MBSE-Enabled Electromagnetic–Thermal–Control Co-Simulation for New Energy Vehicle Motor-Drive Systems: Framework, Numerical Evaluation, and Educational Application

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ABSTRACT Electromagnetic, thermal, and control interactions in new energy vehicle (NEV) motor-drive systems are often modeled and taught as domain-specific problems, which limits requirement traceability and obscures system-level trade-offs. This paper proposes a Model-Based Systems Engineering (MBSE)-based virtual co-simulation framework that links vehicle-level requirements with inverter, permanent-magnet synchronous motor (PMSM), field-oriented control, electromagnetic-loss, and cooling models through explicit interfaces and verification metrics. A temperature-dependent PMSM model is coupled with a lumped winding-hotspot thermal network, allowing stator resistance and permanent-magnet flux linkage to feed back into torque production, voltage demand, and loss prediction. Numerical evaluation was performed by comparing the temperature-coupled model with a fixed-parameter model under prescribed speed and load transitions and by examining cooling-path sensitivity. During the 20-s operating cycle, the coupled model predicted a winding-hotspot temperature of 54.31 °C and total modeled loss energy of 20.68 kJ, compared with 52.82 °C and 19.12 kJ for the fixed-parameter model. A 60-s sensitivity analysis further demonstrated the influence of cooling-path thermal resistance on hotspot temperature and loss accumulation. The framework was embedded in an NEV motor-drive course and assessed through a quasi-experimental cohort comparison. The intervention cohort achieved higher final-examination and overall course scores, whereas the difference in the existing practice-score measure was not statistically significant. Thus, the framework provides a traceable multi-domain co-simulation workflow for NEV motor-drive analysis and preliminary evidence of its educational applicability.

INDEX TERMS Model-Based Systems Engineering; Permanent-Magnet Synchronous Motor; Electromagnetic – Thermal Coupling; Field-Oriented Control; Multi-Domain Co-Simulation; New Energy Vehicle.

I. INTRODUCTION

NEW energy vehicle (NEV) motor-drive systems interact strongly with electromagnetic energy conversion, inverter operation, closed-loop control and thermal behavior. In a PMSM, stator current determines electromagnetic torque and loss generation and temperature rises the stator resistance and permanent magnet flux linkage. These parameters also influence voltage demand, torque capability, efficiency and thermal safety. A reliable motor-drive analysis is therefore dependent on the combination of electromagnetic, thermal, control and system-level requirements rather than independent analysis of individual subsystems [1]–[4].

Conventional simulation environments and virtual labs treat motor electromagnetic modeling, controller design, thermal analysis, and vehicle performance separately. Students or engineers may tune a field-oriented controller or interpret an efficiency map but cannot trace how electromagnetic loss, temperature-dependent parameters, inverter constraints and cooling capability interact together. Despite not having standard interfaces, it is difficult to trace inconsistent assumptions among subsystem models and check whether simulation evidence meets initial vehicle requirements.

Model-Based Systems Engineering (MBSE) can link requirements, system architecture, behavioral models, interfaces and verification evidence. Its formalization of model data between requirements, design, analysis, verification and validation can coordinate multidisciplinary motor drive development [5]. It can explicitly link vehicle torque and speed targets to inverter limits, PMSM electromagnetic behavior, control parameters, loss generation and cooling-system capability in parallel. The same traceable environment can also support virtual engineering education by allowing learners to study cross-domain parameter propagation and system tradeoffs.

We therefore do not propose a new electromagnetic solver or motor-control algorithm, but rather investigate how existing electromagnetic, thermal and control domain models can be integrated into a traceable MBSE virtual simulation workflow and applied in NEV motor-drive education.

RQ1: How can MBSE establish traceability between vehicle requirements, PMSM electromagnetic characteristics, inverter and control models, thermal constraints and system verification evidence?

RQ2: How can the MBSE-enabled co-simulation workflow be implemented in NEV motor-drive education, and what preliminary course-level outcomes are observed after its implementation?

This paper makes three contributions: first, we develop an MBSE architecture linking vehicle requirements to inverter, PMSM, control, loss, and thermal models through explicitly defined interfaces; second, we design a temperature-dependent electromagnetic–thermal–control co-simulation case and quantify parameter drift, loss accumulation, speed response, and cooling-path sensitivity; third, we embed the technical workflow into an NEV motor-drive course and examine its educational application through a quasi-experimental comparison of routinely recorded course outcomes.

II. RESEARCH GAP AND PROBLEM FORMULATION

The problem is not limited to multimedia teaching. At the technical level, NEV motor-drive analysis requires coordination between electromagnetic models, inverter models, and control models, thermal constraints, and vehicle performance requirements. When models are developed independently, differences in parameters, interfaces, assumptions and verification criteria can spread through the system and lead to inconsistent results about torque capacity, loss, temperature, efficiency and safety.

The automotive curriculum spans electrical engineering, mechanical engineering, materials science, thermal engineering, chemistry and intelligent control [6]–[12]. These fields differ in mathematical modeling, control design and performance measures. Simulation-based learning requires mathematical and computational preparation which is difficult to provide in conventional lectures in limited teaching hours. Many virtual simulation resources are discipline specific and provide little interoperability at the system level. Students may learn domain specific theory, but are not able to do integrated analysis or identify cross-domain conflicts (e.g., a lag between motor peak power, battery discharge, inverter limits, and cooling capability).

The research gap is defined as lack of traceable virtual simulation workflow linking system requirements, electromagnetic behavior, control actions, thermal feedback, and verification evidence. In this framework, MBSE is used as integration mechanism and PMSM electromagnetic–thermal–control co-simulation is used as main technical case, retaining educational platform and project implementation for its practical application.

III. MBSE-ENABLED CO-SIMULATION FRAMEWORK AND EDUCATIONAL IMPLEMENTATION

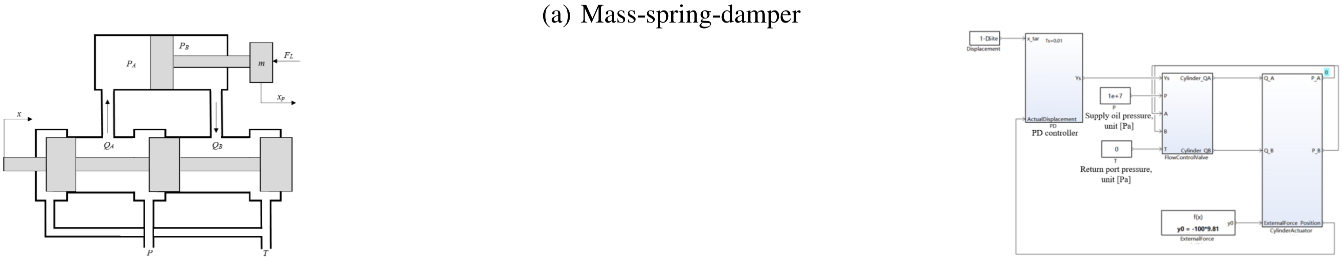
A. INTERDISCIPLINARY RESOURCE ARCHITECTURE AND COURSE INTEGRATION

According to this analysis, virtual simulation-based practical teaching system of NEV intelligent control technology has three main problems: interdisciplinary integration problems; limited number of teaching hours offline; a lack of high-quality virtual simulation resources. To overcome these problems we propose MBSE framework [13], and Global Crown Technology virtual simulation teaching platform for MBSE [14], integrating knowledge from electrical engineering, mechanical engineering, materials engineering and computer science. The four goals of construction scheme are the following: Building an interdisciplinarity knowledge system, an an open-source case repository, virtual simulation experiment projects, blended online-offline teaching model based on project-based learning, smart courses and AI-powered digital textbooks. One of the main goals is to use interactive and real-time feedback to help students solve technical problems faced by simulation tasks, enhance students' understanding, practical skills and innovative capabilities.

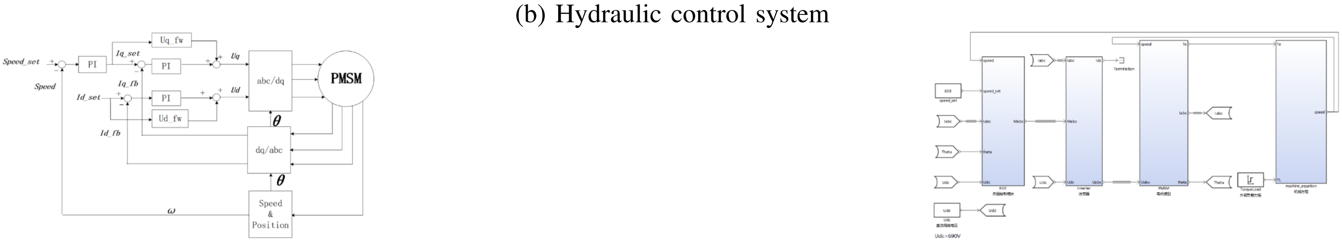
The two foundation courses in the proposed system are Fundamentals of Control Engineering and Fundamentals of New Energy Vehicle Technology. To avoid unnecessary resource development, simulation resources are divided according to shared-base and course-specific-extension. Fundamentals of Control Engineering focuses on basic control-oriented models (DC motor speed control, hydraulic control, stability analysis, basic multi-domain coupling examples), to allow students to learn modeling techniques, control design, and MBSE workflows. Fundamentals of New Energy Vehicle Technology builds on these basic models and applies them to system-level scenarios of NEVs such as battery management, motor-drive integration, thermal management, charging systems, NEV-level optimization. Thus, the two courses share the same resource base MBSE-GCKontrol, but have different learning goals.

The following are the main parts of MBSE process for the EV thermal management system. The thermal management project is used in this course in the context of multi-

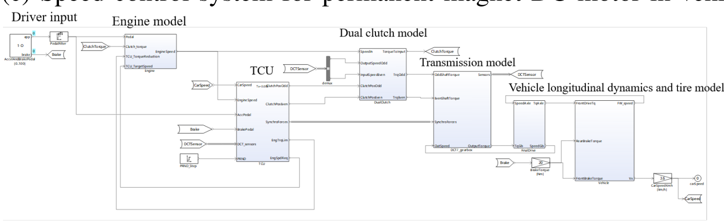
(a) Mass-spring-damper



(b) Hydraulic control system



(c) Speed control system for permanent magnet DC motor in vehicles



(d) Vehicle powertrain control system

Fig. 1. Foundational control-oriented simulation resources developed within the shared MBSE-GCKontrol resource base

domain modelling, PID controller design, stability analysis and system level verification.

Interdisciplinary Project Design

The Multi-physics Coupling Control for Electric Vehicle Thermal Management System project is divided into three areas: control engineering, thermodynamics and materials science. Students from different disciplines work together in teams to solve engineering problems such as battery thermal management, motor cooling control and cabin temperature control, vital for electric vehicle performance and safety.

Cross-Disciplinary Team Collaboration Protocol

Role Allocation Strategy

Student teams have defined roles to make full use of their disciplinary expertise:

Control System Engineer (Control Engineering majors): Design control algorithms, perform stability analyses and optimize system performance.

Thermal Management Specialist (Thermal Engineering majors): Specializes in heat transfer analysis, cooling system design and quantitative evaluation of thermal performance.

Materials Engineer (Materials Science majors): Assesses material characteristics, determines thermal properties, and identifies materials for thermal management.

Systems Integration Engineer: Interfaces with interdisciplinary teams, controls model integration processes and maintains consistency throughout the system.

Knowledge Integration Mechanism:

Weekly cross-disciplinary design reviews, with rotating team leadership to get all disciplines equally involved.

Shared model repositories with version control and change management capabilities to track changes and provide transparency.

Integrated simulation sessions with real-time collaboration functions, allowing team members to collaborate in different disciplines simultaneously and adjust at the same time.

A cross-mentoring system in which students share their domain knowledge with their teammates, to help them better understand the domain.

To map the curriculum for Cross-disciplinary modules:

The thermal management project is aligned with learning objectives from four key disciplines and knowledge is integrated:

Control Engineering: Design of PID control loops, system stability analysis and implementation of feedback control loops.

Thermodynamics: Principles of heat transfer, thermal system design and optimization of cooling efficiency.

Materials Science: Thermal properties of materials, selection of materials and use of thermal interface materials.

Electrical Engineering: Thermal characteristics of batteries, thermal management of electric motors, and cooling of power electronics.

Interdisciplinary Learning Outcomes:

Skill in considering thermal management needs from various disciplines.

Ability to develop integrated control strategies with regard to thermal and material limitations.

Experience with multi-physics simulation and validation of system performance.

Collaborative problem solving between disciplines.

The virtual-simulation teaching material library for virtual simulation has been built on Zhihuishu [15], which consists of multi-physics simulation software packages, cross-disciplinary practical teaching knowledge maps, teaching videos, comprehensive case study materials and adaptive assessment tools.

The teaching implementation is based on an improved BOPPPS framework, which has a cross-disciplinary focus, and is divided into three phases:

Pre-class Phase:

Learning tasks are designed as interdisciplinary team projects and assignments corresponding to the roles. Students use the virtual simulation case platform Zhihuishu to learn from their disciplinary knowledge and gain some understanding of the interfaces across different domains. MBSE-based pre-class activities include:

Role-specific preparatory materials and simulations

Cross-disciplinary reading assignments

Team-based problem formulation exercises

In-class Phase:

Classroom sessions prioritize integrated problem-solving using engineering cases developed through MBSE principles. A flipped classroom approach is adopted, featuring:

Cross-disciplinary design reviews with expert feedback from faculty members specializing in different disciplines.

Hands-on simulation workshops with real-time collaboration across disciplines

Case-based discussions centered on interface management and system-level optimization.

Peer teaching sessions where students explain key disciplinary concepts to teammates.

