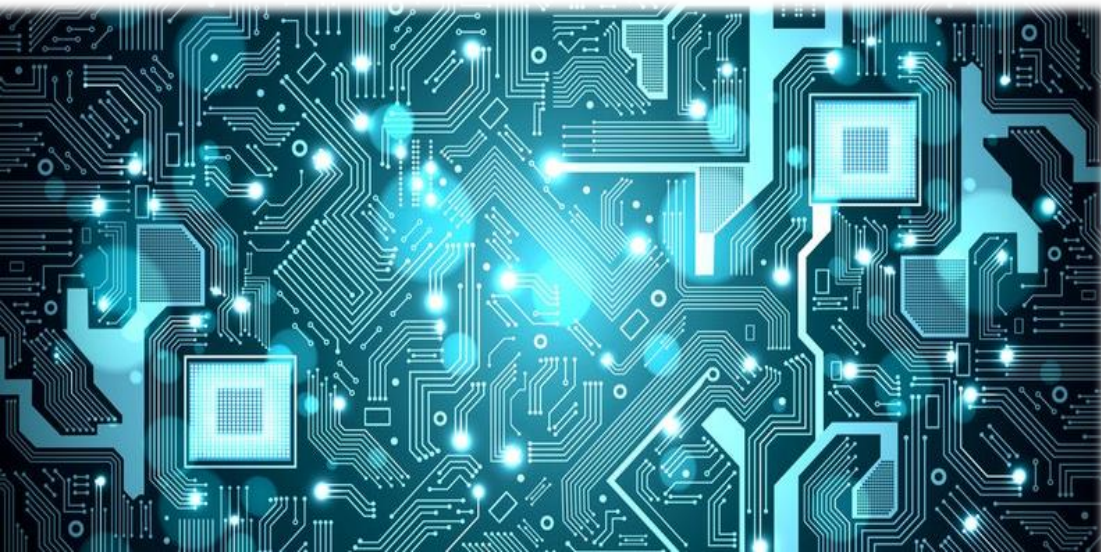




E-DRIVE CONTROLS TOOLCHAIN FOR ACCELERATED DEVELOPMENT



2024/10/08

FABIEN VIDAL-NAQUET



A public sector
R&I body

A training
center

An industrial
group

An international scope in the fields of
energy, transport and the environment

RESPONSIBLE OIL AND GAS

Proposing technologies that
meet the demand for
energy and chemical
products, reducing the
environmental impact

RENEWABLE ENERGIES

Developing solutions to
produce energy, fuels
and chemical intermediates
from renewable sources

CLIMATE, ENVIRONMENT AND CIRCULAR ECONOMY

Reducing the impact of
human and industrial
activities on the climate and
the environment

SUSTAINABLE MOBILITY

Developing effective,
environmentally-friendly
solutions for the transport
sector



1,530
people



1,078 engineers and
technicians dedicated
to research




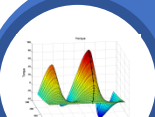
3rd public research
centre for patents

ELECTRIC SYSTEMS DEPARTMENT

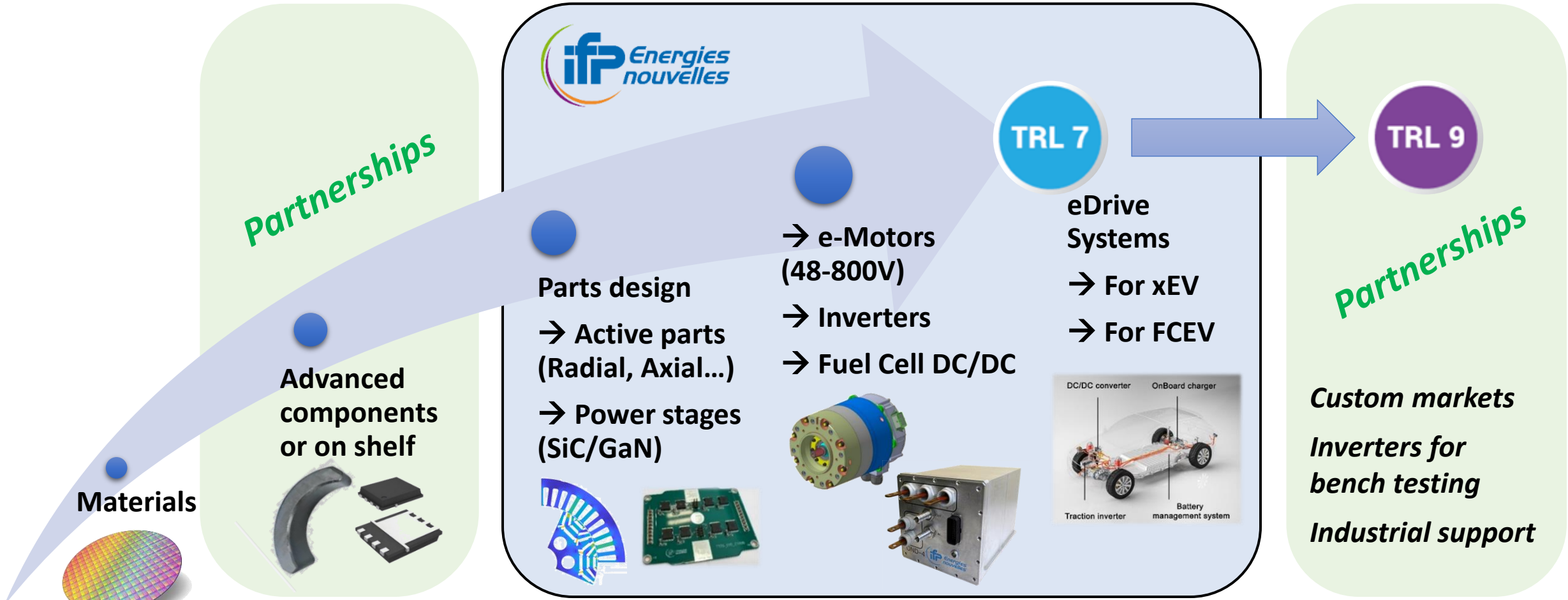


 **Specify** and propose innovative electric systems

 **Design and build** the electric and power electronics components

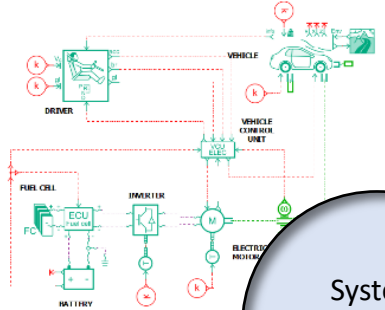
 **Control** and optimize the electric systems on their whole operating area

 **Evaluate** and validate the electric systems on dedicated experimental facilities

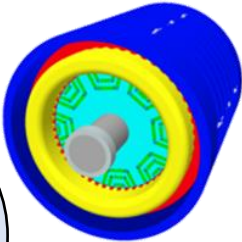


***Towards automotive traction
and fuel cell applications***

Skills available with <100 people

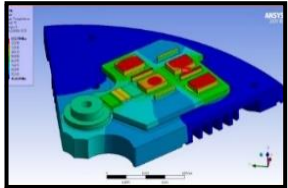
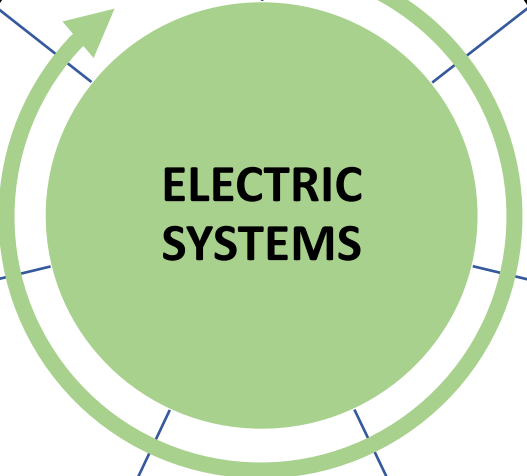


System analysis and simulation

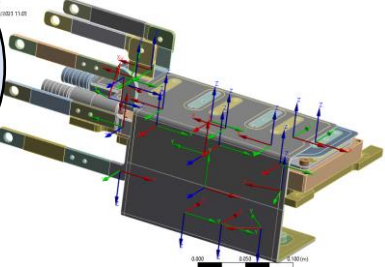


Motors design and simulation (EM, thermal)

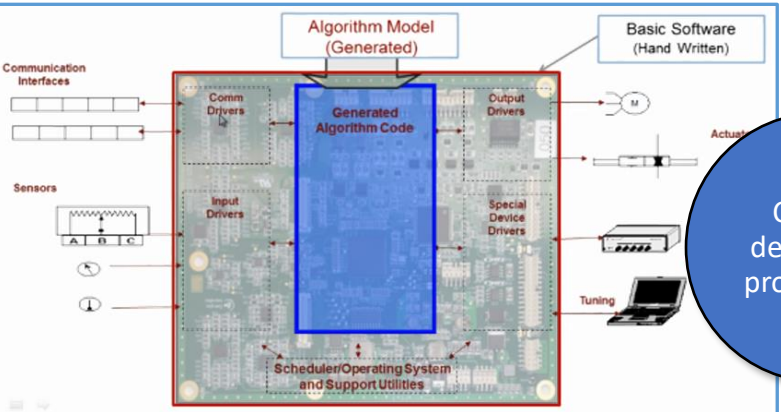
Experimental validation



Electronics design and simulation (EM, thermal)



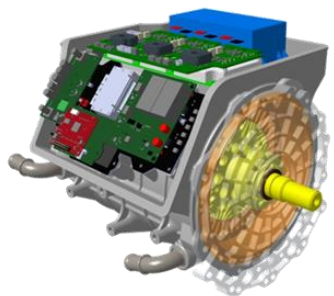
Control design and prototyping



Electric motor and electronics prototyping



Mechanical design



What?

- *IFPEN has developed a unique chain of software tools to support innovation in power electronics and electric motors.*
- *With full vertical integration, from finite element data processing to high-power bench testing, IFPEN drastically reduced its own development times and those of its partners.*

Why?

- *IFPEN has an agile controls team supporting a great number of innovation projects*
 - *But too much time was spent on repetitive tasks, impeding our ability to innovate on controls*
- *Available solutions did not match **our** needs :*
 - *Solutions like those based on AUTOSAR are too heavy and expensive*
 - *Solutions like dSpace cannot be fully integrated and are expensive too*

INTRODUCTION

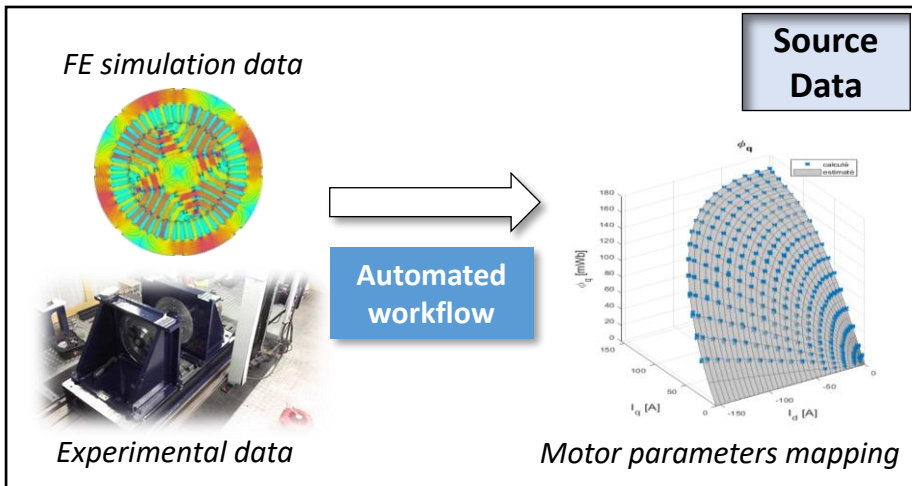
Sustainable
mobility

IFPEN developed a **Full Control Toolchain** for e-Drives

- *To drastically reduce software & control development lead time*
- *To provide ambitious & innovative solutions making sense for industrial applications*

IFPEN developed a **Full Control Toolchain** for e-Drives

- To drastically reduce software & control development lead time
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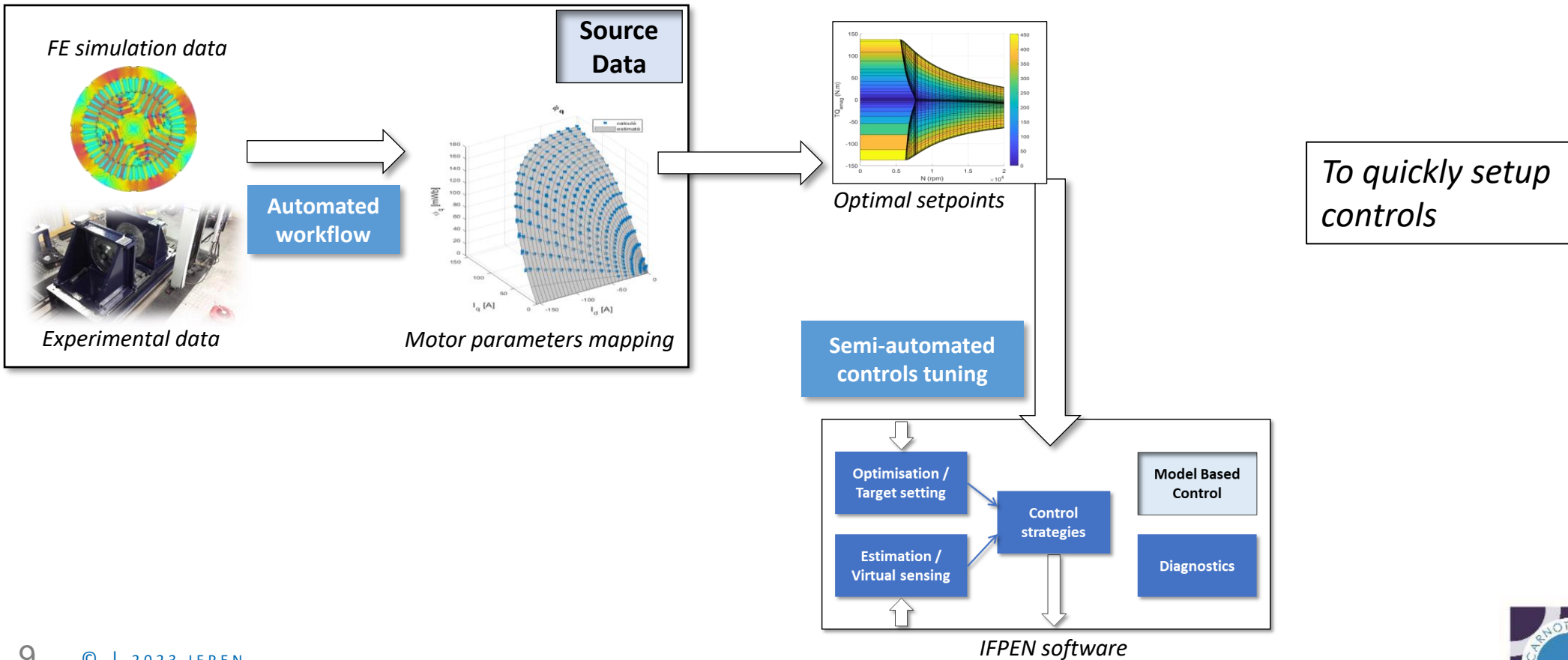


