Thermal Modelling and Design Optimisation of DC-DC Converters

POWER ELECTRONICSUK
Underpinning Research

EPSRC
Pioneering research and skills

Mauro S. Innocente
Smart Vehicles Control Lab (SVeCLab)
Centre for Mobility and Transport (CMT)
Coventry University
Mauro.S.Innocente@coventry.ac.uk

Daniel J. Rogers
Energy and Power Group
University of Oxford
dan.rogers@eng.ox.ac.uk

This work was part-funded via the following research grants:
Investigating the Power Density of Power Electronics (EPSRC 'First Grant' EP/K032984/1)
Optimisable system-level thermal models for power electronic converters (EPSRC Centre for Power Electronics 'Early-Career Researchers Grant' through EP/K035304/1)

Industrial Partners: Rolls-Royce, IMV CORPORATION

1. Introduction

- More Electric Aircraft (MEA) applications require high power-density aiming to reduce weight, complexity, fuel consumption, gas emissions, noise, and operational costs.
- Likewise, environmental impact is reduced by employing electric powertrains alongside internal combustion engines in HEVs.

2. Objectives

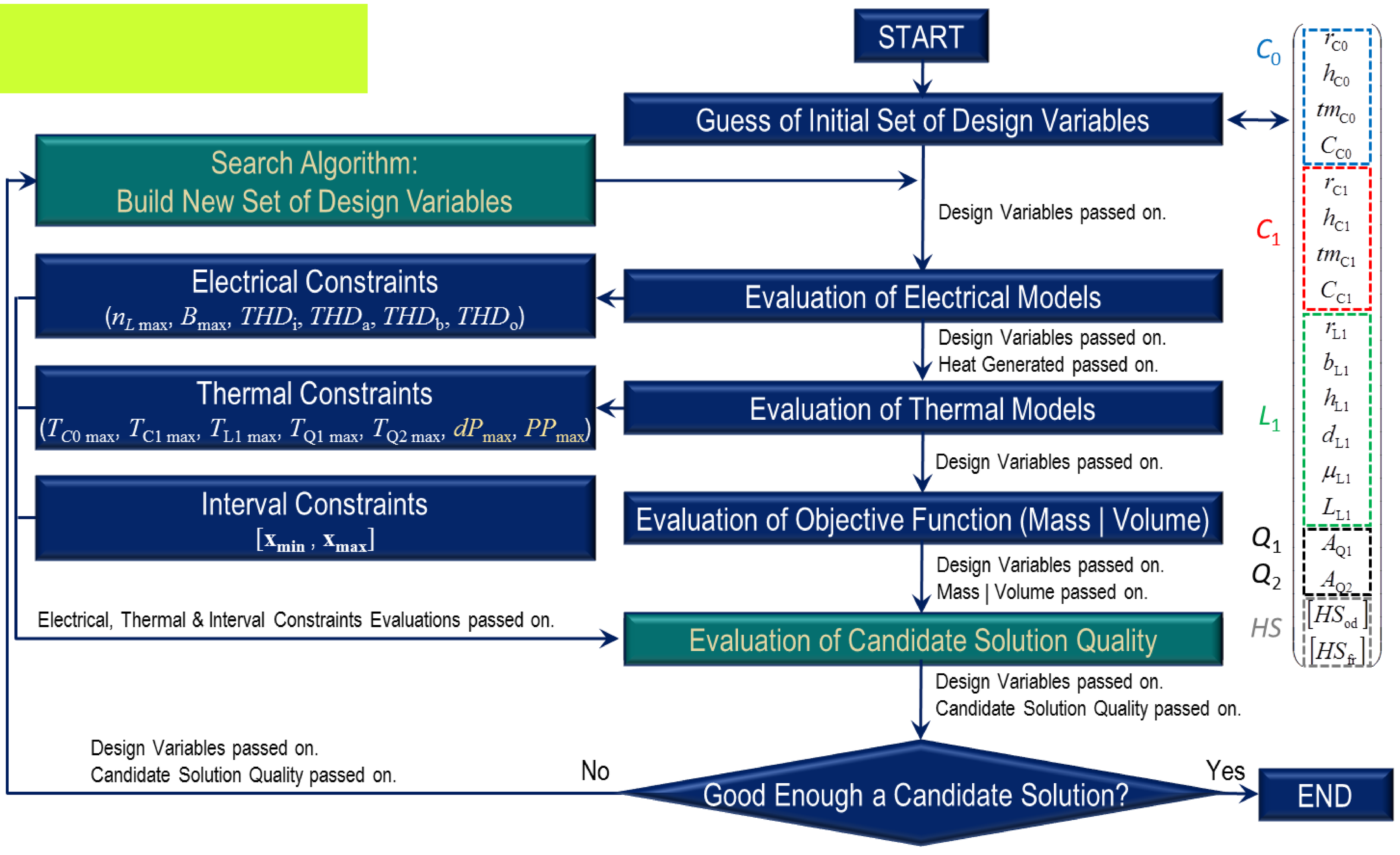
- Develop computationally tractable physics-based thermal models of DC-DC converters suitable for design optimisation.
- Develop optimisation framework for power-dense design of DC-DC converters.
- Design and implement user-friendly Graphical User Interface (GUI) to facilitate the use of the software design tool by the end-user.

