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Integration of CAD electrical machines and apparatuses with multiphysical modelling: An approach to matching electromagnetic and thermal models

Abstract. Isolated use of electromagnetic or thermal calculations in the design of electrical machines and apparatuses is a significant source of engineering errors since operating modes are formed by interrelated field and thermal processes. The purpose of the study was to substantiate and formalise the approach to integrating automated design with multiphysical modelling by matching electromagnetic and thermal models in a single parametric controlled circuit. The methodology was based on normatively consistent modes, cooling conditions, and temperature limits with two-way iterative coupling and spatially consistent transfer of losses to a thermal model with temperature correction of material properties. As a result, a common parametric frame of inputs is formed, which provides a consistent interpretation of load, cooling, temperature acceptability and energy efficiency. A formalised two-way circuit with convergence criteria provided reproducible stabilisation of temperature maxima and total losses. It is shown that spatial mapping of composite losses preserves local overheating zones, while their reduced transfer smooths out the temperature field. Consistent modelling established the heating domain stratification: in the windings about 130-140°C, in the magnetic circuit 105-115°C, in the housing 85-95°C, in the cooling zone 60-70°C. Temperature corrections of electrical and magnetic parameters substantially change the distribution of losses, primarily due to an increase in the resistance of conductors. A comparison of four matching schemes in 40 scenarios showed a convergence of 26 out of 40 for one-way binding to 38 out of 40 for the integrated solution; a

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two-way iterative scheme provided 36 out of 40 with stabilisation in 4-7 cycles, while step-by-step co-modelling required 6-12 exchanges. Practical importance lies in the possibility of direct use of the approach to improve the accuracy of thermal checks, select load modes, and optimise design solutions for electrical products

Keywords: temperature field; two-way circuit; volume source; co-simulation; heat sources; vortex losses

INTRODUCTION

The design of electrical machines and apparatuses increasingly requires an integrated approach since the design of the product, operating modes and operational limitations are formed by interrelated processes, which is advisable to analyse within a single digital design environment. Modern computer-aided design (CAD) of electrical products are increasingly combined with numerical field and multiphysical approaches, which allows simultaneously considering electromagnetic and thermal processes and their mutual influence. For electrical machines and apparatuses, such integration is critical since electromagnetic losses are the primary source of heat generation, the temperature field changes the electrophysical and magnetic parameters of materials, and therefore affects the performance, efficiency and service life of the product. In this context, the results of O. Kostin *et al*. (2022) demonstrated that the analysis of the regime stability of electrical processes requires a formalised approach to the estimation of dynamic modes since even local process instabilities can determine the limits of permissible operating modes and the requirements for calculated reproducibility. The authors stressed that the correctness of engineering conclusions is achieved only if a methodically consistent description of the mode parameters and stability criteria can be included in the digital design circuit. The effect of the electromagnetic system configuration on active losses in static electromagnetic devices is highlighted by O. Sadovoy *et al*. (2022), which showed the dependence of the loss level on the structural organisation of the magnetic path and excitation parameters. Their results indicate that electromagnetic losses should be described as a spatially and regime-dependent value suitable for further transfer to the thermal model as distributed heat sources. The development of the concept of digital doubles of technical objects forms the basis for matching simulation models with operational monitoring data. V. Pliuhin *et al*. (2024) described the implementation features of local and remote digital doubles, emphasising the role of integrating computational models, sensor data, and communication infrastructure to recreate the state of an object over time. This logic is fundamental for electrical machines and apparatuses, as it allows considering electromagnetic and thermal sub-models as interrelated components of a single digital representation of the product. Deepening this approach through algorithmic support and high-performance computing in automated design systems of electrical machines is presented by V. Pliuhin *et al*. (2025), who showed that combining machine learning methods with calculation modules enhances parametric optimisation capabilities and accelerates multi-dimensional multiphysical design iterations.

In applied works on electrical machines, the integration of electromagnetic and thermal analysis is considered as a necessary element of correct design. A. Młot *et al*. (2022) combined electromagnetic analysis, efficiency map, and thermal calculation for an 80 kW Interior Permanent Magnet motor, showing that temperature constraints and losses determine realistic operating modes and permissible loads. Similarly, J.F.D. Santos *et al*. (2022) demonstrated a digital twin induction motor approach using thermomagnetic finite element analysis, in which electromagnetic parameters and heating are consistent as interdependent computational domains for state monitoring and prediction. Methodological generalisations in the field of design automation emphasise that multidisciplinary integration into CAD is increasingly implemented as a link between electromagnetic, thermal, and mechanical sub-models in a single optimisation circuit. N. Umland *et al*. (2023), in a systematic review, demonstrate that the design automation of electric motors is based on the transition from "sequential" calculations to consistent operating flows, where loss sources, temperature limits, and efficiency criteria are accounted for together. An overview and case study of thermal design of cooling systems for a commercial synchronous motor with permanent magnets is provided by H.G. Usca-Gomez *et al*. (2025), which demonstrated the practical significance of integrating modelling, simulation, and thermal analysis for selecting rational cooling solutions and interpreting load modes. An alternative multiphysical methodology for strongly coupled electro-magneto-mechanical problems was proposed by F.M. Reato *et al*. (2023), justifying the feasibility of consistent numerical schemes in cases where electromagnetic effects give rise to mechanical and thermal effects and require joint formulation.

Thereby, applied descriptions of the use of Computer-Aided Design (CAD) electric drives using Finite Element Analysis (FEA) show that the technical integration of tools is already achievable, but the methodological scheme for matching electromagnetic and thermal models within a single parametrically controlled design circuit remains insufficiently formalised for reproducible applications in a wide class of electrical machines and apparatuses. A study by M. Manka *et al*. (2023) highlights the practical role of FEA instruments in the CAD design of electric drives, which actualises the need for a well-defined circuit for transferring electromagnetic losses to the thermal setting and returning temperature corrections to the electromagnetic model as a standard engineering procedure. A consistent analysis of these sources confirms that the effective integration of CAD with multiphysical modelling should be based on a formalised mechanism for two-way binding of electromagnetic and thermal sub-models, which provides a reproducible engineering interpretation of losses, temperature limits, and efficiency indicators in a single project cycle.

The study aimed to provide theoretical substantiation and methodological formalisation of the approach to integrating CAD of electrical machines and apparatuses with multiphysical modelling based on the Coordination of electromagnetic and thermal models in a single parametrically controlled design circuit. The main objectives of the study were: determine the principles and structure of two-way binding of electromagnetic and thermal sub-models through the chain "losses → heat sources → temperature field → temperature parameter corrections"; systematise the methods of model matching in the CAD environment (sequential-iterative binding, co-simulation, integrated multiphysical calculation) and establish the conditions for their correct application for electrical machines and apparatuses; clarify the set of design parameters and criteria that provide an engineering reproducible interpretation of the results of electromagnetic-thermal modelling in the problems of design optimisation, loss reduction and compliance with temperature restrictions.