*Start from data
processing*

INTRODUCTION

IFPEN developed a **Full Control Toolchain** for e-Drives

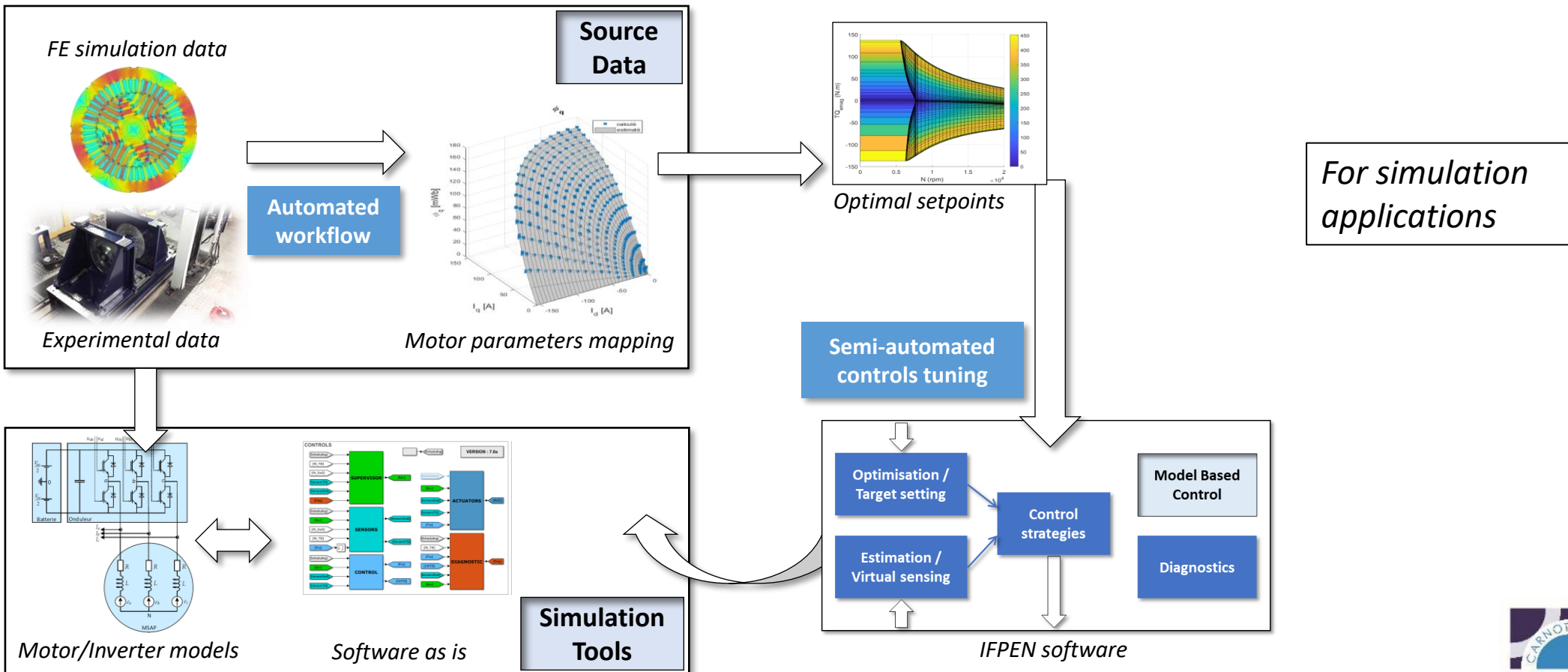
- To drastically reduce software & control development lead time
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INTRODUCTION

IFPEN developed a **Full Control Toolchain** for e-Drives

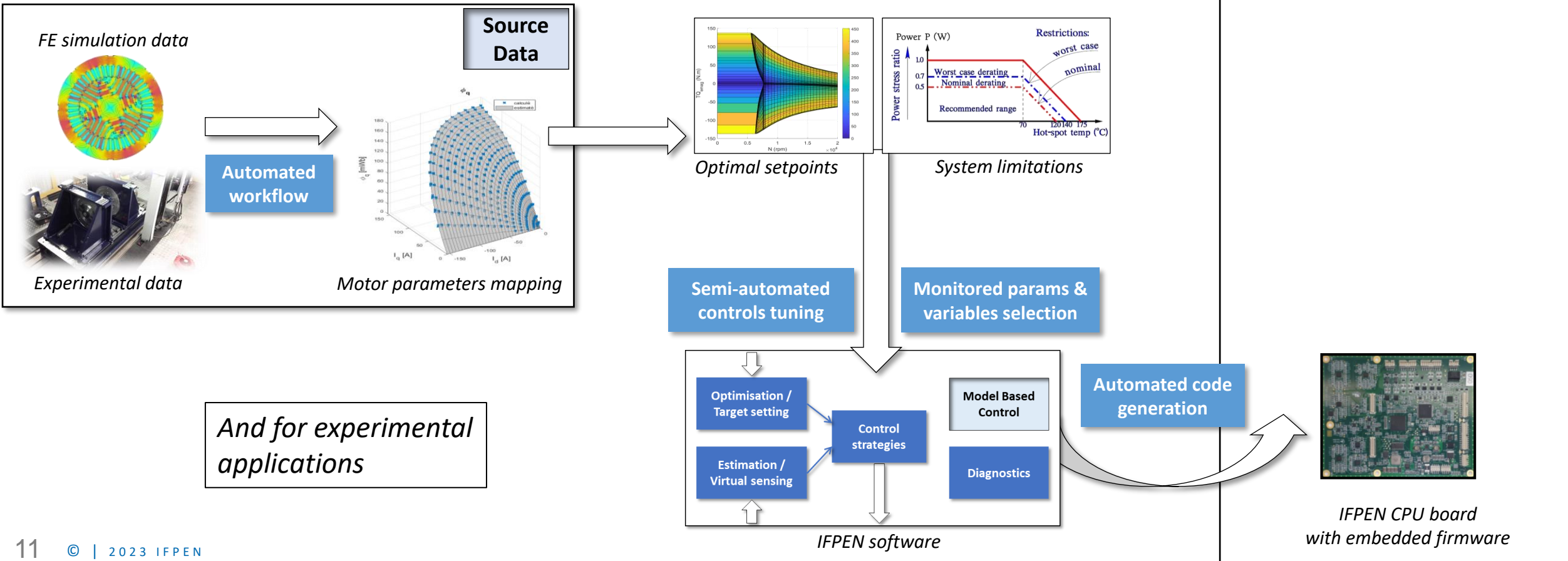
- To drastically reduce software & control development lead time
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INTRODUCTION

IFPEN developed a **Full Control Toolchain** for e-Drives

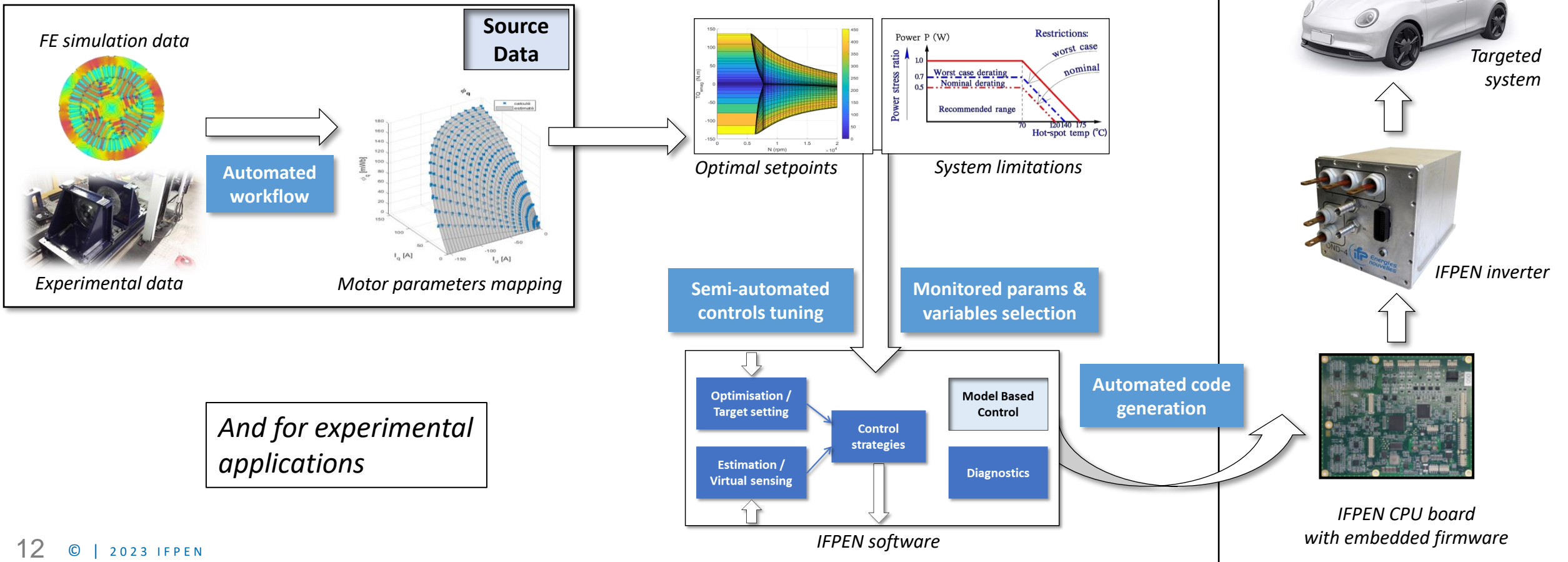
- To drastically reduce software & control development lead time
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INTRODUCTION

IFPEN developed a **Full Control Toolchain** for e-Drives

- To drastically reduce software & control development lead time
- To provide ambitious & innovative solutions making sense for industrial applications



