Electrical Drive System Technology for Next-Generation Electric Vehicles

Nisai H. Fuengwarodsakul

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Outlines

Electrical drives system in electric vehicles

- System overview
- Comparison to ICE

Technology status & further development

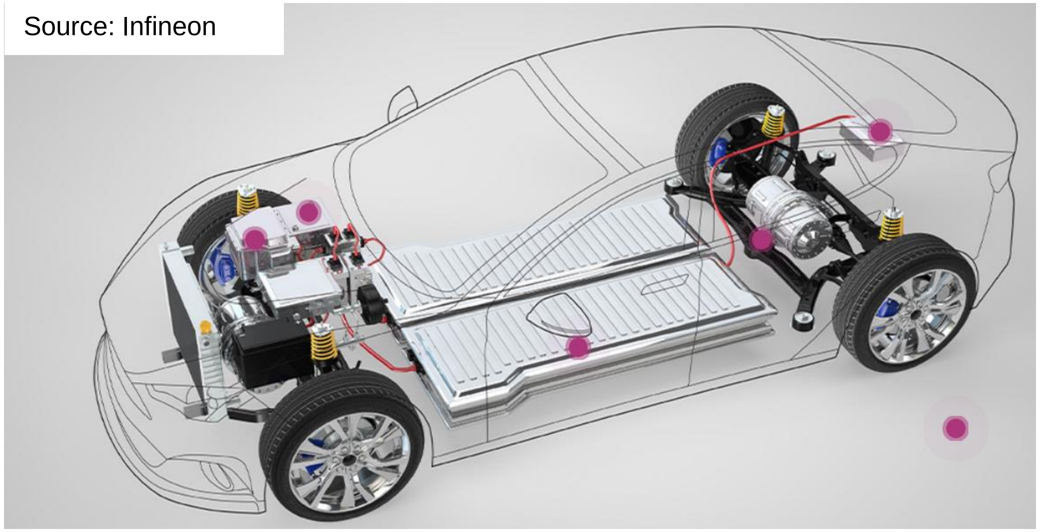
- Electrical machine types
- Integration aspects
- Modern R&D cycle of electrical drive
- Alternative & new design concept
- Trend of new materials

Electrical drives system in electric vehicles

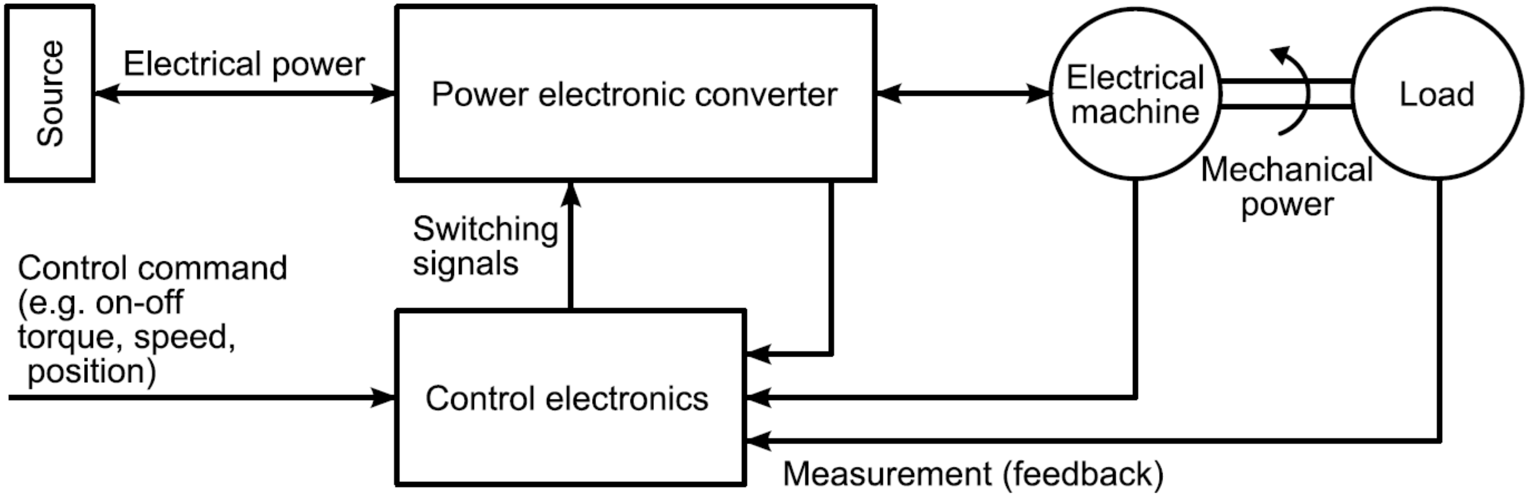
Electrical Drive System for Electric Vehicle

System which converts electrical power into mechanical power and is able to control the mechanical motion.

- **Battery, power electronics converter, electrical machines & control electronics**

