

Metamodel-based Optimization of Coil Units of Axial-Flux Machines and their Validation Using a Test Bench

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Abstract

The demand for high power density in electrical machines has led to the increasing adoption of axial-flux topologies. Due to the strict spatial and gravimetric constraints of these systems, optimizing the coil unit – which constitutes a primary source of thermal and magnetic losses – is a critical design objective. While metamodel-based methodologies enable rapid, multiphysical design exploration, their predictive accuracy relies heavily on empirical validation. Conventional simulation tools require significant computational effort to accurately resolve the coupled effects of manufacturing tolerances, process-induced material degradation, and complex thermal pathways. Consequently, high-quality empirical data is necessary to validate simulation models and train reliable metamodels. However, existing testing frameworks for axial-flux architectures are typically fragmented, evaluating physical domains in isolation and thereby limiting the analysis of coupled multiphysical interactions.

This paper presents a novel, integrated multiphysical test bench designed for the comprehensive validation of axial-flux coil units. Operating at up to 1000 V or 600 A, the platform enables simultaneous thermal, magnetic, and mechanical characterization of a single specimen without requiring a spinning rotor. Key innovations include active field emulation for manipulating the air gap flux density distribution, a 6-DoF hexapod with custom actuators to emulate manufacturing tolerances and measure resultant multidimensional forces, and an automated 6-DoF kinematic 3D Hall sensor system for precise air gap flux and stray flux mapping. The system architecture is coupled with a Digital Twin for asynchronous experiment planning and safe operation. By establishing this infrastructure, the proposed test bench provides the high-fidelity, cross-domain empirical data necessary to transition advanced axial-flux concepts from simulation to validated prototypes.

Keywords: axial-flux, testbench, multiphysics, magnetic measurements, thermal characterization

Introduction and Motivation

The demand for high-performance electrical machines for transport and industry is driving research and innovation, especially in terms of power density, efficiency and thermal management. A particular focus is placed on axial-flux machines. These topologies are highly attractive not only due to their exceptional gravimetric power density – with recent industry benchmarks reaching up to 59 kW/kg [1] – but also regarding other critical high-performance metrics such as overall efficiency, favorable thermal time constants, and scalable production and assembly costs. They are increasingly being adopted beyond automotive applications, from aerospace to auxiliary drives like hydraulic pumps for off-highway applications or coolant pumps in data centers. To push those performance boundaries, continuous design optimization and the exploration of novel materials and cooling concepts are necessary.

Traditionally, the design and optimization of electrical machines is conducted with Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). While FEA and CFD are highly capable, incorporating real-world influences such as manufacturing tolerances, process-induced material changes, and coupled temperature dependencies results in significant computational effort. For novel concepts like direct-liquid-cooled litz wire hollow conductors, validated simulation models or methodologies are often not yet established.

To explore the design space and find an optimal design with minimal computational effort, the optimization of multiphysical systems is increasingly shifting towards metamodel-based methodologies [2]. Metamodels – typically in the form of Functional Mock-up Units (FMUs) – enable the rapid approximation of key performance indicators for complex designs. However, the prediction accuracy is constrained

by the quality and quantity of training data used to train the model.

Acquiring this training data presents a critical challenge, as there is a significant validation gap in the methodology: unlike radial-flux machines, there are no equivalent testing standards for the axial-flux architecture. Existing test procedures are typically fragmented, focusing on a single physical domain (e.g. magnetic or thermal), limiting the ability to evaluate complex, coupled multiphysical interactions.

To bridge this validation gap, a versatile testbench was developed at Hamburg University of Technology (TUHH) specifically for the simultaneous multiphysical characterization of axial-flux coil units (see Figure 1). This paper presents the key features and capabilities, and discusses measurement methods and strategies as well as preliminary results obtained from thermal experiments. Specimens up to a cross-section of 50x50 mm and axial lengths of 100 mm can be accommodated, as well as entire machines up to a diameter of the magnetic circuit of 160 mm. Simultaneous thermal, magnetic, and mechanical test procedures and measurements can be conducted on a specimen in a single setting without the need to transfer it between different test setups.

