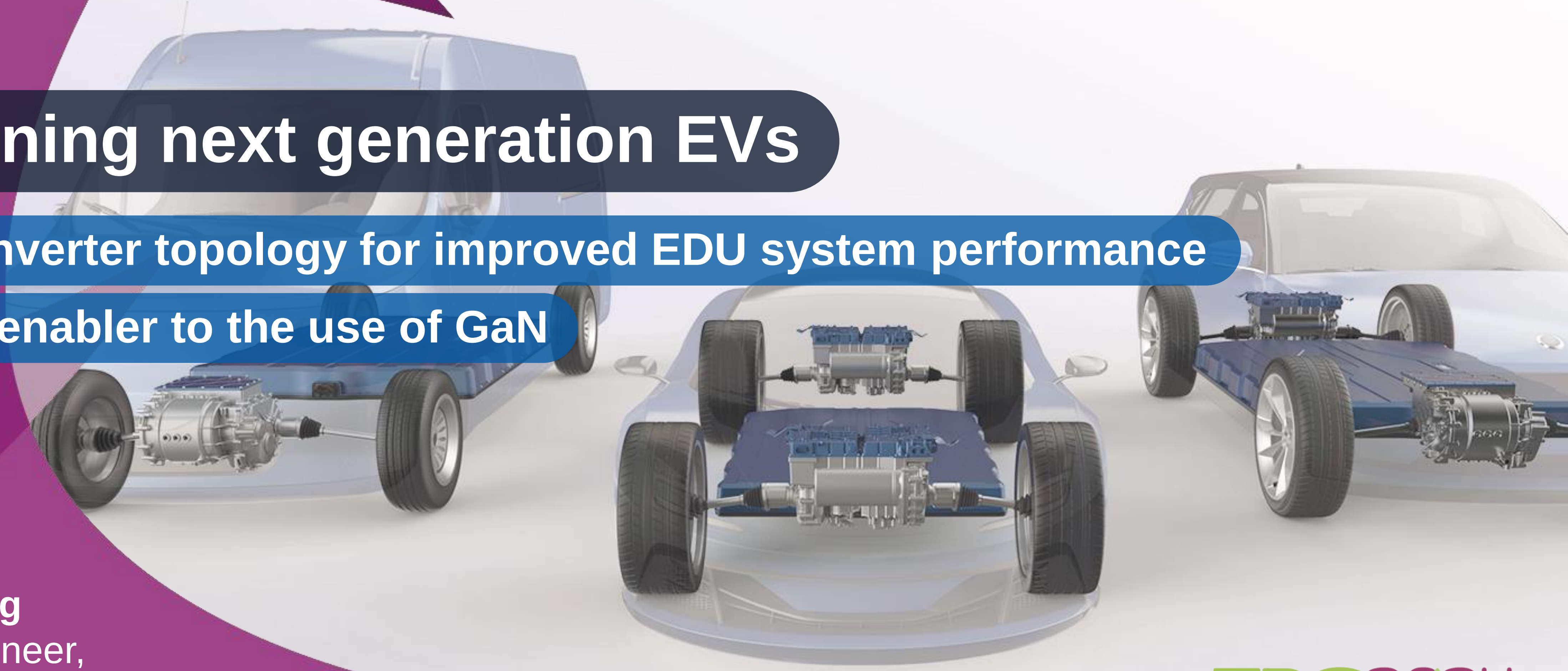


Designing next generation EVs

3-level inverter topology for improved EDU system performance

& as an enabler to the use of GaN

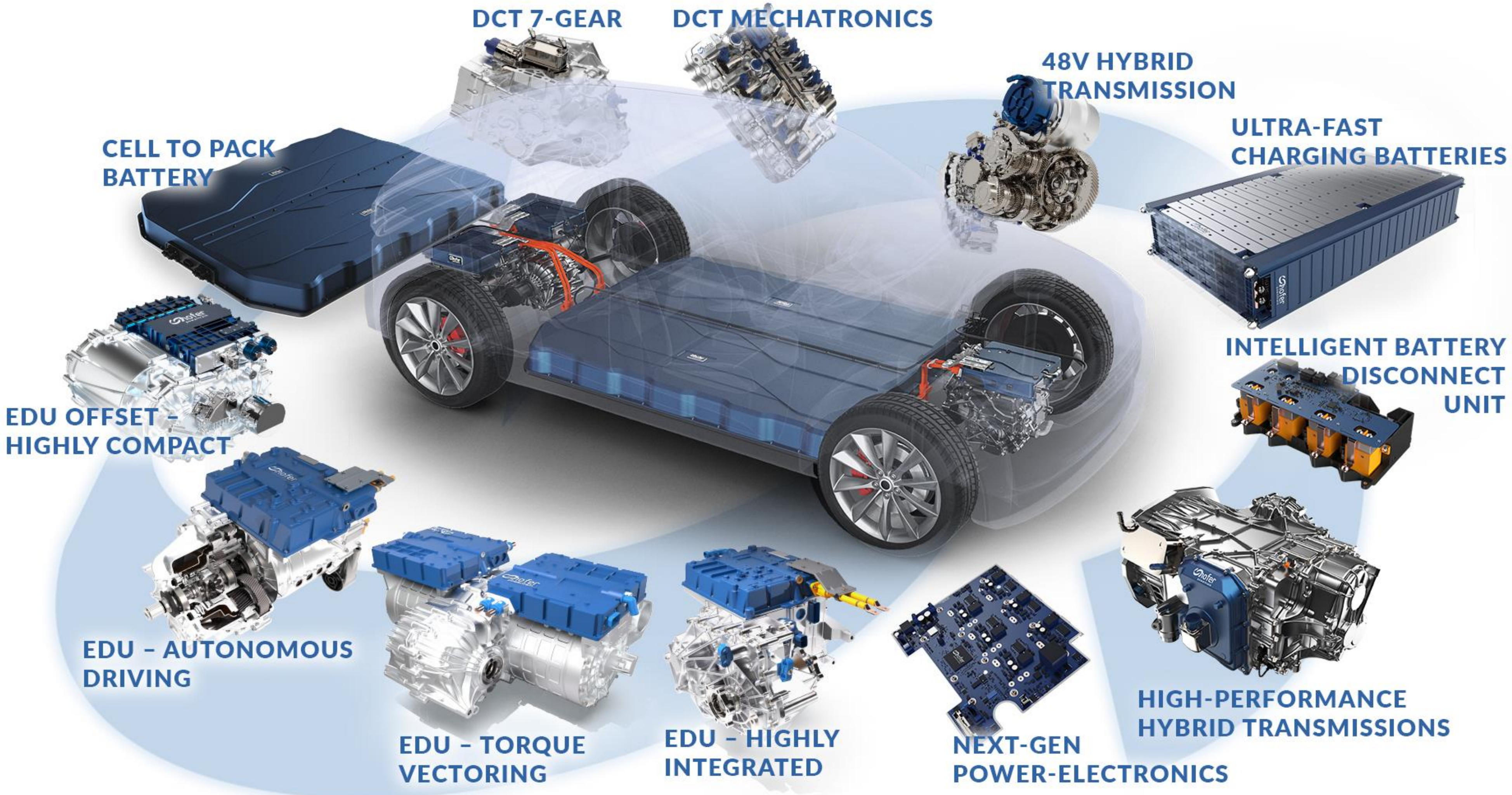
2024

Steve King
Chief Engineer,
Electrical Systems

hofer powertrain

FPC2024 TEN YEARS

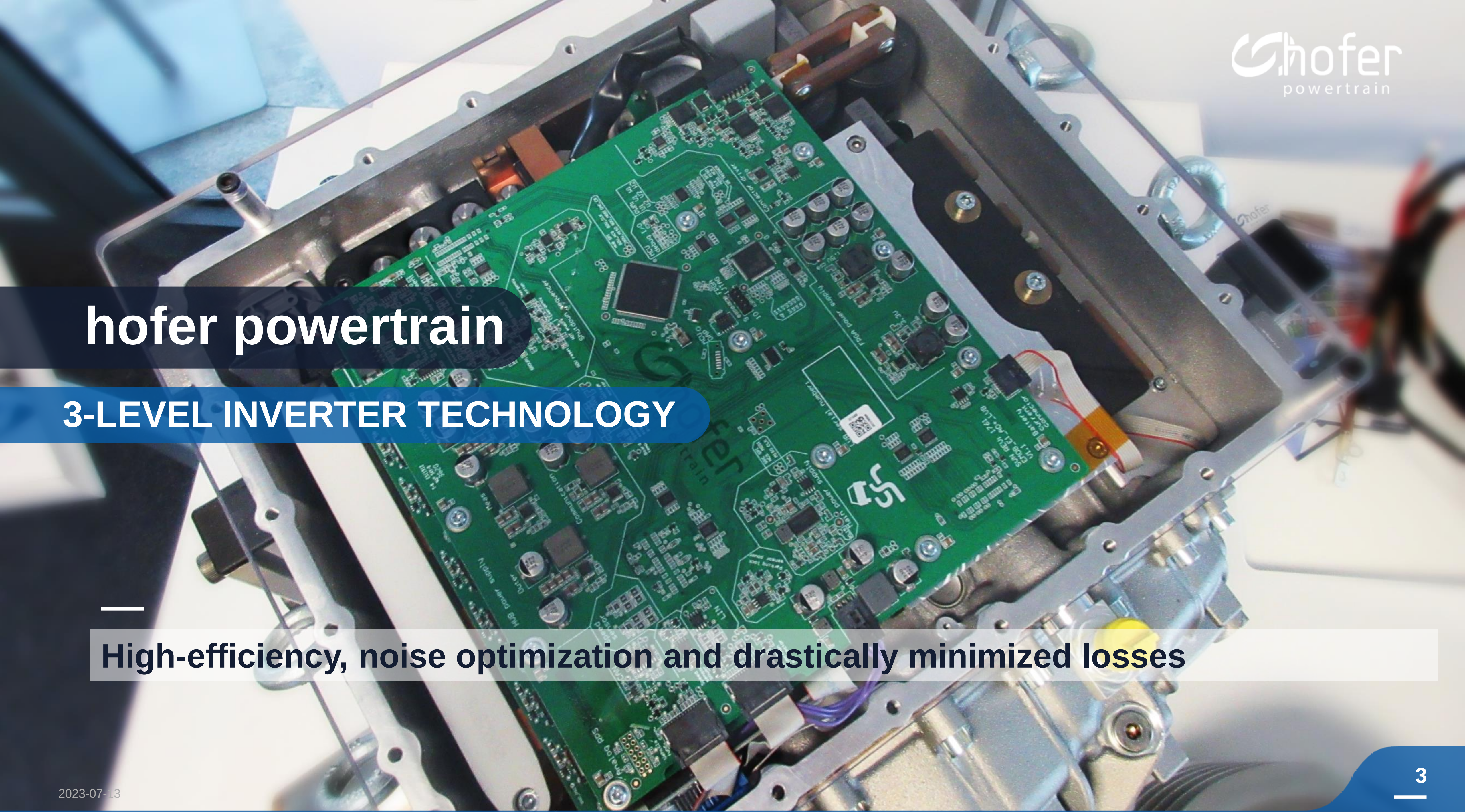
Technology highlights



Mobility expertise since **1980**

Employees worldwide **800+**

Locations worldwide **19**



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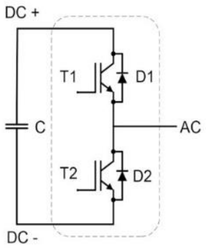
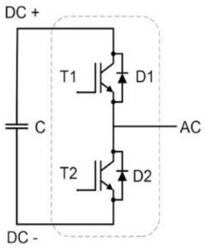
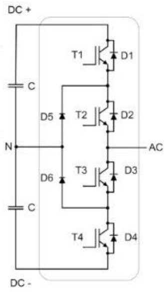
3-LEVEL INVERTER TECHNOLOGY

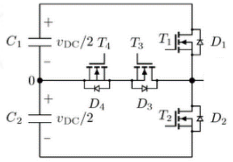
High-efficiency, noise optimization and drastically minimized losses

