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Increasing acceptance of power
electronics by means of active reliability
and talkative power conversion



Fraunhofer Institute for Silicon
Technology ISIT

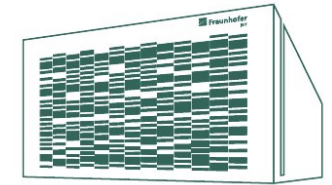


Christian-Albrechts-Universität zu Kiel



Fraunhofer ISIT – the Institute for Silicon Technology

Research and development center for power electronics and MEMS



In Itzehoe since 1996

Competence Center MEMS in Kiel (CAU)
Cooperation with Heide (FHW)



Prof. Dr. Marco Liserre
Acting Managing Director



Prof. Dr. Fabian Lofink
Dep. Managing Director



160 employees
(+ 40 students)



Initial Investment:
125 million €

- 250 million € Industry
- 42 million € Cleanroom II
- 20 million € FMD*



Budget
27 M€/yr



Certified according to
ISO 9001:2015 - Itzehoe

Location Partner



Spin-offs



CAMPTON Diagnostics



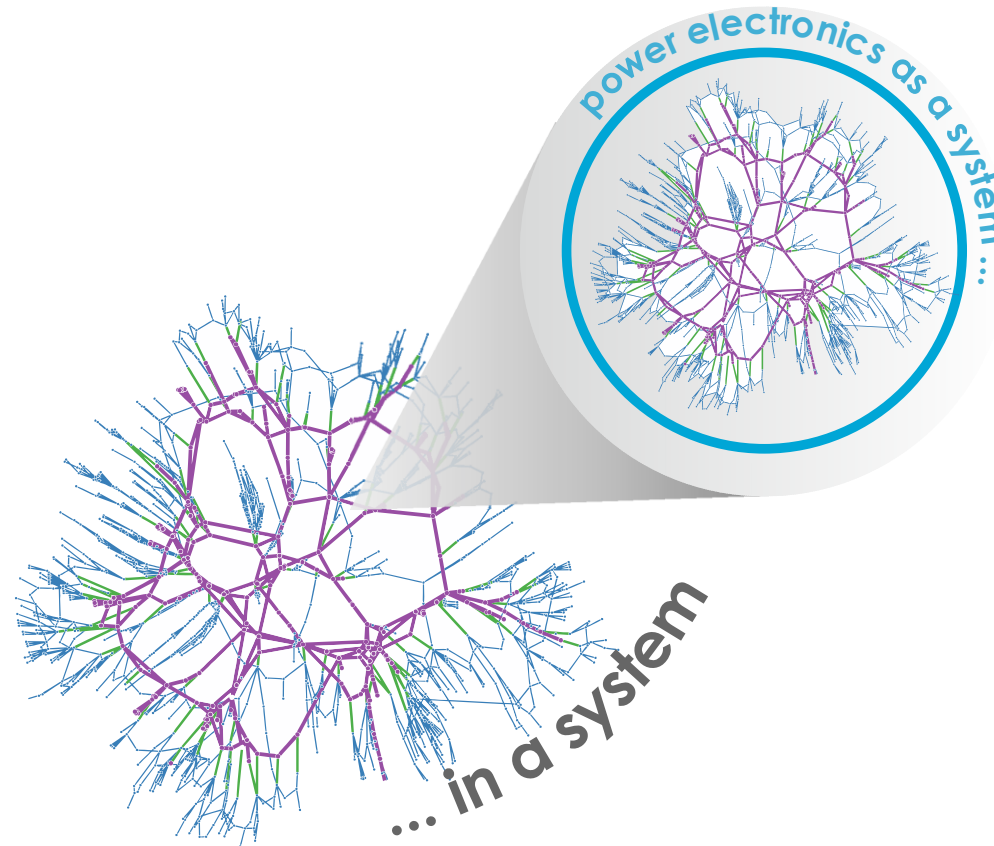
*FMD – Forschungsfabrik Mikroelektronik Deutschland

Importance of Digitalization in Power electronics

Introduction

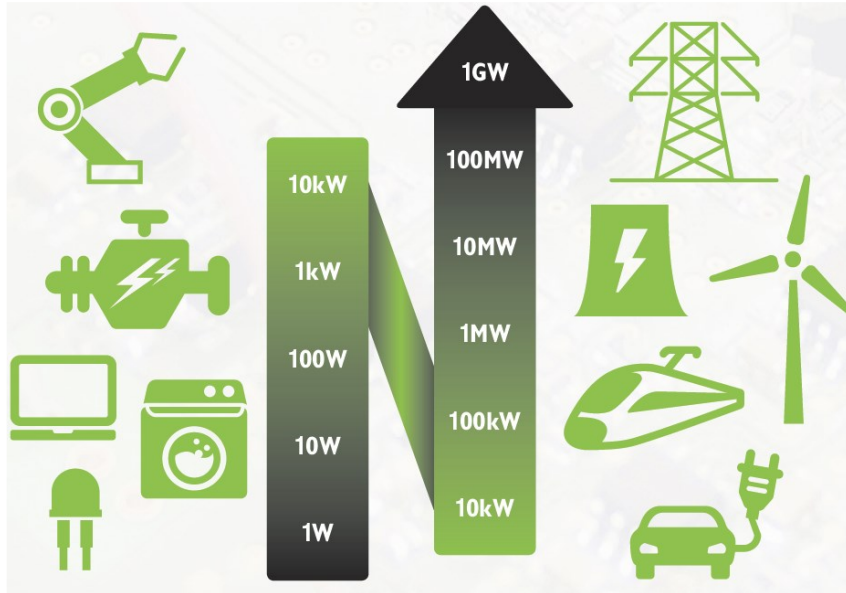
Impact of Power Electronics in Facilitating the Green Transition

Power Electronics is a System into a System



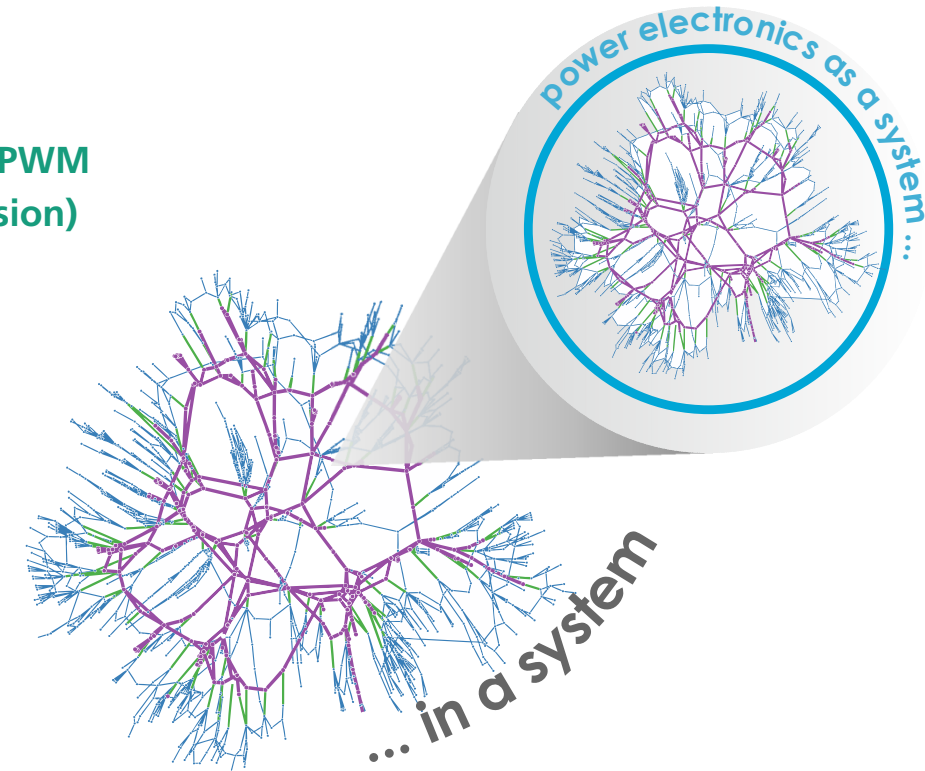
Impact of Power Electronics in Facilitating the Green Transition

Power Electronics is a System into a System



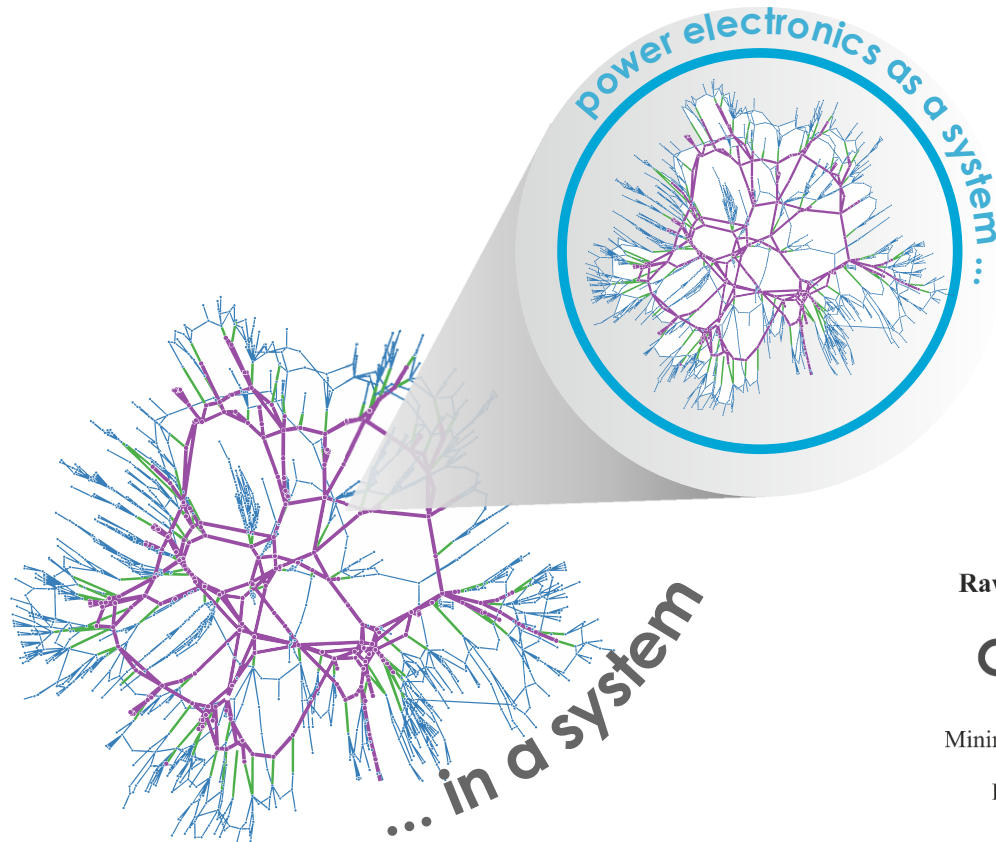
- ✓ Energy saving (30% or More ?)
- ✓ Integration of renewables energies
- ✓ Electronic Grid System
- ✓ **Managing communication with PWM signals (Talkative Power Conversion)**

- ✓ Electrification of transportation sector
- ✓ Key technology in sector-coupling
- ✓ Optimal control of electrochemical processes (catalysis, batteries)

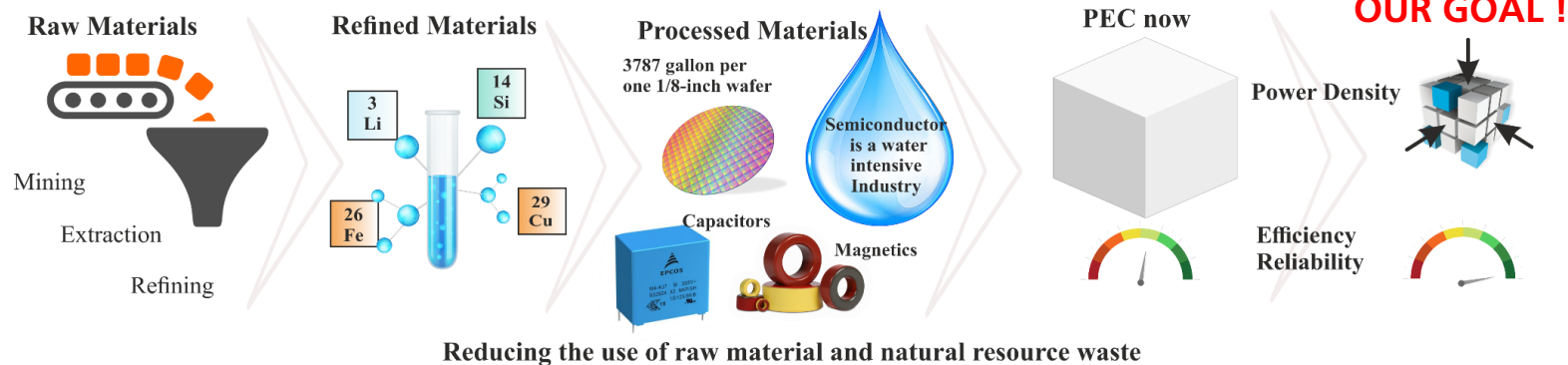


Impact of Power Electronics in Facilitating the Green Transition

Power Electronics is a System into a System



- ✓ smaller PE makes also transport greener
- ✓ PE reduces material use: 1 MVA High frequency Trafo saves 100 Tons CO2 !
- ✓ PE shall be reparable: stop throwing away electronics !
- ✓ **but we have also to use less materials: active reliability for longer life**



Introduction

Digitalisation of power electronics is key for active reliability and talkative power conversion

Technical constraints:

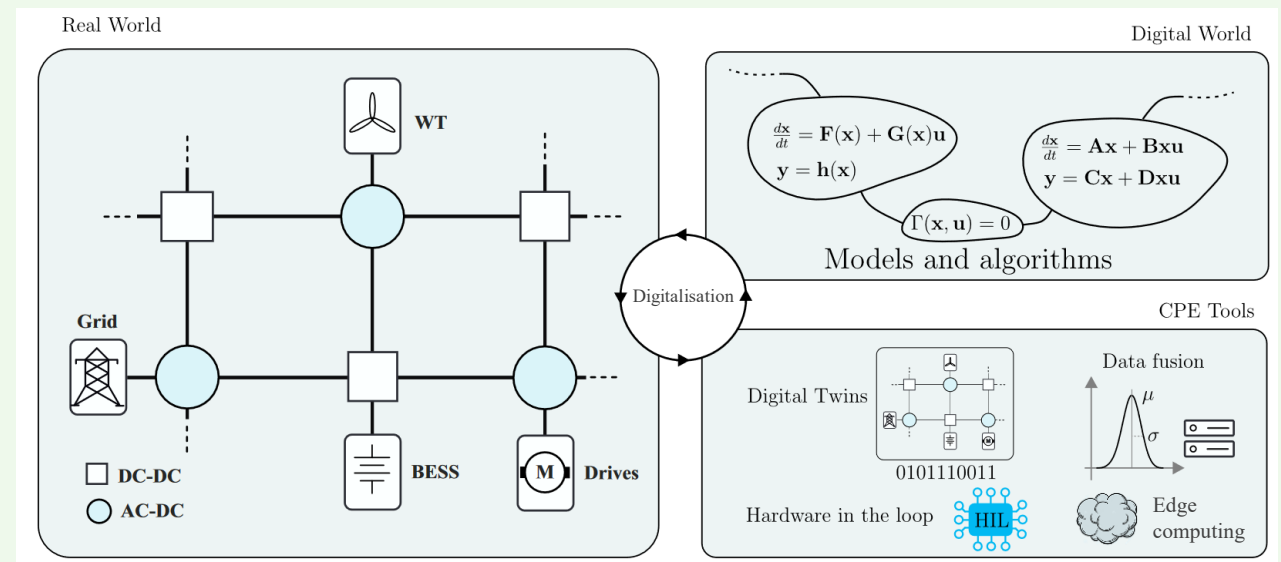
- Complexification of systems, intrinsically multi-physic
- Limited computing resources available
- Uncertainty also associated to new WBG devices

Economical & societal constraints:

- Design and profit margin reduction
- Increased design cycle speed
- Sustainability: efficiency, resource scarcity, e-waste reduction
- Privacy vs. data sharing & processing

➤ Performance improvement:

- Comes from hardware and software combination
- Through system-level design and optimisation
- Using minima extra sensing, and better using available data

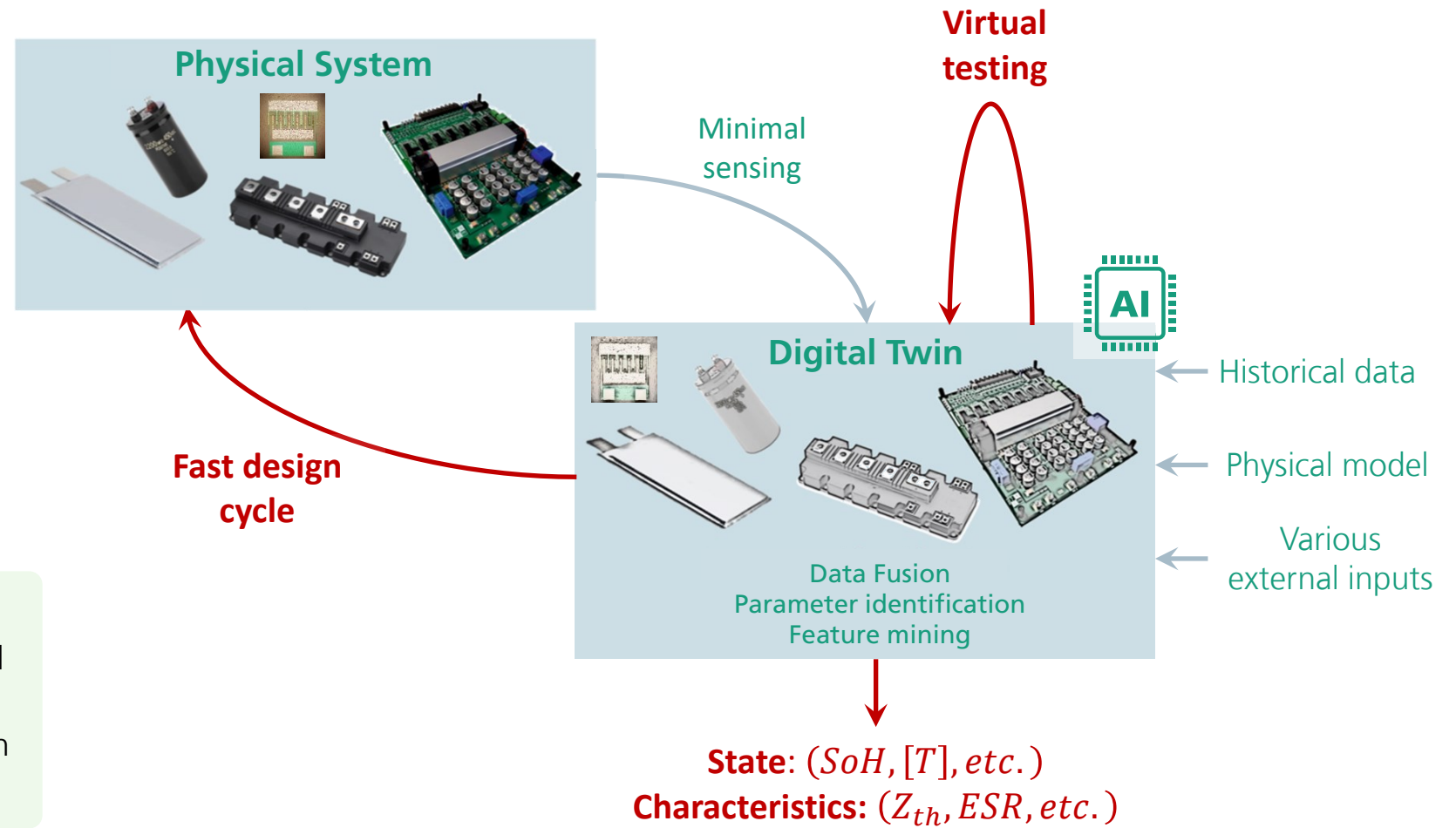


Smart data processing for estimation of temperature, SoH, SoC...