SUMMARY

I) Software calibration and generation

II) Software experimental validation

III) Software simulation tools

SUMMARY

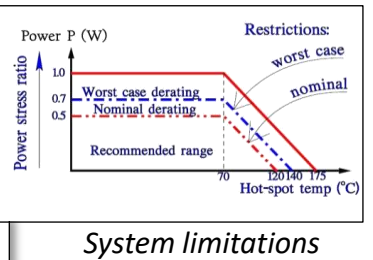
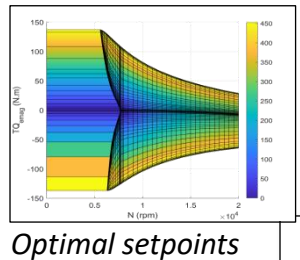
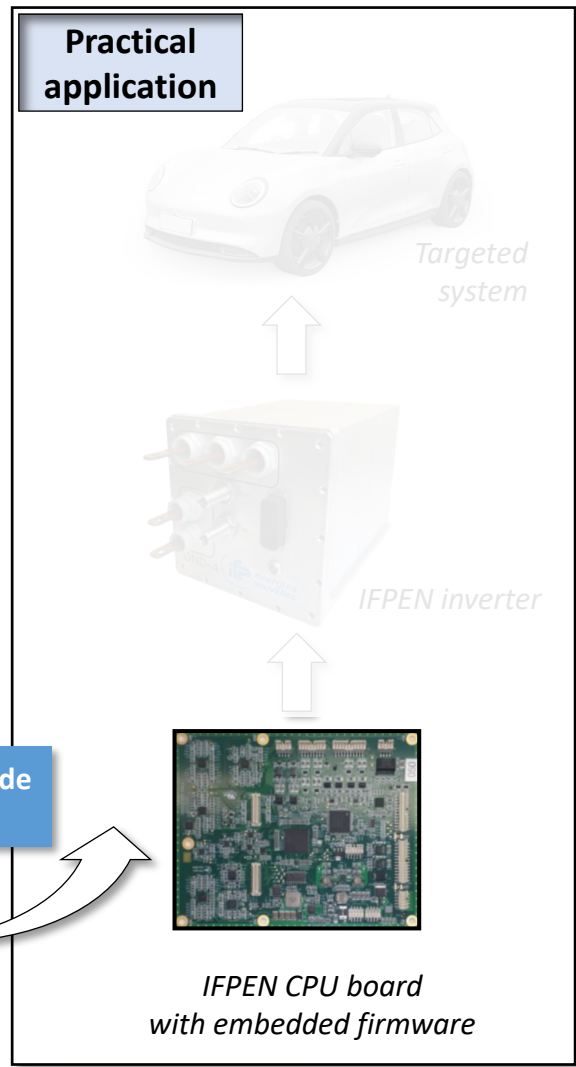
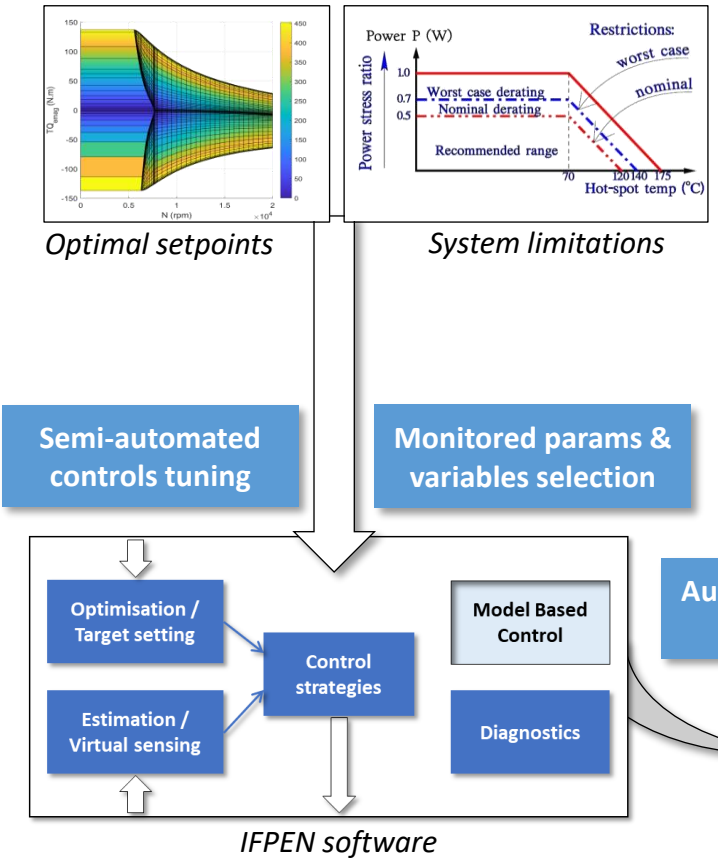
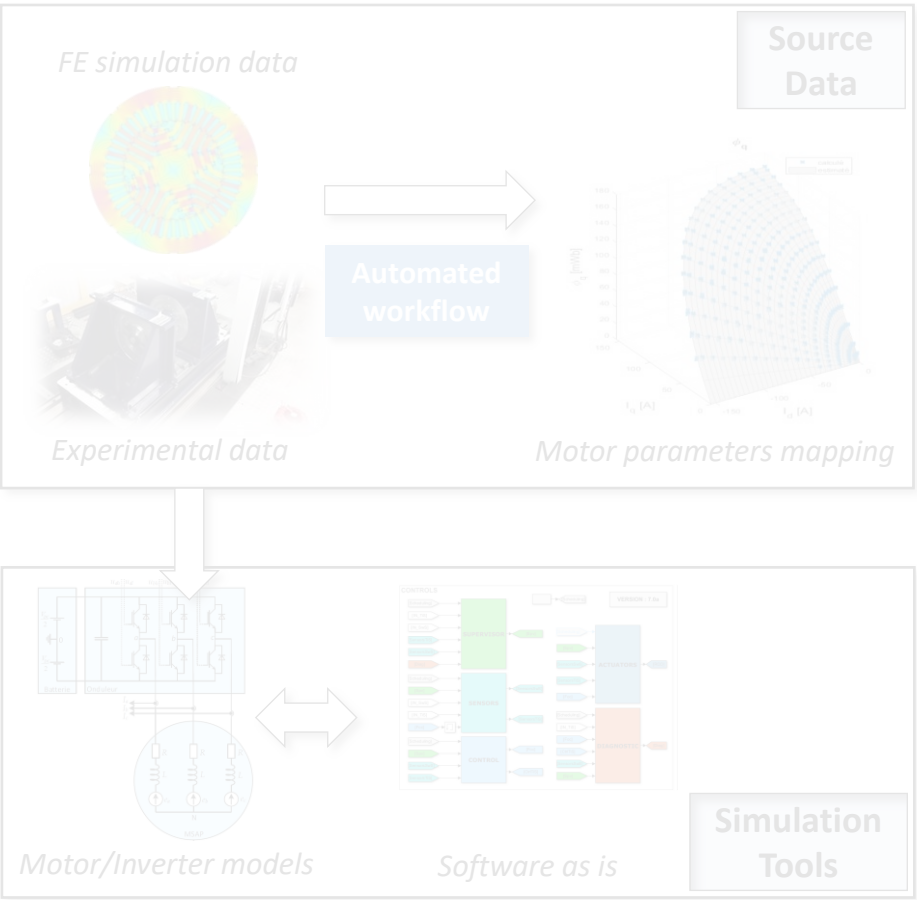
I) Software calibration and generation

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III) Software simulation tools

I) SOFTWARE CALIBRATION AND GENERATION

I) Software calibration and generation

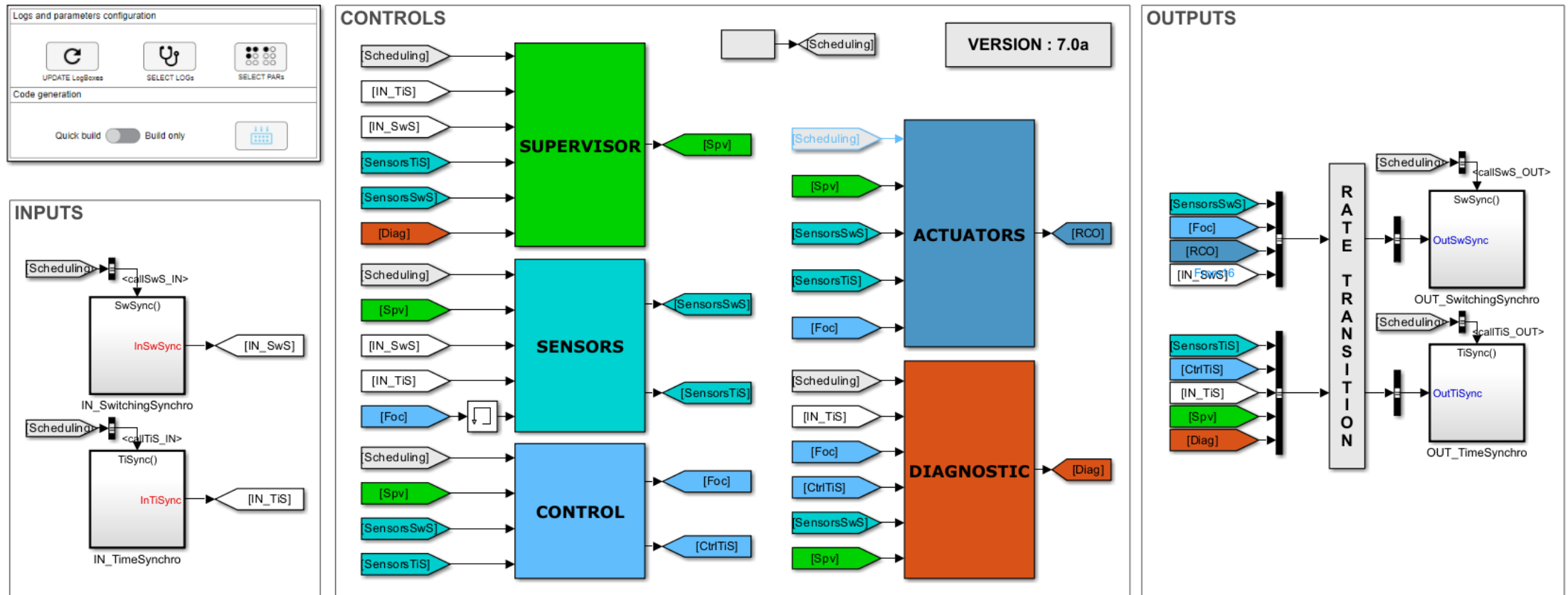


I) SOFTWARE CALIBRATION AND GENERATION

The **toolchain** is articulated around control algorithms in Matlab/Simulink

→ Easy coding facilitates quick development

→ A single engineer can seamlessly setup his system before operating it



I) SOFTWARE CALIBRATION AND GENERATION

System setup is fully done from an App and in-house blocks

→ To select any IFPEN-made inverter targeted and motor calibration

The screenshot shows a software interface for configuring a motor control system. The window title is "Model loaded: CtrlModel_IFP_v7_0a_IHM.slx". The interface is divided into two main sections: "Machine configuration" and "Hardware configuration".

Machine configuration:

- Motor selection: D180_6ph_48V_480A_Ltb
- Winding: STAR Winding

Hardware configuration:

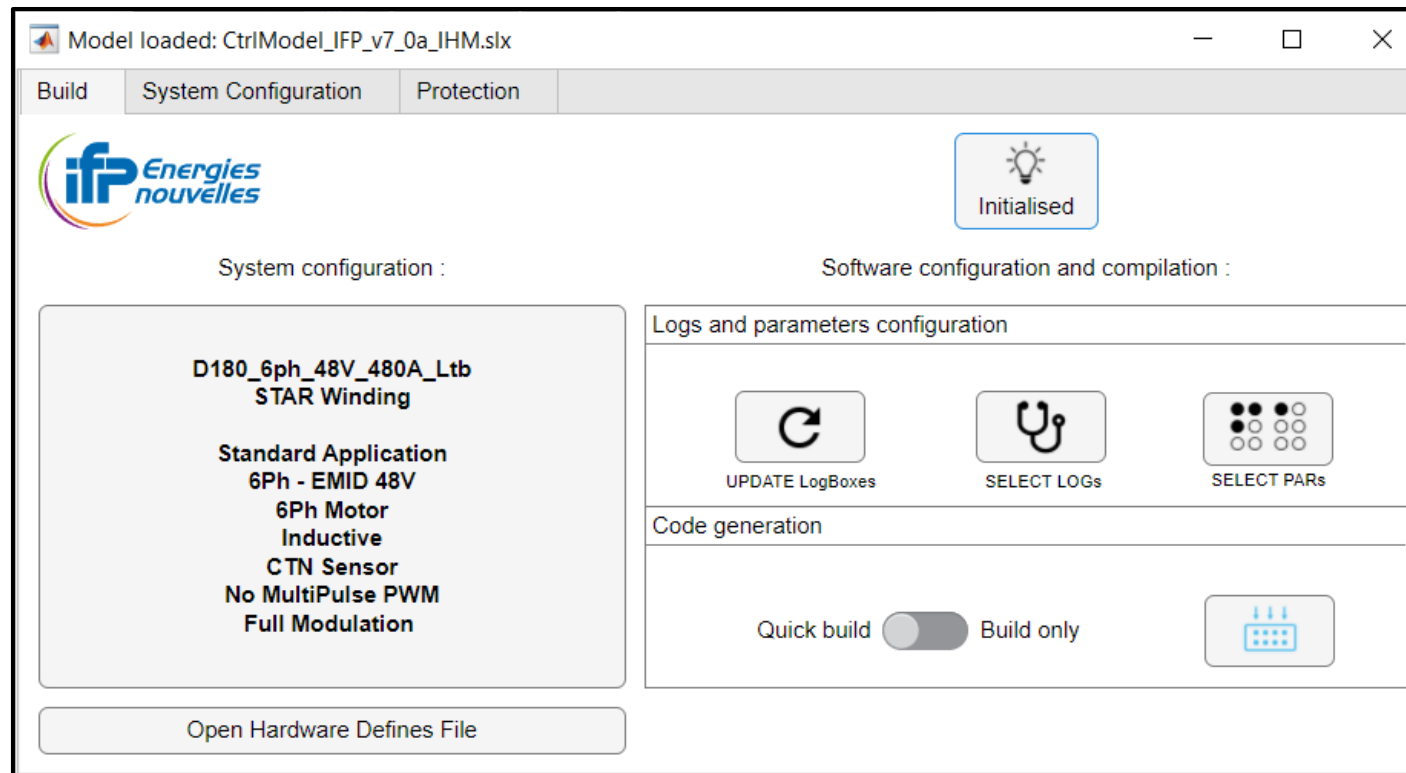
- Application type: Standard Application
- Inverter: 6Ph - EMID 48V
- Motor (Nb phases): 6Ph Motor
- Position Sensor: Inductive
- Thermal Sensor: CTN Sensor
- Multipulse Mode: No MultiPulse PWM
- Mode for 0 or 1 duty cycle value: Full Modulation

Buttons for "Apply" and "Cancel" are located at the bottom left of the interface.