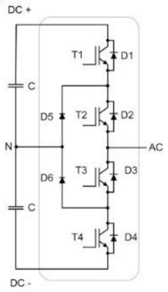
Inverter topologies











	2-level	2-level	3-level	3-level	3-level	3-level
TECHNOLOGY	**2-level IGBT 1200 V**	**2-level SiC 1200 V**	**3-level IGBT 650 V**	**3-level T Type SiC 1200 V**	**3-level SiC 650 V**	**3-level GaN 650 V**
WLTP IMPACT	-	++	++	+++	+++	+++
COSTS	€	€€€	€€	€€€	€€€	€€
TECHNICAL-PERFORMANCE *	-	-	+	+	+	+

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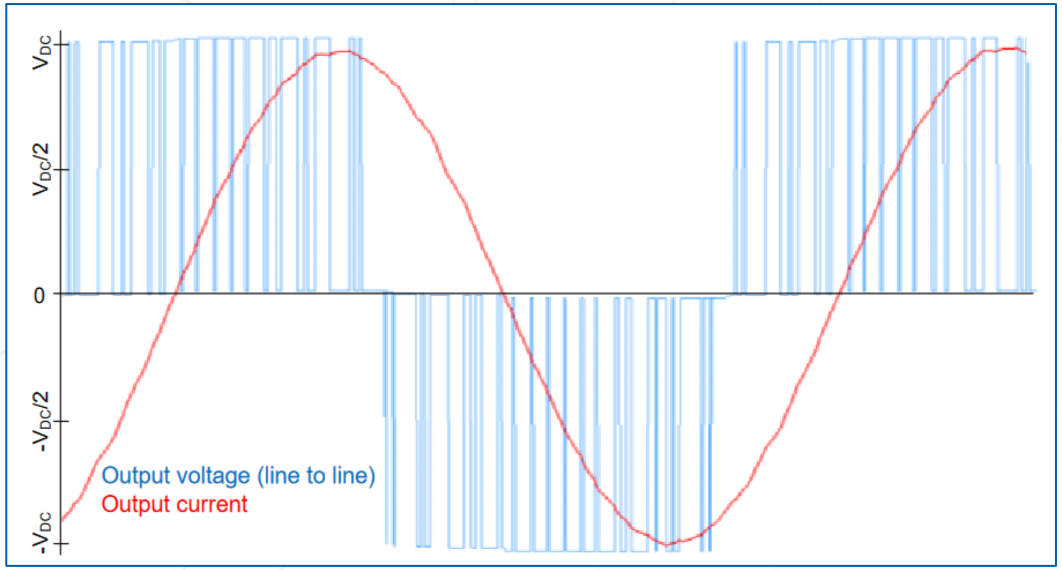
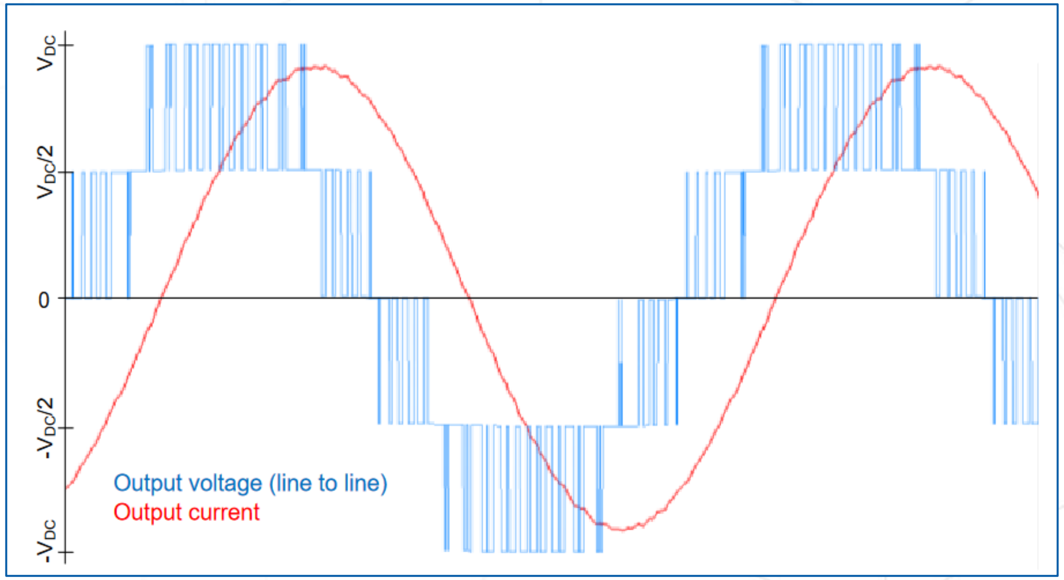
* EMC, NVH, Isolation, THD, Efficiency,

2-level VS. 3-Level





3-level topology introduces limited THD provided to the motor and limited voltage changes during single switching event. THD can be reduced by the factor up to 2.