State identification using advanced digital tools

Digital twins

A versatile high accuracy virtual replica of devices and systems – AI-powered



Digital twins:

- Are measurement-calibrated model
- Are highly accurate
- Are suitable for real time simulation
- Can be dynamically updated

Digital Twin of a power module

Condition monitoring through online thermal impedance identification

Challenge:

- Complex online SoH estimation: degradation precursors (eg. Vce) are multi-variable and have low-sensitivity

Our approach:

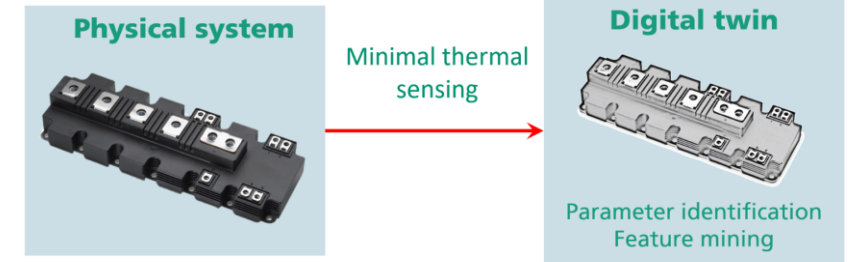
- Online thermal model identification, using minimal sensing
- Identification using Kalman filter, PSO, LSQ, etc.

User benefits:

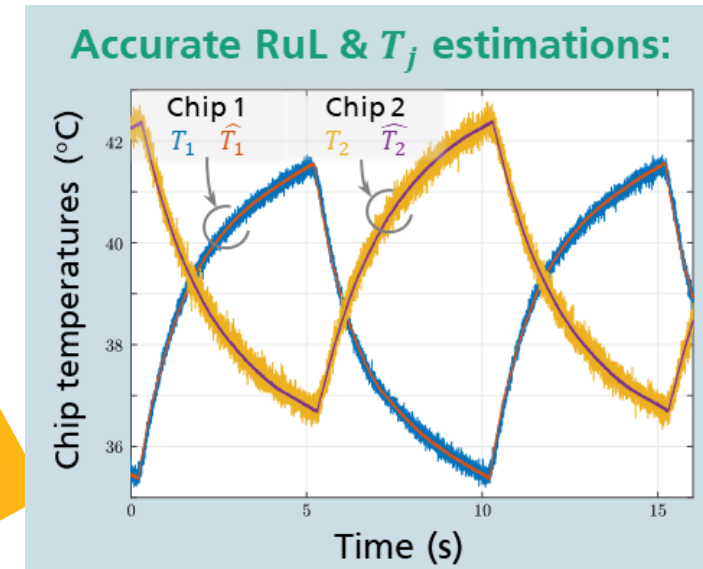
- Online monitoring of thermal system ageing
- Design margin reduction, owing to accurate T_j estimations
- Improved lifetime through active thermal control & PQ-power curve extension

- J. Kuprat, et al., "Real-Time Thermal Characterization of Power Semiconductors using a PSO-based Digital Twin Approach," Eur. Conf. Power Electron. App. (EPE ECCE Eur.), 2022
- J. Kuprat, et al., "Thermal Digital Twin of Power Electronics Modules for Online Thermal Parameter Identification". IEEE J. Emerging Sel. Topics in Power Electron, 2023.

First thermal digital twin

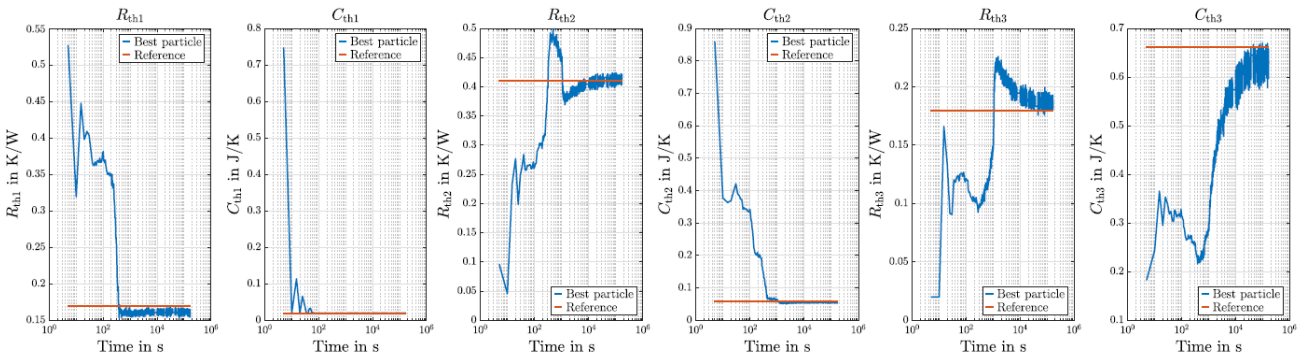
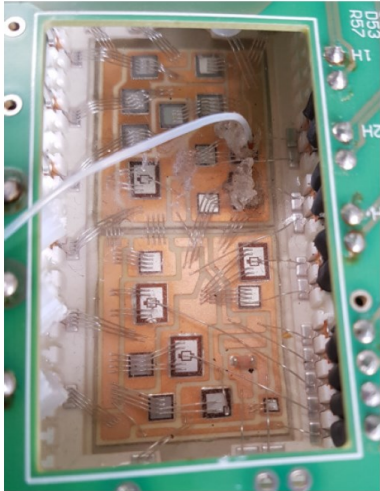
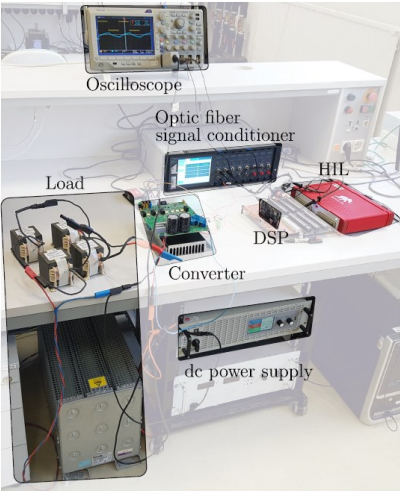
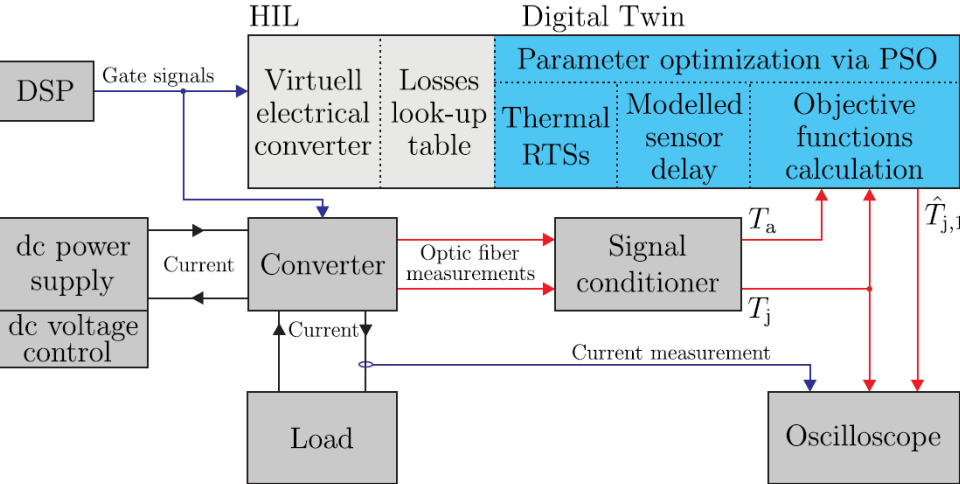


State: (SoH, T_j , etc.)



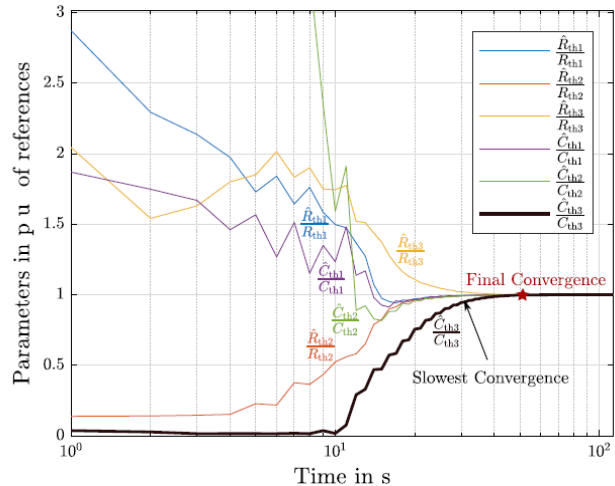
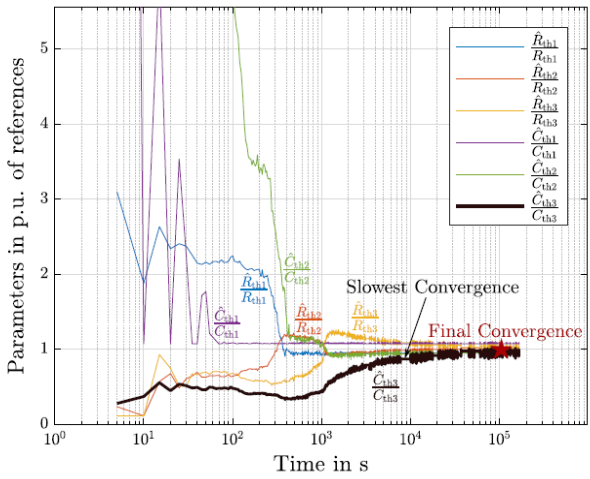
Experimental validation:
Identification of
3-cell Foster model