I) SOFTWARE CALIBRATION AND GENERATION

System setup is fully done from an App and in-house blocks

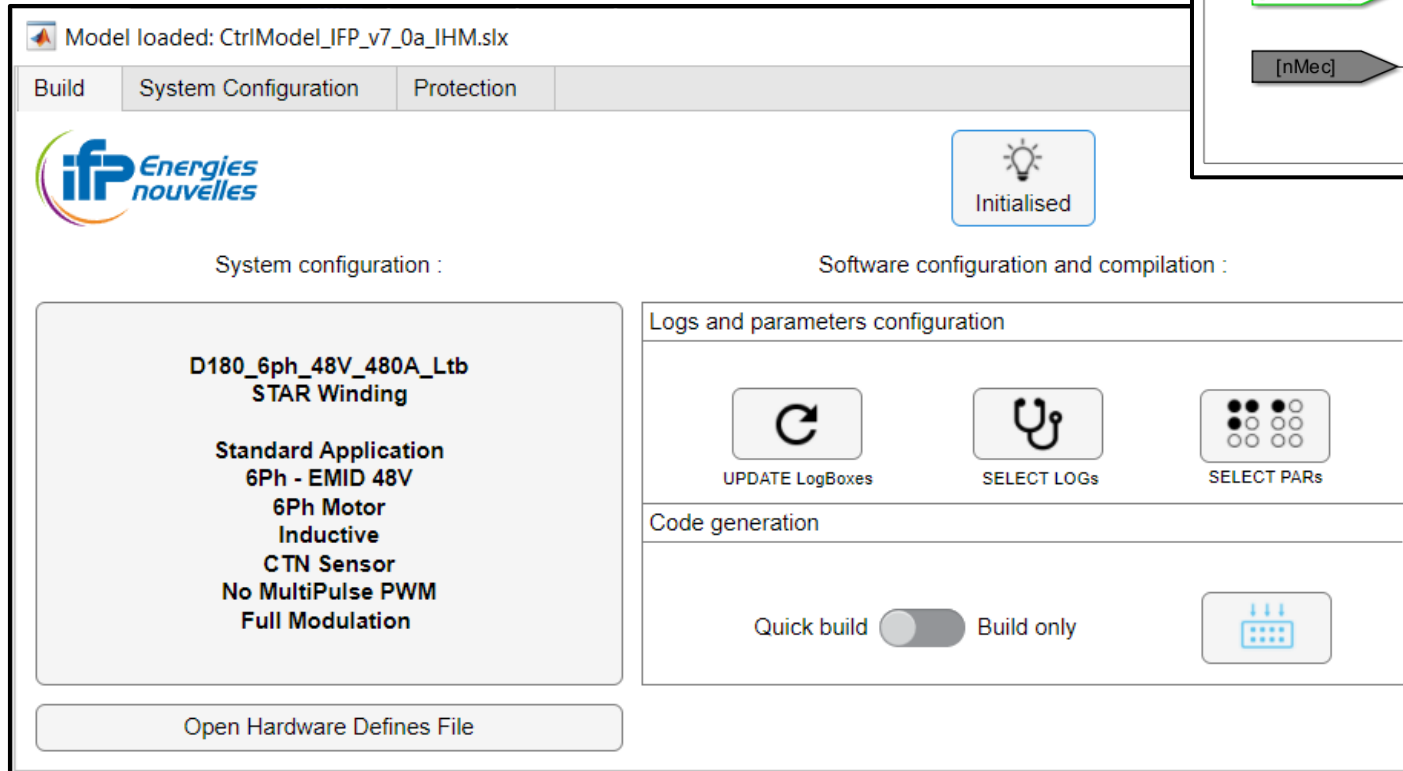
- To select any IFPEN-made inverter targeted and motor calibration
- To manage relevant parameters and signals before code generation



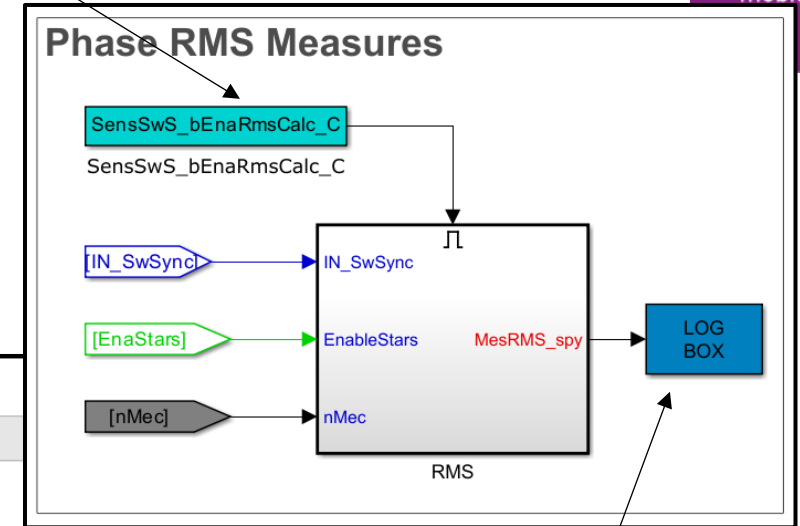
I) SOFTWARE CALIBRATION AND GENERATION

System setup is fully done from an App and in-house blocks

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Parameter



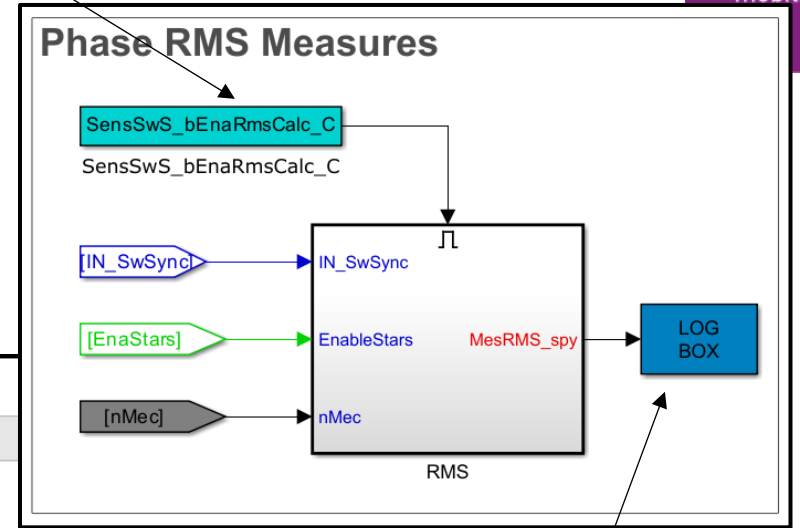
Logged signals

I) SOFTWARE CALIBRATION AND GENERATION

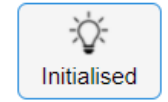
System setup is fully done from an App and in-house blocks

- To select any IFPEN-made inverter targeted and motor calibration
- To manage relevant parameters and signals before code generation

Parameter



The screenshot shows a window titled 'Logged variables selection'. On the left, there is a list of 'AllIFunctions' including 'ActSvm', 'CtrlFoc', 'CtrlFocDQ', 'CtrlFocDQ2D', 'CtrlFocQ', 'CtrlParams', 'CtrlSpMgr', 'CtrlSpMgr1D', 'CtrlSpMgr2D', 'Diag', 'Echo', 'InCAN', 'InCANVCU', 'InSwS', 'InTIS', 'SensSwS', 'SensSwSKalmObs', 'SensSwSNorm', 'SensTIS', 'SensTiSHarmObs', 'Spv', and 'SpvStim'. The main area is divided into two columns for '16kHz' and '1kHz' frequencies. Each column contains a list of parameters with checkboxes. For example, under 16kHz, 'ActSvm_rcaS1' is checked. Under 1kHz, 'ActSvm_vcS2' is checked. At the bottom left, there is a 'Logged signals' section showing '16kHz : 23/50' and '1kHz : 52/240'. There are buttons for 'Apply config from file', 'Cancel', and 'Done'.



Software configuration and compilation :

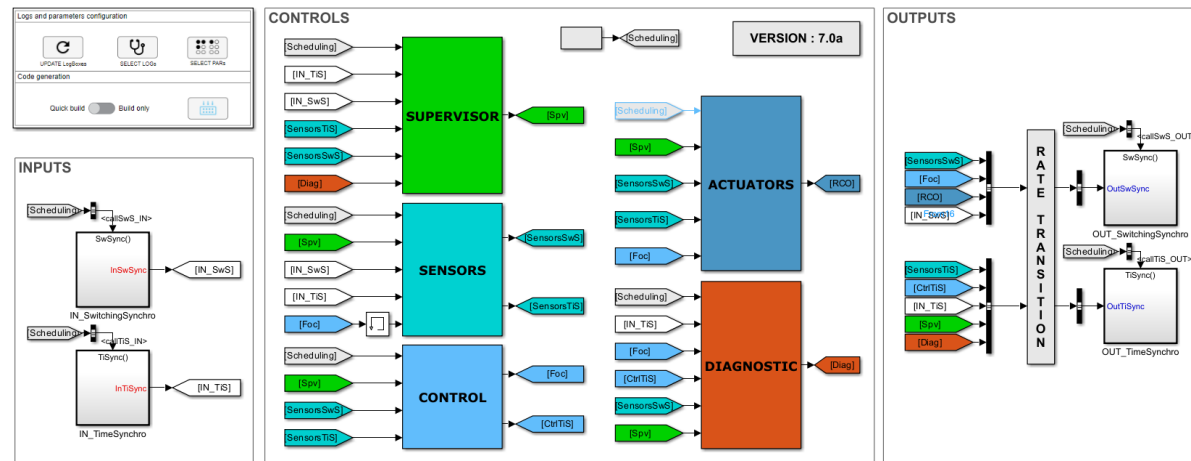
The interface shows several sections. At the top, there is a 'parameters configuration' section. Below it are three buttons: 'UPDATE LogBoxes' (with a refresh icon), 'SELECT LOGS' (with a magnifying glass icon), and 'SELECT PARs' (with a grid icon). Below these is a 'generation' section. At the bottom, there is a 'Quick build' toggle switch (currently off) and a 'Build only' button (with a factory icon).

Logged signals

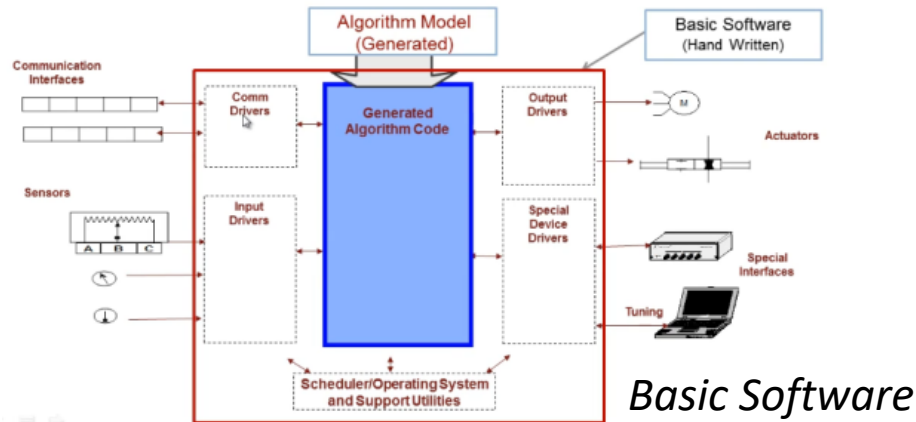
I) SOFTWARE CALIBRATION AND GENERATION

All steps of **code generation** are driven from the App

→ From Simulink code generation to flashing firmware in the inverter

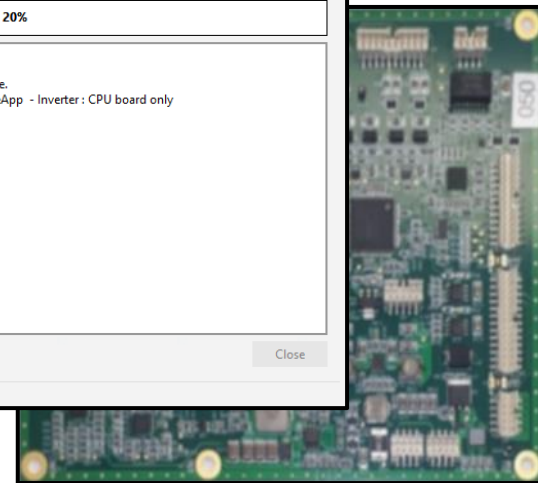
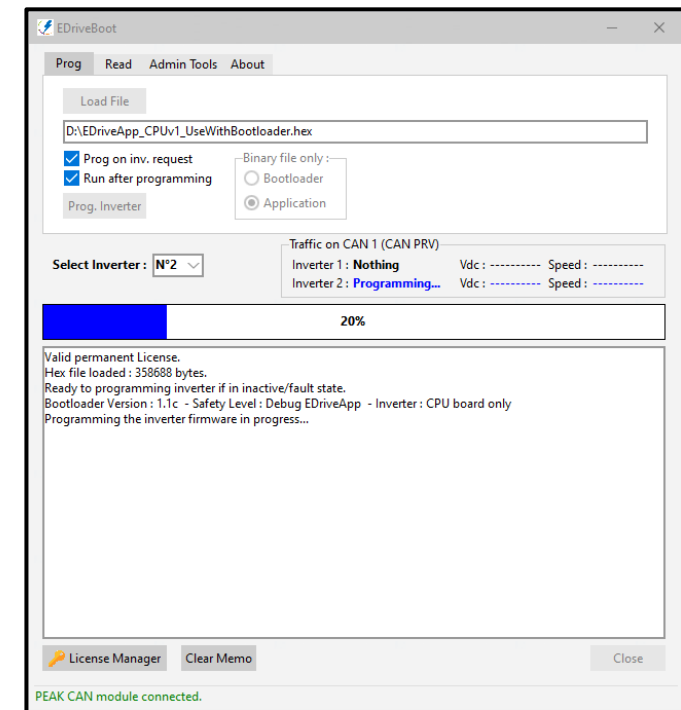