Source: SEMIKRON Application Note AN-11001

3 level topology benefits – NVH behaviour

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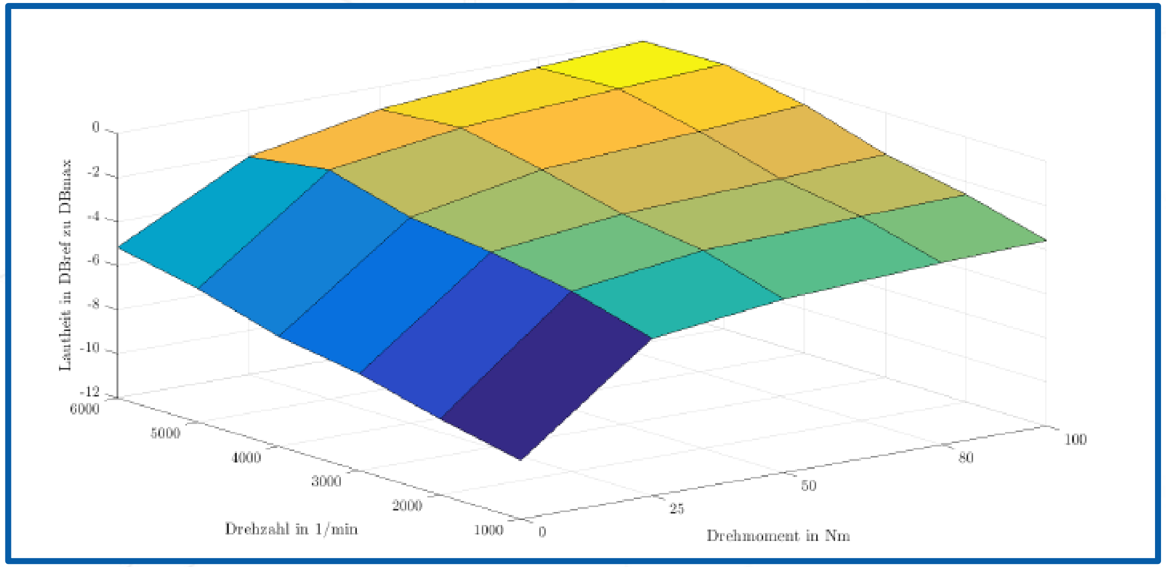
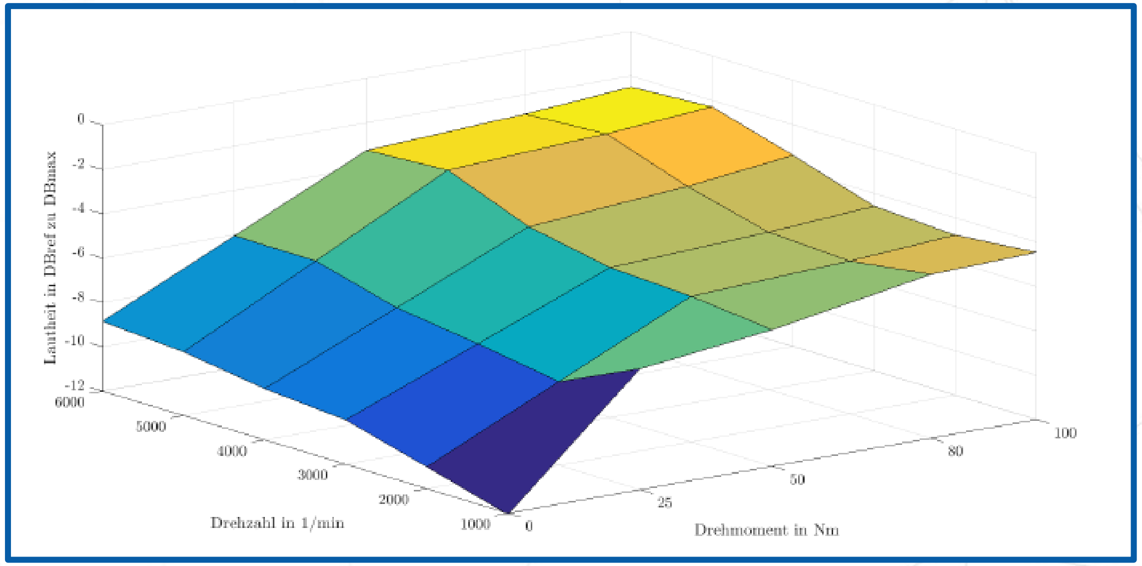
NVH: improved behaviour

- less excitation of the harmonics due to lower ripple current (lower THD)



Level of noise of E-Motor measured with 2L-Inverter *



Level of noise of E-Motor measured with 3L-Inverter *

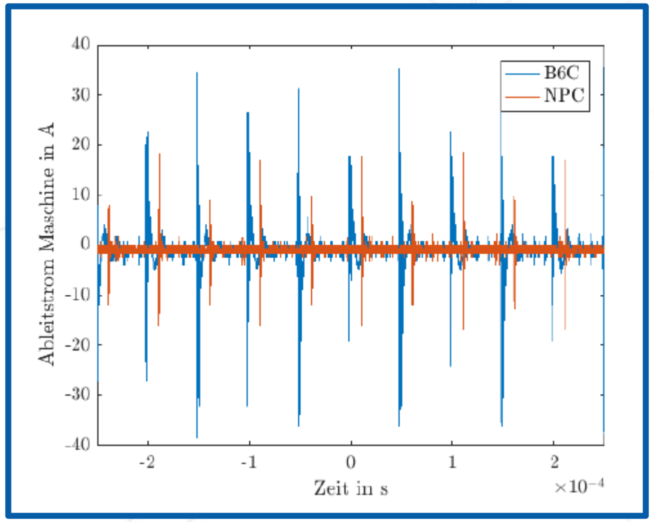
MEASUREMENTS SHOWED THAT NVH IS MORE THAN 25% BETTER, WHEN USING 3L INSTEAD OF 2L

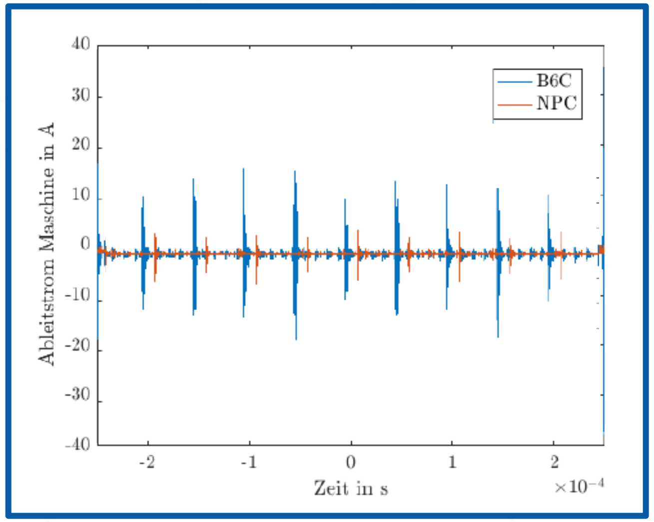
* source: measured by german university

3 level topology benefits – shaft voltage

Shaft Voltage: lower

- the additional voltage level leads to lower common mode voltage
- lower voltage on the shaft reduces stress on the bearings because earth leakage current is much smaller

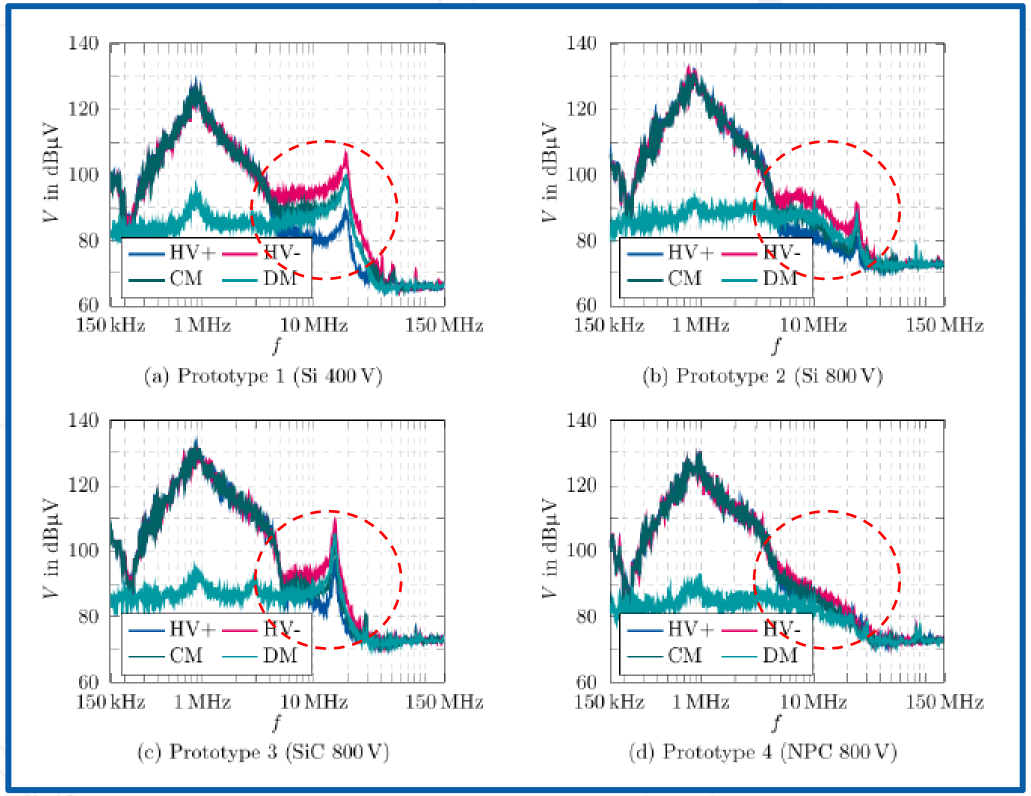




BETTER LEAKAGE-CURRENT BEHAVIOUR OF 3L-INVERTER → REDUCED LEVEL OF COSTLY COUNTERMEASURES

* source: : measured by german university

3 level topology benefits – EMC



EMC: better behaviour

- common mode currents are smaller
- high du/dt is not required which means further reduction of common mode currents