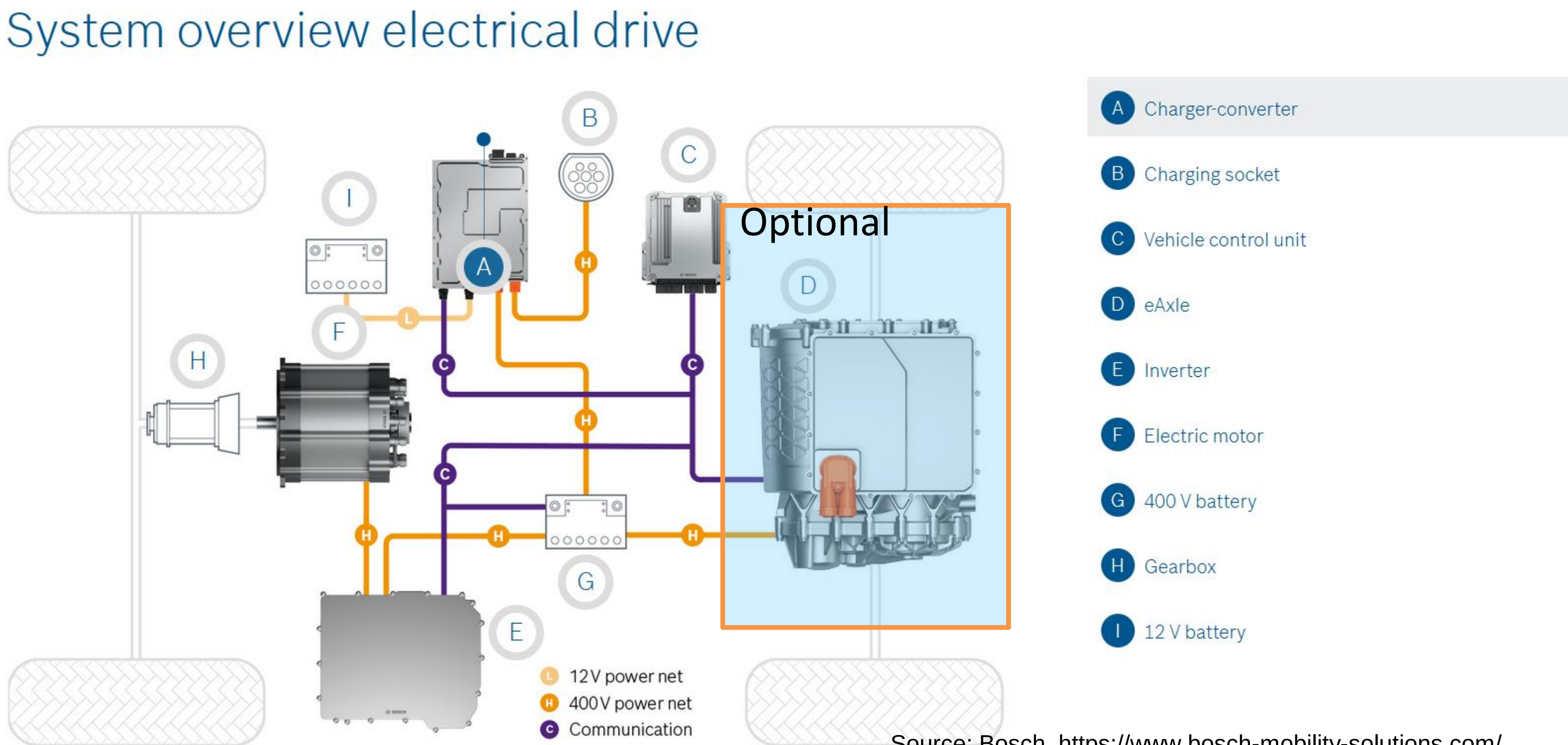


Source: Infineon



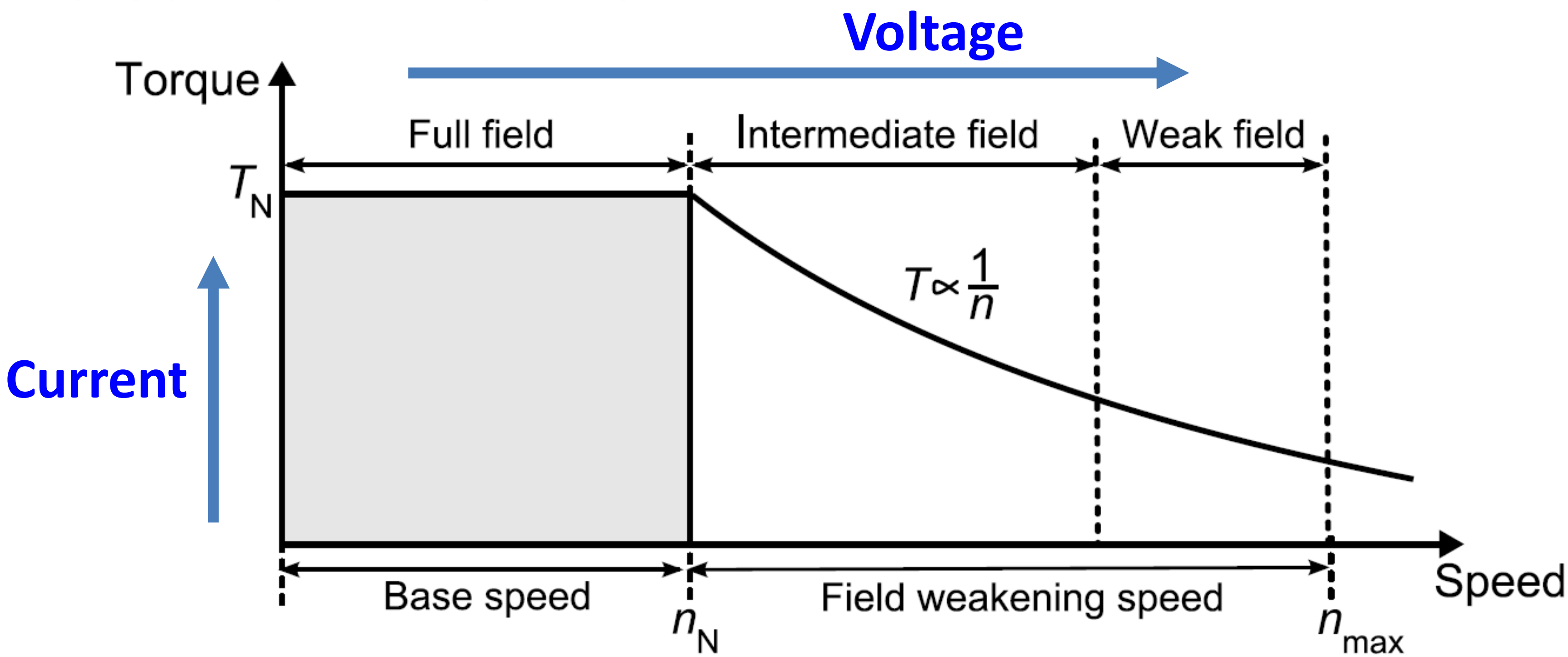
System overview

- 12 V system is still used for lighting and other components (charged by a dc-dc converter)



Source: Bosch, https://www.bosch-mobility-solutions.com/

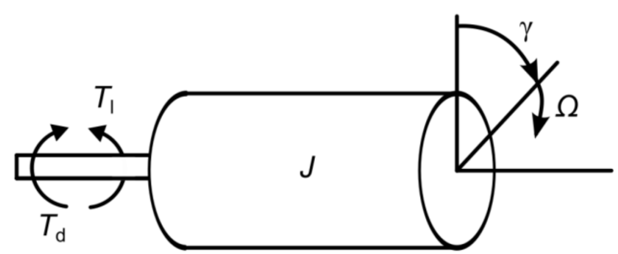
Generic torque-speed characteristic for electrical machine



Power = Torque x Speed

Torque $\propto$ Radius^2

Torque $\propto$ Length



Advantages of electric drive vs ICE in torque-speed curve

Operation from stand still

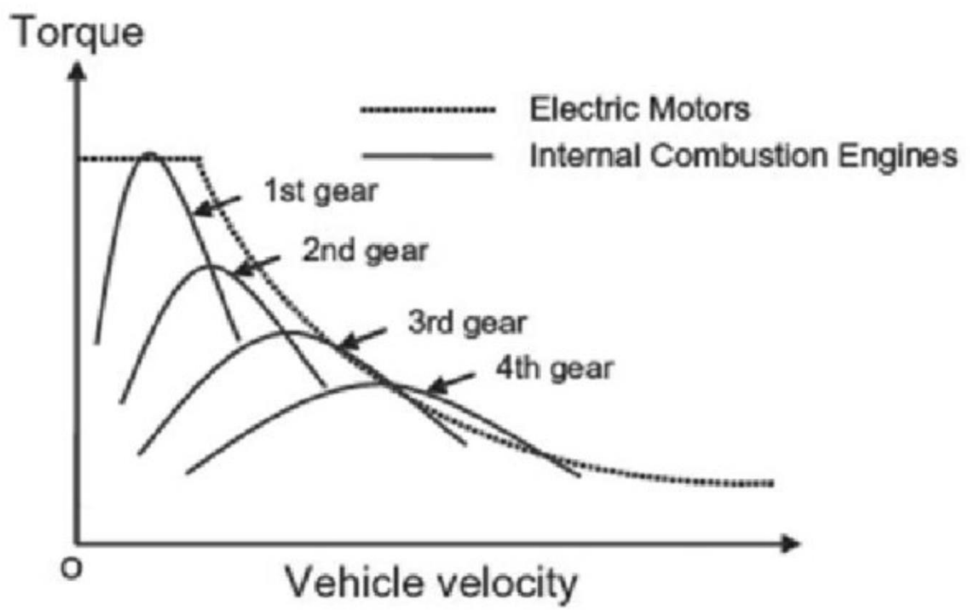
Higher dynamic

More quiet

No emission

Torque Overloading capability

Possibility for renewable energy



Source: R. Zhang, Novel electronic braking system design for EVS…, DOI: 10.1007/s12239-017-0070-0

Efficiency Plug-to-Wheel

- Battery EV Overall 60-80%

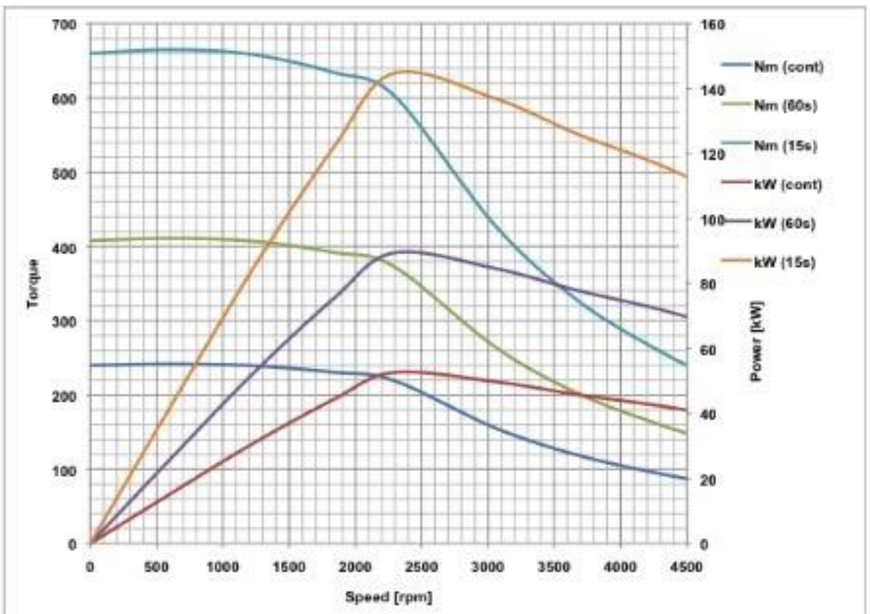
Efficiency Well-to-Wheel

- Battery EV 20-40%
- ICE x-25%

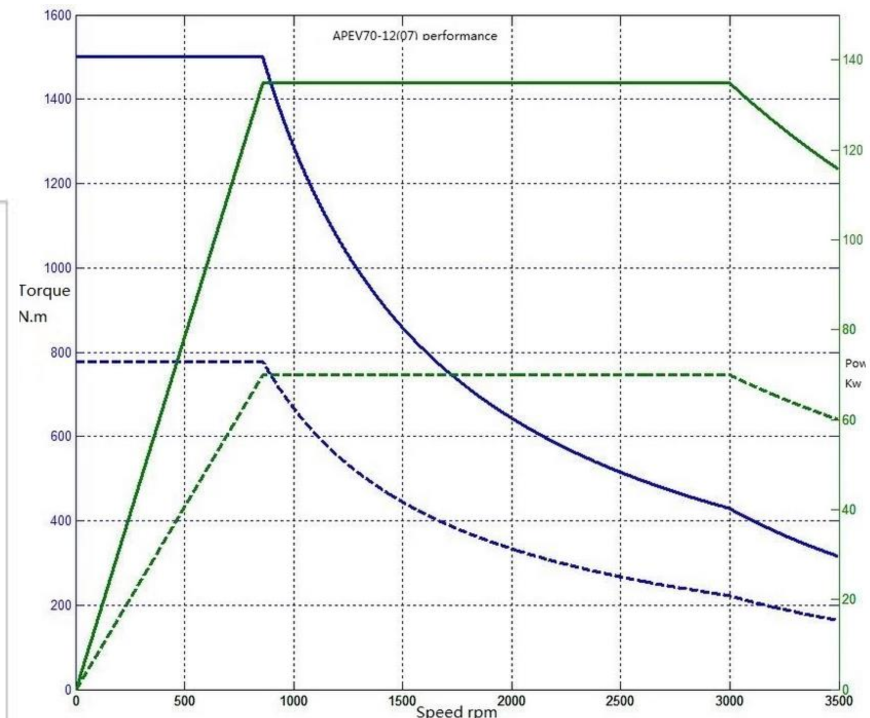
Overloading capability

Performance Prediction 4 Turn:

N_t	4		(Number of Turns)	
Vs_DC	391	V		
S / P	1		(1 for parallel, 2 for series)	
I_nom	300	A		
I_max	380	A		



Practical

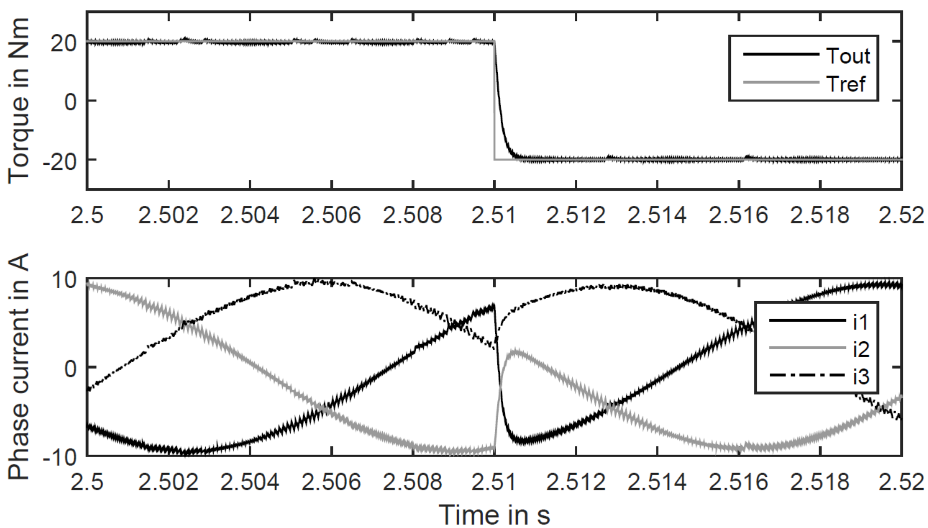


Ideal

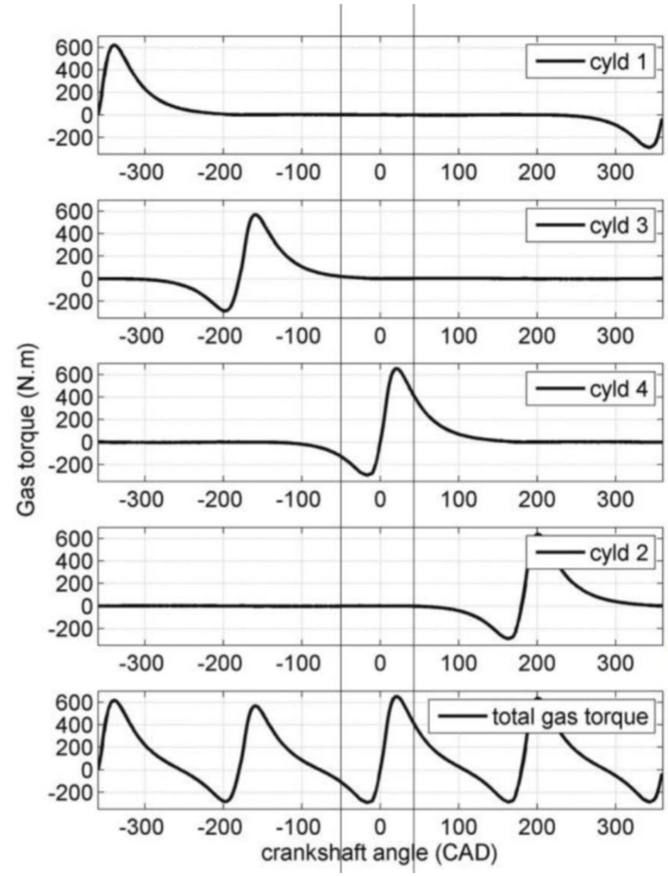
Torque dynamics and ripples: electric drive vs ICE

Extremely fast torque dynamic (time constant of few ms)

Very low ripples



Source: N.H. Fuengwarodsakul, Text book Electrical Drive System Ed.2, 2020.



Source: F. Liu, An Experimental Study on Engine Dynamics Model Based In-Cylinder Pressure Estimation, SAE International

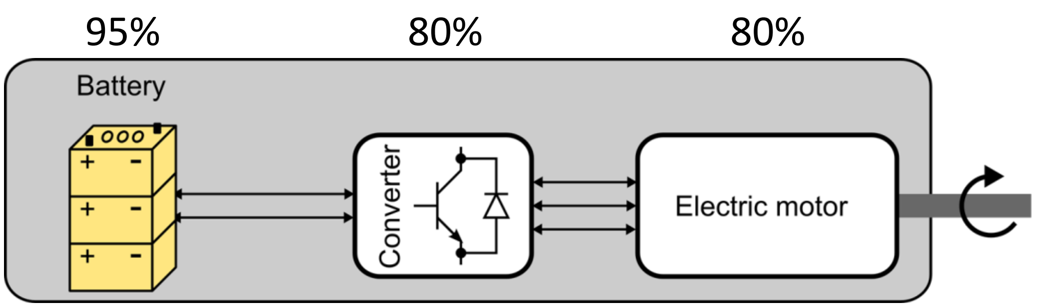
Regenerative braking

- A car with 1000kg at 70kmh has kinetic energy of 189kJ or 52 Wh.
- Energy consumption per km 150-300Wh.
- Not all energy can be regenerated, the electric braking is activated depending on driving control algorithm, in general, not down to standstill.
- Regenerative in the form of engine braking.
- Efficiency of regenerative braking is varies from 20-60% approx.
- In certain case, the regenerative braking is omitted.

