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# Digitalisation of power electronics: state estimation & smart control

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Digitalisation of power electronics

# Introduction

# Introduction

## Digitalisation – ins and outs of power electronics digitalisation

### Technical constraints:

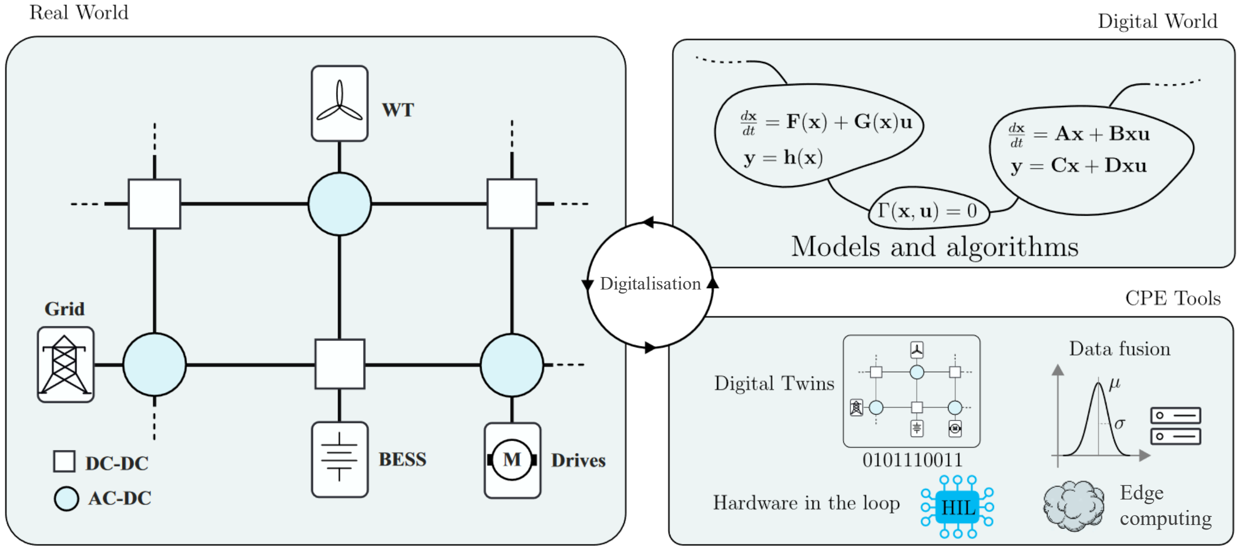
- Complexification of systems, intrinsically multi-physic
- New applications, reduced tolerance to failures and uncertainty
- Reduced robustness of new WBG devices
- Limited computing resources available

### 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



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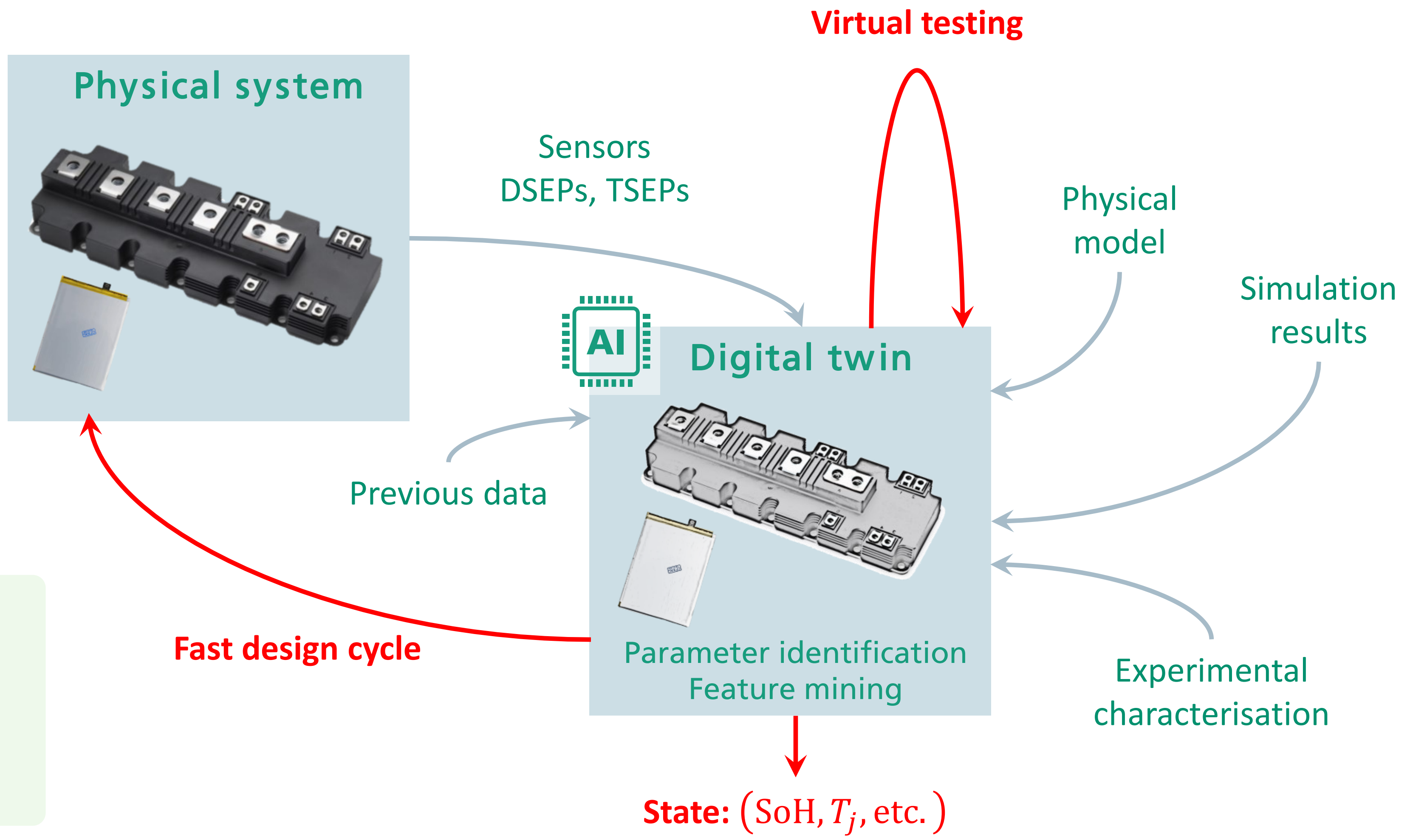
**Digital twins, data-fusion… AI-powered**

# Tools for the digitalisation of power electronics

# Digital twins

A versatile high accuracy virtual replica of devices and systems



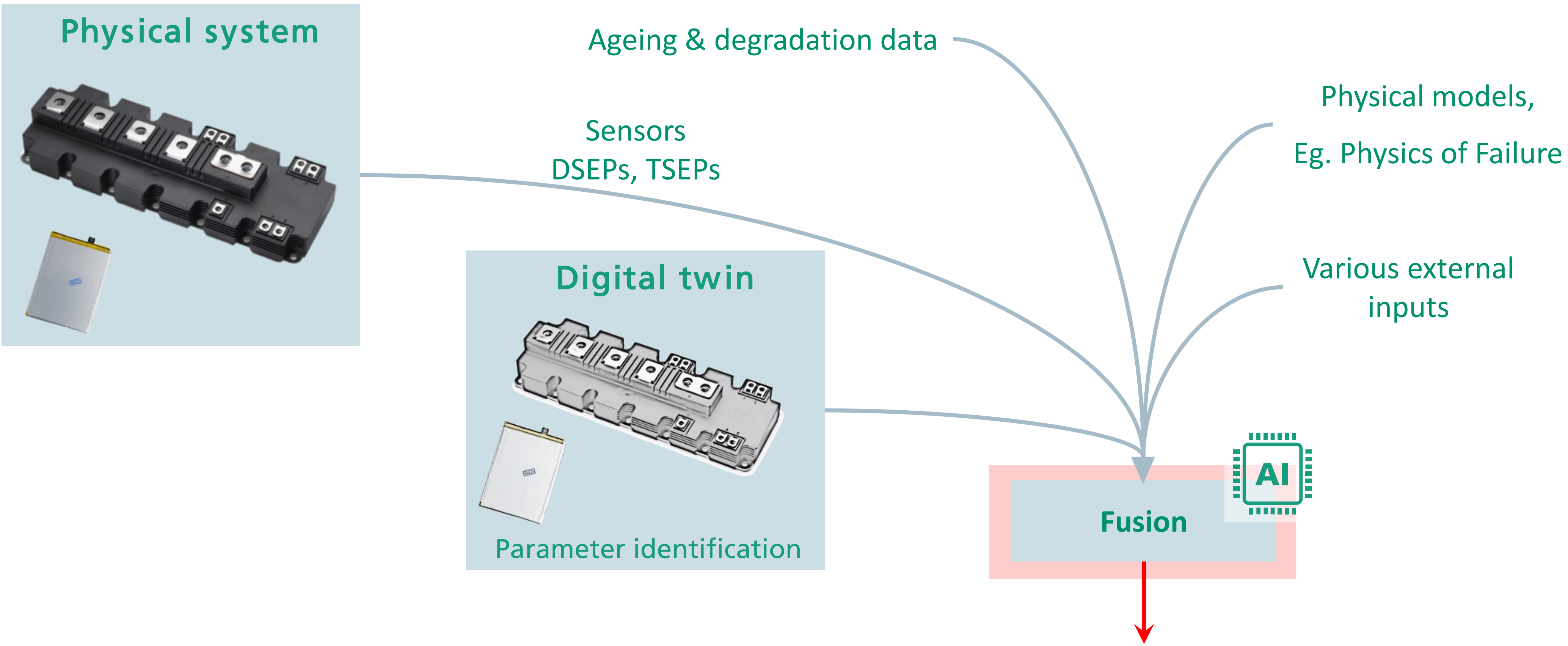

**Digital twins are:**

- Measurement-calibrated model
- Highly accurate
- Suitable for real time simulation
- Can be dynamically updated