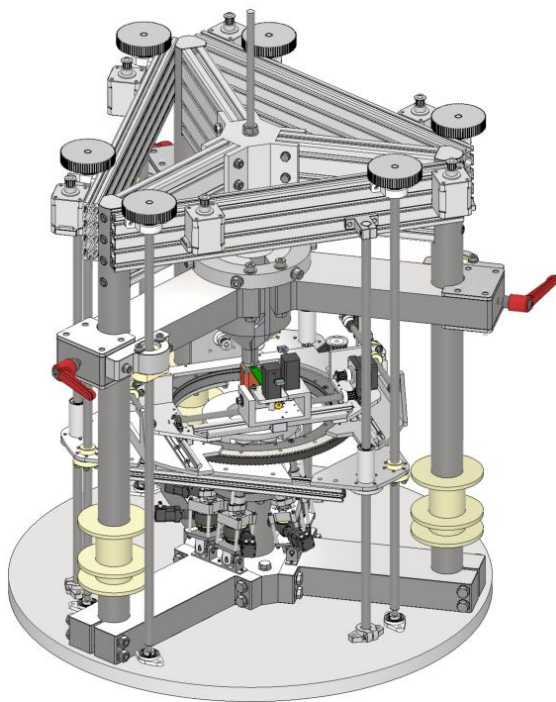


Figure 1: CAD assembly overview of the multiphysical test bench

The Optimization Target: The Coil Unit

Axial-flux machines are subject to strict space and weight constraints, driven by the demanding requirements of the automotive and aerospace sectors. In these highly compact architectures, the stator coil unit represents the primary bottleneck, but it also exhibits the highest potential for optimization [3], primarily due to its unique geometric freedom and the absence of a traditional stator yoke and end windings. While rotor optimization is relatively straightforward and achieved by adjusting permanent magnet grades, thicknesses, and relying on basic rotational forced convection for cooling, the coil unit is subject to concentrated high-frequency losses and complex thermal pathways. Just as stators remain fundamentally similar across synchronous, induction, or reluctance machines despite varying rotor designs, the axial-flux coil unit is a universally critical component that heavily dictates overall machine performance.

In case of the Yokeless and Segmented Armature (YASA) topology [4], the coil unit consists of a magnetically soft core and pole shoes as well as a concentrated single-tooth winding (see Figure 2). Consequently, research is increasingly focused on next-generation materials and topologies for the coil unit. Conductor innovations include the use of direct liquid cooling topologies such as hollow conductors [5], flooded stator cooling [6], aluminium as a conductor material [7] and high thermal conductivity resin-potted coils. Simultaneously, advanced core materials like Soft Magnetic Composites (SMC), nanocrystalline materials, grain-oriented steel and FeCo alloys are being investigated.

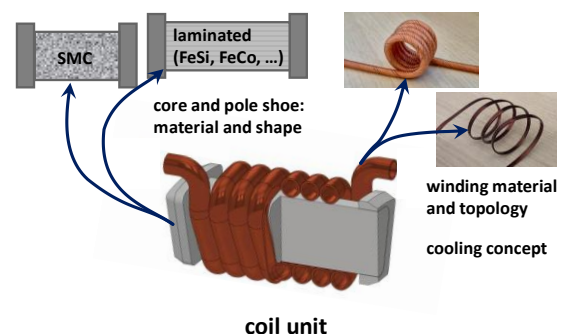


Figure 2: Coil Unit with different parameters that can be varied: material, shape, conductor topology, winding material, cooling concept etc.

Evaluating these novel concepts requires addressing a significant gap of the impact of manufacturing processes on theoretical material properties in the current literature. Unlike radial-flux machines, axial-flux

architectures have a shorter history of extensive research and development, especially given the wide variety of topologically different approaches (e.g., yokeless vs. yoked; single vs. dual rotor or stator). Various manufacturing processes are employed today – such as stacking, baking, grinding, etching, and wire electrical discharge machining (EDM) – and each exerts a different, complex influence on the magnetic material [8]. Furthermore, the cores and pole shoes of axial-flux coil units inherently exhibit complex 3D flux distributions. Validating these degraded, 3D multiphysical states necessitates dedicated empirical testing.

