

Multilevel converters and modulation strategies to mitigate common-mode currents in complex systems

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Outline

- Introduction – High power converters and complex systems
- Semiconductor scaling laws – WBG considerations
- Multilevel converters
- Quasi-Two-Level modulation of multilevel converters
- Common-mode suppression PWM of multilevel converters
- Outlook

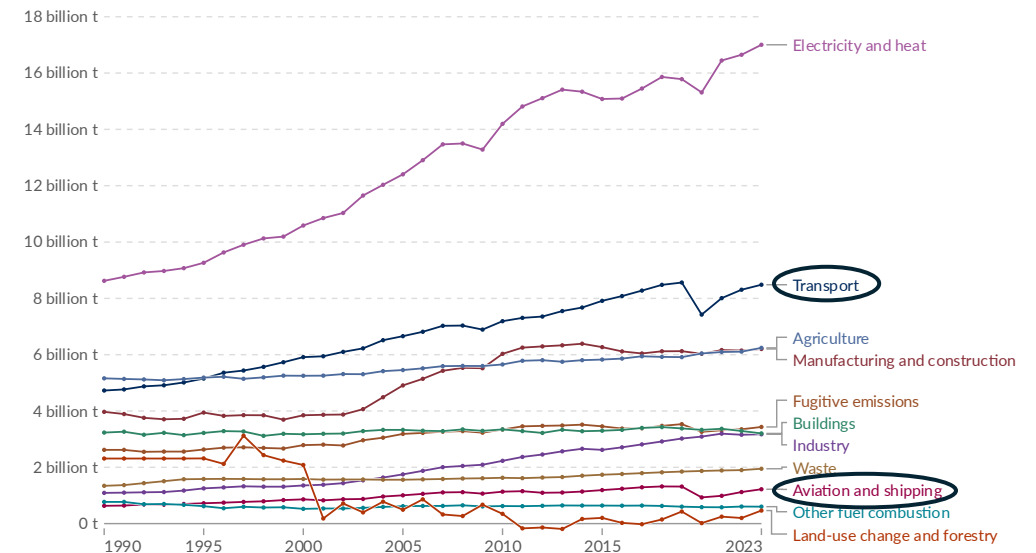
Electrification of transportation – Why?

- Transport is the second-biggest contributor in greenhouse gas emissions.
- Combined transportation is almost 9.6 billion tons of GHG emissions.
- Focus on high-power electrification nowadays.

Greenhouse gas emissions by sector, World

Greenhouse gas emissions are measured in tonnes of carbon dioxide-equivalents over a 100-year timescale.

Our World
in Data



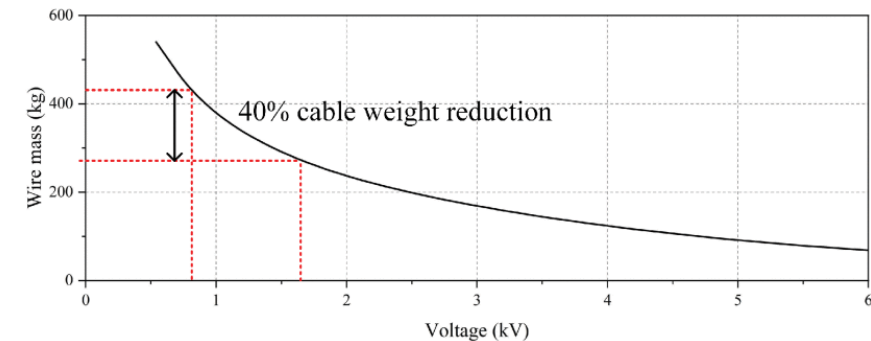
Data source: Climate Watch (2026)

Note: Land-use change emissions can be negative.

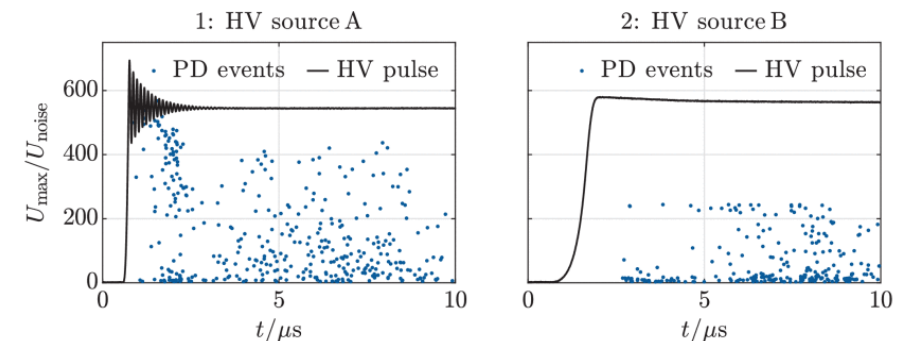
OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

High power converter considerations

- Higher operating voltages
 - Advantages:
 - Can help reduce cable weight.
 - Faster charging.
 - Disadvantages:
 - Typically higher dv/dt -> More EMI issues due to resonances.
 - Partial discharge.
 - Bearing currents.



Reduction in cable weight for a 500kW system with increase in voltage [1].