$$E = \frac{1}{2} m v^2$$

$$= \frac{1}{2} 1000kg \ \left(\frac{70\text{x}1000 kmh}{3600}\right)^2$$

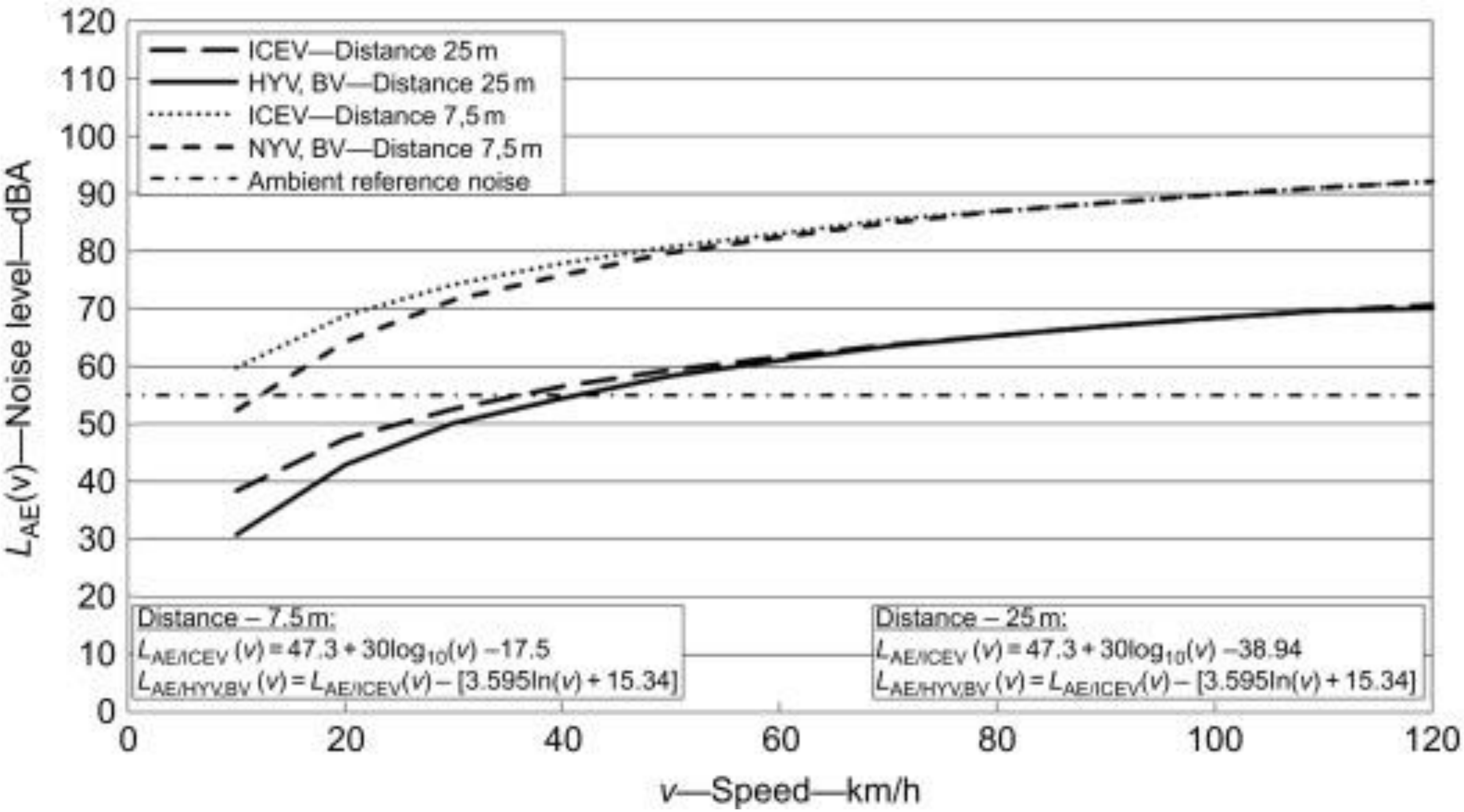
$$= 189\text{kJ} = 52\text{Wh}$$



$$\text{Aver. consumption} \frac{150\text{Wh}}{\text{km}} \text{ for passager car}$$

- Advantages: Energy saving and less wear for mechanical brakes

Acoustic noise of electric drives vs ICE

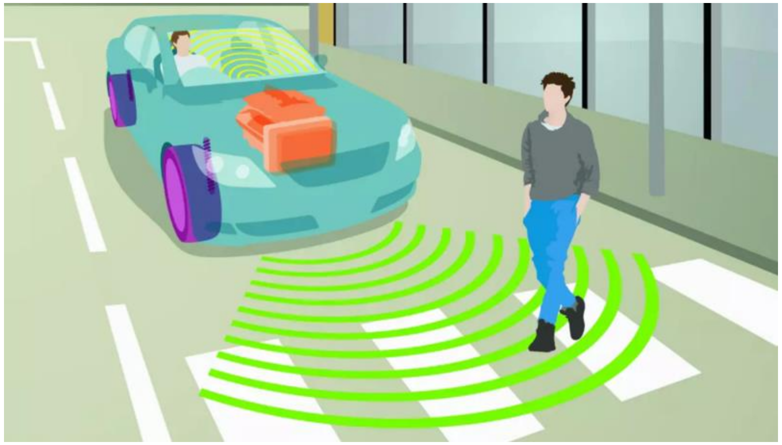


Source: D. Teodorović, M. Janić, Transportation, Environment, and Society in Transportation Engineering, 2017

Acoustic noise problematics in EVs

- Acoustic noise is mainly emitted from the propulsion system.
- Acoustic comfort for passenger is important.
- Pedestrian safety is also a major concern.
- Acoustic Vehicle Alerting System (AVAS)

"From July 1,2019 any electric vehicle with four or more wheels that wants to be approved for road use in the European Union is going to have to have an "Acoustic Vehicle Alert System," or AVAS, fitted, making a continuous noise of at least 56 decibels if the car's going 20 km/h (12 mph) or slower."



Source: https://newatlas.com/eu-ev-acoustic-noise-avas/60022/

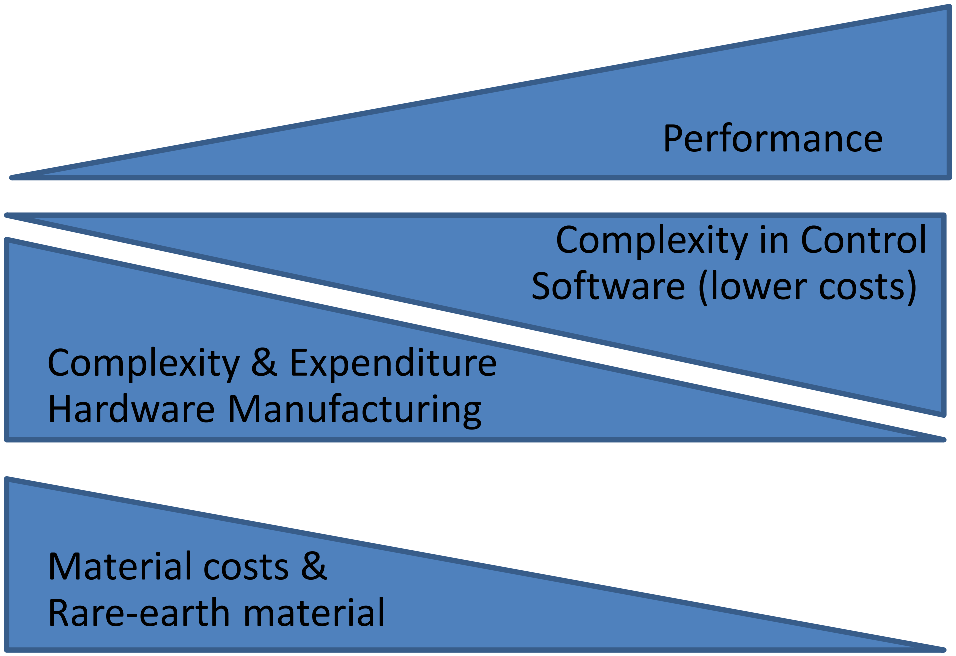
Technology status & further development

Electrical machine types

Electrical machine types and evolution

1. DC-Machine
2. Induction Machine
3. Permanent Magnet Synchronous Machine (Current mainstream)
4. Synchronous Reluctance Machine
5. Switched Reluctance Machine

Future advanced machine concept



Shifting of complexity from hardware to software can be observed from the evolution of electrical drive concept.

(More smartness in software)

Types of motors in electric car

Vehicle	Motor type	Specifics
BMW i3	Interior PM	Rare-earth
Chevrolet Volt	Interior PM	Ferrite/ Rare-earth
Hyunday Sonata	Surface PM	Rare-earth
Mitsubishi PHEV	Interior PM	Rare-earth
Nissan Leaf	Interior PM	Rare-earth
Porsche Panamera	Surface PM	Rare-earth
Tesla S	Induction motor	Copper cage
Toyota Prius	Interior PM	Rare-earth

EV models	EV motors
Fiat Panda Elettra	Series dc motor
Mazda Bongo	Shunt dc motor
Conceptor G-Van	Separately excited dc motor
Suzuki Senior Tricycle	PM dc motor
Fiat Seicento Elettra	Induction motor
Ford Th!nk City	Induction motor
GM EV1	Induction motor
Honda EV Plus	PM synchronous motor
Nissan Altra	PM synchronous motor
Toyota RAV4	PM synchronous motor
Chloride Lucas	Switched reluctance motor

Source: Marco Villani, High Performance Electrical Motors for Automotive Applications – Status and Future of Motors with Low Cost Permanent Magnets

Source: C. C. Chan, K. T. Chau, Modern Electric Vehicle Technology

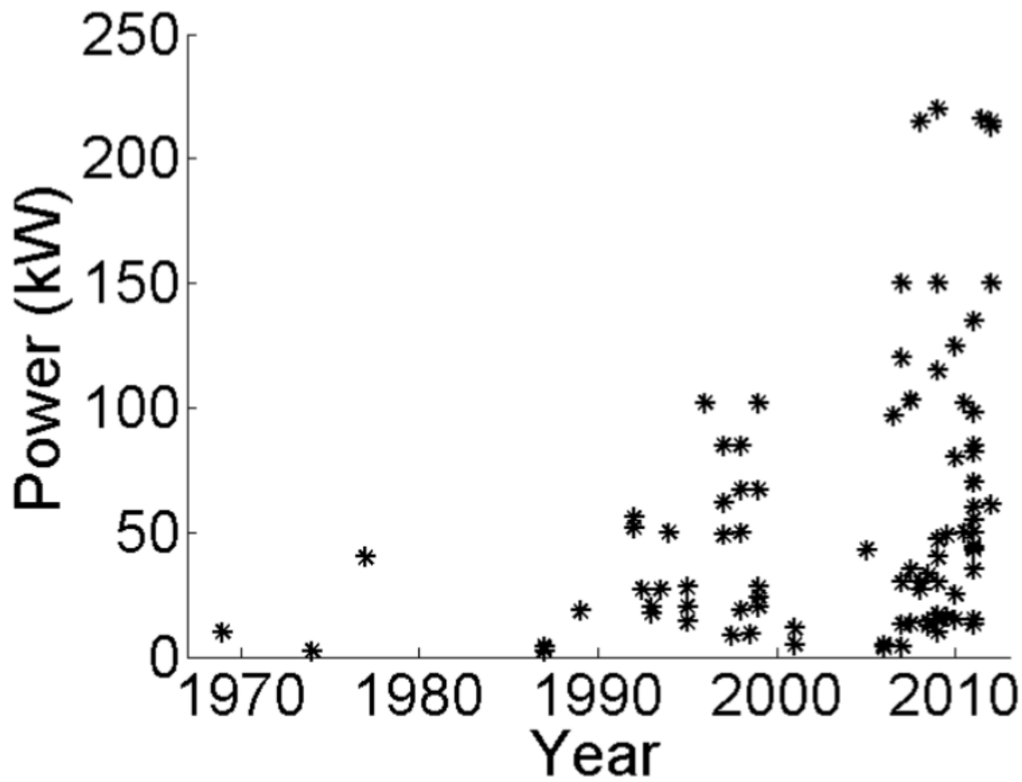
Types of motors in electric car (cont.)