3L INVERTER HAS INTRINSICLY BETTER EMC BEHAVIOUR COMPARED WITH 2L INVERTERS

* source: : measured by german university

Measurement results – Internal motor

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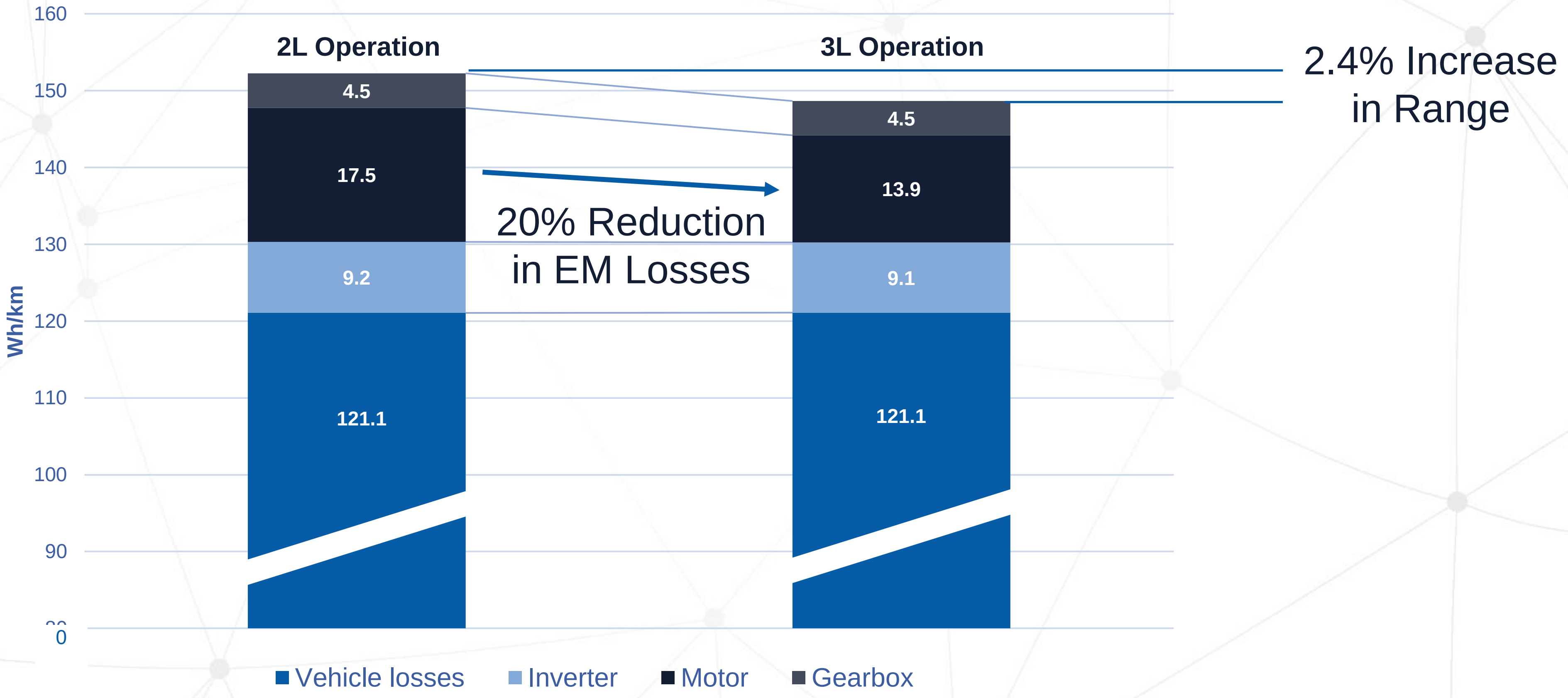
WLTP simulations based on measurements



Reference vehicle data from OEM: J-low segment, 1980kg, 210km/h max

EDU TOP requirement: energy consumption

Delta Motor losses (2L vs. 3L operation) in %

M [Nm]	500	2000	3500	5000	6500	8000	9500	11000	12500	14000	15000
330	n.D.	n.D.	n.D.								
300	n.D.	n.D.	n.D.	n.D.							
250	n.D.	n.D.	n.D.	n.D.	n.D.						
200	n.D.	n.D.	n.D.	n.D.	n.D.	n.D.					
150	n.D.	-8.34%	-9.50%	-3.47%	-1.71%	-0.85%	-0.11%	n.D.			
100	1.69%	-11.67%	-17.16%	-11.68%	-9.11%	-6.79%	-5.42%	n.D.	n.D.	n.D.	n.D.
50	0.06%	-14.60%	-25.09%	-22.73%	-19.66%	-18.23%	-14.77%	n.D.	n.D.	n.D.	n.D.
30	0.02%	-14.82%	-25.64%	-27.63%	-24.65%	-23.40%	-19.85%	n.D.	n.D.	n.D.	n.D.
15	-10.52%	-15.93%	-24.94%	-25.97%	-27.23%	-24.78%	-24.81%	n.D.	n.D.	n.D.	n.D.
5	-22.34%	-19.78%	-25.65%	-31.82%	-29.12%	-29.36%	-27.69%	n.D.	n.D.	n.D.	n.D.

WLTP area

Values in %

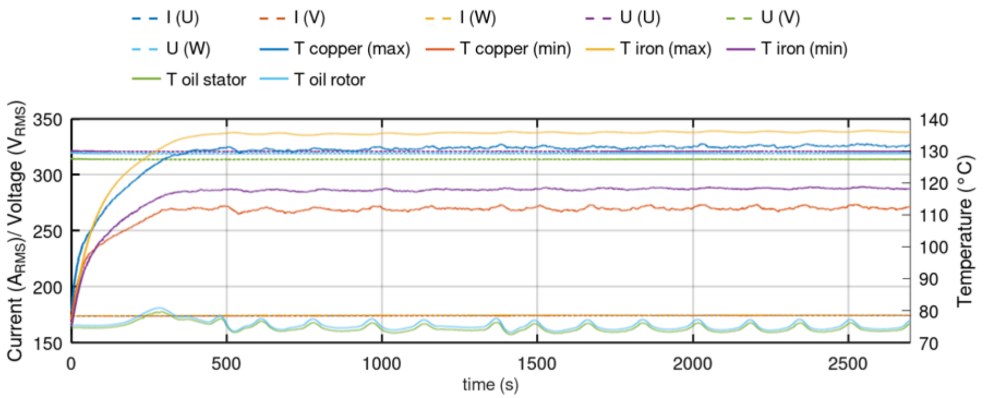
*n.D. no measurement Data

Minus (green) indicates that 3L operated motor has less losses

Measurement results – Internal motor

Continuous power analysis

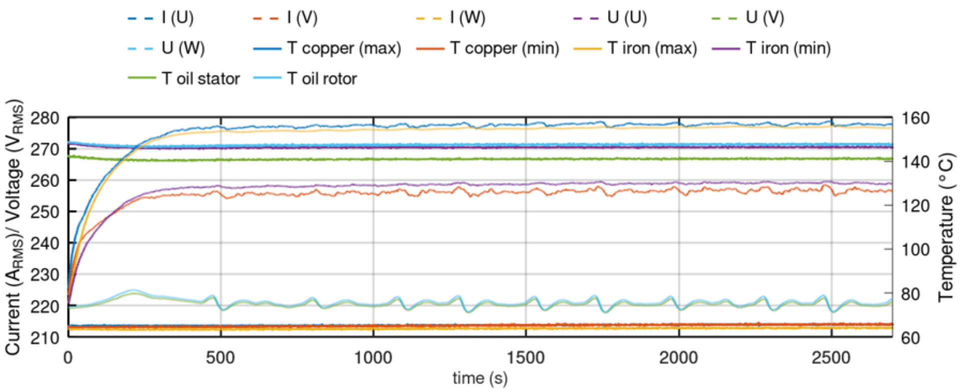
2L OPERATION



Torque $_{mean}$: 190.28 Nm
Speed $_{mean}$: 5240.93 1/min
Power(mech) $_{mean}$: 104.61 kW
Current(Total,AC) $_{mean}$: 174.23 A_{RMS}
Voltage(Total, AC) $_{mean}$: 317.89 V_{RMS}
Power (Total, AC) $_{mean}$: 109.35 kW_{RMS}
φ(Total, AC) $_{mean}$: 48.84 °
Current(Harm1,AC) $_{mean}$: 174.01 A_{RMS}
Voltage(Harm1, AC) $_{mean}$: 235.85 V_{RMS}
Power (Harm1, AC) $_{mean}$: 108.69 kW_{RMS}
φ(Harm1, AC) $_{mean}$: 27.84 °

η(Mot) $_{mean}$: 95.67 %
η(Inv) $_{mean}$: 97.69 %
η(Total) $_{mean}$: 93.46 %
I-THD $_{mean}$: 4.86 %
U-THD $_{mean}$: 60.68 %
P-THD $_{mean}$: 0.48 %
MRAML $_{mean}$: 4081.18 W
IRAML $_{mean}$: 656.78 W
Oil-Feed-Temperature $_{mean}$: 75.09 °C
Copper-Temp $_{max}$: 132.28 °C
Iron-Temp $_{max}$: 136.37 °C