Multiphysical Test Bench Architecture

The test bench is conceptualized as a highly modular, multi-domain architecture. The core hardware comprises a main frame integrating a custom 6-Degree-of-Freedom (6-DoF) hexapod structure and a central platform designed to securely hold the specimen. A dedicated measurement PC is responsible for the synchronous recording of all data and the execution of real-time control algorithms.

The test bench is deeply integrated with the Power-Hardware-in-the-Loop laboratory (PHiLsLab) infrastructure at TUHH [9]. This integration provides critical high-voltage, high-current and high-frequency power supplies, high-speed measurement recorders, auxiliary diagnostic equipment, and fluid thermal interfaces.

A key advantage of this architecture is its dynamic real-time emulation capability. Realistic operational scenarios, including the application of arbitrary voltage curves, can be emulated and controlled in real time. This positions the platform as an exceptional prototype testing infrastructure, enabling not only the isolated testing of the coil unit but also its interaction with peripheral hardware. For example, the system can analyze a coil's thermal and magnetic response to high-frequency ripple voltages when supplied by an external integrated inverter, or it can emulate inverters and other dynamic loads via Power-Hardware-in-the-Loop (PHiL). The overarching capabilities and boundary parameters of the test bench are summarized in Table 1.

Table 1: Test bench specifications and maximum parameters for dimensions, voltage, current, and frequency.

Property	Value	Unit
number of coil units	1...3	-
maximum diameter	50	mm
maximum length	100	mm
maximum current	600	A
maximum voltage (DC)	1000	V
maximum peak voltage (AC / arbitrary waveform)	424	V
max. frequency	30	kHz

Measurement Subsystems & Methodology

1. Digital Twin Integration & Safe Operation

The physical test bench is coupled with a Digital Twin, which is utilized offline and asynchronously to guide the experimental process. The workflow is iterative: initial, approximate coil parameters are derived from the simulation for experiment planning. Following the physical measurements, the empirical data is used to refine the parameters within the Digital Twin, continuously improving model fidelity for subsequent test iterations.

To ensure safe operation during these rigorous tests, the Digital Twin is utilized to estimate expected threshold values for multidimensional forces, temperatures, and induced voltages. If physical sensors detect values approaching these simulated thresholds, the system issues operator warnings. Experiments are strictly supervised, and operating parameters are raised gradually to safely approach physical edge cases. Furthermore, the Digital Twin employs a numerical optimization routine in MATLAB, controlling a COMSOL model to calculate the exact manipulation coil voltages required to achieve desired, inhomogeneous flux density distributions in the air gap for active field emulation.

2. Emulation of Manufacturing Tolerances

Manufacturing and assembly tolerances – such as discrepancies in iron core lengths, pole shoe assembly positions, or air gap widths – create unintended and unbalanced magnetic forces under load. Specifically, an uneven air gap directly results in asymmetrical magnetic forces that significantly accelerates bearing wear. Under high-frequency excitation, these static and dynamic forces translate into high-frequency vibrations that can ultimately cause structural machine failure. The severity of these vibrations is heavily dependent on the chosen manufacturing process and material of the

machine casing, whether it be milled aluminum, carbon fiber reinforced polymers (CFRP), or injection-molded reinforced thermoplasts. The test bench is designed to determine which tolerance classes are acceptable to prevent these failure modes, thereby informing the viability of specific manufacturing processes.

To empirically emulate these mechanical tolerances, the test bench utilizes a 6-DoF hexapod mechanism (see Figure 4). A critical feature of this system is the custom design of its linear actuators, developed specifically to withstand high magnetic forces (up to 2.5 kN) while exhibiting minimal structural deflection over a precise travel range. Off-the-shelf linear actuators capable of meeting these strict requirements are prohibitively expensive and typically overengineered; thus, the custom design provides a necessary and cost-effective solution for accurate tolerance emulation.