Validation and Comparison



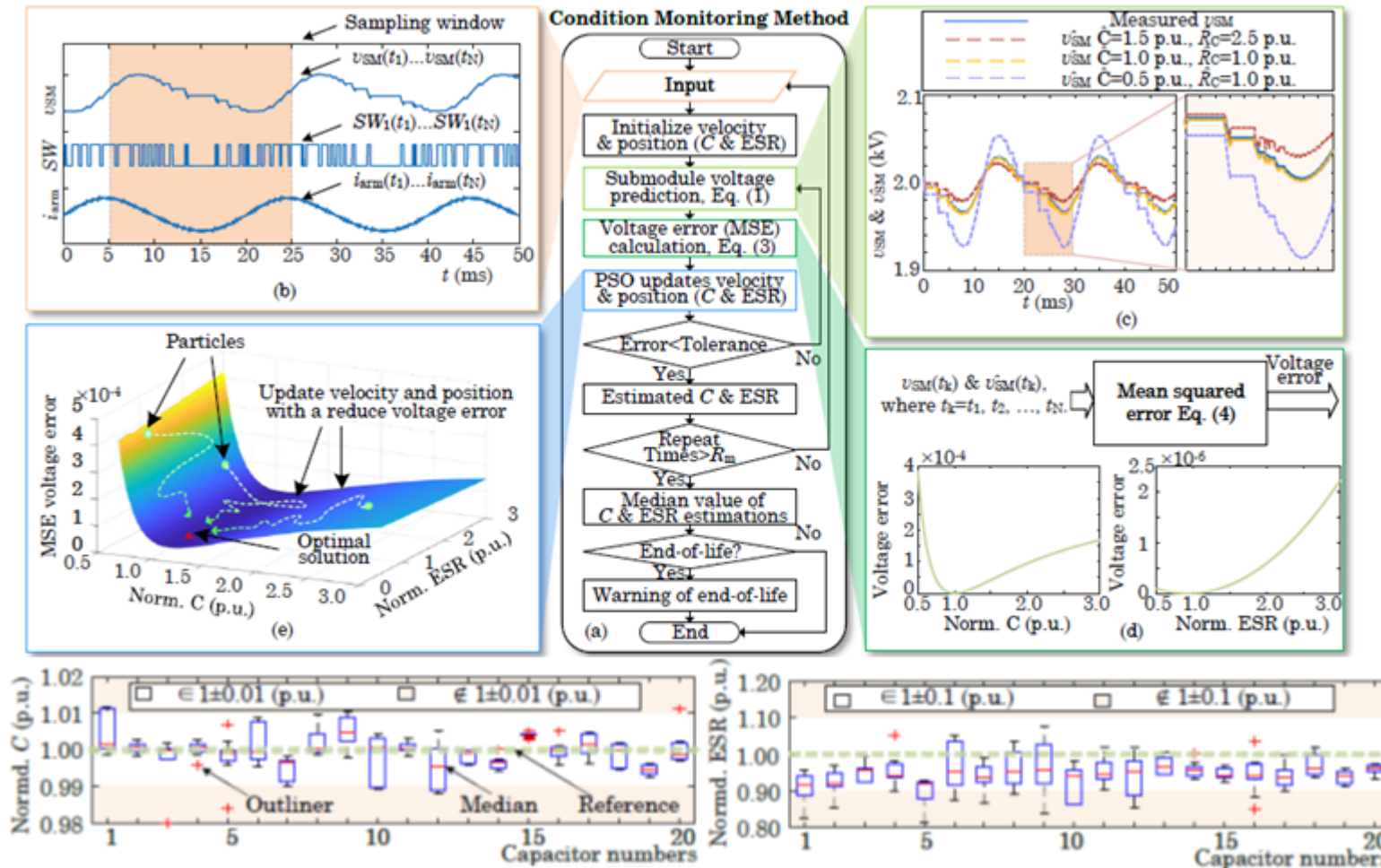
PSO

Kalman Filter



Digital Twin of MMC DC-link capacitor

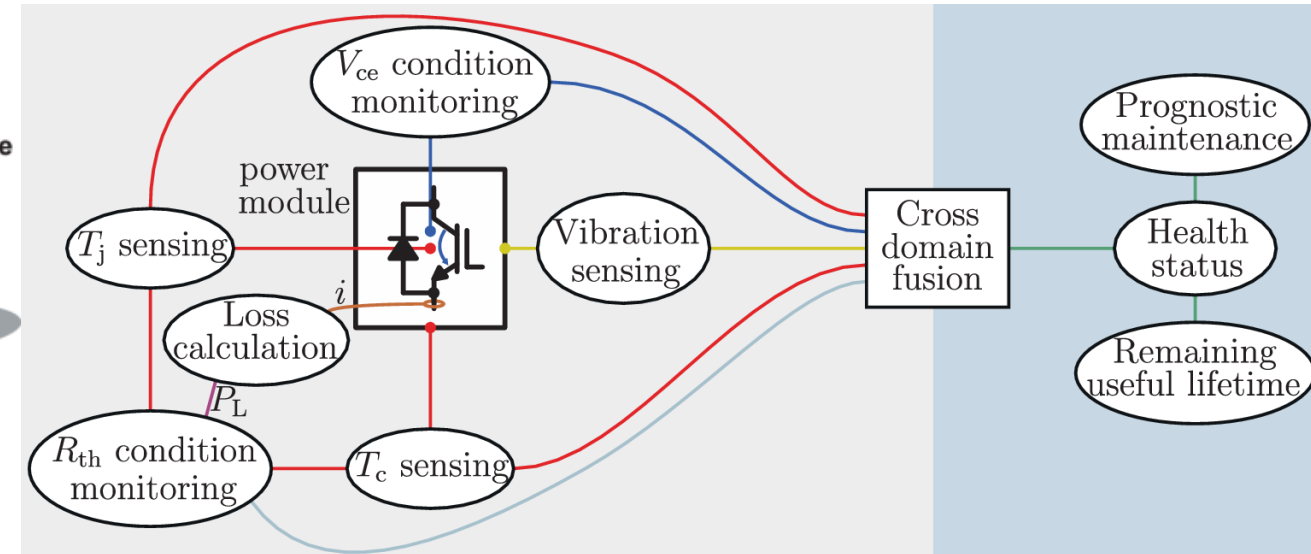
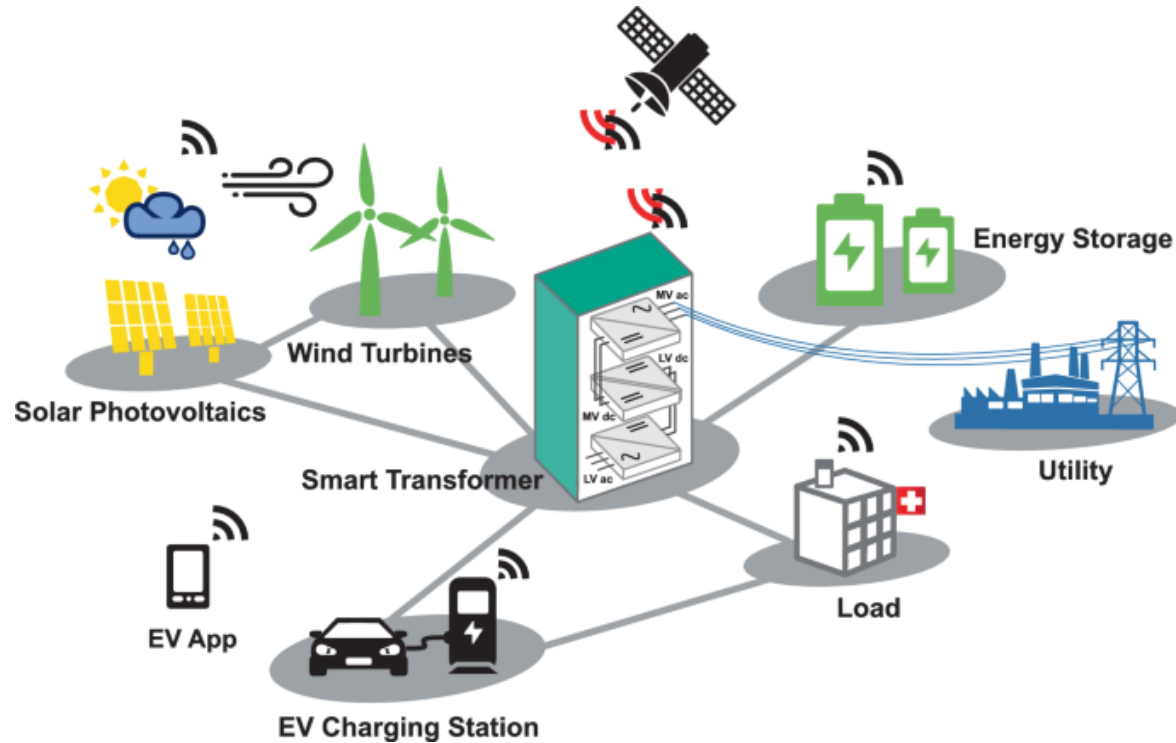
Condition monitoring through online parameter identification: (C , ESR)



Shuyu Ou, et al. "Monolithic Data-Driven Condition Monitoring Strategy for MMC Considering C and ESR." IEEE Trans. Power Electron. (2025).

Data-fusion for power electronics

Merging different data



Sante, P., Landsiedel, O., Kuprat, J. et al. Cross domain fusion in power electronics dominated distribution grids. Informatik Spektrum 45, 284–289 (2022).

Data-fusion for power module condition monitoring

Merging different SOH estimators

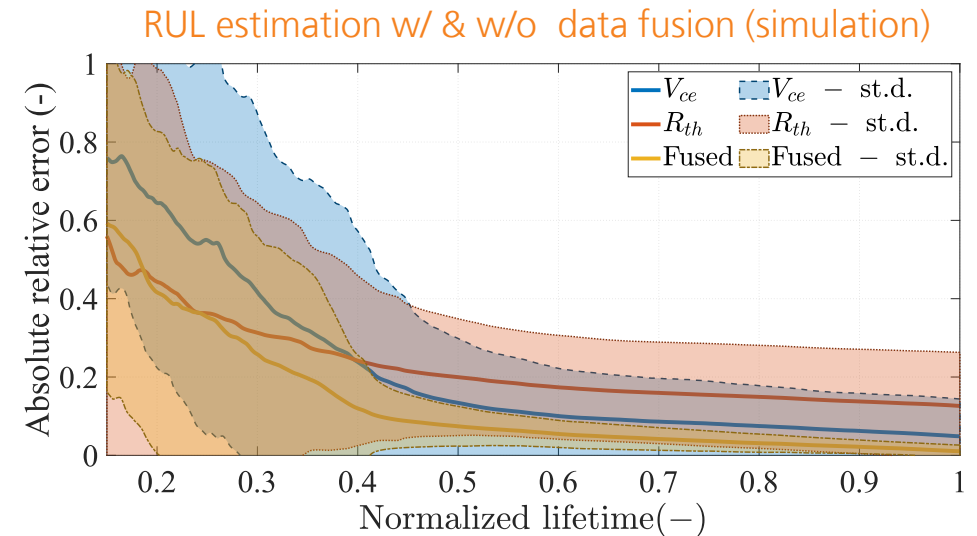
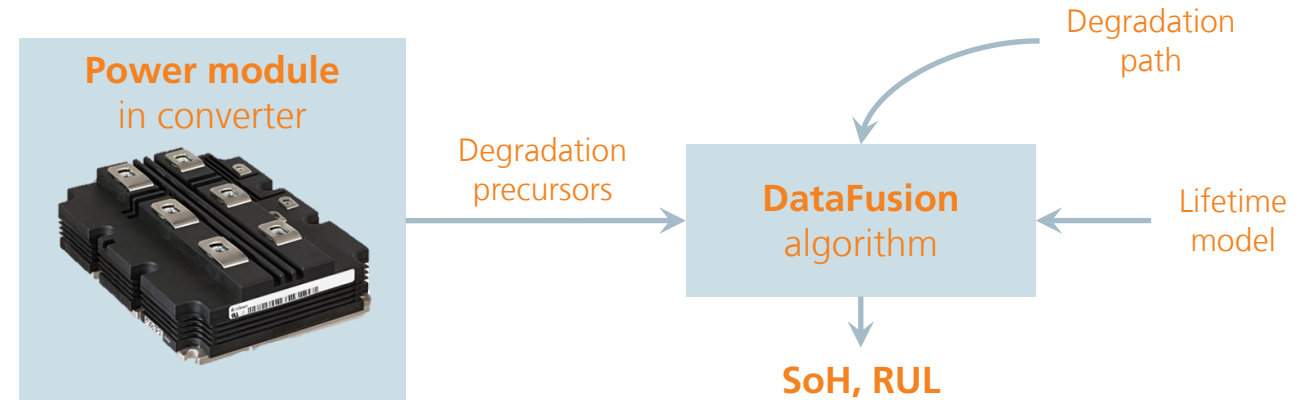
Approach:

- Optimally merge SoH estimations from multiple degradation precursors (V_{ce} , R_{th})
- Validation using Monte-Carlo simulations

Results:

- Quasi-systematic **reduction in error & uncertainty of SoH and RuL estimation**, vs use of a single precursor
- Increased accuracy of online condition monitoring
- Reduced impact of degradation path uncertainty
- Improved robustness vs. sensor shifts and failure

M. Votava, et al., "Multi-sensor Data Fusion for Prediction of Remaining Useful Life of IGBT Power Modules", ESREF'24, Italy



Vce for Tj Estimation of IGBT

Data-driven approaches

Challenge:

- Real-time and precise Junction temperature (T_j) estimation.
- Temperature Sensitive Electrical Parameters (TSEPs):
 T_j indicator, but sensitive to noise and difficult for dynamic est.
- Inflection point** : $T_{j1} = T_{j2} = f(V_{ce(on)}, I_c)$
Change in Negative – Positive temperature coefficient

Our approach:

- Machine Learning (Supervised Learning)
- Recurrent Neural Network (RNN): Long-Short term Memory (LSTM)

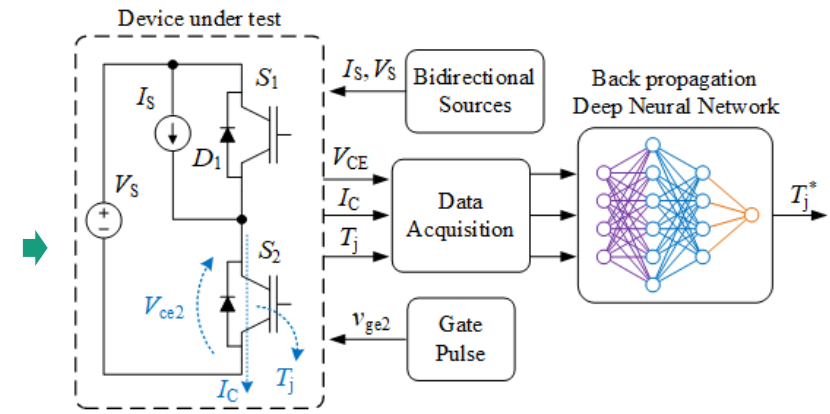
User benefits:

- Precise T_j estimation without expensive monitoring equipment
- Used for active reliability of Power electronics converters
- Maximized performance under safety margin with T_j estimation

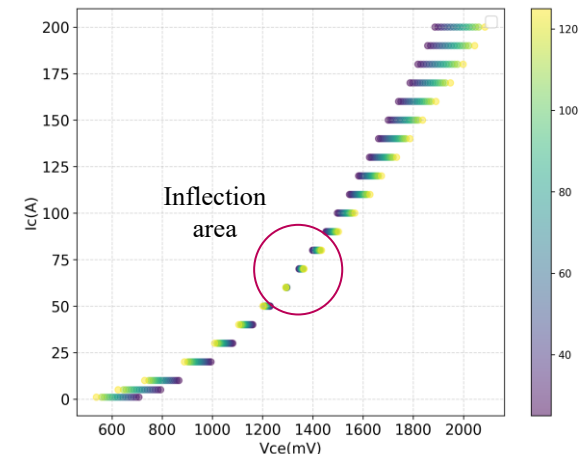
V.Y. Konda, J.-H. Jung and M. Liserre, "Intelligent Junction Temperature Estimation of an IGBT Using Machine Learning and Vce Measurement," 2024 IEEE 15th Int. Symp. Power Electron. for Distributed Gen. Syst. (PEDG), Luxembourg, 2024



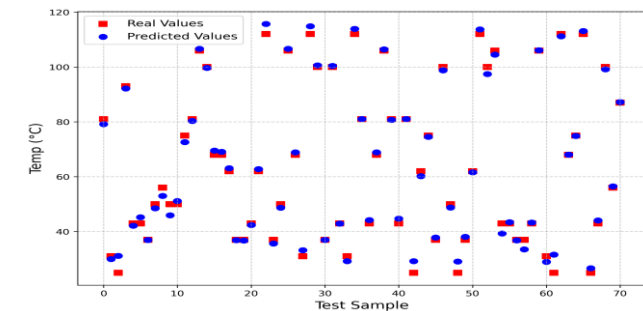
IGBT open module under test



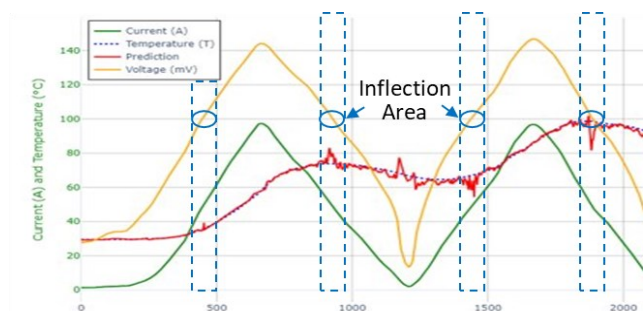
Configuration of T_j estimation using ML with V_{ce}



Junction temperature according to V_{ce} and I_c



Validation of Sequential model predictions



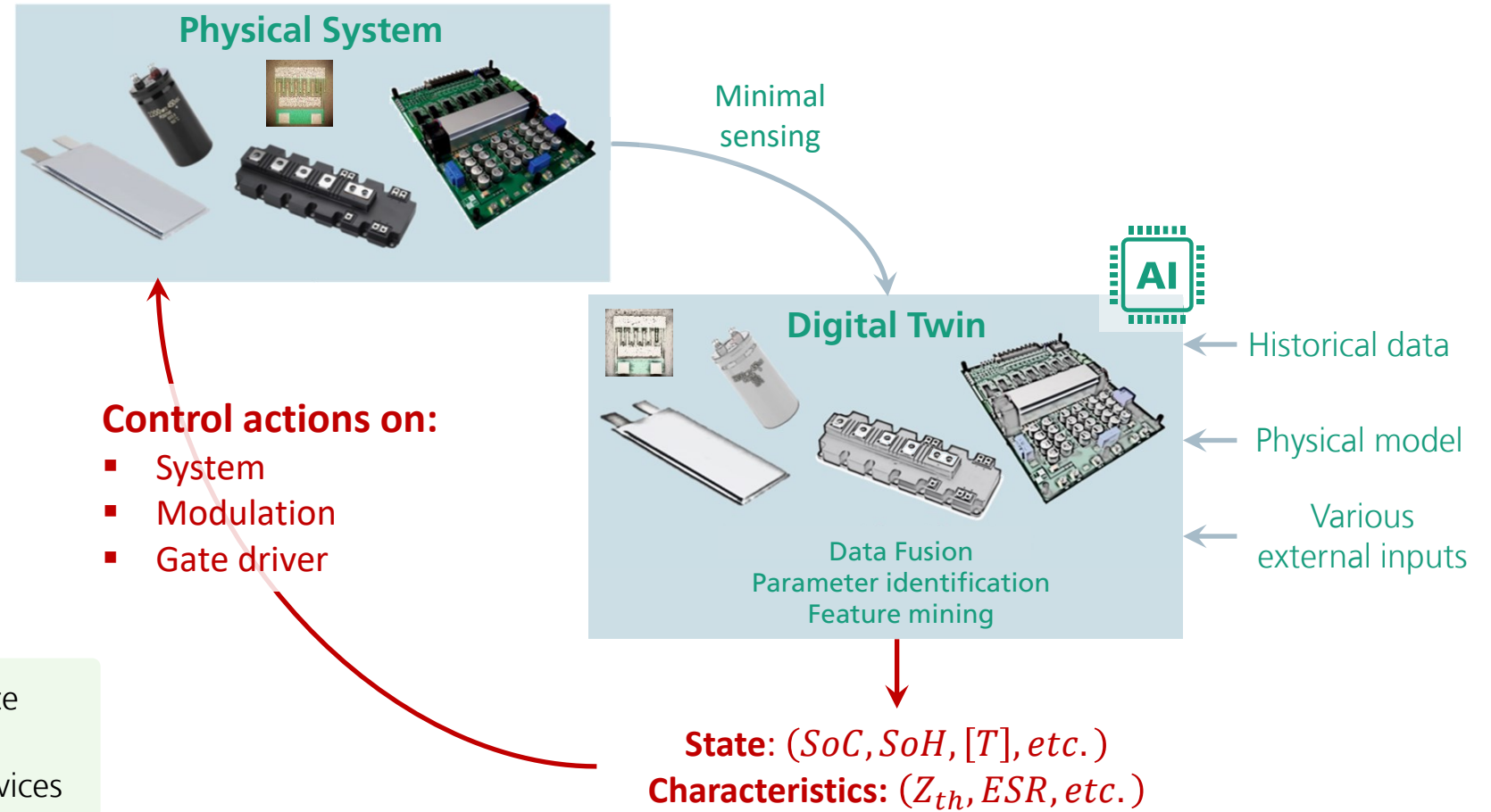
Validation under continuous conditions



Optimal multiobjective control of power converters

Active Reliability

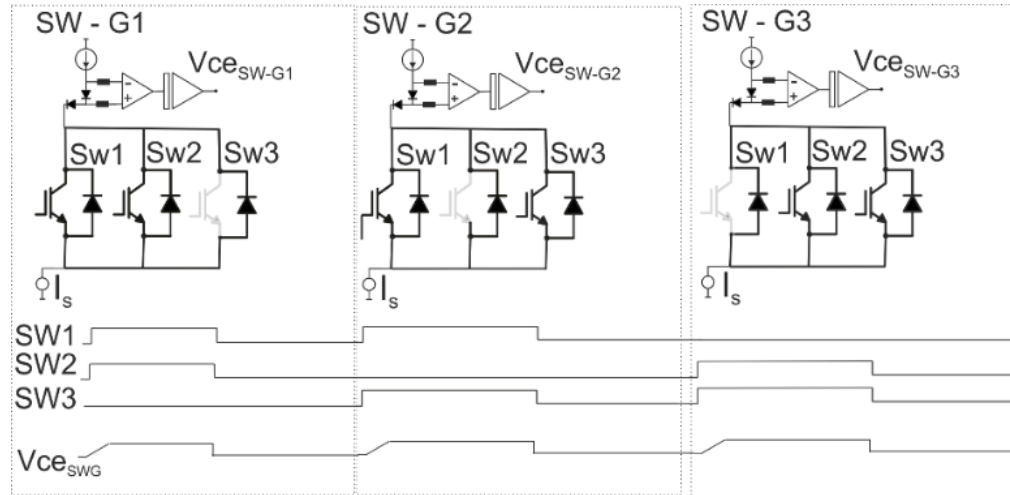
Active Reliability



- Reduced ageing, delayed maintenance
- Increased overload capability
- Balancing thermal stress of power devices