3L OPERATION

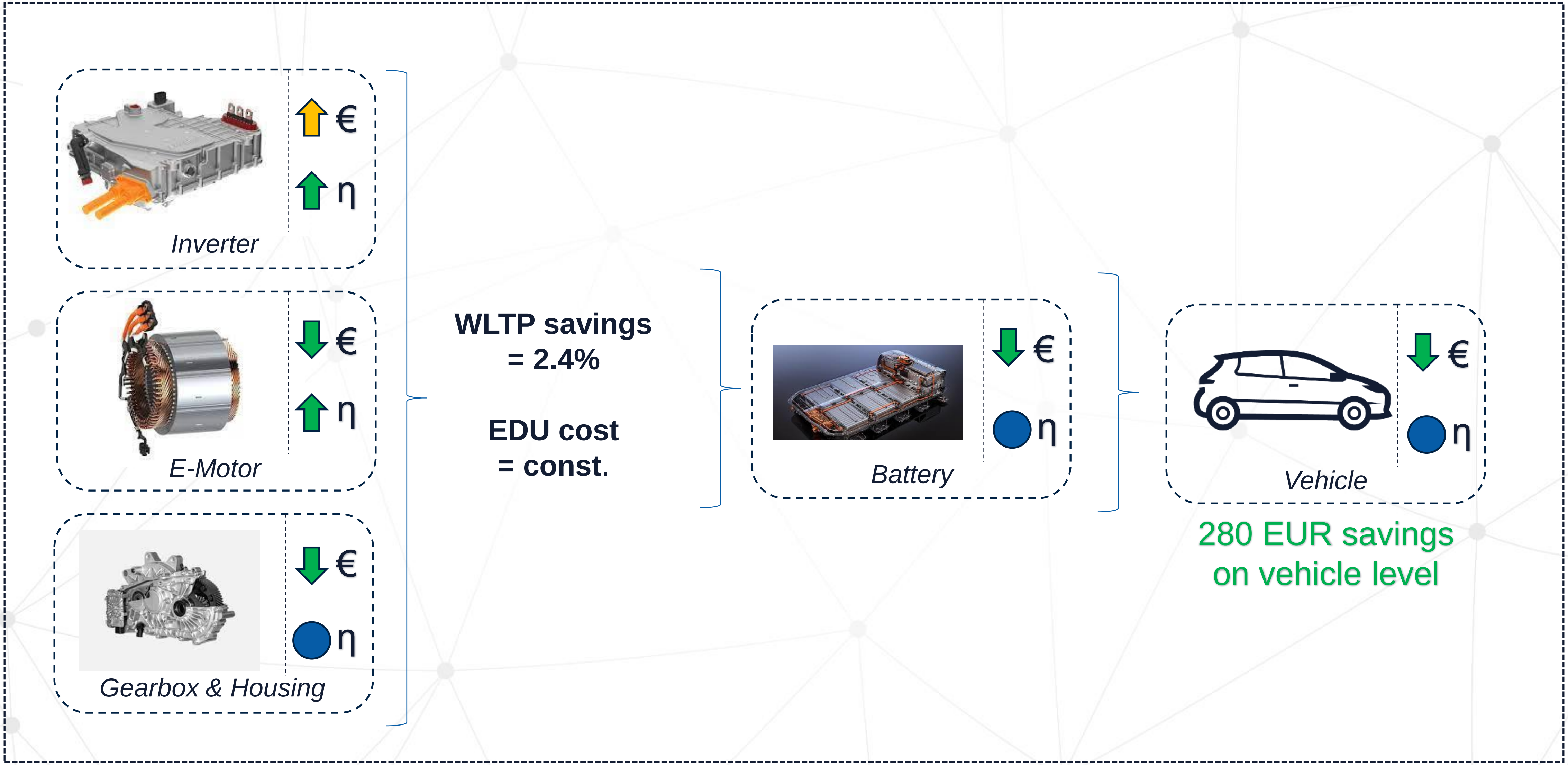


Torque $_{mean}$: 232.78 Nm
Speed $_{mean}$: 5240.86 1/min
Power(mech) $_{mean}$: 127.98 kW
Current(Total,AC) $_{mean}$: 213.30 A_{RMS}
Voltage(Total, AC) $_{mean}$: 269.38 V_{RMS}
Power (Total, AC) $_{mean}$: 134.45 kW_{RMS}
φ(Total, AC) $_{mean}$: 38.74 °
Current(Harm1,AC) $_{mean}$: 212.94 A_{RMS}
Voltage(Harm1, AC) $_{mean}$: 249.11 V_{RMS}
Power (Harm1, AC) $_{mean}$: 134.04 kW_{RMS}
φ(Harm1, AC) $_{mean}$: 32.44 °

η(Mot) $_{mean}$: 95.18 %
η(Inv) $_{mean}$: 97.90 %
η(Total) $_{mean}$: 93.19 %
I-THD $_{mean}$: 5.69 %
U-THD $_{mean}$: 38.00 %
P-THD $_{mean}$: 0.31 %
MRAML $_{mean}$: 6060.57 W
IRAML $_{mean}$: 417.80 W
Oil-Feed-Temperature $_{mean}$: 75.37 °C
Copper-Temp $_{max}$: 158.19 °C
Iron-Temp $_{max}$: 156.03 °C

MORE THAN 20% CONTINUOUS POWER !

3L system cost impact



Assumptions: SUV, 350kW peak power, 100kWh battery

Evolution of our 3-Level technology

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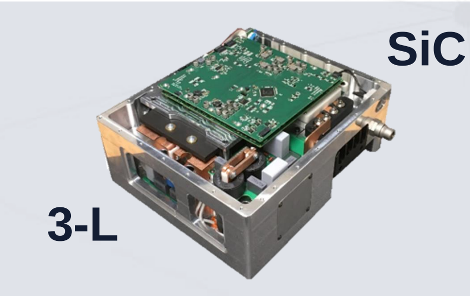
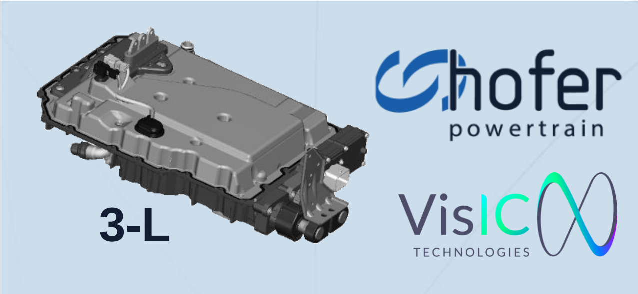




5 years ago

- Basic investigations of 3-level topologies
- Topology comparisons
- Lab demonstrator

4 years ago

- A-sample based on NPC IGBT topology
- Design of modulation strategies
- Shown very positive impact on WLTP

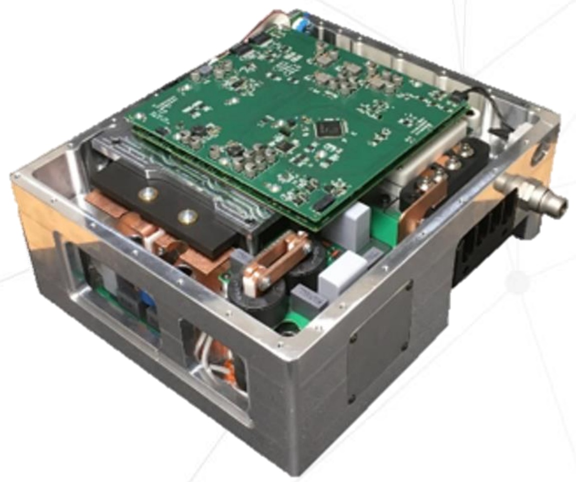
3 years ago

- A-sample based on NPC SIC topology
- Benchmark towards todays 2-L-SIC mainstream

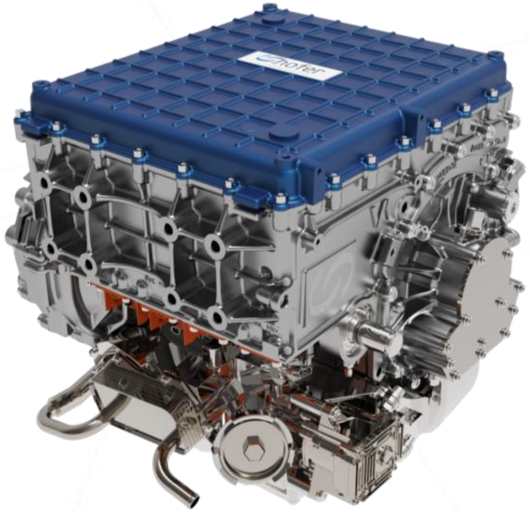
TODAY

- Strategic collaboration with GaN supplier VisIC
- Development of the A-sample for 3-L-GaN 800V Inverter
- Design of 3-level GaN power module

3L NPC A1-sample



Standalone Inverter



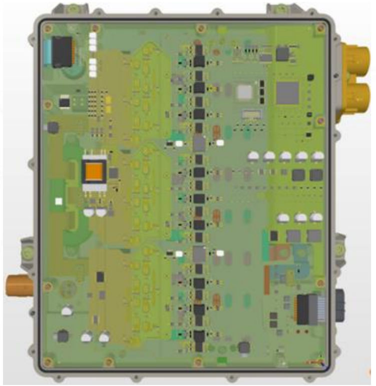
3in1 EDU

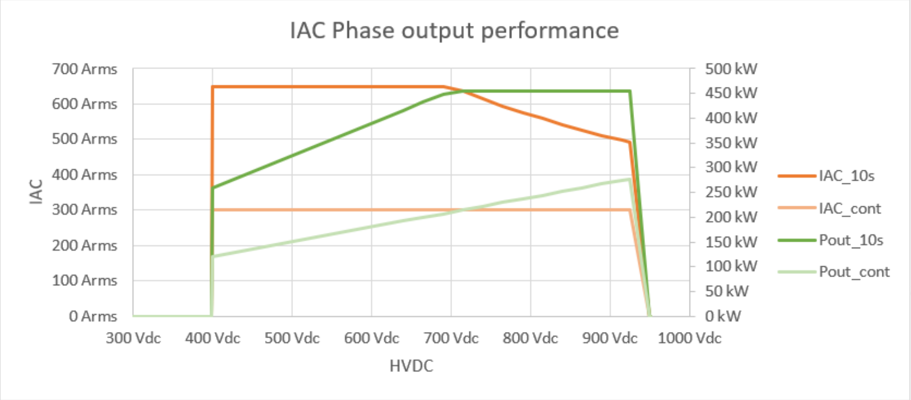
3x Power-Module
Starpower 750V NPC IGBT (custom made)