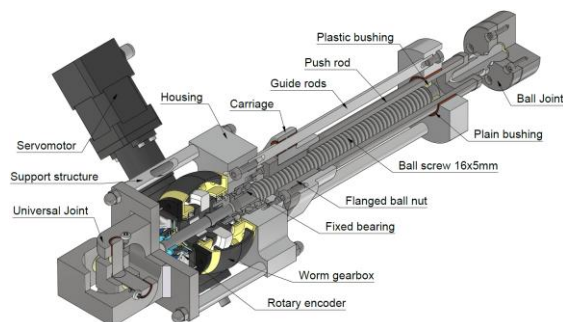


Figure 3: Custom-designed linear actuator for the hexapod

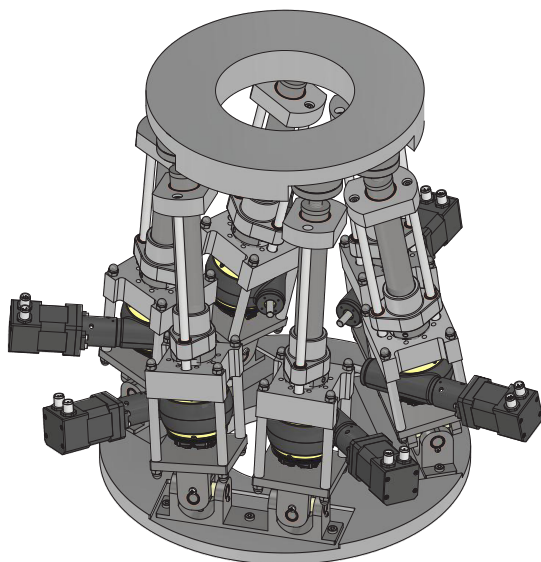


Figure 4: 6-DoF hexapod mechanism with custom linear actuators for manipulating the pose of the specimen between the two test bench air gaps

3. Multidimensional Force Measurement

Force and torque measurements are integrated directly into the custom linear actuators of the hexapod, enabling precise 6-DoF mechanical characterization without the need for separate, bulky external load cells. To achieve high fidelity across varied operating conditions, a dual-sensor concept is implemented. Piezoelectric sensors are utilized to capture high-dynamic, high-frequency vibrations, where their fast response times excel. In tandem, strain gauges are deployed to measure static loads and long-term baseline forces, effectively compensating for the inherent temporal drift of piezoelectric materials and being able to measure remanent magnetic forces.

4. Fundamental Electrical Measurements

High-precision electrical measurement forms the foundation for all subsequent magnetic and thermal characterizations. The core measurement equipment consists of two coupled ZES Zimmer LMG671 power analyzers. While standard experiments run at moderate sampling rates, the system features an extreme maximum bandwidth of 1.2 MS/s to capture highly dynamic edge cases, e.g. for high-frequency experiments or non-sinusoidal waveforms. The measurement tolerances and low measurement uncertainty of this device are critical capabilities of the overall platform. Temperature data is synchronized continuously, utilizing either an external NI USB-6210 DAQ or directly through the LMG's Process Signal Interface (PSI) at a rate of 100 S/s.

A strict 4-wire measurement topology is utilized: current is measured through high-cross-section supply cables, while voltage is probed directly across the specimen itself. This isolates the true impedance and power losses of the coil unit, eliminating parasitic errors caused by the electrical resistance and thermal heating of the supply infrastructure.

The power supply infrastructure is highly versatile. DC characterizations are powered by precision laboratory sources, while AC scenarios utilize a three-phase Spitzenberger & Spies APS7500 system capable of generating arbitrary signal waveforms. Combined with an additional high-current transformer and an optional B6 rectifier setup, currents of up to 1800 A can be supplied. This configuration was successfully proven during the testing of litz wire hollow conductors [10], although the maximum current is realistically limited to 600A.

by the current sensors and supply wires. Crucially, the Spitzenberger units are linear power sources rather than Switched-Mode Power Supplies (SMPS). This provides an exceptionally pure, noise-free signal, which is mathematically vital for ensuring accuracy when integrating induced voltage $u_{ind} = -\frac{d\Phi}{dt}$ to calculate the flux density B for magnetic characterization.