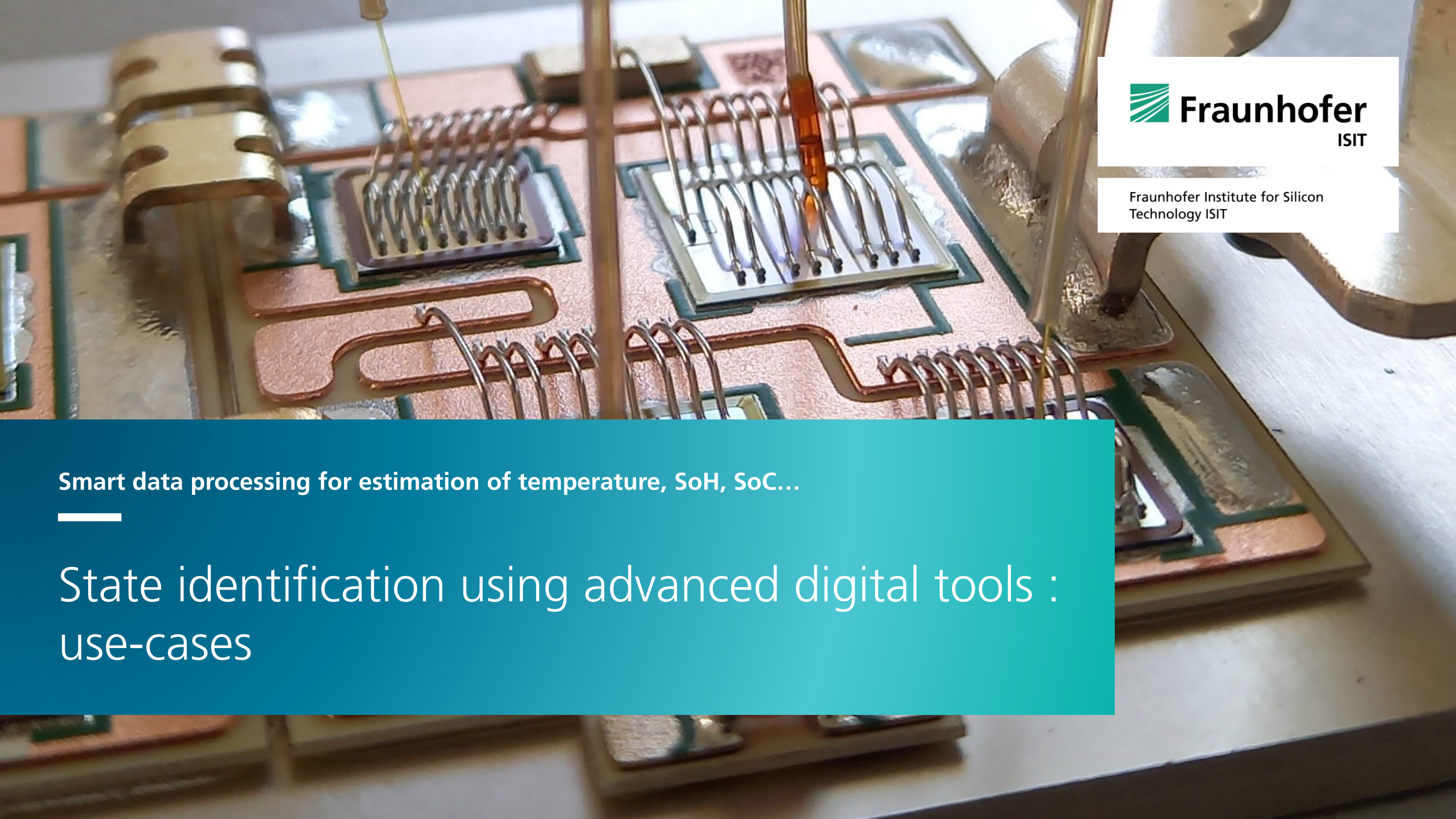
# Data Fusion

## Combining information from different sources to achieve high accuracy




**State:** $(\mathrm{SoH}, T_j, \mathrm{etc.})$



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**Smart data processing for estimation of temperature, SoH, SoC…**

# State identification using advanced digital tools : use-cases

# Power module thermal Digital Twin

## Condition monitoring through online thermal impedance identification

### Challenge:

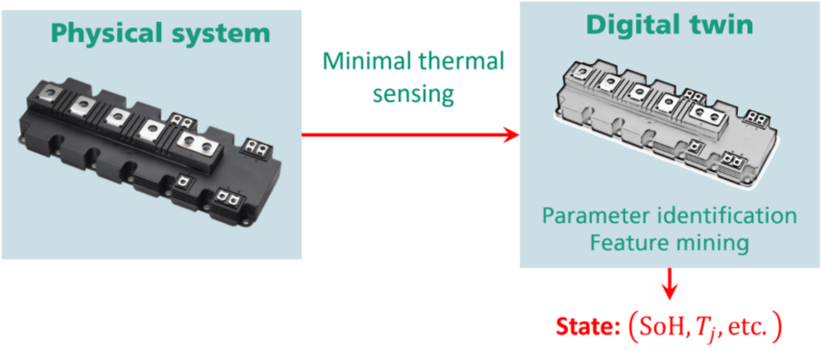
- Complex online SoH estimation: degradation precursors (eg. Vce) are multi-variable and have low-sensitivity

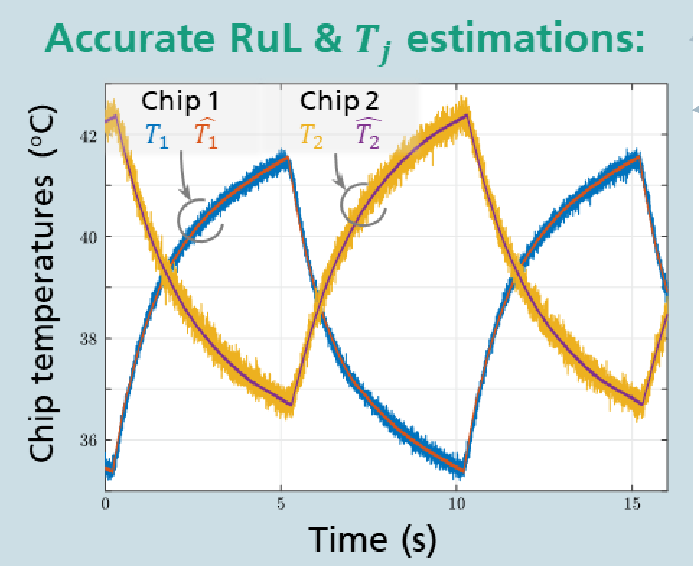
### Our approach:

- 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 Tj estimations
- Improved lifetime through active thermal control & PQ-power curve extension




Experimental validation: Identification of 3-cell Foster model

First thermal digital twin


- 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.

# Data-fusion for power module condition monitoring

## First results

### Approach:

- Optimally merge SoH estimations from multiple degradation precursors (Vce, Rth)
- 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", accepted to ESREF'24

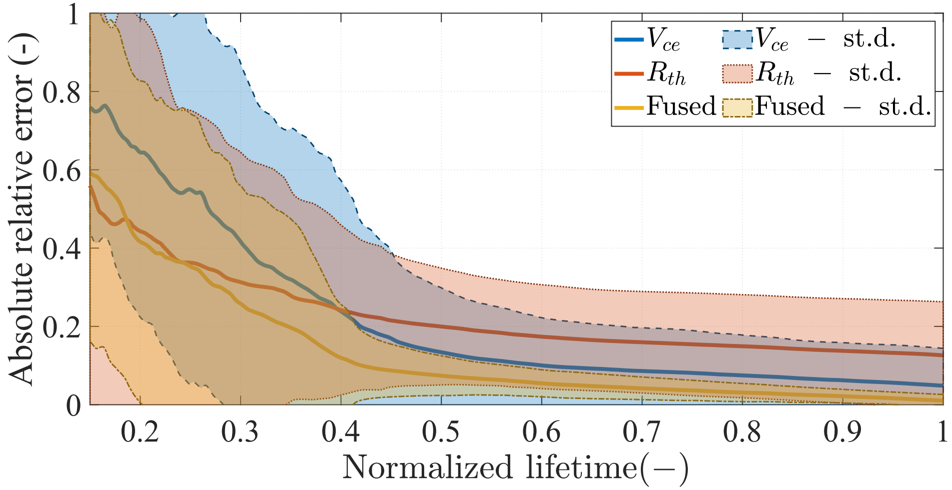
**Power module** in converter

Degradation precursors → **DataFusion** algorithm ← Lifetime model

Degradation path → **DataFusion** algorithm

**DataFusion** algorithm → **SoH, RUL**

RUL estimation w/ & w/o data fusion (simulation)



# Artificial intelligence

## ML based Tj Estimation of an IGBT using Vce

### Effective thermal monitoring is essential for reliable operation of IGBTs

**Temperature sensitive Electrical Parameter (TSEP)**

- On-state voltage (Vce) : proportional to junction temperature (Tj)
- But, a low sensitivity → Supplement is required.
- Machine learning can be used to improve
- Inflection point of Vce and Ic profile.