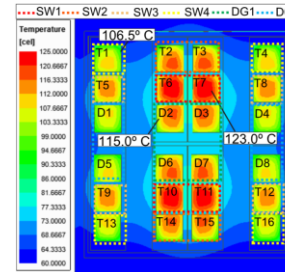
Die-level active thermal control for T_j homogenisation

Pulse shadowing

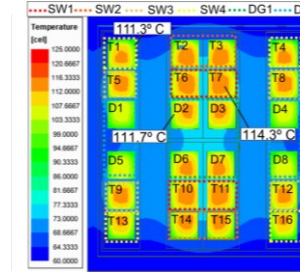


- Loss-manipulation to achieve thermal balancing and reduce peak thermal stress
- Manipulation of:
 - Turn-on or -off loss: die-soft switching
 - Conduction & switching loss: pulse shadowing

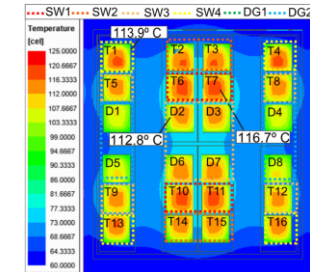
No T_j control



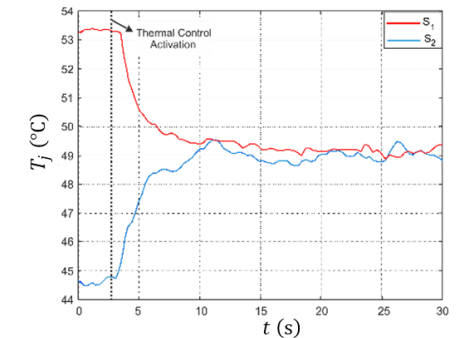
Turn-off loss control:



Pulse shadowing:



$T_j(t)$ deduced from V_{ce} measurement



V. Ferreira, M. Andresen, B. Cardoso and M. Liserre, "Pulse-Shadowing-Based Thermal Balancing in Multichip Modules," in IEEE Trans. Ind. Applications, vol. 56, no. 4, 2020

V. Ferreira, M. Andresen, B. Cardoso and M. Liserre, "Selective Soft-Switching for Thermal Balancing in IGBT-Based Multichip Systems," in IEEE Trans. Emerg. Sel. Topics Power Electron., vol. 9, no. 4, 2021

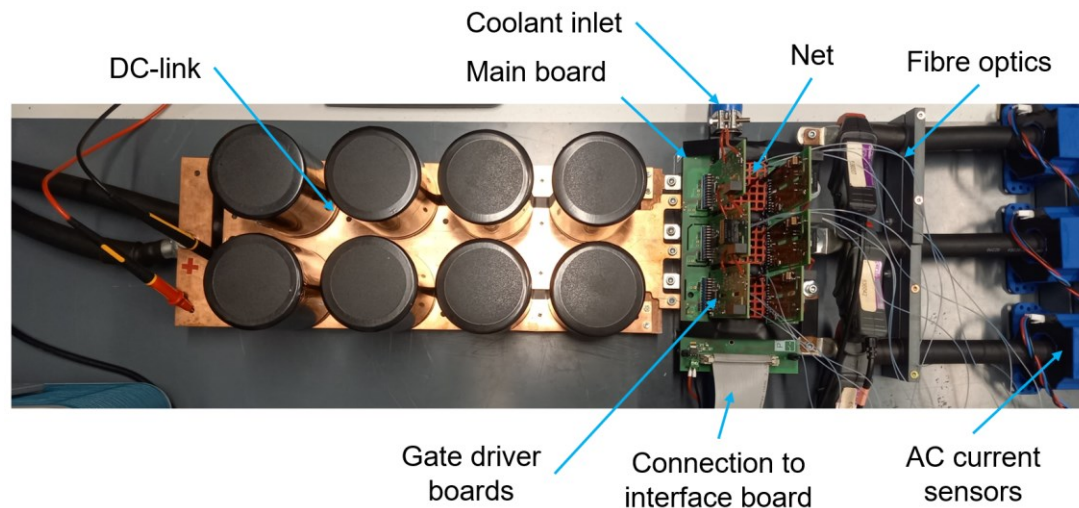
Power module of traction inverter: thermal monitoring and control

An application in electromobility – industrial project

3-Phase 100 kW Si-IGBT inverter, 400 Vdc

Power module under test:

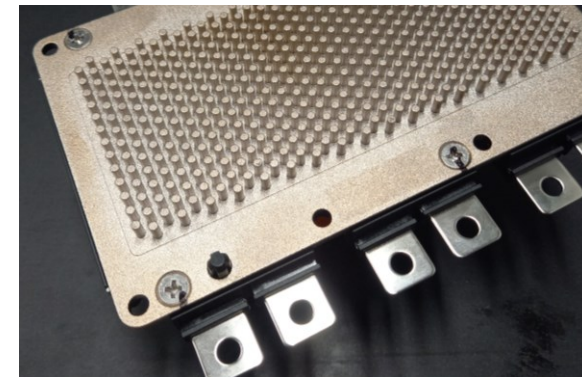
- Six-pack, multi-chip with 42 dies
- High performance cooling (pin fins)
- Rated: 750 V – 450 A
- WLTC-3b mission profile



Project objectives:

- Development of a 100 kW circulating power set-up
- Full thermal characterisation and model extraction
- **Development of:**
 - T_j estimator and observer
 - $\Delta R_{th}/R_{th}$ estimator

Active thermal control using f_{sw} control for thermal cycling reduction



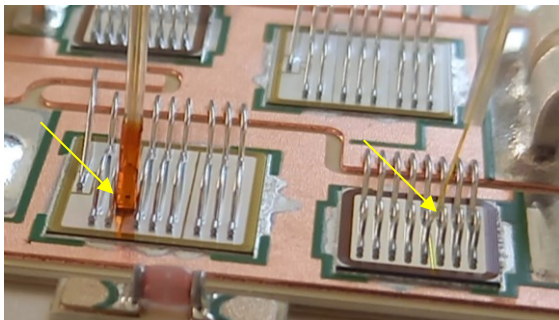
Thermal characterisation & model extraction

Z_{th} characterisation:

- High accuracy (fiber optics)
- High speed ($t_r \sim 100$ ms, $f_{samp} = 1$ kHz)
- Local probing (hotspot): $150\text{ }\mu\text{m}$

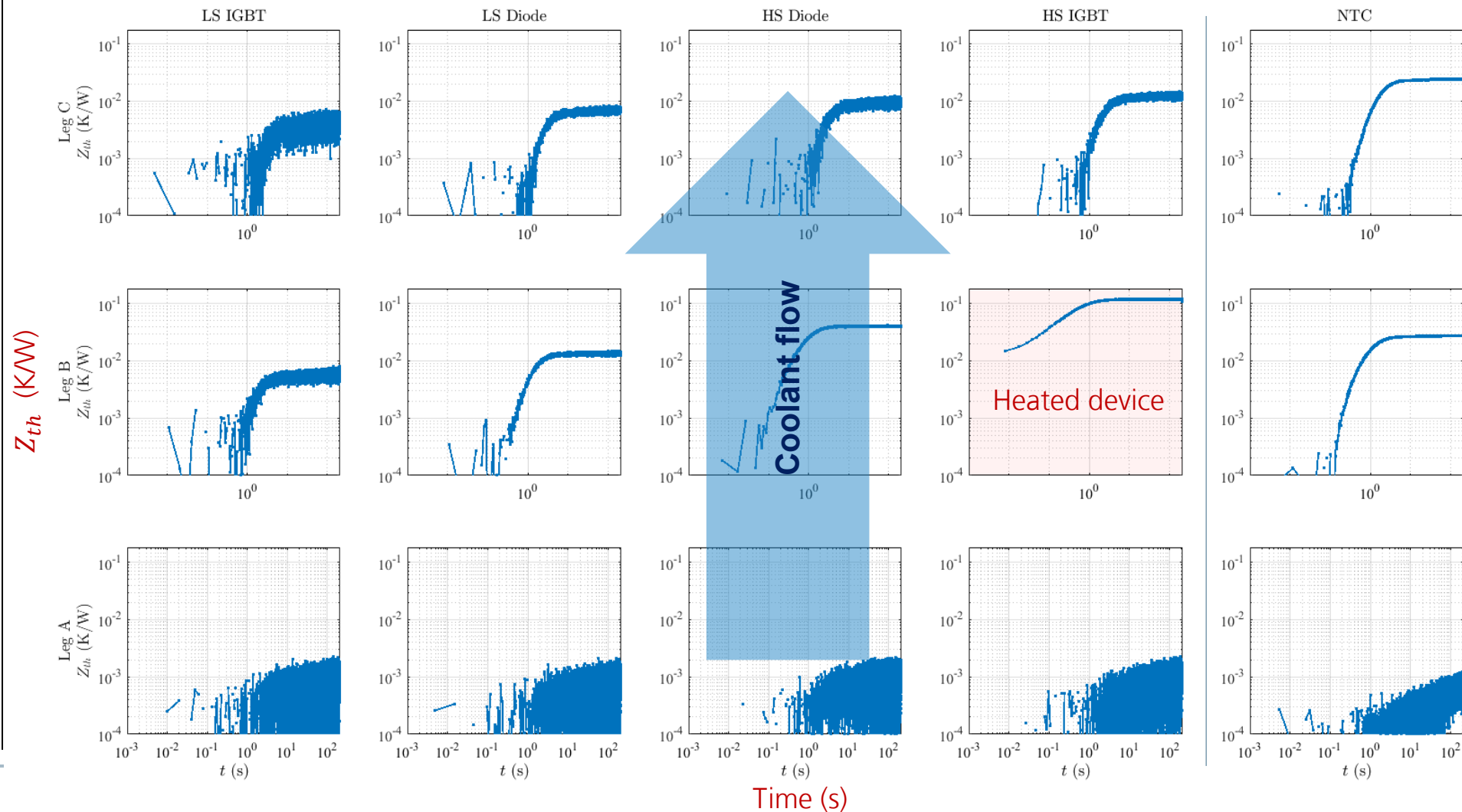
Model extraction:

- 3-cell Foster network
- Offline fitting
- Multi-step prediction



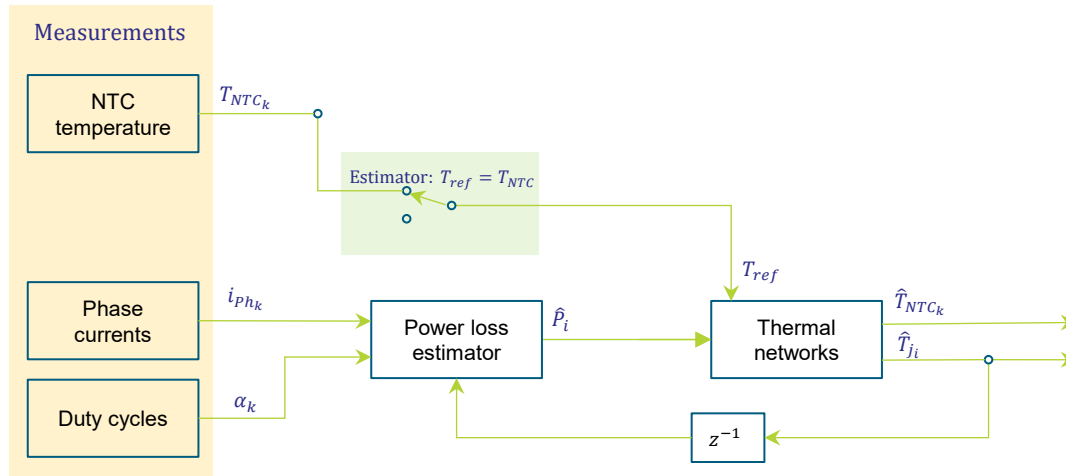
Fiber-optics based sensors

Thermal step response



Thermal estimators

Correction through an observer

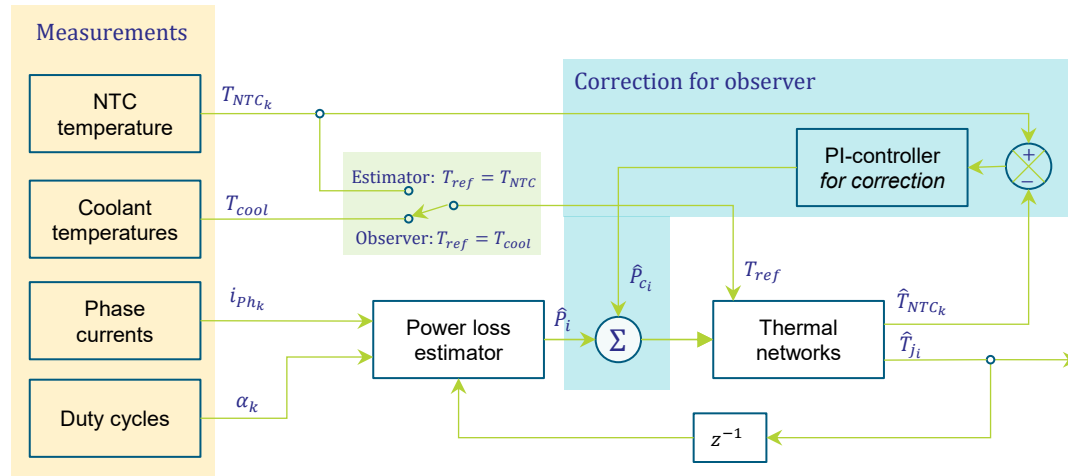


Tj-estimator:

- Open loop
- Use standard NTC: no extra sensor required
- Does not account for the parameter shift or initial tolerance
- ± 2 K error with thermal characterisation | no loss characterisation

Thermal estimators

Correction through an observer



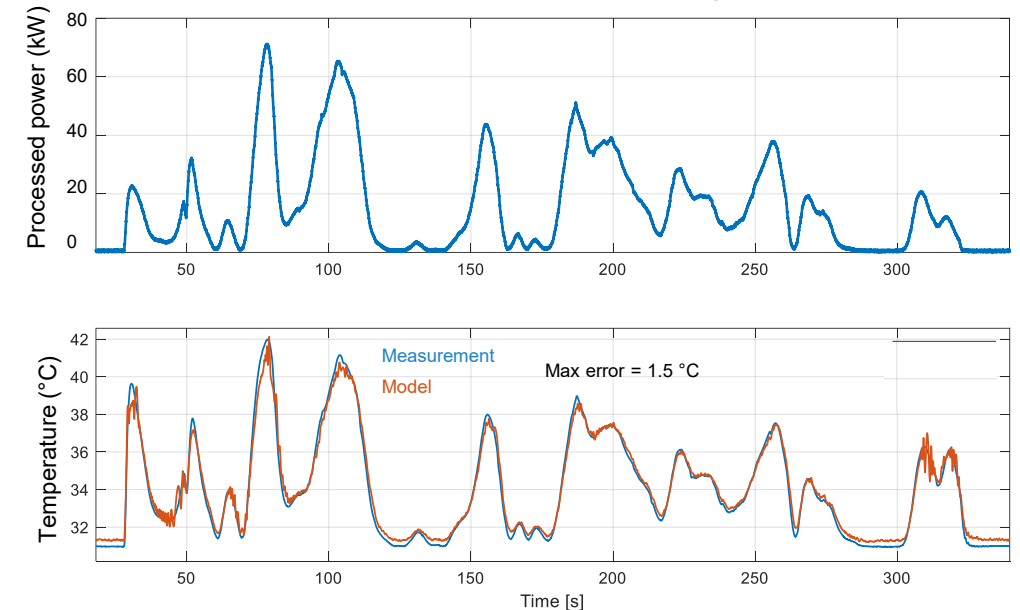
Tj-estimator:

- Open loop
- Use standard NTC: no extra sensor required
- Does not account for the parameter shift or initial tolerance
- ± 2 K error with thermal characterisation | no loss characterisation

Tj-observer:

- Close-loop structure: compensate effects of ageing and initial tolerance
- Require extra temperature sensor
- ± 1.5 K error with thermal characterisation | no loss characterisation

Experimental validation of the Tj-observer



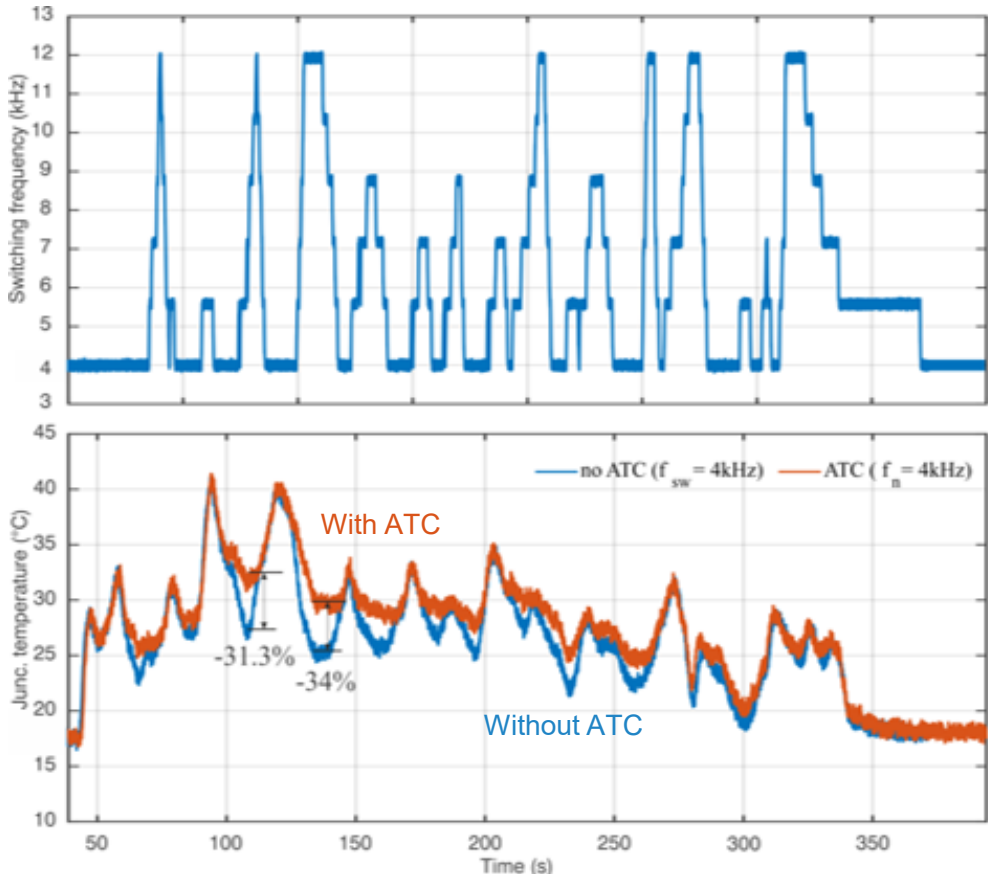
Switching-frequency based active thermal control

