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Vienna Rectifier Front-End Dual Three-Phase PMSM Drive with Synergetic Control

Takanobu Ohno* , Michael Haider, Spasoje Mirić

University of Innsbruck, Institute for Mechatronics
Innsbruck Drives and Energy Systems Laboratory (iDES)
Technikerstraße 13a, Floor 1, Office 128
https://www.uibk.ac.at/mechatronik/ides/

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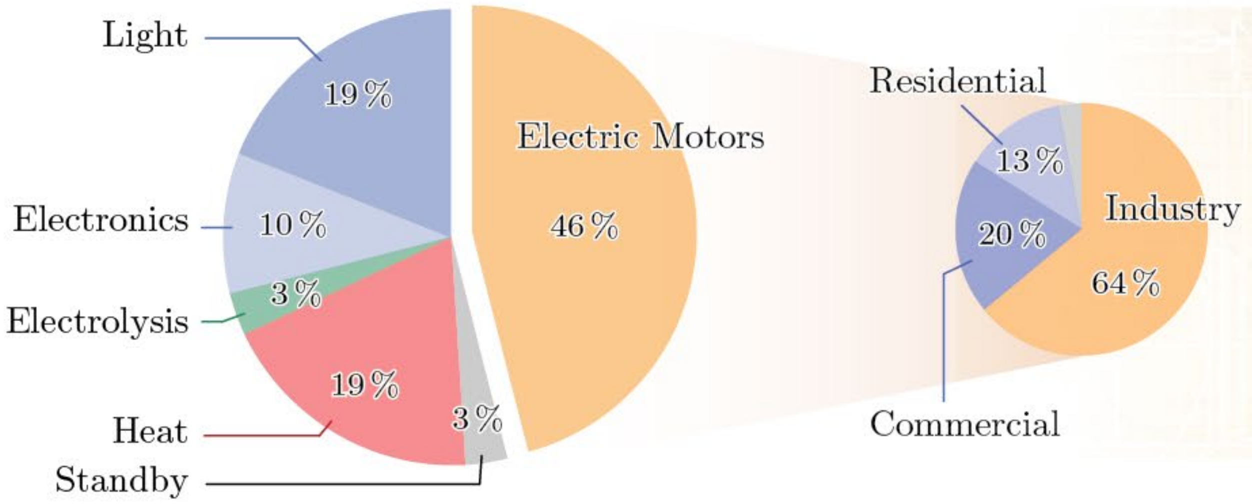
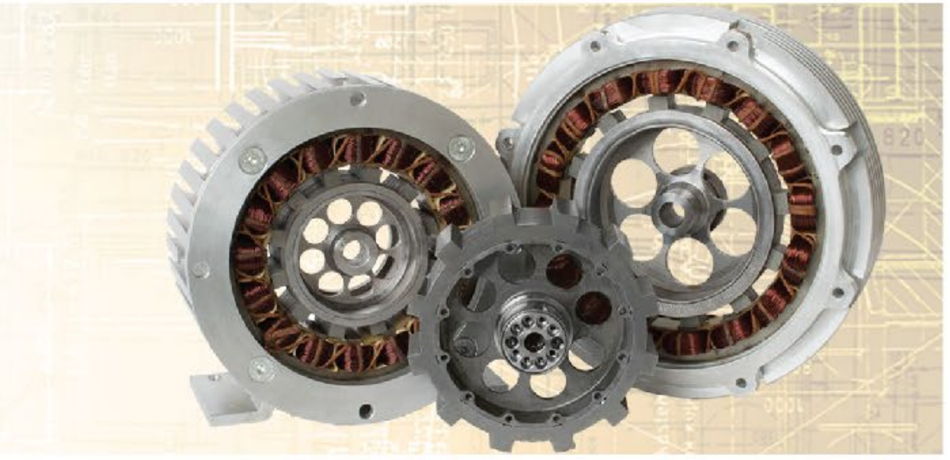
Introduction: Energy Impact and Future Outlook of Drive Systems

- Nearly 50 % of electricity used in industry is consumed by motor systems
- Enhancing their efficiency and control performance directly reduces global CO_2 emissions and energy costs





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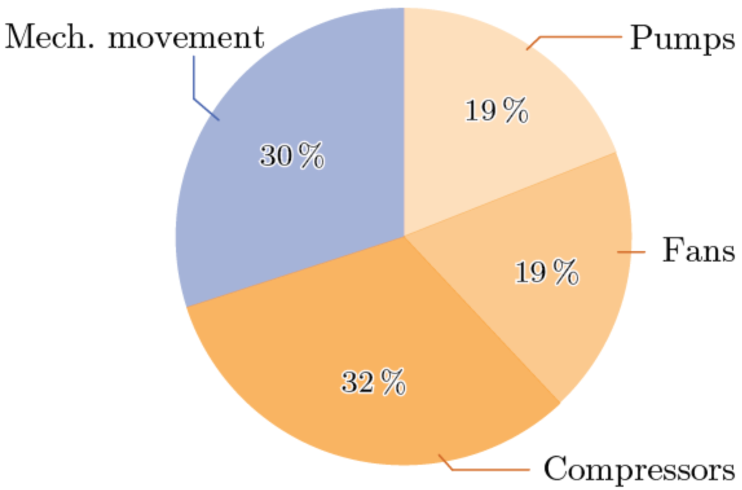
Eestimated share of global electricity demand by end-use [1*]

- The major applications of electric motors are pumps, fans, and compressors, representing the largest share of energy demand
- Implementing variable-speed drives (VSDs) can yield up to 10 % energy savings in these applications
- The market trend is shifting toward high-efficiency, high-power, grid-connected industrial drives

[1*] Paul Waide, Conrad U. Braunner, „Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems“, IEA, 2011.
[2*] Alexander Schröder, Johannes Liebertseder, Marting Doppelbauer „Sutdy on The Energy-saving Potential of Electric Motors with Variable-Speed Drives in The European Union“, CEMEP, 2023.

Introduction: Energy Impact and Future Outlook of Drive Systems

- Around 50 % of electricity used in industry is consumed by motor systems — mainly pumps, fans, and compressors.
- Improving their efficiency and control performance has a direct impact on the global CO_2 footprint and energy cost.



Estimated share of global motor electricity demand by application[1*]

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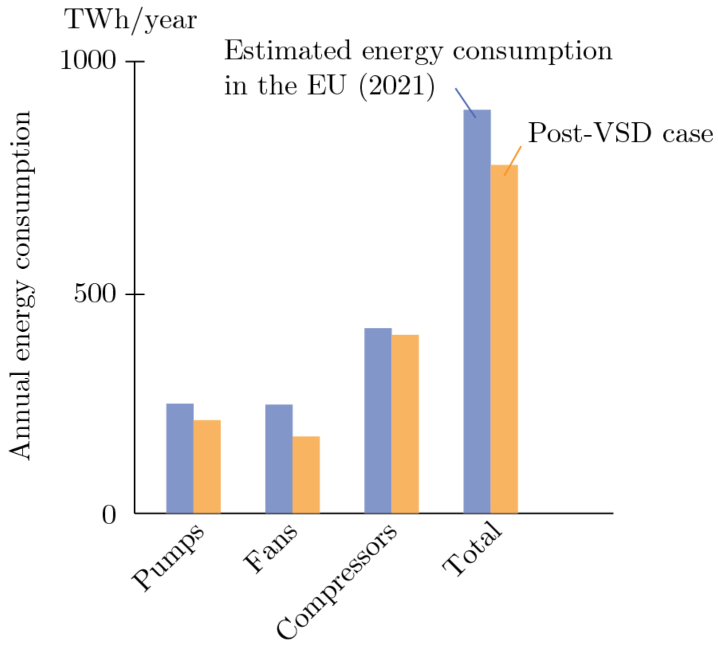

Éstimated energy saving potential applying VSD [2*]