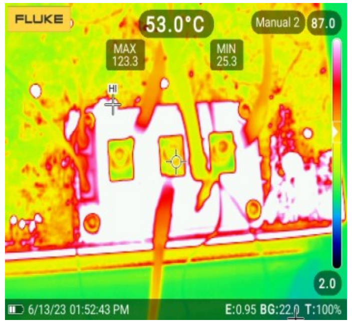
**Machine learning (Supervised learning)**

**achieve improved accuracy of the estimation.**

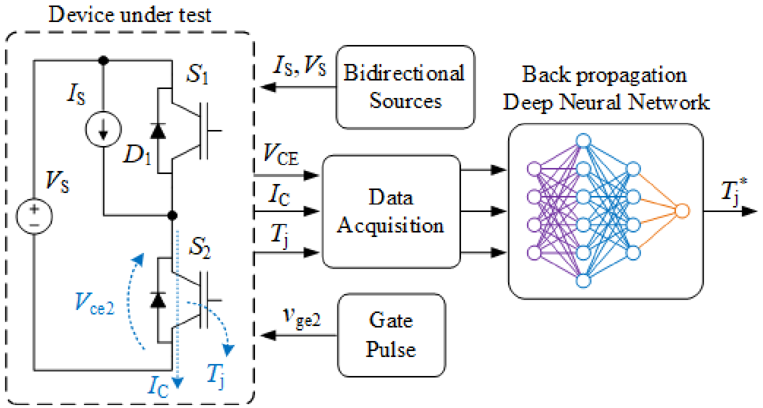
**reduce the need for direct measurements.**

**Result and Conclusion**

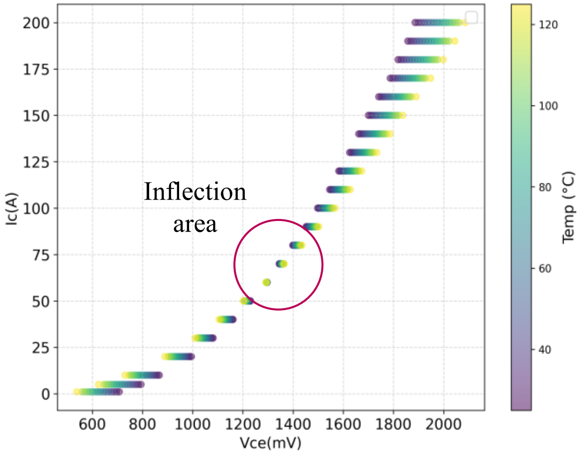
**Key findings includes model prediction accuracy near inflection area: Support Vector Regression (SVR) : 99%**



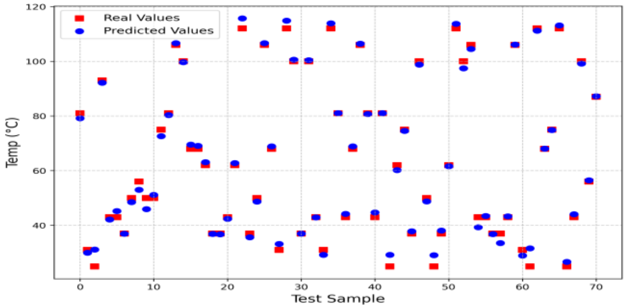
IGBT open module under test



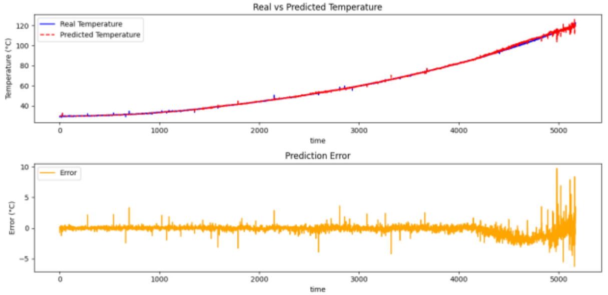
Configuration of $T_j$ estimation using ML with $V_{ce}$



Junction temperature according to $V_{ce}$ and $I_c$



Validation of Sequential model predictions



Validation under continuous conditions

# Battery management systems

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

### Challenge:

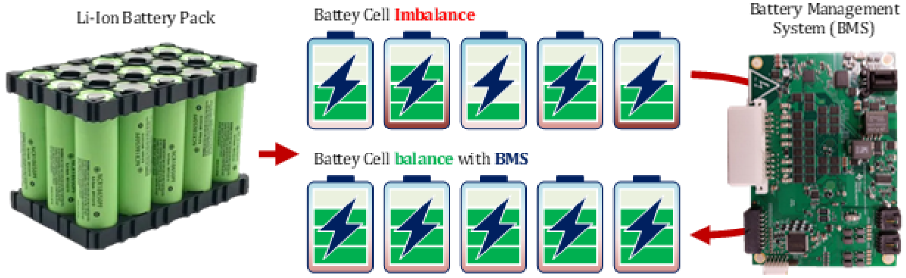
- Lithium ion battery performance in term of efficiency, lifetime and safety is directly a function of battery internal states, i.e. SOX.
- Internal states are difficults to measure directly and precise estimation techniques are required

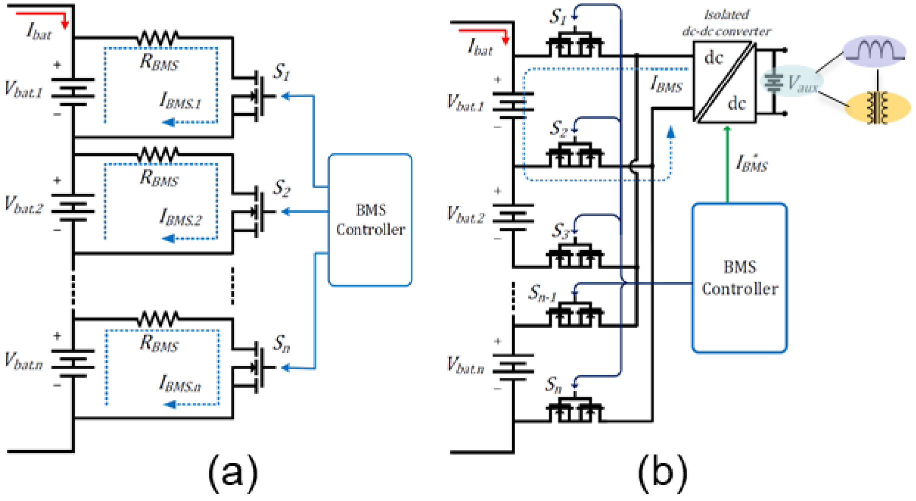
### Our approach:

- Application of Unscented Kalman Filter (UKF)) for SOC estimation
- Utilization of passive and active balancing as well as reconfigurable batteries
- Reinforcement Learning (RL) for SOC and Temperature balancing

### User benefits:

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




< BMS (a) Passive (b) Active >

- 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.

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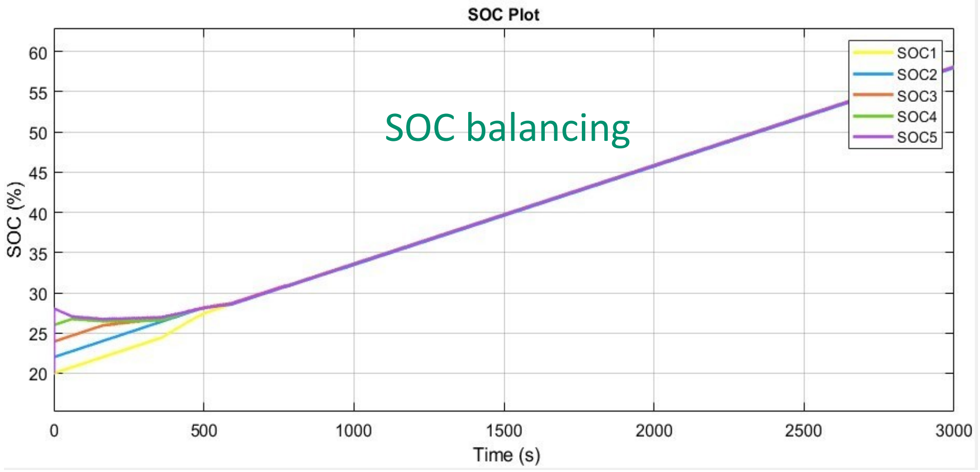