Controls



Basic Software

Code generation and update is done in less than 5 minutes

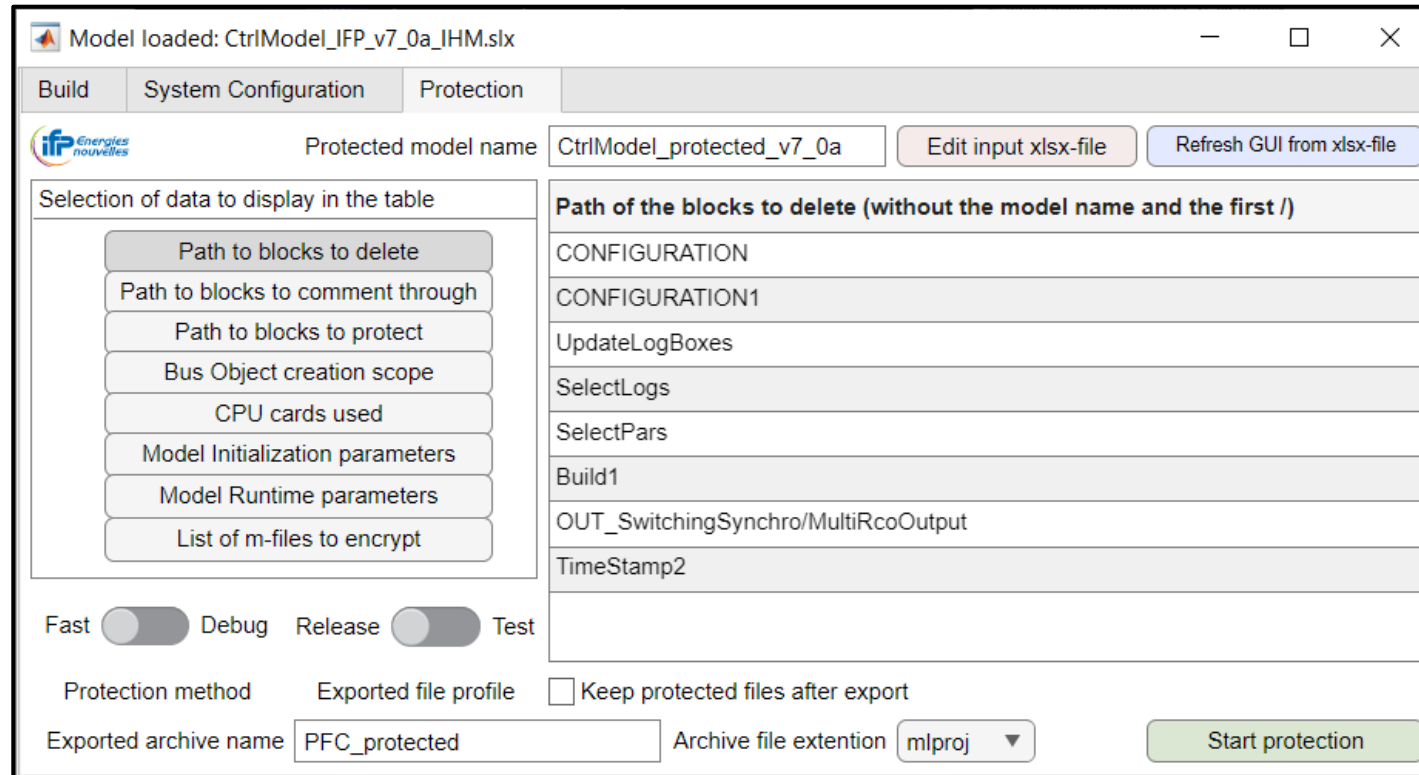


I) SOFTWARE CALIBRATION AND GENERATION

All steps of **code generation** are driven from the App

→ From Simulink code generation to flashing firmware in the inverter

→ Including an option to fully/partially protect our code for external use



Automatic model
reference creation
→ share .slxp files

SUMMARY

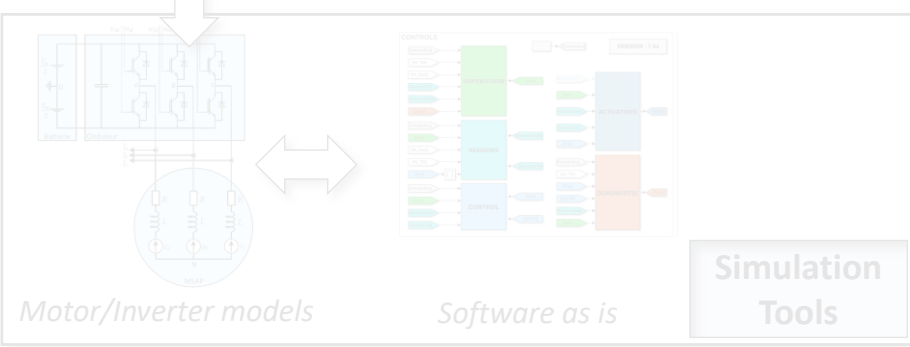
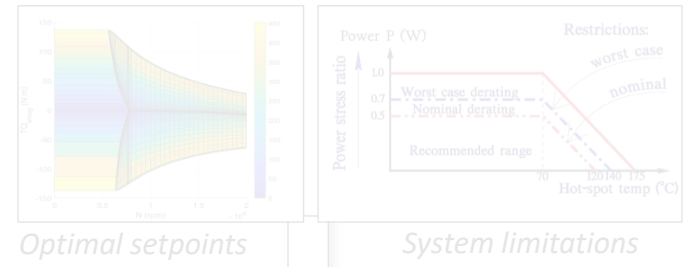
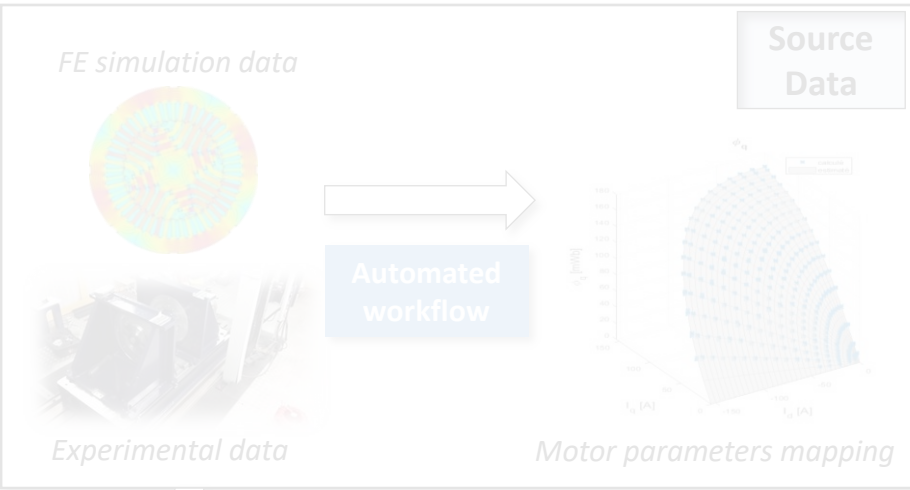
I) Software calibration and generation

II) Software experimental validation

III) Software simulation tools

II) SOFTWARE EXPERIMENTAL VALIDATION

II) Software experimental validation



Semi-automated controls tuning

Monitored params &

Optimisation / Target setting

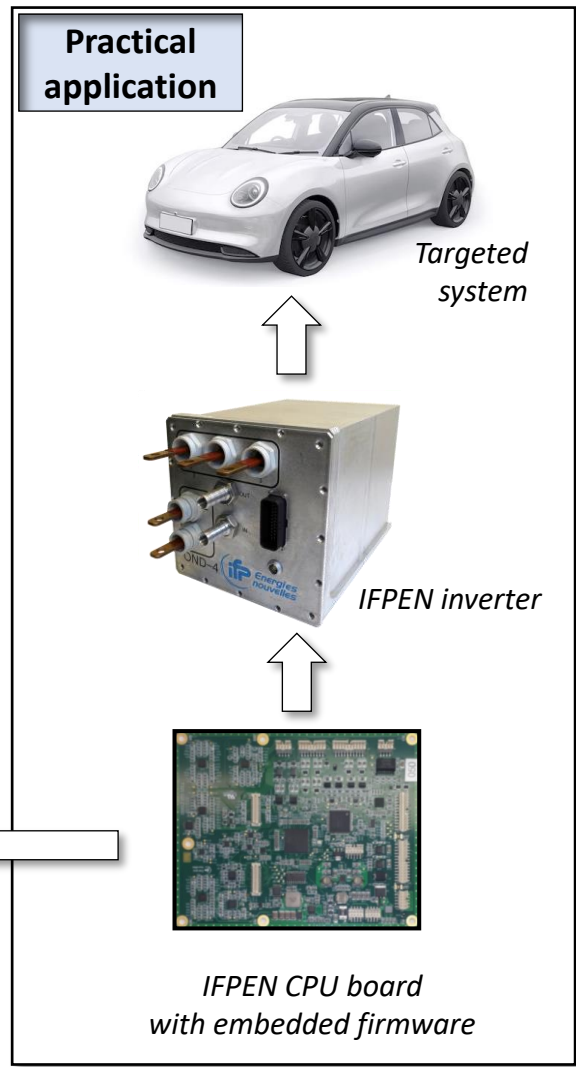
Estimation / Virtual sensing

IFPEN software

Inverter 1		Inverter 2	
Speed Ctrl	Firmware	Cur Auto	Firmware
Speed: 2000	Ver: 1.0.0	Cur Auto: 1.0.0	Ver: 1.0.0
DC Bus: 48.1 V	Ic: 61.0 A	DC Bus: 47.6 V	Ic: 112.6 A
Temp: 28.8 °C	In1: 26.4 °C	Temp: 32.5 °C	In1: 29.3 °C
Cpu: 31.9 °C	In2: 27.0 °C	Cpu: 32.5 °C	In2: 29.3 °C
Current Regulator: P: 0.87, I: 17.3, V: 284.8	Current Regulator: P: 0.87, I: 18.3, V: 299.9		
Position Sensor: Sin Max: 2.928 V, Cos Max: 2.990 V, Sin Min: 2.913 V, Cos Min: 2.989 V, Phi: 6.23 °	Position Sensor: Sin Max: 2.969 V, Cos Max: 2.972 V, Sin Min: 1.975 V, Cos Min: 2.981 V, Phi: 6.85 °		

Motor Speed Inverter 1: 1999 rpm

Motor Speed Inverter 2: 1998 rpm



II) SOFTWARE EXPERIMENTAL VALIDATION

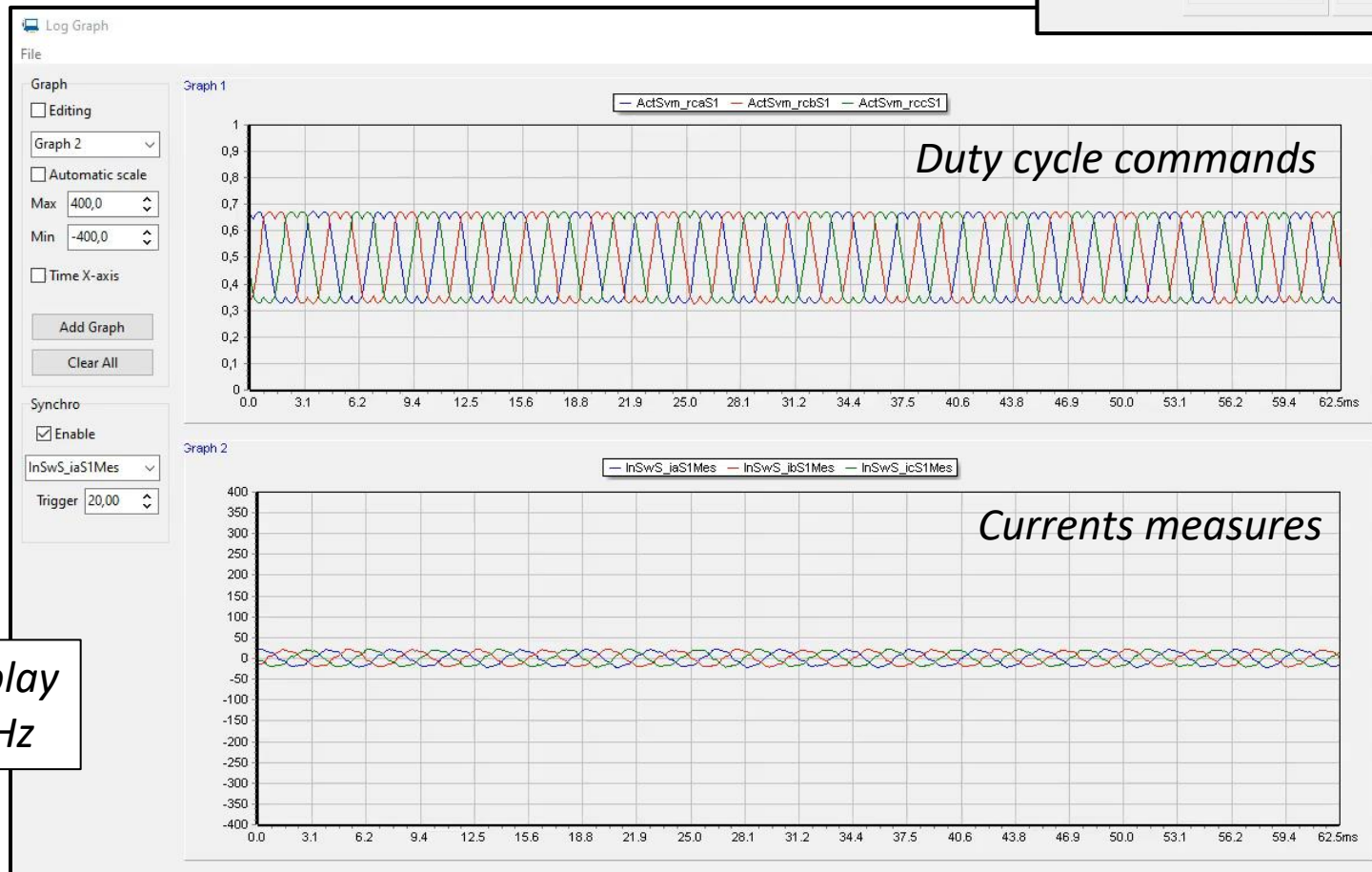
The toolchain includes a practical **Human Machine Interface**