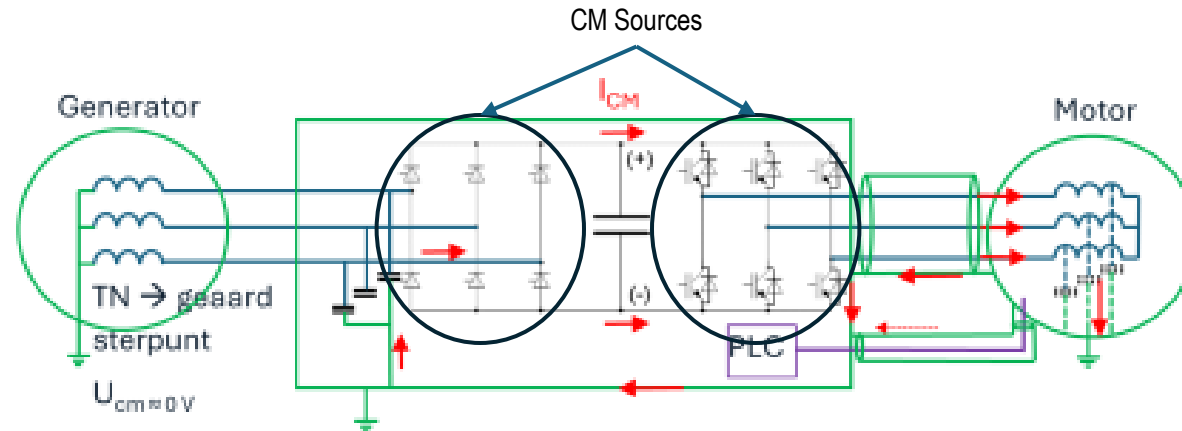


Increase in PD events with higher applied voltage [2].

[1] X. Liu *et al.*, "500-kW Resonant Switched-Capacitor Converter for 1600-V Electric Trucks and Electric Aircraft Powertrain Application," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 13, no. 4, pp. 4617-4634, Aug. 2025, doi: 10.1109/JESTPE.2025.3528028.

[2] A. Rauscher, S. Kalamkar and C. Endisch, "Impact of High Voltage Waveform on Partial Discharge Inception in Electrical Machines," 2024 IEEE 33rd International Symposium on Industrial Electronics (ISIE), Ulsan, Korea, Republic of, 2024, pp. 1-6, doi: 10.1109/ISIE54533.2024.10595712.

Complex systems – Common-mode currents

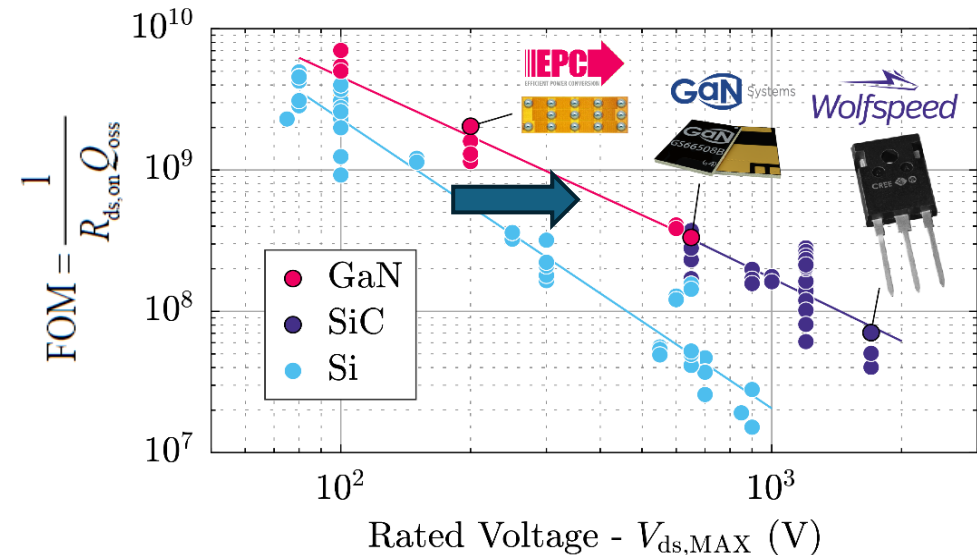
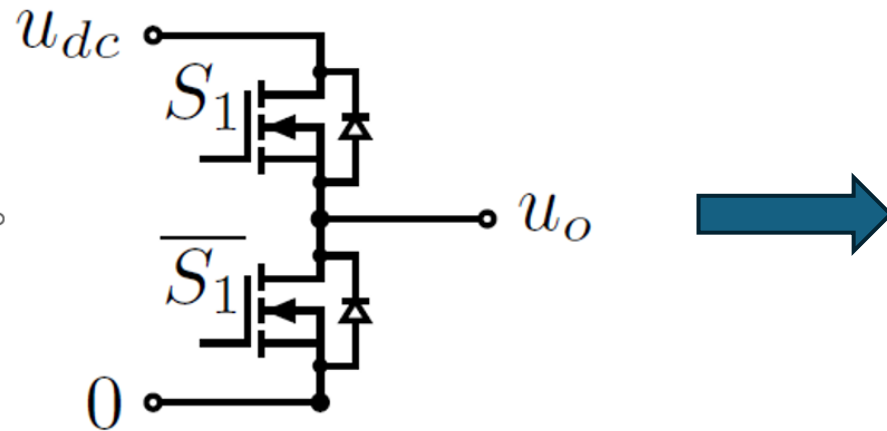


Back-to-back generator motor system with the path for CM currents shown [1].

- Parasitic capacitances distributed all over the system -> Path for CM currents.
- Careful considerations need to be made during voltage/power scale-up.