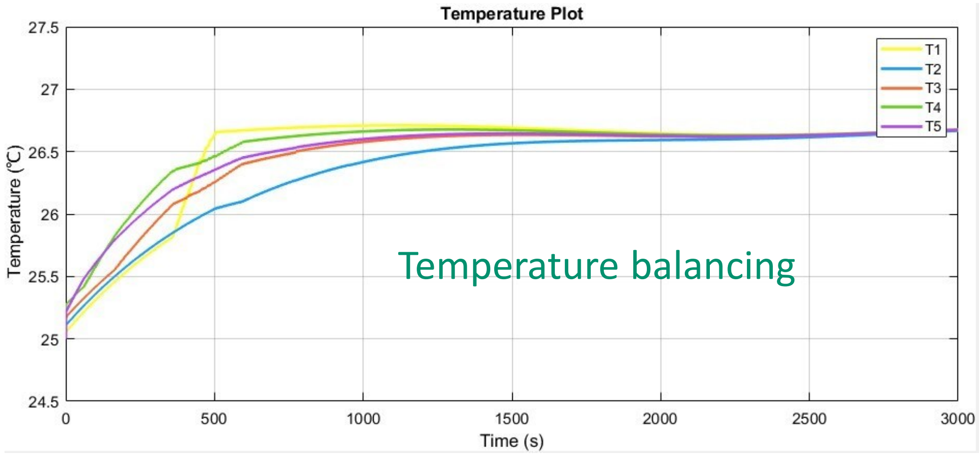


 


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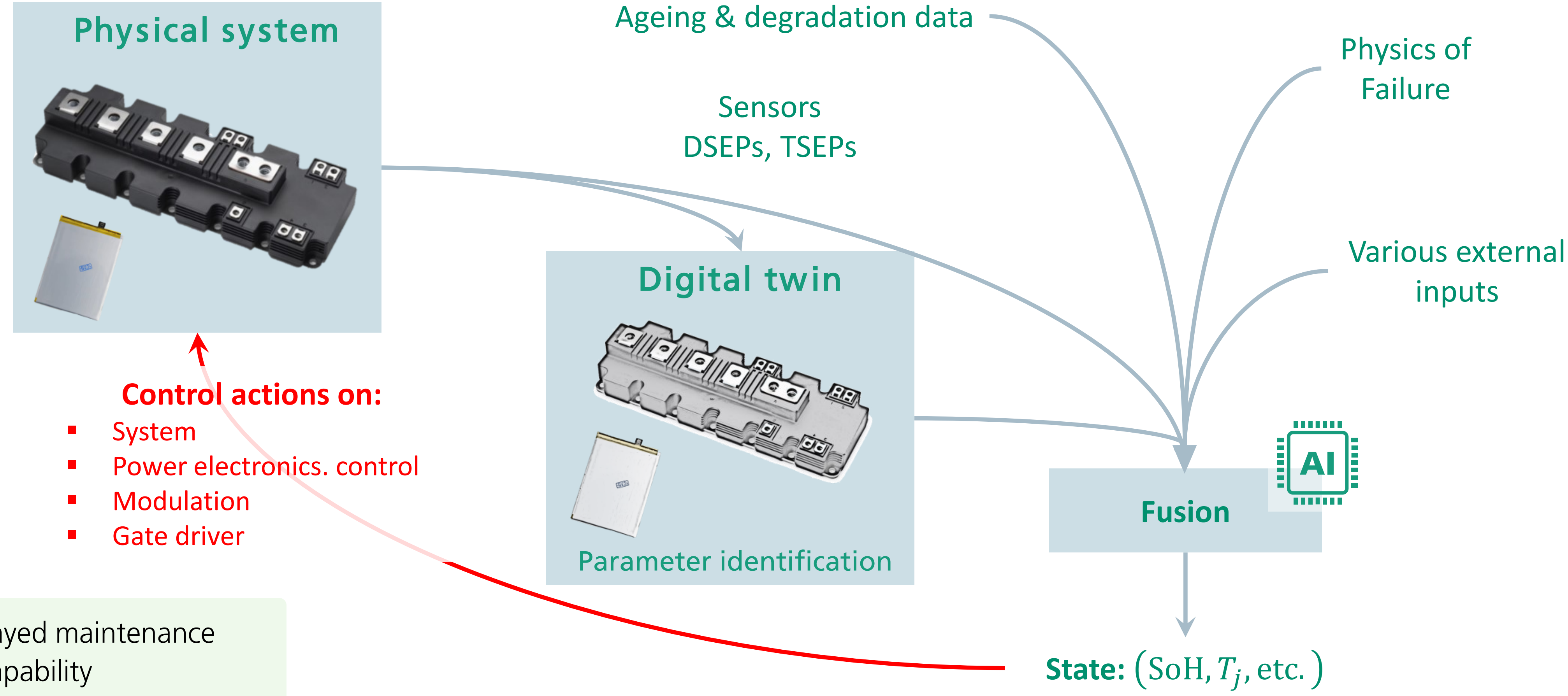
**Optimal multiobjective control of power converters and energy systems**

# Smart control of power electronics

# Control for improved reliability and performances




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

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# Power routing

## Application example: Multiphase Drives (9 phases) in mine hoist


Highly stressful application

Asymmetry of power module leads to uneven thermal distribution

Higher number of phases:

- Power routing with reduced extra heating in other phases
- Fault Tolerance

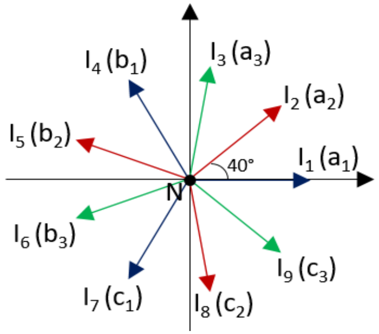
Capability to work under soft unbalance conditions:

- Power routing maintaining magnetic balance

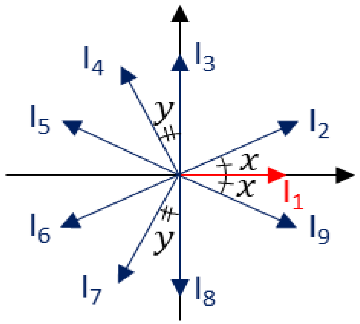
Our approach: power routing:

- Adjust phaseshift and amplitude of phase voltages

No power routing




With power routing




V. Ferreira, R. Bastos, T. Souza, M. Liserre, , B. Cardoso “Power Routing to Enhance the Lifetime of Multiphase Drives”, Energy Conversion Congress & Expo ECCE 2019.

# Power routing

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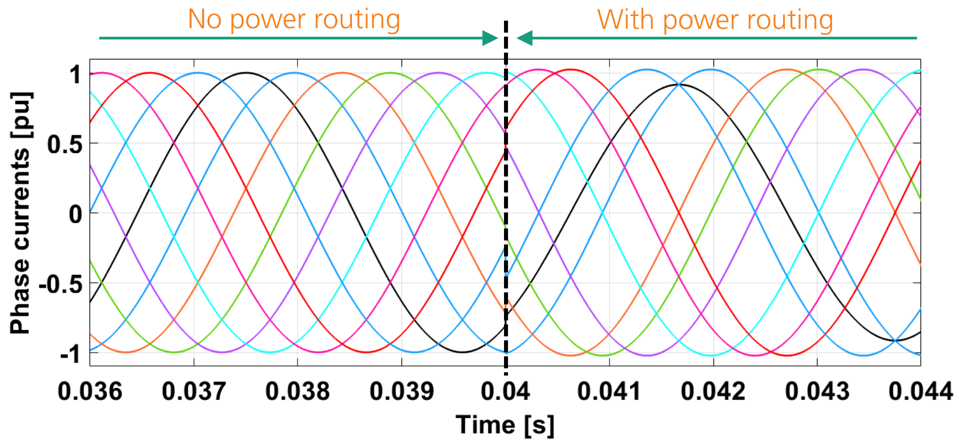