5. Active Field Emulation

To evaluate the specimen under realistic dynamic conditions without requiring a physical spinning rotor, an active field emulation mechanism is utilized. The specimen is positioned between two pole shoes, where the top pole shoe is separated into three magnetically isolated iron return paths (see Figure 5). Each path is equipped with an independent manipulation coil acting as a secondary electromagnet. These manipulation coils generate an assisting or opposing magnetic voltage to actively manipulate the primary flux generated by the specimen.

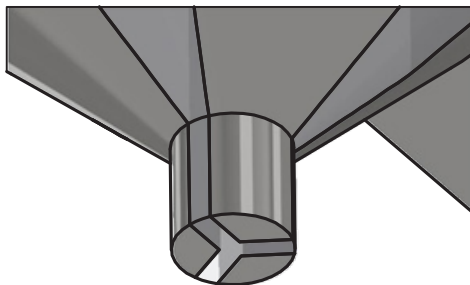


Figure 5: Separated top pole shoe with magnetically isolated iron return paths

This setup treats the air gap boundary as a black box, allowing for the emulation of arbitrary surface flux density distributions. Different scenarios such as the transient passage of a permanent magnet pole or shifting reluctance paths towards the shortest flux path are possible. Compared to state-of-the-art methods that rely on passive measurement or mechanical alteration of the air gap [11], this active electronic shaping provides vastly superior experimental flexibility. While the ultimate goal is dynamic real-time emulation, initial testing focuses on applying static DC currents to emulate discrete "snapshots" of various rotor positions, as this approach is computationally highly reliable to optimize within the COMSOL Digital Twin. The results of the active field emulation in the Digital Twin can be seen in Figure 6.

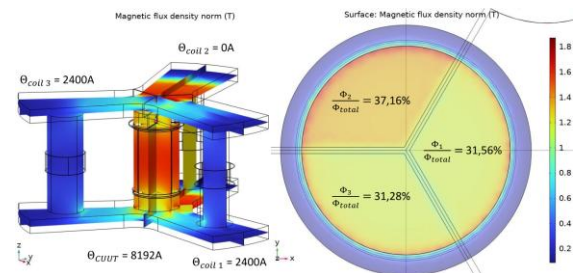


Figure 6: Electromagnetic FEM Digital Twin and manipulated air gap flux density distribution (here: shown with a coil unit originally planned to be significantly larger)

6. Magnetic Characterization

The magnetic characterization of the specimen's soft magnetic material is based on the principles of the DIN EN IEC 62044-3 standard. However, direct application of the norm is impossible due to the complex, mixed-material nature of the test rig, which combines the solid iron of the test bench with the laminated or SMC materials of the specimen. To capture the induced voltage safely and accurately, dedicated measurement coils – either a single extended coil on the lower pole shoe or separate coils on the three upper iron return paths – are used. This prevents the exposure of measurement equipment to dangerously high voltages that can occur in the primary windings at high flux densities and frequencies.

This infrastructure enables the mathematical reconstruction of B-H curves from the induced voltage and current measurements. Simulation studies have proven this reconstruction is highly viable even with noisy data with a Signal-to-Noise Ratio of 40dB (see Figure 7).

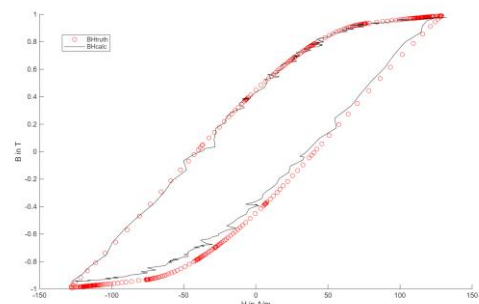


Figure 7: Reconstruction of a B-H-curve (black) from noisy measurement with an SNR of 40dB; red: ground truth B-H-curve in Simulink