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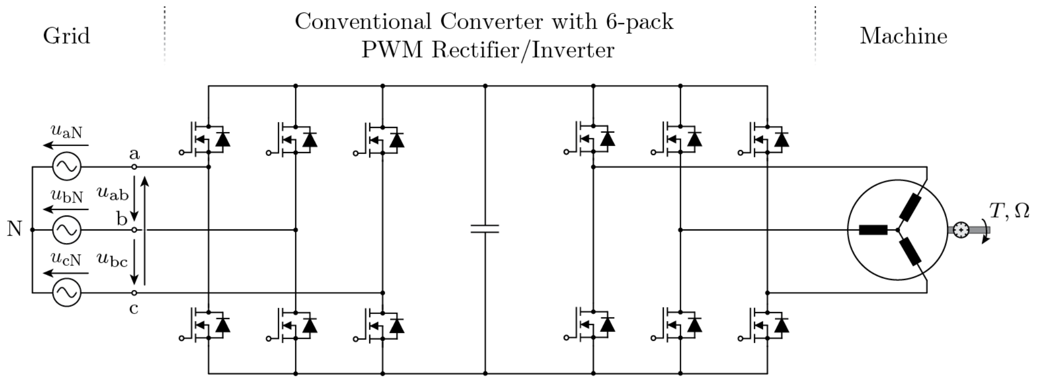
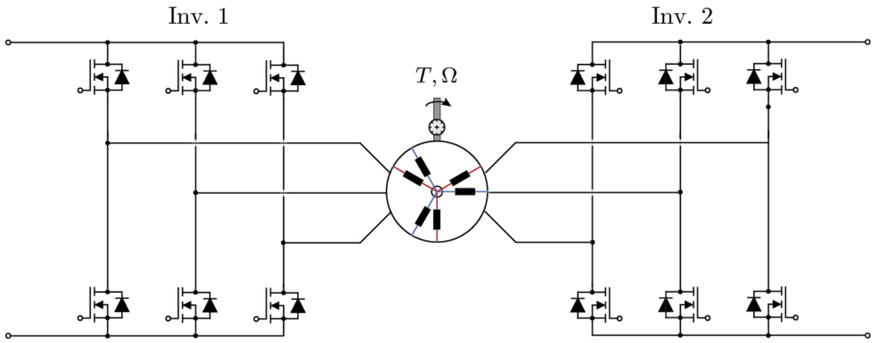
Introduction: Conventional VSD System

- . Well-established back-to-back PWM rectifier-inverter configuration
- Designed for efficient and torque control in various industrial drives



Conventional VSD system

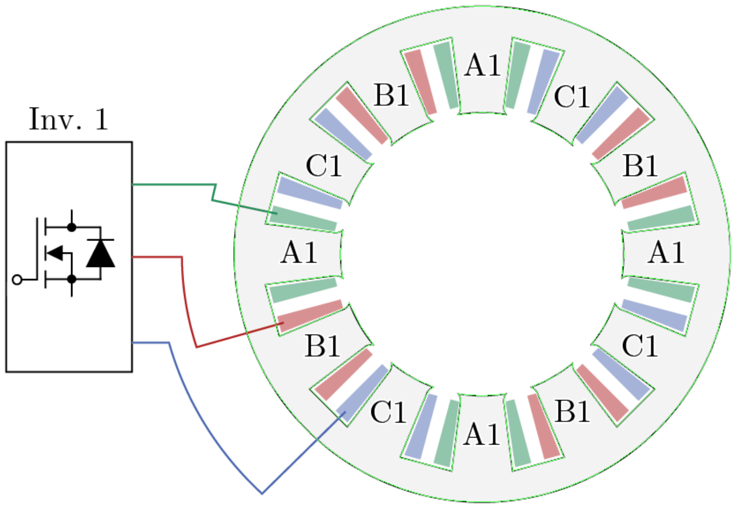


Multi phase machine VSD system

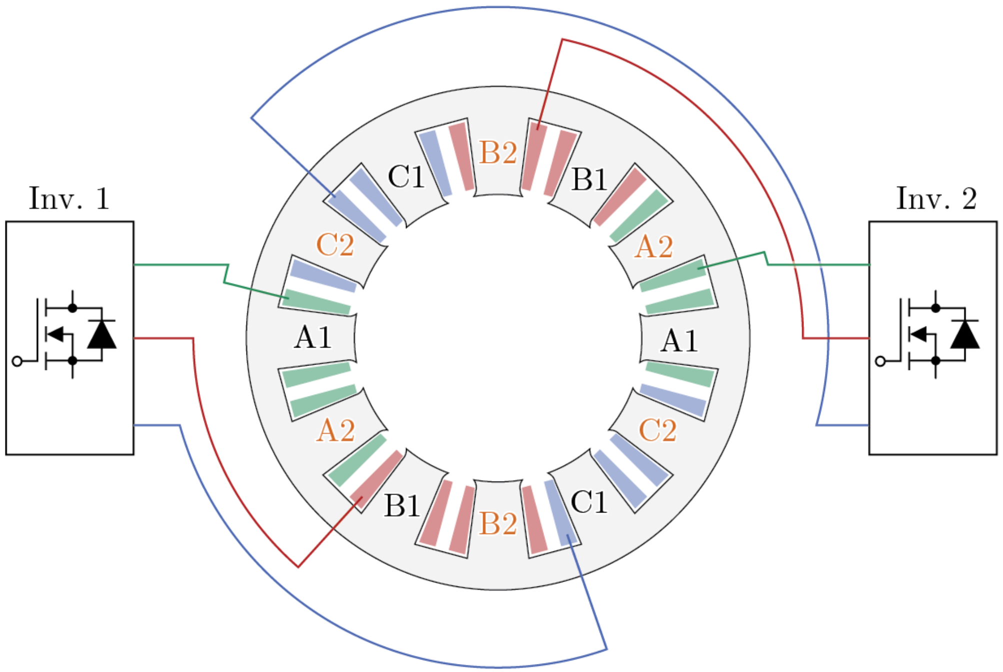
- Further improvements in power efficiency, density, low torque ripple, and fault tolerance are increasingly demanded
- Multi-phase motor systems are emerging as a promising solution beyond conventional three-phase VSDs

Introduction: Dual Three-Phase Machine

- Shares the same mechanical structure as a conventional three-phase machine, realized simply by reconfiguring the stator winding
- Better fault tolerance, torque ripple, and reduced device stress
- Enables enhanced performance without major mechanical redesign



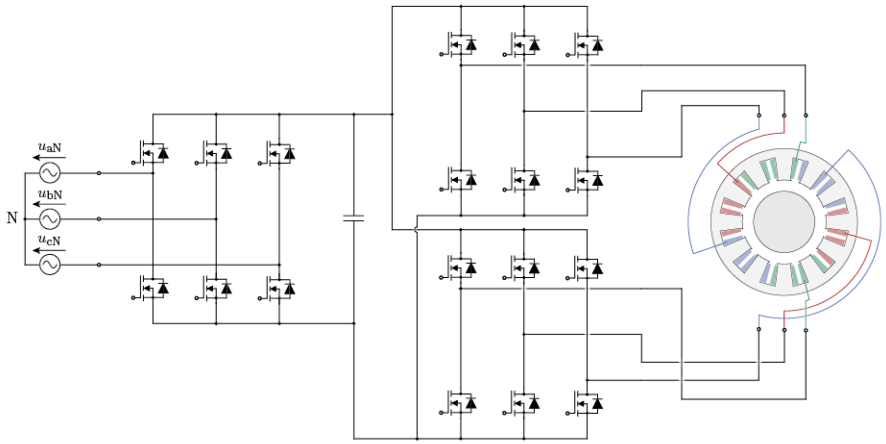
Standard 3-phase machine



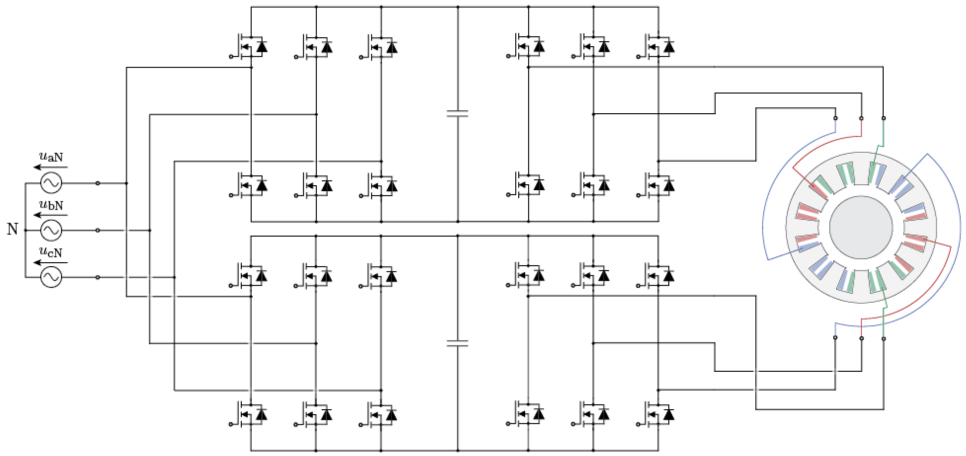
Dual three-phase machine

Introduction: Conventional Dual Three-Phase Machine Drive Systems

- Two configurations have been studied:
  - Parallel inverters connected to a common DC link after active front end (AFE)
  - Independent AFEs, each feeding its own inverter