Post-class Phase:

Student teams complete comprehensive engineering assignments that require integrated virtual simulation modeling and performance testing across multiple domains. Post-class activities include:

Team-based simulation projects with integrated deliverables

Cross-disciplinary peer review activities

Reflective exercises on interdisciplinary collaboration experiences

Faculty mentoring sessions focused on addressing persistent challenges in model integration.

The teaching resources are supported by Global Crown Technology's GCKontrol Workbox, which provides multi-physics simulation capabilities. This supports the development of a virtual simulation-based practical teaching course in the online world emphasizes cross-disciplinary integration. Students develop theoretical knowledge, practical skills, collaborative capabilities, and systems thinking through systematic modeling approaches.

Table II illustrates that the first course introduces control models, interface specifications, and MBSE workflows with a common body of work, whereas the second course leverages the common body of work for NEV engineering scenarios by utilizing an AI-powered digital textbook. This helps to maintain continuity between courses and avoid repetition of simulation resources.

Interdisciplinary Project-Based Learning with Deep MBSE Integration:

It is a project in which student teams have to mimic a real engineering context and carry out the requirements analysis to the validation of the system.

Requirements Definition Phase:

Initially, student teams must collaboratively analyze project requirements, develop a requirements specification document, and clarify KPIs for the thermal management system. These KPIs include temperature control accuracy, response speed, and energy consumption. Teams also define requirements for distinct components such as the battery, motor, and cabin.

System Architecture Modeling Phase:

Control engineering, thermal management, materials science team members develop the system architecture model. Models describe the relationships and information exchange between sensors, controllers, actuators (pumps, valves, fans) and cooling circuits. Modeling tools and examples are provided by the AI-powered digital textbook.

Model Verification and Iteration:

Students from different disciplines develop high-fidelity discipline-specific sub-models (control algorithm models, thermo-fluidic models, material thermal property models) to simulate according to the unified architecture. Students compare simulation results with requirements and optimize their designs by iterating. For example, control engineering students tune PID parameters by taking thermal inertia of the system provided by thermal management students and limits of material temperature provided by materials science students.

CDTCP: Cross-Disciplinary Team Collaboration Protocol

TABLE I. Foundational Control-Oriented Simulation Resources and Learning Tasks in Fundamentals of Control Engineering

Chapter	Title	Key Knowledge Points	Learning Tasks	Resource Dependency	GCKontrol-Based Resources and Applications	Duration
I. Introduction to Control Systems	Fundamentals and Interdisciplinary Nature	Feedback mechanisms and their roles in automated control systems; systems-thinking fundamentals; interface characteristics among mechanical, electrical, and thermal subsystems; interdisciplinary design rationale in EV and robotic systems.	1. Analyze an automotive adaptive cruise control case and identify components across mechanical, electrical, and control domains. 2. Develop a high-level system architecture diagram showing information flow and energy flow across subsystem boundaries.	Partially platform-supported	Independent: case analysis and system architecture sketching. Platform-supported: interactive multi-physics vehicle-system demonstration using GCKontrol to visualize electrical inputs, mechanical outputs, and thermal effects.	25 min
II. Mathematical Foundations	Modeling of Multi-Domain Physical Systems	Differential-equation modeling of electromechanical and electro-thermal systems; Laplace-transform applications; block-diagram reduction; Mason's gain formula for multi-domain signal-flow analysis.	1. Derive the transfer function of a DC motor by integrating electrical circuit equations and mechanical load dynamics. 2. Construct and simplify a battery-system block diagram with electrical performance and thermal feedback loops.	Partially platform-supported	Independent: transfer-function derivation and block-diagram simplification. Platform-supported: electro-thermal model assembly and coupling-effect analysis using a multi-domain modeling module.	15 min
III. Time-Domain Analysis	Performance of Integrated Systems	Time-domain performance indicators, including rise time, settling time, overshoot, and steady-state error; influence of load torque fluctuation, thermal drift, and electrical noise on system response.	1. Simulate the step response of a coupled electromechanical system and evaluate rise time, overshoot, and settling time. 2. Calculate the steady-state error of a temperature-control system under electrical noise disturbance.	Partially platform-supported	Independent: analytical calculation of time-domain indicators. Platform-supported: time-domain simulation and performance visualization using GCKontrol-based response-analysis tools.	20 min
IV. Stability Analysis	Routh-Hurwitz and Root Locus for Complex Systems	Routh-Hurwitz stability criterion; root-locus analysis; stability margins under multi-domain parameter variation; effects of mechanical inertia and thermal lag on stable control gain ranges.	1. Use the Routh-Hurwitz criterion to determine the stable controller-gain range for a system with thermal lag. 2. Sketch the root locus of a position-control system and analyze the influence of mechanical inertia on pole distribution.	Partially platform-supported	Independent: Routh-Hurwitz calculation and root-locus sketching. Platform-supported: simulation-based validation of stability criteria and gain-margin changes using stability-analysis modules.	20 min
V. Control Design Methods	Interdisciplinary Control Strategies	PID controller design under multi-domain constraints; trade-offs among response speed, energy efficiency, thermal load, and mechanical wear; control co-design of physical systems and controllers.	1. Design a cooling-fan controller that balances battery temperature regulation and energy consumption. 2. Tune a PID controller for an electric power steering system while considering steering response and energy efficiency.	Platform-supported	Platform-supported: parameterized thermal-management control simulation, PID tuning, KPI tracking, and cross-domain trade-off analysis using GCKontrol.	30 min
VI. Frequency-Domain Analysis	Bode Analysis and System Bandwidth	Frequency-response characteristics of multi-domain systems; bandwidth limitations caused by mechanical inertia and thermal time constants; Bode-plot-based robust controller design.	1. Generate the Bode plot of a motor-driven system and identify dominant poles from electrical and mechanical components. 2. Design a lead compensator to meet target bandwidth while satisfying thermal-dissipation constraints.	Partially platform-supported	Independent: frequency-response interpretation and compensator-design calculation. Platform-supported: Bode-plot generation, resonance identification, and bandwidth validation using frequency-response simulation tools.	25 min
VII. Capstone Project	Complex System Integration and Validation	Systems Engineering V-model; MBSE-based requirement definition, interface management, model integration, and system-level verification; cross-domain KPI definition and validation.	1. Work in interdisciplinary teams to integrate battery, motor, vehicle-dynamics, and driver models into a full-vehicle simulation. 2. Define cross-domain KPIs and conduct validation tests against initial requirements.	Platform-dependent	Platform-dependent: full-vehicle simulation model library, requirement-traceability functions, subsystem-interface verification, and system-level validation using GCKontrol or equivalent vehicle-system simulation tools.	35 min

Allocate roles and responsibilities:

Control Engineering Specialists: They are responsible for developing models of the system, designing control algorithms and optimizing the performance of the thermal management system.

Thermal Management Engineers: Analyze heat transfer, design cooling systems, evaluate thermal performance.

Material Science Experts: Responsible for material selection for system components, material thermal property analysis and optimization of thermal interface materials.

Systems Integration Leaders: Responsible for coordinating interdisciplinary interfaces, and for maintaining system-level consistency throughout the project life cycle.

Knowledge Integration Framework:

Cross-disciplinary design review meetings, with a rotating leadership role, once a week.

Version control and configuration management-enabled shared model repositories.

Collaborative real-time tools, integrated simulation.

Inter-disciplinary cross-mentoring systems for knowledge sharing.

Seamless collaboration tools within the AI-powered textbook platform for easy communication.

The teacher(s) will complete a Curriculum Mapping document for each Interdisciplinary Module.

The thermal management project encompasses learning objectives from the following disciplines:

Control Engineering: Design of PID control systems, system stability analysis, and feedback control system design.

Thermodynamics: Principles of heat transfer, design of thermal systems, and optimization of cooling efficiency.

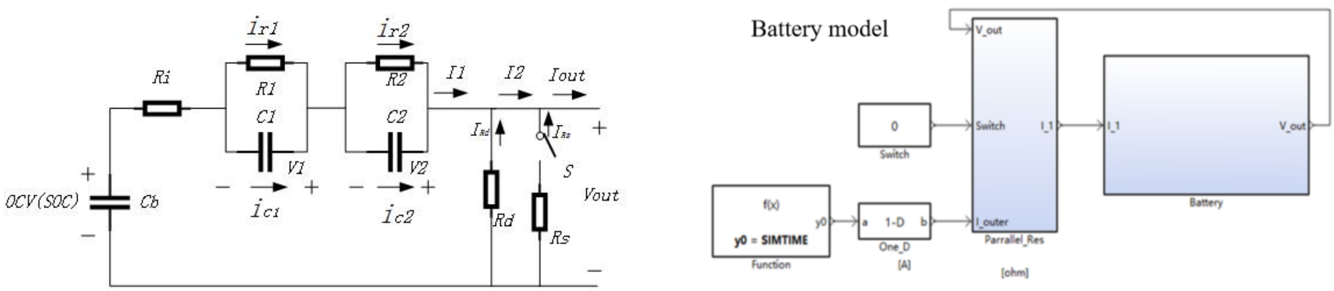
Materials Science: Analysis of material thermal properties, criteria for material selection, and application of thermal interface materials.

Systems Engineering: Management of project requirements, control of system interfaces, and execution of verification and validation processes.

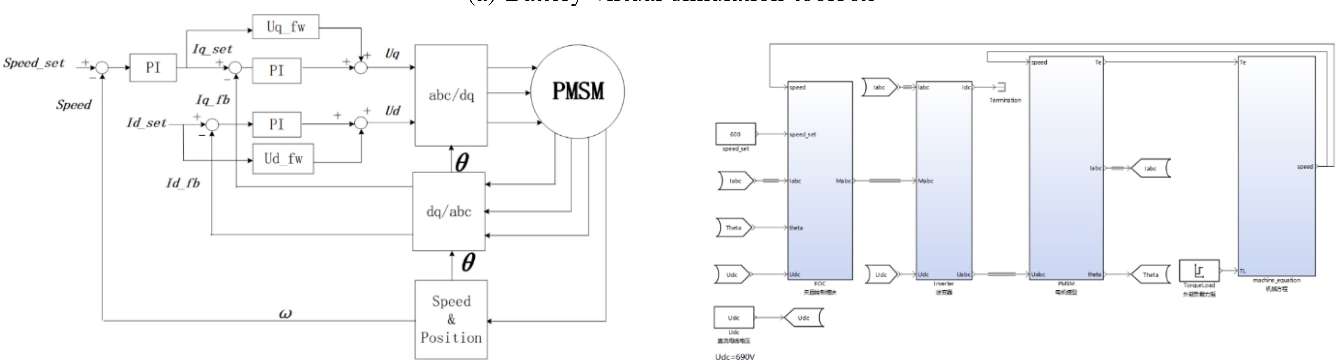
Contextualized BOPPPS Implementation for the NEV Thermal Management Project

TABLE II. NEV-Specific Simulation Resource Extensions and Learning Tasks in Fundamentals of New Energy Vehicle Technology

Resource category	Role in Fundamentals of Control Engineering	Role in Fundamentals of New Energy Vehicle Technology	Relationship between the two courses	Redundancy-control strategy
Basic control models	Used to teach transfer functions, PID control, stability analysis, frequency response, and time-domain performance.	Reused as prerequisite control blocks in NEV subsystems such as motor control, battery thermal control, and charging control.	Foundational-to-applied relationship	Develop once in Section 3.1 and reuse in Section 3.2 with NEV-specific parameters.
DC motor speed-control model	Used as a representative electromechanical control example for controller design and response analysis.	Extended to NEV motor-drive scenarios with efficiency, thermal, and drive-cycle constraints.	Model reuse and contextual extension	Shared motor-control model; only application scenarios and constraints are modified.
Multi-domain coupling model	Used to introduce interactions among electrical, mechanical, and thermal domains.	Applied to battery-pack thermal management, motor cooling, and full-vehicle energy management.	Conceptual and technical extension	Reuse interface definitions and coupling logic; add NEV subsystem data.
MBSE workflow resources	Used to teach requirements definition, architecture modeling, model verification, and traceability.	Applied to NEV system-level projects, including battery, motor, thermal, and vehicle architecture integration.	Methodological continuity	Common MBSE workflow templates are shared across both courses.
Thermal management case	Used as a control-oriented example for multi-physics control and system validation.	Used as an NEV-specific comprehensive project involving battery, motor, cabin, and material constraints.	Same case, different learning focus	3.1 emphasizes control logic; 3.2 emphasizes vehicle-system application and interdisciplinary design.
AI digital textbook resources	Not the main resource carrier; used only as supplementary guidance if needed.	Serves as the main organizing carrier for NEV-specific cases, adaptive learning, and extended project materials.	Course-specific extension	AI textbook organizes and extends shared models rather than rebuilding them.
Full-vehicle simulation resources	Introduced only as a capstone or demonstration case for system-level thinking.	Used as the main application environment for vehicle-level optimization and validation.	Progressive deepening	Basic exposure in 3.1; full application and assessment in 3.2.



(a) Battery virtual simulation toolbox



(b) Speed control toolbox for permanent magnet DC motors in vehicles

Fig. 2. NEV-specific simulation resources extended from the shared MBSE-GCKontrol resource base

The enhanced BOPPPS framework is implemented in this course through a three-phase instructional process that corresponds to the six BOPPPS components shown in Figure 3.

Pre-class Phase: Bridge-in, Objective, and Pre-assessment.

Bridge-in students experience real NEV engineering scenarios such as battery thermal runaway, motor cooling conflict, cabin thermal comfort, and energy-efficiency tradeoff. Simulation cases are presented in the AI-powered digital textbook, Zhihuishu MOOC, and virtual simulation cases. Objective students learn measurable learning outcomes such as MBSE-based requirement definition, thermal management system architecture modeling, multi-domain simulation and system verification. Pre-assessment students complete online quizzes, role-specific preparatory tasks, and preliminary simulation exercises to test their prior knowledge of control engineering, thermodynamics, materials science and NEV systems.