→ Automatically adapted to signals and parameters selected

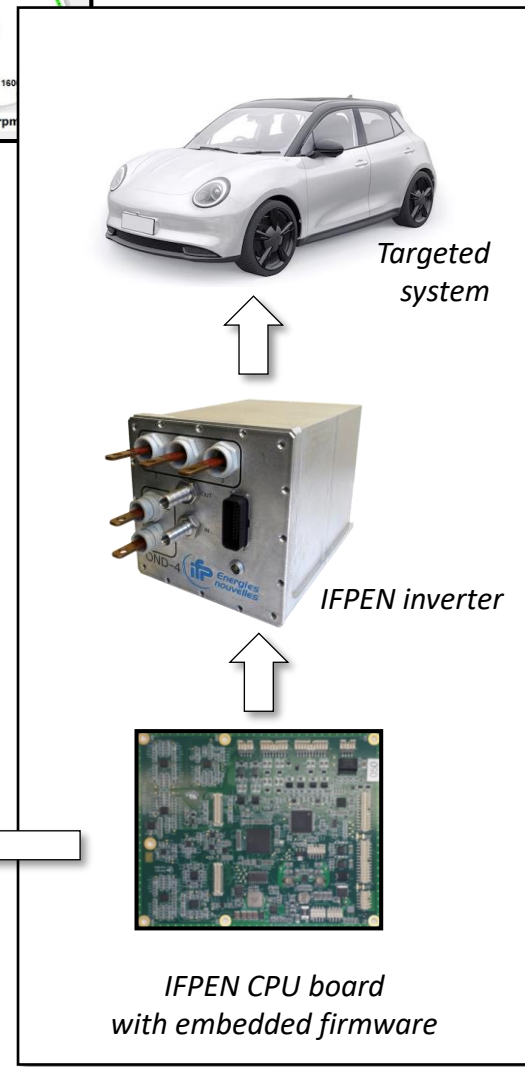
→ Easy to edit for fast-prototyping



Sustainable mobility



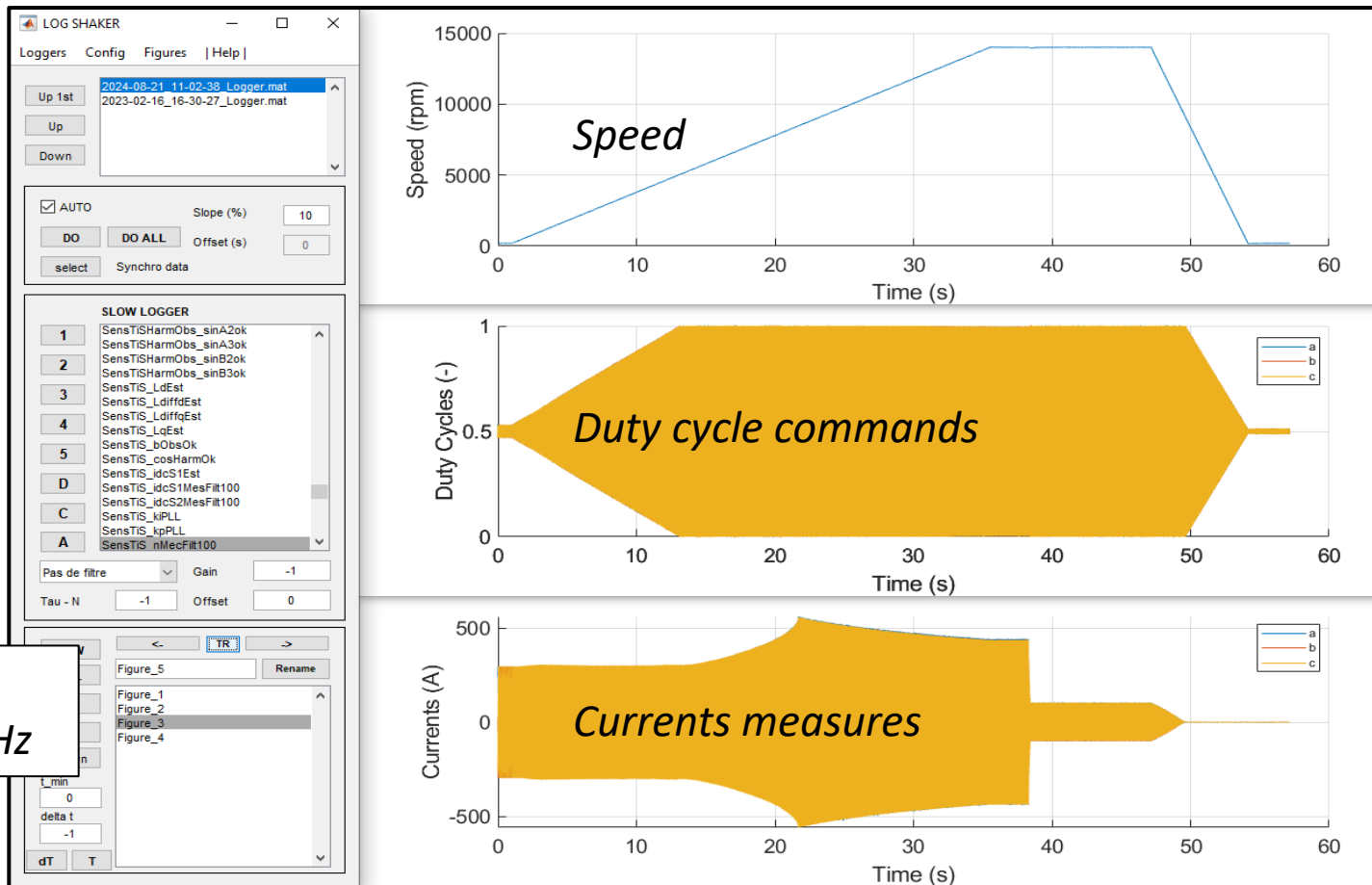
Live display @20+ kHz



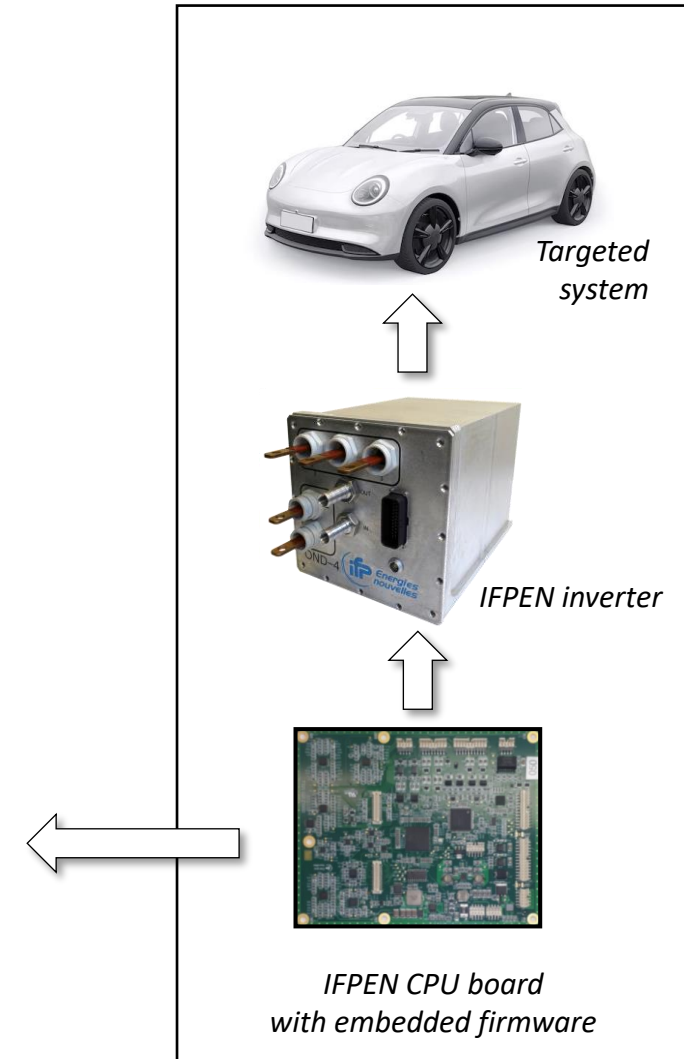
II) SOFTWARE EXPERIMENTAL VALIDATION

The toolchain includes also a dedicated **signals analysis tool**

- A dataset & display setup manager
- With synchronization, filtering and correction functions



Analysis @20+ kHz

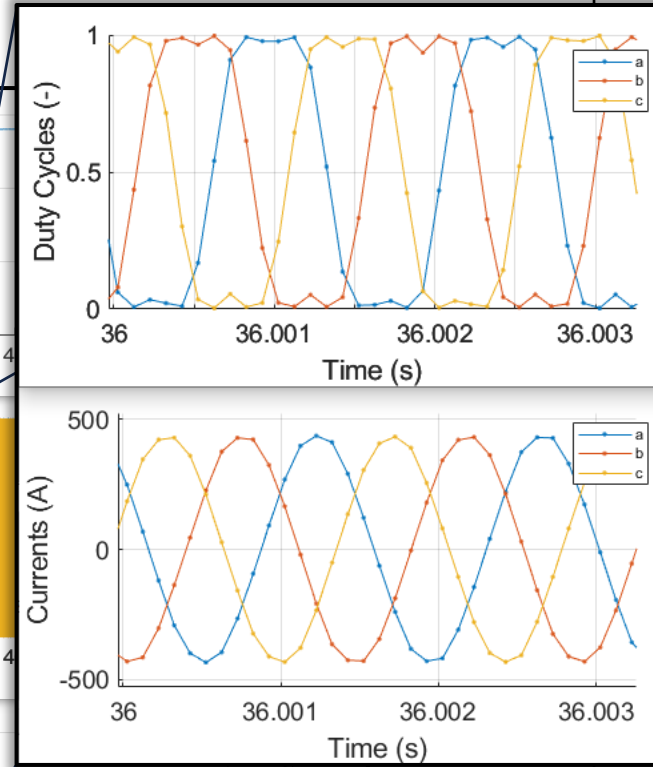
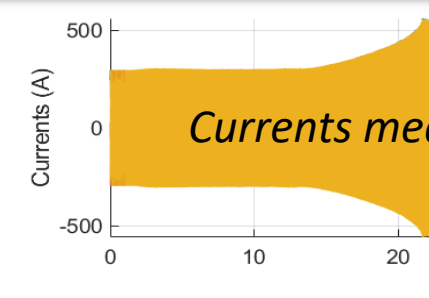
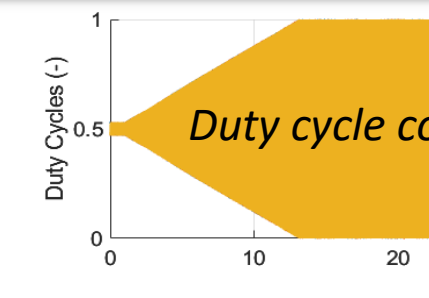
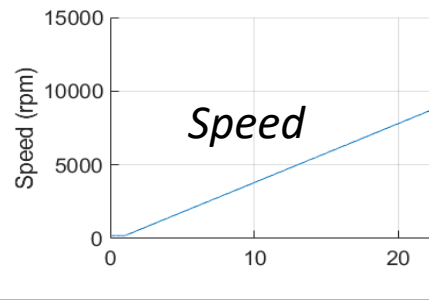
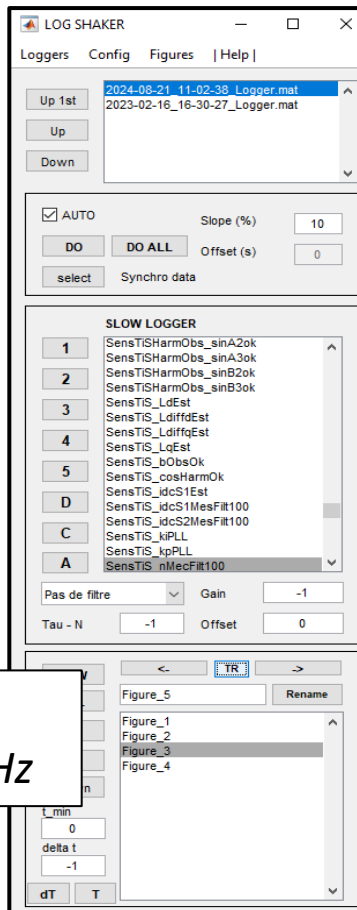


II) SOFTWARE EXPERIMENTAL VALIDATION

Tens of signals logged @ 20+ kHz without duration limits

The toolchain includes also a dedicated **signals analysis tool**

- A dataset & display setup manager
- With synchronization, filtering and correction functions