Model	Battery type	Energy storage (kWh)	Nominal range (km)	Market release	Power (kW)	Motor type
Tesla Model S	Li	42	258	2012	215	IM
Tesla Model S	Li	65	370	2012	215	IM
Tesla Model S	Li	85	483	2012	215	IM
Lightning GT	Li	40	240	2012	150	PM
Hyundai BlueOn	Li	16,4	140	2012	61	PM
Honda Fit EV	Li		113	2012		IM
Toyota RAV4 EV	Li	30	160	2012		IM
Saab 9-3 ePower	Li	35,5	200	2011	135	
CODA Sedan	Li	34	193	2011	100	
Ford Focus Electric	Li	23	160	2011	100	IM
Skoda Octavia Green E Line	Li	26,5	140	2011	85	
Volvo C30 DRIVe Electric	Li	24	150	2011	82	
Renault Fluence Z.E.	Li	22	161	2011	70	SB
Renault ZOE	Li	22	160	2011	60	SB
Tata Indica Vista EV	Li	26,5	241	2011	55	PM
Ford Tourneo Connect EV	Li	21	160	2011	50	IM
Kangoo Express Z.E	Li	22	170	2011	44	SB
Fiat Doblò	Li	18	140	2011	43	IM
Peugeot iOn	Li	16	130	2011	35	PM
Renault Twizy	Li	7	100	2011	15	
REVA NXR	Pb	9,6	160	2011	13	IM
BYD F3M	Li	15	100	2010	125	PM
Nissan Leaf	Li	24	175	2010	80	PM
Ford Transit Connect EV	Li	28	129	2010	50	IM
Citroen C zero	Li	16	130	2010	49	PM
Gordon Murray T-27	Li	12	130	2010	25	
Wheego Whip LiFe	Li	30	161	2010	15	IM
Venturi Fétish	Li	54	340	2009	220	
Mini E	Li	35	195	2009	150	IM
BYD e6	Li	60	330	2009	115	PM
Mitsubishi i MiEV	Li	16	160	2009	47	PM
Subaru Stella EV	Li	9,2	80	2009	40	
Smart ED	Li	16,5	135	2009	30	PM
Citroën C1 ev'ie	Li	30	110	2009	30	IM

Source: de Santiago, J., Bernhoff, H., Ekergård, B., Eriksson, S., Ferhatovic, S. et al. (2012) "Electrical Motor Drivelines in Commercial All Electric Vehicles: a Review“, IEEE Transactions on Vehicular Technology
SB = Synchronous brushed

Driving power of electric cars

- ► Driving power by electric motor sufficiently covers all EV power requirements.

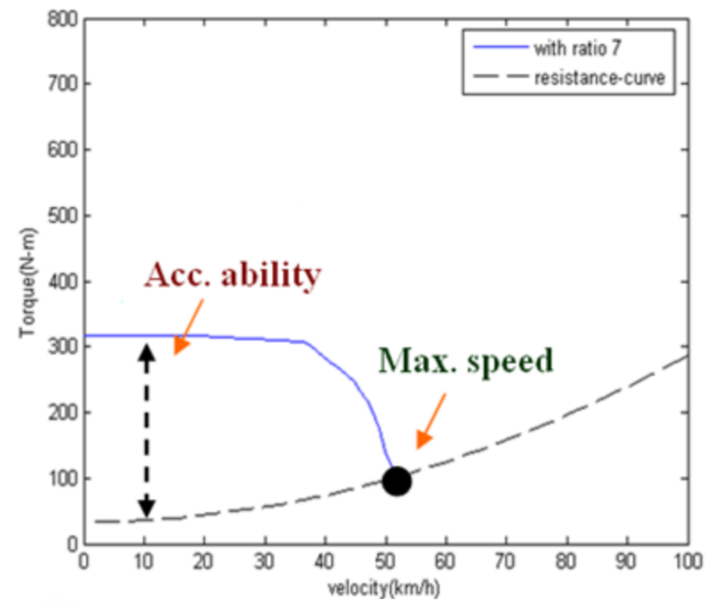


Source: de Santiago, J., Bernhoff, H., Ekergård, B., Eriksson, S., Ferhatovic, S. et al. (2012) "Electrical Motor Drivelines in Commercial All Electric Vehicles: a Review", IEEE Transactions on Vehicular Technology

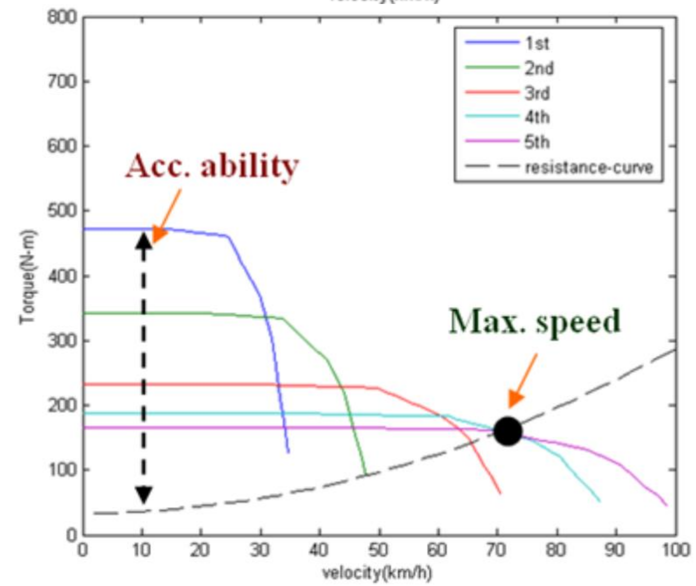
Integration aspects

Mechanical coupling

- Direct drive (rare)
- Multiple gear ratio (rare, old models)
- Fixed speed ratio transmission
- Freewheel gear (small vehicles)



- Hub motor or integrated wheel motor
  - Popular in small vehicles
  - Limited use in large vehicles due to large spring mass.



Source: CHANG CHIH-MING, SIAO JHENG-CIN, Performance Analysis of EV Powertrain system with/without transmission, EVS25

Multi-objective control of electrical drives in electric vehicles

Sophisticated control scheme for achieving different objectives.

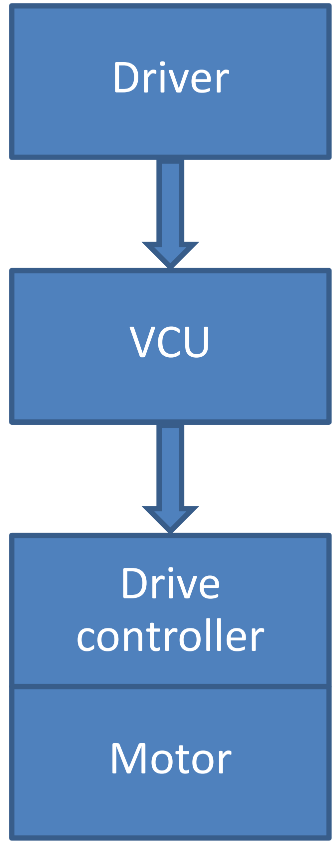
- Control accuracy
- Efficiency
- Dynamic response
- Acoustic noise & vibration

Example 1 : Electric vehicle drive

- Efficiency
- Dynamic response

Supervisory controller could optimize the drive behaviors by

Example of Electric Vehicles



User

Supervisory controller
- Fuzzy logics
- Predictive control
- Etc.