Switching frequency variation enable effective temperature control:

- Leading to significantly reduced thermal cycling
- Inducing increase in switching power loss
- Trade lifetime for efficiency

Case index	Operation	Nominal frequency	f_{min}	f_{max}	Energy loss (kJ)	Accumulated Damage (normalised)	Max ΔT_j reduction
1	No ATC	4 kHz	--	--	6.22	100%	--
2	No ATC	8 kHz	--	--	12.5	350%	--
3	With ATC	4 kHz	4 kHz	12 kHz	8.55	85%	-34% vs case 1
4	With ATC	8 kHz	4 kHz	12 kHz	11.2	75%	-65% vs case 1
5	With ATC	8 kHz	6 kHz	10 kHz	12	158%	-15% vs case 2

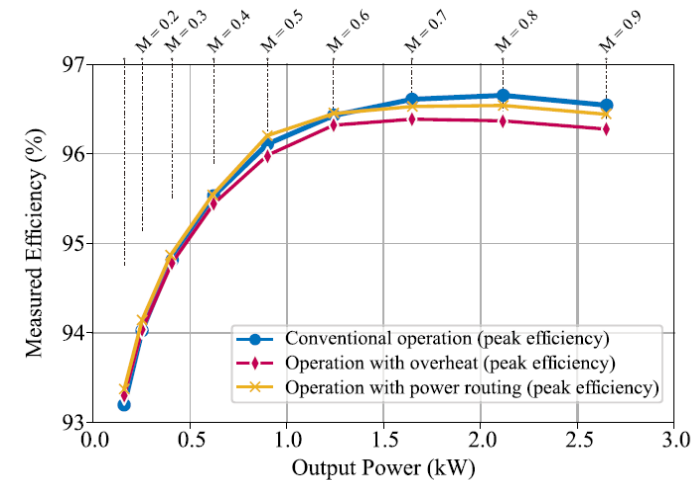
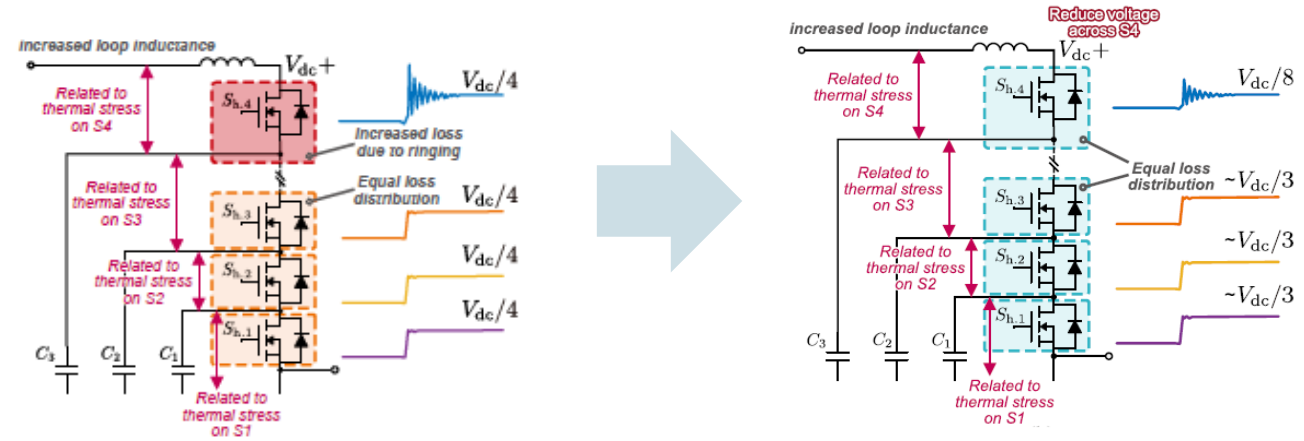
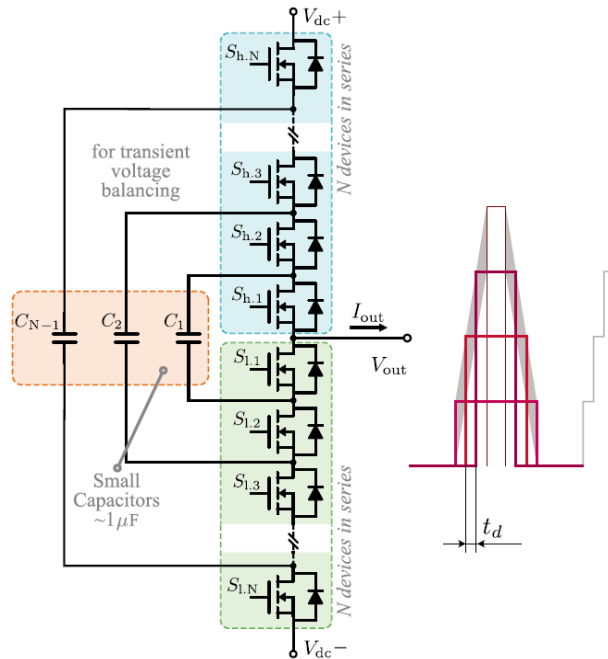
Effect of ATC ($f_n = 4$ kHz, $f_{sw} \in [4, 12]$ kHz) on T_j



Power Routing in quasi two-level converter

Mismatches in switching characteristics:

- turning-on and turning-off times,
- switching loop,
- stray inductance



A. Tcai, T. Wijekoon, M. Liserre, "Thermal Control of Quasi-2-Level Super-Switch by Power Routing," in IEEE Transactions on Industrial Electronics, 2023.

Charging strategies for lithium-ion batteries

Temperature regulation for individual cells using passive balancing

Challenge:

- The temperature of the Lithium-ion (Li-ion) battery packs are not constraint elevating the safety risks.

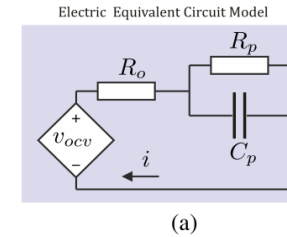
Our approach:

- An integrated charging and balancing is formulated incorporating thermal limits of Li-ion battery cells and optimized using MPC
- Dissipating resistors sizing is incorporated in the optimization process

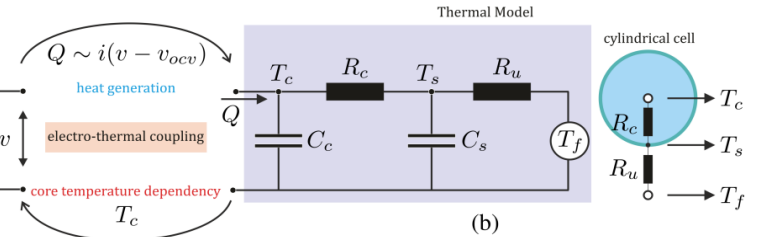
User benefits:

- Increased safety while using the low cost and simple passive balancing
- Reduced charge time

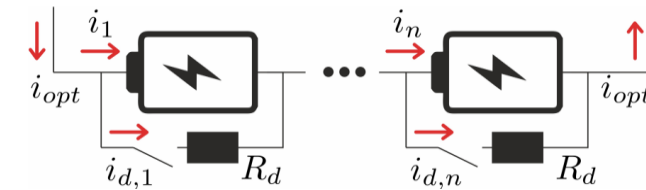
Cell electrical model



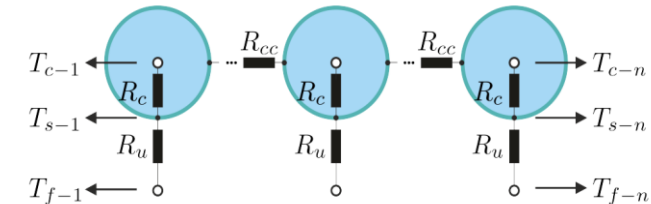
Cell thermal model



Pack electrical model



Pack thermal model

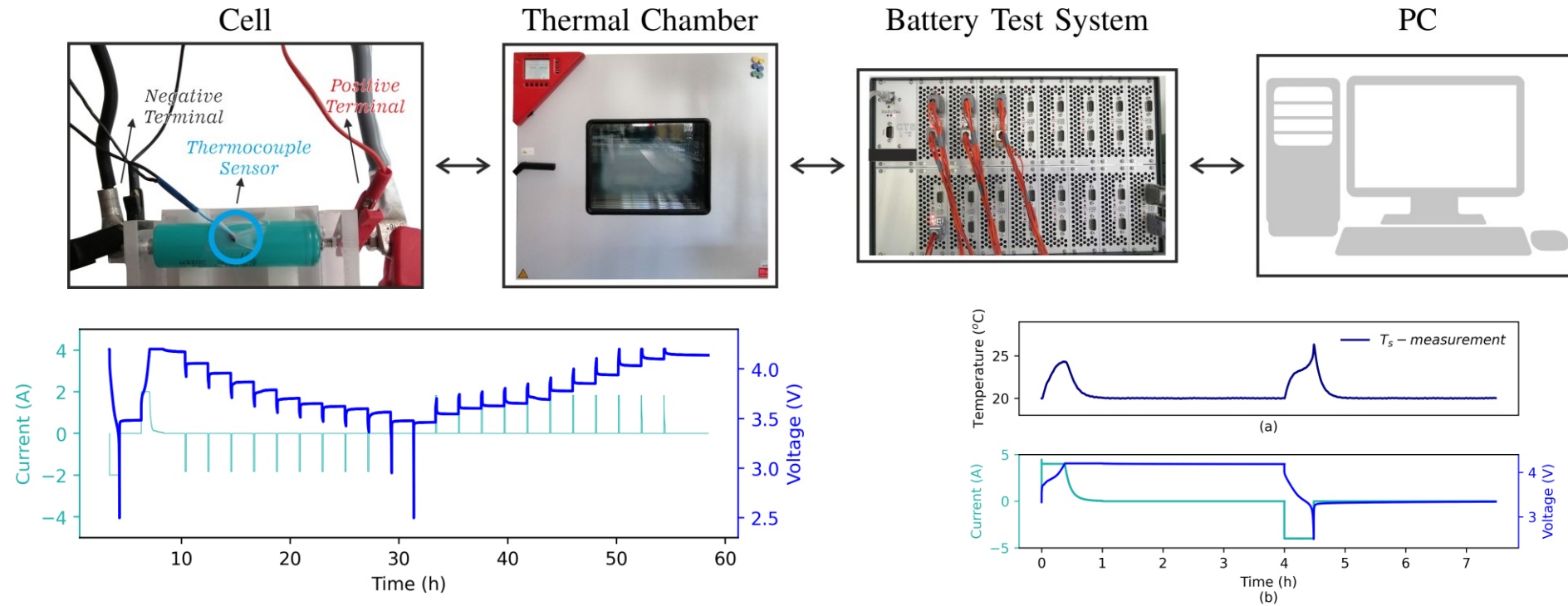


G. D. Astudillo, H. Beiranvand, F. Cecati, C. Werlich, A. Würsig and M. Liserre, "Integrated Strategy for Optimized Charging and Balancing of Lithium-Ion Battery Packs," in *IEEE Transactions on Transportation Electrification*, vol. 11, no. 1, pp. 4980-4991, Feb. 2025, doi: 10.1109/TTE.2024.3473989.

Charging strategies for lithium-ion batteries

Temperature regulation for individual cells using passive balancing

Model parameter identification



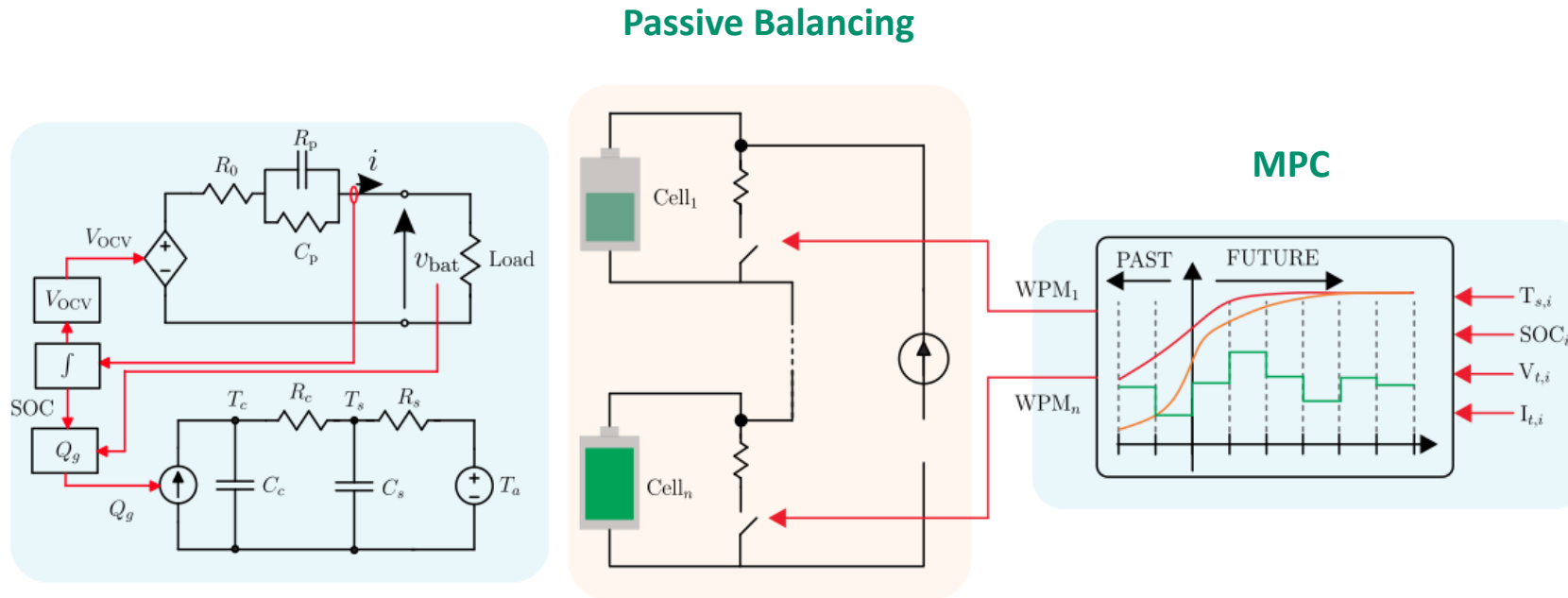
Open Circuit Voltage (OCV) characterization

Surface temperature characterization

G. D. Astudillo, H. Beiranvand, F. Cecati, C. Werlich, A. Würsig and M. Liserre, "Integrated Strategy for Optimized Charging and Balancing of Lithium-Ion Battery Packs," in *IEEE Transactions on Transportation Electrification*, vol. 11, no. 1, pp. 4980-4991, Feb. 2025, doi: 10.1109/TTE.2024.3473989.

