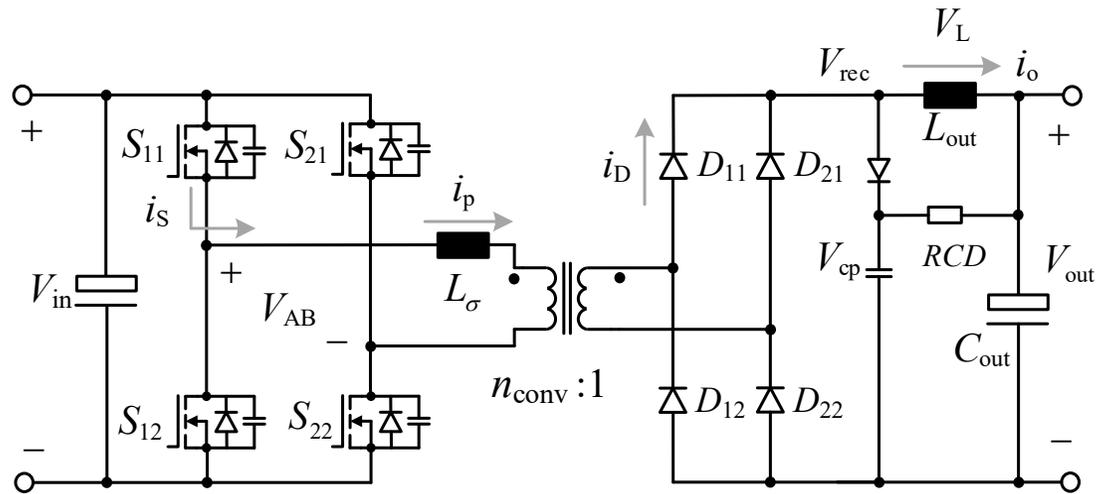
Back-end: DC/DC Conversion for OBC and FCS Solutions

Fast EV Chargers: Reconfigurable Charger for Wide Battery Voltage Range

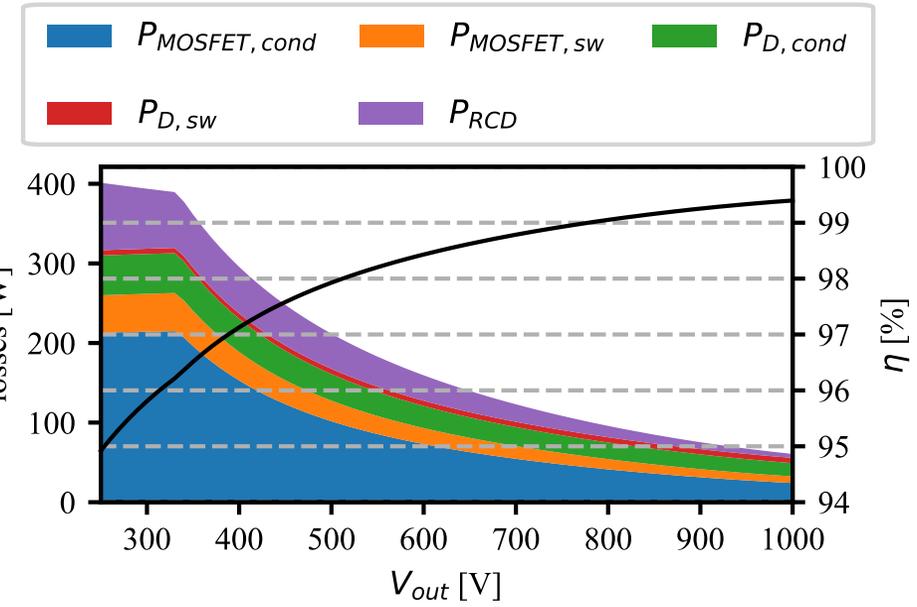
Motivation: Maintaining excellent efficiency while charging onboard batteries of different voltage ranges

Source: Dingsihao Lyu, Thiago Batista Soeiro, and Pavol Bauer, "Design and Implementation of a Reconfigurable Phase-Shift Full-Bridge Converter for Wide Voltage Range EV Charging Applications," IEEE Transactions on Transportation Electrification, 2022.

The circuit schematic of the conventional PSFB DC/DC converter



- ◆ Simple structure
- ◆ Zero-Voltage-Switching (ZVS)
- ◆ Simple phase-shift control
- ◆ High efficiency at high duty cycle
- ◆ Poor efficiency at low duty cycle



poor efficiency for charging 400V EVs

High efficiency for charging 800V EVs

Three Phase Fast Chargers

Back-end: DC/DC Conversion for OBC and FCS Solutions

Dingsihao Lyu



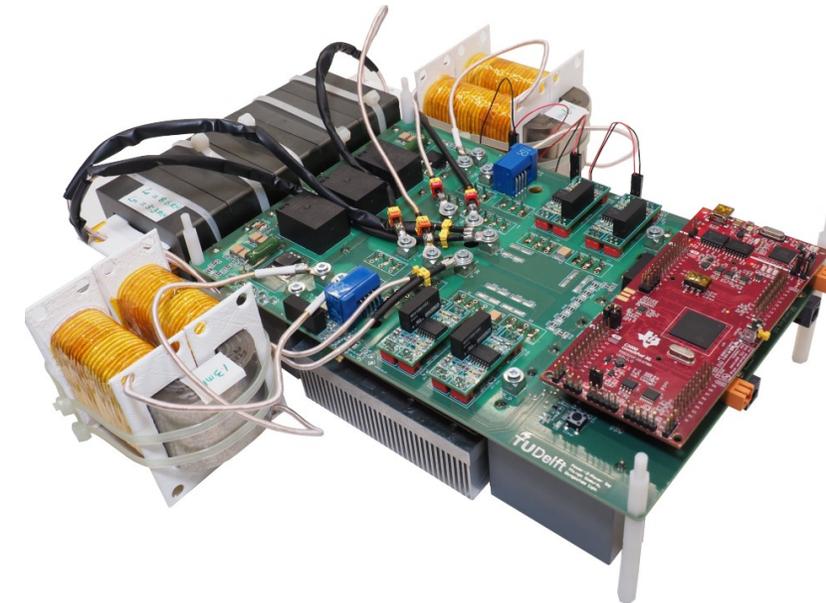
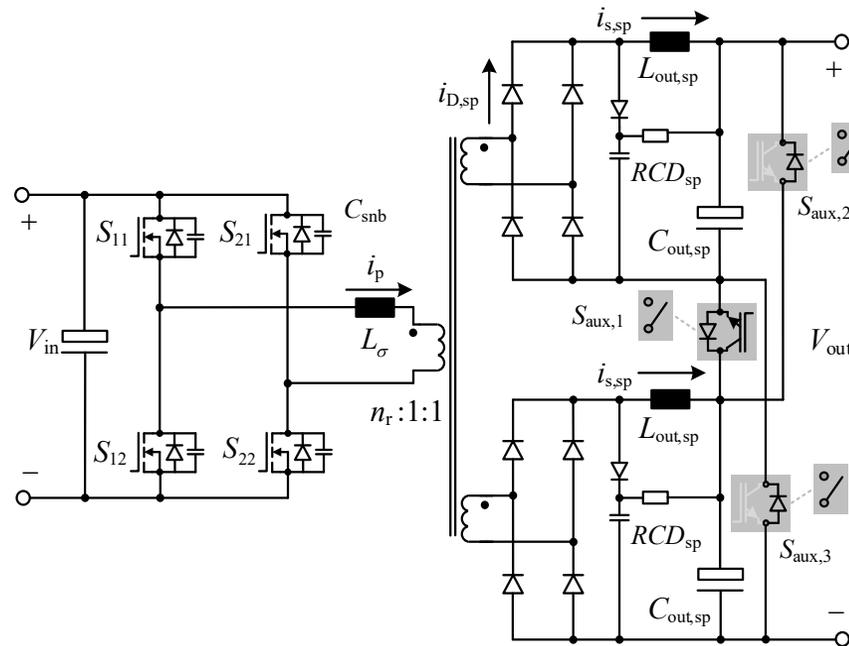
Fast EV Chargers: Reconfigurable Charger for Wide Battery Voltage Range

In Literature: Re-configurable PSFB with reduced conduction losses and versatile snubber circuits

Source: Dingsihao Lyu, Thiago Batista Soeiro, and Pavol Bauer, "Design and Implementation of a Reconfigurable Phase-Shift Full-Bridge Converter for Wide Voltage Range EV Charging Applications," IEEE Transactions on Transportation Electrification, 2022.

r-PSFB converter

- Modified PSFB converter with reconfigurable circuitry structure improves greatly the efficiency performance in wide voltage range
- Easy to control