Product readiness

A1-SAMPLE	
No. of Phases	3
Peak Performance (10s)	360 Arms, 260 kW @ 800V
Continuous Performance ($I_{AC,rms,cont}$ @ 75°C @ 8l/min)	230 Arms, 165 kW @ 800 V
Liquid Cooling (water/glycol; 50/50)	-40 °C…65 °C -10 °C…55 °C @ 8 l/min without current derating
PWM Frequency	10 kHz* *except hillhold
LV123 Voltage class	HV_3 or higher
Power Module	3L NPC (IGBT) Starpower
Enclosure	closed
Active short circuit (ASC) function	Not implemented
Motor operation	ASM and PSM

3L TNPC A1-sample requirements



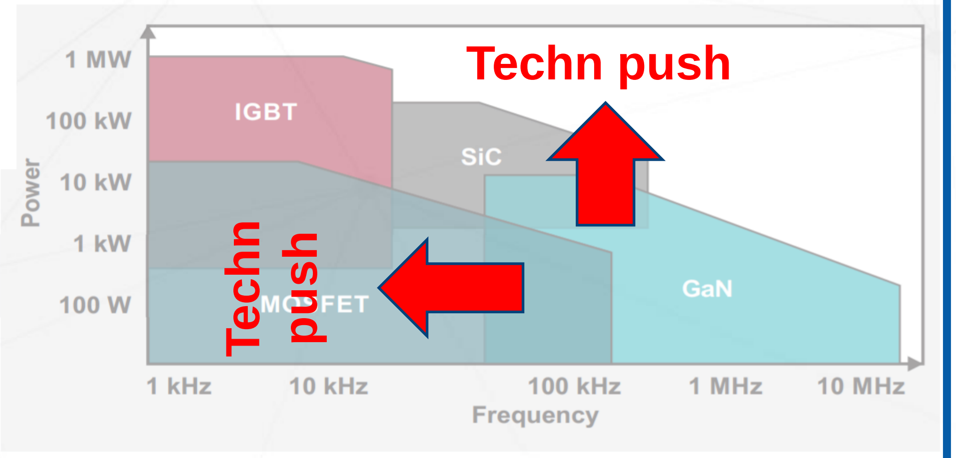


A1-sample	
Parameter	**Value**
HV DC voltage	450 V … 925 V
Peak current (10 sec)	650 Arms, 470 kW (600 Arms A-sample)
Cont. current	300 Arms, 220 kW (280 Arms A-sample)
E-Machine sensor	Incremental (ASM) Resolver (PSM)
Functional safety	ASIL-D prepared
Cyber-security	Not included
EMC	CIPRS25, Class 3
housing	Milled stand-alone packaging
ASPICE	CL1
µC	Infineon Aurix TC2xx, later change to TC3xx possible
E-machine interface	ASM, PSM and EESM

Under development

GaN- Gallium Nitride

SEMICONDUCTOR LANDSCAPE & GaN CHARACTERIZATION



MATURITY:

Very fast switching is challenging for power stage design

PERFORMANCE JUDGEMENT:

- Switching losses << SiC
- Conductive losses > SiC

COST PERFORMANCE:

Estimation for > 2027 material costs up to 2x lower than SiC

CONCLUSION

- Performance will be comparable to SiC at **reduced costs** of the power chips **up to factor 2**
- GaN technology is expected to be ready for automotive serial production around **2027**
- Currently GaN based 800V inverters **are only possible** with **multi-level** inverters

Roadmap for 3L-GaN

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2022	2023						2024	
	Jan Feb	March April	May June	July Aug	Sept Okt	Nov Dec	Jan Feb	March April

M1

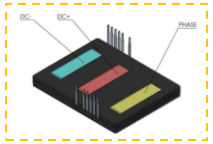
A0-sample (MVP) ready

In progress

A 1– sample (800V / 360A)

M2

Running on testbench with **own** POW-Modules



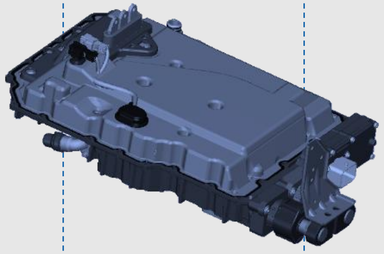
In progress

POW module kick-off

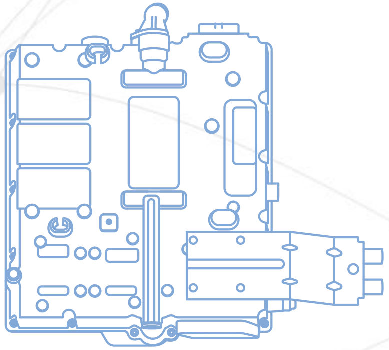
VisIC power module development (800V / 500A)

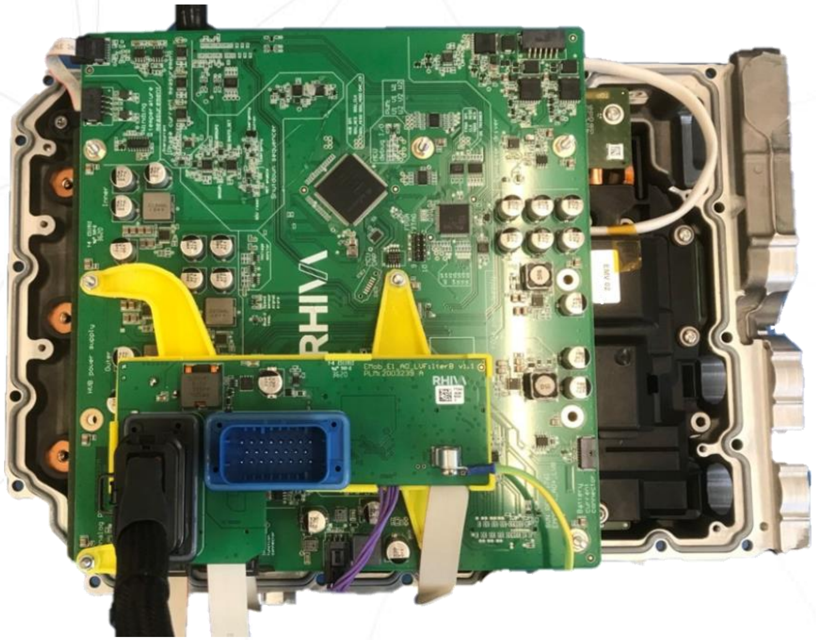
VisIC TECHNOLOGIES

3L



GaN NPC A0-sample





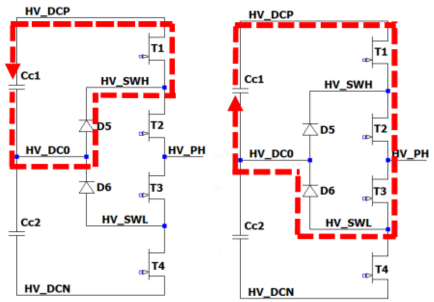
3x PCB based
Power-Module
VisIC V08TC65S2A

Product readiness

A0 SAMPLE	
No. of Phases	3
Peak Performance (10s)	100 Arms @ 800V
Continuous Performance ($I_{AC,rms,cont}$ @ 25°C @ 8l/min)	70 Arms @ 800V
Liquid Cooling (water/glycol; 50/50)	25 °C @ 8 l/min without current derating
PWM Frequency	10 kHz
LV123 Voltage class	HV_3 or higher
GaN power Module	Discrete VisIC V08 device
Enclosure	open
Active short circuit (ASC) function	Not implemented
Dimensions	Based on HED3.0 platform with minor adaptions
Motor operation	Induction Motor

GaN NPC A1-sample requirements

- **Electrical performance optimisation**
  - Stray inductance of power module & DC-Link cap.