MATERIALS AND METHODS

The study was performed as a theoretical one with elements of methodological formalisation and was aimed at building a reproducible approach to the coordination of electromagnetic and thermal models in the digital design circuit of automated design systems for electrical machines and apparatuses. The basic source of requirements for cooling methods and a unified description of heat sink schemes for rotating electric machines was the IEC 60034-6:1991 (1991), which was used for the normative correct setting of the IC code and matching the boundary conditions of thermal analysis with the type of cooling that determines the permissible temperature rises and the nature of heat exchange. Since the correct comparison of electromagnetic and thermal results depends on a consistent description of operating modes and passport characteristics, the regulatory basis for parameterisation of modes and operating indicators was formed by IEC 60034-1:2022 (2022), which provided uniform rules for interpreting nominal modes, load states, and related restrictions. IEC 60034-18-1:2022 (2022) provided a documentary basis for determining the requirements for insulation systems and the logic of their functional assessment for methodically correct inclusion of temperature restrictions in the design circuit and their connection with the stability and resource of electrical machines, which was used as a reference for substantiating permissible temperature limits and criteria for the acceptability of thermal regimes during engineering interpretation temperature fields. Since the key link between electromagnetic and thermal sub-models is the transfer of electromagnetic losses in the form of thermal sources, the basic regulatory source of methods for determining losses and efficiency from tests was IEC 60034-2-1:2024 (2024), which is used to unify the interpretation of composite losses to be reflected in the electromagnetic model and transferred to the heat setting.

IEC 60034-30-1:2025 (2025) was applied to ensure comparability of design solutions in terms of energy efficiency and to correctly assign results to efficiency classes, which was used as a framework for engineering interpretation of the impact of model matching on losses and efficiency improvement potential within the International Efficiency (IE) standard classification. The object of methodological analysis was generalised parametric models of electrical machines and electromagnetic apparatuses presented in the form of CAD structures with related material and mode parameters. The consideration covered geometric representations of the active part (magnetic circuit, windings, conductors, air gaps, structural shells) and sets of temperature-dependent electrophysical and thermophysical characteristics of materials necessary for the implementation of two-way binding of sub-models. For comparative analysis, four classes of calculation and model matching scenarios ($n = 40$) were formed, which differed in the structure of binding of electromagnetic and thermal sub-models: one-way schemes for transferring losses to a thermal problem; sequential-iterative schemes with temperature feedback; co-simulation statements for variable modes; integrated multiphysical statements with simultaneous problem solving. A set of scenarios was based on a partial multi-factor variation plan aimed at representative and uniform coverage of the parametric space without completely iterating through all possible combinations. There were six groups of factors that determine the electromagnetic-thermal interaction:

- the type of cooling system (two levels, in particular, different International Cooling (IC) codes);
- the convective heat transfer coefficient h (three levels within the characteristic engineering range for air cooling);
- thermal contact supports between structural layers (two levels-nominal and elevated);
- the temperature coefficient of electrical resistance of windings (two levels within the standard permissible deviations for copper);
- the load mode and power frequency (three levels: partial, nominal, and overload modes);
- the material of the magnetic circuit (two options with different specific losses).

Given the multidimensional nature of the problem, a complete factor plan would result in an excessive sample size, so a reduced balanced selection of 10 representative combinations was applied, including extreme and central levels of factors and ensuring that individual variables did not dominate. Each of these combinations was implemented in four matching schemes, which formed a common set of 40 scenarios. This structure of the research plan allowed correctly separating the influence of physical parameters from the influence of the binding algorithm and ensuring the methodological purity of the comparative analysis.

The methodological part was based on the system, structural-functional, and parametric analysis of multiphysical models and was implemented as a formalised two-way computational circuit "electromagnetic losses → equivalent heat sources → temperature field → temperature parameter corrections → refined electromagnetic calculation" with the specified convergence criteria. Within this circuit, the electromagnetic results were interpreted not as isolated fields but as design input data for a thermal sub-model: loss mapping was performed in a spatially distributed form with reduction to bulk heat sources and with control of the correctness of transfer between grids/geometric domains. Feedback was implemented through the return of the temperature field to the electromagnetic setting by updating the temperature-dependent properties of materials and winding parameters, which allowed reproducing the physically correct interaction "heating → parameter change → loss change" within the iterative process. The electromagnetic sub-model was considered in a field quasi-stationary formulation with the determination of distributed losses in conductors and magnetic materials, including Joule losses in windings and composite losses in the magnetic circuit, as well as, if necessary, additional vortex losses in structural elements.

The thermal sub-model was formed as a problem of heat transfer considering thermal conductivity in solids, convective heat exchange at boundaries, and contact thermal resistances in multilayer structures; the problem of boundary conditions provided for parameterisation of heat transfer coefficients and description of cooling paths as engineering heat exchange conditions. Parametric coupling was performed due to the temperature dependences of the electrical resistance of the conductors, specific losses, and magnetic characteristics, which ensured a consistent update of losses after each cycle of thermal calculation. Iterative matching was completed when convergence was achieved according to the stabilisation criteria of maximum temperatures and total losses, and in the absence of significant changes in critical local heating zones (winding parts, zones of increased losses in steel, areas of contact with the heat sink). For comparative evaluation of binding schemes, the convergence stability under changing cooling boundary conditions, the sensitivity of temperature maxima to changes in thermal resistances of layers, and the consistency of the energy balance between sub-models were additionally analysed. Numerical implementation of the generalised approach was performed in COMSOL Multiphysics 6.2, in Computer-Aided Design/Computer-Aided Engineering (CAD/CAE)-flow with heat exchange simulation in ANSYS Fluent, with specialised parameterisation of electrical machines in ANSYS Motor-CAD, and parametric run automation and post-processing – in MATLAB/Simulink R2024a and Python 3.12. The applied method provided reproducible and normatively interpreted matching of electromagnetic and thermal calculations in the CAD circuit, allowing comparing binding schemes in terms of convergence, sensitivity to limiting cooling conditions, and suitability for design optimisation accounting for temperature restrictions and losses.

RESULTS

Regulatory and parametric framework for matching electromagnetic and thermal sub-models

In the process of methodological formalisation of the initial conditions of multiphysical coordination, a systematic comparison of regulatory requirements for operating modes, cooling schemes, permissible temperature limits, and energy efficiency indicators was conducted. Based on this comparison, a consistent set of parameters is formed, which is used as a common input frame for electromagnetic and thermal statements, an interpretive basis for transferring losses to thermal sources and checking the permissibility of temperature regimes. The analysis of the generated parametric set revealed that the reproducibility of electromagnetic-thermal modelling in the design CAD circuit is determined precisely by the unified standard setting of load modes, cooling IC codes, insulation temperature limits, and interpretive efficiency criteria. Matching sub-models requires treating these values as interrelated computational constraints, rather than as independent reference characteristics (Table 1).