The circuit schematic and prototype picture of the reconfigurable r-PSFB converter

Three Phase Fast Chargers

Dingsihao Lyu



Back-end: DC/DC Conversion for OBC and FCS Solutions

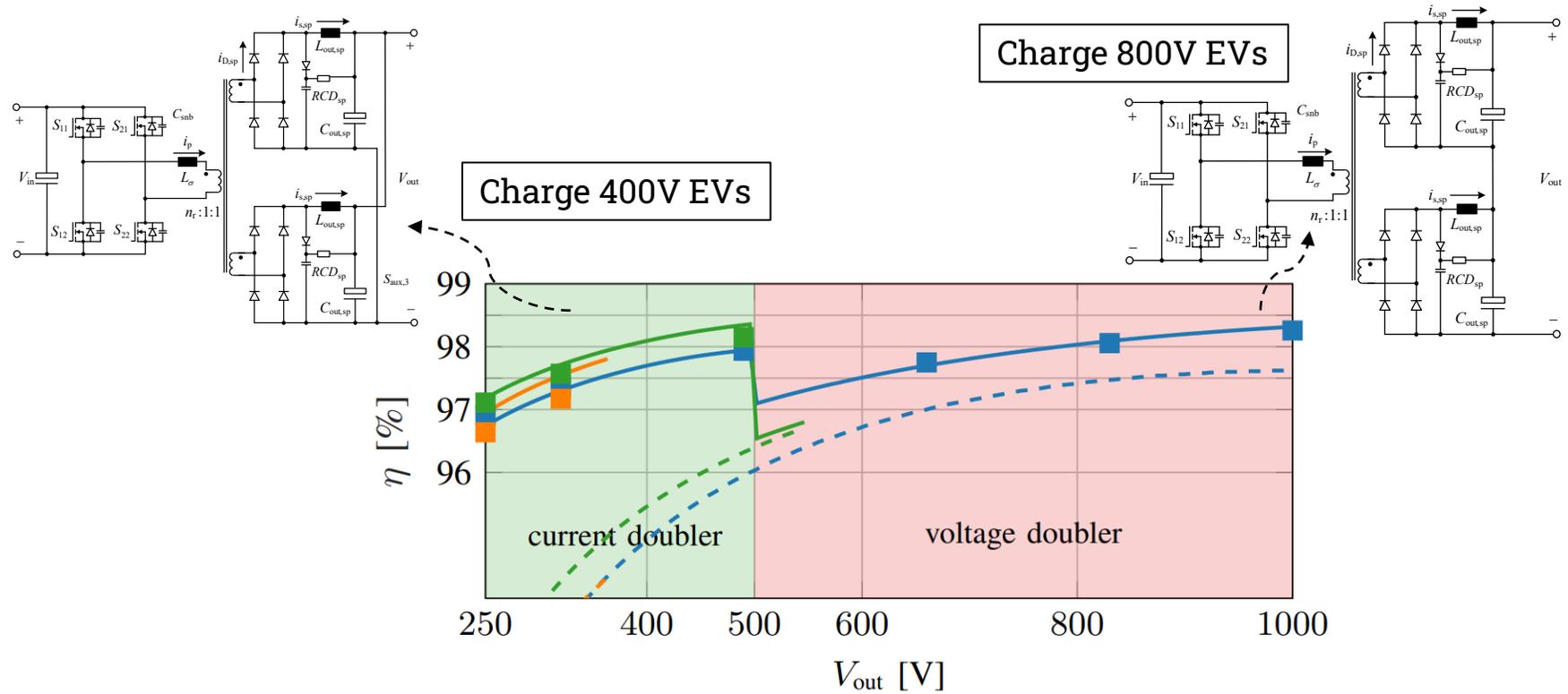
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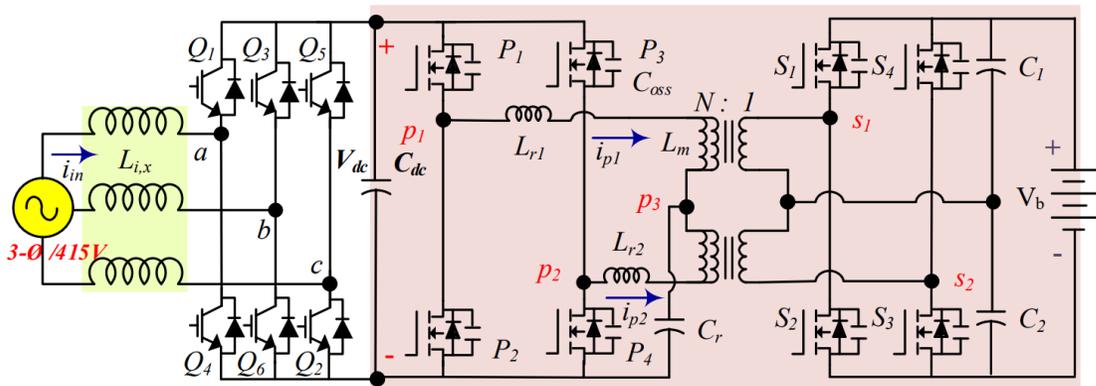


Three Phase Fast Chargers

Back-end: DC/DC Conversion for OBC and FCS Solutions

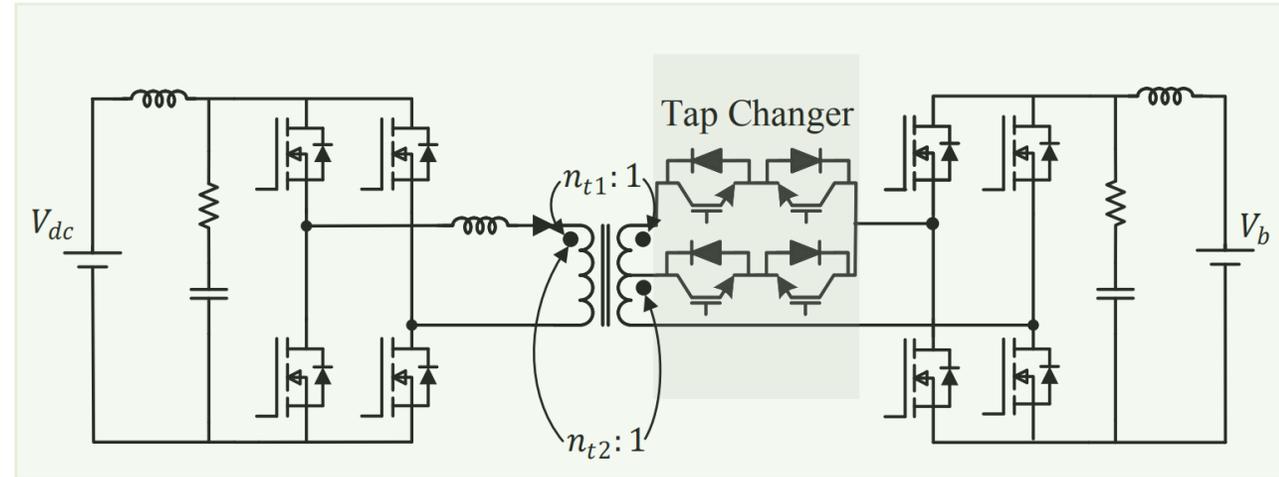
Fast EV Chargers: Reconfigurable Charger for Wide Battery Voltage Range

Further Reading: Reconfiguration for V2G Operation



Adaptive Dual-Active Bridge
Reconfigurable as an LLC Resonant Doubler or
Half-bridge LLC Converter

Saran Chaurasiya, Bhim Singh, "An **Adaptive EV Charger Based** Reconfigurable Bidirectional Isolated DC-DC Converter with Wide Voltage Range of Operation" IEEE Transportation Electrification Conference and Expo, 2022



Active Tap Changer for Dual-Active Bridge
A four-quadrant switch can be used to change the effective secondary winding turns

Sayandev Ghosh, Bhim Singh, "A **Reconfigurable Dual Active Bridge** Converter with Wide ZVS Range for Charging of Electric Vehicles", IEEE International Conference on Power Electronics, Drives and Energy Systems, 2020