[1] Source: [Common mode - Nieuwe ontwikkelingen en normontwikkeling - FHI, federatie van technologiebranches](#)

Semiconductor choice – Power inverters

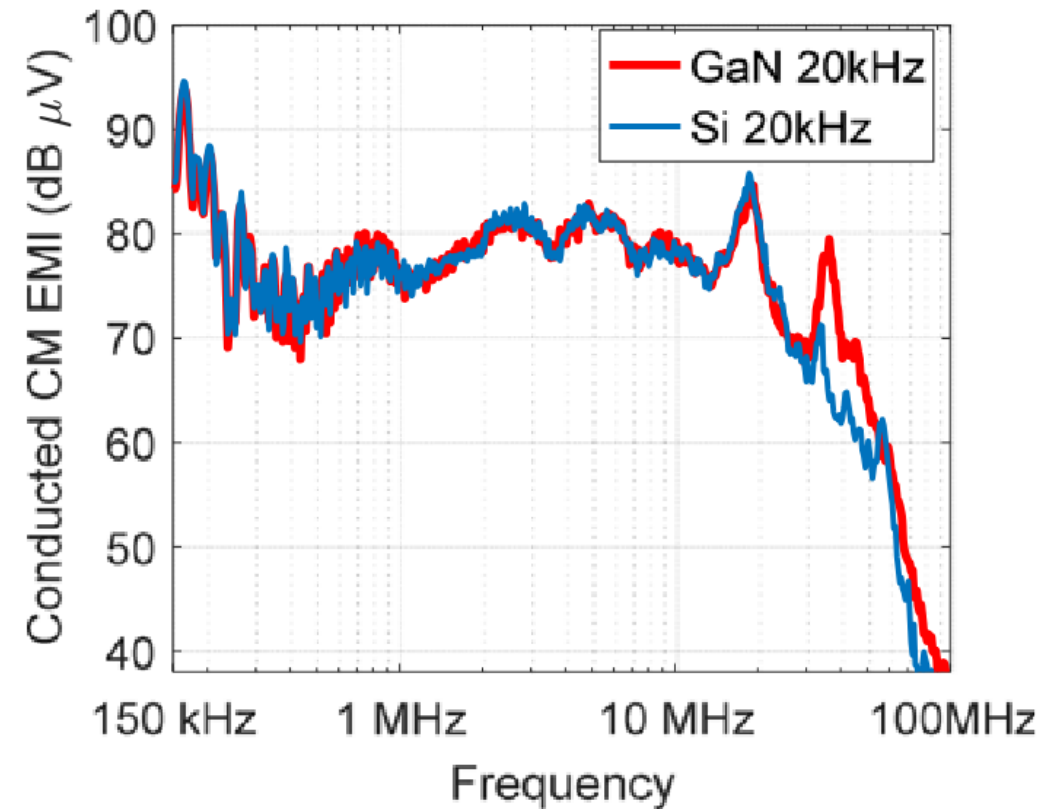


Device Figure-of-Merit (FOM) vs Blocking voltage (Source: ETH Zurich/APEC 2021)

- Wide band-gap devices (SiC/GaN) have significantly higher performance compared to Si.

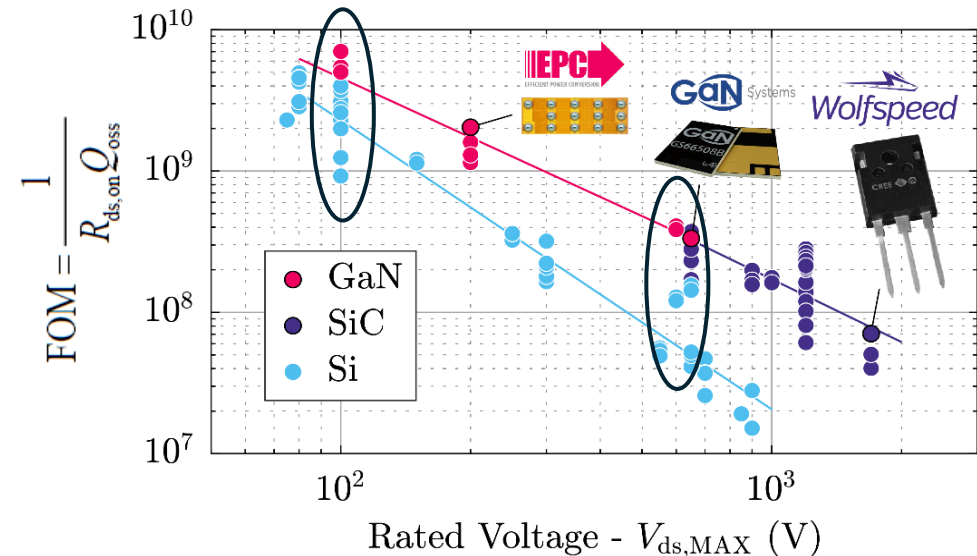
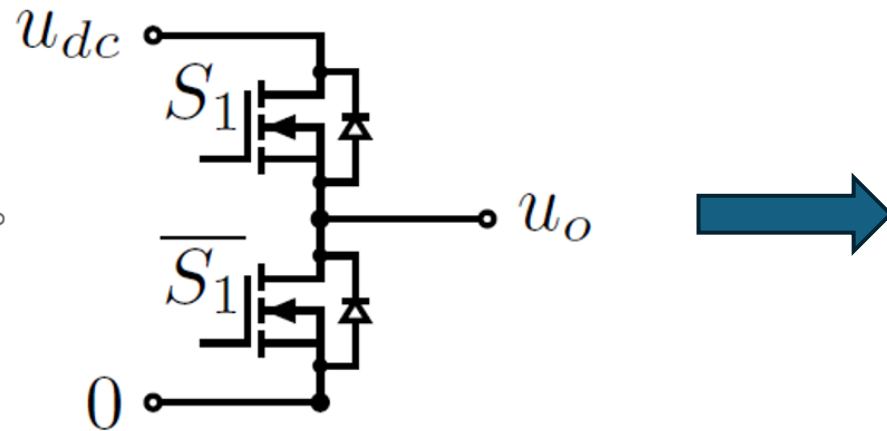
WBG semiconductors – Considerations

- Due to high dv/dt , higher frequencies can be excited compared to Si devices.
- Double edged sword between performance and EMI.