Shared DC link configuration [3*]



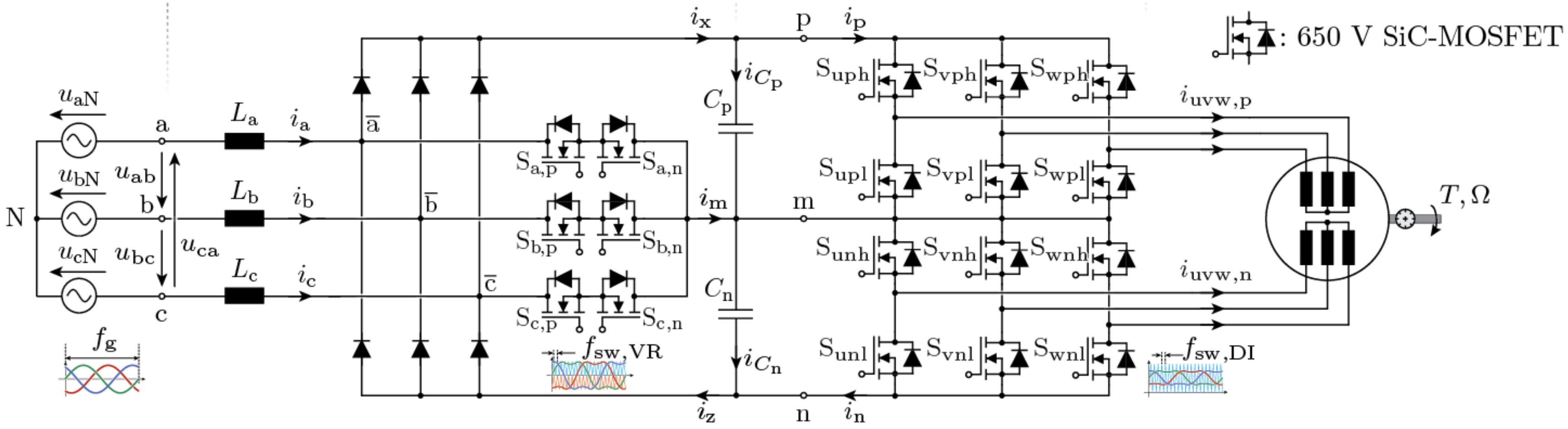
Indipendent DC link configuration [4*]

- In both cases, 1.2 kV semiconductor devices are required for 400 V line-to-line AC input for secure margin of modulation for AFEs

[3*] J. Karttunen, et.al, „Dual Three-Phase Permanent Magnet Synchronous Machine Supplied by Two Independent Voltage Source Inverters", *Proc. of the International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, 2012
[4*] Euzeli C. dos Santos, et.al, „Six-Phase Machine Drive System With Reversible Parallel AC-DC-AC Converters", *Trans. on Indstrial Electronics*, Vol. 58, No. 5, 2011

Introduction: Proposed Configuration

- Vienna Rectifier (VR) front-end providing a neutral point
- Stacked Inverters are connected across the neutral point, enabling balanced DC input



Proposed Vienna Rectifier front-end stacked inverter-based dual-three-phase PMSM drive system

- The DC link capacitors only process switching frequency ripple enable film or ceramic capacitor technology
- Each inverter operates at 400 V, allowing the use of 600 V devices

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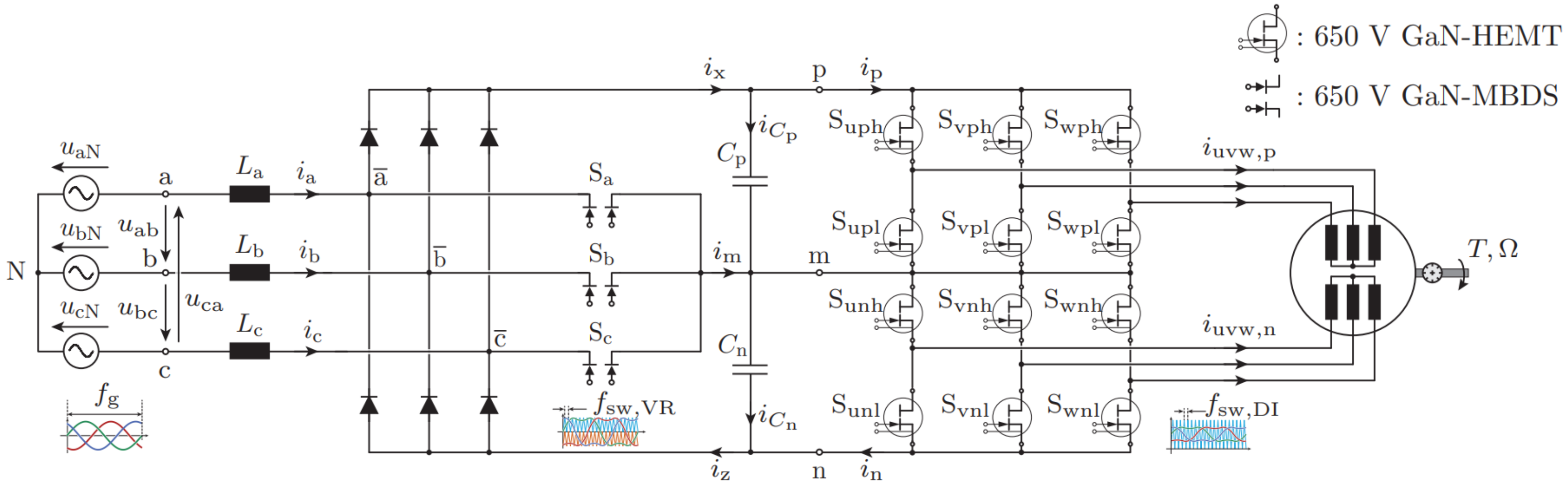
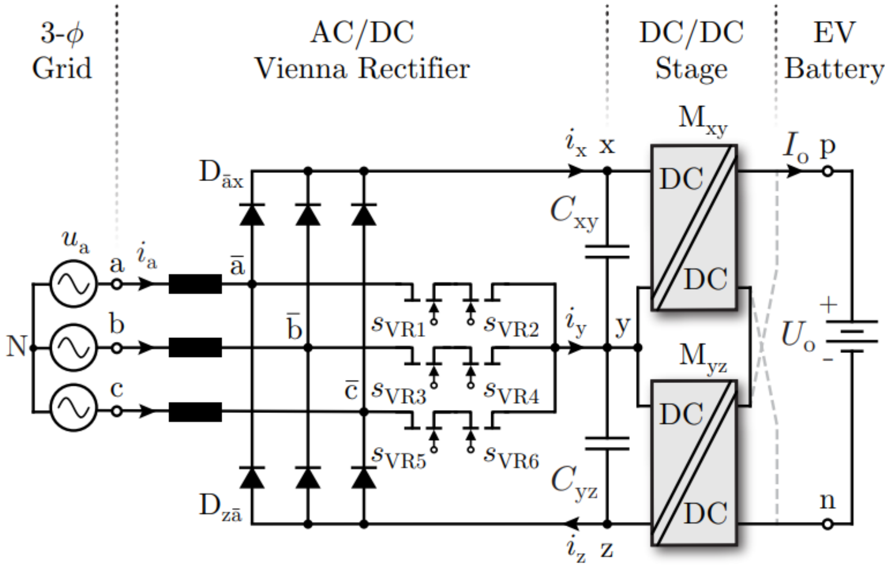


Proposed Vienna Rectifier front-end stacked inverter-based dual-three-phase PMSM drive system