Three Phase Fast Chargers

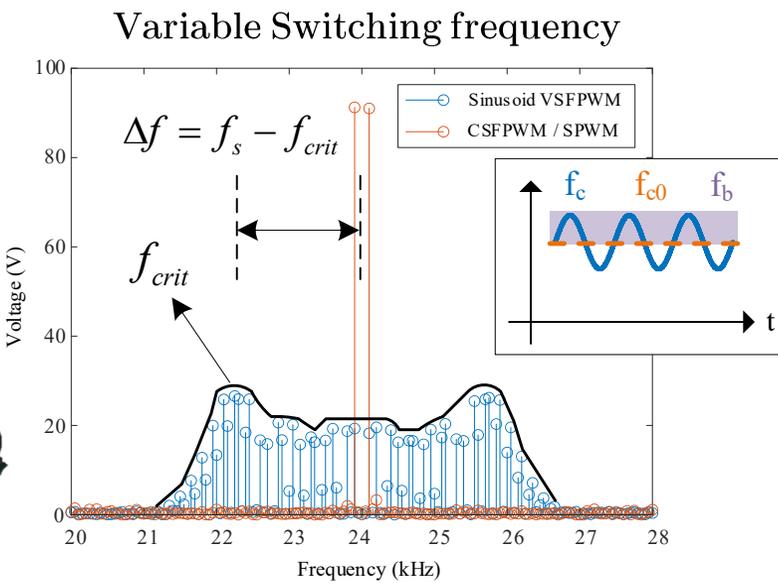
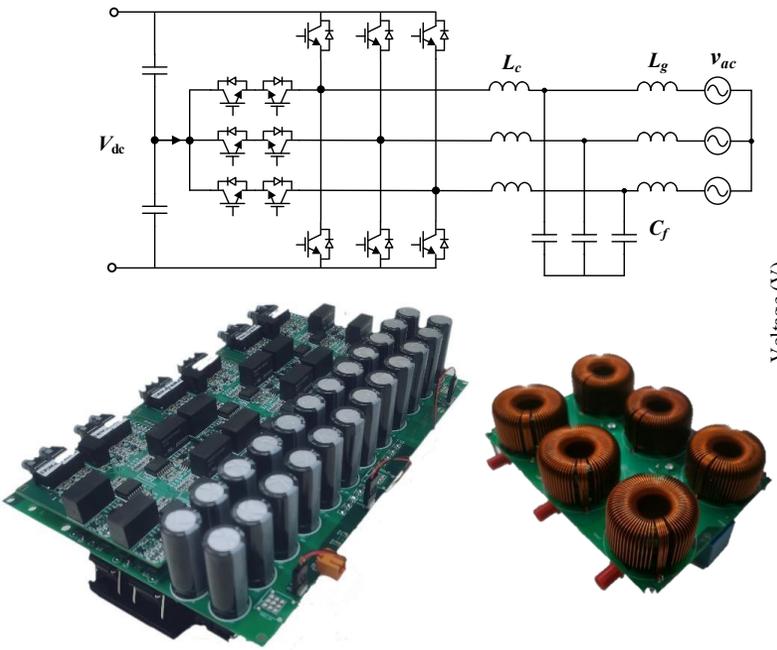
Front-end: AC/DC Conversion for OBC and FCS or Wireless Solutions

Fast EV Chargers: Optimizing the Front-End Topology

In Literature: 11 kW IGBT-Based T-type Converter



11 kW Power Electronics Building Block



Test Specifications

Items	Info
Switching frequency	Max. 16,05 kHz
Tested power	10 ~ 11,5 kW
Tested DC link voltage	630~750 V
Power factor	1
PWM	SVPWM & DPWM1
Max. Modulation index	1,15
Grid line voltage	(400V .. 480V) ± 10%

Three Phase Fast Chargers

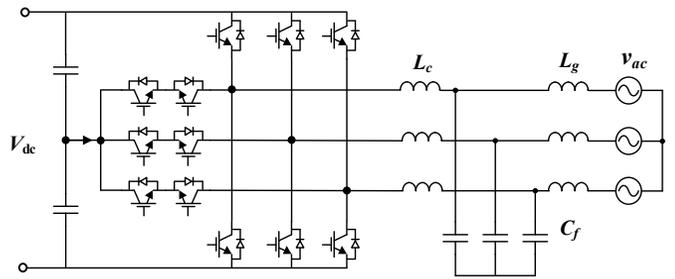
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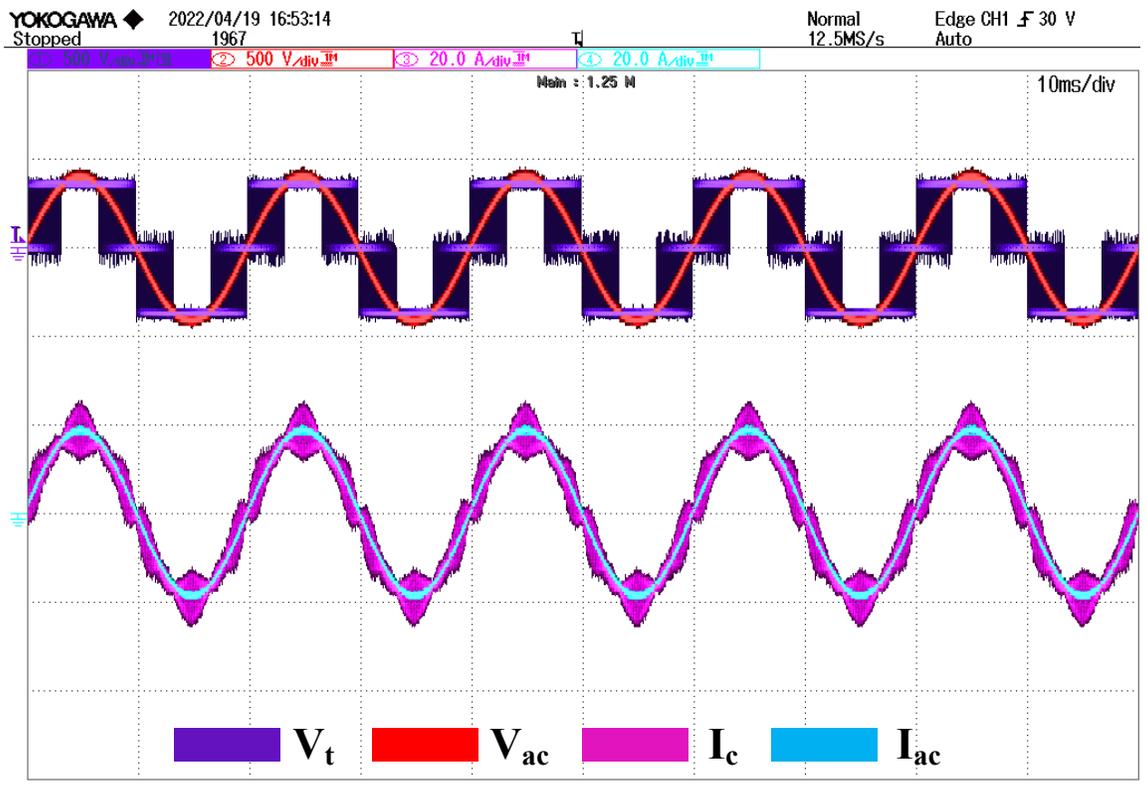
Yang Wu

Fast EV Chargers: Optimizing the Front-End Topology

11 kW Power Electronics Building Block



◆ Respectable Peak Efficiency for a IGBT-based Rectifier



U _{rms1}	480.97	V
I _{rms1}	12.157	A
P _Σ	9.793	kW
U _{dc3}	0.6778	kV
I _{dc3}	14.622	A
P ₃	9.911	kW
η ₁	98.813	%