To isolate the specimen's true core losses from the inherent parasitic losses of the test bench, a step-by-step empirical substitution method is applied:

- Small-signal DC and AC impedance baselines (up to 10 kHz) are established for the coil both within the test bench and in free air.
- Total losses are recorded with closed pole shoes across varying frequencies and amplitudes.
- The exact measurements are repeated using a solid cylinder "dummy" specimen (constructed from the test bench material, matching the pole shoe dimensions) across varying air gap lengths.
- Data from these steps is used to construct a precise approximation model of the test bench's inherent losses.
- During actual specimen testing, the modeled bench losses are subtracted from the total measured losses, isolating the empirical core loss of the prototype.

7. 3D Air Gap Flux Mapping

To validate the simulated air gap flux density, a 6-DoF sensor kinematic system is employed (see Figure 8), equipped with a SENM3Dx 3D Hall sensor [12]. The sensor is embedded in a specifically designed PCB measuring less than 1 mm in thickness, allowing insertion into minimal air gaps. The sensor's Flux Sensitive Volume (FSV) is located approximately 0.35 mm below the cap surface, enabling the measurement point to reach within ~0.5 mm of the specimen surface.

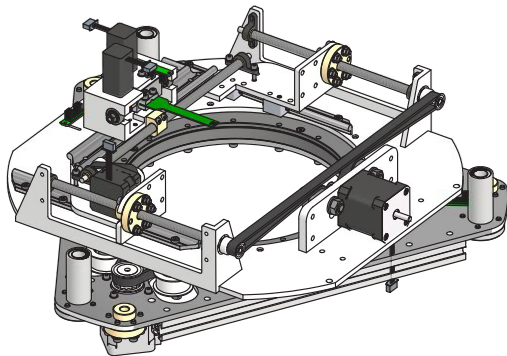


Figure 8: 6-DoF kinematic for mapping the flux density in and around the air gap (isolated view)

To eliminate manual positioning errors and expedite mapping, the sensor's movement is automated using ROS2. The path planning algorithm utilizes a simplified CAD representation of the coil unit to execute precise spatial sweeps, see Figure 9. This integration also features essential collision detection to protect the fragile sensor PCB during automated operation.

At the same time, the test bench was designed to accommodate a rotor, stator or even an entire machine to measure the flux density of surface permanent magnets, the flux density at the stator surface or even in the air gap during static operation (without rotation).

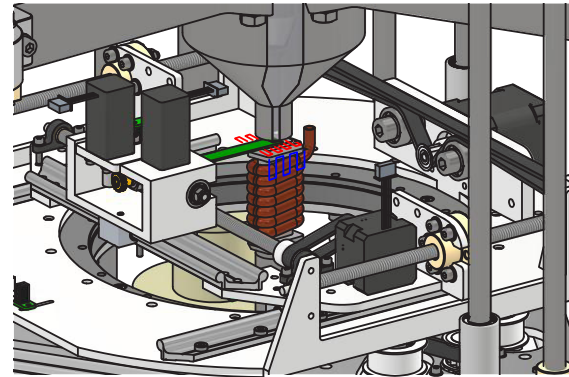


Figure 9: Possible measurement path in the air gap (red) and around the pole shoe for stray flux measurement

8. Thermal & Hydraulic Characterization

Thermal modeling is a primary focus of the test bench, supported by a comprehensive array of temperature and flow sensors to capture complex thermal gradients. The primary internal temperature of the copper winding is calculated indirectly from its electrical impedance. Because the baseline small-signal DC impedance is established prior to testing, real-time shifts in the active impedance during operation directly correlate to the average internal conductor temperature. While the raw electrical signal requires numerical filtering within the power analyzer to mitigate inherent noise, this methodology provides highly accurate internal thermal data without embedding destructive physical sensors into the winding structure. This impedance-based approach is supplemented by an extensive network of external sensors: multiple surface thermocouples (Type K) monitor localized thermal boundaries, two high-precision Pt100 sensors track the coolant fluid inlet and outlet temperatures, and a volumetric fluid flow meter enables full calorimetric power loss measurements. Additionally, a thermographic camera is utilized for the manual validation of surface temperature distributions. Together, this multi-domain thermal data provides the empirical foundation required for the creation and parameter identification of advanced thermal models.