Table 1. Normatively agreed parameters of modes, cooling and temperature limits for electromagnetic-thermal modelling

Standard parameter block	What exactly is unified in the project circuit	Role in the electromagnetic sub-model	Role in the thermal sub-model	Engineering result of approval
Operating modes and passport parameterisation	Nominal mode, load conditions, interpretation of "rating and performance" as a single basis for comparing scenarios	Fixes basic operating states for calculating fields and losses (load/current/mode matching)	Provides a correct comparison of temperature fields with exactly the mode for which passport restrictions are defined	The only interpretation of "mode → loss → heat load", which eliminates discrepancies between the "electric" and "thermal" descriptions of the machine condition
Cooling type and IC code (cooling methods)	IC code as a standardised description of the heat sink scheme and heat exchange conditions	Sets an engineering-correct framework of assumptions for addressing thermal limitations in the selection of permissible loads and scenarios	Defines the type of boundary conditions: the nature of convection, the organisation of heat exchange, the consistency of "cooling – permissible temperature rise"	Normatively correct setting of the boundary conditions of the thermal problem, compatible with the passport mode and design type

Continued Table 1.

Standard parameter block	What exactly is unified in the project circuit	Role in the electromagnetic sub-model	Role in the thermal sub-model	Engineering result of approval
Temperature limits of thermal regime acceptability due to insulation requirements	Logic of functional evaluation of the insulation system and permissible temperature limits as an acceptability criterion	Determines the permissible temperature limits within which electromagnetic parameters are considered acceptable after temperature correction	Sets the temperature field acceptability criterion: T_{max} control in critical zones (winding/insulation)	Linking the thermal result to a clear "acceptable/ unacceptable" criterion in terms of insulation temperature endurance
Energy efficiency and IE classes as an interpretive framework	IE energy efficiency classes as a standardised field for interpreting the impact of losses and modes	Allows interpreting total losses and their changes when matching models in terms of energy efficiency	Indirectly fixes the requirement for thermal mode due to the permissibility of losses and operating states for a given IE class	Conversion of coordination results from the "temperature/loss" level to the standard comparable energy efficiency level for project solutions
Consistent set of output parameters for reproducible scripts (n-script input frame)	Uniform input assumptions for comparing matching schemes: mode → IC code → temperature limits → performance interpretation	Fixes comparable conditions for calculating losses between scenarios	Fixes comparable cooling conditions and temperature acceptability criteria between scenarios	Ensures that the results of different binding schemes are correctly compared as obtained under the same regulatory and parametric framework

Source: compiled by the authors according to IEC 60034-6:1991 (1991), IEC 60034-1:2022 (2022), IEC 60034-18-1:2022 (2022), IEC 60034-2-1:2024 (2024), IEC 60034-30-1:2025 (2025)

The analysis of the parameters summarised in Table 1 showed that the normative characteristics within the electromagnetic-thermal agreement perform the function of a common "parametric interface" between sub-models, setting the same logic for describing the mode, cooling, temperature acceptability, and energy efficiency. The operating modes unified in accordance with IEC 60034-1:2022 (2022) define the design states for which electromagnetic losses are formed as a mode-dependent value suitable for transfer to a thermal setting. The cooling IC code specified in IEC 60034-6:1991 (1991) specifies the type and structure of the heat sink as a normatively correct basis for forming the boundary conditions of heat exchange, which directly affects the permissible temperature rises and the nature of the temperature field. Temperature limits of acceptability, linked to the requirements for functional evaluation of insulation systems according to IEC 60034-18-1:2022 (2022), translate the thermal result from a descriptive level to a criterion verification level, as they allow temperature maxima to be interpreted not simply as calculated values, but as threshold limits that determine the acceptability of a design solution. The inclusion of energy efficiency classes according to IEC 60034-30-1:2025 (2025) provides a standardised context for interpreting the impact of model matching on losses, which allows comparing alternatives both for local temperature peaks and integral energy performance within the IE classification. The consistent application of these parameters eliminates the typical methodological discrepancy between sub-models when electromagnetic losses are calculated for conditions that do not correspond to the actual type of cooling, or when the thermal field is estimated without a formalised tolerance criterion from the point of view of insulation and passport regime. As a result, the formed normative-parametric framework provides reproducible initial conditions for further two-way binding along the chain "losses → heat sources → temperature field → temperature parameter corrections" since it makes unambiguous both the method of setting the mode and cooling, and the criteria for the acceptability of the obtained temperature and efficiency results.

Formalised two-way computational model matching circuit

In the course of the study, a generalised two-way computational circuit for matching electromagnetic and thermal sub-models is constructed, in which both calculations are combined by an iterative cycle with controlled feedback (Fig. 1). Within this circuit, standardised data exchange points are defined: transfer of distributed losses from the electromagnetic problem to the thermal problem in the form of equivalent volumetric heat sources and return of the temperature field to the electromagnetic setting through updating the temperature-dependent parameters of materials and windings. Parametric update rules and iterative process convergence criteria are formalised for each transfer point. Analysis of the obtained structure showed that reproducible matching in the CAD circuit requires not only the presence of two calculated domains but also a well-defined computational scheme of two-way binding with fixed data transfer points and formal conditions for completing iterations.