Three Phase Fast Chargers

Front-end: AC/DC Conversion for OBC and FCS or Wireless Solutions



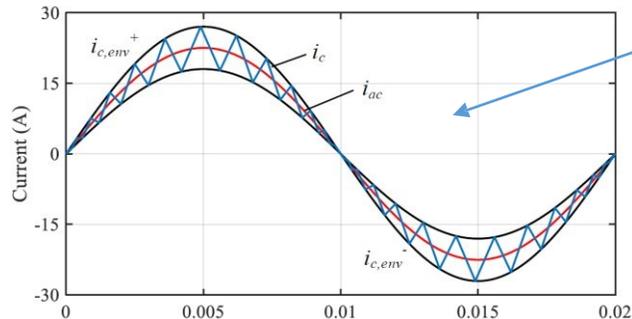
Yang Wu

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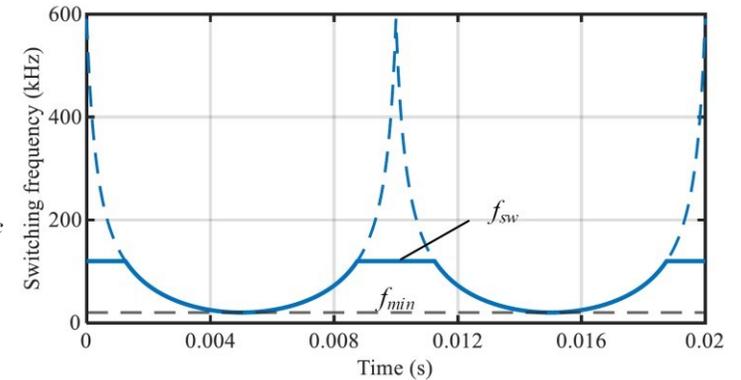
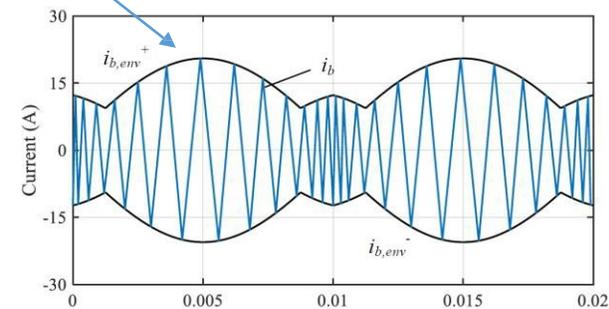
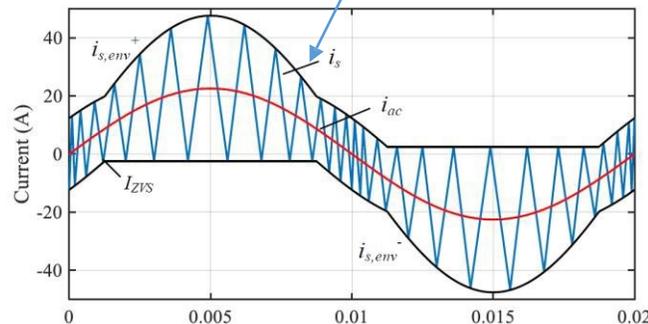
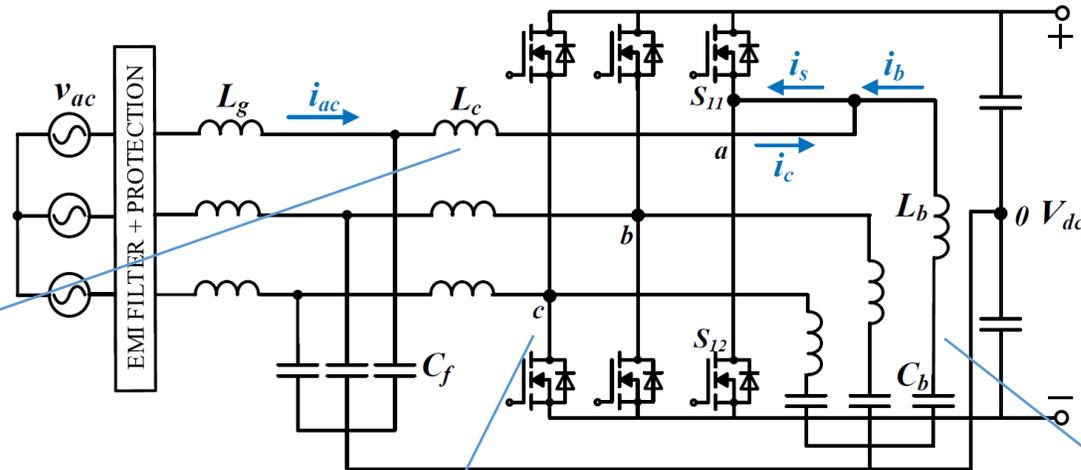
In Literature: Frequency Modulation for Grid-Connected VSC and 3Φ iTCM

Source: Jian Sun, Yang Wu, Thiago Batista Soeiro, Zian Qin and Pavol Bauer "ZVS Turn-on integrated Triangular Current Mode Three-phase PFC for EV On-board Chargers", IEEE PEMC 2020

Three-phase version of iTCM concept



98.81% efficient
12.46 kW/L
1.87 kW/kg



Three Phase Fast Chargers

Front-end: AC/DC Conversion for OBC and FCS or Wireless Solutions

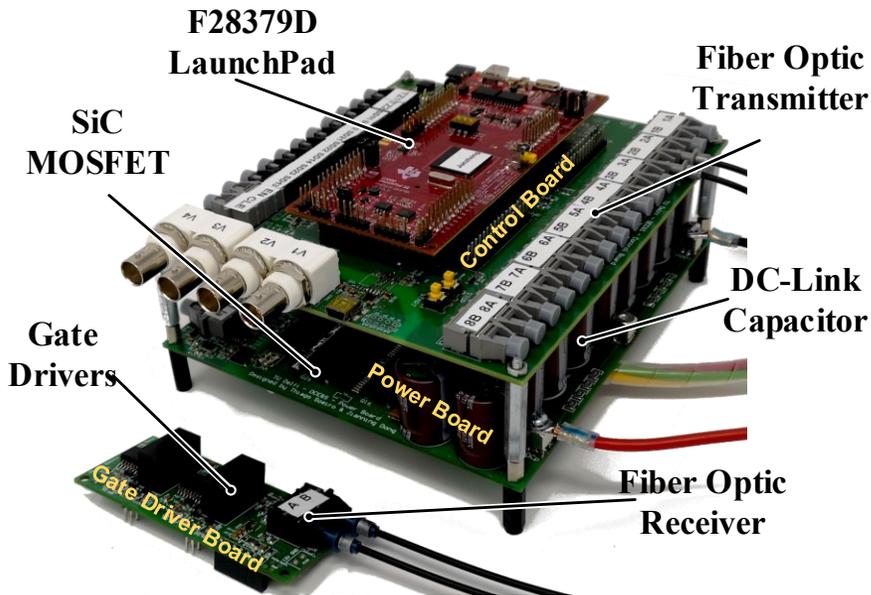


Yang Wu

Fast EV Chargers: Optimizing the Front-End Topology

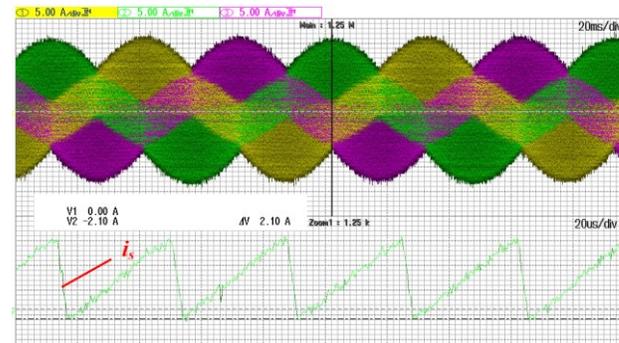
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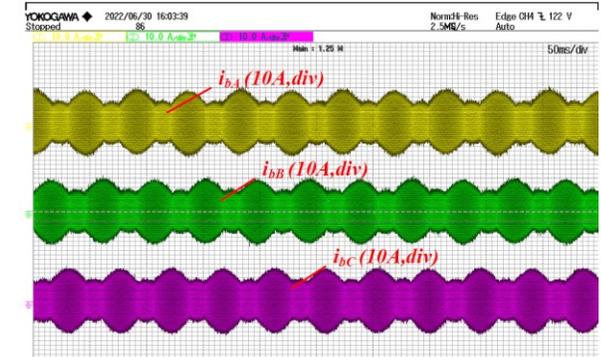


98.81% efficient
12.46 kW/L
1.87 kW/kg

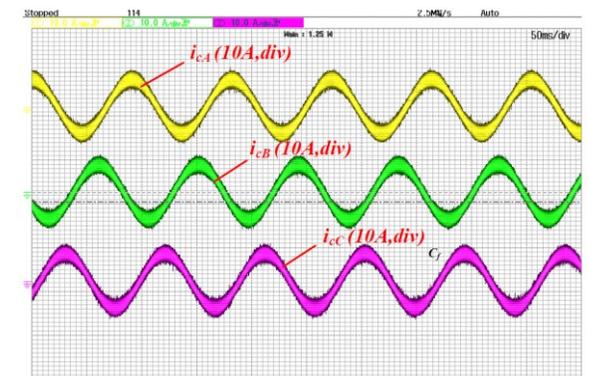
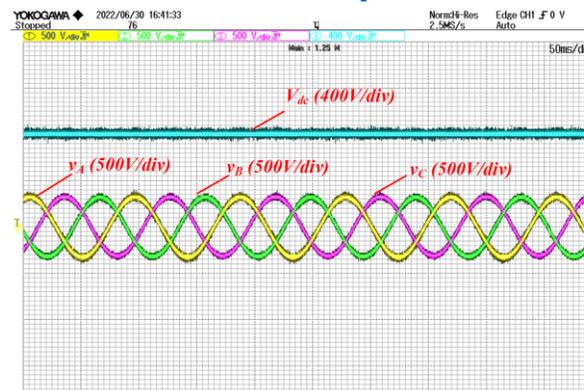
Exp. Semiconductor Current