Charging strategies for lithium-ion batteries

Temperature regulation for individual cells using passive balancing



Objectives (J_H):

1. Balancing the SOC
2. Balancing the temperature
3. Limit the max. temperature

$$\min_i J_H$$

$$\text{s.t. : } \forall k \in \{0, \dots, H-1\}$$

$$\mathbf{x}_{k+1} = f(\mathbf{x}[k], \mathbf{i}[k])$$

$$i_{\min} \leq i_{\text{opt}}[k] \leq i_{\max}$$

$$v_{\min} \leq v_j[k] \leq v_{\max}$$

$$\chi_{\min} \leq \chi_j[k] \leq \chi_e$$

$$(i_{\text{opt}}[k] - i_j[k])(v_{c,j}[k] + v_{ocv} + i_j[k]R_o) \leq P_d$$

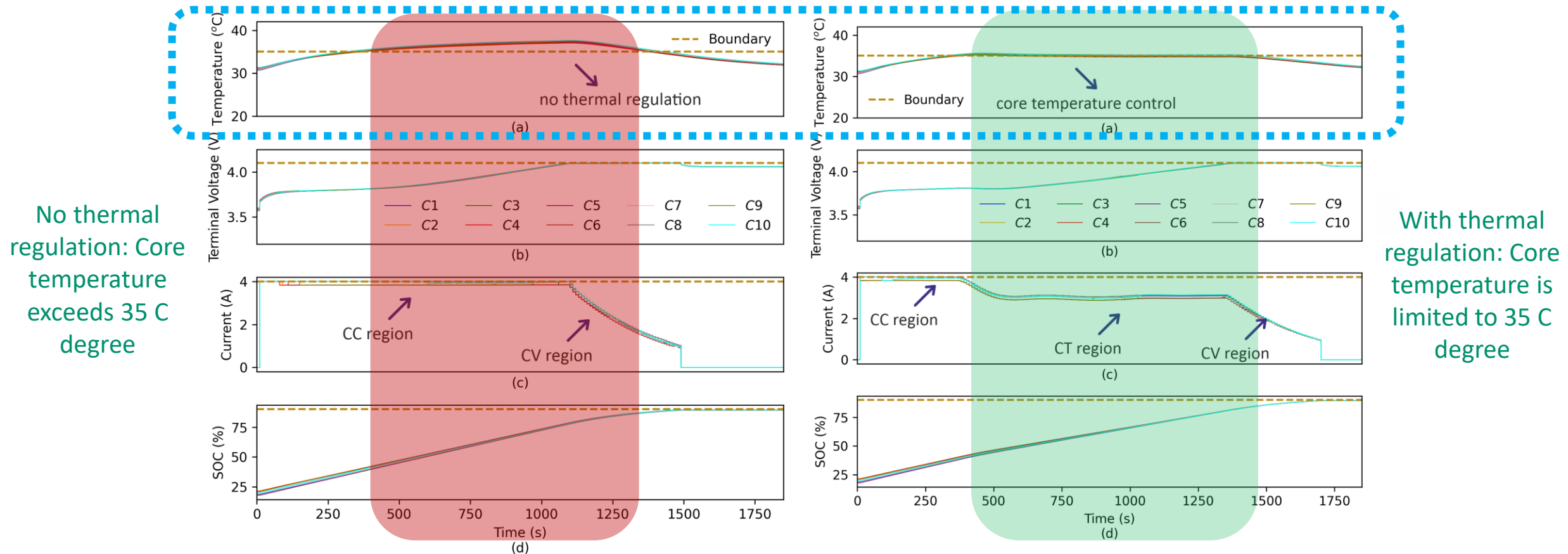
$$\max(0, i_{j\min}[k]) \leq i_j[k] \leq i_{\text{opt}}[k]$$

$$\text{for } j = 1, \dots, n$$

G. D. Astudillo, H. Beiranvand, F. Cecati, C. Werlich, A. Würsig and M. Liserre, "Integrated Strategy for Optimized Charging and Balancing of Lithium-Ion Battery Packs," in *IEEE Transactions on Transportation Electrification*, vol. 11, no. 1, pp. 4980-4991, Feb. 2025, doi: 10.1109/TTE.2024.3473989.

Charging strategies for lithium-ion batteries

Temperature regulation for individual cells using passive balancing



G. D. Astudillo, H. Beiranvand, F. Cecati, C. Werlich, A. Würsig and M. Liserre, "Integrated Strategy for Optimized Charging and Balancing of Lithium-Ion Battery Packs," in *IEEE Transactions on Transportation Electrification*, vol. 11, no. 1, pp. 4980-4991, Feb. 2025, doi: 10.1109/TTE.2024.3473989.

Charging strategies for lithium-ion batteries

Temperature regulation for differently aged battery cells in a pack

Challenge:

- Cells with unequal SoH create different thermal characteristics
- The lifetime of conventional battery packs is determined by the weakest cell
- Several conflicting functions should be performed by BMS

Our approach:

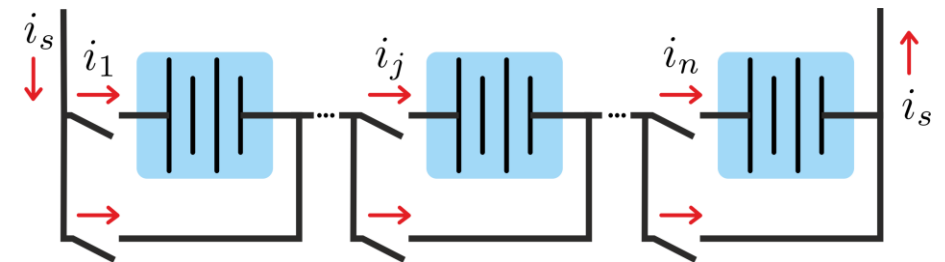
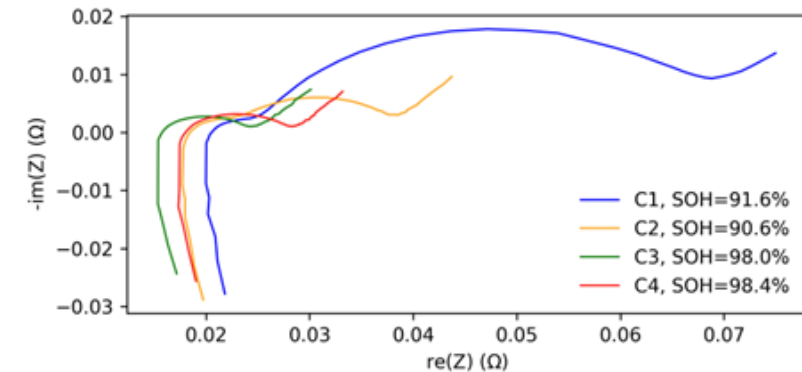
- Using reconfigurable batteries to integrate cells with different SoH
- Applying model predictive control (MPC) to balance SOC, SOT, and track the temperature trajectory
- Scalable methods with computational burden equivalent to only the weakest cell

User benefits:

- Increased safety (and probably lifetime)
- Enhanced fault tolerance (faulty cell is bypassed without violating the performance)

G. D. Astudillo, H. Beiranvand, F. Cecati, A. Würsig and M. Liserre "MPC-based Charge and Temperature Homogenization and Regulation for Series-Reconfigurable Lithium-Ion Battery Packs", Accepted in IEEE Journal of emerging and selected topics on Power Electronics, 2025.

Cells with different SoH



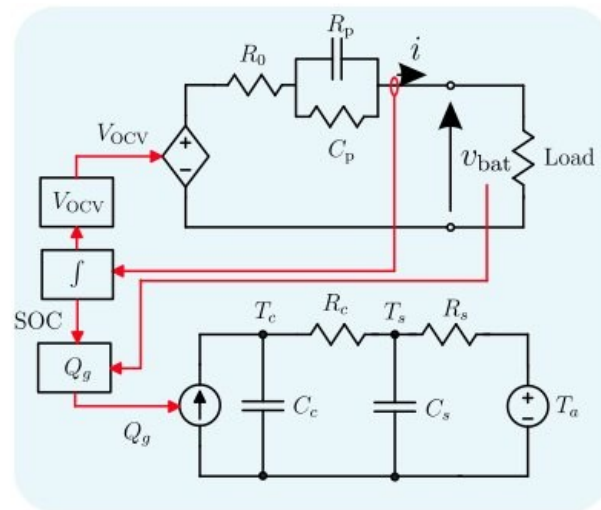
Reconfigurable BMS

Charging strategies for lithium-ion batteries

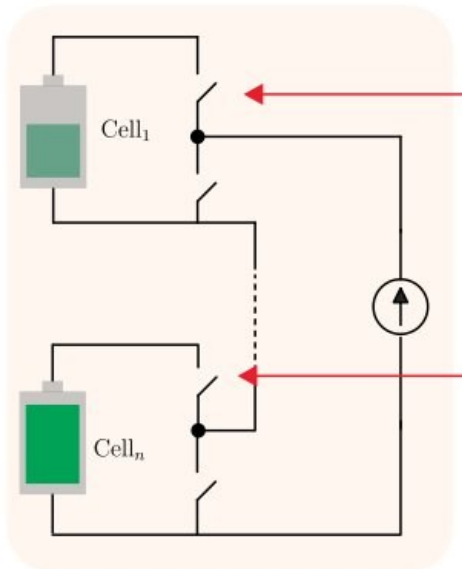
Temperature regulation for differently aged battery cells in a pack

Objectives (J_H):

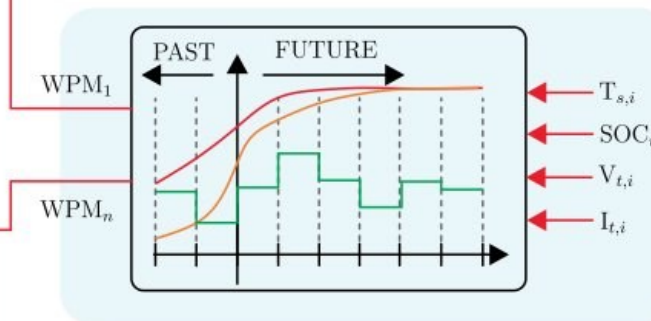
1. Balancing the SOC
2. Balancing the temperature
3. Limit the max. temperature



Reconfigurable battery



MPC



$$\begin{aligned} & \min_i J_H \\ & s.t. : \forall k \in \{0, \dots, H-1\} \\ & \mathbf{x}^w[k+1] = f(\mathbf{x}^w[k], i[k]) \\ & i_{min} \leq i_{opt}[k] \leq i_{max} \\ & v[k] \leq v_{max} \end{aligned}$$

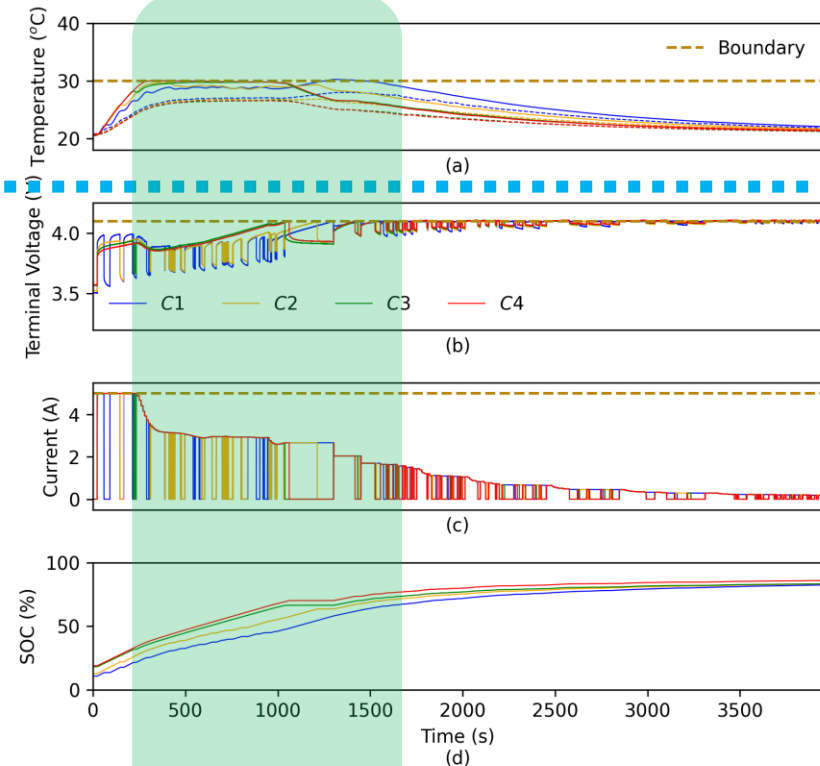
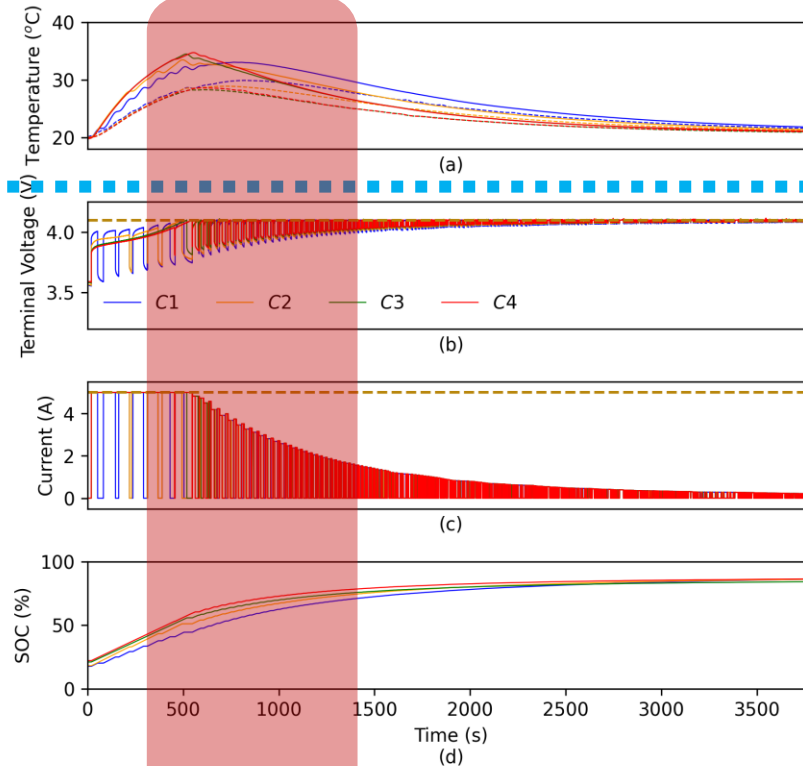
G. D. Astudillo, H. Beiranvand, F. Cecati, A. Würsig and M. Liserre "MPC-based Charge and Temperature Homogenization and Regulation for Series-Reconfigurable Lithium-Ion Battery Packs", Accepted in IEEE Journal of emerging and selected topics on Power Electronics, 2025.

Charging strategies for lithium-ion batteries

Temperature regulation for differently aged battery cells in a pack

Experimental results

No thermal regulation: Core temperature exceeds 30 C degree



With thermal regulation: Core temperature is limited to 30 C degree

G. D. Astudillo, H. Beiranvand, F. Cecati, A. Würsig and M. Liserre "MPC-based Charge and Temperature Homogenization and Regulation for Series-Reconfigurable Lithium-Ion Battery Packs", Accepted in IEEE Journal of emerging and selected topics on Power Electronics, 2025.

Active Reliability in Battery Management Systems

Simultaneous state-of-charge (SOC) and Temperature balancing in lithium-ion batteries

Challenge:

- **Multi-objective balancing algorithm:** SOC & Cell temperature
 - For safety of battery packs, SOC balance is important as well as cell temperature
- **Active cell balancing:** Fast balancing with higher current, but complex to control
- Complex algorithm is required to select proper cells and current level.

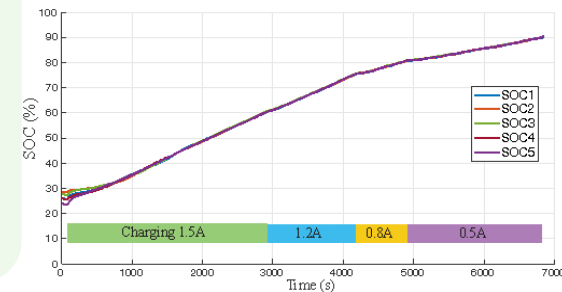
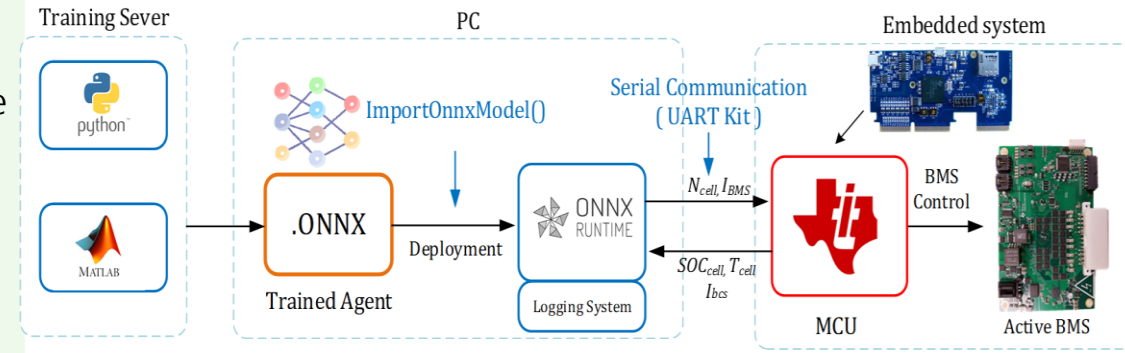
Our approach:

- Application of Unscented Kalman Filter (UKF) for SOC estimation
- Utilization of active cell balancing with an isolated dc-dc converter.
- Reinforcement Learning (RL) for SOC and Cell temperature balancing

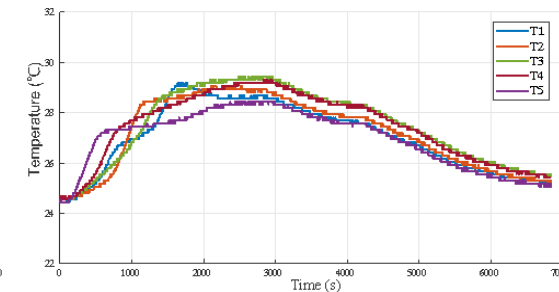
User benefits:

- Prolongation of battery lifetime
- Increased safety margins owing to active temperature control and balancing

- K. Harwardt, J. Hung, H. Beiranvand, D. Nowotka, and M. Liserre, "Lithium-Ion Battery Management System with Reinforcement Learning for Balancing State of Charge and Cell Temperature ", Powertech 2023, Belgrade.