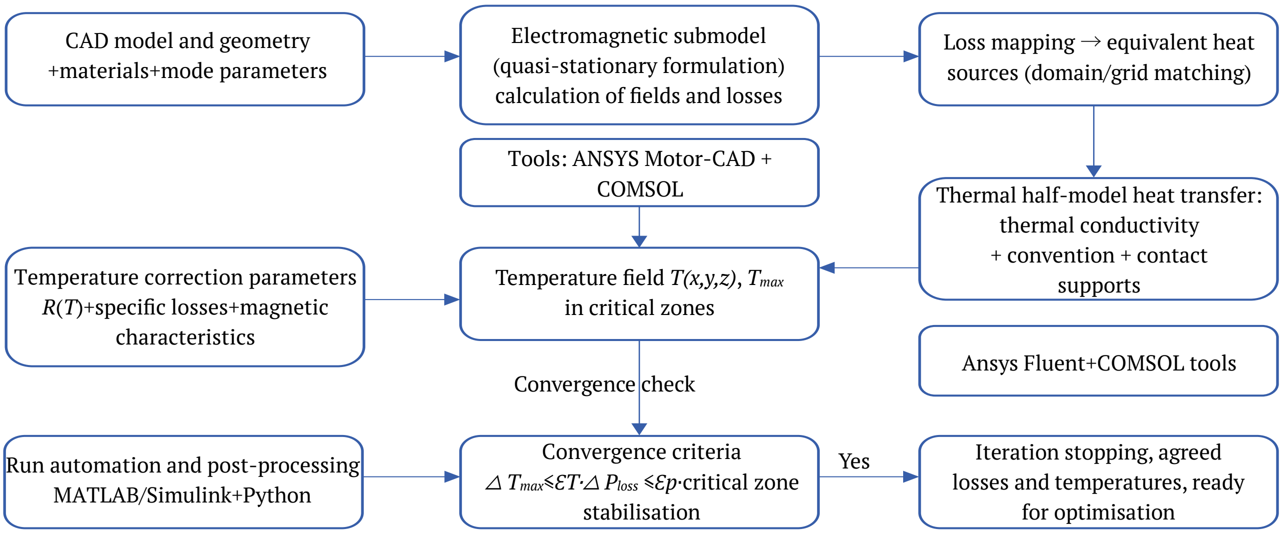

Figure 1. Formalised two-way scheme for matching electromagnetic and thermal sub-models in a CAD environment
Source: compiled by the authors according to the described computational scheme and matching procedures in COMSOL Multiphysics 6.2, ANSYS Fluent, ANSYS motor-CAD, MATLAB/Simulink R2024a

Figure 1 shows a block diagram of a two-way circuit in which the initial electromagnetic calculation forms a spatially distributed map of losses in conductors and magnetic materials. These losses go through the normalisation and spatial mapping stages and are converted into equivalent heat sources consistent with the geometric domains of the thermal model. After solving the heat transfer problem, a temperature field is formed with the allocation of local maxima and critical heating zones, which is then used for parametric updating of electrical resistance, specific losses, and magnetic characteristics. The updated set of parameters is returned to the electromagnetic sub-model, where an updated loss calculation is performed, after which the cycle is repeated. Analysis of the constructed circuit has shown that the fundamental condition for its reproducibility is not the fact of iterationism itself, but the formalisation of stopping criteria. The methodological scheme uses simultaneous stabilisation of three groups of indicators as convergence criteria: maximum temperatures in critical zones, total electromagnetic losses, and local loss densities in domains with increased heat dissipation. In particular, maximum temperatures in critical zones are considered stable if their change between iterations does not exceed ±2°C. The total losses are stabilised at a change of no more than ±1%, which corresponds, for example, to 2-5 W for a device with a total loss of about 500 W. Local loss densities in domains with increased heat dissipation are assumed to be stable when the deviation between iterations does not exceed ±2%, which is for a local density of 1.2 W/cm^3 corresponds to the limits of 0.024 W/cm^3. The use of such numerical thresholds provides methodically reproducible updating of electrophysical and thermal characteristics in a two-way electromagnetic-thermal circuit.

The circuit is considered convergent only if there are no changes in these metrics between adjacent iterations. In addition, it has been established that the formalised bilateral circuit is suitable for various coordination schemes – sequential-iterative, co-simulation, and integrated multiphysics – provided that the same data transfer points and convergence criteria are maintained. This ensures comparability of results between scenarios and allows interpreting differences as a consequence of the binding structure, rather than different rules for exchanging parameters. Summarising, the constructed formalised two-way computational circuit sets the reproducible algorithmic basis for matching electromagnetic and thermal sub-models, fixes data exchange interfaces, and criteria for completing iterations, and thereby translates multiphysical matching from the level of instrumental practice to the level of standardised engineering procedure.

Structuring of electromagnetic losses and rules for their transfer to thermal staging

Within the constructed computational circuit, the structuring of electromagnetic losses is performed with their formalised separation by physical nature, spatial localisation, and the method of transfer to thermal staging. Losses are interpreted as distributed energy sources to be reduced to consistent calculated domains of the thermal model with control of volume, material, and mode compliance. The basic groups of losses that are subject to mandatory mapping have been identified: Joule losses in windings, losses in the magnetic circuit (hysteresis and eddy current losses), additional load losses, and local eddy losses in structural elements. For each group, the conversion rule to the thermal equivalent is established – in the form of a volume or surface heat source – with the fixing of the calculated domain and the parameter transmitted to the thermal problem. A generalised correspondence between the components of losses, their physical nature, and the transfer rules is presented in Table 2.

Table 2. Correspondence of components of electromagnetic losses to types of heat sources and settlement domains

Component of electromagnetic losses	Physical mechanism	Primary calculation in the electromagnetic (EM) model	Type of heat source in a thermal sub-model	Spatial transfer domain	Thermal mapping rule
Joule losses in windings	Ohmic heating of conductors	Current density distribution and $R(T)$	Volumetric heat source	Winding volume	Integral losses are distributed over the volume of the conductor, considering the fill factor and the temperature dependence of the resistance
Losses in the steel of the magnetic circuit (hysteresis)	Magnetic hysteresis loop	Local specific losses in the core	Volumetric heat source	Slats/segments of the magnetic circuit	Specific losses are multiplied by the local volume of the domain linked to the material domain
Steel losses (eddy currents)	Induced currents in the core	Frequency-dependent losses	Volumetric heat source	Magnetic circuit	Mapping is performed on an element grid with aggregation into thermal subdomains
Additional load losses	Scattering, field harmonics	Balance/residual losses	Generalised volume source	Active part (consolidated domain)	Distributed proportionally to energy-loaded areas according to the accepted weighting rule
Local vortex losses in structural parts	Eddy currents	Local losses in detail	Local volume or surface source	Fasteners, screens, massive metal parts	Bound to the corresponding CAD domains as separate thermal regions
Surface losses from stray currents	Surface effect	Surface loss density	Surface heat load	Surfaces of the leading parts	Converted to the limit thermal condition (heat flux)

Source: compiled by the authors according to the rules for determining and interpreting losses in accordance with IEC 60034-2-1:2024 (2024) with implementation in COMSOL Multiphysics 6.2 and Ansys Motor-CAD

The generalised matching analysis in Table 2 showed that the key condition for correct transfer is domain-oriented mapping, where each loss component is passed not as a reduced number, but as a spatially bound distribution. This ensures consistency of the energy balance between sub-models and enables the correct reproduction of local temperature maxima in windings, zones of increased magnetic losses, and structural elements. Separately, it was identified that aggregated transfer of total losses without spatial decomposition leads to smoothing of the temperature field and loss of sensitivity of the model to design solutions for cooling. That is why the rule of mandatory decomposition of losses by domain is applied in the agreed circuit, followed by reduction to equivalent heat sources of a given type. As a result, the structuring of composite losses and the formalisation of the rules for their mapping provided a reproducible procedure for the transition from electromagnetic calculation to thermal setting, consistent with the normative interpretation of losses and suitable for a multi-criteria multiphysical design circuit.