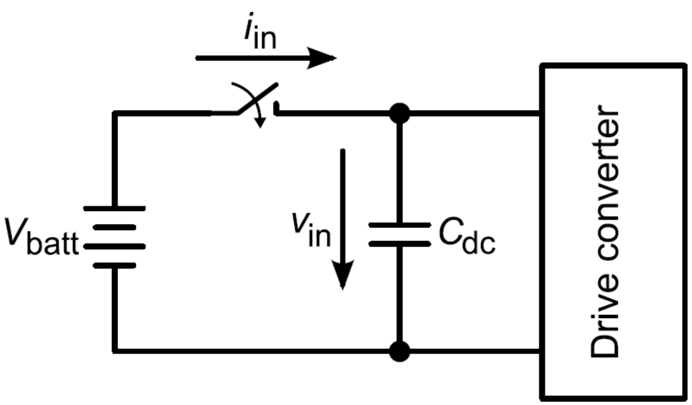
Drive controller
- Nonlinear control for nonlinear operating range
- Acoustic noise minimization

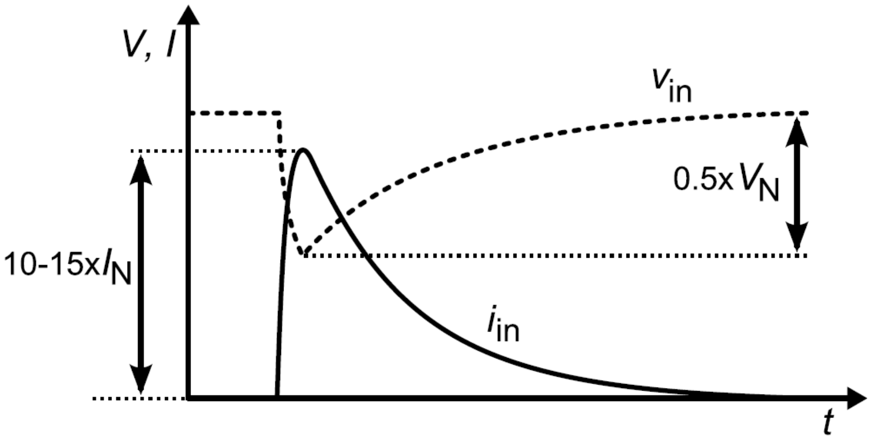
Inrush current of electrical drive converter

- Inrush current occurs during the initial connection between the battery and the drive converter for charging the input large DC-link capacitors.

Negative consequences:

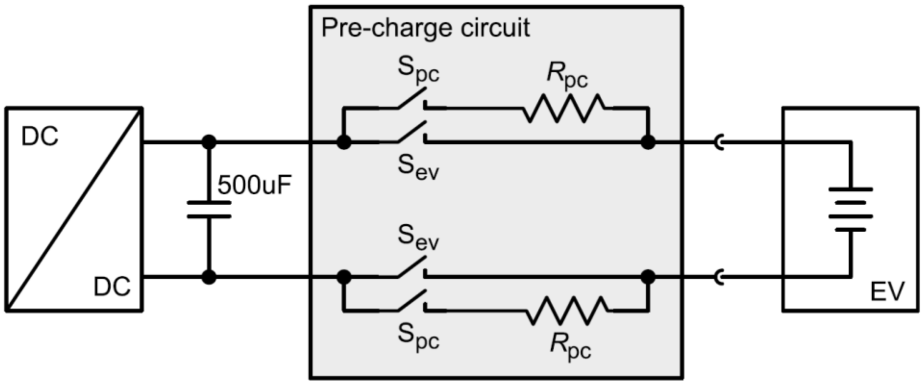
- Gradual damage to components, e.g. capacitor and relay contacts
- Mistaken fault detection by overcurrent or undervoltage protection
- High current surge causing unintended behaviors



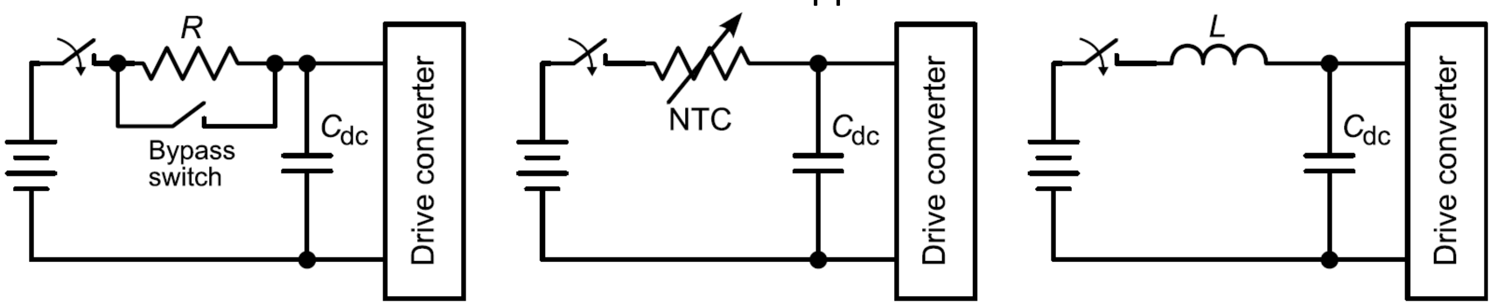


Inrush current mitigation

- Pre-charge circuit is required with coordination by vehicle controller.
- Advanced inrush current mitigation with semiconductor switches for high power range still under development



Fundamental approaches



a) resistor b) thermistor c) inductor

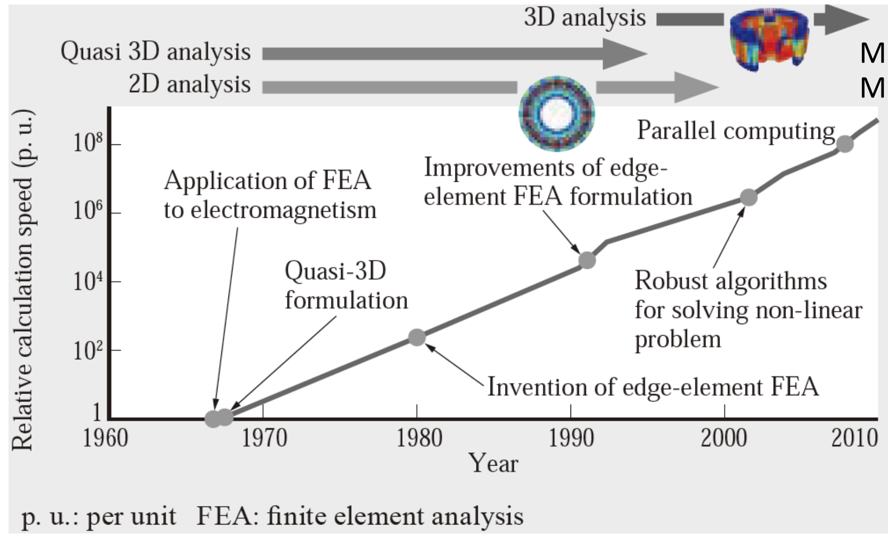
Modern R&D cycle of electrical drive

FEA for predicting performance of designed motor

Precise performance prediction of designed motor could help:

- **speed-up development cycle**
- **saving prototype costs**
- **improved accuracy of design optimization**

Source: H. Mikami, et. al, Historical Evolution of Motor Technology

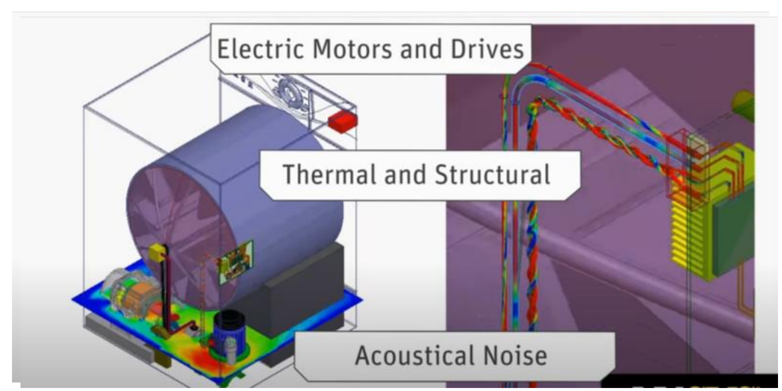


Multi-physic & Multi-domain

2020

Recent development

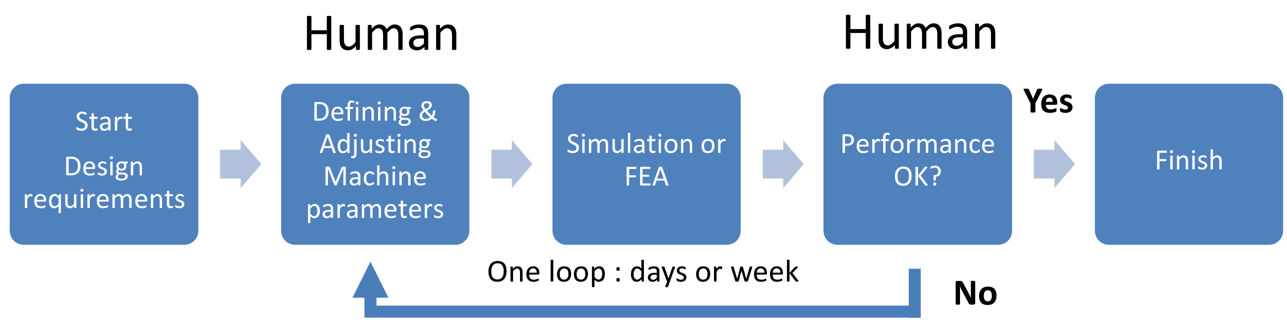
- **Multi-physics and Multi-domain simulation linked to dynamic model (Simulink, Simplorer, etc)**
- **Electromagnetic + Thermal + Electrical + Mechanical**
- **Performance, control, temperature and vibration & acoustic noise**