Exp. Notch LC Current

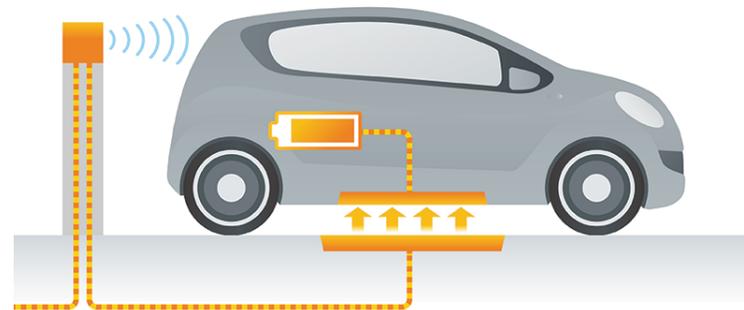


Exp. LCL Filter Current and DC-link Voltage



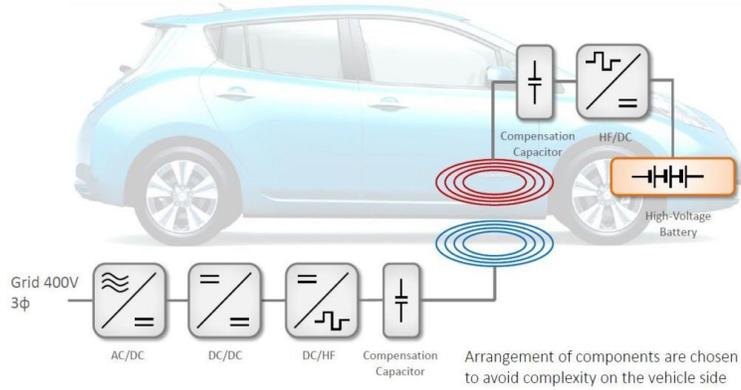
Wireless EV Chargers

Cut the cord!



Wireless EV Chargers

Typical wireless charging setup



Source: insideevs.com/30-kw-wireless-charging-for-your-nissan-leaf-chademo-ev-anyone/



TESLA plugless system (Source: www.tesla.com)



BMW wireless charging pad (Source: www.bmw.de)



WARTSILA wireless coastal ferry MW charger (Source: www.wartsila.com)

Yes, that's a wirelessly charged ship!!!

Wireless EV Chargers

Research in wireless charging, why?

How to get rid of the cord altogether?

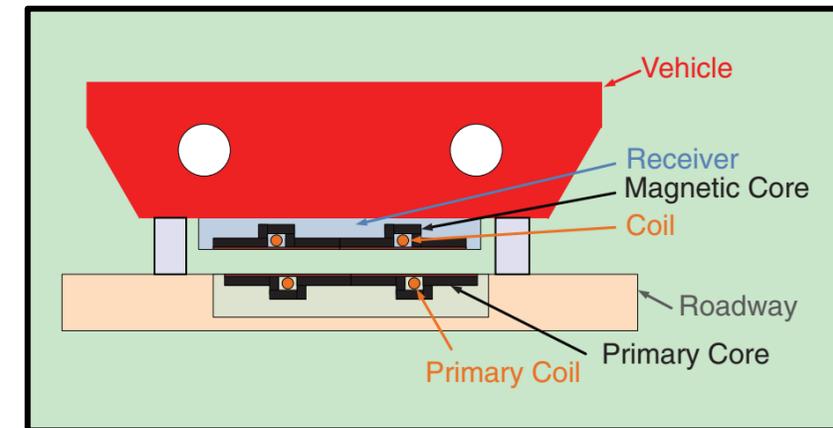
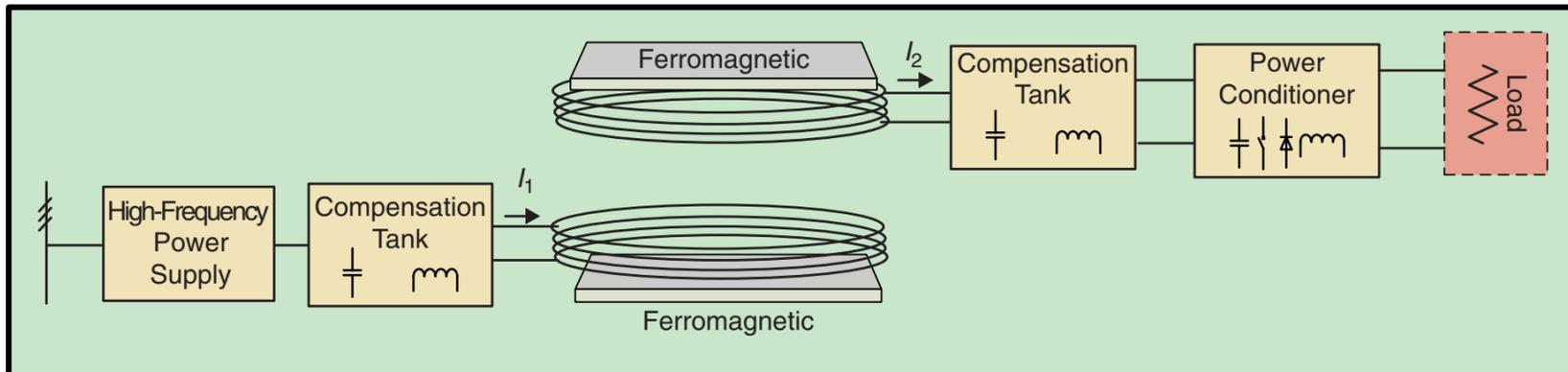
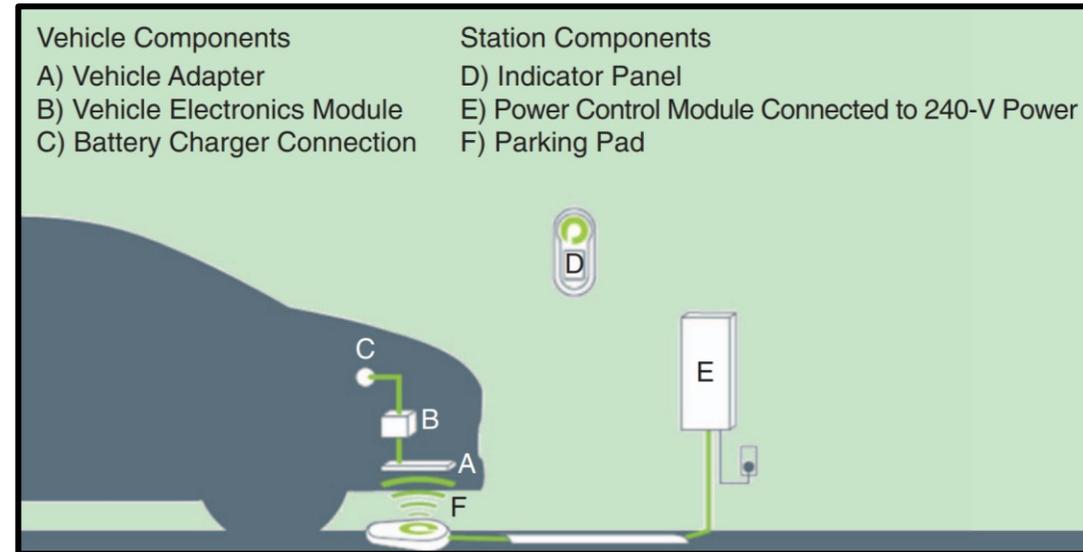
Static, Opportunity, Dynamic WPT → charging without knowing

How to ensure WPT takes place efficiently?

Improved misalignment performance → better overall efficiency

How to optimize coil design for multifunctionality?