Results of constructing the temperature field and identifying critical heating zones

Within the framework of a consistent electromagnetic-thermal formulation, temperature fields were constructed for all calculated scenarios. Analysis of the spatial temperature distribution showed stable structural inhomogeneity, which is determined not only by the level of total losses but also by the configuration of heat sink paths, the type of cooling, and the value of contact thermal resistances. Generalisation of the results of 40 scenarios showed that even at close integral loss values, temperature maxima are localised in different domains depending on the cooling IC code, convection parameters, and thermal interconnection of layers. This confirms the need for spatially consistent, rather than averaged, thermal analysis. Figure 2 shows a generalised map of temperature fields, where the average, maximum, and critical temperatures for the main structural domains are spatially compared: windings, magnetic core, housing, and cooling zones.

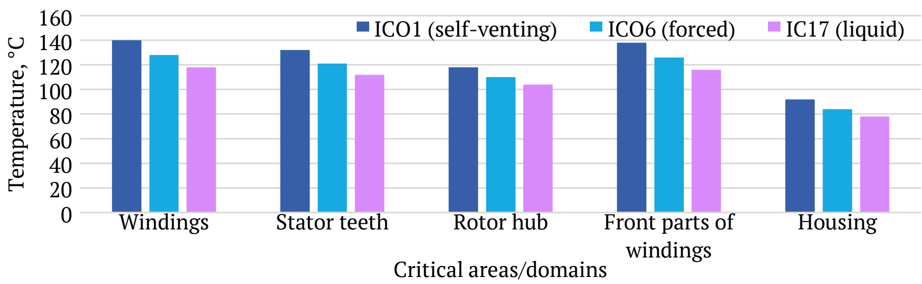

Figure 2. Generalised map of temperature fields and critical heating zones in a coordinated electromagnetic-thermal formulation

Source: compiled by the authors on the basis of a thermal sub-model of heat transfer with parameterisation of cooling conditions by IEC 60034-6:1991 (1991) with numerical implementation in Ansys Fluent and COMSOL Multiphysics 6.2

According to Figure 2, the highest temperatures are recorded in the windings: maximum ≈130°C, critical value ≈140°C, average ≈110°C, which forms the upper cluster and corresponds to the domain with the highest specific loss generation. Next in terms of heating level is the magnetic circuit: maximum ≈105°C, critical ≈115°C, average ≈90°C, i.e., lower than the windings, but higher than the housing. The housing is characterised by lower values: maximum ≈85°C, critical ≈95°C, and average ≈70°C, reflecting a more efficient heat sink. The lowest temperatures are observed in the cooling zone: maximum ≈60°C, critical ≈70°C, average ≈50°C, i.e., the lower limit of the temperature field, relative to which the heating gradient of other domains is formed. Generalisation of the results of temperature modelling confirmed that critical heating zones are scenario-dependent and should be determined in the coupled electromagnetic-thermal state since their position and intensity change after temperature correction of material parameters. This means that the engineering correct interpretation of thermal constraints and verification of permissible modes is possible only in an iterative two-way matching circuit, and the use of an isolated thermal estimate without updated losses leads to a shift in the assessment of risk zones.

Temperature-parametric feedback and refinement of the electromagnetic calculation

As part of the consistent electromagnetic-thermal analysis, the temperature field obtained at the previous iteration of the thermal calculation was used to update the temperature-dependent electrophysical and magnetic parameters in the corresponding calculated domains. A two-way binding circuit "temperature field → parameter correction → repeated electromagnetic calculation" was implemented, which specified the electrical resistivity of conductors, magnetic permeability, and specific losses in the magnetic circuit. Generalised temperature corrections of parameters and their impact on refined losses and performance characteristics are shown in Table 3.

Table 3. Temperature corrections of electrophysical and magnetic parameters and their impact on electromagnetic results

Parameter (notation)	Where it is used in the model	How it changes with temperature (qualitatively)	What corrects in the EM calculation	Expected direction of impact on losses/characteristics
Electrical resistance of the winding ($R_w(T)$)	Windings/conductors	Increases with increasing T	Joule loss $P_{Cu} = I^2R$; local heat sources in windings	Losses in copper ↑, winding temperature ↑, (efficiency)↓; at constant torque, current may increase in certain modes
Conductor resistivity ($p_e(T)$)	Conductors, conductive busbars	Increases with increasing T	Current distribution, current density J, ohmic losses	Ohmic losses↑, increasing the thermal load of conductor zones
Specific losses in steel ($P_{Fe}(T)$)	Magnetic circuit (yoke/prongs)	Temperature-dependent (often weak, but significant for modes/materials)	Hysteresis and eddy current losses; balance of steel losses	Changes in steel losses (often moderate), redistribution of heat sources in the magnetic circuit; risk of local maxima in areas of increased induction
Magnetic permeability/magnetisation curve ($\mu(T)$, B-H (T))	Magnetic circuit	Effective permeability may decrease; saturation occurs "earlier"	Operating point on B-H, induction B, flow coupling, field distribution	Possible reduction of torque/EMF or the need for more current; indirectly may increase losses in copper
Residual induction/coercive force of a permanent magnet, ($Br(T)$, $Hc(T)$) if there are permanent magnets	Rotor/magnets	Usually decreases with increasing T	Main flux from a permanent magnet, EMF, moment constant	Flow ↓ → moment/EMF ↓, to maintain the mode, the current increases → P_{Cu} ↑; additionally, the risks of overheating of magnets increase
Equivalent conductivity/loss in structural elements ($P_{add}(T)$)	Covers, screens, fasteners (in the presence of vortex losses)	Indirectly depends on $\rho(T)$	Additional vortex losses in metal parts	Additional losses may vary; affect local heating of structural elements
Insulation system temperature limits (T_{lim})	Windings/insulation	The norm sets the permissible range T	Thermal mode acceptability criterion, optimisation "stop condition"	Defines limits for modes and design; when exceeded, changes in cooling/materials/current density are required

Note: EMF – electromagnetic force
Source: it is formed by the authors according to the method of parametric Binding of sub-models and the normative interpretation of permissible temperature limits by IEC 60034-18-1:2022 (2022) with calculated implementation in Ansys Motor-CAD and COMSOL Multiphysics 6.2