In-class Phase: Participatory Learning.

Participatory Learning is based around team modeling and simulation tasks. Using GCKontrol and the AI-powered digital textbook students build thermal management models, subsystem interfaces, control parameters, cross-disciplinary design reviews. Classroom exercises include team presentations, simulation exercises, peer teaching, instructor-led lessons on interface management, system tradeoffs and model verification.

Post-class Phase: Post-assessment, Summary.

The students present simulation reports, project deliverables, and system validation results in Post-assessment stage. Artifacts are assessed on technical correctness, quality of model integration, collaboration and engineering feasibility. In Summary stage, students practice reflections about implementation of MBSE, collaboration between disciplines, value-oriented engineering decisions and constraints of their technical solutions. In this stage students will develop systems thinking and ready for future car optimization tasks.

Interdisciplinary Learning Assessment:

The assessment system includes:

Group project assignments that evaluate individual disciplinary work and system performance.

Multidisciplinary collaboration and knowledge sharing effectiveness assessment from peers.

Systems thinking demonstrated through cross-disciplinary design reviews and presentations.

Integrated system validation exercises requiring multidisciplinary inputs for comprehensive validation.

Value-oriented learning activities are integrated in the project learning activities throughout the course, without being presented as ideology. Students learn about social and strategic importance of engineering innovation by discussing case studies for NEV industry development, carbon-neutrality targets, connected vehicle technology connecting drivers, vehicles, and infrastructure. For thermal management project, students study safety hazards in battery thermal runaway and design faulttolerant control methods, which improve students engineering responsibilities and safety consciousness. Students are required to document the technical solutions they developed in interteam projects addressing energy efficiency, environmental impact, and practical applications. Reflections, simulation reports, peer evaluations, project presentations, etc. document the process and evidence for later evaluation of the integration of technical learning and value-oriented education. Table III. Case resources, project tasks and learning materials are distributed through AI digital textbook, Zhihuishu MOOC, SPOC systems. Corresponding resources are launched through the AI digital textbook system, Zhihuishu MOOC, and SPOC system, aiming for the coordinated construction of technical ability and value-oriented awareness.

B. ADVANCED MULTIMEDIA INTEGRATION

Both courses work on the same MBSE–GCKontrol resource base. The control course establishes reuse models and MBSE workflows while the NEV course extends these resources through AI driven digital textbooks and system-level projects. This approach reduces redundant resource construction and supports learning from control theory to NEV integration.

1) Current Limitations

Most of the time multimedia content is one way. It is used as video lectures, readable documents, static simulation demonstrations, and it lacks dynamic responsiveness and adaptive personalization. Virtual simulations are used, but often only a demonstration of basic operation and are only valid at fixed parameters values. They are not enough to support interactive inquiry (multivariable sensitivity analysis, system fault injection, etc.) for real-world engineering systems.

2) Proposed Enhancements

The system will feature advanced functionality for providing a smart interactive learning environment, rather than a resource delivery system, including the following:

Advanced Functions of AI-Powered Digital Textbooks

The AI digital textbook introduced in the preceding resource design will be improved to break free from the traditional e-book model and be deeply integrated with the adaptive learning system and interactive simulation:

Adaptive Content Personalization (Behavior-Triggered Content Delivery):

The textbook will adjust depth of content and level of content depending on interaction data (time on task, simulation attempts, errors, quiz performance). If a student has trouble with a particular battery thermal management system, for example, then the system will automatically send out other micro-lectures, hints, or case studies that take the student from basic level strategies to advanced strategies. Also, the algorithm for content recommendation will be tailored to learning styles (visual, kinesthetic) and will be personalized in the type of multimedia resources (animations, interactive graphs, virtual labs).

Embedded Interactive Simulations (Parametric Modeling in Textual Content):

GCKontrol simulation tools will be embedded in the textual content of the textbook. This allows students to model and simulate parameters without changing context. In interactive module, for instance, one explanation of a permanent magnet DC motor speed control will be included, so students can change the PID or load torque parameters directly in

TABLE III. Interdisciplinary NEV Course with Technical Simulation Resource Specifications

Chapter	Title	Key Knowledge Points	Learning Tasks	Interdisciplinary Focus	Technical Specification of Simulation Resources	Teaching Applications
Ch. 1 1hr	Introduction to NEVs: Overview and Development	Classification of NEVs by power source and system configuration; global energy-transition trends; NEV policy frameworks; environmental impact and sustainability indicators.	1. Classify BEV, HEV, PHEV, and FCV architectures. 2. Identify subsystem connections among powertrain, thermal management, and control systems. 3. Evaluate CO_2-reduction effects under different NEV adoption scenarios.	Technology–Policy–Economics Nexus: NEV development is shaped by policy, market demand, environmental constraints, and engineering innovation.	Interactive 3D NEV classification module with selectable BEV, HEV, PHEV, and FCV architectures; visualized power-flow paths; subsystem-function mapping; configurable environmental-impact parameters.	Pre-class: students explore NEV architectures using the interactive 3D module. In class: instructors compare international NEV policies and technical pathways. Hands-on: students simulate CO_2-reduction scenarios under different adoption assumptions.
Ch. 2 5hrs	EV Power Batteries: Battery Technologies and BMS	Electrochemical properties of battery chemistries; battery performance indicators; BMS functions; SOC/SOH estimation; aging mechanisms; thermal runaway and safety constraints.	1. Compare battery chemistries and performance limitations. 2. Design BMS algorithms for SOC estimation, thermal control, and safety protection. 3. Analyze battery aging and conduct fault-diagnosis simulation.	Electro-Chemo-Thermo-Mechanical Integration: Battery packs integrate electrochemistry, thermal management, mechanical packaging, and control algorithms.	Electro-thermal coupled battery-pack simulation module with SOC/SOH estimation, temperature-field visualization, thermal-runaway scenario modeling, aging-parameter tracking, and fault-diagnosis functions.	Lecture: demonstrate battery thermal runaway and aging effects. Hands-on: students design BMS control strategies under thermal and aging constraints. Project: students optimize battery-pack configuration for a specific vehicle application.
Ch. 3 7hrs	EV Motor Drive System: Motor Technologies	Electromagnetic principles of PMSM and induction motors; motor-control characteristics; torque-speed curves; Field-Oriented Control (FOC); Direct Torque Control (DTC); thermal and acoustic constraints.	1. Analyze the suitability of different motor types for NEV applications. 2. Develop motor-control strategies that coordinate torque delivery and thermal management. 3. Optimize FOC parameters under efficiency and temperature constraints.	Electromagnetic–Thermal–Acoustic–Control Co-Design: Motor-drive design requires simultaneous consideration of electromagnetic torque, cooling, vibration/noise, and control performance.	PMSM motor-drive co-simulation module integrating electromagnetic torque calculation, inverter-control logic, thermal-load estimation, acoustic-noise analysis, efficiency-map modeling, and HIL-compatible controller-testing interfaces.	Lecture: explain acoustic noise and thermal effects in motor drives. Hands-on: students tune FOC parameters and observe efficiency-temperature trade-offs. Project: teams compete to optimize torque density, efficiency, and thermal safety.
Ch. 4 3hrs	Pure Electric Vehicles: Structure and Design	Vehicle-level powertrain architecture; power battery and motor matching; chassis and energy-storage integration; MBSE-based requirement flow-down; multi-objective optimization.	1. Develop a vehicle-level architecture aligned with MBSE principles. 2. Match motor, battery, and transmission parameters according to performance targets. 3. Resolve conflicting design requirements through multi-objective optimization.	MBSE as the Integrative Framework: MBSE manages requirement decomposition, subsystem interfaces, trade-off analysis, and system-level validation.	MBSE-based vehicle-system optimization module supporting requirement traceability, parameter-sweep analysis, motor-battery-transmission matching, multi-objective optimization, and subsystem-interface verification.	Lecture: demonstrate requirement flow-down from vehicle-level targets to subsystem specifications. Hands-on: students design complete EV architectures. Project: teams run full-vehicle simulations under different driving conditions.
Ch. 5 7hrs	Hybrid Electric Vehicles: HEV Technologies	HEV architectures; operating modes; power-split strategies; rule-based, optimization-based, and learning-based energy-management methods; fuel economy and emissions evaluation.	1. Compare HEV configurations and operating modes. 2. Develop energy-management strategies under driving-cycle constraints. 3. Evaluate fuel economy, emissions, and dynamic performance.	Optimal Control Across Energy Domains: HEVs require coordinated power distribution between fuel and electric energy sources.	HEV energy-management simulation module with engine-motor power-split modeling, battery SOC tracking, driving-cycle simulation, Model Predictive Control (MPC) testing, and real-time control-interface capability.	Lecture: compare HEV configurations using operational data. Hands-on: students implement energy-management strategies with MPC. Project: teams optimize HEV control strategies for specific driving patterns.
Ch. 6 3hrs	Fuel Cell Vehicles: FCV Technologies	Fuel-cell electrochemistry; hydrogen supply; air-management systems; thermal management; high-power electronics; hydrogen safety and failure-mode analysis.	1. Analyze fuel-cell system components and integration challenges. 2. Develop hydrogen-supply and air-management control strategies. 3. Conduct virtual validation of hydrogen-safety scenarios and fault responses.	Electro-Chemical–Thermal–Safety Engineering: FCVs integrate electrochemistry, fluid dynamics, thermal management, power electronics, and safety engineering.	FCV system simulation module with hydrogen-supply control, air-management modeling, stack-efficiency calculation, thermal-response simulation, hydrogen-leakage scenario modeling, and fault-response validation.	Lecture: demonstrate FCV transient response and efficiency characteristics. Hands-on: students develop FCV control strategies under variable load conditions. Project: teams design safety systems and emergency-response procedures.
Ch. 7 2hrs	Charging Technology: Charging Systems	Charging standards; charging infrastructure; smart charging; grid constraints; user behavior; interoperability; V2G/V2X concepts.	1. Analyze charging-system performance and compatibility. 2. Develop smart-charging strategies considering grid load and user demand. 3. Evaluate Vehicle-to-Grid business and technical scenarios.	Vehicle–Grid–User Interface: Charging systems link vehicle batteries, on-board chargers, power grids, and user behavior.	Charging-system simulation module with grid-load modeling, charging-power scheduling, user-demand parameterization, charger-vehicle compatibility testing, and V2G energy-flow simulation.	Lecture: compare NEV charging standards and infrastructure deployment. Hands-on: students design smart-charging algorithms. Project: teams develop a V2G implementation plan and evaluate technical feasibility.
Ch. 8 9hrs	New Technologies: Emerging Technologies	Autonomous driving; vehicle connectivity; cybersecurity; intelligent control; V2X communication; functional safety; system reliability.	1. Design integrated architectures combining perception, decision-making, and control subsystems. 2. Evaluate safety, cybersecurity, and reliability impacts using virtual scenarios. 3. Conduct fault-injection and functional-safety validation.	Cyber-Physical System Challenge: Autonomous and connected NEVs integrate automotive engineering, software, AI, communication networks, cybersecurity, and ethics.	Autonomous-driving scenario simulation module with sensor-perception modeling, decision-control interface testing, V2X communication scenarios, cybersecurity-risk simulation, fault-injection functions, and functional-safety validation.	Lecture: demonstrate autonomous-driving scenarios and functional-safety analysis. Hands-on: students test perception-control interactions. Project: teams design an autonomous-driving function and prepare a safety case.

the text, and see the output response (speed and current) immediately.

Advanced GCKontrol Applications in Problem-Based Learning (PBL)

The capabilities of the GCKontrol platform will be extended to higher-order inquiry in PBL projects, going beyond just operational demonstration, to enable in-depth engineering analysis:

Multivariable Sensitivity Analysis:

Students will use GCKontrol's DOE and optimization toolboxes in an interdisciplinary project such as designing a thermal management system for an electric vehicle. They will set different input variables such as coolant flow rate, ambient temperature, control gains, batch simulations, or optimization algorithms (e.g. genetic algorithms). This allows them to quickly assess what effect each variable has on performance parameters such as maximum temperature and energy efficiency, and learn design parameters, coupling effects in different domains, and skills in system optimization and data-driven decision making.

System fault mode test:

User-defined fault injection scenarios will be run on the platform in real-life systems. Students can intentionally inject faults (e.g. sensor loss, actuator saturation, battery performance degradation) to powertrain or thermal management system models and see how the system behaves when fault occurs and prove faulttolerant control strategies. This practice helps them understand vulnerabilities of the system, fault propagation mechanisms, reliability design principles, and general engineering safety awareness.

The enhancements to multimedia integration make learning easier, more exploratory and more personal. This framework provides technology for traceable co-simulation in Section 3.3 and online–offline project implementation in Section 3.4 in order to develop inter-disciplinary innovation skills.

To make explicit the technical implementation of shared MBSE–GCKontrol resource base, this section formally formalizes PMSM drive case as electromagnetic–thermal–

control co-simulation workflow. The numerical reference implementation used in Section 4.1 is written in MATLAB. Model structure, interfaces and verification metrics are organized so that the workflow can be transferred to MBSE–GCKontrol teaching environment and binds previous multimedia and problem-based learning functions to traceable engineering models, parameters and verification metrics.