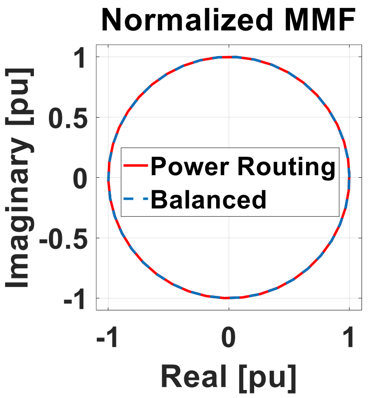


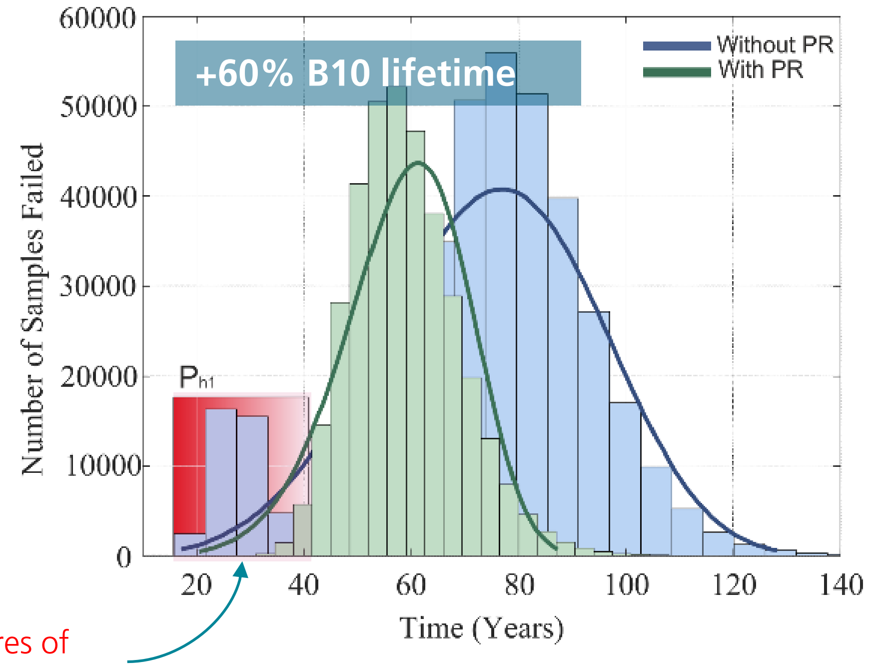


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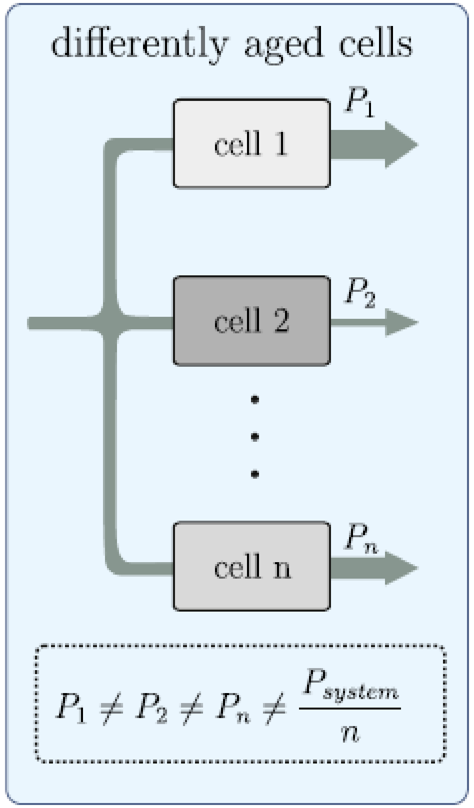
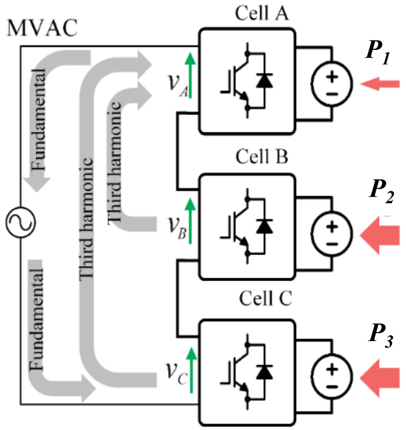
# Power routing

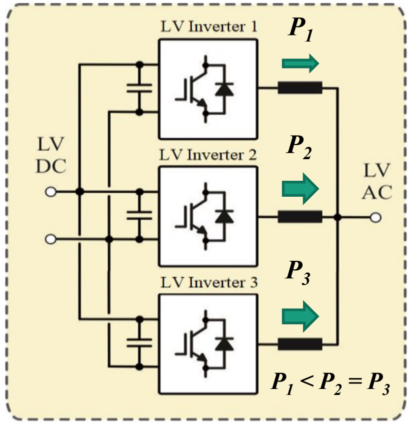
## Application example: Modular Power Converters (CHB Multilevel / Parallel Converters)




Main principle of Power Routing




CHB multilevel converters



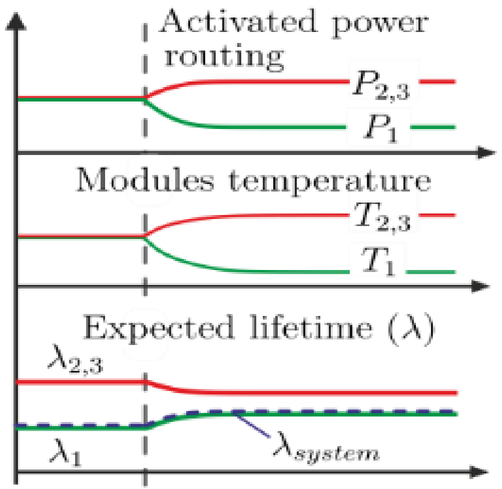

Parallel converters

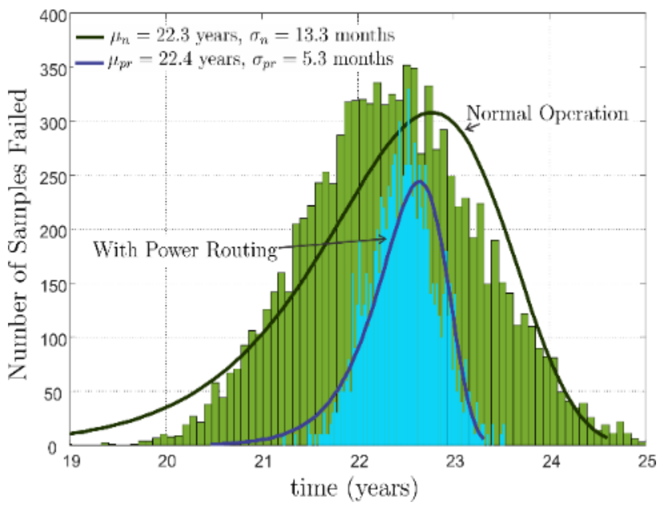
**Unequal power P1 , P2 and P3 are processed**

**Devices connected to the cells suffer different stresses**

**Concept requires a sufficient margin of vgrid / vdc**

**Potential of the algorithm is mission profile dependent**




Unequal power processing ($P_1$, $P_2$ and $P_3$) and result of the power routing

V. Raveendran, et al., "Thermal Stress Based Power Routing of Smart Transformer With CHB and DAB Converters," in IEEE Trans. on Power Electron., vol. 35, no. 4, pp. 4205-4215, 2020.

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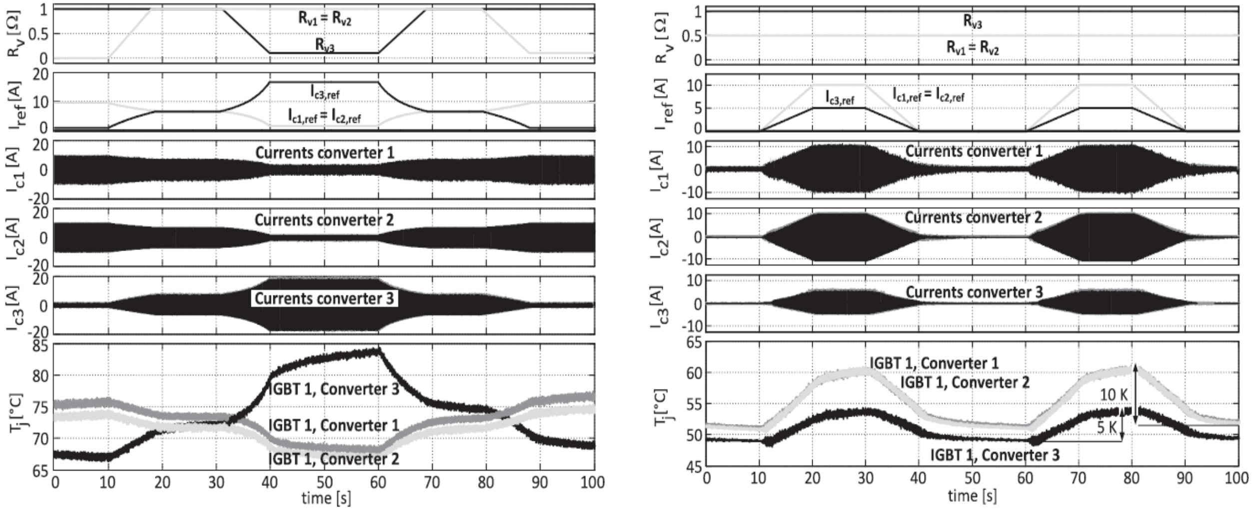
# Power routing

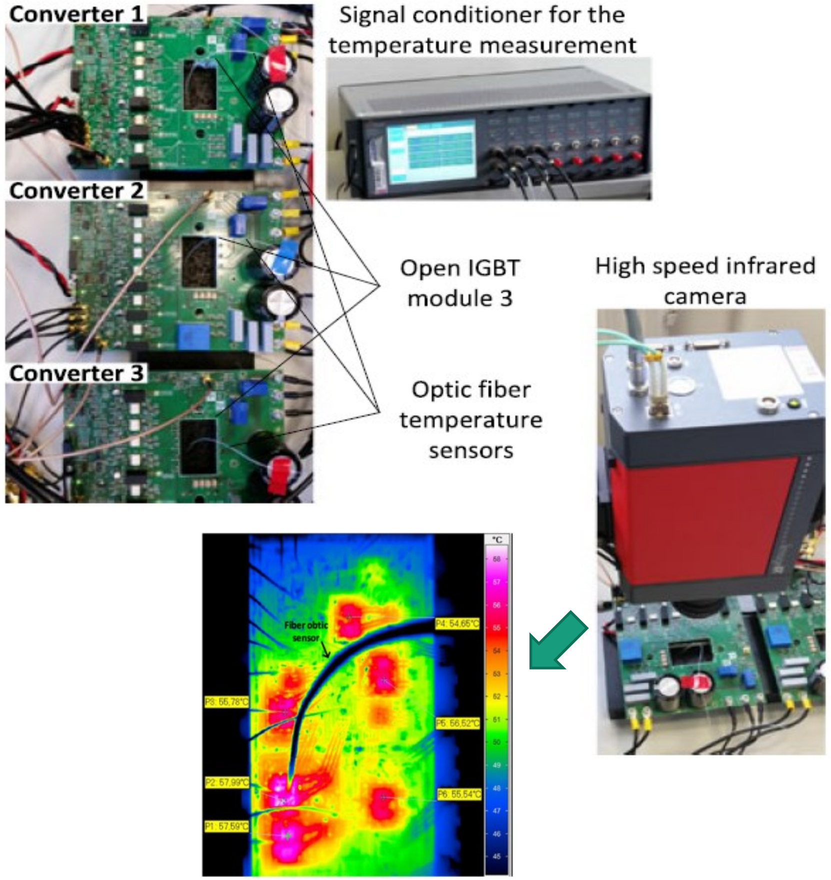
## Application example: Modular Power Converters (CHB Multilevel / Parallel Converters)

- **Junction temperature of modular converters can be managed by using Power Routing.**
  - ✓ **Realization of Maintenance Scheduling**




Experimental result of Power Routing in three parallel converters

M. Andresen, et al., "Lifetime-Based Power Routing in Parallel Converters for Smart Transformer Application," in IEEE Trans. on Ind. Electron., vol. 65, no. 2, pp. 1675-1684, 2018.