As shown in Table 3, temperature-parametric feedback changes electromagnetic results not through a single coefficient, but through a consistent set of corrections to the electrophysical and magnetic properties of materials. The most sensitive channel of influence is the temperature dependence of the electrical resistance of windings and conductors: as the temperature increases, R and resistivity increase, which directly increases the Joule losses I^2R and forms a positive thermal reverse circuit "heating → resistance → loss → additional heating". This means that without updating the temperature parameters, the electromagnetic calculation systematically underestimates the losses in copper and the associated temperature peaks. The second most important block of changes is related to magnetic characteristics. Temperature corrections of the magnetisation curves and effective magnetic permeability shift the operating point of the magnetic circuit and can lead to earlier saturation of individual sections. In the calculated terms, this manifests itself as a change in the distribution of induction and flow coupling, which affects the EMF and moment characteristics and indirectly – the current load of the windings. For machines with permanent magnets, a temperature decrease in the residual induction and coercive force is additionally triggered, which reduces the useful magnetic flux and requires current compensation, again increasing copper losses. Corrections for specific losses in steel and additional losses in structural elements have a more moderate but spatially important effect: they change the map of the distribution of heat sources in the magnetic circuit and adjacent metal parts. This does not always dramatically change the total losses, but it strongly affects the local heating zones that determine the critical temperature nodes of the model. Analysis of the influence of temperature corrections on electromagnetic results showed that the most significant changes are localised in areas where increased losses and limited heat dissipation are combined, primarily in the winding parts and adjacent areas of the magnetic circuit. In these domains, the refinement of parameters leads to a redistribution of specific losses and to changes in the integral indicators used in the design interpretation (in particular, total losses, efficiency, and temperature-limited load modes). Temperature-parametric feedback is not an auxiliary option, but a mandatory procedure for reproducible electromagnetic-thermal matching, since it determines whether the repeated electromagnetic calculation will correspond to the actual thermal conditions of the product and whether engineering conclusions regarding losses and modes will be correct within the accepted temperature limits.

The results of comparison of matching schemes in the electromagnetic-thermal formulation (n = 40 scenarios) showed that the convergence and stability of the calculation process are determined not only by the numerical method, but primarily by the structure of the sub-model binding and whether temperature feedback is implemented in the circuit "losses → heat sources → temperature field → temperature parameter corrections". With identical initial geometric and operating parameters, schemes without full two-way coupling demonstrate formal solution attainability only in terms of cooling conditions, whereas two-way approaches provide reproducible stabilisation of both temperature maxima and total losses when boundary conditions vary. Table 4 shows a comparison of four binding schemes by the proportion of convergent scenarios, the nature of convergence (monotonic/vibrational), the average number of iterations to stabilisation, sensitivity to changes in heat transfer coefficients, and contact thermal resistances, in addition to suitability for design optimisation problems.

Table 4. Comparative indicators of convergence and stability of electromagnetic-thermal matching schemes

Sub-model binding scheme	Communication structure	Convergent scenarios, n/40	The nature of convergence	Typical number of cycles/ exchanges before stabilisation*	Sensitivity to cooling conditions (h, IC code)**	Sensitivity to contact thermal resistances	Consistency of the energy balance "losses ↔ heat"	Suitability for project optimisation	Computational cost
1) One-way transfer "loss → heat"	electromagnetic model→ thermal model (TH) (without *T*-feedback)	26/40	Formally stable, but without self-consistency of losses	1	High (risk of T_{max} bias with h variation)	Medium-high	Limited (unaccounted for *T*-effect on EM parameters)	High speed, but low physical correctness	Low
2) Sequential-iterative bilateral coordination	EM ⇄ TH (iterations with parameter updates)	36/40	Mostly monotonous	4-7 (median 5)	Low-medium (T_{max} and P_{loss} stabilisation in most modes)	Medium	High (convergence control by ΔT_{max} and ΔP_{loss})	High (best quality/time balance)	Medium
3) Co-simulation (variable modes / time exchange)	EM ⇄ TH (exchange per step/interval)	32/40	Possible fluctuations under "harsh" conditions	6-12 exchanges (median 8)	Medium-high (depends on the exchange settings)	High	Medium-high (sensitive to the exchange step)	High for variable modes, medium for mass runs	Medium-high
4) Integrated multi-physical calculation	joint solution EM+TH	38/40	Rack (least risk of swaying)	1 (conjugate solution)	Low	Medium	Very high	High as referent/ verification, medium for serial optimisation	High

Note: *"cycles/exchanges" refers to the steps taken to meet the convergence criteria for stabilising maximum temperatures and total losses (for example, conditionally: ΔT_{max} and ΔP_{loss} below specified thresholds); **"sensitivity to cooling conditions" is interpreted as the tendency of the circuit to change T_{max}/gradients and convergence when varying heat transfer coefficients and boundary conditions, parameterised through the IC code
Source: generated by the authors based on the results of parametric runs and post-processing in MATLAB/Simulink R2024a and Python 3.12 using calculation models in COMSOL Multiphysics 6.2 and ANSYS Fluent

Generalisation of indicators from Table 4 confirmed that the key factor of convergence and reproducibility of electromagnetic-thermal matching is the presence of temperature-parametric feedback and the way data exchange between sub-models is organised. The integrated multiphysical scheme showed the highest proportion of convergent scenarios – 38/40, while the lowest was the one-sided transfer of "loss → heat" – 26/40, which records a gap of 12 scenarios between the minimum and maximum convergence. In terms of the rate of stabilisation, the minimum value is 1 cycle/solution in schemes 1 and 4, but these are different in the meaning of "1": in Scheme 1, it is achieved without temperature feedback, while in scheme 4 – as a conjugate solution with full self-matching; the largest typical number of steps/exchanges is observed in the co – simulation-6-12 (median 8), which is the upper limit on labour intensity among the above schemes. In terms of cooling sensitivity, the extreme values are centred at the poles: the highest is in scheme 1, the lowest is in scheme 4, which is consistent with the fact that the conjugate solution itself minimises the "gap" between losses and the temperature field under variable boundary conditions. A systematic comparison of the results showed that the key indicator of the "engineering quality" of the scheme is not only the fact of achieving convergence, but also the consistency of the energy balance and the absence of a systematic shift in temperature maxima under small changes in boundary conditions. That is why, in design problems where serial parametric runs and design optimisation are required, it is advisable to adopt sequential-iterative two-way matching as the basic working procedure, using the integrated multiphysical scheme as a control (reference) to check the correctness of settings and for scenarios with the most severe thermal constraints.