3. Research Methodology

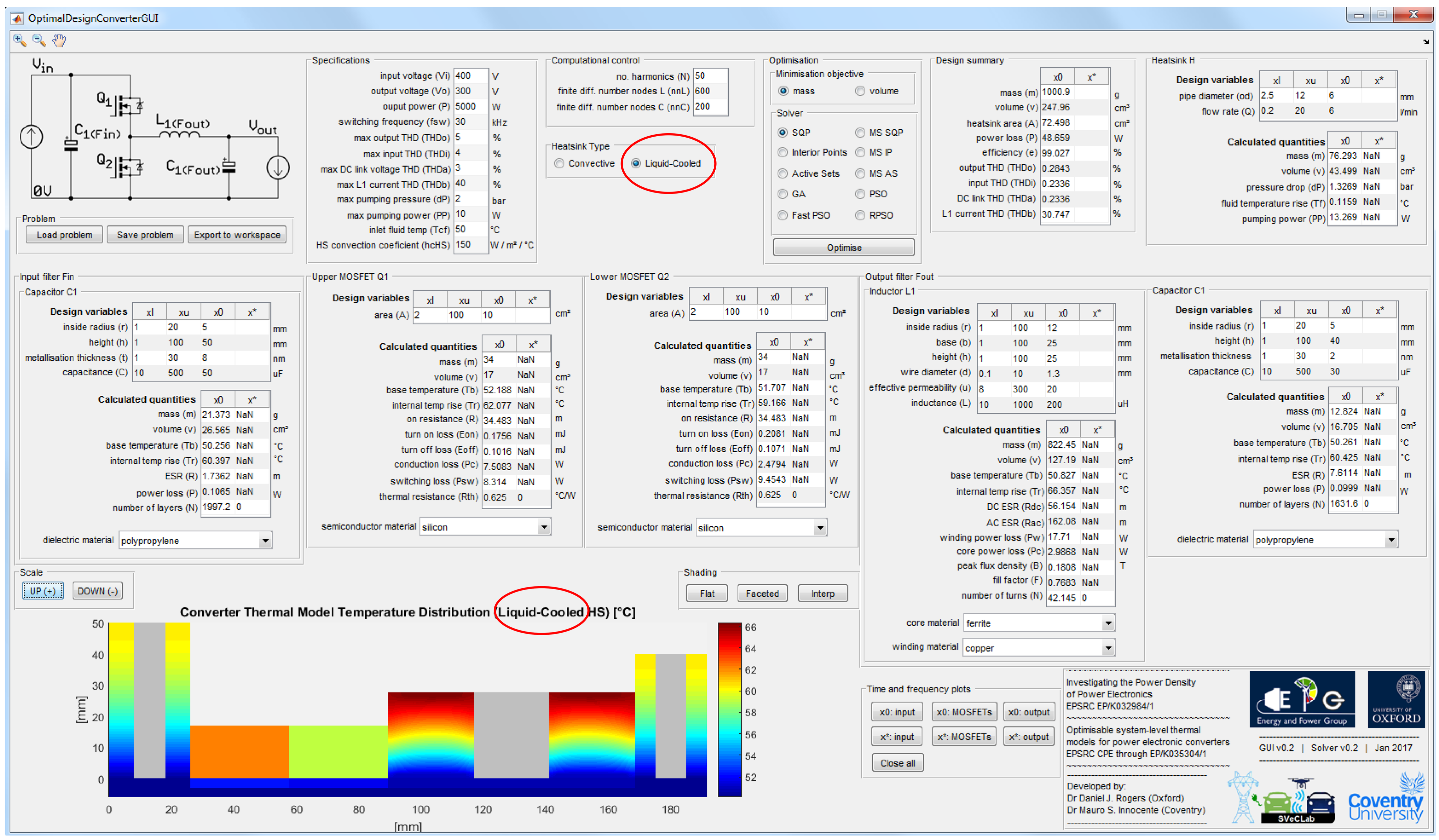
- System-level electrical models.
- Linear, efficient, physics-based thermal models (material properties independent of temperature).
- Optimal design framework with decoupled thermal and electrical models.
- Thermal models of passive components (C_0, C_1, L_1) using Finite Difference Method (FDM) and axisymmetric model to solve Heat Equation:

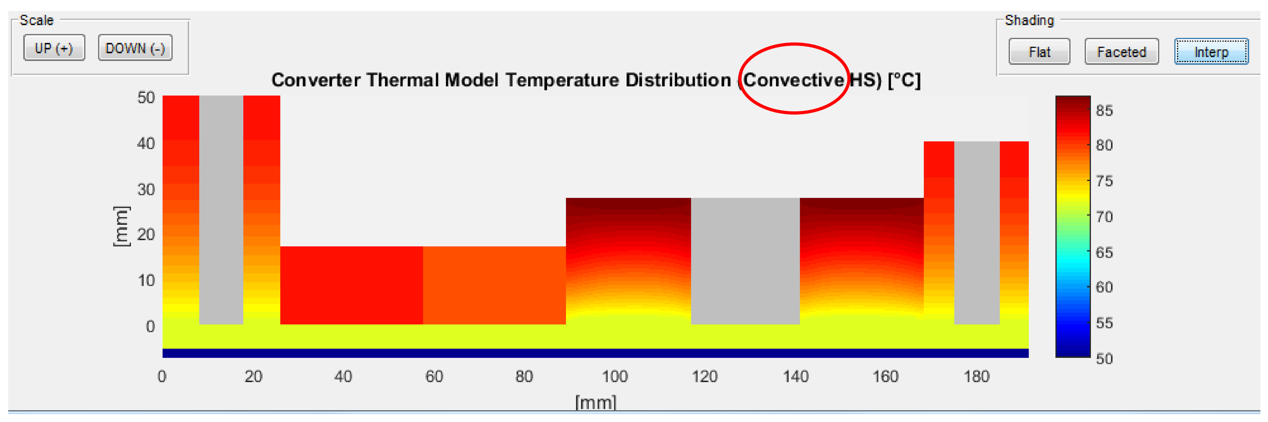
$$\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}}{k}=\frac{1}{\alpha}\cdot\frac{\partial T}{\partial t}$$

- Thermal models of switches (Q_1, Q_2) as lumped thermal resistances.
- Two thermal models of heat-sink supported:
  1) Convective (cold-plate, no fins, uniform temperature T_{HS}): $$T_{HS}=T_{cf}+\frac{q_{total}}{h_c\cdot A_{HS}}$$
  2) Liquid-cooled (straight, parallel pipes): This adds two design variables (liquid flow rate HS_{fr} and pipe diameter Hs_{od}) and two constraints (pressure drop dp_{max} and pumping power PP_{max}).
- Off-the-shelf commercial optimiser and in-house PSO plugged in.