[1] D. Han, S. Li, Y. Wu, W. Choi and B. Sarlioglu, "Comparative Analysis on Conducted CM EMI Emission of Motor Drives: WBG Versus Si Devices," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 10, pp. 8353-8363, Oct. 2017, doi: 10.1109/TIE.2017.2681968.

Semiconductor choice – Power inverters

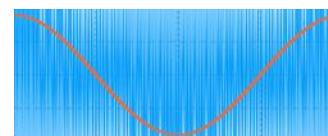
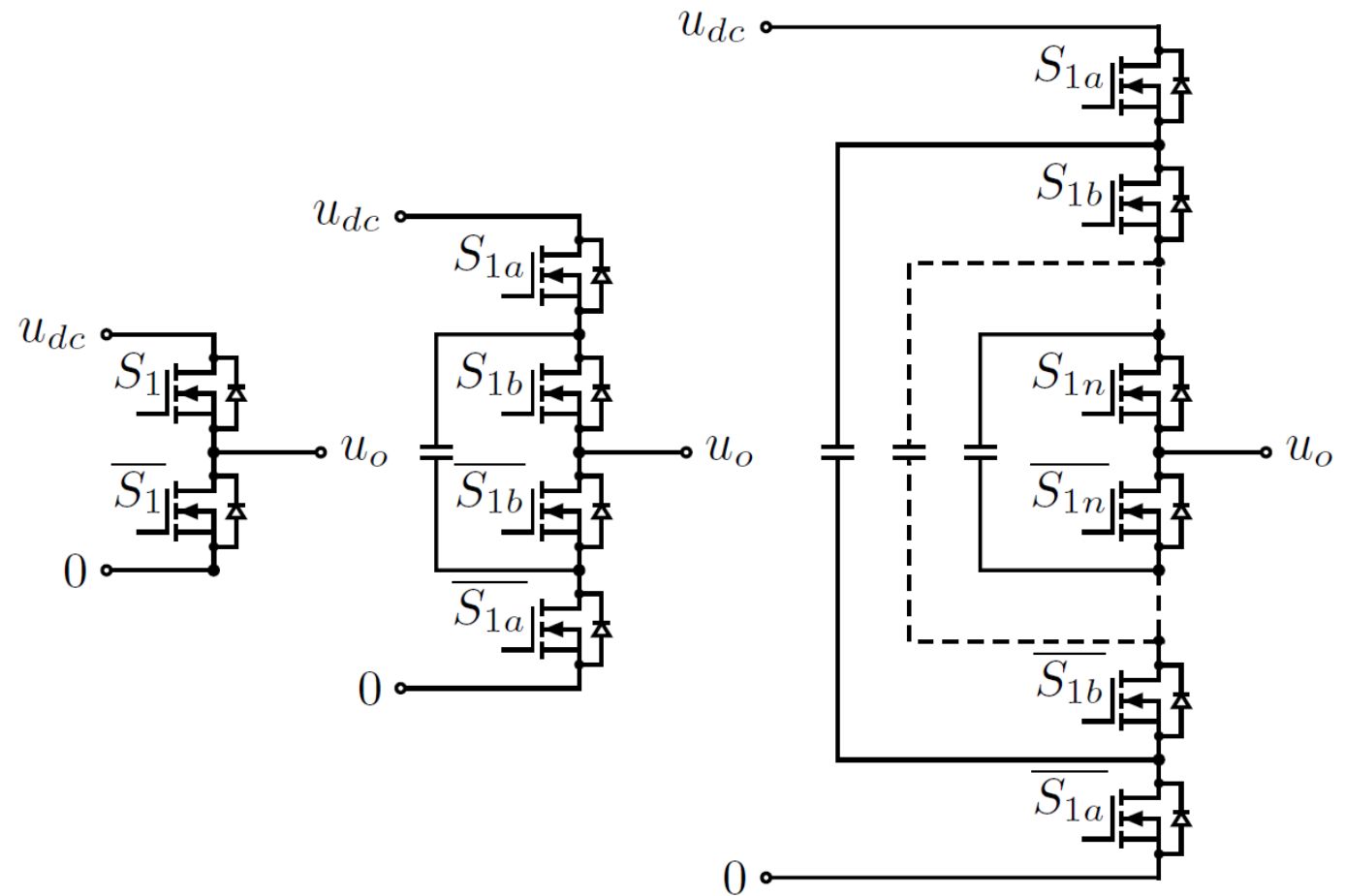


Device Figure-of-Merit (FOM) vs Blocking voltage (Source: ETH Zurich/APEC 2021)

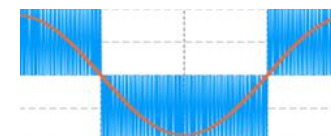
- More interestingly, low-voltage devices follow a power law increase in performance.
- Multilevel converters – Take advantage of low-voltage devices.

Multilevel converters

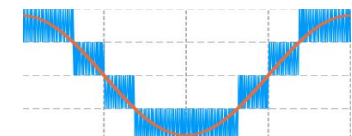
- Replacing one high-voltage device with series-connected low voltage devices.
- Better output voltage quality i.e. smaller filters.