DISCUSSION

A comparison of the established patterns of electromagnetic-thermal matching with current publications on multiphysics design and digital engineering has shown that the integration of CAD systems for electrical machines and devices with related electromagnetic and thermal models is developing as a common trend in the formalisation of exchange interfaces, convergence criteria and reproducible scenario settings in the CAD/CAE circuit. It is demonstrated that the reproducibility of integration of design modelling with multiphysical coordination was determined not by the presence of separate calculation domains, but by the formalisation of a bilateral computational circuit with fixed data transfer points and iteration completion criteria, which ensured the stabilisation of temperature maxima and total losses in a series of parametric runs. This statement was in accordance with the approach of P. Eitz *et al*. (2024), where multiphysical calculation was interpreted as a formalised workflow with controlled sub-model binding in a parametric modelling environment. A similar emphasis on the role of the binding structure and the correctness of state exchange between physical sub-models was reflected in the results of G. Mauromicale *et al*. (2023), which shows that multiphysical models lose their engineering suitability in the absence of consistent interfaces between Electrical and thermal quantities, which directly echoes the need to fix the points "losses → heat sources" and "temperature field → parameter updates". It was determined that the key condition for the correct binding of electromagnetic and thermal statements was domain-oriented spatial mapping of composite losses, in which Joule, magnetic, and local vortex losses were transmitted to the thermal model as distributed sources, and not as an aggregated total value; aggregation itself led to smoothing of the temperature field and loss of sensitivity to local overheating zones. This pattern was consistent with the conclusions drawn by C. Guo *et al*. (2022), where electromagnetic-thermal coupling for machines with permanent magnets and cooling channels was considered through the spatial correspondence of heat sources to structural domains, which determined local temperature peaks and their engineering interpretation. The consistency of the effect of the cooling configuration on the localisation of temperature maxima was reflected in the results of J. Chang & C. Wang (2022), which states that changing the organisation of the heat sink changes not so much the integral heating level, but the position and amplitude of critical zones, which coincided in interpretation with the established domain temperature stratification. It is shown that the normative-parametric unification of operating modes, cooling method, and temperature acceptability was functionally necessary for the reproducibility of comparing binding schemes since it provided the same "input base" for all scenarios and excluded situations where losses were calculated for conditions that were not equivalent to the limiting thermal conditions. The need to consider temperature rise as a target and control indicator for engineering solutions was consistent in the nature of the manifestation, with the results of H. Liu *et al*. (2024), where co-optimisation of electromagnetic and thermal solutions was aimed at minimising temperature gain, which was conceptually consistent with the use of temperature maximal stabilisation as a criterion for convergence and suitability of the solution.

It was established that temperature-parametric feedback determined the refinement of electromagnetic losses due to the temperature dependence of the resistance of conductors and changes in magnetic characteristics, forming a positive circuit "heating → resistance growth → loss growth → additional heating", and that is why circuits without full two-way binding showed lower reproducibility in terms of cooling conditions. This interpretation of the need for multipole binding was in line with the results of H. Cho *et al*. (2024), where it is shown that reliable mode estimation requires simultaneous consideration of the interaction of several physical subsystems, and a separate calculation distorts local constraints and mechanisms of critical zone formation. The parallel with the engineering need to maintain the manageability of complex design circuits through formalised procedures for processing and interpreting results echoed the generalisations of G. Li *et al*. (2024) on the role of intelligent methods in the design of complex electronic systems, which in this context corresponded to the use of standardised convergence and post-processing criteria for serial scenario runs. It was determined that comparing matching schemes was only technically informative if the same data transfer points and convergence criteria were maintained, as this ensured that the results were compared as an effect of the binding structure rather than as a consequence of incompatible exchange rules. This statement correlated with the conclusions of X. Wang *et al*. (2023) that in multiphysics design of complex systems, it is not the "presence of many physics" that is decisive, but the standardisation of interfaces and the coordination of data flows between domains, without which the comparability of scenarios is destroyed. The practical feasibility of using a specialised software environment for the design interpretation of thermal checks and losses in permanent magnet machines corresponded to the conclusions of F.A. Coteț *et al*. (2023) on the usefulness of using engineering design tools for electrical machines under the condition of correct binding and interpretation, which in this study was provided through a normative parametric framework and a two-way circuit with convergence confirmed on a set of 40 scenarios.

It is established that the domain temperature stratification in the coupled electromagnetic-thermal setting had a reproducible profile with maxima in the windings of about 130-140°C, in the magnetic circuit of 105-115°C, in the housing of 85-95°C, and in the cooling zone of 60-70°C, which fixed critical heating nodes precisely as a function of the spatial distribution of losses and heat dissipation paths. This logic of interpreting electrothermal constraints corresponded to an approach of A. Shandilya & V. Kumar (2024), where electrothermal analysis for traction drives was interpreted through local temperature peaks and their relationship to load and cooling modes. The analogy with multiscale coupling "2-D (dimensional) electromagnetic staging-3-D thermal staging" was traced in a paper of A. Ebrahimi Shohani *et al*. (2025), where dimensional separation was used to reproduce local thermal effects in complex geometry; in the above results, a similar need was manifested through the requirement of domain-oriented loss mapping, which preserved local temperature maxima rather than averaging them. Clarification of the role of the digital design circuit as a control system for multiphysical models echoed N.Y. Choi & S.U. Zhang (2025), where a combination of multiphysical simulation and project support algorithms was used to improve the reproducibility of high-level design solutions; in this case, formalised data exchange points and convergence criteria acted as such a "managed circuit". The correlation with the procedural formalisation of calculations through the experimental plan and the compared statements was traced in the study of N.Y. Choi *et al*. (2025), where benchmarking of thermal and electrical characteristics was based on comparable scenarios and controlled parameter variations; in the presented results, a similar function was performed by a unified input frame and comparability of 40 scenarios. It was recorded that the normative parametric unification of modes, cooling conditions, and temperature limits created a common parametric interface of sub-models and made the comparison of binding schemes correct, since all 40 scenarios had the same input base. This principle of "single input base → comparable scenarios → comparable binding structure effect" was in accordance with R. Cinar *et al*. (2025), where CAD-FEA automation was reduced to ensuring repeatability of statements and results when parameters vary. The generalisation of integrated multiphysical modelling in microsystems parallels the findings of A. Ghaemi *et al*. (2025), where the performance of the integrated model was determined by the consistency of domains and the correctness of energy transfer between them; in this case, domain-oriented loss mapping and convergence criteria performed a similar function.