4. Example



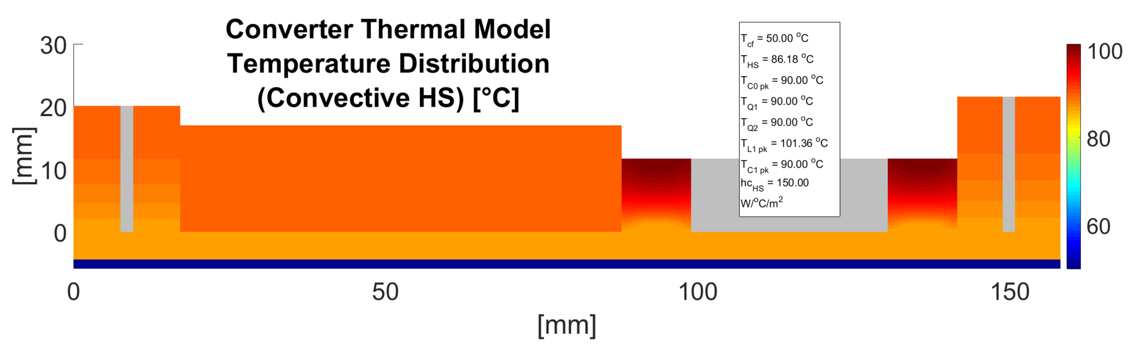


Same DC-DC Converter Design and problem specifications as in GUI (left), but different heat dissipation at heatsink.

Optimal Design (convective HS)

m = 345 g

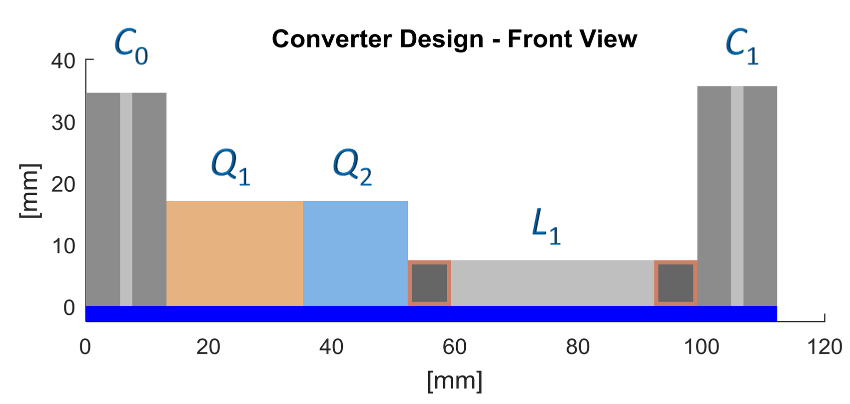
Active Constraints
- ✓ $n_{L\,max}$
- ✓ B_{max}
- ✓ $T_{C0\,max}$
- ✓ $T_{C1\,max}$
- ✓ $T_{Q1\,max}$
- ✓ $T_{Q2\,max}$