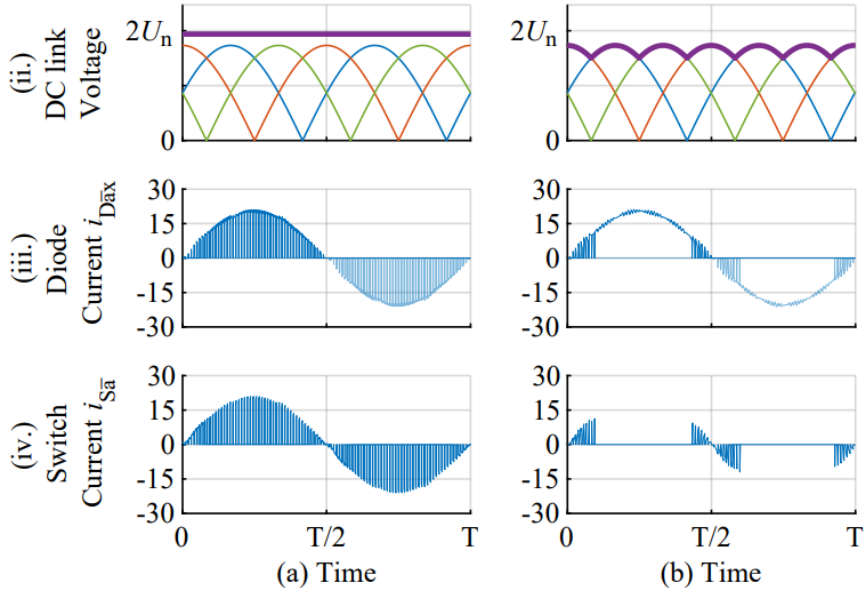
- The DC link capacitors only process switching frequency ripple enable film or ceramic capacitor technology
- Each inverter operates at 400 V, allowing the use of 600 V devices
- Enable use of GaN FETs for the inverter, and monolithic bidirectional GaN Devices for the VR
- With the boost capability and synergetic control of the VR, the system achieves efficient operation across a wide speed range

Introduction: Synergetic Control

- Synergetic Control have been developed in the literatures of EV charging system
- It enables over 66 % reduction in switching losses when applied to the Vienna Rectifier (VR)



Conceptual power circuit of synergetic control for EV charger [5*]



Wavefroms of VR operating with 3/3-PWM and 1/3-PWM [5*]

- The same control principle can be effectively extended to the proposed configuration

[5*] Yunni Li, et.al, „Optimal Synergetic Operation and Experimental Evaluation of an Ultra-Compact GaN-Based Three-Phase 10 kW EV Charger“, IEEE Trans. Transp. Electrfic. Vol. 10, Issue. 2, 2024.

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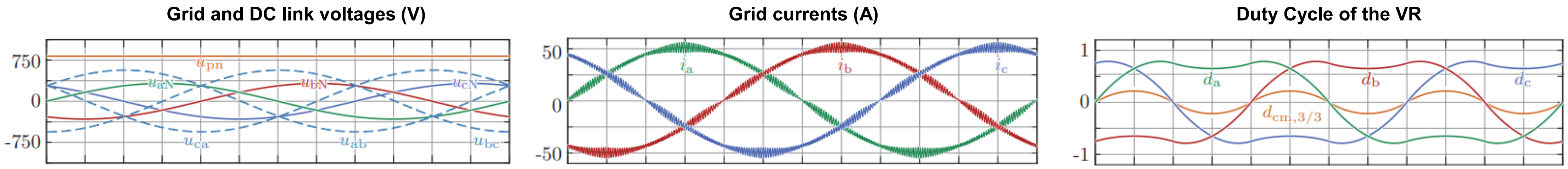
Operation: High-Speed Operation (3/3-PWM, full-boost mode)

- The VR boosts the DC link voltage to maintain current control capability against the rising motor back-EMF
- The VR simultaneously performs power factor correction (PFC), keeping grid currents sinusoidal

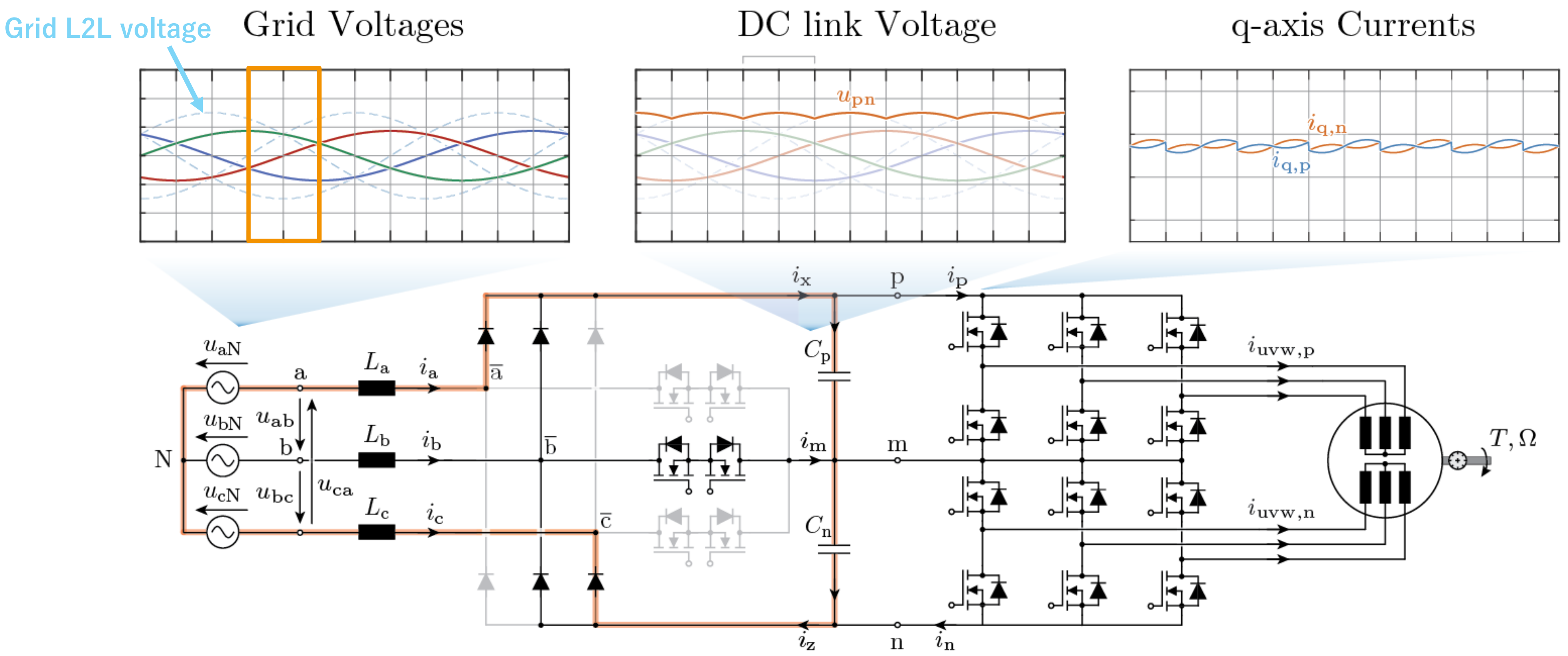


Waveforms of Vienna Rectifier at high-speed operation

- The common-mode voltage of the VR is controlled to ensure zero-midpoint current
- Each inverter applies field-oriented control (FOC) to regulate its respective phase current

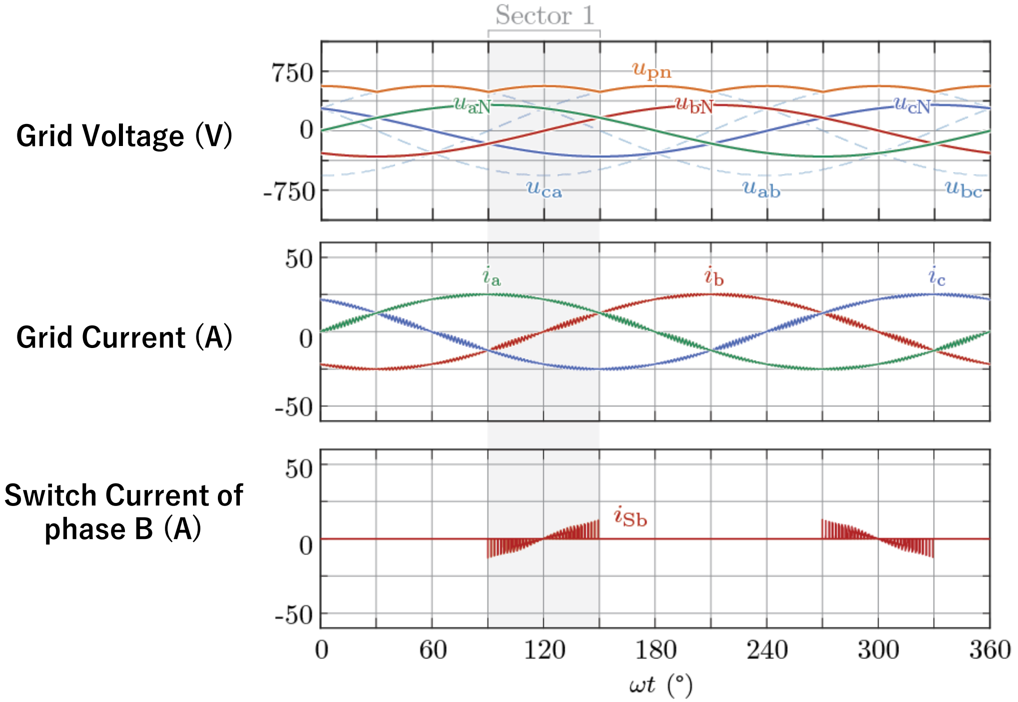
Operation: Low-Speed Operation (1/3-PWM)