Experimental setups and junction temperature measurement results using high-speed infrared camera.

# Charging strategies for lithium-ion batteries

## Maximizing the real-time efficiency of the battery pack and battery system

### Challenge:

- The elevated charging current rate (C-rate) to achieve fast charging can geopardize the safety and lifetime of the lithium-ion batteries.

### Our approach:

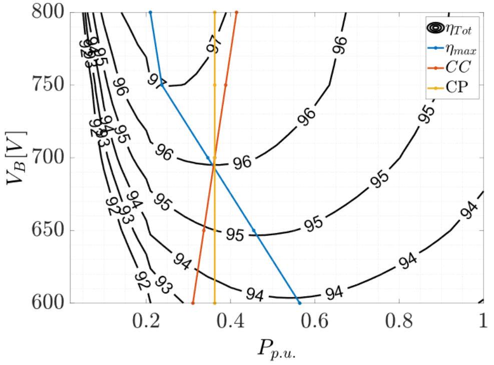
- Deriving varying current profiles charging strategies considering the internal states of the battery
- Computing the effect of battery voltage variation on the DAB losses
- Estimate the battery internal losses (equivalent circuit)

### User benefits:

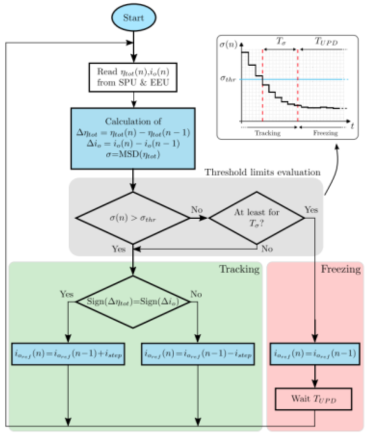
- Prolongation of battery lifetime
- Minimized power losses at the system level

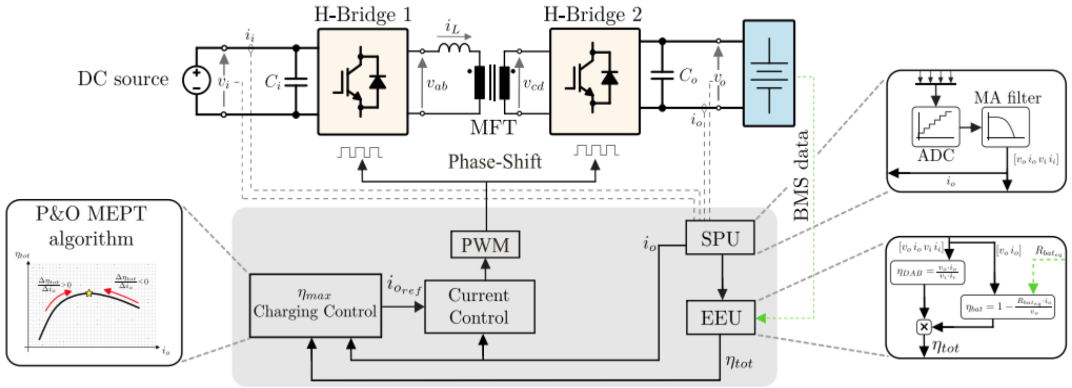
N. Blasuttigh, H. Beiranvand, T. Pereira, S. Castellan, A. M. Pavan and M. Liserre, "ηmax-Charging Strategy for Lithium-Ion Batteries: Theory, Design, and Validation," in IEEE Trans. Power Electron., vol. 39, no. 7, 2024, doi: 10.1109/TPEL.2024.3381644.

Efficiency Optimization




$\eta_{max}$-Charging Strategy Numerical Algorithm




Implementation

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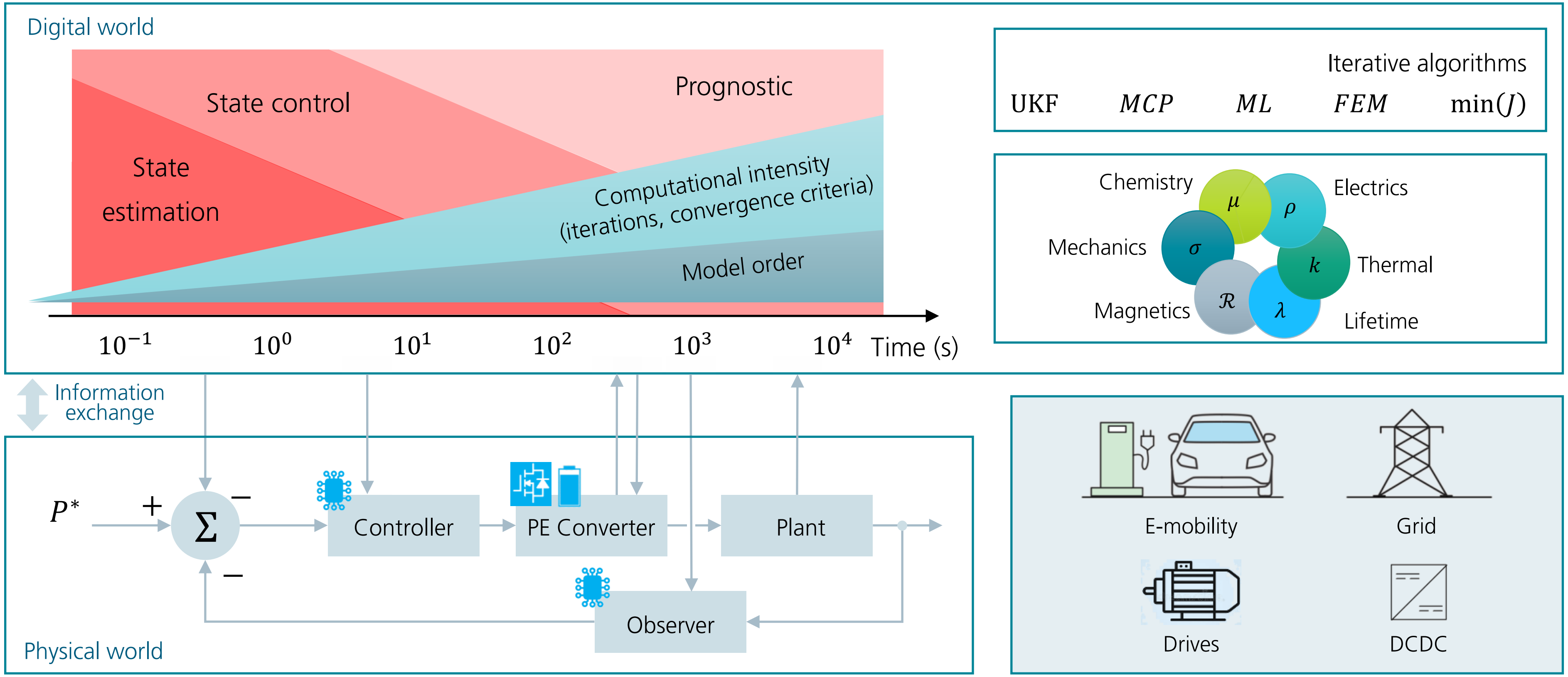
Digitalisation of power electronics: state estimation & smart control

# Take away & discussion

# Conclusion

## Digitalisation for states estimation, prognostics, and control



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# Digitalization
# Empowering the Future of Power Electronics

Special Session Smart Energy Conversion
ECCE Europe 2024

Dr. Martin Bischoff
Siemens Technology



SIEMENS

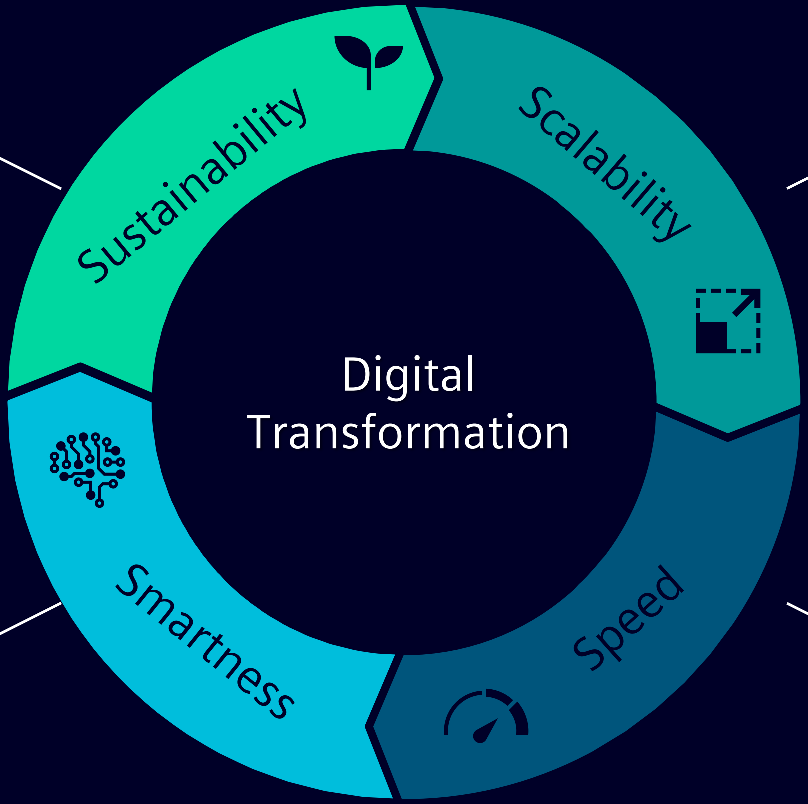
# Todays Focus Areas in Power Electronics are interdependent and empowered by the Digital Transformation.