SOC



Temperature

SOC and Cell temperature balancing under charging process

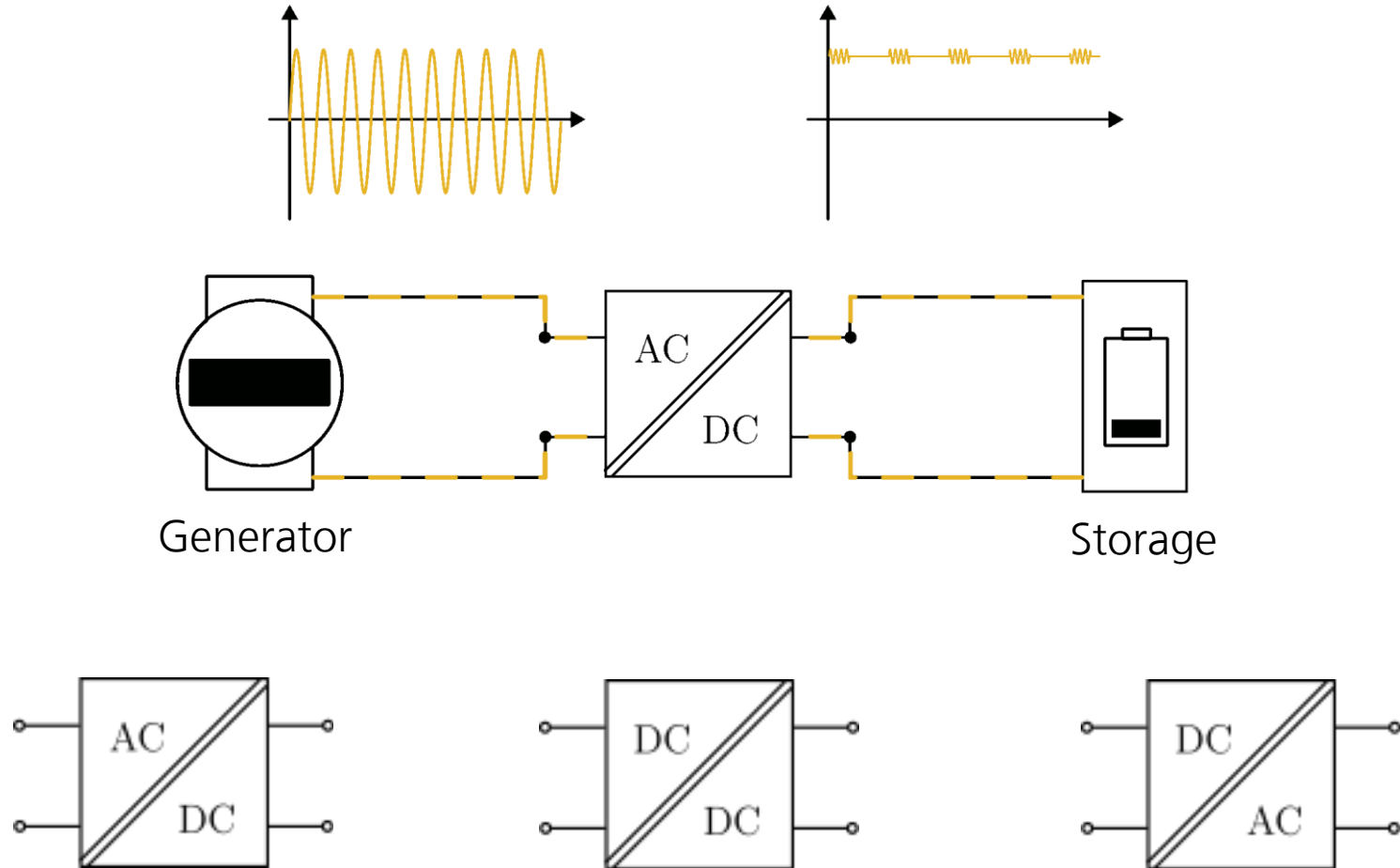
 **HYDROGEN**
ENERGY STORAGE

Energy & Data transferred together

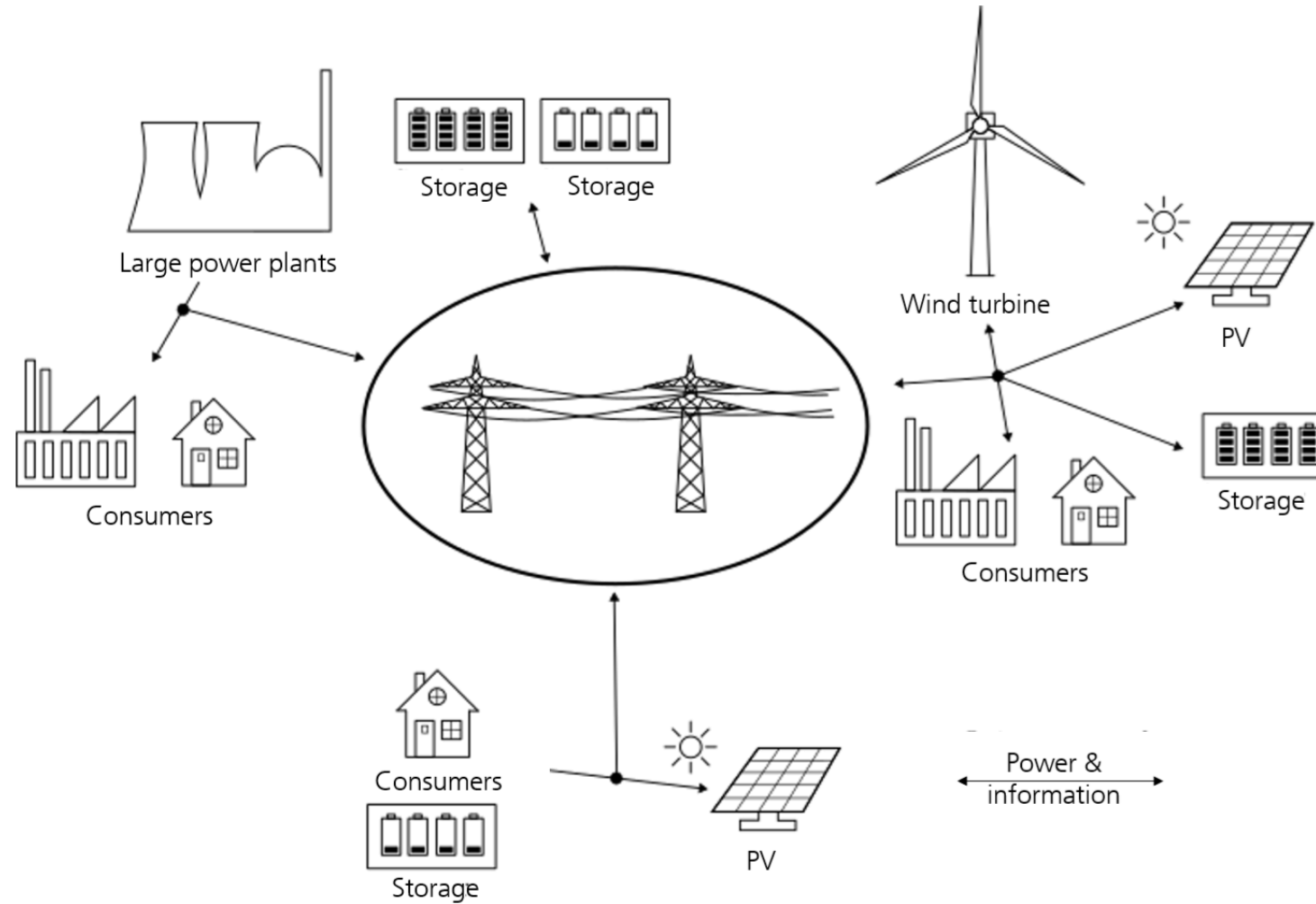
Talkative power conversion

Communicative capabilities of a power converter

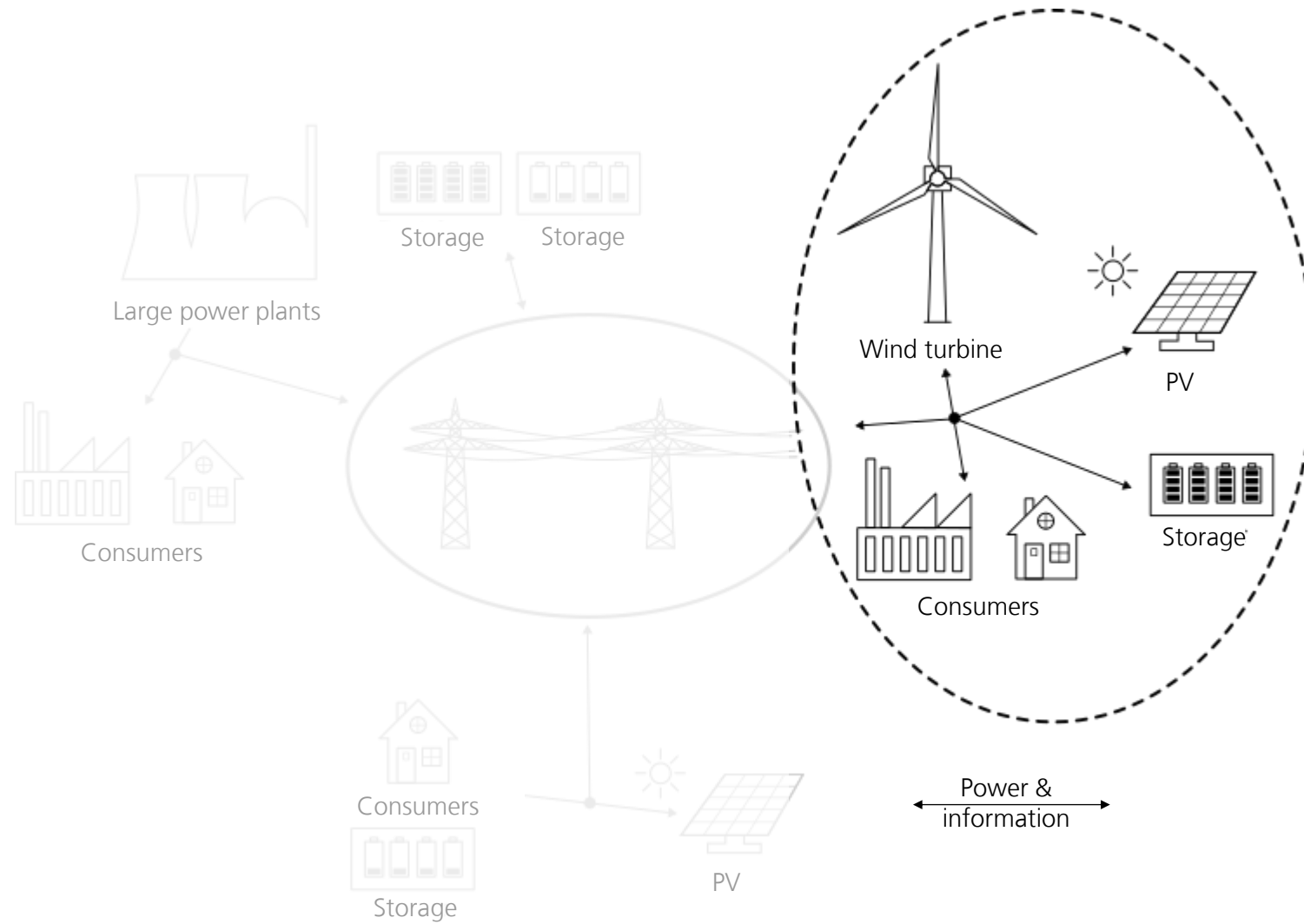
Communication on a DC link using the voltage ripple