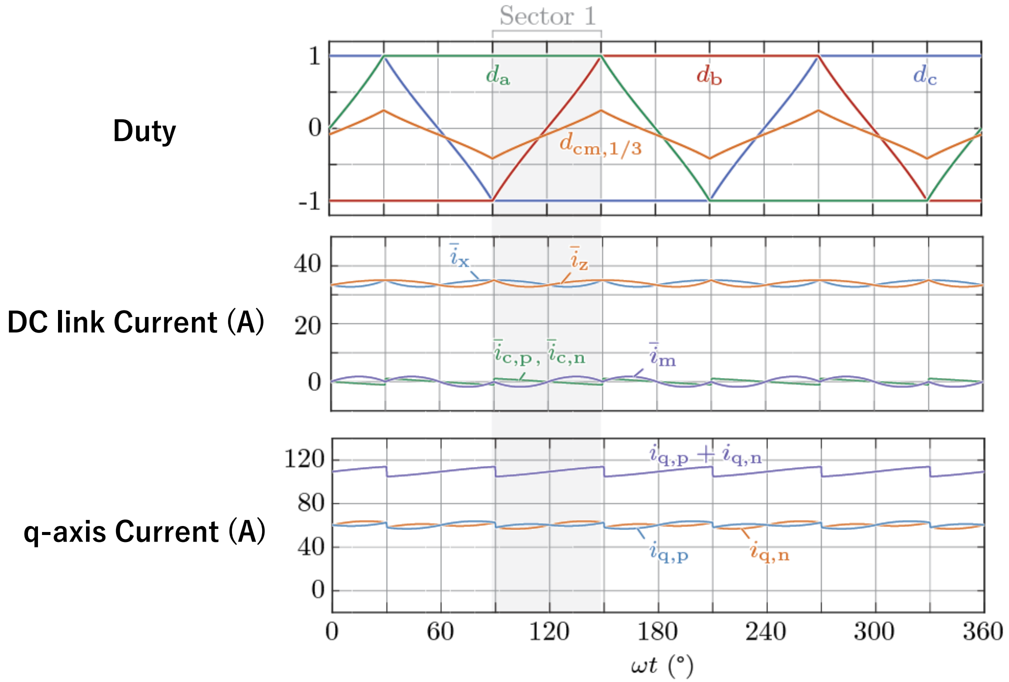
- At low speed, the machine back-EMF is small, and the required DC-link voltage is lower than the grid line-to-line voltage
- The q-axis current component of the inverters supports maintaining the DC-link voltage equal to the grid voltage
- Single-phase switching of the VR is sufficient to sustain power factor correction（PFC）operation



Operation: Low-Speed Operation (1/3-PWM)

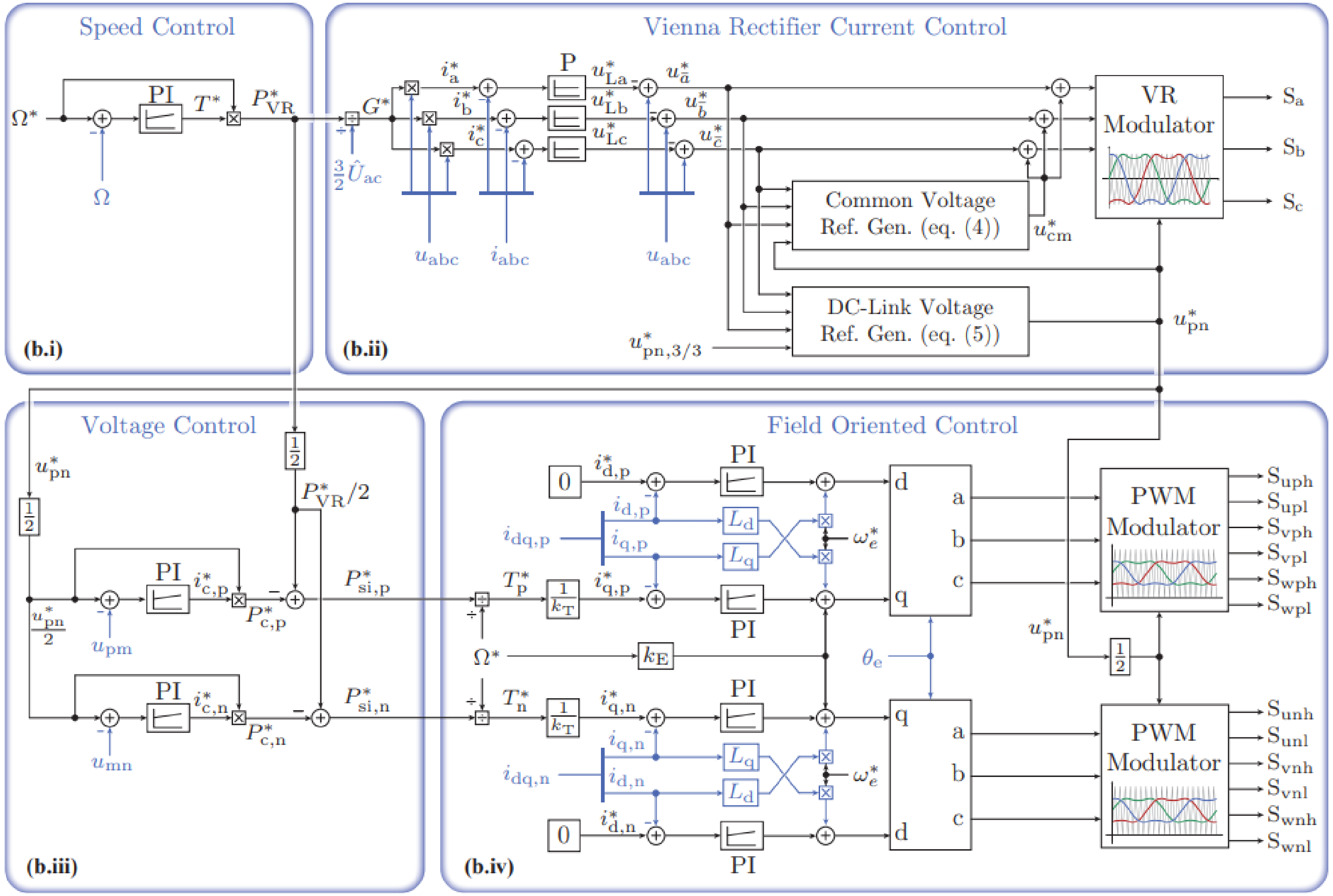
- High-frequency switching is active only during one-third of the grid period, resulting in over 66 % reduction in VR switching losses
- Through synergetic control with the stacked inverters, the grid currents remain sinusoidal with near-unity power factor
- The common-mode voltage of the VR is modulated to generate the 1/3-PWM duty cycles