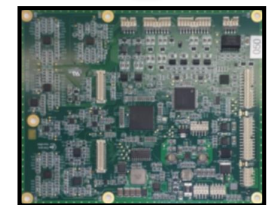
Analysis @20+ kHz



Targeted system



IPFEN inverter



IPFEN CPU board with embedded firmware

SUMMARY

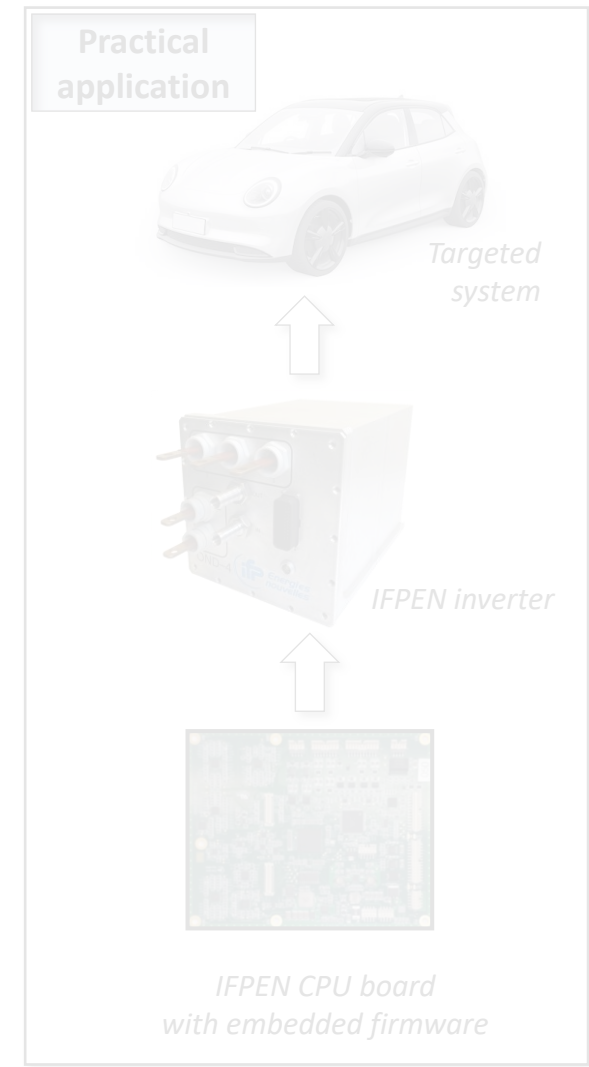
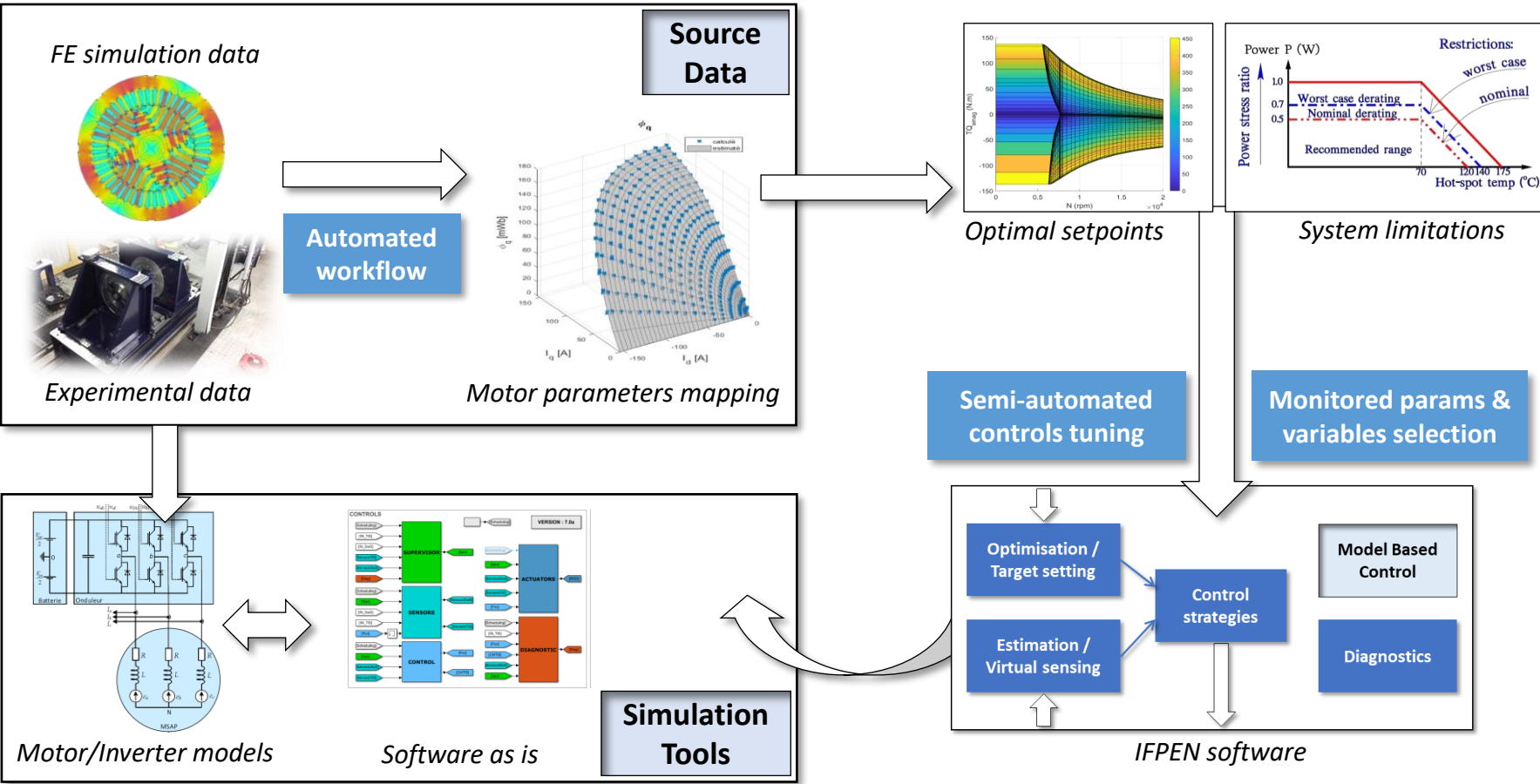
I) Software calibration and generation

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III) SOFTWARE SIMULATION TOOLS

III) Software simulation tools

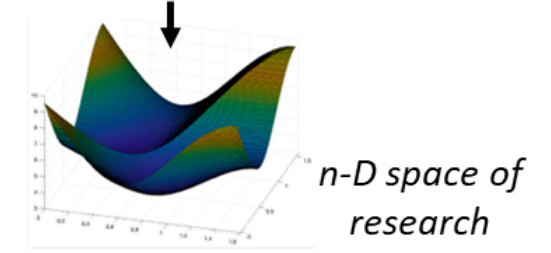
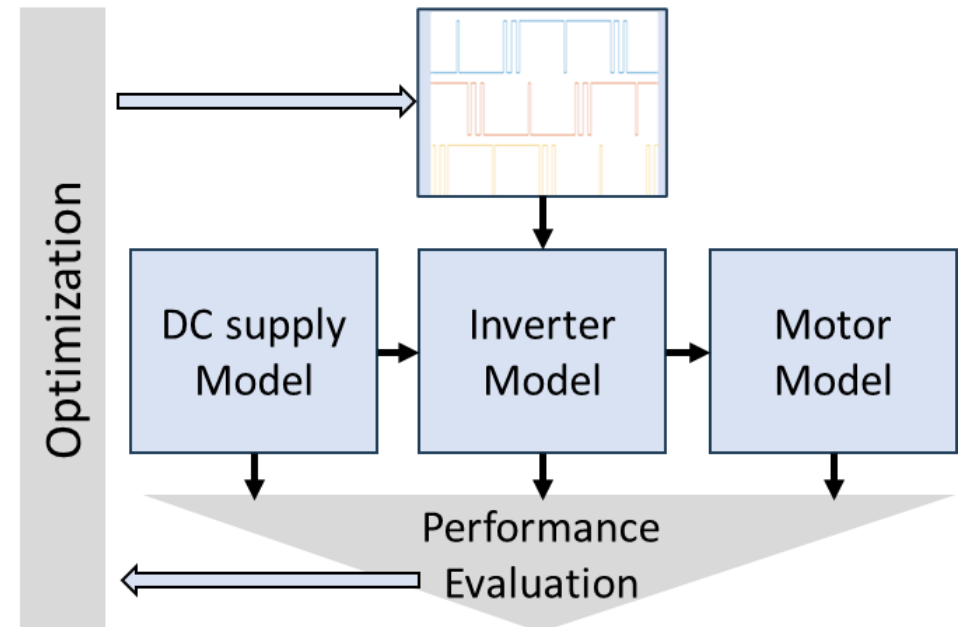
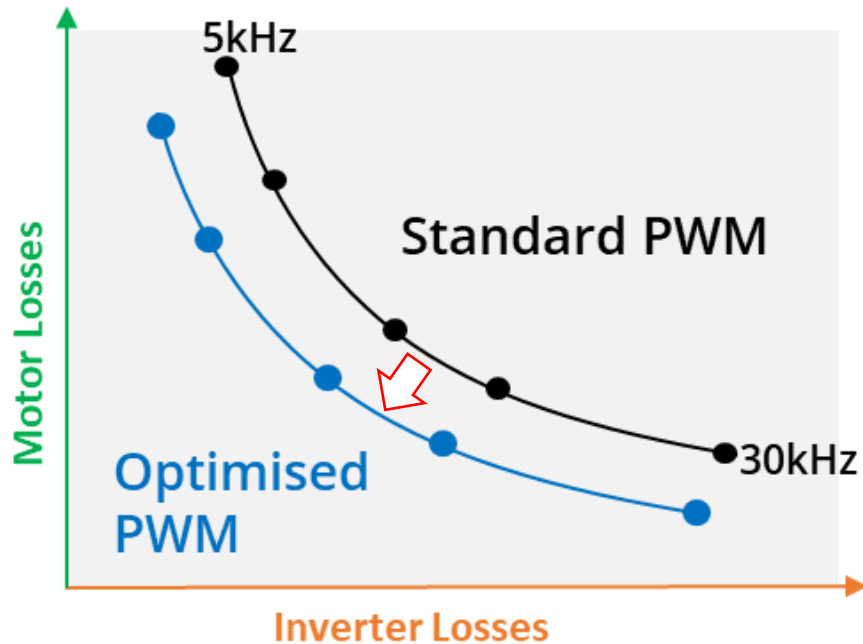


III) SOFTWARE SIMULATION TOOLS

The objective is to **replace control laws bench evaluation with simulation** as much as possible

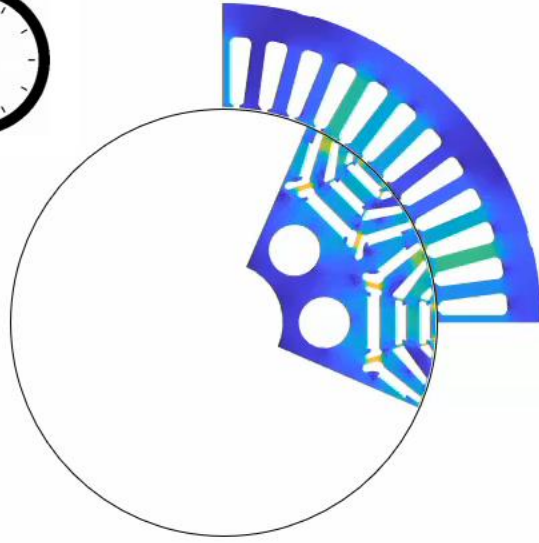
- *Performance criteria : efficiency under constraints (DC ripple, NVH, Torque ripple, CPU load, etc.)*
- *Usually evaluated on the bench due to system complexity, but degrees of freedom are too numerous*