2-level



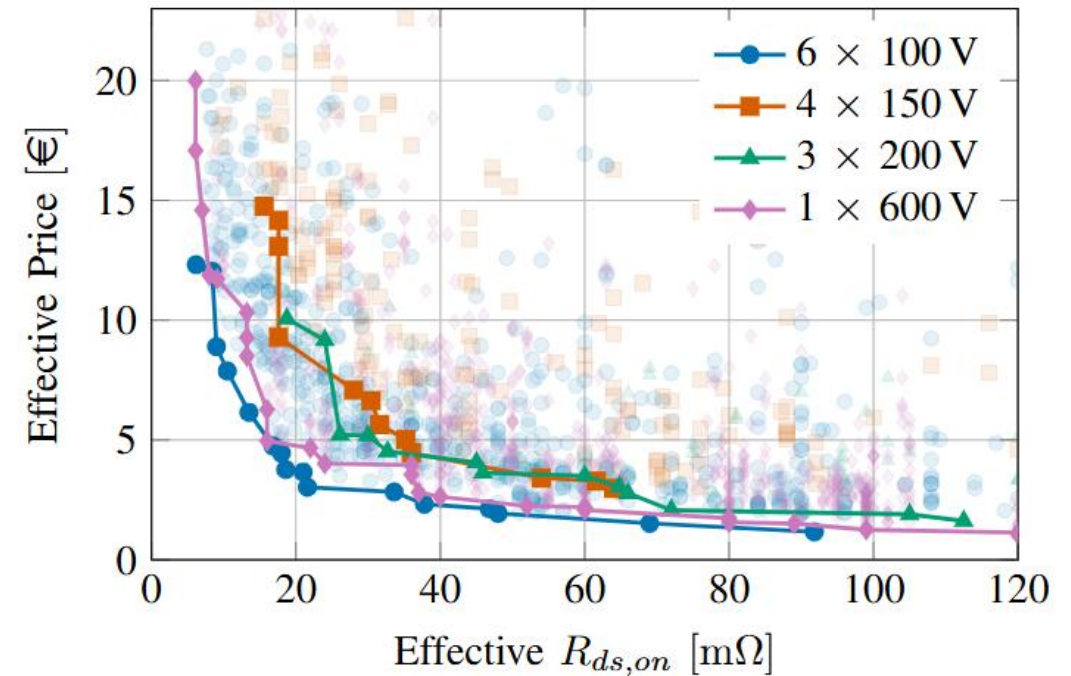
3-level



n-level

Multilevel converters

- More devices – More cost?
 - Not necessarily!
- Though,
 - Control complexity is higher
 - Auxiliary costs are not included.

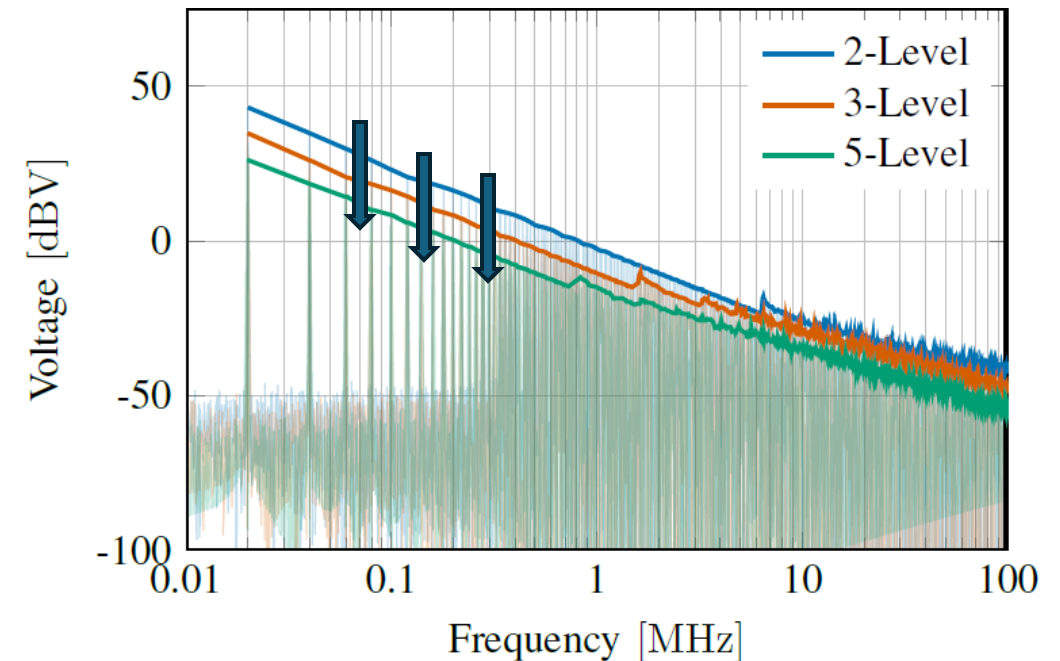


Device data price comparison from Digikey for MOQ of 5000 [1].