**CO2-Neutrality**
25% of CO2 emitted by industry
**Energy Efficiency**
70% of el. power in industry for drives
**Resource Efficiency**
13% only, of global waste is recycled

**Circular Economy & Novel business models** inverter-as-a-service, design implications

**IT/OT Integration**
Condition monitoring, preventive maintenance, lifetime extension

**Internet of Things, Internet of Energy**
Open APIs, updateability, interoperability monitoring & control




**Fossile Era -> All-Electric Society**

- Renewable energy
- Power grid
- Large-scale storage
- Battery storage
- Health care
- Data centers

**Modular Building Blocks vs. Integrated System**
Model-based development & AI for design optimization

**Market-readiness of innovations Product cycles**
HW products, embedded software, Digital services

**Reduce time-to-market**
Data management
Model-based development
Generative AI

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# Todays Focus Areas in Power Electronics are interdependent and empowered by the Digital Transformation.

Industrial inverter market: €54bn (2018), €91bn (2023), €134bn (2028)

**CO2-Neutrality**
25% of $CO_2$ emitted by industry
**Energy Efficiency**
70% of el. power in industry for drives
**Resource Efficiency**
13% only, of global waste is recycled

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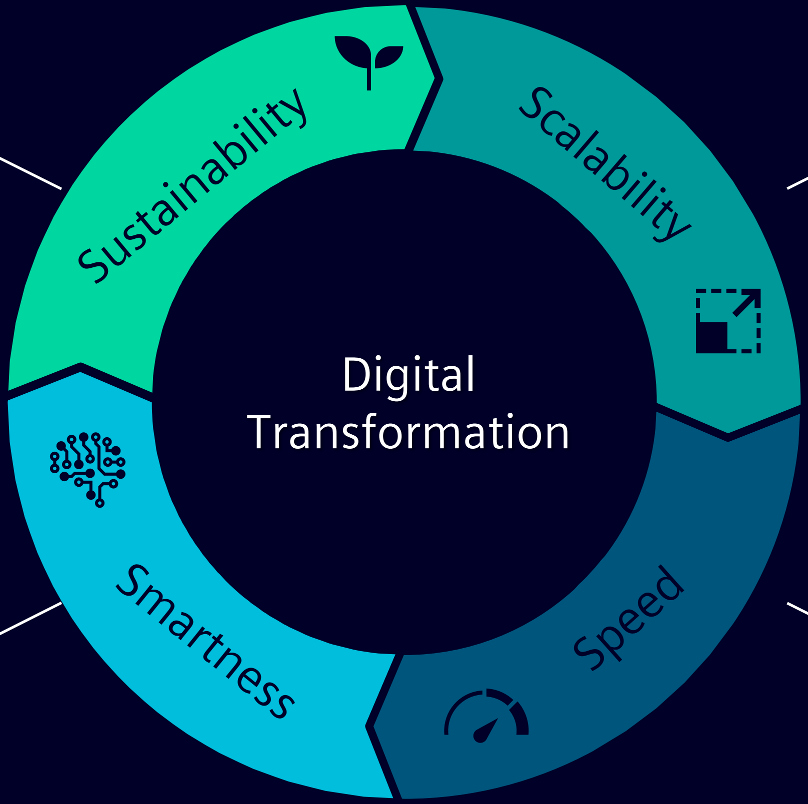


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Data management
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Generative AI

 

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# Model-based Inverter Certification
Siemens and UL Solutions
demonstrate paradigm shift

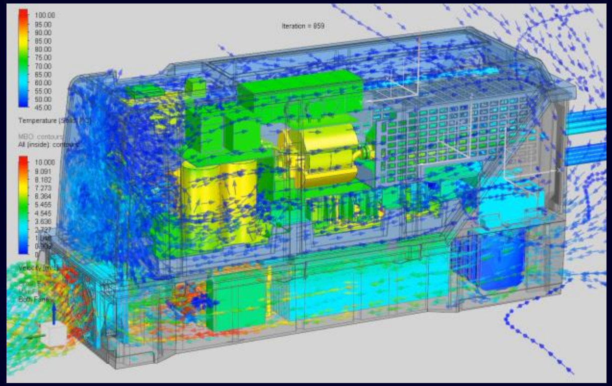
Drive series G220  1.1kW - 55kW


CONJUGATE HEAT TRANSFER MODELING OF SIEMENS FS D1 GPD IP20 400V 22kW C2 FSD PRODUCT

FULL INDEPENDENT MODEL VERIFICATION & VALIDATION & UQ ASSESSMENT

DISTRIBUTION: CLIENT CONFIDENTIAL
Version 1.0 July 18, 2022

Empowering Trust™



**Independent Model Verification & Validation Reports:**
Door opener for the acceptance of simulation results
in product certification as UL and CE.

## Why – Customer Challenge

- Certification requires exhaustive physical tests
  -> high costs, efforts & long time-to-market

## How – Technical Approach

- Perform tests on digital simulations


## What - Benefits

- Reduced costs and efforts for tests
- Accelerated time-to-market
- Reduced development risk
  by continuous tests during development (agile)
- Better design space exploration
- Scalability by parallelization



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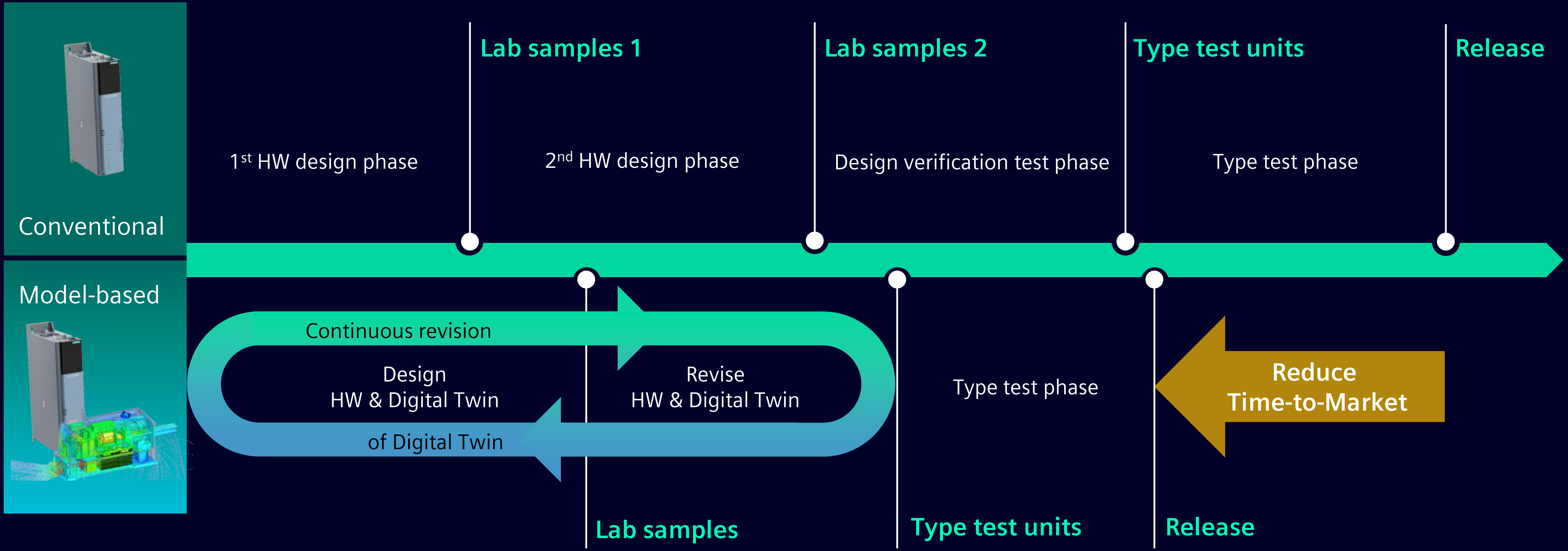
# Model-based Design Process
# Reduce Time-to-Market & Increase Product Quality