C. MBSE-ENABLED ELECTROMAGNETIC–THERMAL–CONTROL CO-SIMULATION OF THE PMSM DRIVE

To direct technical connection between the learning approach and electromagnetic system analysis, a permanent magnet synchronous motor (PMSM) drive was chosen as cross-domain case. The model is organized according to the requirement–architecture–behavior–verification chain. Vehicle torque and speed requirements are allocated to inverter, PMSM, controller and cooling subsystems; signals, units, parameter sources and validation metrics are kept as traceable model interfaces. The case cannot only be visual demonstration of motor operation, but also quantitative investigation of electromagnetic torque production, temperature-dependent parameters, loss generation, cooling-path constraints and closed-loop control performance. This requirement–architecture–behavior–verification organization is consistent with MBSE practice and coupled electro-thermal analysis for EV motor drives [1], [5].

1) Electromagnetic and Mechanical Model

The PMSM is represented in the rotor-oriented d–q reference frame. The electrical dynamics are expressed as

$$v_d = R_s(T_w)i_d + L_d\frac{di_d}{dt} - \omega_e L_q i_q \tag{1}$$

$$v_q = R_s(T_w)i_q + L_q\frac{di_q}{dt} + \omega_e\left[L_d i_d + \psi_f(T_w)\right] \tag{2}$$

where v_d and v_q are the d- and q-axis stator voltages, i_d and i_q are the currents, L_d and L_q are the synchronous inductances, R_s is the temperature-dependent stator resistance, ψ_f is the permanent magnet flux linkage, $\omega_e = p\omega_m$ is the electrical angular speed of p pole pairs. Electromagnetic torque and mechanical properties are

$$T_e = \frac{3}{2}p\left[\psi_f(T_w)i_q + (L_d - L_q)i_d i_q\right] \tag{3}$$

$$J\frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \tag{4}$$

where J is the lumped inertia, B is the viscous coefficient, and T_L is the external load torque. Q-axis current is controlled by the outer speed loop, and d-axis reference zero in the non-field weakening region. Inner proportional–integral current controllers are the standard d–q decoupling terms and DC-link voltage-vector limit.

2) Electromagnetic Loss and Thermal Feedback Model

The electromagnetic model is coupled to a lumped winding-hotspot thermal network. Copper loss is calculated from d–q current magnitude, and a reduced iron-loss term is used to preserve the principal speed- and flux-dependent effect without introducing a computationally expensive finite element solver into each teaching iteration. Lumped-parameter thermal networks and coupled electro-thermal models are widely used to relate machine losses, cooling paths and hotspot temperature [1]–[3].

$$P_{cu} = \frac{3}{2}R_s(T_w)\left(i_d^2 + i_q^2\right) \tag{5}$$

$$P_{fe} = k_{fe}\omega_e^2\psi_f^2 \tag{6}$$

$$C_{th}\frac{dT_w}{dt} = P_{cu} + P_{fe} + P_{stray} - \frac{T_w - T_{amb}}{R_{th}} \tag{7}$$

Here, T_w is the winding-hotspot temperature, T_{amb} is the coolant or ambient temperature, R_{th} and C_{th} are the equivalent thermal resistance and capacitance, and P_{stray} is a lumped term representing inverter and mechanical losses. Temperature feedback to the electromagnetic subsystem is represented by

$$R_s(T_w) = R_{s0}\left[1 + \alpha_{Cu}(T_w - T_0)\right] \tag{8}$$

$$\psi_f(T_w) = \psi_{f0}\left[1 + \alpha_{PM}(T_w - T_0)\right] \tag{9}$$

This bidirectional coupling makes this case suitable for studying a technically important feedback path: electromagnetic current produces heat, temperature alters resistance and magnet flux, voltage demand, torque production and loss change. In the MBSE model, these relationships are explicitly mapped to speed-tracking accuracy, current limit, maximum winding temperature, loss energy, cooling-system capability. Temperature-dependent flux linkage and resistance play important roles in maintaining torque and parameters accuracy in EV-oriented PMSM [4].

3) Simulation Conditions and Verification Metrics

A reproducible numerical case has been implemented in MATLAB using averaged inverter and cascaded field-oriented control structure. Speed commands from 0 to 3200 r/min and load transitions from 0 to 110 Nm are executed. Two models were tested (i) coupled model R_s and ψ_f changing with temperature, (ii) fixed parameter model. Another parameter study varied cooling path thermal resistance from 0.08 to 0.18 K/W. The representative values are shown in Table IV and are used to define a teaching benchmark and must be replaced by the parameters mentioned when hardware-level validation is claimed. MATLAB is used as numerical verification environment for the results reported in Section 4.1, and GCKontrol is used as implementation environment in Section 3.4.

At the technical level, we implement it in teaching the framework online–offline virtual simulation described below. The numerical results in Section 4.1 are generated in

TABLE IV. Representative parameters of the PMSM electromagnetic–thermal–control case

Parameter	Symbol	Unit	Value
Pole pairs	p	–	4
Stator resistance at 25 °C	R_{s0}	Ω	0.025
d-axis inductance	L_d	mH	0.35
q-axis inductance	L_q	mH	0.55
PM flux linkage at 25 °C	ψ_{f0}	Wb	0.11
DC-link voltage	V_{dc}	V	360
Current limit	I_{max}	A	260
Equivalent inertia	J	kg·m^2	0.08
Ambient/coolant temperature	T_{amb}	°C	35
Hotspot thermal capacitance	C_{th}	J/K	1000
Baseline thermal resistance	R_{th}	K/W	0.12

MATLAB, while the model construction, parameter analysis and verification results are mapped to MBSE–GCKontrol teaching workflow described in Section 3.4, so that technical and educational implementations are traceable. Appendix A lists the system-level PEV implementation.

D. EDUCATIONAL IMPLEMENTATION OF THE MBSE-ENABLED VIRTUAL SIMULATION FRAMEWORK

This implementation builds on the multimedia integration and PMSM co-simulation framework described in Sections 3.2 and 3.3 and uses Global Crown Technology's MBSE-enabled digital-twin technology. The PMSM numerical case described in Section 4.1 is evaluated in MATLAB and MBSE–GCKontrol environment is used for teaching-resource integration, collaboration modeling and project-based exploration. It builds and releases integrated digital virtual-simulation teaching resources on Zhihuishu platform. Its goal is to create a complete teaching system that combines modern teaching methods and advanced technology. It is based on BOPPPS (Bridge-In, Objective, Pre-assessment, Participatory Learning, Post-assessment, Summary) instructional model and Outcome Based Education and emphasizes project-based learning. This is not technical training; rather it creates a whole educational environment which prepares students to deal with engineering problems in the rapidly changing NEV industry.

Since this study focuses on technical learning result and students' competence, value-oriented component is presented as a way to design and implement a course and not as a completely proven result (see Table V). It is not meant to be an exhaustive study of teaching activities, learning products and assessment targets of value-oriented education, but identifies some and recognizes that value-oriented education will be evaluated in future versions.

1) Comprehensive Integration of the BOPPPS Framework in Virtual Simulation Teaching

Each teaching unit is organized in the BOPPPS framework. Students can learn thoroughly and effectively through virtual simulations. The elements of this system framework are well implemented to ensure the effectiveness of virtual simulation teaching systems:

Virtual simulation modules open with engineering scenarios (bridge-in). Examples include BMS failures or NEV motor control problems. The situations that are provided through the use of multimedia link theory and practice, involve students and show the interdisciplinary nature of the field.

Learning goals are clear and quantifiable for each simulation project. Learning goals focus on a person using skills in the application area rather than learning them. Learning results are guaranteed to meet industry requirements for NEV professionals. Learning goals are communicated to students at the beginning of each module.

Students take pre-assessments prior to each virtual simulation session. They also carry out preliminary simulation activities on the platform. This allows teachers to pinpoint gaps in knowledge from one subject area to another and provide appropriate instruction for students who have varying academic backgrounds.

Participatory Learning:

The center of the teaching part is based on the GCKontrol platform of Global Crown Technology that allows the collaboration modeling and simulation of engineering problems. Students solve complex engineering problems working together, go through the whole systems engineering process, design a model, and analyze its performance. This collaborative process is embodied by the BOPPPS component Participatory Learning.

Post-assessment:

After completing simulation activities, students are assessed in real-time through the platform's built-in assessment system. These assessments provide on-time feedback on learning outcomes. Specifically, they assess students' ability to combine interdisciplinary knowledge and apply it to real-life situations.

Summary:

Each session ends with reflections which allow the teacher and student to "summarise" the learning session. This summarizes learning objectives, focuses on the relation of interrelated knowledge and helps students build their understanding of systems thinking, which is important for systems engineering.

2) Systematic Implementation of the OBE Concept in Teaching Evaluation

The teaching evaluation system has been well embedded in the OBE concept. This integration makes sure that all pedagogical activities and technologies are geared towards training specific skills that match students' learning needs and industry needs.

Comprehensive Assessment Framework:

The assessment of students' ability to apply knowledge that links the disciplines to real simulation scenarios and exhibit new problem solving skills. The outcomes approach links simulation activities to desired learning outcomes and ensures that the evaluation matches learning outcomes.

Industry Aligned Competencies:

TABLE V. Implementation Pathway and Teaching Evidence of Value-Oriented Education

Value-oriented objective	Teaching implementation	Learning artifact	Observable evidence of integration	Assessment indicator
Understanding the strategic significance of NEV development	Case discussion on China's NEV industry development, carbon-neutrality goals, and intelligent connected vehicle technologies	Individual reflection report or group discussion record	Reflection prompts requiring students to explain how NEV technologies contribute to green development, carbon neutrality, and national industrial strategy	Ability to explain the relationship among NEV technology, green development, and national industrial strategy
Engineering responsibility and safety awareness	Fault-injection simulation involving battery thermal runaway, sensor failure, or motor-control instability	Fault-analysis report and safety-control proposal	Fault-analysis worksheets documenting risk identification, failure propagation, safety consequences, and proposed fault-tolerant control measures	Identification of safety risks, ethical responsibility, and engineering mitigation measures
Innovation spirit	MBSE-based interdisciplinary project requiring students to propose improved control or energy-management strategies	Project proposal, simulation model, and optimization report	Project reports containing alternative technical schemes, simulation-based validation results, and justification of innovative design decisions	Novelty, feasibility, interdisciplinary integration, and evidence-based validation
Collaborative responsibility	Cross-disciplinary team roles and rotating design-review leadership	Peer evaluation and team contribution record	Peer-evaluation forms documenting role fulfillment, contribution quality, communication effectiveness, and responsibility sharing	Quality of collaboration, communication, and responsibility sharing
Environmental and social responsibility	Simulation comparison of energy consumption, CO_2 reduction, and vehicle efficiency under different technical schemes	Sustainability analysis section in project report	Sustainability-analysis sections comparing energy consumption, CO_2 reduction potential, environmental trade-offs, and real-world feasibility	Ability to connect technical decisions with environmental impact and social value

Simulation tasks are designed to deal with real engineering problems in the NEV industry. This allows fair assessment of the professional readiness of the student and practical application to industry relevant situations. Industry focused skills can easily be applied to practical work situations.

Continuous Improvement Mechanism:
Assessment feedback is regularly reviewed to improve teaching methods and/or enhance the design of simulations. This process forms a continuous cycle of learning quality improvement, which will be adjusted according to the development of NEV industry and students' learning needs.

3) Synergistic Integration of Theoretical Frameworks and Technical Implementation

The use of the BOPPPS instructional model, along with the OBE and MBSE methodology creates a pedagogical-technical synergy that changes the concept of learning experiences. This integration is possible on several levels:

BOPPPS Model:
BOPPPS model is a model of teaching that can be used to create realistic high-fidelity simulation environments using MBSE technology that use each stage of instruction and use technologies for learning, not just for technology.

OBE for Targeted Competency Cultivation:
Targeted competencies cultivated with the OBE framework, the teaching method and technical tools are aligned with targeted competencies. This gives rise to a goal-oriented learning environment with the focus on skills training; the technological investments serve directly the attainment of predetermined learning outcomes.

Transformation of Active Learning:
It fosters the transition from passive transfer of information to the development of skills. The students develop understanding through a hands-on problem-solving process in dynamic virtual environments that represent both BOPPPS and OBE. This process connects the theoretical knowledge with the practical engineering application.

This method allows students from different fields to use their particular knowledge and skills and consider simulation tools for new engineering design. It improves learning and eliminates the lack of real engineering case studies in traditional teaching models. Figure 3 is therefore not a resource framework but an integrated instructional logic. The BOPPPS components of Figure 3 are not used as generic instruction model but are modeled in Section 3.1 by NEV thermal management project. Each component is associated with specific AI textbook resources, GCKontrol simulation tasks and interdisciplinary learning artifacts.

The course is systematic with a closed-loop teaching process that is in line with the "Golden Course" and based on the integrated BOPPPS-OBE framework [16]–[19]. This process combines learning condition analysis, online pre-assessment, interactive immersive learning, multi-dimensional assessment, and cycles of continuous improvement.