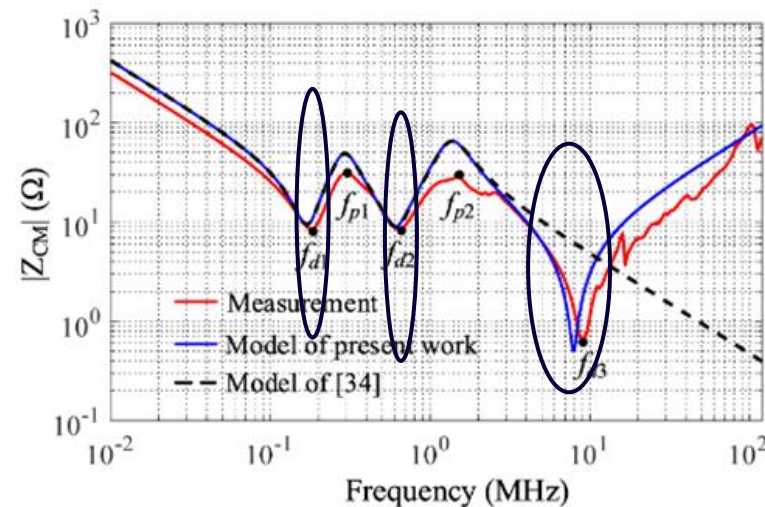
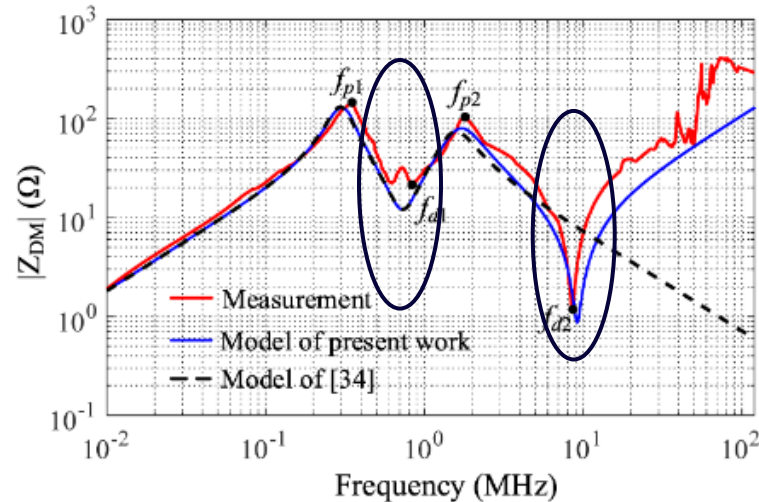
[1] A. K. Iyer, Y. Wu, H. Polinder and T. Batista Soeiro, "Impact of Quasi-Two-Level Converters on Common-Mode Currents in Inverter-Fed Drive Systems," in IEEE Transactions on Industrial Electronics, doi: 10.1109/TIE.2026.3672842.

Multilevel converters – Harmonic impact

- Advantages
 - Constant reduction in output voltage harmonics.
 - Can be beneficial in reducing both CM/DM filters.
- Drawbacks
 - Cannot be used for targeted mitigation of harmonics. – Why?



Typical system impedance – Motor drives



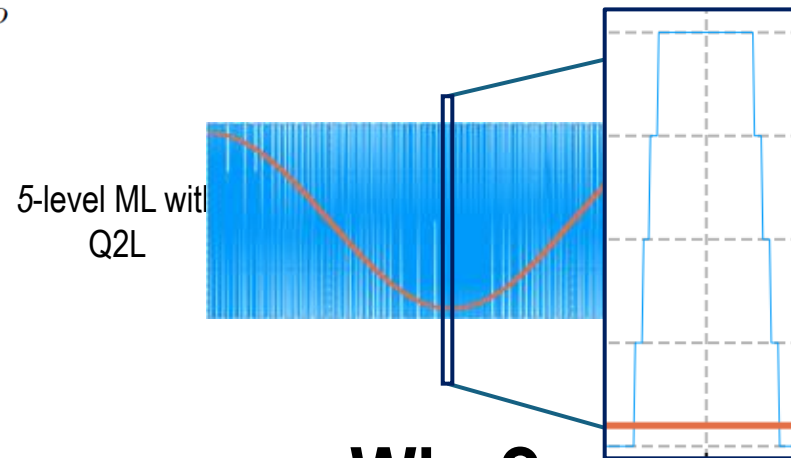
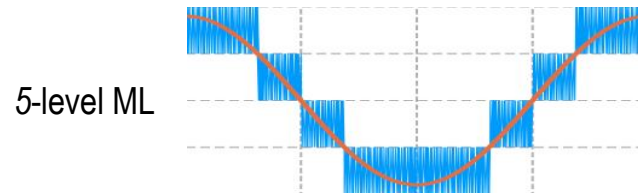
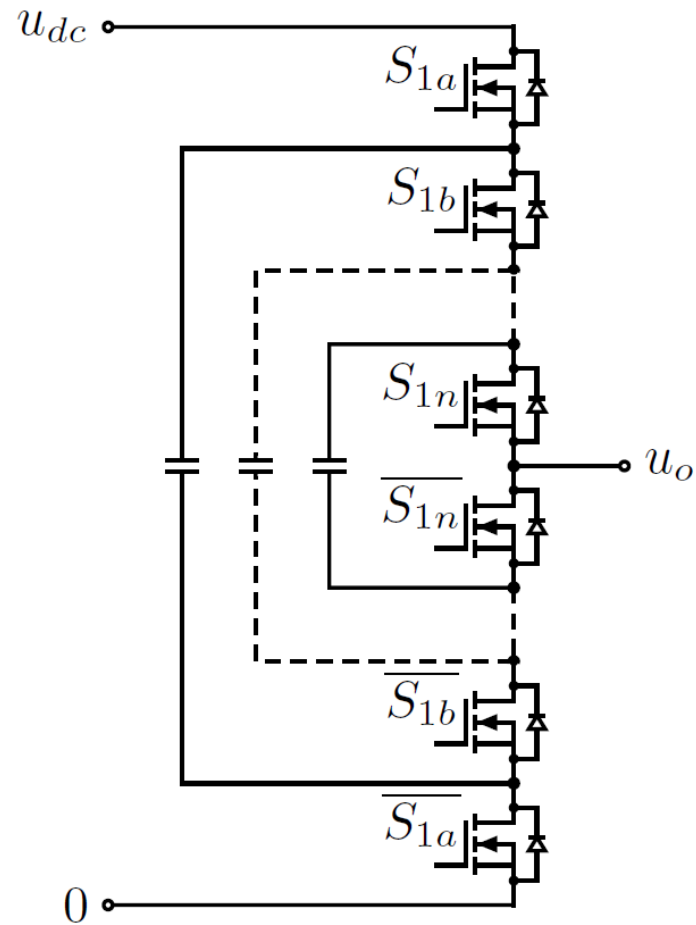
$$I(f) = \frac{V(f)}{Z(f)}$$

Differential and common-mode impedance profile of a typical motor [1].