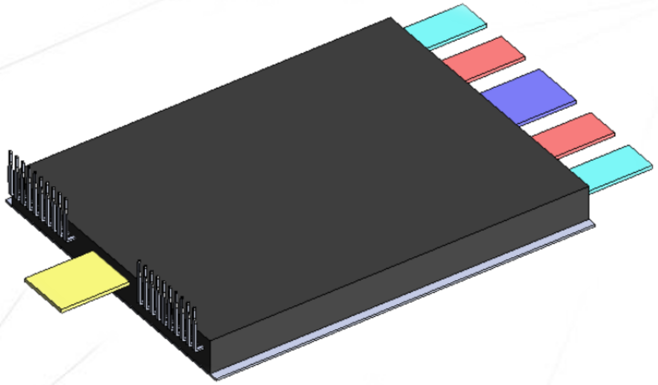


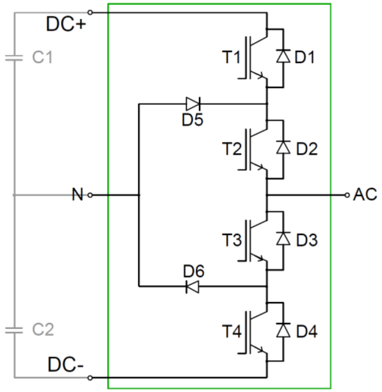
- **Testing**
  - Welcome test: **T**aking **I**nto **O**peration (TIO)
  - Switching characterisation with **M**ulti-**P**ulse **T**est (MPT)
  - Open loop (U/f) continuous operation (UPF)
    - Thermal characterisation
  - Test bench operation with ASM
    - Efficiency
    - WLTP
    - Benchmark (3L IGBT NPC vs 3L SiC NPC vs 3L GaN NPC)

Under development

A1-SAMPLE	
No. of Phases	3
Peak Performance (10s)	360 Arms @ 800 V
Continuous Performance ($I_{AC,rms,cont}$ @ 25°C @ 8l/min)	230 Arms @ 800 V
Liquid Cooling (water/glycol; 50/50)	-40 °C…65 °C -10 °C…55 °C @ 8 l/min without current derating
PWM Frequency	10 kHz
LV123 Voltage class	HV_3 or higher
GaN power Module	Discrete VisIC V08 device
Enclosure	open
Active short circuit (ASC) function	implemented
Dimensions	tbd
Motor operation	Induction Motor

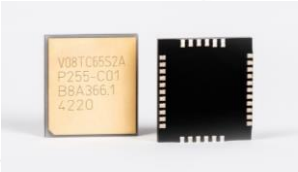
VisIC GaN 800V 3L NPC Power Module





NPC schematic

3x Power-Module
VisIC D3GaN
V08TC65S2A



A1-SAMPLE	
No. of Phases	3
Peak Performance (30s)	500 Arms @ 500-850 V; max. 10 kHz, 65°C, 8 l/min
Continuous Performance ($I_{AC,rms,cont}$ @ 65°C @ 8 l/min)	300 A_{rms} @ 500-850V, 65°C, 8 l/min
Liquid Cooling (water/glycol; 50/50)	-40°C…65°C -10°C…55°C @ 8 l/min without current derating
Ambient Temperature	-40°C…85°C -10°C…65°C without derating
PWM Frequency	10-20 kHz
Electrical Peak Power @ ($I_{AC,rms,peak}$; cos(ϕ)=0.85; m=1)	350 kW @ 800 V 10 s, max. 10 kHz, cos(φ)=0.85, m=1, 65°C, 8 l/min

Under development

Summary 3-Level topology

Status

- hofer already have over 5 years experience in developing 3L inverters for automotive and are actively supporting a number of European OEMs to accelerate their adoption of the technology
- In our continuing development of this technology we are actively looking for partners who are interested in the advantages that it can bring to their systems

Efficiency

- E-Motor losses can be reduced by up to 32 %
- Within WLTP Energy consumption of the E-Motor is reduced by 20 %
- WLTP range extension is at 2.4% !
- Continuous power of the motor can be increased by up to 20 %

Cost

- 3L technology offers increased system efficiency at reduced system cost in addition to EMC, NVH and isolation benefits
- Cost to efficiency benefits become particularly prevelant when 3L is used as an enabler for GaN in 800V systems

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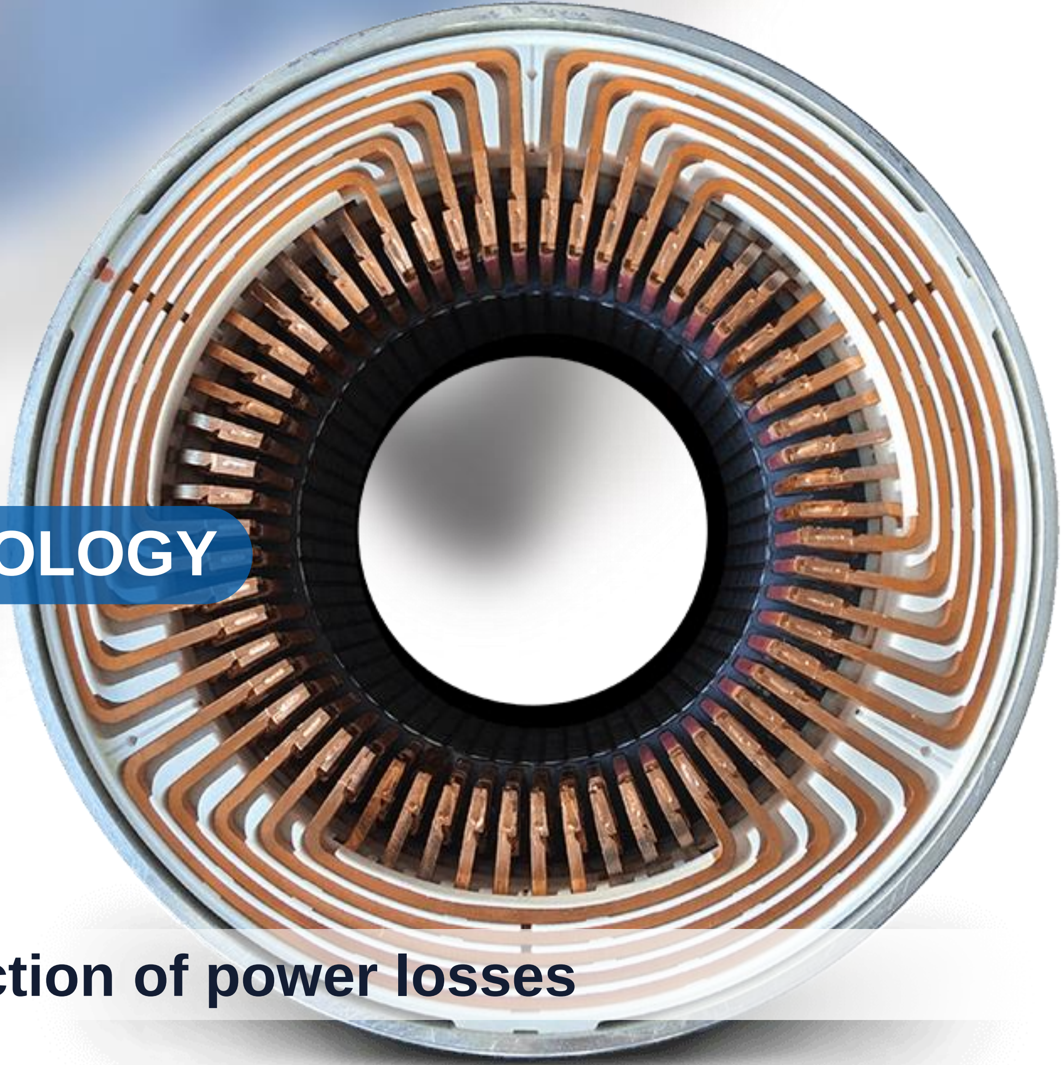
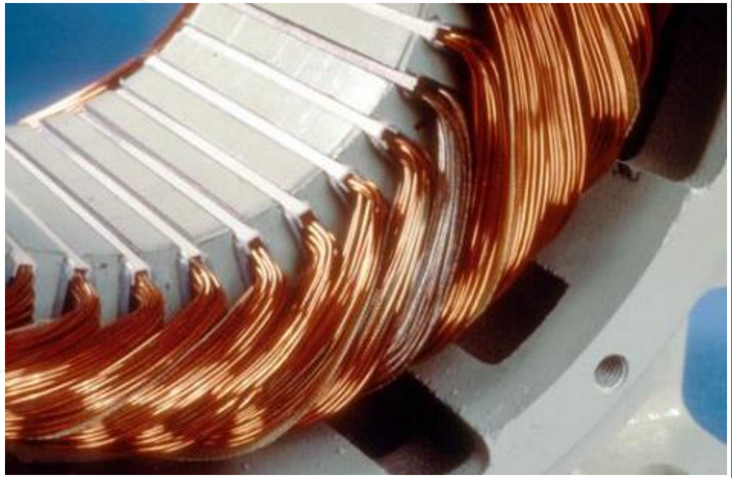
FORM LITZ WIRE WINDING TECHNOLOGY

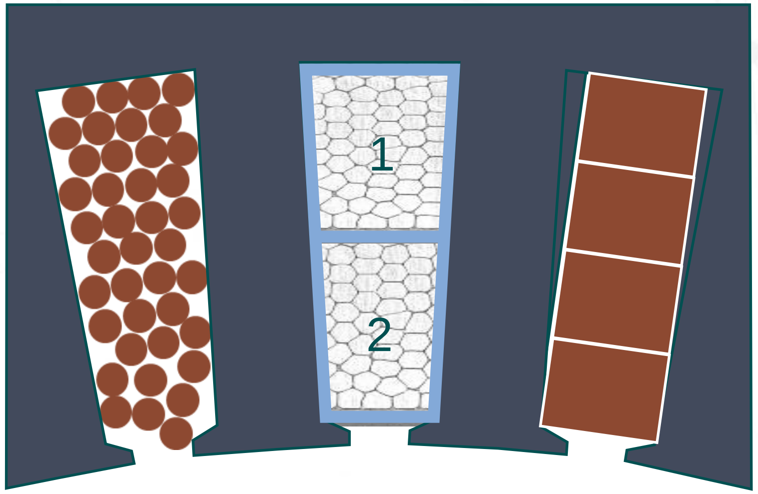


Increase of power density and reduction of power losses

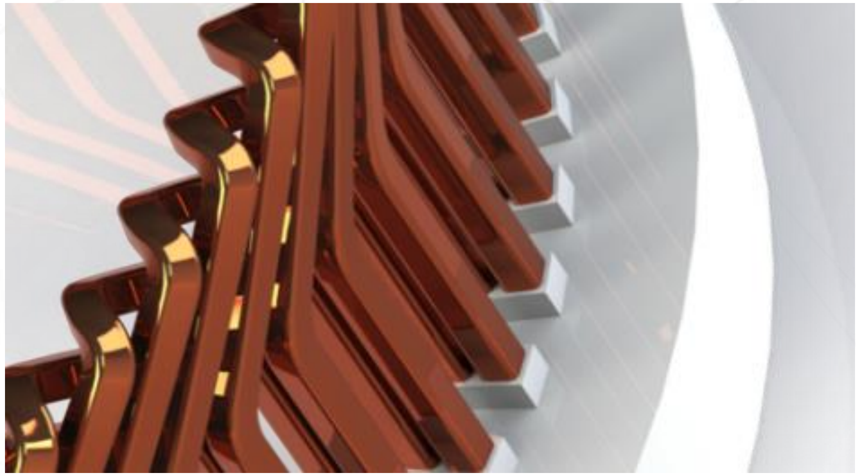
Form Litz Wire Winding (FLW) vs. Hairpin vs. Pull in