For the overall instructional design, a blended multi-dimensional and multi-level teaching resource system has been constructed to support it, as shown in Figure 3. This system comprises:

Paper-based and Electronic Teaching Resources: These include textual materials, selected electronic resources, Flash animations, virtual simulation resources, engineering cases and reference documents;

Teaching File: This includes Course Syllabus, Course Requirements, Experiment instructions and Course Directions;

Writing Process Tools: Including PPT/Flash presentations, virtual experiments, course videos, online tutorials and other auxiliary resources;

Interactive Evaluation Mechanisms: Assignments, Tests, Online exam question bank, Problem discussion and Interactive Q&A sessions;

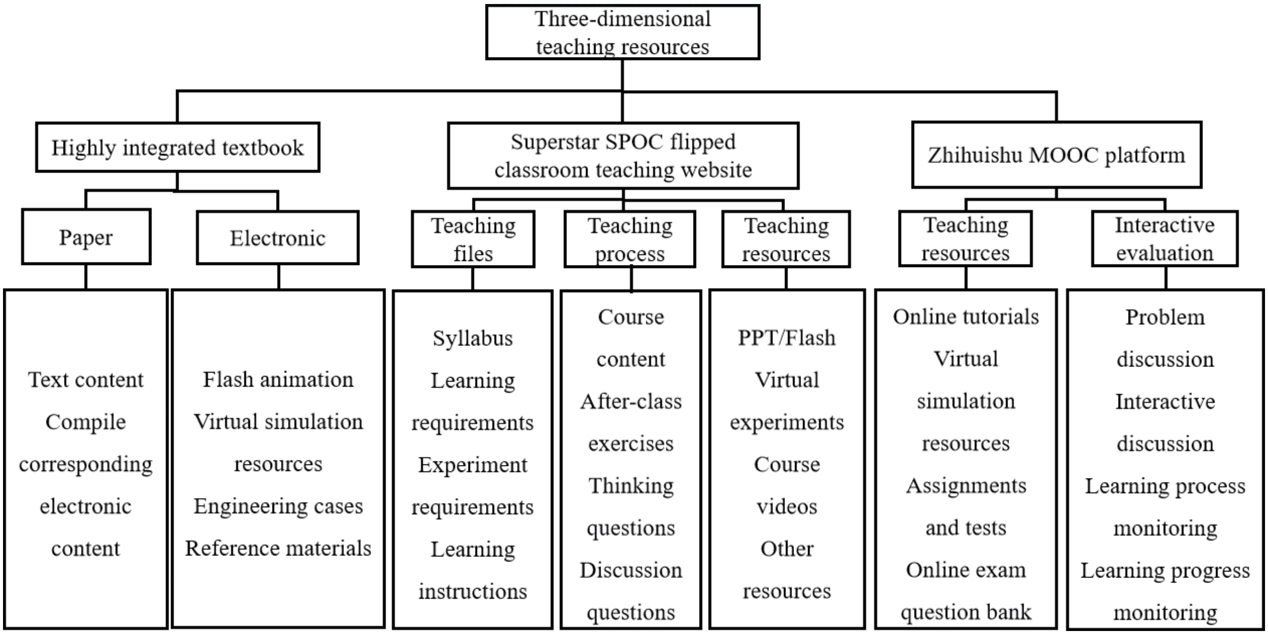


Fig. 3. Construction of blended multi-dimensional and multi-level teaching resources

Learning Process Monitoring Functions: Monitoring of student progress and involvement with instructional content. They are provided through the integrated platforms such as the highly interactive digital textbook, the SPOC flipped classroom website, and the Zhihuishu MOOC platform. They are both strong supports for all the instructional activities.

The teaching model is implemented by following the teaching path of blended teaching as shown in Figure 4, which is divided into three continuous parts: teaching design stage, interactive stage of flipped learning, and multi-dimensional evaluation stage. It will be implemented in the following steps:

① Pre-class Phase (BOPPPS Bridge-in, Objective, Pre-assessment Phases):

This phase is similar to the foundation & design phase in Fig. 4. Knowledge review, clarifying learning objectives, identifying key and difficult concepts and knowledge pretest are given. Students are given preview tasks (i.e., quiz on the basics of virtual simulation and discussion of virtual simulation design). Through Zhihuishu, students can view the virtual simulation teaching cases (important part of electronic resources shown in Fig. 3) and access the virtual simulation exercise question bank (categorized under Interactive Evaluation in Fig. 3) to learn at their own pace. Utilizing the GCKontrol virtual simulation toolbox provided by Global Crown Technology, students of different majors can use their background and expertise to choose simulation resources appropriate for their interests and specialties.

② In-class Phase (BOPPPS Participatory Learning Phase):

This stage represents the "Flipped Classroom Interactive Immersive Learning" part of Figure 4, which is the offline part of the learning. Classroom sessions are organized around interactions between instructor and student (see Teaching Process section in Figure 3), comments, online tutoring, discussions on difficult concepts picked up in preview and practice. Classroom is a lively workshop consisting of an engineering case, student presentations, peer exchange and discussion, and simulations. These activities promote resource sharing, problem solving, and problem solving between teachers and students, in order to solve common problems encountered in virtual simulation modeling and testing.

③ Post-class Phase (BOPPPS Post-assessment and Summary Phases):

Students then have more challenging tasks after class such as virtual simulation modeling and performance testing on real engineering cases. They also watch common virtual simulation guidance videos regularly, and do virtual simulations through SPOC. These activities are part of the online learning track (Figure 4), which includes MOOC courses and online assignments. Using Interactive Evaluation and Learning Process Monitoring functions (Figure 3), instructors grade assignments, give online tutoring, hold discussions, summarize common problems and highlight them in the next flipped class lesson.

④ Grade Evaluation (OBE-based Assessment):

The OBE concept is used to guide the evaluation process to meet the course objectives and graduation requirements [17]. A multi-dimensional assessment system with process and summative components is adopted and supported directly by the framework shown in Figure 4.

The weighting scheme was derived based on the relation between course objectives, expected learning outcomes and assessment tasks. In particular, the virtual simulation practical teaching score is 40% of the total grade and directly measures the basic applied skills of the students such as modeling using MBSE, virtual simulation operation, knowledge integration, system validation, engineering problem solving.

The final exam carries a weight of 50%, and the score of the flipping classroom's theoretical teaching is for continuous participation, pre-class preparation, and formative learning, which is 10%.

This system comprises hybrid teaching and consists of the following:

Offline Learning Evaluation: Final exam, simulation project reports, thematic presentations, interactive performance, and in-person attendance;

Online Learning Evaluation: MOOC course completion, online test scores, assignment performance, effective interactions, and thematic discussion responses.

This comprehensive approach to assessment reflects students' learning in all areas.

Flipped Classroom Theoretical Teaching Score (10%): The theoretical teaching score is made up of four elements:

Pre-class online learning tasks (20%): Evaluates success in completing preview tasks and participating in online learning activities;

Online exercises during in-person sessions (30%): Assesses performance of exercises completed online through the use of online resources during in-person sessions;

Regular Online and Offline assignments (30%): graded online and in-person task outcomes;

In-person attendance and online discussion participation (20%): Based on attendance and substantive contributions to discussions.

The Flipped Classroom Virtual Simulation Practical Teaching Score is based on 40% of the student's score. The Flipped Classroom Virtual Simulation Practical Teaching Score is 40% of the student's score.

The practical teaching score focuses on the use of the virtual simulation platform, including:

Online practice tasks (20%): These are pre-class tasks from online preview activities and virtual simulation exercises;

Online exercises during in-person practical sessions (30%): Evaluates performance of practical tasks performed online on the simulation platform in class;

Regular practical assignments (30%): assesses results of activities from simulation assignments after class;

Offline attendance and online discussions (20%): Records attendance to simulation teaching and the quality of online communication.

Final Exam (50%):

Summarizing evaluation is given through a written exam at the end of the course that includes theoretical and practical questions and open questions concerning engineering ethics, NEV technology innovations, environment, safety-critical decisions. For instance, students should discuss battery thermal management methods that affect system performance, safety, energy efficiency, and sustainability. The following open questions are questions which stimulate critical thinking and reflection.

TABLE VI. Comparison of temperature-coupled and fixed-parameter models for the 20-s cycle

Model	Max T ($^{\circ}$C)	Max R_s (Ω)	Min ψ_f (Wb)	Loss energy (kJ)	RMS speed error (r/min)
Thermally coupled	54.31	0.02788	0.10645	20.68	125.3
Fixed parameters	52.82	0.02500	0.11000	19.12	123.9

IV. TECHNICAL AND EDUCATIONAL EVALUATION

The evaluation comprises two complementary components. First, the PMSM case is evaluated numerically through temperature-coupled versus fixed-parameter comparison and cooling-path sensitivity analysis. Second, the educational application is examined through a quasi-experimental comparison of routinely recorded course outcomes between the intervention and comparison cohorts. Together, these components provide technical verification of the traceable multi-domain workflow and preliminary evidence regarding its educational application.

Before evaluating the educational outcomes, the technical behavior of the integrated case was examined to verify that the proposed environment can expose measurable electromagnetic, thermal, and control-domain interactions rather than serving only as a multimedia demonstration. The numerical evaluation in this section was conducted in MATLAB using the reference implementation described in Section 3.3. The MBSE–GCKontrol platform is used in the subsequent educational implementation; it is not the numerical solver used to generate the results reported here.

A. NUMERICAL RESULTS OF THE ELECTROMAGNETIC–THERMAL–CONTROL CO-SIMULATION

Figure 5 shows the dynamic speed response under the prescribed speed and load transitions. The controller kept the operating sequence running as it is at 260A current limits. The coupled model produced a mean absolute speed error of 50.2 r/min without the first 0.5 seconds after each command or load transition. We do not claim a new motor control algorithm but prove that our proposed MBSE environment can be traceable from the vehicle level of operation to electromagnetic variables and the system level verification. The electromagnetic–thermal feedback changes both the predicted loss and the temperature direction. The thermally coupled model reached 54.31 °C for 20 s compared to 52.82 °C for the fixed-parameter model. The total model loss energy increased from 19.12kJ to 20.68kJ, increasing about 8.2%. The stator resistance increased from its 35 °C initial value of 0.02598 to 0.02788 (+7.3%) and the PM flux linkage decreased from 0.10879to 0.10645 Wb (2.1%). These differences show how a fixed-temperature motor representation can underpredict heat generation and parameter drift in repeated-drive or high-load simulations.

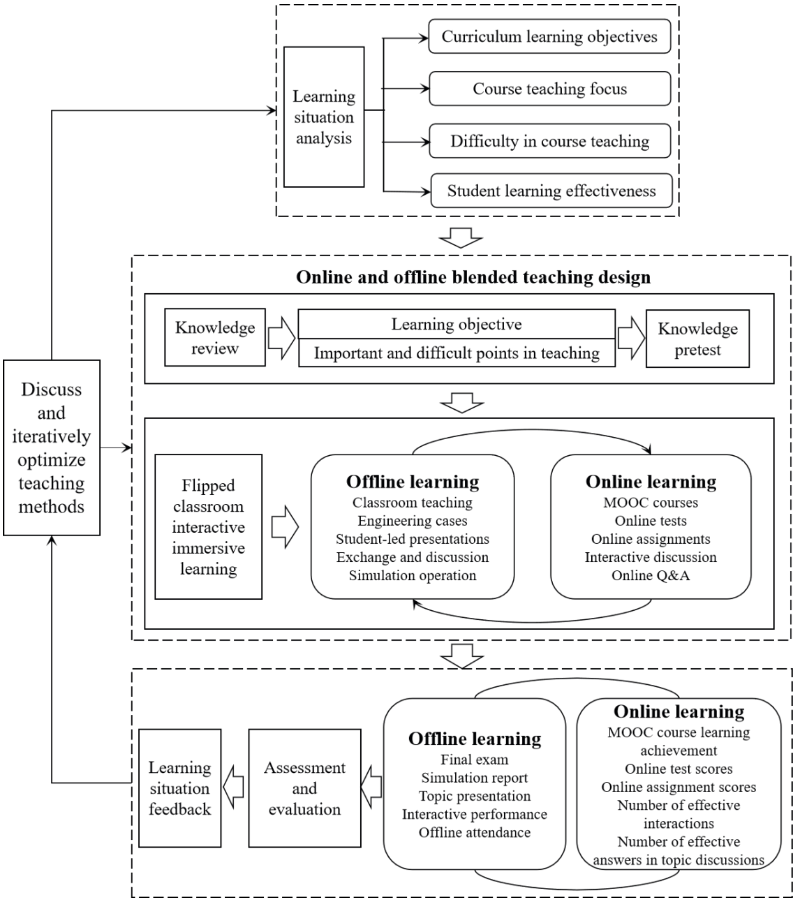


Fig. 4. Implementation path of blended teaching

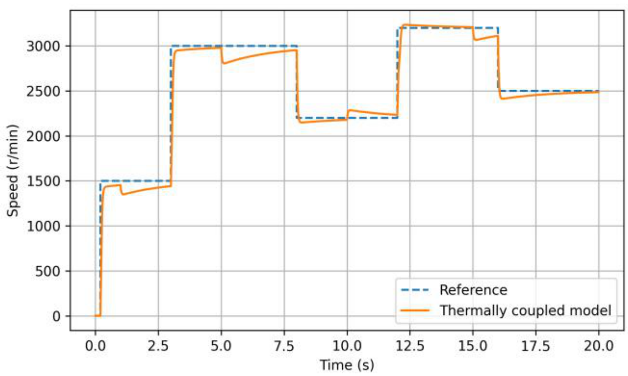


Fig. 5. PMSM speed response under speed-command and load-torque transitions

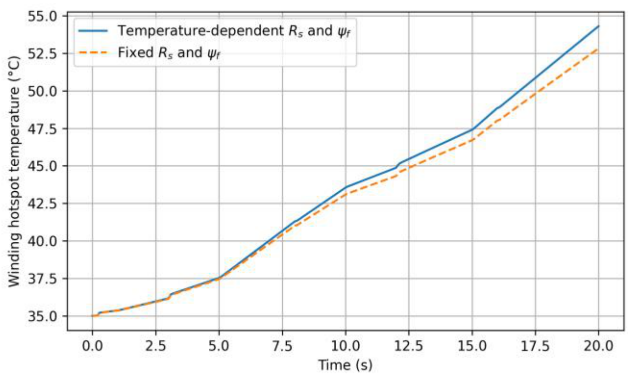


Fig. 6. Winding-hotspot temperature predicted with and without temperature-dependent electromagnetic parameters

Cooling path sensitivity was evaluated for 60s high-load continuation. Reducing R_{th} from 0.18 K/W reduces the final hot spot temperature from 114.57 to 100.85 K/W.The result implies a direct engineering tradeoff between cooling design and electromagnetic loss: weaker cooling path increases winding temperature, increases resistance and copper loss and increases heat generation. Students can connect this response to the MBSE requirement $T_w = 120$ K/W, identify the responsible interfaces and compare controller derating, cooling improvement or motor-sizing alternatives.