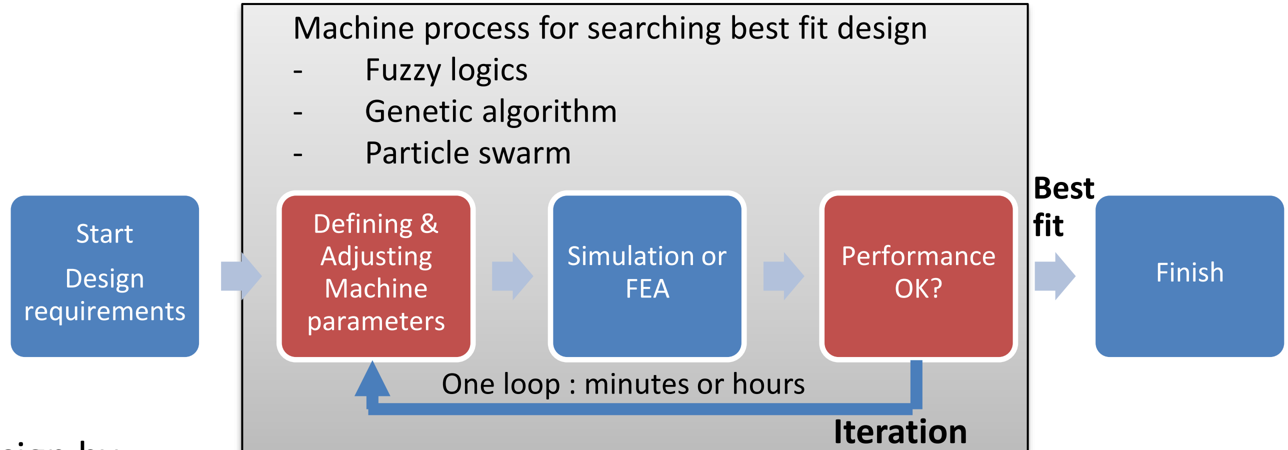
Source: ANSYS (Excerpt from Youtube)

Automation and AI for motor design optimization

Manual optimization



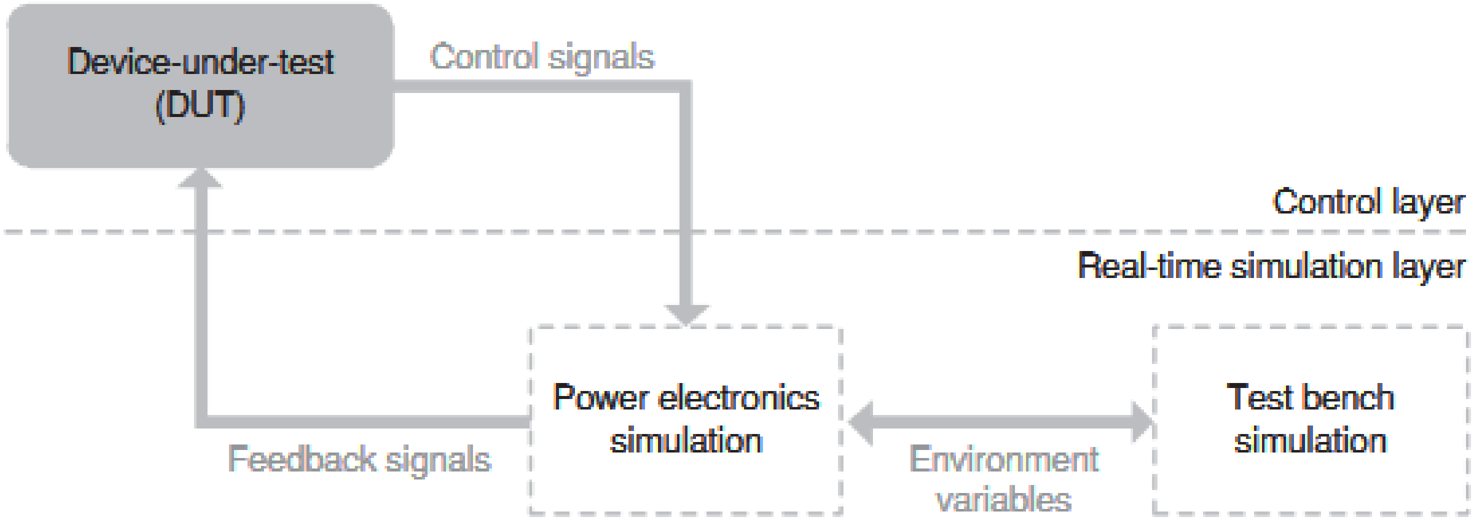
Automated optimization



Efficient, rapid and accurate design by
- Automatic generation of FEA machine model
- Automatic and reliable performance assessment

Hardware-in-the-loop for electrical drive system

- Using hardware in-the-loop can shorten the development of control software & controller unit (widely applied for automotive industry)
- Recent advancement with power hardware in the loop with emulation by power electronics load to represent real current & voltage, (for example, dSPACE)
- Highly cost-intensive equipment and with requirements of high-skill users



Source: J. J. Poon, M. A. Kinsy, N. A. Pallo, S. Devadas and I. L. Celanovic, "Hardware-in-the-loop testing for electric vehicle drive applications," 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2012, pp. 2576-2582, doi: 10.1109/APEC.2012.6166186.

Advanced & alternative design concept

Integration between Motor & Converter

Integrated Drives

Compactness aspect

- Higher torque and power density
- Less required space – good for space-limited applications, e.g. EVs.

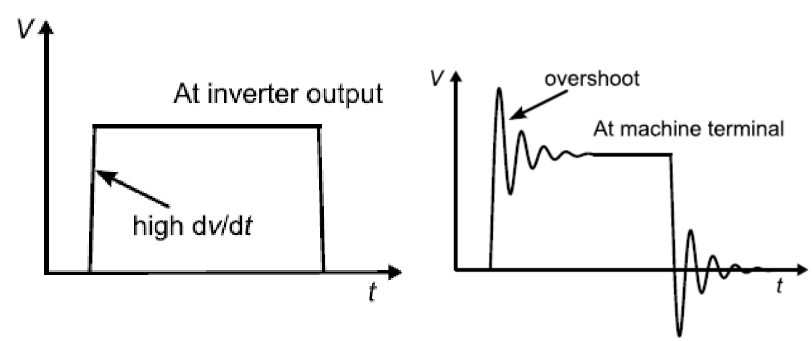
Costs aspect

- Lower effort for EMC
- Less high voltage wire harness

Source: US Department of energy (DOE)
http://energy.gov/sites/prod/files/2014/09/f18/fy_2014_vto_amr_apeem_overview-final_version.pdf

Challenges

- Temperature increase in semiconductor devices due to close physical integration
- Design of cooling



Further degree of integration

- Motor & PE converter

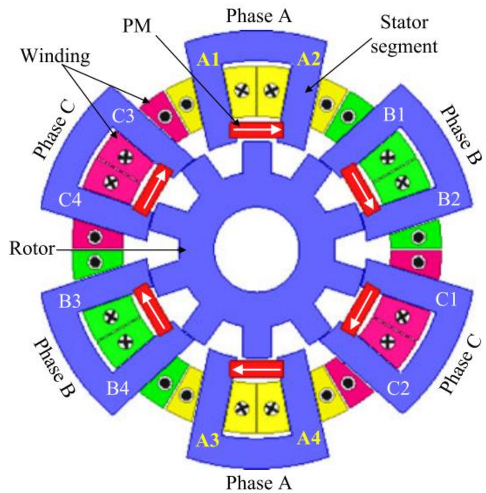
- Motor + PE converter + Transmission

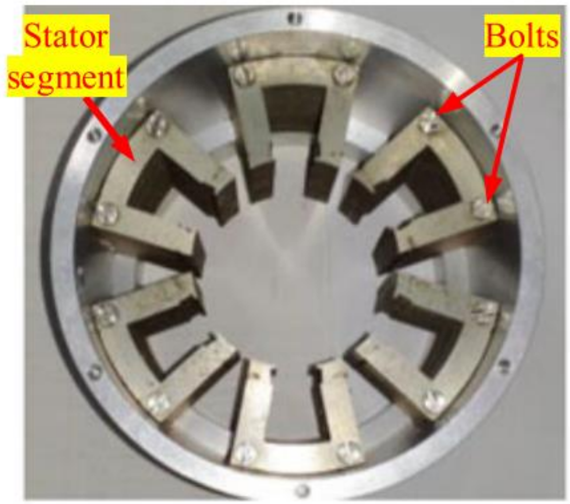
Motivation: Reduction of development cycle & Modularity

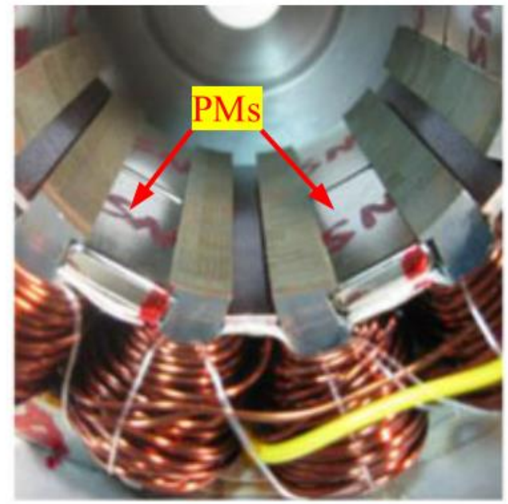
Source: Bosch, https://www.bosch-mobility-solutions.com/