Optimization Workflow

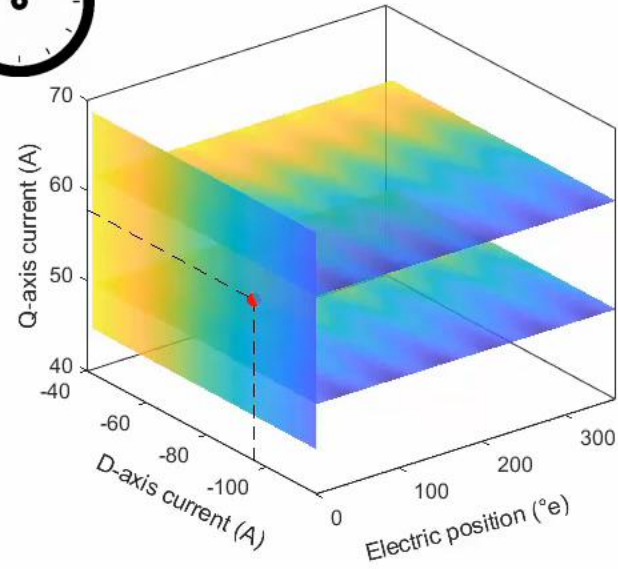


NB : PWM = Pulse Width Modulation

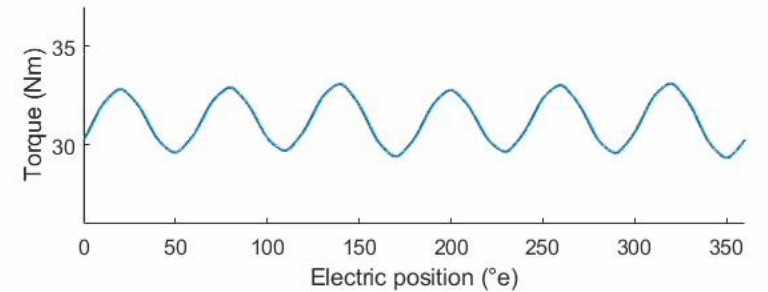
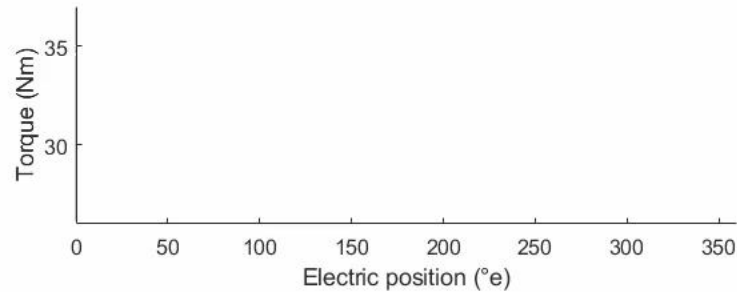
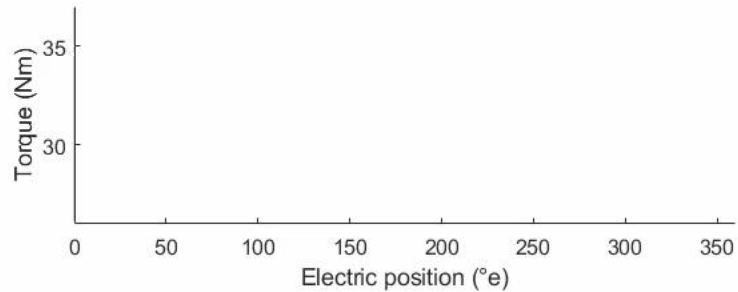
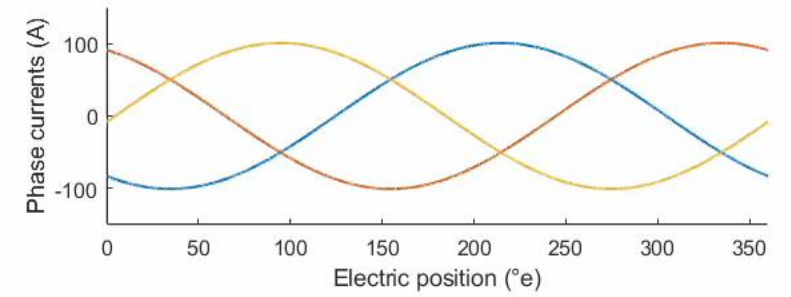
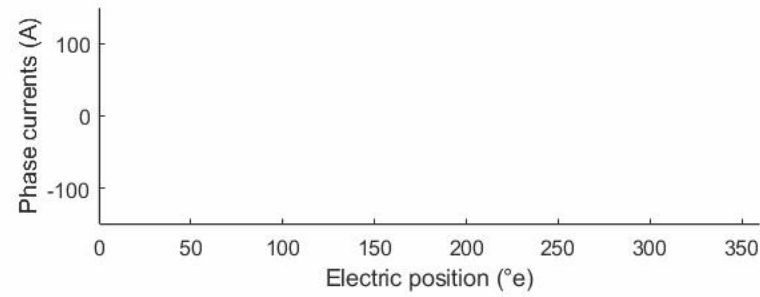
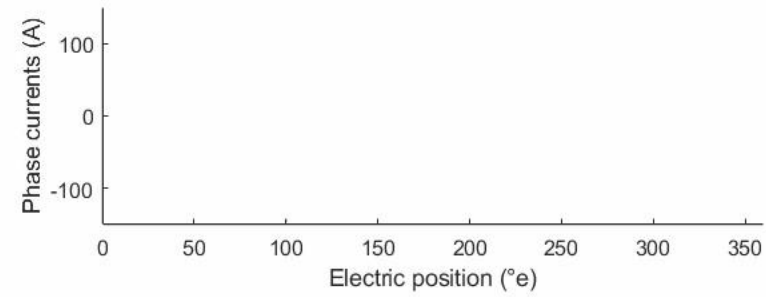
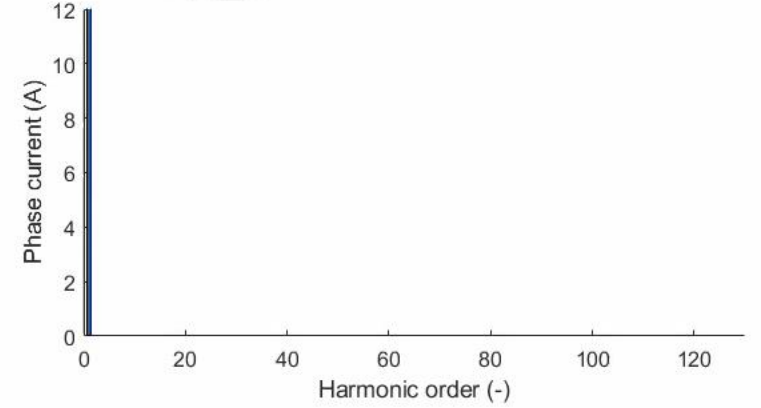
Finite Elements



Time-based reduced model



Frequency-based reduced model

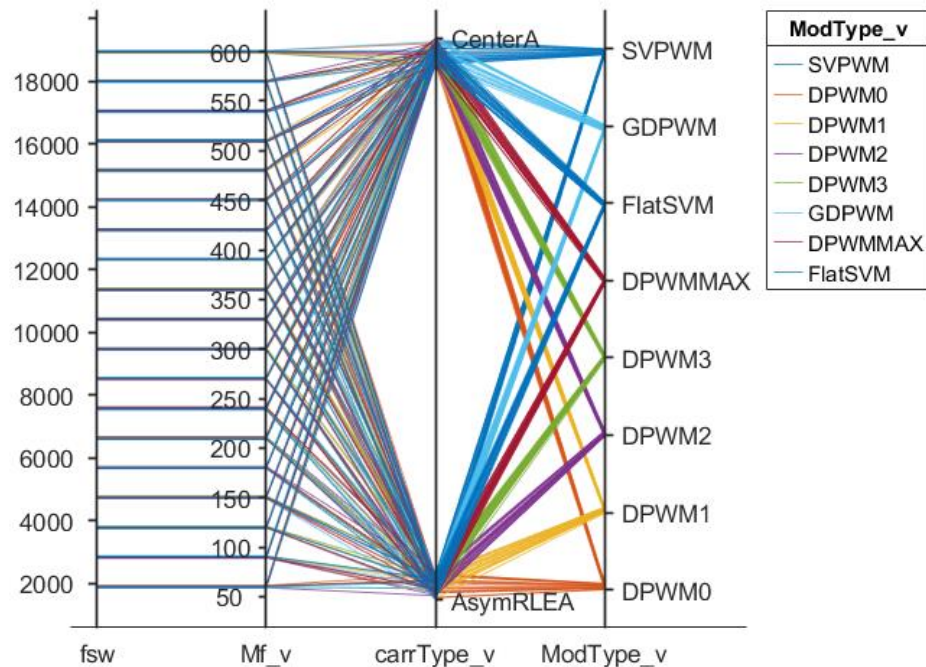


III) SOFTWARE SIMULATION TOOLS

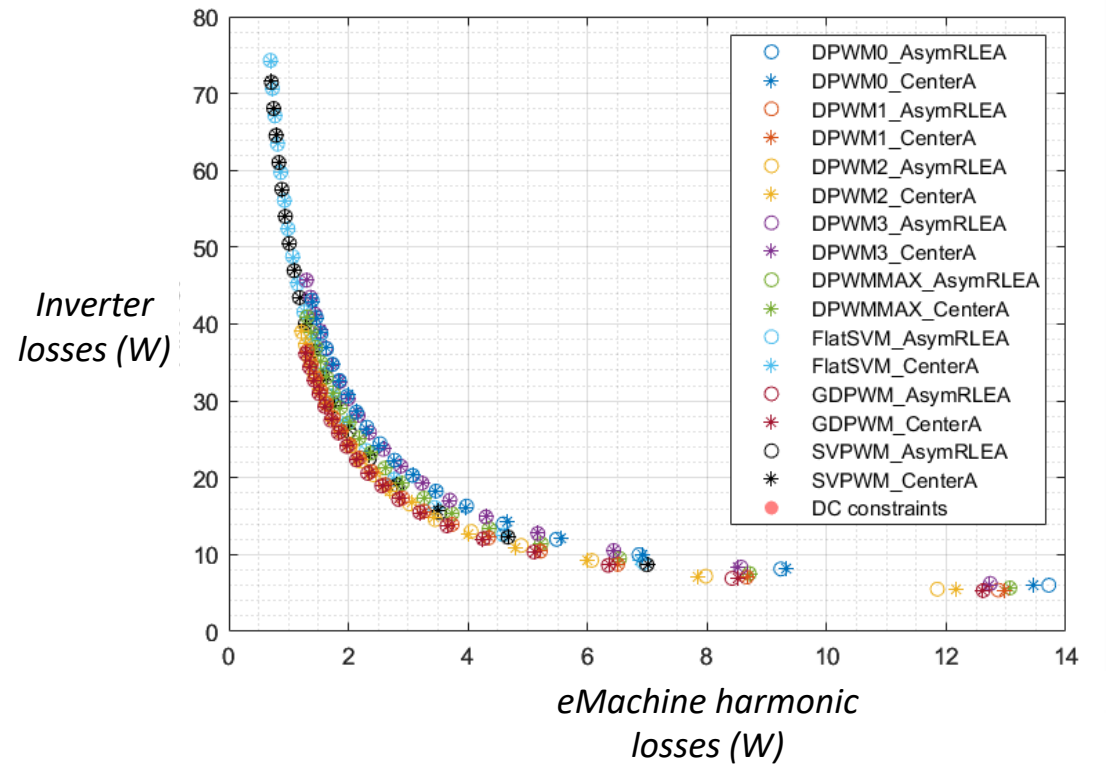
These models are used in our **optimization** process

→ We now use our fast-computing models to evaluate a great number of configurations efficiently (~50000 evaluations/hour)

Configurations evaluated



Resulting Pareto front



Achievements

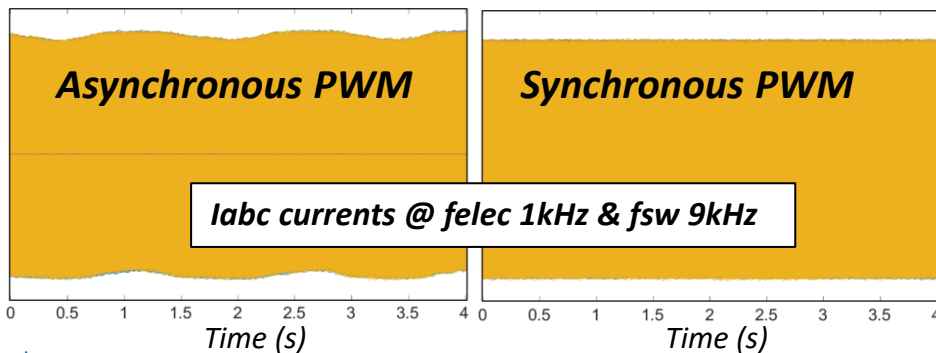
- *An efficient workflow tailored to our needs, and advanced modeling of physics, are leveraged to develop innovative control strategies*
- *Within 5 years with a controls team of 3 people (now 5)*
 - *70+ CPU boards made and integrated in 10 different IFPEN prototype inverters*
 - *60+ different electric motors driven with these, often for 24/7 bench tests*
 - *20~ patents filed for innovative motor control solutions*

Achievements

- An efficient workflow tailored to our needs, and advanced modeling of physics, are leveraged to develop innovative control strategies
- Within 5 years with a controls team of 3 people (now 5)
 - 70+ CPU boards made and integrated in 10 different IFPEN prototype inverters
 - 60+ different electric motors driven with these, often for 24/7 bench tests
 - 20~ patents filed for innovative motor control solutions

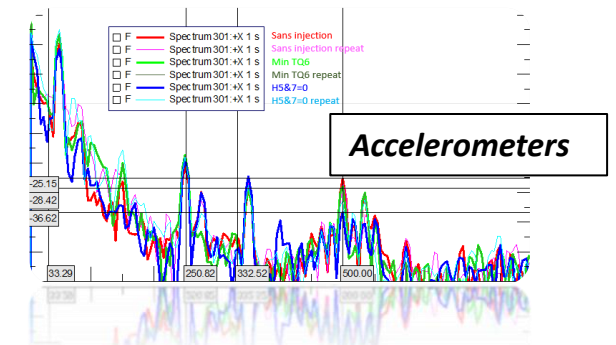
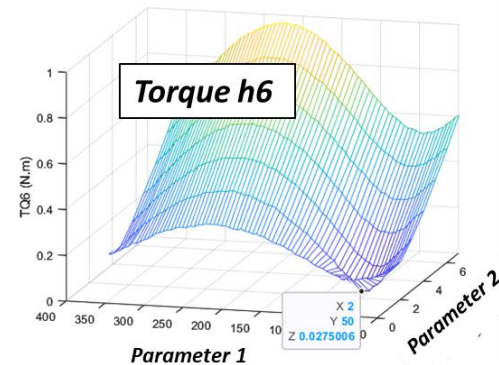
→ Synchronous PWM

- Efficient overmodulation : power ↗ ↗
- Lower frequency @ high speed : losses ↘
- DC bus ripple mitigation : Capacitors volume ↘



→ Harmonics injection

- For compensation of torque harmonics and airgap radial forces : material cost ↘
- Operational in steady-state and during speed transients



One step further : Gen2 SiC inverter dedicated to motor bench testing

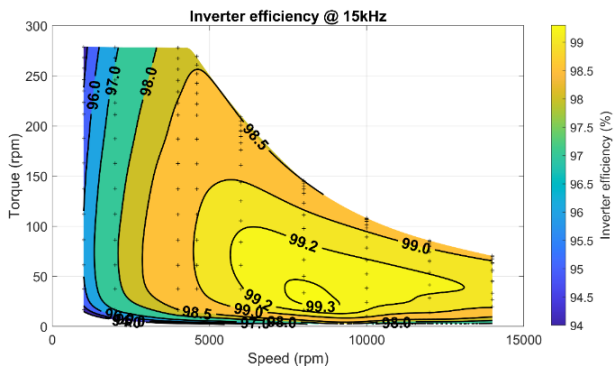
- Objective: support motor and control technology development for industrial partners
- Method: a versatile, high-performance inverter, marketed in partnership with ALPHEE Engineering

→ The inverter

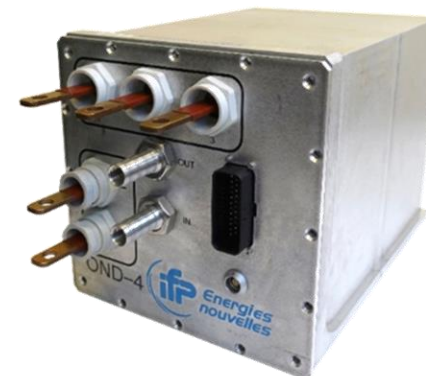
- Delivers 500 Arms and operates up to 50 kHz
- Benefits from efficient calibration and unique control methods for motor characterization
- Features our latest advances in controls: synchronous motor control, current injection for NVH reduction, etc.

→ The partnership

- Launched in early 2024, it has led to the manufacture of 6 SiC inverters
- The SME Alphée handles manufacturing, marketing, commissioning and after-sales service.



Peak power	320 kW
Continuous power	250 kW
Max current	500 Arms
Efficiency	99% on wide area
DC Voltage	500 - 800V
Switching frequency	5 – 50 kHz



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