PULL IN WINDING (PIW)



FLW – FORM LITZ WIRE



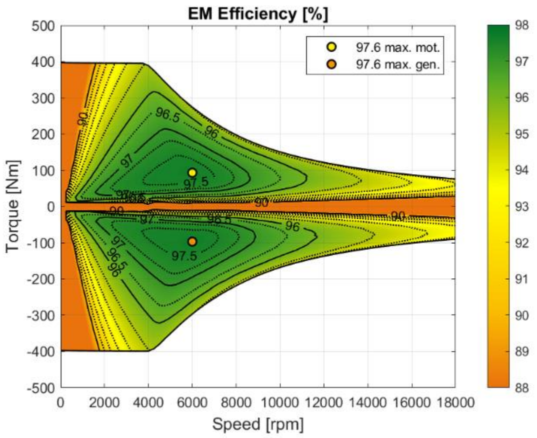
HAIRPIN WINDING

- Copper density of hairpin
- Cross section of pull in
- Heat transfer better than pull in / hairpin
- High frequency performance of pull in
- Results in maximized current density

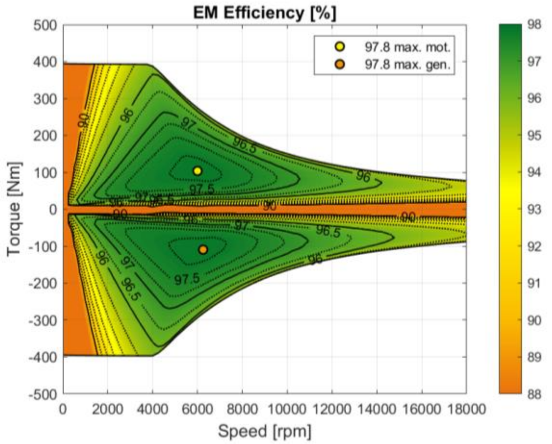
PSM Benchmark: FLW ↔ Hairpin

Efficiency comparison:

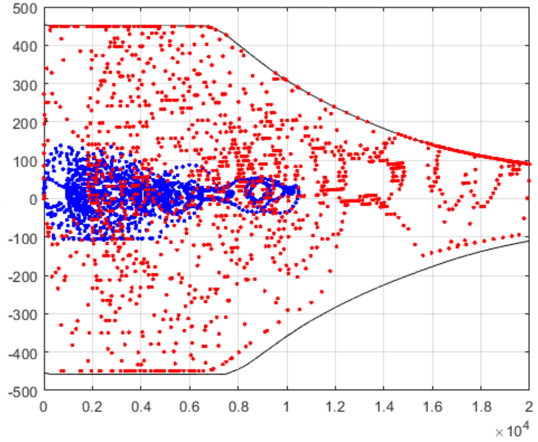
PSM: 8 Layer Hairpin:

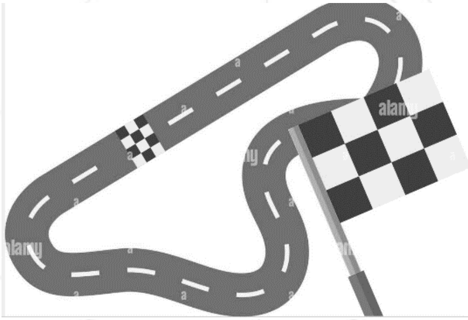


PSM: Form Litz Wire



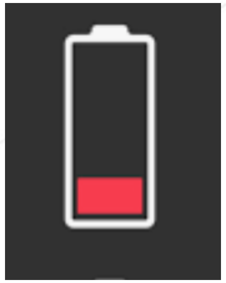
WLTP scaled (red) vs. orig. WLTP(blue)





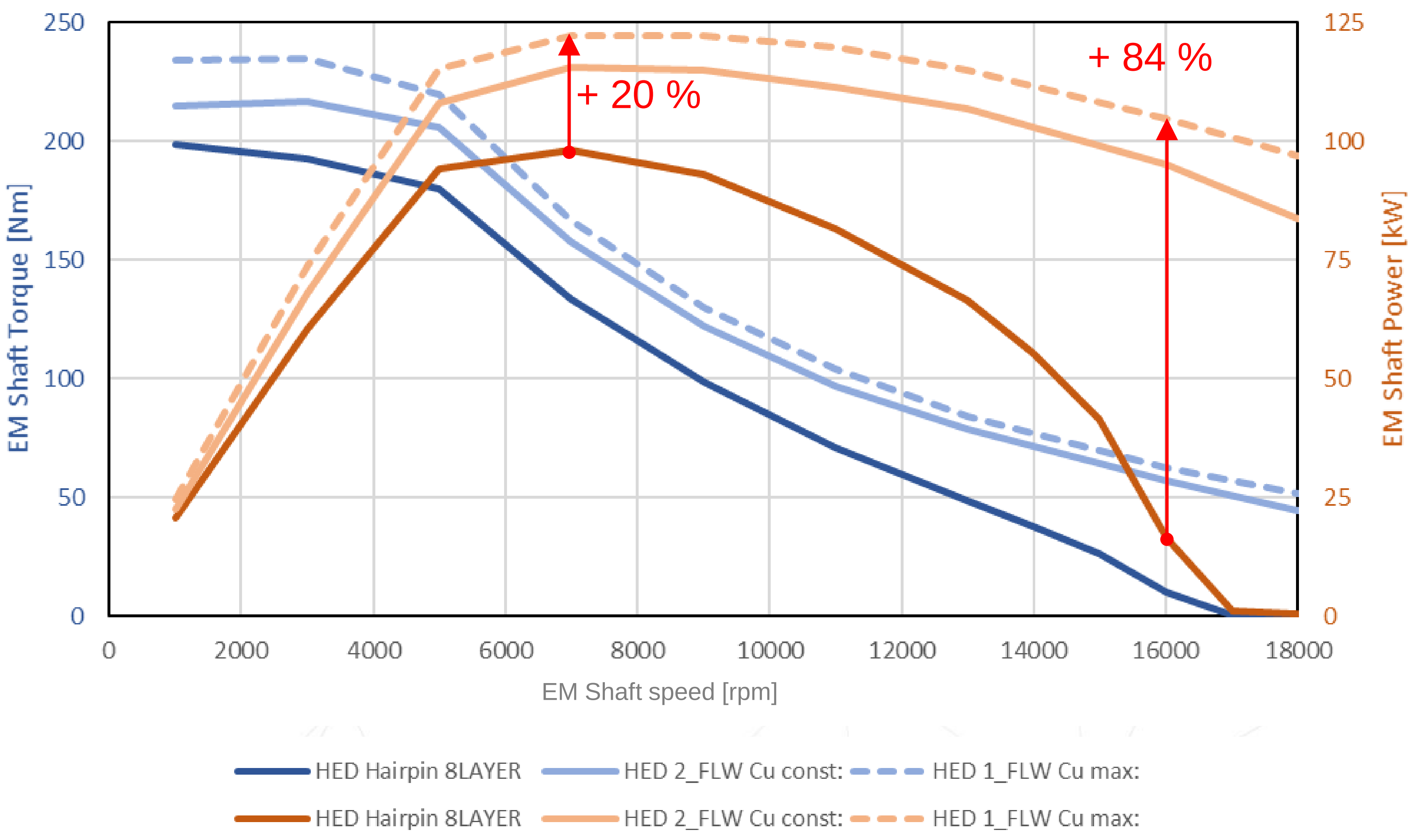
WLTP cycle was scaled to max. speed and torque. «WLTP cycle on the race track»

	PSM HAIRPIN	PSM FLW	Delta per cycle	Delta at 90 kWh Battery	Range increase
Consumed energy	14.67 kWh	14.38 kWh	0.29 kWh	1.82 kWh	2 %
Loss energy	1.69 kWh	1.40 kWh			



PSM Benchmark: FLW ↔ Hairpin

PERFORMANCE: CONTINUOUS TORQUE AND POWER



Summary – Form litz winding

POWER DENSITY	▪ Form litz winding has potential to higher power-density for IM & PSM of more than 20%
INDUSTRIALIZATION	▪ Form litz winding has potential to reduce material costs by up to 20% ▪ Industrialization has been constantly improved during the development phases ▪ Same machinery and tools can now be used as for Hairpin technology

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