TABLE VII. Cooling-path sensitivity over the 60-s simulation

R_{th} (K/W)	Final T_w (°C)	Loss energy (kJ)
0.08	100.85	89.36
0.12	108.65	90.54
0.18	114.57	91.43

These numerical results address RQ1 by demonstrating that

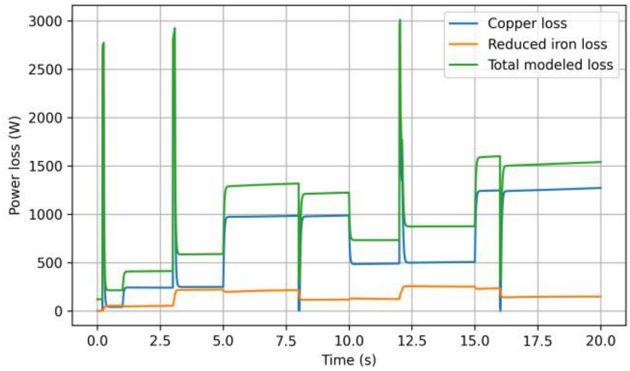


Fig. 7. Copper, reduced iron, and total modeled losses in the thermally coupled case

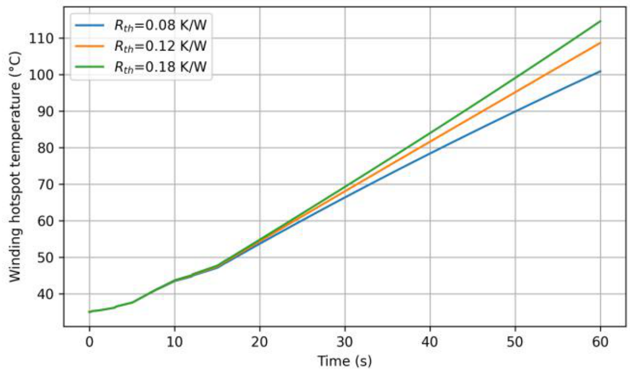


Fig. 8. Sensitivity of winding-hotspot temperature to cooling-path thermal resistance

the MBSE framework can maintain traceable relations between vehicle-level operating requirements, electromagnetic state variables, temperature-dependent parameters, cooling constraints, and verification requirements. Having established the model-level behavior and cross-domain trade-offs of the PMSM case, we next examine the implementation of the MBSE–multimedia framework in teaching and compare the available course-level outcomes between the two cohorts.

B. EDUCATIONAL EVALUATION DESIGN

The educational application was examined using a quasi-experimental cohort comparison involving two parallel third-year classes in the Spring 2024 semester. The intervention cohort (Class A, N = 104) used the MBSE-enabled virtual-simulation teaching framework, whereas the comparison cohort (Class B, N = 107) received the conventional course implementation. Students were assigned through existing classes rather than random allocation.

C. EDUCATIONAL OUTCOME COMPARISON

Table VIII summarizes the available course-performance outcomes for the intervention and comparison cohorts. The intervention cohort had a higher final-examination score (73.2 ± 11.4) than the comparison cohort (50.9 ± 16.5), and the overall course score was also higher (80.1 ± 8.1 vs. 67.3 ± 11.5). The practical-assessment scores were similar (90.4 ± 6.5 vs. 91.6 ± 5.4).

The present analysis is based on routinely recorded course-assessment outcomes available for both cohorts: final-examination score, practical-assessment score, and overall course score. The practical-assessment score was an existing course measure of practical activities and task completion rather than a dedicated measure of interdisciplinary systems-integration competence.

The final-examination mean difference was 22.3 points (95% CI: 18.46–26.14), Welch's t(188.82) = 11.45, $p < 0.001$, Hedges' g = 1.56. The overall course-score mean difference was 12.8 points (95% CI: 10.10–15.50), Welch's t(190.70) = 9.37, $p < 0.001$, Hedges' g = 1.28. The practical-assessment difference was not statistically significant (95% CI: –2.82 to 0.42), Welch's t(200.06) = 1.46, p = 0.147, with an effect-size magnitude of 0.20.

Thus, the observed between-cohort differences were concentrated in the final examination and overall course performance rather than in the existing practical-assessment measure. Because the study used intact classes without random allocation and no baseline equivalence measure was available, these results should be interpreted as cohort-level associations. The existing assessment records do not provide a dedicated quantitative measure of interdisciplinary systems-integration competence; therefore, the present educational evidence does not establish improvement in cross-domain problem-solving ability.

D. DISCUSSION

The results should be interpreted from two perspectives: technical value of the MBSE-enabled co-simulation workflow and its preliminary educational application. At the technical level, the PMSM case shows that electromagnetic loss generation, temperature-dependent motor parameters, closed-loop control behavior, and cooling constraints can be organized within a requirement–architecture–behavior–verification chain. Educationally, the intervention cohort obtained higher final-examination and overall course scores than the comparison cohort, whereas the existing practical-assessment score did not differ significantly. These findings support a preliminary association with selected course-level outcomes rather than a general claim that all aspects of practical or interdisciplinary competence improved.

In order to improve interface consistency, MBSE requires each subsystem model to be connected explicitly by inputs, outputs, units, parameter sources, assumptions and verification criteria [5]. Vehicle torque and speed requirements are assigned to the inverter, PMSM, controller and cooling models, electromagnetic model provides torque and loss information, thermal model returns winding temperature and temperature-dependent stator resistance and permanent magnet flux linkage to electromagnetic and control models. This traceable interface minimizes the likelihood that independently developed models use inconsistent variables,

TABLE VIII. Comparison of Course-Performance Outcomes Between Intervention and Comparison Cohorts

Assessment Item	Intervention Cohort (N=104) Mean ± SD	Comparison Cohort (N=107) Mean ± SD	p-value (Welch's t-test)
Final Exam Score	73.2 ± 11.4	50.9 ± 16.5	< 0.001
Practice Score	90.4 ± 6.5	91.6 ± 5.4	0.135
Overall Course Score	80.1 ± 8.1	67.3 ± 11.5	< 0.001

parameter definitions or operating assumptions. In addition, it can also be tracked across subsystem boundaries and assessed against system performance.

The numerical results demonstrate the engineering insight provided by cross-domain coupling. During the 20-s operating time, the temperature-coupled model predicted winding-hotspot temperature 54.31C and total model loss 20.68KJ compared to 52.82C and 19.12KJ for fixed-parameter model. Winding temperature increases stator resistance and copper loss, while the decrease of permanent-magnet flux changes torque production and voltage demand. Cooling-path sensitivity study showed thermal resistance affected hotspot temperature and accumulated loss. These interactions cannot be understood when electromagnetic, thermal and control models are considered independently [1]–[4].

Student or engineer users are not only benefiting from additional simulation resources. The framework provides the possibility to observe why a good controller in fixed-parameter motor model may not give the same result after thermal feedback, why improved cooling could change electrical loss and control margins, and why a locally optimized controller, motor or cooling subsystem may not provide the best solution at the system level. In this way, users can analyze parameter propagation, competing requirements, cross-domain tradeoffs rather than controller tuning, electromagnetic performance, thermal management as tasks isolated from each other.

The framework also can be used for computational electromagnetics and coupled field system development. The lumped electromagnetic and thermal models can be replaced behavior components of the same MBSE model. Higher-fidelity finite-element electromagnetic models, experimentally identified loss maps, reduced-order thermal models, Functional Mock-up Units can be added without changing the requirement and verification structure. Same workflow can support parameter-sensitivity studies, fault injection, model-in-the-loop and software-in-the-loop testing, and, after calibration of the model, hardware-in-the-loop verification. This contribution is not new electromagnetic solver, but reusable model organizing model, interfaces, requirements and verification evidence at different levels of model fidelity [1]–[3], [5].

Educationally, the intervention cohort obtained higher final-examination and overall course scores, whereas the existing practical-assessment score did not differ significantly between cohorts. These findings indicate an association between implementation of the MBSE-enabled teaching framework and selected course-level outcomes, but they do not demonstrate improvement across all dimensions of practical competence. The non-significant practical-score result is particularly important because this score was an existing course measure and was not designed to isolate interdisciplinary systems-integration competence.

The educational findings should also be interpreted in light of the non-randomized, single-institution cohort design. Without random allocation or a dedicated baseline measure of interdisciplinary competence, pre-existing differences between the two classes cannot be excluded. The results therefore represent preliminary associations rather than causal evidence of instructional effectiveness. Future educational studies should use prospective baseline measures, dedicated performance tasks, and validated cross-domain assessment instruments. At the technical level, the PMSM and thermal parameters used in the numerical case are representative teaching-case values. The results demonstrate the internal operation of the coupling and traceability workflow, but not hardware validation. Further evaluation should use identified motor parameters, finite-element or experimental reference data, and calibrated models before hardware-level validation is claimed.

APPENDIX: IMPLEMENTATION OF AN MBSE-DRIVEN VIRTUAL SIMULATION TEACHING CASE FOR PURE ELECTRIC VEHICLE POWERTRAIN SYSTEM INTEGRATION

A.1 PROJECT DESCRIPTION AND PEDAGOGICAL OBJECTIVES

This Appendix implements the framework described in Sections 3.1–3.4 by implementing a powertrain development case for a pure electric vehicle (PEV) with single-speed reducer. Since Section 3.3 deals with electromagnetic–thermal–control behavior of PMSM, Appendix extends the same MBSE requirement–architecture–behavior–verification chain to the whole powertrain and its project teaching sequence. The primary goals are to allow students:

Apply MBSE principles to formally define system requirements, architect a multi-domain powertrain model, and validate performance against predefined targets.

Integrate knowledge from vehicle dynamics, electrical engineering, electrochemistry, and control theory to size key powertrain components (e.g., traction motor, battery pack).

Leverage the GCKontrol platform for collaborative modeling, multi-variable sensitivity analysis, and system-level fault injection testing—transcending basic operational demonstrations to develop systems thinking.

A.2 MBSE-BASED INSTRUCTIONAL IMPLEMENTATION FRAMEWORK

A.2.1 System Architecture and Modeling Approach

The model architecture adheres to the integrated system design principles central to MBSE, encompassing five core modules that mirror real-world engineering interfaces:
Driver Model
Vehicle Control Unit (VCU) Model
Traction Battery & Battery Management System (BMS) Model
Permanent Magnet Synchronous Motor (PMSM) & Single-Speed Transmission Model
Vehicle Longitudinal Dynamics Model
The powertrain configuration illustrated in Figure A.1 integrates the traction motor, motor controller, and fixed-ratio reducer into a single assembly. This design offers advantages in structural compactness and mechanical transmission efficiency, while introducing typical engineering challenges in power matching and thermal management—challenges that demand cross-disciplinary collaboration.

A.2.2 Parameter Framework for Interdisciplinary Analysis

The teaching case establishes a comprehensive parameter system to enable quantitative analysis across multiple engineering domains. Key parameters include, but are not limited to those presented in Table A.1 and Table A.2.

A.3 MBSE WORKFLOW IMPLEMENTATION IN TEACHING ACTIVITIES

A.3.1 Requirements Definition Phase (Interdisciplinary Analysis)

Students analyze predefined vehicle parameters and performance targets to establish formal, verifiable system requirements. Representative requirements include:
Functional Requirement: “The powertrain shall propel the vehicle to meet specified acceleration and speed targets"
Performance Requirement: “NEDC energy consumption shall not exceed EC_{NEDC} kWh/100km"
Safety Requirement: “Battery SOC shall be maintained within within safe operating limits"

A.3.2 System Architecture Modeling Phase

Using the GCKontrol platform, students construct a unified architectural model that defines interfaces between subsystems. This includes specifying signal types (e.g., CAN bus messages), data ranges, and unit conventions for critical parameters such as torque commands, motor speed feedback, and energy flow parameters.