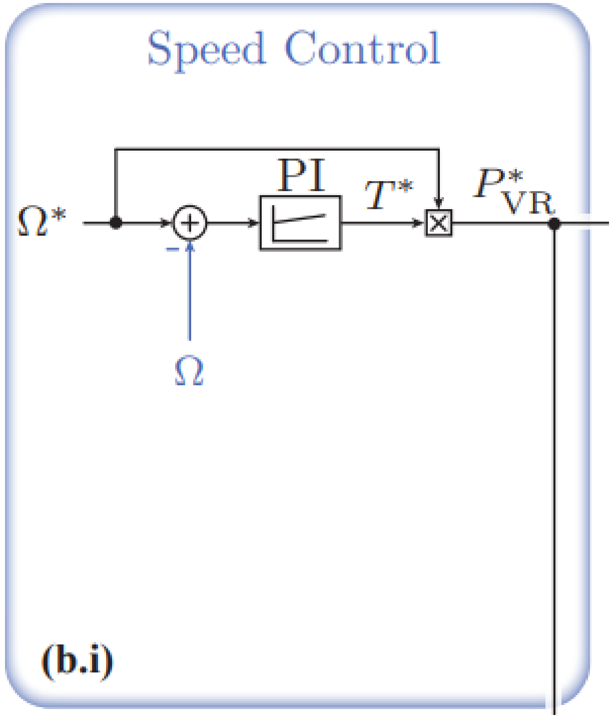
- The midpoint and DC-link capacitor currents fluctuate, but the resulting energy ripple is absorbed by the motor's mechanical inertia

Operation: Control Structure



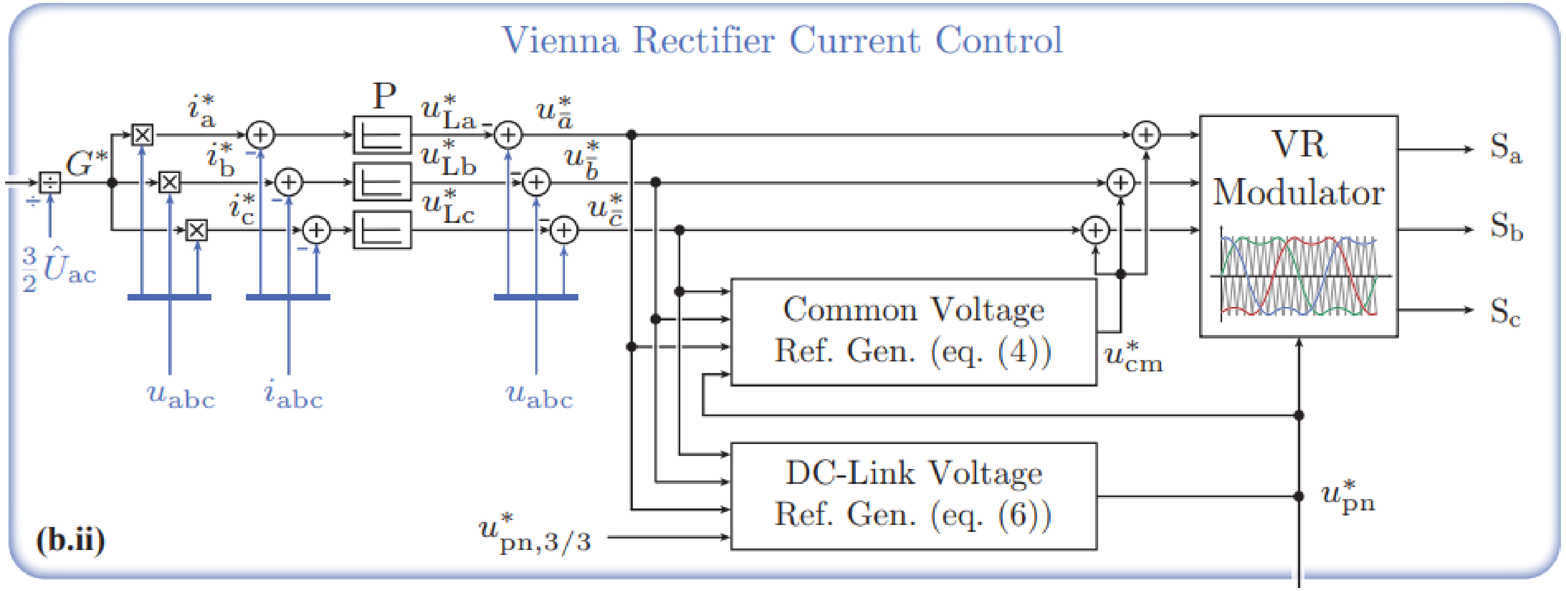
Operation: Speed Control

- The speed controller, forming the outermost control loop, operates with the lowest bandwidth
- Determines the required mechanical power, provided to later-stage controllers



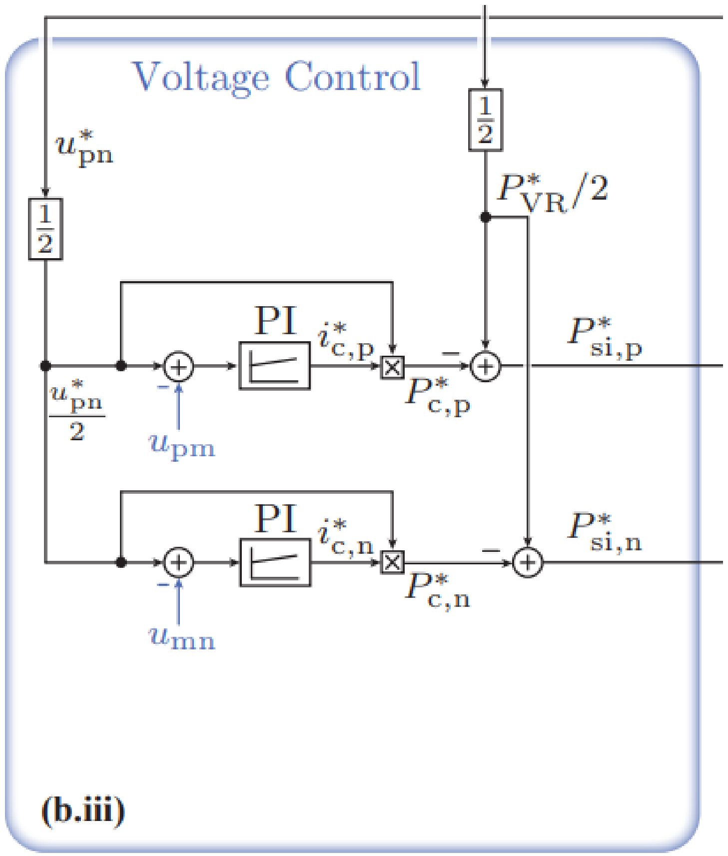
Operation: Current Control of the VR

- The power reference from the speed controller is fed into the VR current controller
- The inner control loops of the VR regulate the grid currents to follow their references
- Based on the voltage reference and operating state of the VR, the common-mode and DC-link voltage references are calculated