Adaptable primary → more compatibility at back-end



By Srdjan Lukic and Zeljko Pantic "Cutting the Cord: Static and dynamic inductive wireless charging of electric vehicles", IEEE Electrification Magazine, 2013

Wireless EV Chargers

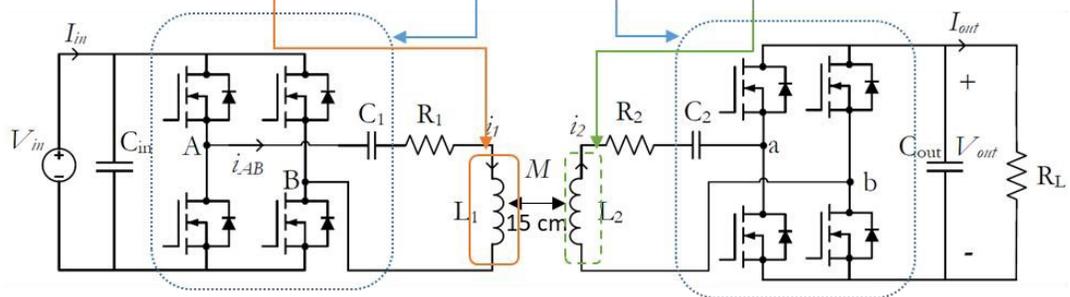
Back-end: DC/DC Conversion for Wireless EV Charging

Contactless Chargers: Multi-objective Design Improving Misalignment Performance

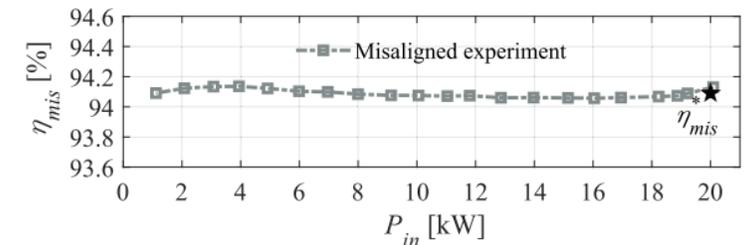
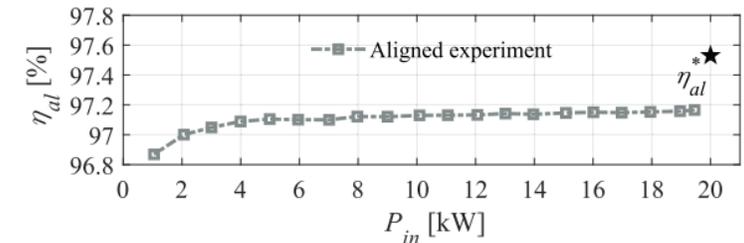
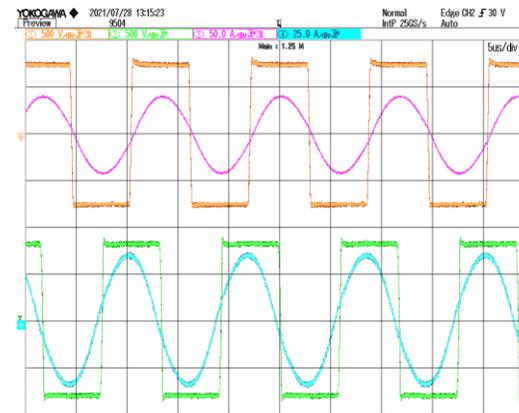
In Literature: Explore the boundaries of the efficiency of high power IPT systems

Source: Wenli Shi, Jianning Dong, Thiago Soeiro, Calvin Riekerk, Francesca Grazian, Guangyao Yu, and Pavol Bauer, "Design of a highly efficient 20 kW inductive power transfer system with improved misalignment performance," IEEE Transactions on Transportation Electrification, 2021.

Version: 22 kW Converter



• 97,2% Peak Efficiency @ 20 kW



Wireless EV Chargers

Dr. Francesca Grazian



Back-end: DC/DC Conversion for Wireless EV Charging

Contactless Chargers: V/I Doubler for Efficient Wireless Charging for 400 V, 800 V batteries

In Literature: Voltage or Current Doubler (V/I-D) Converter for Wireless Charging of EVs

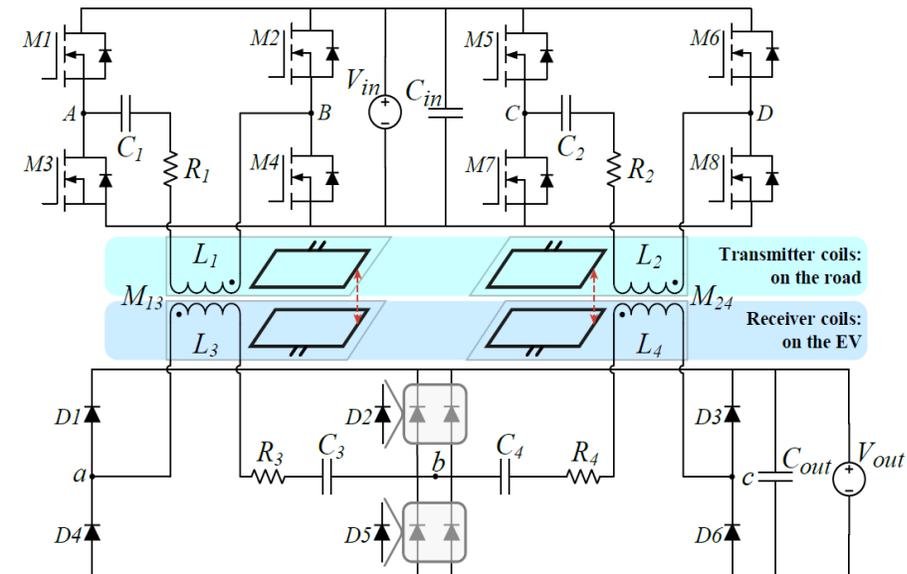
Source: Francesca Grazian, Thiago Batista Soeiro, and Pavol Bauer, "Voltage/Current Doubler Converter for an Efficient Wireless Charging of Electric Vehicles With 400-V and 800-V Battery Voltages," IEEE Transactions on Industrial Electronics, 2023.

Charging for **Autonomous** Diving Taxi



- The circuit features reconfigurability Series or Parallel Connection of Secondary Transformer by operation of the H-bridge Converter in-phase (series) or anti-phase (parallel)
- **Two H-Bridges and Two Secondary Windings are Needed!**

S-S Compensation



Wireless EV Chargers

Dr. Francesca Grazian

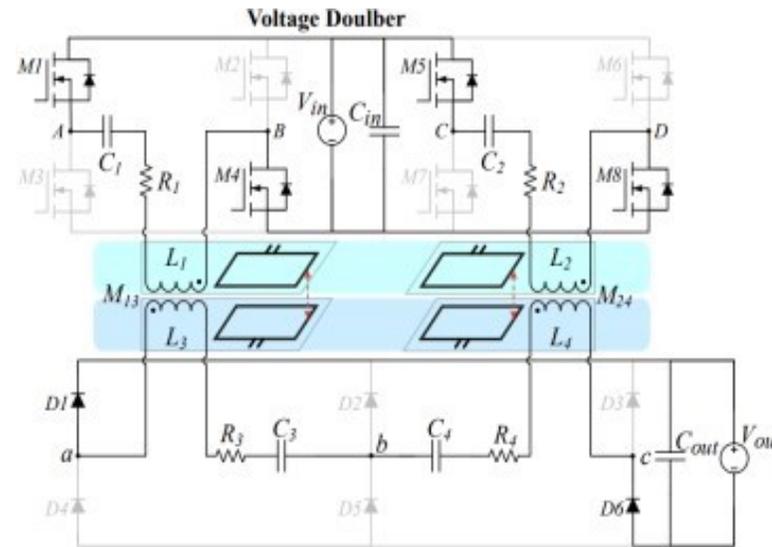
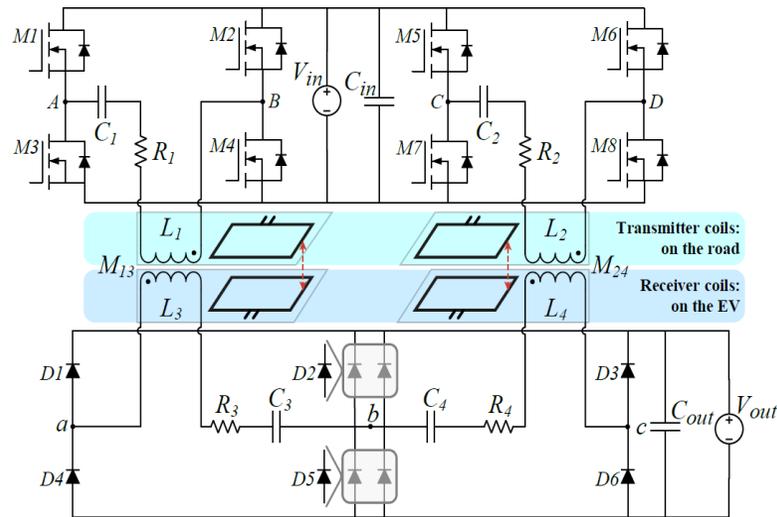