A.3.3 Component Matching Through Interdisciplinary Integration

The case implements integrated component sizing to demonstrate cross-domain dependencies:
Motor Peak Power Matching:
Specifically, the peak power of the traction motor ($P_{e\text{-max}}$) must satisfy three key power demands:

1. Maximum power required at the vehicle's top speed ($P_{\max\text{-spd}}$)
2. Maximum power demand during acceleration ($P_{\max\text{-acce}}$)
3. Maximum power required for climbing slopes ($P_{\max\text{-}\alpha}$)

Where,

$$P_{e\text{-}\max} \geq \max(P_{\max\text{-spd}}, P_{\max\text{-acce}}, P_{\max\text{-}\alpha})$$

In the Formulas,

$$P_{\max\text{-spd}} = \frac{1}{\eta_T}\left(\frac{mgfu_{\max}}{3600} + \frac{C_D A u_{\max}^3}{76140}\right)$$

$$P_{\max\text{-}\alpha} = \frac{1}{\eta_T}\left(\frac{mgf\cos\alpha\, u_{i,\max}}{3600} + \frac{C_D A u_{i,\max}^3}{76140} + \frac{mg\sin\alpha\, u_{i,\max}}{3600}\right)$$

$$P_{\max\text{-acce}} = \frac{1}{3600\eta_T}\left(\frac{2}{3}mgfu_f + \frac{2}{5} \times \frac{C_D A u_f^3}{21.15} + \frac{\delta m u_f^2}{2t}\right)$$

In the formulas:
u_f represents the final speed of the vehicle on a flat road after accelerating from 0 to within a specified time period.
u_{i_max} represents the maximum speed of the vehicle when traveling on a slope with an inclination angle.
u_{max} represents the maximum speed of the vehicle on a flat, straight road.
Transmission Ratio Matching:
Upper Limit of Transmission Ratio
The transmission ratio $i_g$is constrained by the motor's maximum speed and the vehicle's maximum speed, as these two parameters jointly determine i_g. The upper limit is calculated via:

$$i_g \leq 0.377\frac{n_{\max}}{u_{\max}}r$$

Where:
r represents the tire rolling radius.
n_{max} represents the motor's maximum speed (unit: rpm).
u_{max} represents the maximum vehicle speed (unit: km/h).
Lower Limit of Transmission Ratio
The transmission ratio i_g is also limited by the vehicle's maximum torque demand. The lower limit is defined as:

$$i_g \geq \frac{r}{T_{e,\max}\eta_T}\left(mgf\cos\alpha + \frac{C_D A u_{i,\max}^2}{21.15} + mg\sin\alpha\right)$$

Where:
T_{emax} represents the peak torque of the motor.
Battery Capacity Configuration:

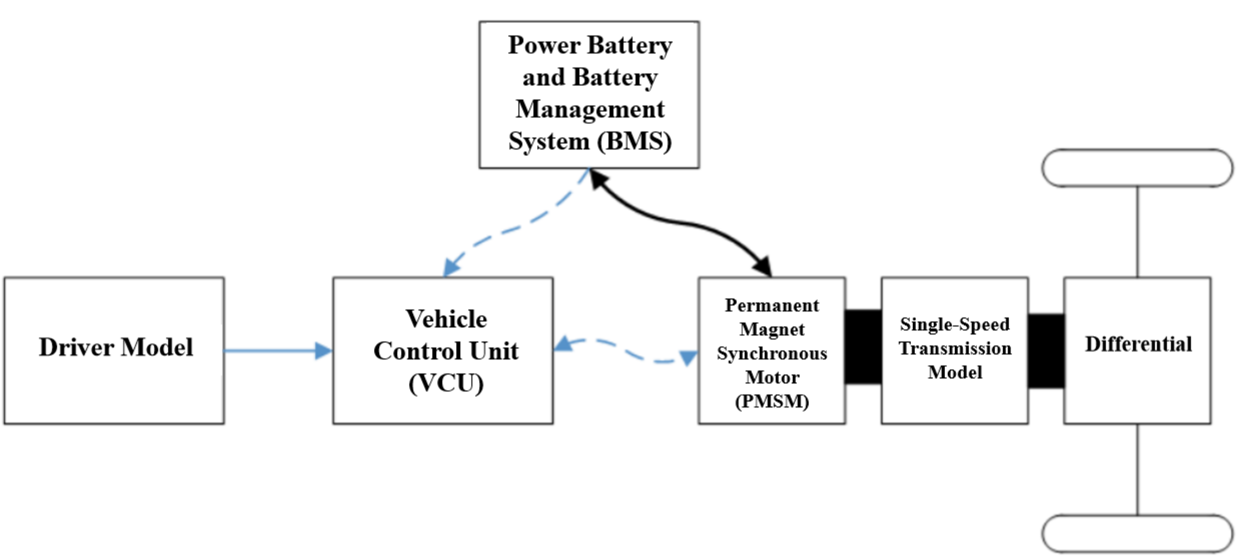


Fig. A.1. Architecture Diagram of the Three-Electric System for a Fixed-Ratio PEV

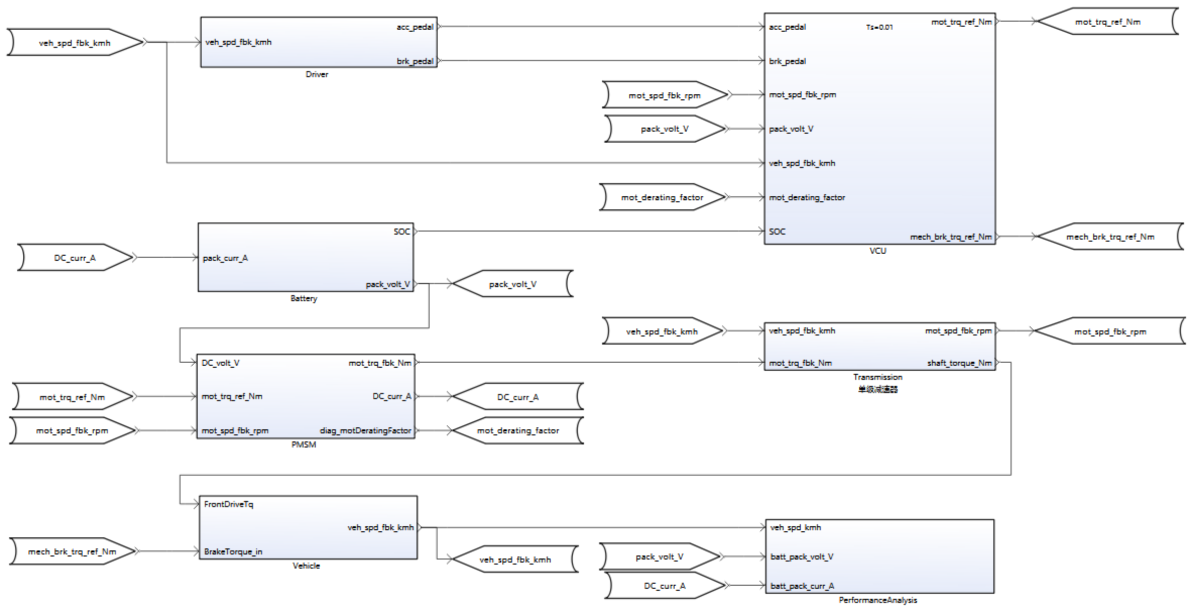


Fig. A.2. PEV Dynamic Performance and Energy Economy Model

TABLE A.1. Vehicle Parameters

Parameter Name	Symbol	Unit	Parameter Value
Curb Mass	m_{unla}	kg	1450
Test Mass	m_h	kg	1675
Gross Vehicle Mass	m_α	kg	1900
Wheelbase	L	mm	2610
Distance from CG to Rear Axle	L_2	mm	1435
CG Height at GVM	h_g	mm	460
Tire Rolling Radius	r	m	0.308
Rolling Resistance Coefficient	f	–	0.012
Aerodynamic Drag Coefficient	C_D	–	0.32
Frontal Area	A	m^2	2.11
Rotational Mass Factor	δ	–	1.05

TABLE A.2. Dynamic Performance and Energy Economy Targets

Parameter Name	Symbol	Unit	Parameter Value
Maximum Speed	u_{max}	*km/h*	≥ 135
0-100 km/h Acceleration Performance	t_2	*s*	≤ 13
NEDC Cycle Electric Consumption	EC_{NEDC}	*kWh/100km*	≤ 13
Range at 60 km/h Continuous Driving	S	*km*	≥ 500

The battery pack comprises strings of cells connected in series and cells connected in parallel within each string. Each unit cell has a voltage $U_{cell}[unit : V]$, and the battery pack requires a total voltage $U_{br}[uint : V]$, and the battery pack's required unit count is determined as:

$$n_S = \frac{U_{br}}{U_{cell}}$$

The battery pack capacity and and each cell has a capacity are represented by $C_{cell}[unit : Ah]$ and $C_b[unit : Ah]$, respectively, where the battery pack's unit parallel count is determined as:

$$n_p \geq \frac{C_b}{C_{cell}}$$

The required battery capacity for the continuous driving cycle is represented by:

$$W_e = \frac{P_{\text{spd60}} S}{u}$$

Where:
$W_e[unit : kWh]$ represents the energy required to complete a driving cycle $S[unit : km]$ at a speed of $u = 60km/h$.
The battery capacity required based on the motor's peak power should satisfy:

$$C_{b1} \geq \frac{1000 W_e}{(SOC_{high} - SOC_{low}) U_{br}}$$

Where:
SOC_{high} represents the maximum allowable SOC of the battery (typically 0.9).
SOC_{low} represents the minimum allowable SOC of the battery (typically 0.1).
Additionally, the battery capacity must align with the battery's maximum discharge rate:

$$C_{b2} \geq \frac{1000}{kU_{br}} \left(P_{e,\max} + P_{aux}\right)$$

Where:
k represents the battery's maximum discharge rate, typically $k = 6.5h^{-1}$.
$P_{aux}[unit : kW]$ represents the auxiliary power consumption of the vehicle, typically 3~5 kW.
Finally, the total battery capacity is represented by:

$$C_b \geq \max(C_{b1}, C_{b2})$$

A.4 DRIVER MODEL: A DUAL-MODE IMPLEMENTATION FOR PERFORMANCE AND ECONOMY VALIDATION

Within the MBSE-guided virtual simulation framework, the Driver Model incorporates dual operational modes to support validation of both energy economy and dynamic performance—mirroring real-world vehicle testing scenarios.

1. **Closed-Loop Control for NEDC Cycle:**
   Under the NEDC conditions, the Driver Model acts as a closed-loop controller, which adjusts the accelerator and brake positions depending on the speed difference between the target speed profile and the actual speed of the cycle, which simulates human driving behavior to obtain precise speed tracking, which is important for evaluating the energy economy of the vehicle.
2. **Open-Loop Control for Dynamic Performance:**
   For dynamic performance simulations (e.g. 0–100 km/h acceleration test), open-loop control is used, with a fixed 100% accelerator pedal signal and 0% brake pedal signal, corresponding to Wide open-throttle (WOT) operation in physical vehicle tests.

A.5 VCU MODEL: THE CENTRAL CONTROLLER FOR INTEGRATED SYSTEM COORDINATION

The VCU model functions as the central control hub of the powertrain, executing core control logic that integrates multi-domain signals—consistent with the system architecture derived from MBSE principles.
Multi-Domain Signal Integration:
The VCU model receives a comprehensive suite of input signals, including pedal position commands from the Driver Model, State of Charge (SOC) data from the Battery Model, and real-time operational data (e.g., vehicle speed, motor speed, DC bus voltage, and motor diagnostic signals).
Model driven torque arbitrage:
By combining these inputs with the motor's external characteristic map (a very important cross-disciplinary dataset), the VCU tries to generate two commands: the required motor torque and the mechanical braking torque. The driver intent interpretation, battery energy state management and powertrain capacity constraints are combined to ensure a smooth, efficient and safe operation of the vehicle.

A.6 MOTOR MODEL: A PRAGMATIC APPROACH FOR EFFICIENT SYSTEM SIMULATION

Complementing the temperature-dependent d–q model used for focused electrothermal analysis in Section 3.3, this appendix adopts a pragmatic PMSM representation to sup-

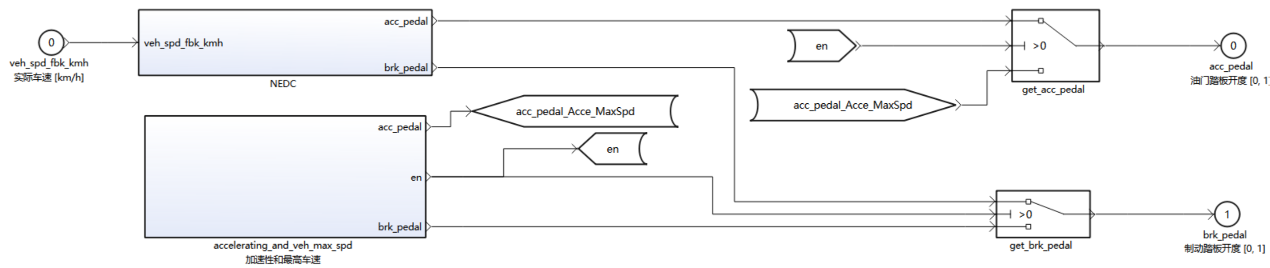


Fig. A.3. Driver Model - NEDC Configuration

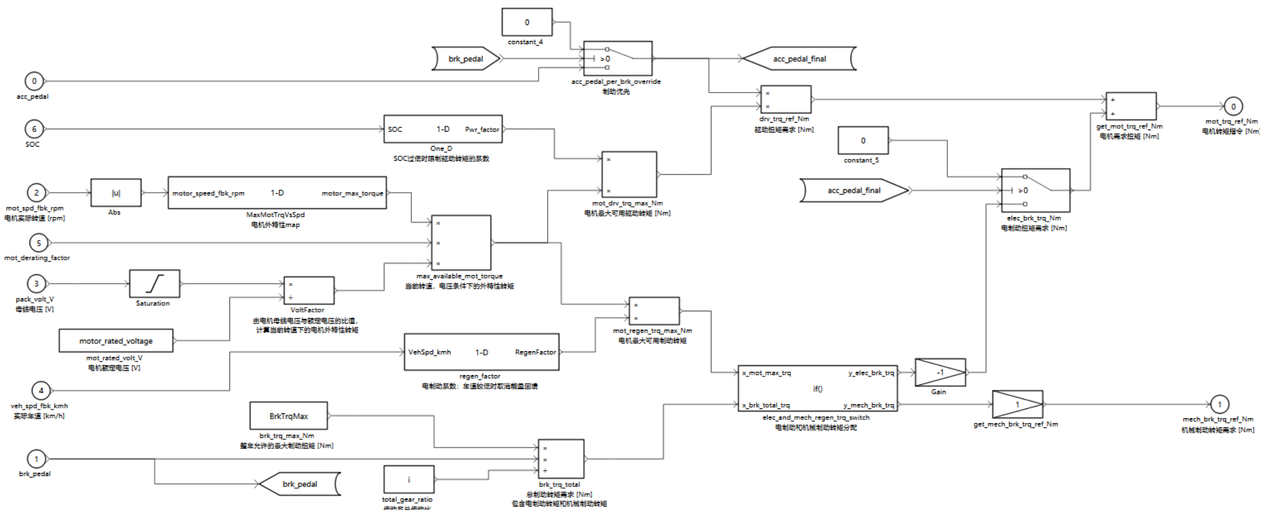


Fig. A.4. Vehicle Control Unit (VCU) Model Architecture

port rapid system-level iteration, component matching, and sensitivity analysis.