An additional parallel regarding the controllability of multiphysical productions through standardised channel and profile configurations in microfluidic systems was observed in a study by P. Sai Kumar & S. Goel (2025), where the comparability of variants was provided by a structured variation of geometry and boundary conditions; unified modes, heat exchange conditions, and convergence control played a similar role in the presented results. Based on the comparison of coupling structures, it was established that "1 cycle" in a unilateral scheme and "1 conjugate solution" in an integrated multiphysical scheme have different engineering meanings: the former did not include temperature parameter updates, while the latter ensured self-consistency of losses and temperature field, which was reflected in the maximum convergence of 38/40. This difference in the interpretation of "speed" correlated with Z. Dong *et al*. (2025), where multiphysical models demonstrated that a formally shorter calculation can be methodically incomplete without correct domain binding. An analogy to the applied problems of electric and magnetic fields in high-voltage apparatuses was presented in a study by E. Tunç & M. Fidan (2025), where multiphysical modelling in the field calculation environment required a correct Binding of boundary conditions and material parameters; in the above results, a similar requirement was realised through the transfer of the temperature field to the update of electrophysical parameters. It is recorded that for design problems with serial parametric runs, the two-way iterative scheme turned out to be the most balanced in terms of "quality/time", since it provided a convergence of 36/40 for 4-7 cycles, while the integrated conjugate solution, although it gave 38/40, was characterised by a higher computational cost. This approach to the choice of the "working" and "reference" schemes was consistent with the work of S. Pavalkis & M. Otte (2025), where digital procedures were selected based on the scalability and cost of calculations while maintaining the quality of verification. A parallel with benchmark initiatives for traction electric motors was observed in L. Solimene *et al*. (2025), which emphasised the need for comparable data and uniform comparison procedures for multiphysical models; a unified input framework and formalised convergence criteria for a set of 40 scenarios played a similar role in the presented results.

Thus, the results of the study showed that the integration of CAD of electric machines and apparatuses with multiphysical modelling should be based on the interrelated formalisation of operating modes, cooling conditions and temperature acceptability, since it was their consistent task that determined the correctness of transferring electromagnetic losses to the thermal setting, localisation of critical heating zones and engineering interpretation of the results. Systematic comparison of the obtained regularities with the conclusions of modern research in the field of multiphysical design confirmed that the key role is played by standardised exchange interfaces between sub-models, domain-oriented mapping of heat sources, and the presence of temperature-parametric feedback as conditions for reproducible self-agreement of electromagnetic and thermal estimates in the design circuit.

CONCLUSIONS

Within the framework of the conducted research, a reproducible engineering procedure for electromagnetic-thermal matching in a multiphysical CAD circuit was formed on the basis of normative-parametric unification of the initial conditions, formalised two-way computational binding, and domain-oriented transfer of losses to the thermal setting. The constructed normatively consistent framework of modes, cooling IC code, insulation temperature limits, and energy efficiency classes provided a common parametric interface of sub-models and eliminated the discrepancy between the electromagnetic state description and thermal boundary conditions. Formalisation of a two-way computational circuit with fixed data transmission points and convergence criteria established a reproducible iterative matching scheme for the "losses → heat sources → temperature field → temperature parameter corrections" circuit, suitable for parametric scenarios and comparative runs. The structuring of electromagnetic losses, divided into Joule, magnetic, additional load, and local vortex components and their mandatory spatial mapping into thermal domains ensured the correctness of the energy balance and the preservation of local temperature maxima, while the aggregate transfer of total losses showed a loss of spatial sensitivity of the temperature field. Consistent temperature modelling recorded a stable heating domain stratification: for TMAX windings ≈130°C and critical values ≈140°C, for a magnetic circuit ≈105/115°C, for a housing ≈85/95°C, for a cooling zone ≈60/70°C, which confirmed the scenario-dependent localisation of critical zones, and the need for a connected, rather than isolated, thermal calculation. Temperature-parametric feedback showed a systemic effect on electromagnetic results through an increase in R(T) and P(T), a shift in the B-H characteristics, and a decrease in the parameters of permanent magnets, which forms an additional gain loop for copper losses and changes the distribution of heat sources in iterations. Comparison of matching schemes on a set of 40 scenarios established a convergence range from 26/40 for a one-way transfer of "loss → heat" to 38/40 for an integrated multiphysical solution; a series-iterative two-way scheme provided 36/40 matching scenarios with typical stabilisation in 4-7 cycles (median 5), while co-modelling required 6-12 exchanges (median 8) and showed higher sensitivity to heat exchange parameters and contact resistances.

Thus, the results proved that the effective integration of CAD of electrical machines and apparatuses with multiphysical modelling is implemented through a standardised two-way circuit of coordination of electromagnetic and thermal models with normatively unified inputs, formalised data exchange interfaces, and temperature parameter updating. The best balance of accuracy, stability, and computational cost for design tasks provides sequential-iterative two-way matching, while integrated multiphysical calculation can be used as a reference for verification and modes with rigid thermal constraints. Further research should be aimed at expanding multi-domain cooling models, automated optimisation of design parameters in a connected circuit, and experimental validation of temperature-loss maps for various types of electrical machines and apparatuses.

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Інтеграція САПР електричних машин і апаратів із мультифізичним моделюванням: підхід до узгодження електромагнітних і теплових моделей

Анотація. Ізольоване використання електромагнітних або теплових розрахунків під час проєктування електричних машин і апаратів є суттєвим джерелом інженерних похибок, оскільки робочі режими формуються взаємопов'язаними польовими й тепловими процесами. Метою дослідження було обґрунтувати та формалізувати підхід до інтеграції автоматизованого проєктування з мультифізичним моделюванням через узгодження електромагнітної та теплової моделей у єдиному параметрично керованому контурі. Методологія ґрунтувалася на нормативно узгоджених режимах, умовах охолодження та температурних межах із двостороннім ітераційним зв'язуванням і просторово узгодженим перенесенням втрат у теплову модель з температурною корекцією властивостей матеріалів. У результаті сформовано спільну параметричну рамку входів, що забезпечує узгоджене трактування навантаження, охолодження, температурної прийнятності та енергетичної результативності. Формалізований двосторонній контур із критеріями збіжності забезпечив відтворювану стабілізацію температурних максимумів і сумарних втрат. Показано, що просторове картування складових втрат зберігає локальні зони перегріву, тоді як їх зведене перенесення згладжує температурне поле. Узгоджене моделювання встановило доменну стратифікацію нагріву: в обмотках близько 130-140 °C, у магнітопроводі 105-115 °C, у корпусі 85-95 °C, у зоні охолодження 60-70 °C. Температурні корекції електричних і магнітних параметрів суттєво змінюють розподіл втрат, насамперед через зростання опору провідників. Порівняння чотирьох схем узгодження на 40 сценаріях показало збіжність від 26 з 40 для одностороннього зв'язування до 38 з 40 для інтегрованого розв'язання; двостороння ітераційна схема забезпечила 36 з 40 зі стабілізацією за 4-7 циклів, тоді як покрокове спільне моделювання потребувало 6-12 обмінів. Практична значимість полягає у можливості безпосереднього використання підходу для підвищення точності теплових перевірок, вибору режимів навантаження та оптимізації конструктивних рішень електротехнічних виробів

Ключові слова: температурне поле; двосторонній контур; об'ємне джерело; ко-симуляція; теплові джерела; вихрові втрати