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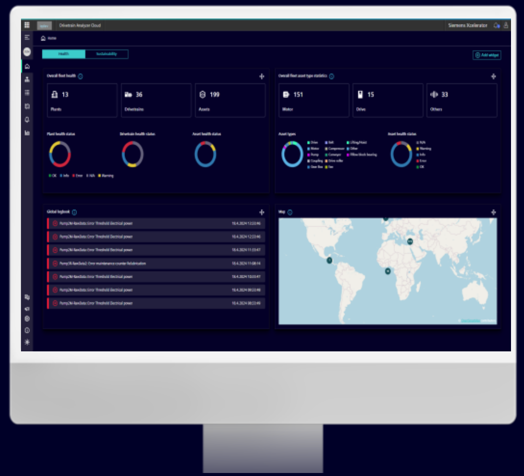
# Digital Drive Train
## Predictive maintenance of motors and drive applications using AI

### Drivetrain Analyzer Cloud
Cloud-based monitoring solution

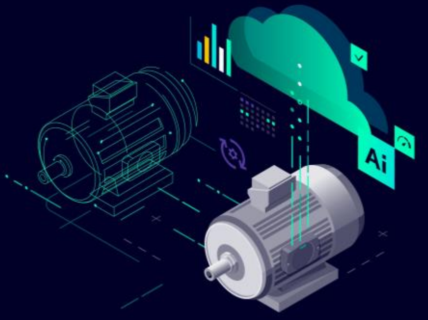

### Connection Module IOT
Plug-&-play connectivity
Sensor module for induction motors of any brand



### Insights Hub App
- Operation state monitoring
- Anomaly & fault detection
- Energy & maintenance optimization

### Why – Customer Challenge
42 % of unplanned downtime due to equipment failure which costs manufacturers up to 50 bn USD / year[1]

### How – Technical Approach
**Condition Monitoring:** Compare motor operation w/ reference model
**Fault Identification:** AI-based frequency analysis



### What - Benefits
**Up to 30% lifetime extension**
by optimized maintenance schedules
**8 % - 12 % productivity increase**
by avoiding unexpected production stops
**10 % energy cost and CO2 reduction**
by data analytics & AI

# Siemens Xcelerator
## The open digital Business Platform for accelerating the digital transformation

Software Applications

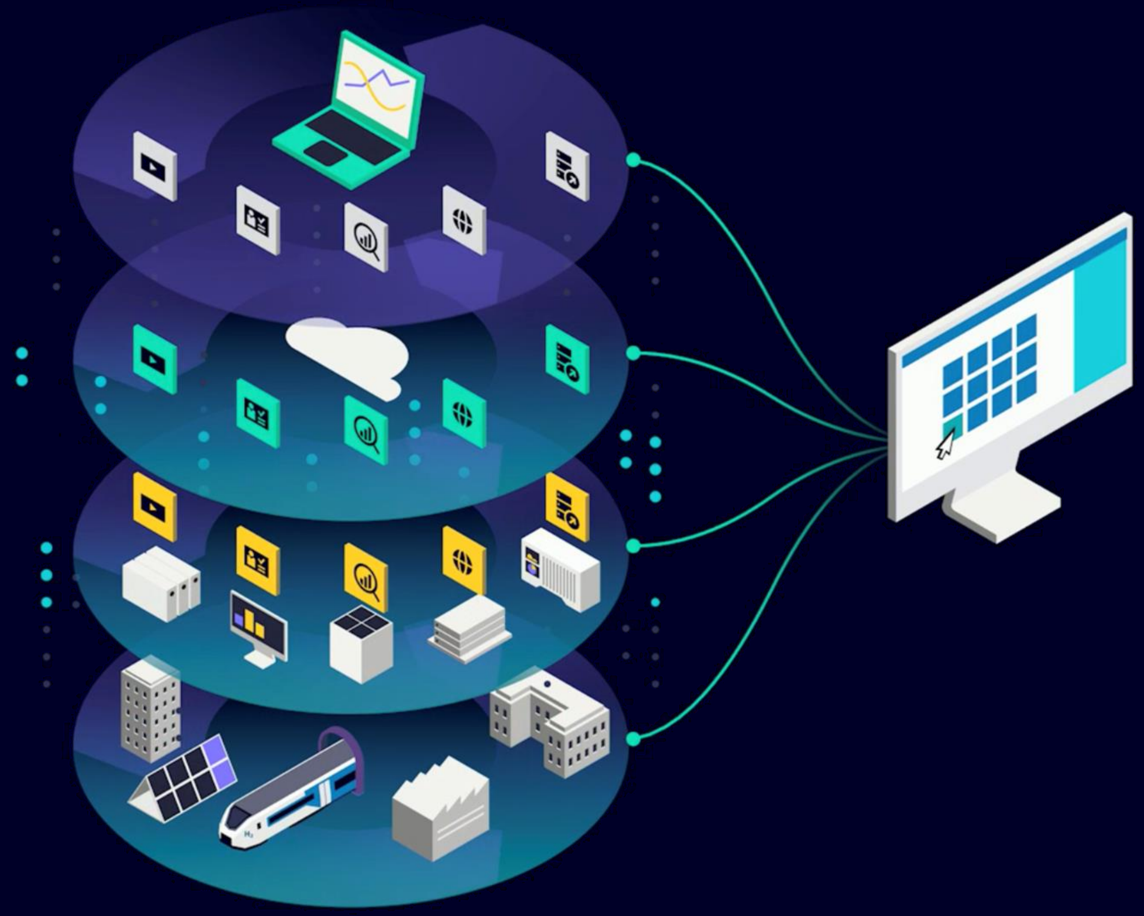
Cloud

Edge Computing

Field Devices, Inverters, Motors

IT

OT



- Interoperable
- Open
- Flexible
- As-a-service

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# Contact

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# Smart converters for Gaudino S.R.L.

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# About the presenter

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# Smart Converters for Gaudino S.R.L
## Some wording

**Smart features include**

- Edge functionality based on native processing power of the converters
- "Drive as a sensor", using the native sensors of the converter
- External sensors using the native connection ports of the converter

- **Smart services include**
  - Platform functionality, cloud-based or on-premise
  - External devices, not native to the converter, with edge capability, gateways, and memory
  - (Additional) analytic power in the platform
  - People, expert and admin users, who enrich the data and normally provide the main value

# Smart Converters for Gaudino S.R.L
## The case



**Background**

- Rivoira Group is a leading producer of apples, kiwis and other fruit
- Gaudino S.R.L. makes high quality refrigeration systems, supplier to Rivoira
- Danfoss is a producer of frequency converters, supplier to Gaudino

**Challenges**

- Rivoira cannot afford plant downtime, especially during the apple harvest seasons. Unforeseen downtime translates into a very high cost.
- Gaudino have warranty obligations and other liabilities for delivered machines, and generally want to protect their stellar reputation
- Gaudino deliveries include a control system, but this does not allow them to be "predictive“ or do trouble-shooting. They asked Danfoss for support in finding a solution to this need

# Smart Converters for Gaudino S.R.L
## Technical solution



**Condition Based Monitoring**

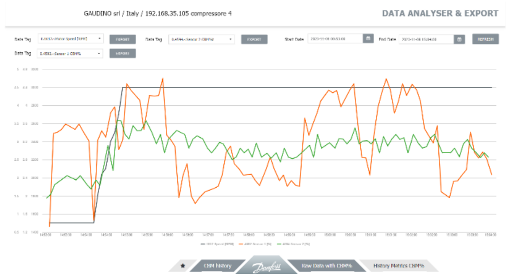
- Smart feature for predictive maintenance, integrated in Danfoss drives
- Anomaly detection, with baselining
- Stator current, load envelope, vibration and other adjacent sensors,

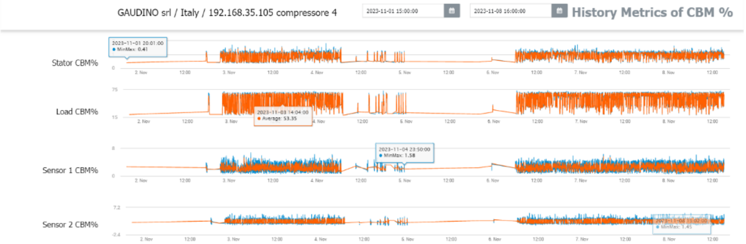
**DrivePro Remote Monitoring**

- Smart service, based on IOT platform
- Remote control of the situation with automatic alerts, data history and secure access for off-site users
- Inhouse experts of Gaudino can escalate support cases to Danfoss service partners whenever necessary

# **Smart Converters for Gaudino S.R.L**
# November 2023

- **Historical performance of the system:** several grid-side voltage surges were detected that would have damaged the machine over time. Rivoira brought the issue to power utility Enel for a solution




- **Detection of a small load-side anomaly, caused by a valve with a developing fault:** Rivoira replaced the valve under warranty without much effort, thus avoiding much bigger problems and cost from damage to the compressor and inverter.
- see also **https://youtu.be/bdlAPyICQDg**

# Smart Converters for Gaudino S.R.L
## Key takeaways

- For Rivoira, the value was avoidance of downtime
- For Gaudino, the value was reduced warranty cost and good customer satisfaction
- Value creation was enabled by the smart converters, smart features and services, but the main value was created by the engineers of Gaudino
- Real-life smart converter functionality is still mainly about anomaly detection, and about how to deliver alerts and historical data to expert users in a smart way. The automated diagnostic capability is quite limited.
- All this could have been done with traditional technology, but setting it up with fieldbus and MES would be extensive and expensive work, with unwanted impact on sub-systems

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