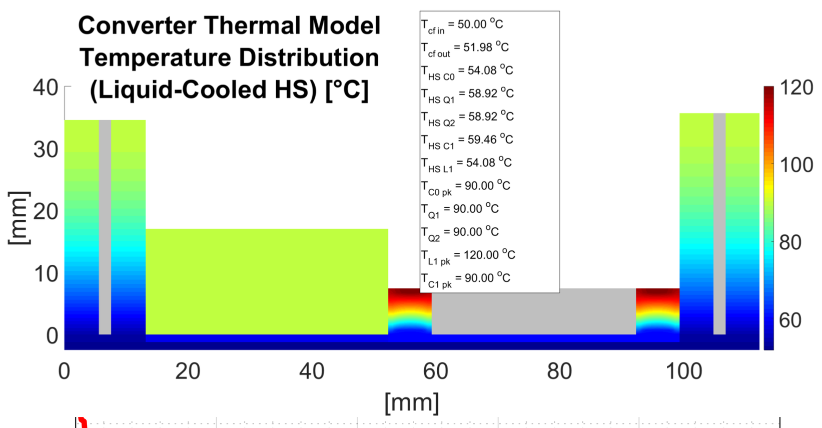


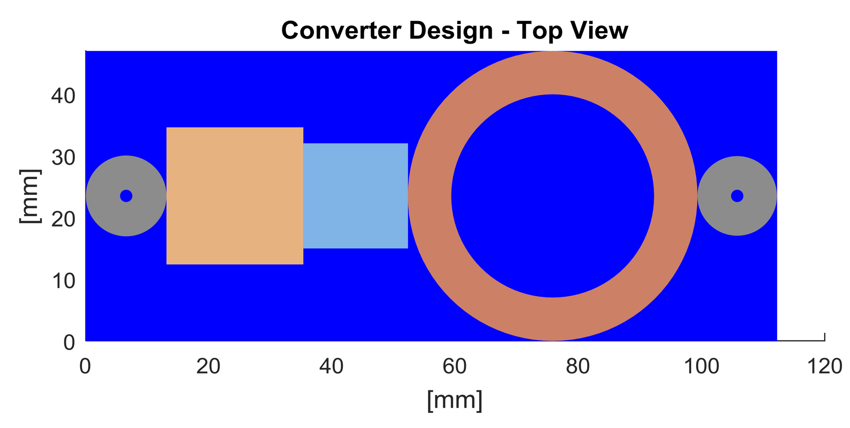
Optimal Design (liquid-cooled HS)

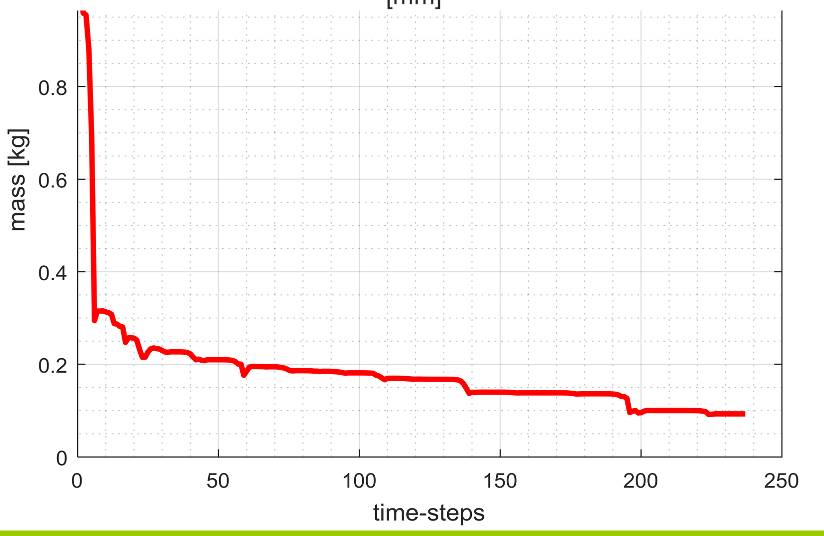
m = 93 g

Active Constraints
- ✓ $n_{L\,max}$
- ✓ B_{max}
- ✓ $T_{C0\,max}$
- ✓ $T_{C1\,max}$
- ✓ $T_{L1\,max}$
- ✓ $T_{Q1\,max}$
- ✓ $T_{Q2\,max}$
- ✓ dP_{max}









5. Conclusions and Future Work

- Efficient physics-based thermal models are feasible to be embedded in optimal design tool.
- Most constraints typically active at optimal design.
- Validation of efficient models to be pursued using High Fidelity (HF) models and commercial software.
- Validation of HF models to be pursured via Hardware-in-the-Loop (HiL) simulations.
- More advanced efficient models of heat-sink are needed for convective and liquid-cooled dissipations.
- Robust/Stochastic optimisation by introducing uncertainty in design specifications and variables.
- Surrogate modelling for efficient sampling of stochastic variables/specifications, and for design optimisation.
- Multi-objective optimal design of power converter.

University of BRISTOL · UNIVERSITY of GREENWICH · Imperial College London · MANCHESTER 1824 · Newcastle University · The University of Nottingham · The University Of Sheffield. · University of Strathclyde · THE UNIVERSITY OF WARWICK