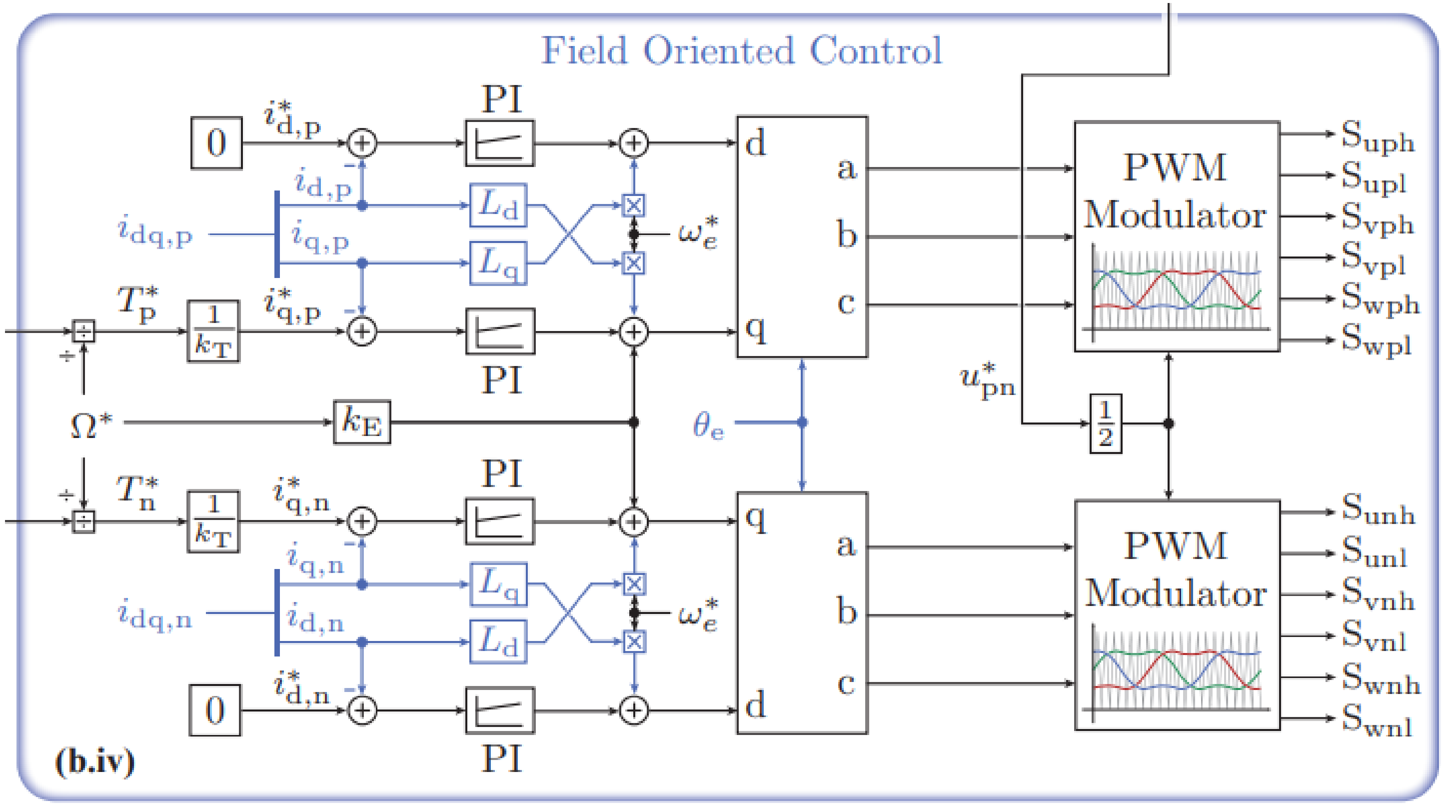
Operation: Voltage Control in 1/3-PWM

- From the voltage reference, the required capacitor power is calculated within the voltage control loop
- The sum of the mechanical power reference and the capacitor power reference is forwarded to the stacked inverter control stage



Operation: Motor Phase Current Control

- Field-oriented control (FOC) is applied to each inverter to regulate the motor phase currents
- The FOC ensures that the torque-producing and flux-producing current components accurately follow their references



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Simulation Results: Simulation Conditions

- The DC-link voltage reference is generated according to a V/f-based profile
- The current control margin $\gamma = 1.2$ is applied to ensure sufficient voltage headroom for accurate current regulation

TABLE I: Simulation parameters.

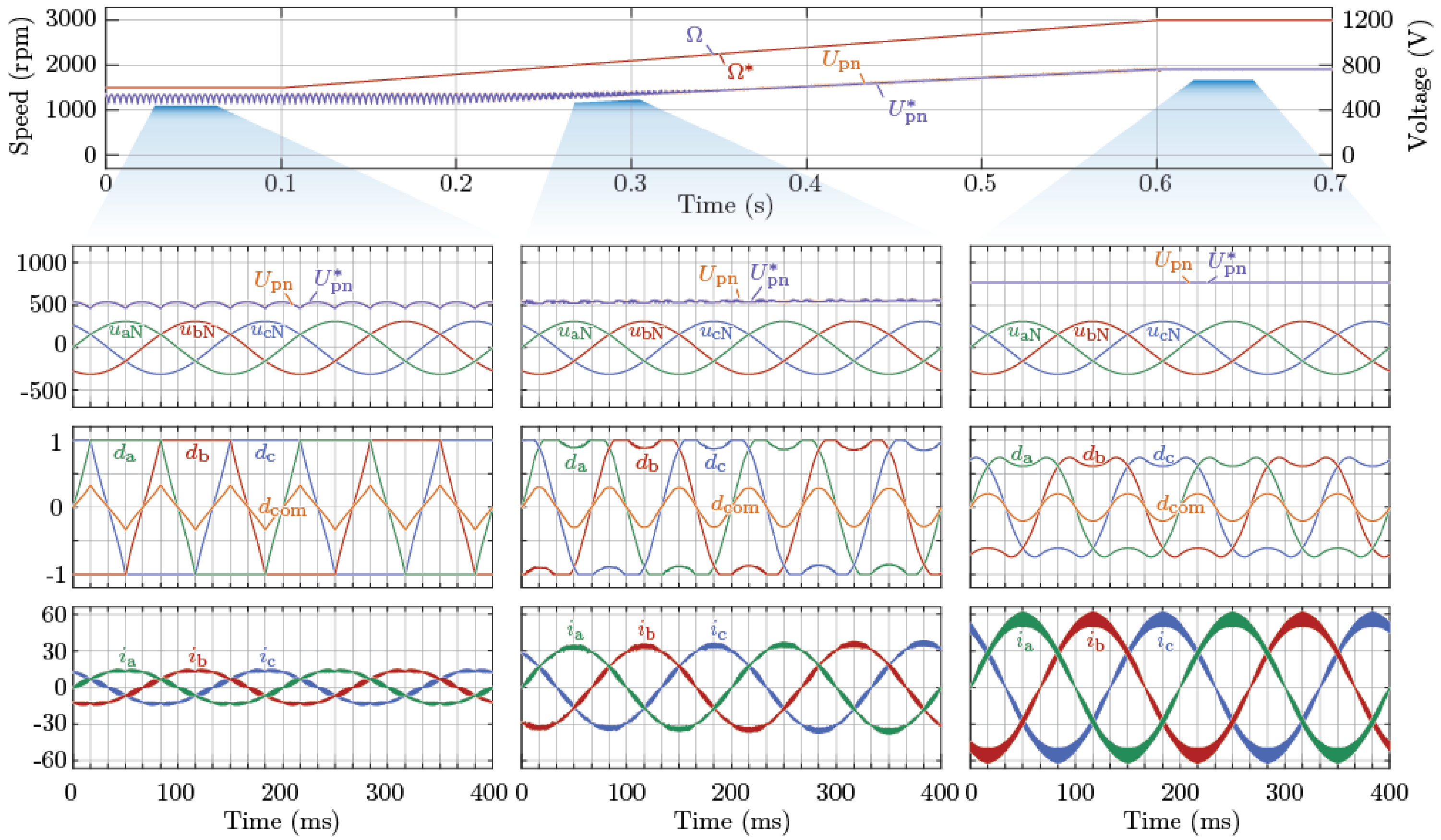
Parameter	Symbol	Value
Vienna Rectifier		
Grid voltage (line to neutral)	$\hat{U}_{ac}$	325 Vpk
Grid frequency	f_g	50 Hz
Switching frequency	$f_{sw,vr}$	100 kHz
Input inductance	$L_{\{a,b,c\}}$	100 µH
DC-link voltage	u_{pn}	560 V to 800 V
DC-link capacitance	C_p, C_n	10 µF
Stacked Inverters		
DC-link voltage	u_{pm}, u_{mn}	280 V to 500 V
Switching frequency	$f_{sw,si}$	100 kHz
dPMSM		
Flux linkage	$\hat{\Phi}$	0.25 Wb
Stator inductance	L_s	2 mH
Number of pole pairs	N_{pp}	2
Moment of inertia	J	0.0446 kg m^2
Nominal phase voltage peak	$\hat{U}$	260 V
Nominal load torque	$T_{load,nom}$	79.6 Nm
Nominal mech. power	P_{nom}	25 kW
Nominal mech. speed	n_{nom}	3000 rpm
Control Parameters		
Bandwidth of speed controller	$f_{bw,speed}$	400 Hz
Bandwidth of VR current controller	$f_{bw,vr}$	10 kHz
Bandwidth of voltage controller	$f_{bw,voltage}$	2 kHz
Bandwidth of dq current controller	$f_{bw,dq}$	10 kHz

voltage reference

$$u_{pn}^{*} = \gamma \frac{\text{nominal DC link Voltage}}{\text{nominal speed}} \Omega^{*}$$