Back-end: DC/DC Conversion for Wireless EV Charging

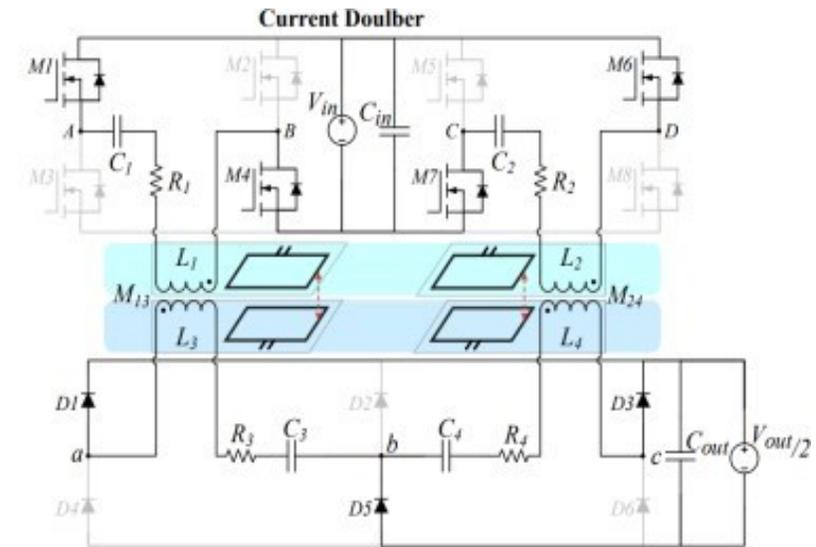
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Series Connection



Parallel Connection



The circuit features reconfigurability Series or Parallel Connection of Secondary Transformer by operation of the H-bridge Converter in-phase (series) or anti-phase (parallel)

Wireless EV Chargers

Dr. Francesca Grazian

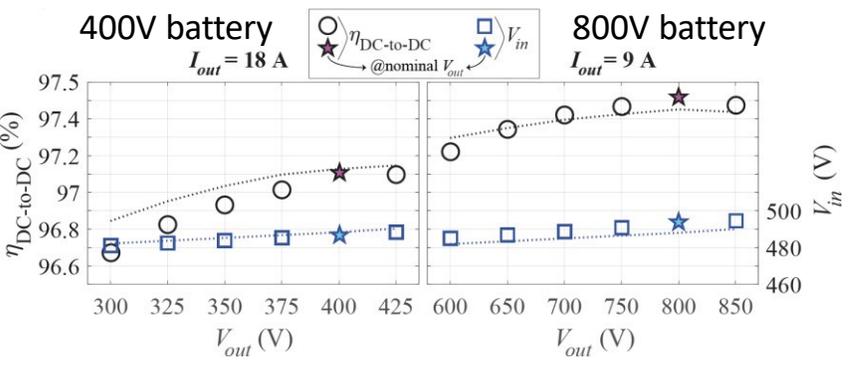
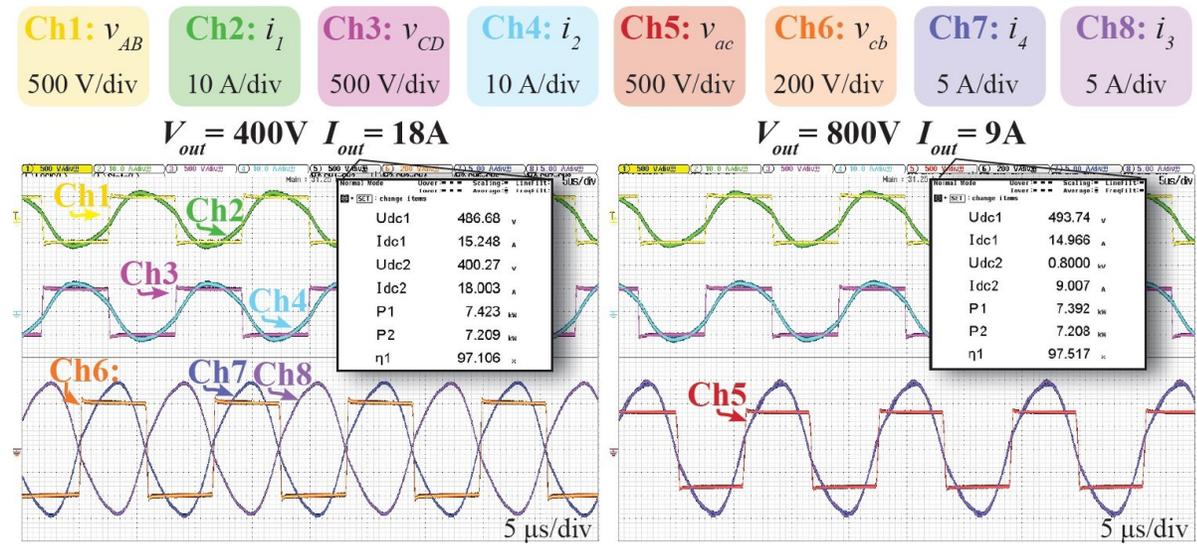
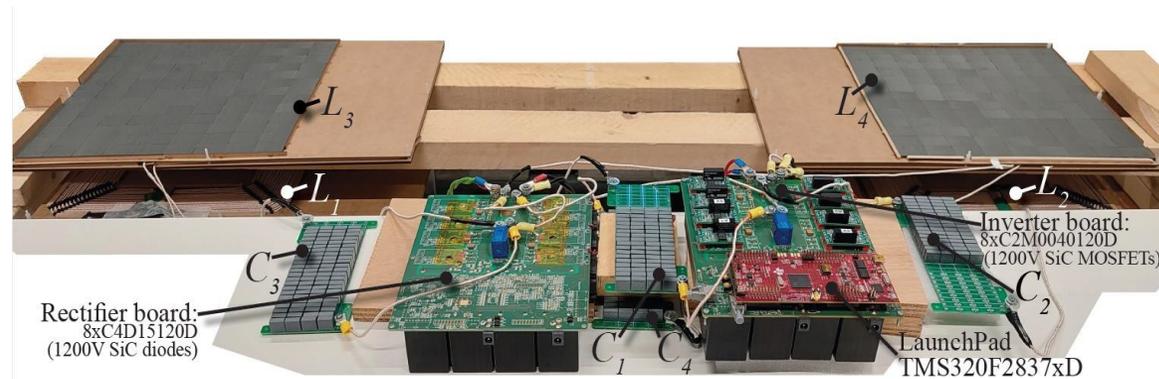


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Source: Francesca Grazian, Thiago Batista Soeiro, and Pavol Bauer, "Voltage/Current Doubler Converter for an Efficient Wireless Charging of Electric Vehicles With 400-V and 800-V Battery Voltages," IEEE Transactions on Industrial Electronics, 2023.



High efficiency charging at the same rated power for 400V or 800V EV batteries.
 Unfortunately it needs two coils!!! It needs two H-bridges but the current are evenly shared

Wireless EV Chargers

Dr. Francesca Grazian

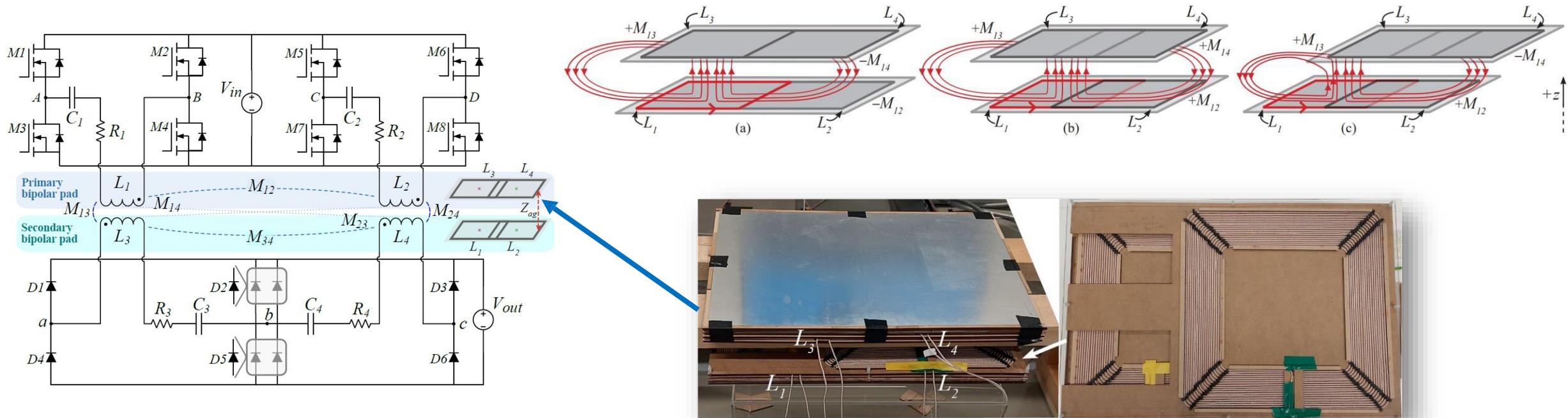


Back-end: DC/DC Conversion for Wireless EV Charging

Contactless Chargers: Compact and Single-Coil Solution for V/I Doubler

In Literature: Voltage or Current Doubler (V/I-D) Converter with coupled Bipolar pads (BPPs) → Compact solution

Source: Francesca Grazian, Thiago Batista Soeiro, and Pavol Bauer, "Voltage/Current Doubler Converter for Electric Vehicle Wireless Charging Employing Bipolar Pads," IEEE Journal of Emerging and Selected Topics in Power Electronics, 2023.