Modularized or segmented machine concept

Hybrid-Excitation SRM







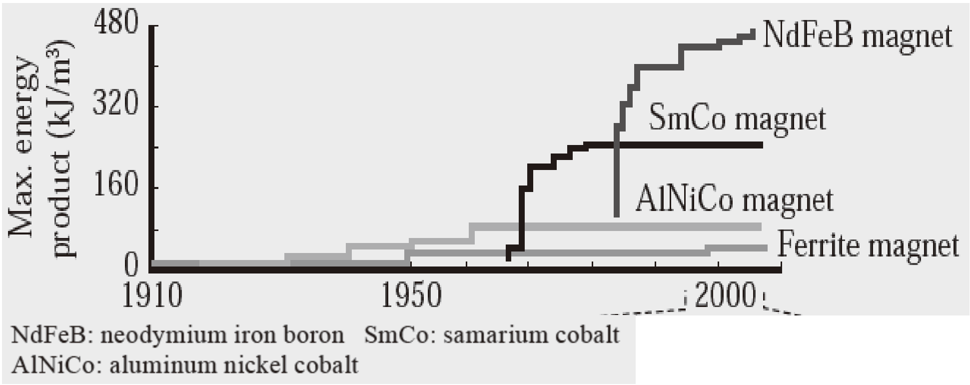
Source: DING et al.: CHARACTERISTICS ASSESSMENT AND COMPARATIVE STUDY OF A SEGMENTED-STATOR PERMANENT-MAGNET, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 33, NO. 1, JANUARY 2018

Advantages of segmented or modularized machine

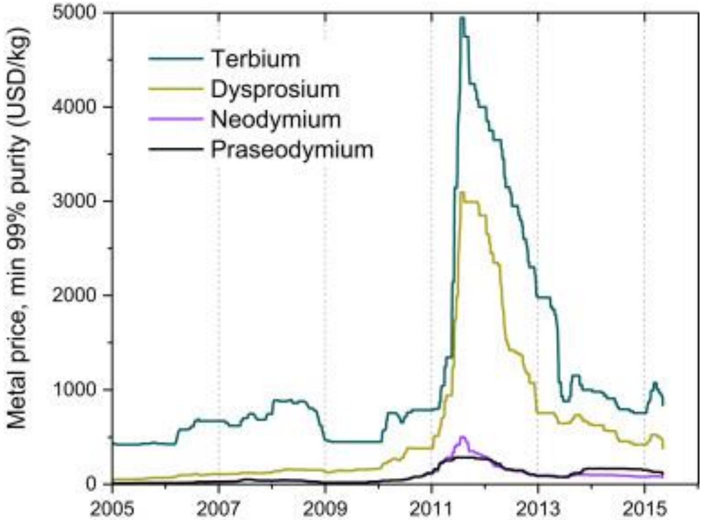
- Lighter weight
- Simple manufacturing
- Pre-fabrication process with lower expenditure is possible.

Trend of new materials

Magnetic material & No-rare earth concept

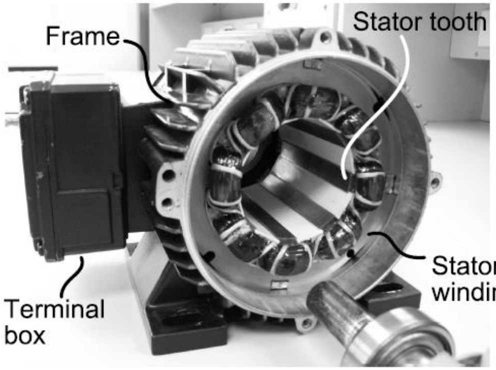


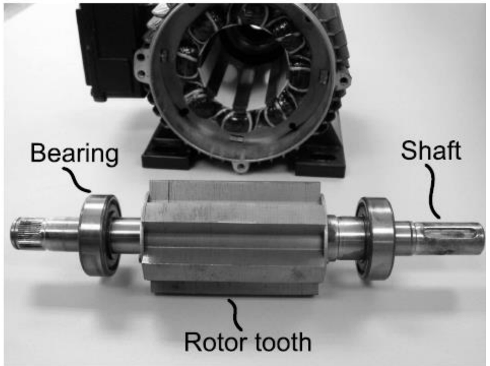
Source: H. Mikami, et. al, Historical Evolution of Motor Technology



Source: C.C. Pavel, et. Al., Substitution strategies for reducing the use of rare earths in wind turbines, Resources Policy, Volume 52, June 2017, Pages 349-357

- Magnetic material by rare-earth increases power and torque performance of electrical machines greatly. (permanent magnet synchronous machine)
- On the other hands, due to costs and availability, there are attempts to develop no-rare-earth electrical machine (induction machine and reluctance machine) to reach comparable performance.





Switched reluctance machine

Wide Bandgap (WBG) Semiconductor Devices for Electrical Drives – GaN and SiC

Pros against Si-based

- Lower on-resistance – higher efficiency
  - thinner voltage blocking layer, hence, reduced on-resistance by two orders of magnitude
- Higher temperature ability – now 200 Cdeg limited by packaging technology
- Lower gate charge – higher switching speed and frequency

Cons against Si-based

- Higher cost
- Challenges in EMC – high dv/dt

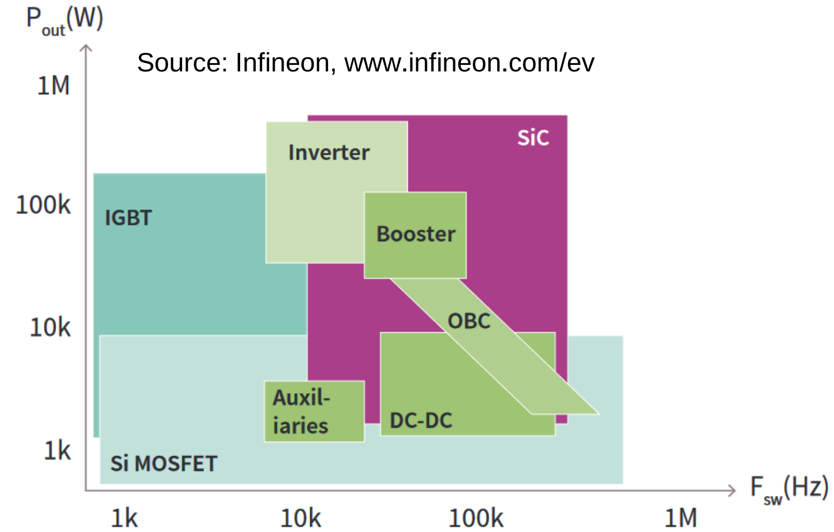


TABLE I
PROPERTIES OF WIDE BANDGAP DEVICES

Property	Si	GaN	SiC
Bandgap (eV)	1.1	3.4	3.2
Electron mobility (cm^2/Vs)	1450	2000	900
Critical electric field (MV/cm)	0.3	3.5	3.0
Electron saturation velocity (10^7 cm/s)	1.0	2.5	2.2
Thermal conductivity (W/cm-K)	1.5	1.3	5.0
Maximum operating temperature (°C)	200	300	600
Specific heat capacity (J/KgK)	712	490	681

Source: A. Morya, Wide Bandgap Devices in AC Electric Drives: Opportunities and Challenges, IEEE Transactions on Transportation Electrification 5(1):3-20, Mar 2019.

WBG for electrical drives

High efficiency

- Efficiency-critical application

High frequency capability

- To maintain low current ripple in low inductance motor (uH range) – large air-gap SMPMSM or low leakage inductance traction motor IM
- High speed drive with fundamental frequency of several kHz – switching frequency range 50-100kHz

High temperature capability

- High ambient temperature application – Integrated Drives, harsh environment

SIC INVERTER PROTOTYPES FOR TRACTION APPLICATIONS

Reference and year	Description	Power	Efficiency
[76], 2017	EV inverter made of 900 V half bridge modules	200 kVA	Mean 96% and peak 98.1% for Vdc=450 V
[77], 2017	EV inverter 1200 V half bridge modules	110 kVA	Mean 96.3% and peak 98.9%
[78], 2017	Front end boost + 3 phase VSI for EV, 1 kV dc bus	100 kW	-
[79], 2018	Megawatt-scale inverter based on a three-level active neutral-point-clamped (3L-ANPC) for hybrid-electric aircraft		99%
[80], 2018	EV inverter with specially designed 2 in 1 module	128 kW	-
[81], 2017	HEV power control unit comprising front end boost and two inverters	430 kVA	-
[82], 2018	EV inverter	60 kW	-
[83], 2016	Front end boost + VSI for EV	55 kW	99% peak
[84], 2018	EV inverter	30 kW	99.5% peak
[85], 2018	3-level T-type traction inverter	250 kW	98% peak

Source: A. Morya, Wide Bandgap Devices in AC Electric Drives: Opportunities and Challenges, IEEE Transactions on Transportation Electrification 5(1):3-20, Mar 2019.

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Nisai H. Fuengwarodsakul

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