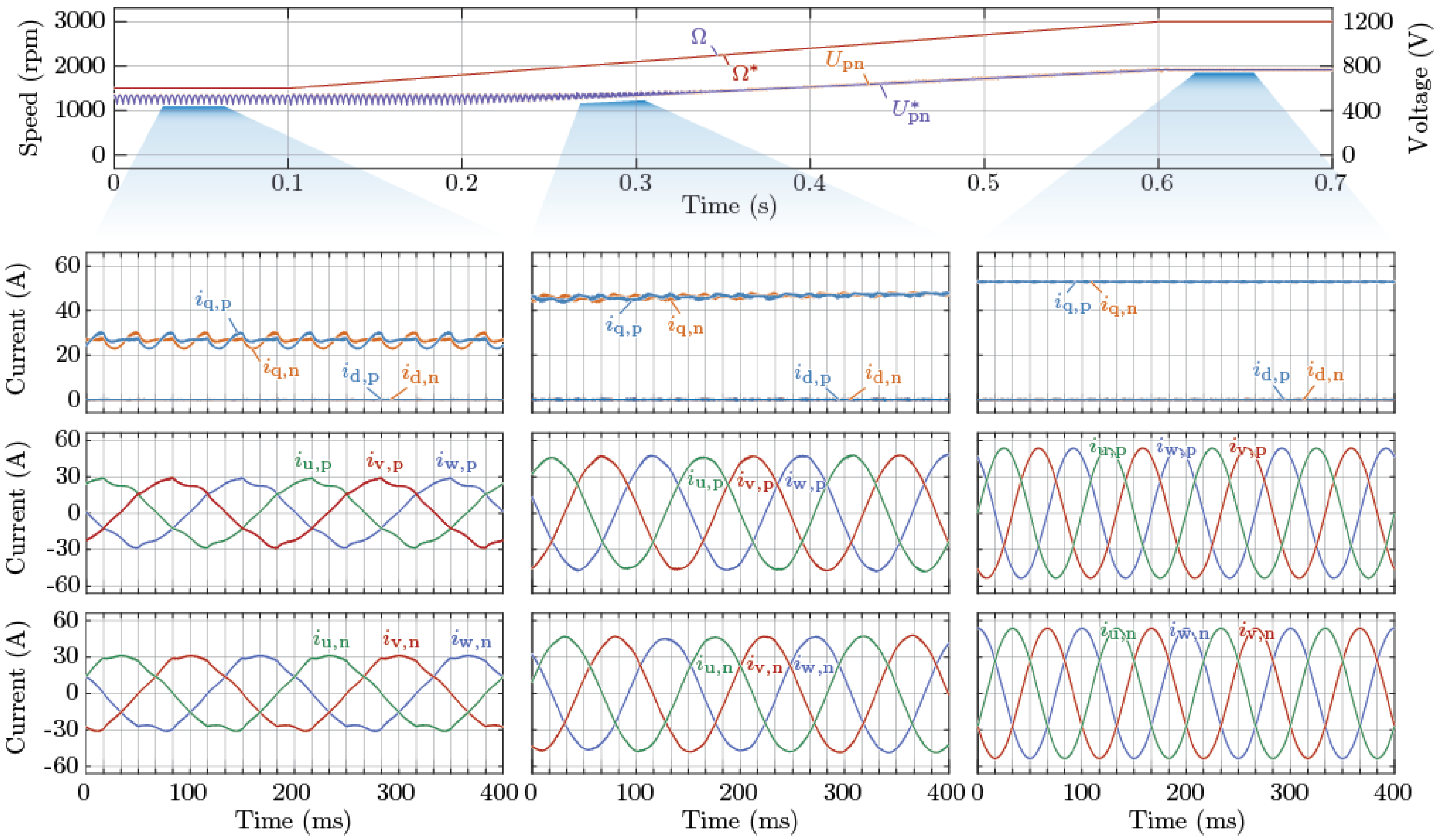
Simulation Results: Vienna Rectifier Operation

- Both speed and DC link voltage track the references
- According to speed, the operation mode transitions smoothly, keeping PFC operation



Simulation Results: Stacked Inverter Operation

- The q-axis current intentionally fluctuates to shape the DC-link voltage into a humped profile under synergetic control



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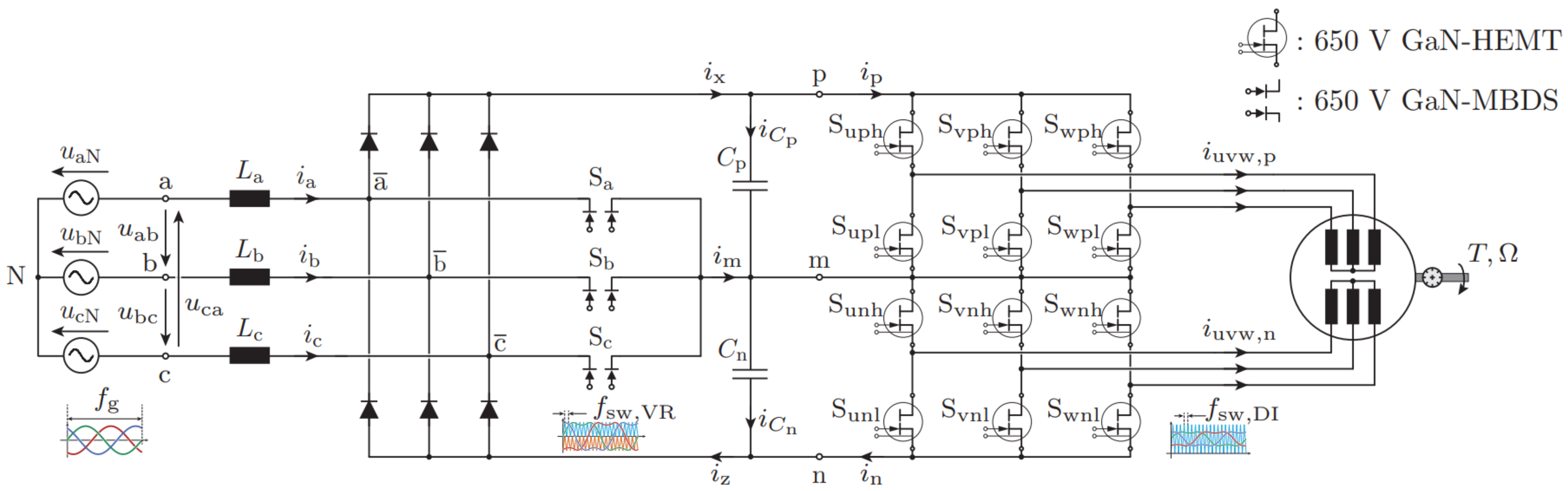
Conclusions

- A novel Vienna-rectifier-based dual three-phase PMSM (VR-dPMSM) drive architecture was introduced..
- The system enables operation with 600 V-class devices, allowing the use of GaN transistors and GaN-MBDSs.
- High performance drives can be feasible with boost characteristic and synergetic conrol across the wide speed range.



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Thank you!

Motor Phase Current RMS

■ Motor phase current ripple

$$i_{\mathrm{uvw,RMS}} = \frac{I_\mathrm{q}}{\sqrt{2}} \left\{ 1 + \frac{1}{I_\mathrm{q}^2/2} \left[\frac{1}{4} \sum_{n=1}^{\infty} i_{\mathrm{m,ripple}}(n)^2 + \frac{1}{4} \sum_{n=1}^{\infty} i_{\mathrm{c,ripple}}(n)^2 \right] \right\}^{1/2}$$

$$= \frac{I_\mathrm{q}}{\sqrt{2}} \sqrt{1 + 0.0032 + 0.195 \cdot \left(\frac{C \cdot 2\pi f_\mathrm{g} \cdot \hat{U}_\mathrm{ac}}{\hat{I}_\mathrm{ac}} \right)^2}, \quad (7)$$

Caused by midpoint current (0.16 %)

Caused by capacitor current (0.004 %)

■ Motor phase current ripple

$$P_C = \frac{U^*_{\mathrm{pn},1/3} \bar{i}_{C,1/3}}{2} = -\frac{3}{4} C \hat{U}_\mathrm{ac}^2 \omega_\mathrm{g} \cos \omega_\mathrm{g} t \sin \omega_\mathrm{g} t. \quad (2)$$

$$|\Delta\Omega| = \left| \frac{1}{J} \int \frac{2P_C}{\Omega^*} dt - \left\langle \frac{1}{J} \int \frac{2P_C}{\Omega^*} dt \right\rangle \right| = \frac{3C\hat{U}_\mathrm{ac}^2}{8J\Omega^*}.$$

0.26 rpm wihtout speed controller