Beyond thermal data, the test bench empirically verifies the hydraulic pressure drop across the specimen's cooling system (e.g., direct-liquid-cooled hollow conductors). Contrasting these

empirical measurements with theoretical calculations (such as the Gnielinski correlation [13]) is critical to investigate novel cooling concepts for their suitability (with respect to the necessary pump pressure) and validate simulation models. By sweeping through different volumetric flow rates, coolant types, and simulated power losses, the platform enables the comprehensive benchmarking, model verification and model calibration of novel cooling concepts.

Preliminary Experimental Results

To demonstrate the data acquisition capabilities of the test bench, preliminary thermal evaluation experiments were conducted under load, utilizing a novel litz wire hollow conductor prototype as the test specimen.

The primary objective of these experiments was to rigorously investigate the performance limits of the novel conductor topology, evaluating its capability to sustain unprecedented, record-breaking continuous current densities under extreme thermal loads. Concurrently, these experiments demonstrated the immense value of the test bench's comprehensive thermal monitoring capabilities. The system successfully captured and contrasted the distinct thermal gradients between the coolant stream temperature, the external surface temperature, and the internal impedance-derived conductor temperature, see Figure 10.

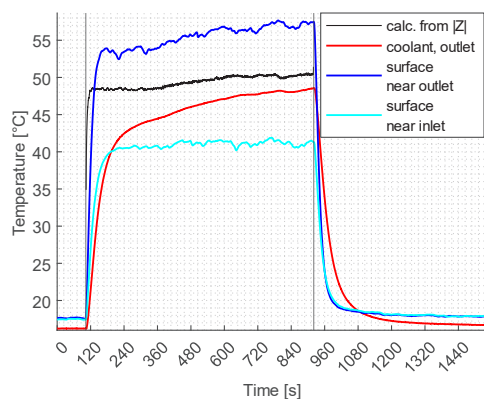


Figure 10: Transient temperature curves comparing internal impedance, surface, and coolant temperatures over time ($j = 100 \text{ A/mm}^2$)

Capturing these distinct thermal gradients and their respective temporal response delays is crucial. This multidimensional, high-resolution thermal data provides the exact empirical foundation required for the accurate parameter identification of advanced thermal models, laying the groundwork for training Lumped-Parameter Thermal Networks (LPTNs) or the Thermal Neural Networks (TNNs) discussed in the introduction.

Conclusion and Outlook

The conceptual and infrastructural foundation for a fully integrated, multiphysical test bench has been successfully established at TUHH. Key systems, including the high-precision electrical measurement infrastructure, versatile power emulation, and core thermal evaluation concepts, are already operational. Furthermore, foundational simulations regarding the Digital Twin, magnetic characterization methodologies, and active field manipulation have been fully developed and proven theoretically. Even in its current build phase, this architecture clearly demonstrates the capacity to capture the complex, multi-domain data required to finally bridge the validation gap for metamodel-based axial-flux machine design.

Immediate next steps focus on manufacturing of the magnetic circuit, final dimensioning and assembly of the custom hexapod actuators with their integrated force sensors, and the finalization of the ROS2-driven 6-DoF Hall sensor kinematics. Upgrades to specific hydraulic sensors have already been done (pressure and volumetric flow rate), with results from repeated experiments expected in Q2 2026.

Once physical commissioning is complete, research will shift toward validating the simulated magnetic characterization and active field manipulation models on real hardware. Ultimately, the acquired measurement data and the resulting validated simulation models will be utilized to optimize axial-flux machines across a wide variety of combinations involving different materials, geometric shapes, conductor topologies, and novel cooling concepts. This high-fidelity empirical foundation will directly support the overarching research methodology: generating highly accurate metamodels and Functional Mock-up Units (FMUs) to rapidly explore the design space and accelerate future motor development.

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