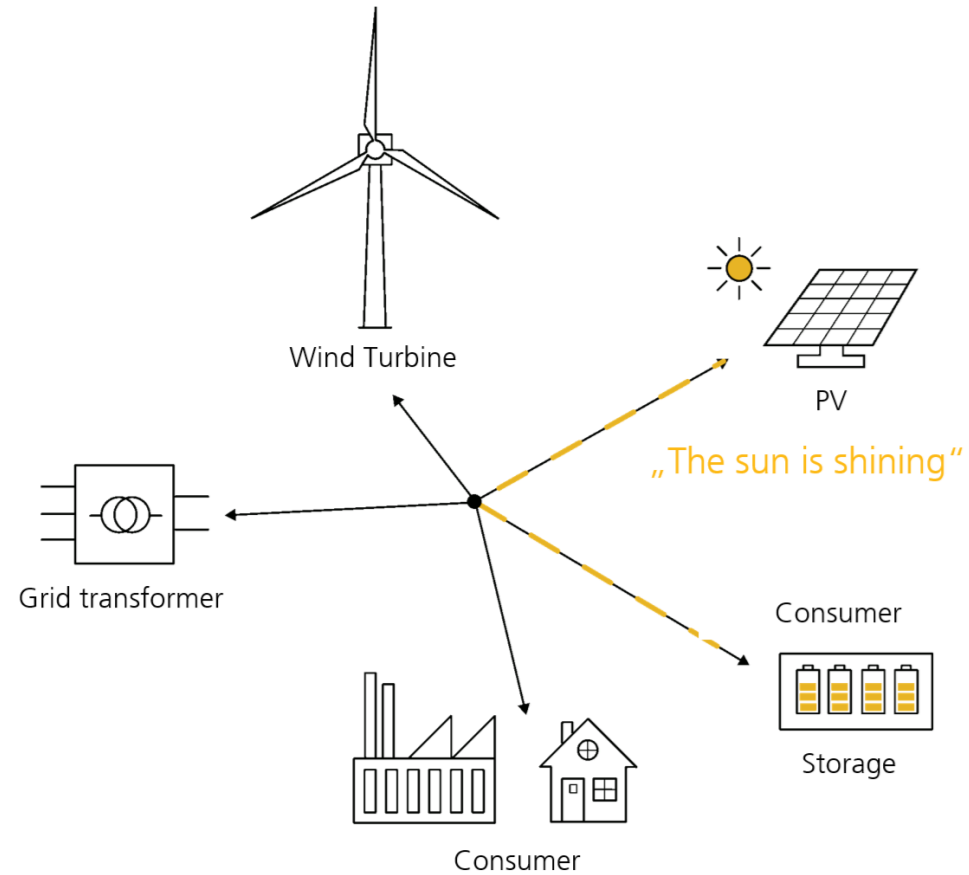
Smart grid



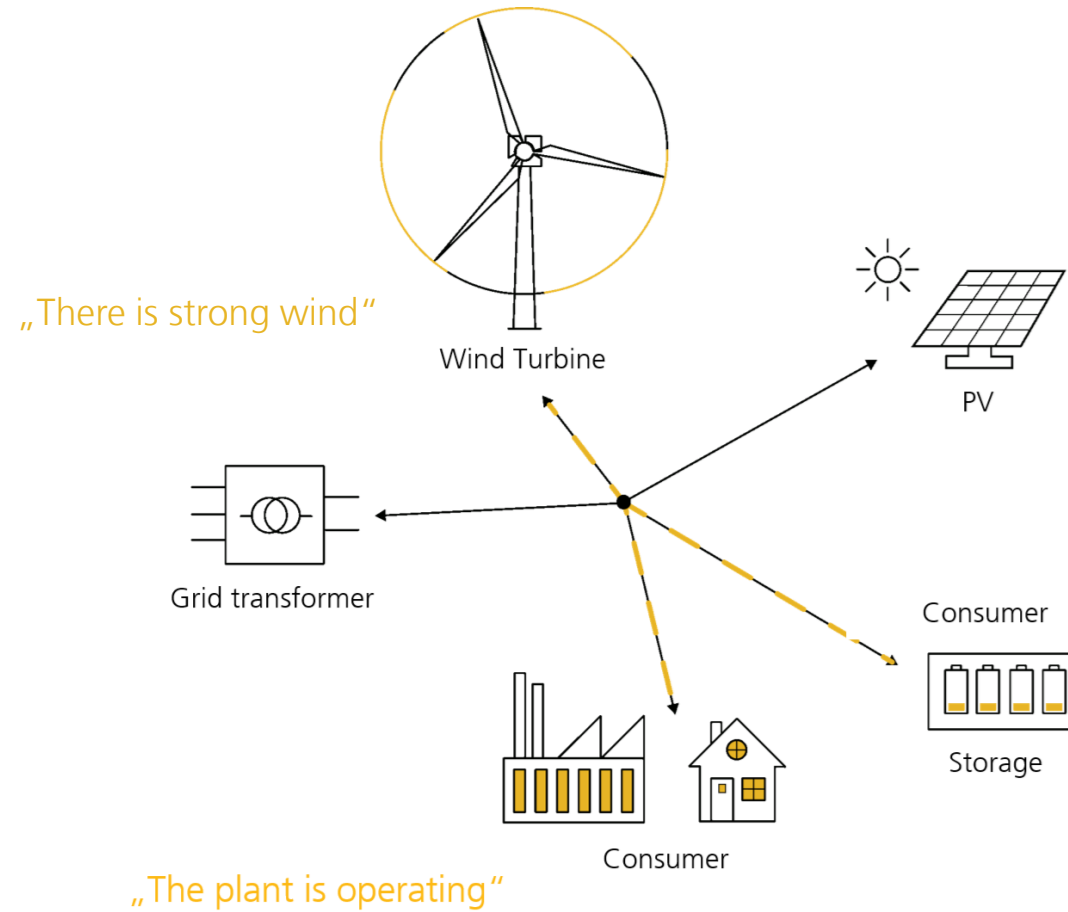
Smart grid



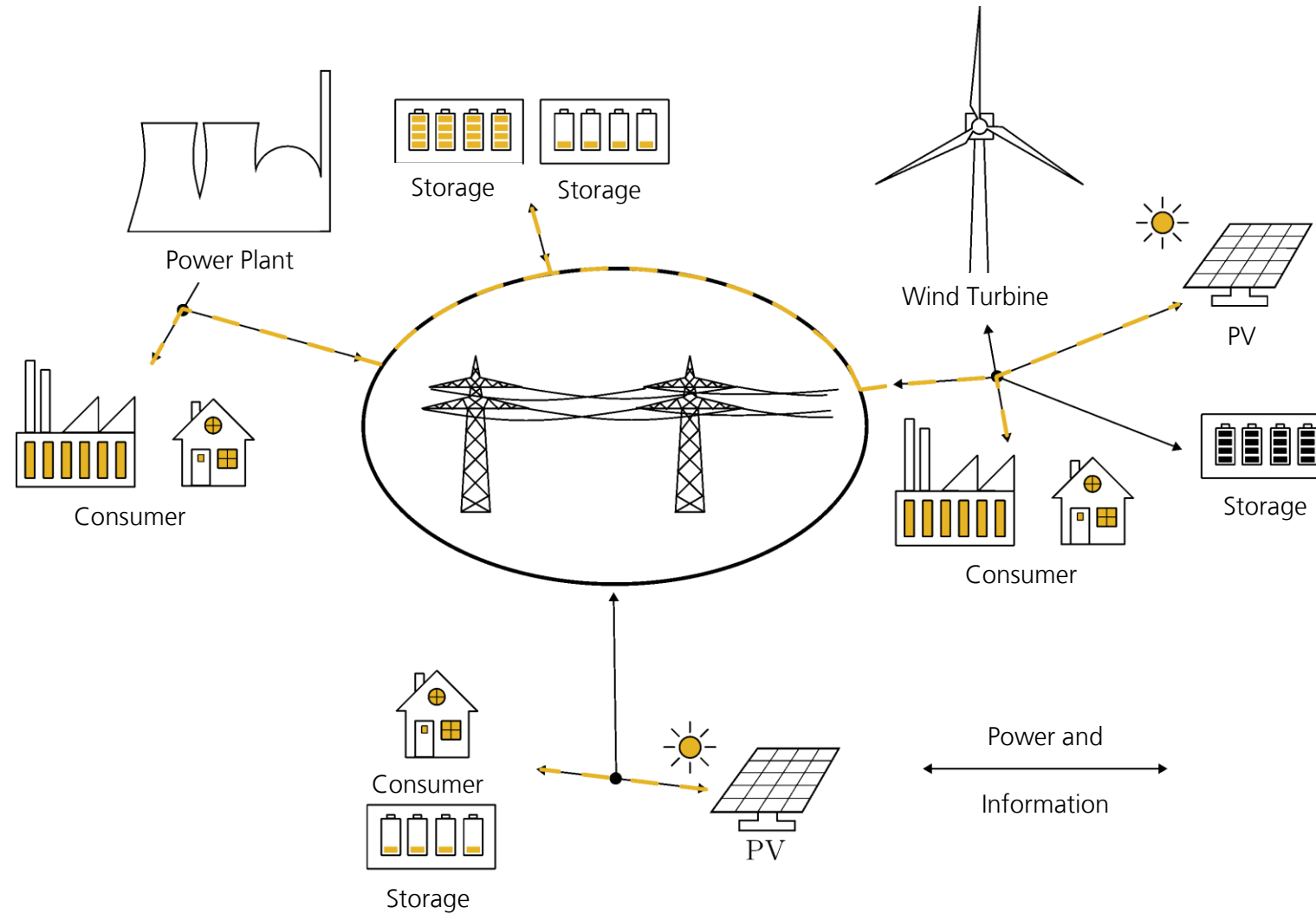
Communication in the grid



Communication in the grid



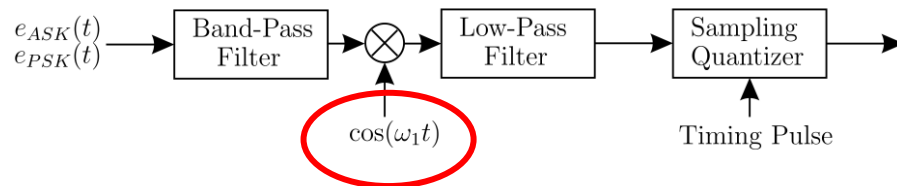
Communication in the grid



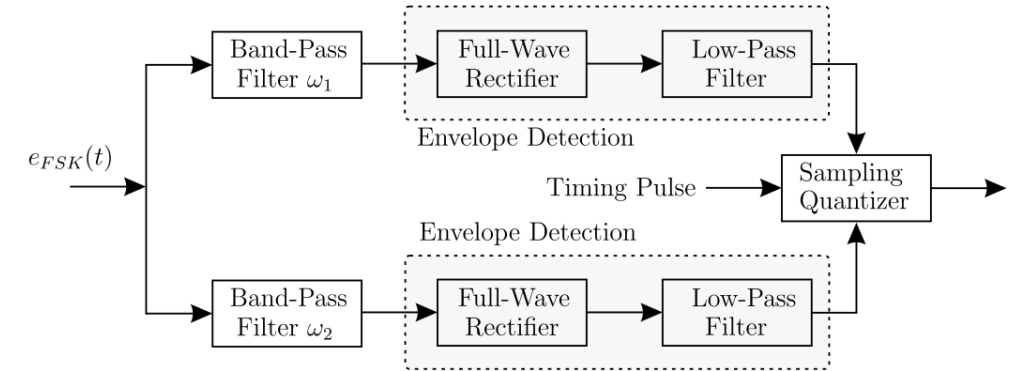
TPC Demodulations

There are two main types of demodulation techniques:

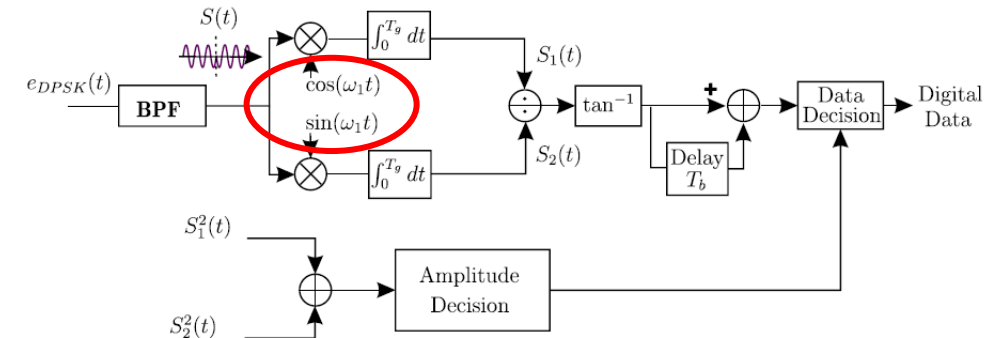
- I. **Non-coherent:** No need for the carrier signal
- II. **Coherent:** Sensitive to noise, coherent signal must same frequency and phase with carrier. **Coherent demodulation** consists in multiplying the received signal with a sinusoid of the same frequency and phase of the carrier. A local oscillator generates this sinusoid.



Coherent demodulation for ASK and PSK



Non-coherent demodulation for FSK

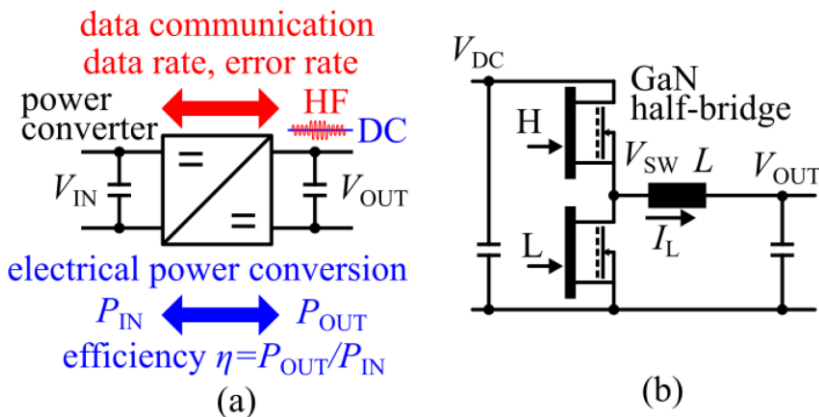


Coherent demodulation process of PWM-FH-DPSK

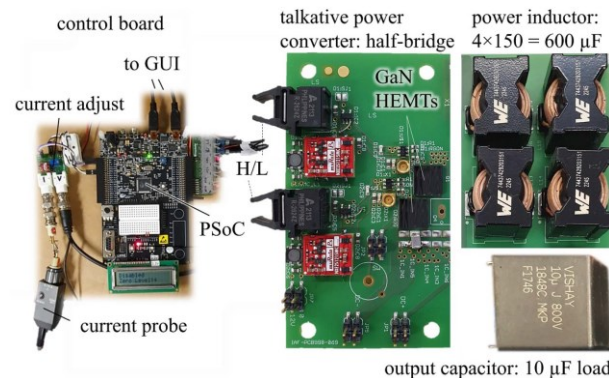
P. A. Hoeher, M. Mewis and M. Liserre, "Channel Coding and Receiver Design for Simultaneous Wireline Information and Power Transfer," in IEEE Open Journal of Power Electronics, vol. 2, pp. 545-558, 2021.

TPC by means of analog hysteretic current control

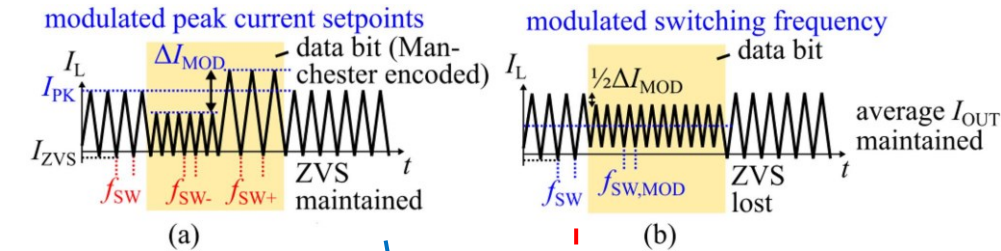
- A modified **analog hysteretic current control** is proposed and compared with digital modulation
- Measurements show that, compared with the digital PWM, a wider range of current ripple modulation is available for data transfer before the power efficiency drops



Non-isolated DC-DC converters

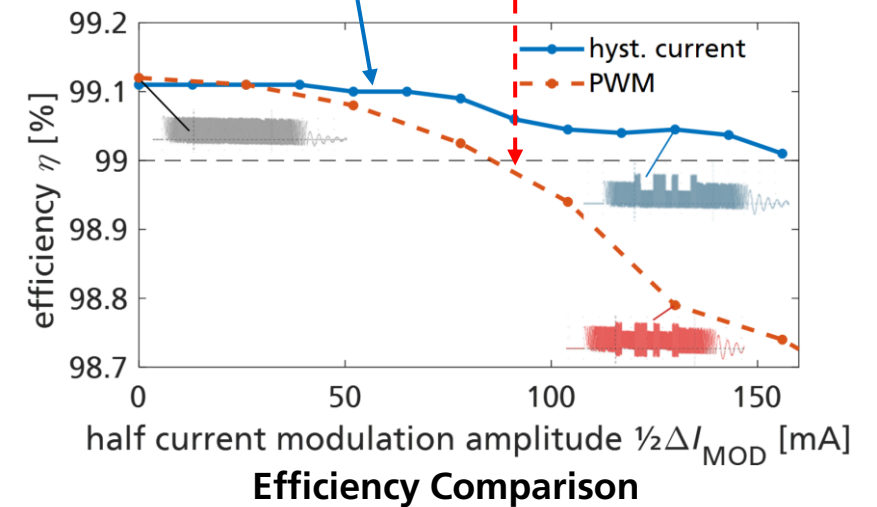


Prototype



analog hysteretic current control

digital PWM

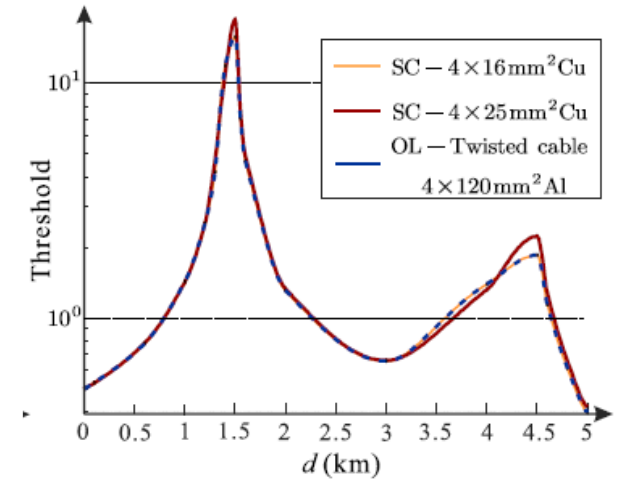
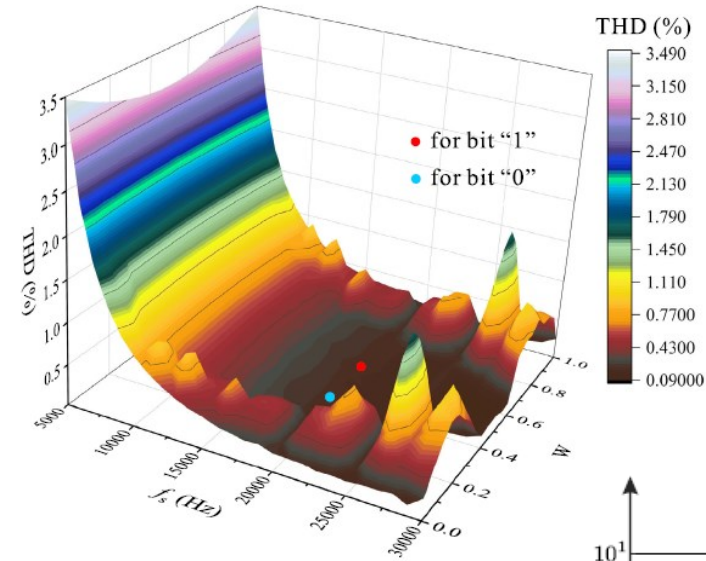
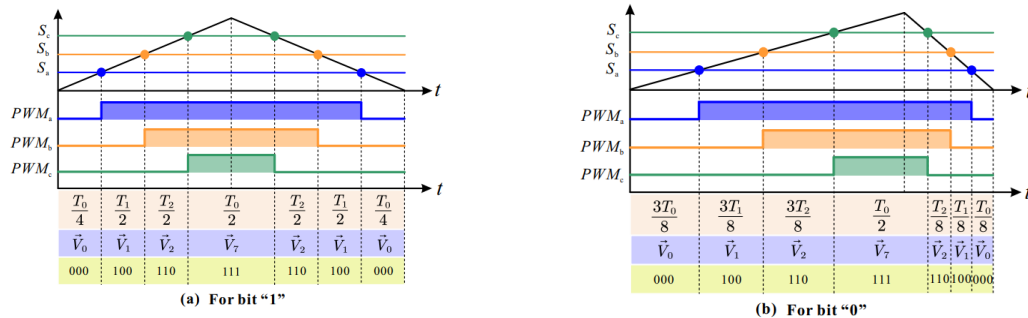
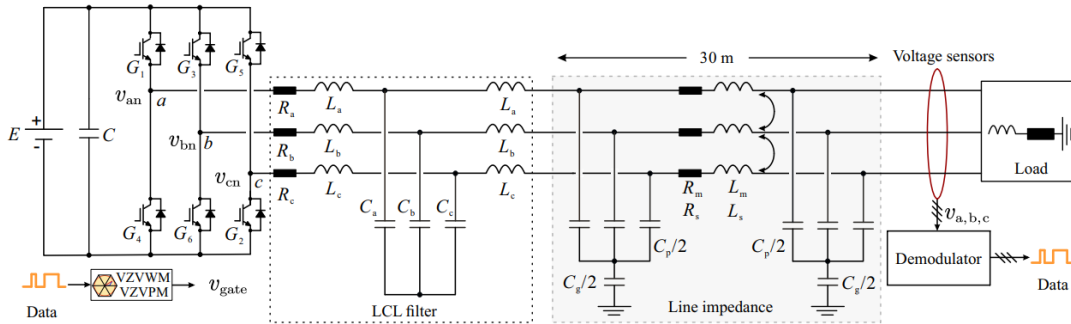


S. Mönch, C. Kuring, X. Geng, P. A. Hoehner, M. Liserre, R. Quay, S. Dieckerhoff., "Efficient Talkative Power Conversion With Quasi-Square-Wave Zero-Voltage Switching Hysteretic Current Control," in IEEE Transactions on Power Electronics, vol. 38, no. 10, pp. 12383-12387.

TPC in three-phase converters

▼ Three-phase AC/DC converter:

space-vector pulse width modulation (SVPWM)-based TPC techniques including both variable zero vector width modulation (VZVWM) and **variable zero vector position modulation (VZVPM)**



Y. Leng, R. Zhu, M. Liserre and P. Adam Hoehner, "Variable Zero-Vector-Width-Based Three-Phase DC/AC Talkative Power Conversion," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 12, no. 4, pp. 3402-3414, Aug. 2024.

Increasing acceptance of power electronics by means of active reliability and talkative power conversion

Take away & discussion

Conclusions

First step is to know PE and the component operated by PE:

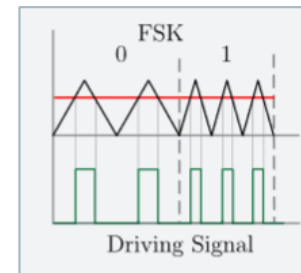
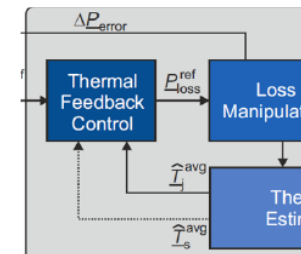
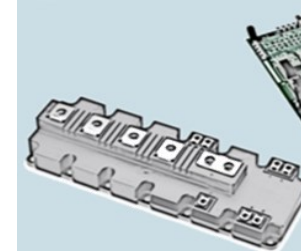
- Digital Twin is a complete solution
- Data Fusion helps in increasing accuracy
- Data-driven approach for complex interdependencies

Acceptance through higher reliability:

- Active reliability of power modules in electromobility
- By modular system, power routing allows re-balancing the system
- Active reliability of battery cells to balance SOC and Temperature

Acceptance through new services:

- Power Conversion can be made “talkative”
- It works for dc/dc, dc/ac, even for isolated dc/dc converters or wireless
- Is the new revolution for power electronics ?



Data and algorithms instead of Sensors !

Balancing by power routing !

The ripple is not anymore bad !

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