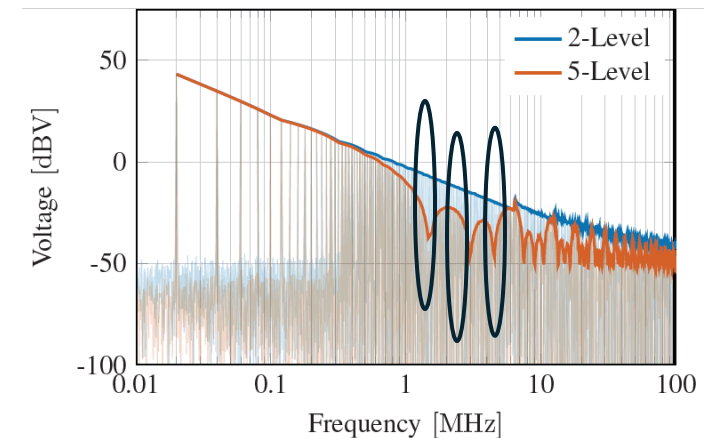
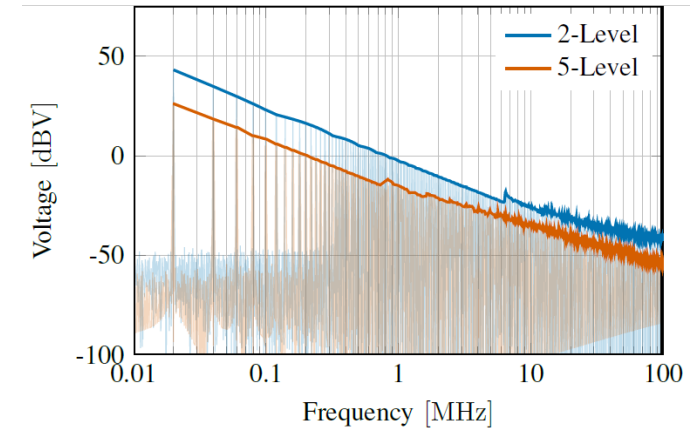
- Resonances cause high emissions in certain bands.
- With the voltage and impedance profiles, DM and CM noise can be predicted.

[1] K. Wang, H. Lu, C. Chen and Y. Xiong, "Modeling of System-Level Conducted EMI of the High-Voltage Electric Drive System in Electric Vehicles," in IEEE Transactions on Electromagnetic Compatibility, vol. 64, no. 3, pp. 741-749, June 2022, doi: 10.1109/TEMC.2022.3147521.

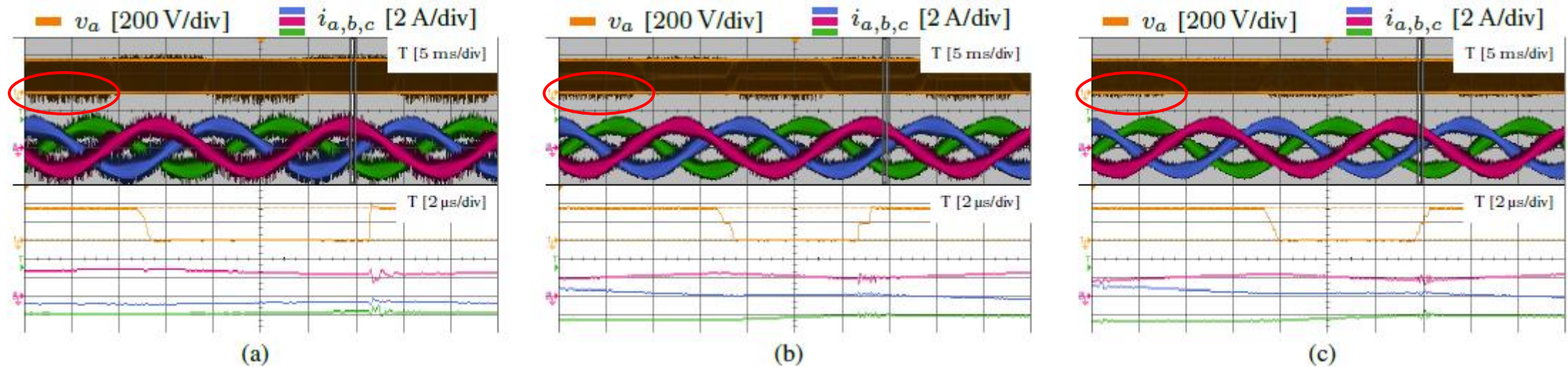
Quasi-Two-Level modulation of ML converters



Why?