Efficiency Map-Based Modeling:

Rather than using computationally intensive mathematical models rooted in fundamental electromagnetic theory, the project constructs the PMSM model using a pre-calibrated motor efficiency map. This design significantly reduces computational resource consumption and accelerates simulation runtime, without compromising the accuracy required for teaching and system-level analysis.

Support for Advanced Pedagogical Activities:

The enhanced simulation efficiency directly aligns with the teaching system's needs, enabling activities such as running large-scale parameter variation tests for sensitivity analysis or Monte Carlo simulations. These activities would be prohibitively slow with high-fidelity physics-based models.

A.7 ADVANCED PEDAGOGICAL APPLICATIONS USING GCKONTROL

A.7.1 Multivariable Sensitivity Analysis

Students leverage Design of Experiments (DOE) methodologies to analyze how variations in key parameters—including tire rolling resistance coefficient, aerodynamic drag coefficient, and accessory power consumption—jointly influence vehicle range and acceleration performance. This exercise cultivates students' system optimization skills and deepens their understanding of multi-domain coupling effects.

A.7.2 System Fault Mode Testing

The GCKontrol platform supports intentional fault injection scenarios, such as sensor malfunctions and component degradation. Students observe the powertrain's dynamic response under these fault conditions and design targeted fault-tolerant control strategies. This practice deepens their comprehension of system reliability engineering and safety design principles.

A.8 IMPLEMENTATION WITHIN THE BOPPPS/OBE FRAMEWORK

A.8.1 Pre-class Preparation

Students familiarize themselves with vehicle parameters and performance objectives via the AI-enhanced digital textbook, completing preliminary quizzes that address interdisciplinary challenges. Template models are supplied through the GCKontrol platform to facilitate initial exploration.

A.8.2 In-class Collaborative Learning

Working in interdisciplinary teams, students utilize GCKontrol to construct and simulate the integrated system

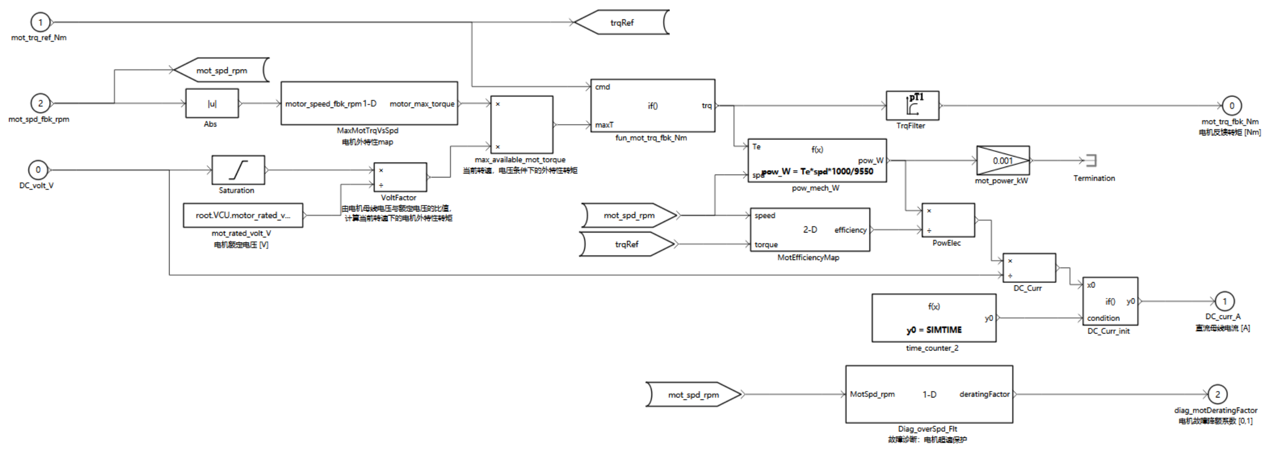


Fig. A.5. Motor Model based on Efficiency Map

model. Instructional sessions, facilitated by the instructor, concentrate on implementing MBSE workflows and resolving cross-disciplinary issues, with particular emphasis on interface compatibility among subsystems.

A.8.3 Post-class Assessment and Reflection

Teams are required to submit simulation reports detailing sensitivity analysis and fault testing outcomes. Online forums facilitate discussions regarding interdisciplinary collaboration challenges. The assessment rubric evaluates three key dimensions: model accuracy (30%), analytical depth (40%), and collaborative contribution (30%).

A.9 MODEL VALIDATION AND PERFORMANCE ANALYSIS

Consistent with Sections 3.3 and 4.1, the following results evaluate the system-level PEV requirements defined in Appendix A.3 and complement the focused PMSM electrothermal evaluation in the main text:

TABLE A.3. Simulation Validation Results

Performance Metric	Target Value	Achieved Value	Validation Status
0-100 km/h Acceleration Time	7.4 s	7.4 s	Met
Maximum Speed	151 km/h	151 km/h	Met
NEDC Energy Consumption	6.3075 kWh/100km	6.3075 kWh/100km	Met

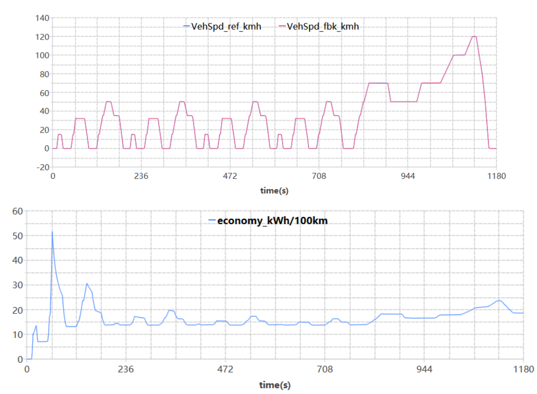


Fig. A.6. NEDC Cycle Energy Consumption per 100 km

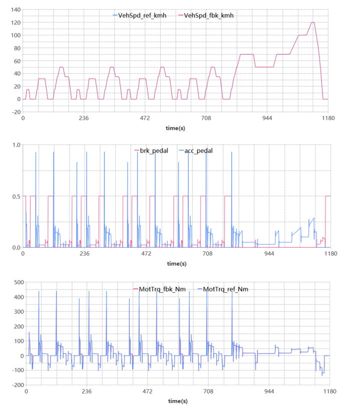


Fig. A.7. NEDC Cycle Speed Tracking and Motor Torque Control

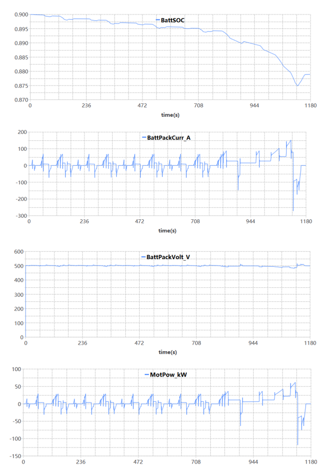


Fig. A.8. NEDC Cycle Battery SOC and Current Variation

A.10 CONCLUSION AND EDUCATIONAL VALUE

This implementation closes the loop established in the main text by translating traceable requirements, subsystem interfaces and simulation evidence into staged learning activities.

As a concrete implementation context for RQ1 and RQ2, we can implement theoretical MBSE in real engineering education. Throughout the entire system development life cycle (from requirements definition to validation and analysis) students develop technical skills, systems thinking, interdisciplinarity communication and new problem solving skills, and GCKontrol supports exploration beyond basic demonstration.

The model's capacity for real-time simulation and Functional Mock-up Unit (FMU) export further enables deployment in Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), and Hardware-in-the-Loop (HIL) scenarios, providing a transition from educational simulation to professional engineering practice. This synchronization with industrial workflows improves practical relevance of learning and supports industry ready competencies in the educational reform goals of this paper.

V. CONCLUSION AND PROSPECTS

This paper has developed MBSE-enabled electromagnetic–thermal–control co-simulation framework for NEV motor drive systems linking vehicle-level torque and speed requirements with inverter, PMSM, field-oriented-control, electromagnetic-loss, thermal and cooling models through traceable modeling and verification. Its main technical contribution is explicitly organizing cross-domain requirements, model interfaces, parameter dependencies and verification evidences in a single virtual environment.

The numerical case showed that temperature-dependent electromagnetic parameters influence motor-drive prediction. In comparison with fixed parameters the thermally coupled model predicted a higher winding-hotspot temperature and higher loss energy over the specified run time.The cooling-path sensitivity analysis showed the interaction between thermal resistance, winding temperature, stator resistance and electromagnetic loss.These results show that electromagnetic-thermal-and control domain interactions are important for system-level motor-drive analysis. They should however be understood as numerical teaching-case results and not as hardware validation since representative parameters were used.

Educational application was examined through a quasi-experimental cohort comparison. The intervention cohort achieved higher final-examination and overall course scores than the comparison cohort, whereas the difference in the existing practical-assessment measure was not statistically significant. Because the study lacked random allocation and a dedicated baseline or cross-domain competency measure, these findings should be interpreted as preliminary associations rather than causal evidence of educational effectiveness. The results support the feasibility of embedding the co-simulation workflow in teaching, while direct claims about improved interdisciplinary competence require prospective evaluation.

The scientific and practical importance of this work is to show how MBSE can organize electromagnetic–thermal–control models, system requirements, subsystem interfaces, and verification data at different model-fidelity levels. Future work will replace representative teaching parameters with experimentally identified or finite-element-derived motor data, introduce higher-fidelity electromagnetic loss and thermal models, add electromagnetic compatibility and fault-propagation scenarios, and extend the workflow to MIL, SIL, and HIL validation. Multi-institutional educational studies with randomized or matched comparison groups, prospective baseline assessments, and dedicated cross-domain assessment tools will also be needed to evaluate educational effects more precisely.

A. RESEARCH LIMITATIONS AND IMPLEMENTATION CHALLENGES

In addition to the limitations identified in the discussion, the present study provides an initial technical and educational evaluation, but several implementation-related constraints remain.

(1) Sample and contextual constraints: Empirical validation was conducted in one academic institution and on a relatively small number of students. The results of the study need to be replicated in other academic environments and with students who have varying academic backgrounds.

(2) Temporal scope: the teaching practice took place during a single semester of the school year, limiting our ability to examine the long-term impact of the system on students' innovative skills and professional growth.

(3) Current virtual simulation resources: While the existing virtual simulation resources are adequate for the main areas of powertrain and control systems, they lack the resources for emerging areas like intelligent networking, vehicle-infrastructure cooperation, and swarm intelligence.

(4) Educational measurement constraints: The present educational evaluation was restricted to routinely recorded course-performance measures. Dedicated questionnaire data, standardized pre/post measures of interdisciplinary competence, platform-usage analytics, and systematically coded project evidence were not collected as part of the evaluation design. Accordingly, the study cannot directly quantify changes in interdisciplinary integration, engagement, innovation, or value-oriented learning. Future prospective studies should incorporate validated instruments and predefined assessment rubrics.

An interdisciplinary gap in faculty literacy is one of the main challenges: faculty preparedness for integrated teaching. Many instructors have significant domain knowledge but lack knowledge of MBSE methodologies, or experience in conducting cross-disciplinary project-based learning.

Requirements for computational resources: running massive data-intensive multi-physics simulation tasks as well as real-time collaborative modeling requires significant computational infrastructure. This resource level could prove elusive for many institutions, thus compounding educational inequity.

Interoperability and complexity of model integration: MBSE helps with interoperability, but there are technical and administrative challenges to developing and maintaining coherent digital twins of vehicle systems.

B. FUTURE RESEARCH DIRECTIONS

Future research directions will be based on the findings and identified limitations.

(1) Pedagogical integration and system optimization: virtual simulation resource library with cross-disciplinary use cases: Intelligent driving, V2X communication, integrated energy management; virtual reality/augmented reality (VR/AR) technologies: use virtual simulation environments. Connection between functionalities of MBSE and specific goals will be explicitized.

(2) Application contexts: The teaching system will be promoted for applications in different types of universities and academic areas to evaluate its effectiveness in larger educational contexts.How it will also be applied to vocational education and industrial training programs, and to enhance partnership between industry and academia through joint labs and enterprise sponsored programs.

(3) Theoretical background and mechanism analysis: further studies are needed to understand causalities and mechanisms of how virtual simulation with MBSE supports interdisciplinary thinking and systems engineering skills, including a rigorous theoretical framework linking model design, cognitive load management and collaborative learning to the development of interdisciplinary innovation skills.

(4) Follow-up studies: future research will implement long-term follow-up procedures to assess the long-term effect of the system on students' career paths and innovative skills. This will give a strong evidence base to evaluate the educational effectiveness and long-term value of the system.

(5) Integration of new technologies: Integration of new technologies like AI for personalized learning path recommendation and automated assessment, big data analytics for learning analytics and predictive modeling for smart tutoring, adaptive learning services, and effective use of resources.

Overall, the proposed framework provides a feasible path linking electromagnetic–thermal–control analysis with MBSE requirement traceability and educational implementation. Future refinements should prioritize parameter identification, finite-element or experimental calibration, MIL/SIL/HIL validation and multi-institutional replication while retaining the platform, content resources and inter-institutional project structure. Appendix A illustrates this path with a complete PEV teaching case.

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