Voltage or Current Doubler (V/I-D) Converter with coupled Bipolar pads (BPPs) → Compact solution

Wireless EV Chargers

Dr. Francesca Grazian

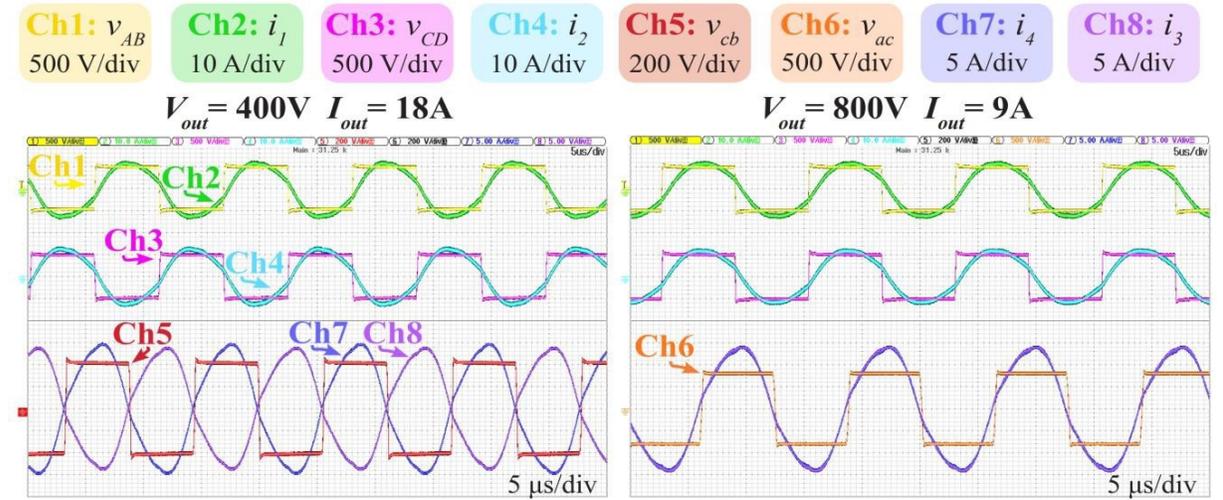
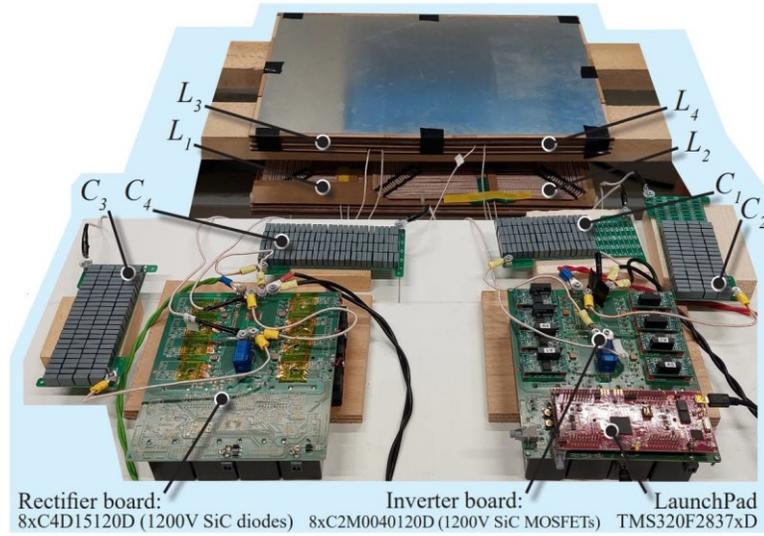


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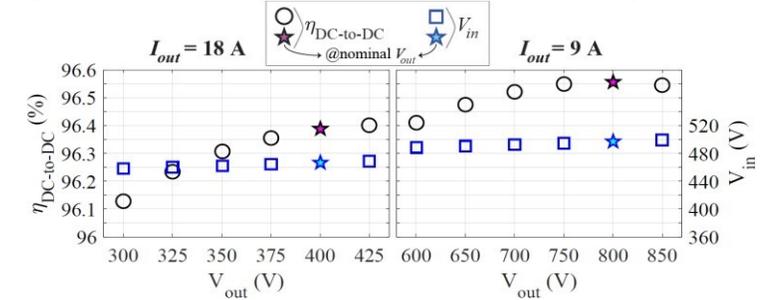
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- ◆ Fundamental to enable EV wireless charging in public/shared parking infrastructures (with High Efficiency for both 400V and 800V batteries).
- ◆ Simpler circuit on board the EV: power transfer control only at the source-side.
- ◆ Slight efficiency difference in the two modes.
- ◆ BPPs: interoperability with standard coils.



Summary



EV Market is growing: Battery- based transport is on the rise



Standards and regulations govern charging rate limits



Slow and fast chargers all need attention with evolving PE technology



Size is the ultimate constraint in OBCs, volume reduction remains the goal



Multifunctionality and grid-compliance are challenges in fast chargers



WPT is promising, misalignment and efficiency performance need optimization

Further Reading

Our Research on EV Charging Technologies Published in Journals (From 2021 to 2024)

- [0] G. Zhu, J. Dong, T. B. Soeiro, H. Vahedi and P. Bauer, "Dual-Side Capacitor Tuning and Cooperative Control for Efficiency-Optimized Wide Output Voltages in Wireless EV Charging," in IEEE Transactions on Industrial Electronics, doi: 10.1109/TIE.2024.3436666.
- [1] G. Zhang, Y. Wu, J. Xu and T. B. Soeiro, "ITCM-Operated Three-Phase Three-Wire Voltage-Source Converter System Featuring Capacitor-Split Virtual Ground Connection," in IEEE Transactions on Power Electronics, vol. 39, no. 8, pp. 9415- 9429, Aug. 2024, doi: 10.1109/TPEL.2024.3395706.
- [2] Y. Wu, J. Xu, T. B. Soeiro, P. Bauer and Z. Qin, "Frequency Design of Three-phase Active Front-End Converter with Reduced Filter in EV Chargers," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2024.3381167.
- [3] S. Qazi, P. Venugopal, A. J. Watson, P. Wheeler and T. B. Soeiro, "Design and Analysis of Reconfigurable Resonant Converter With Ultrawide Output Voltage Range," in IEEE Transactions on Power Electronics, vol. 39, no. 5, pp. 5750-5763, May 2024, doi: 10.1109/TPEL.2024.3365391.
- [4] D. Lyu, C. Straathof, T. B. Soeiro, Z. Qin and P. Bauer, "ZVS-Optimized Constant and Variable Switching Frequency Modulation Schemes for Dual Active Bridge Converters," in IEEE Open Journal of Power Electronics, vol. 4, pp. 801-816, 2023, doi: 10.1109/OJPEL.2023.3319970.
- [5] L. Gong et al., "A Simplified All-ZVS Strategy for High-Frequency Triple Active Bridge Converters With Designed Magnetizing Inductance," in IEEE Transactions on Power Electronics, vol. 38, no. 11, pp. 13781-13797, Nov. 2023, doi: 10.1109/TPEL.2023.3304316.
- [6] Y. Bi et al., "An Improved Combined Current Control for Single-Phase Operation Mode of Single-/Three-Phase EV Charging System With Voltage Ripple Suppression," in IEEE Transactions on Power Electronics, vol. 38, no. 11, pp. 13635-13649, Nov. 2023, doi: 10.1109/TPEL.2023.3290798.
- [7] S. Qazi et al., "Powering Maritime: Challenges and prospects in ship electrification," in IEEE Electrification Magazine, vol. 11, no. 2, pp. 74-87, June 2023, doi: 10.1109/MELE.2023.3264926.
- [8] Y. Bi et al., "An Integrated Power Decoupling Method for Single-Phase EV Onboard Charger in V2G Application," in IEEE Transactions on Power Electronics, vol. 38, no. 8, pp. 9635-9646, Aug. 2023, doi: 10.1109/TPEL.2023.3281085.
- [9] B. O. Aarninkhof, D. Lyu, T. B. Soeiro and P. Bauer, "A Reconfigurable Two-stage 11kW DC-DC Resonant Converter for EV Charging with a 150-1000V Output Voltage Range," in IEEE Transactions on Transportation Electrification, doi: 10.1109/TTE.2023.3279211.
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Thank You

QUESTIONS?