Quasi-Two-Level modulation of ML converters



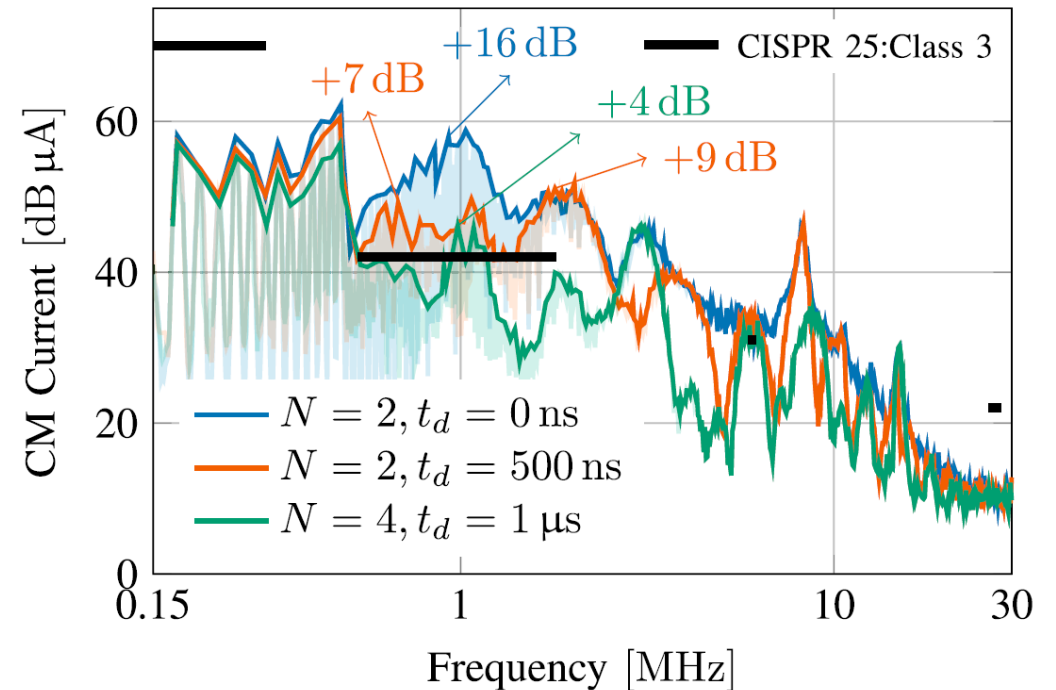
Experimental operation of an (a) 2-level, (b) 3-level and (c) 5-level converters in Q2L mode.

- Smaller flying capacitors/clamping diodes.
- Semiconductor performance of lower voltage devices leveraged!
- Trade-off on output voltage quality.

Impact of Q2L modulation on CM currents

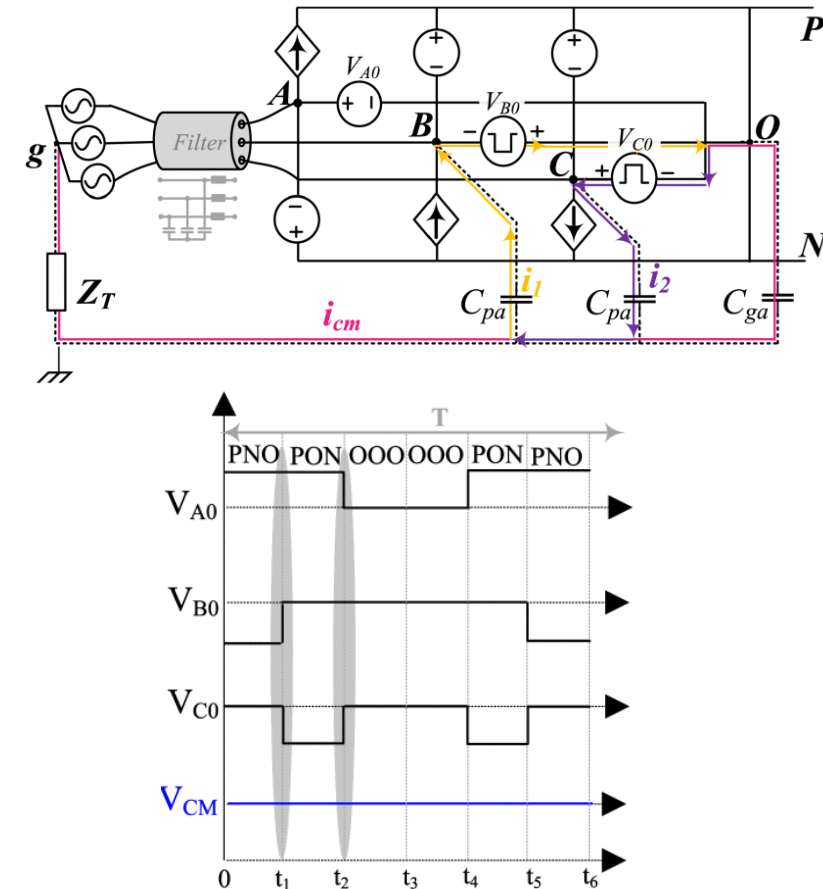
- Smaller CM chokes!
- Tunable based on the system impedance.
- In this example, 5-level Q2L can reduce the peak by up to **12 dB**.

- Further reading:



Common-mode suppression PWM

- Theoretically zero common-mode voltage.
- Provide local bypass path for common-mode currents.
- Non-idealities prevent full elimination.
- Trade-off of higher DM noise.



Source: R. Nibaruta, S. Qazi, A. K. Iyer, P. Venugopal, V. Havryliuk and T. B. Soeiro, "Electric Vehicle Charging System Utilizing a Transformerless Common Mode Voltage Suppression Technique," in IEEE Transactions on Industry Applications, vol. 62, no. 1, pp. 1171-1183, Jan.-Feb. 2026, doi: 10.1109/TIA.2025.3590674.

Outlook

- No silver bullet in common-mode emissions.
- System needs to be characterised well.
- Multilevel converters offer high performance from low-voltage devices.
- Quasi-Two-Level modulation offers high-frequency harmonic reduction.
- Multilevel converters offer flexibility in their modulation schemes to allow mitigating CM and DM effects as dictated by the application.

Questions?



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