

Teaching Design and New Engineering Education Practice for the Interdisciplinary Course "Energy Storage Technologies for Smart Grids"

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Abstract: Facing the critical demands of energy transition and new power systems, new engineering education necessitates cultivating interdisciplinary talents with solid theory, cross-boundary vision, and engineering innovation. Interdisciplinary course construction is key to meeting this challenge and breaking traditional disciplinary barriers. Focusing on the frontier course "Energy Storage Technologies for Smart Grids," this paper systematically explores its innovative teaching design and implementation. The course establishes a progressive modular framework that includes Fundamental Cognition, Core Principles, and Cutting-edge Applications. It integrates diverse strategies like in-depth lectures, engineering case analysis, and topical seminars. A competency-oriented evaluation system, centred on process-based assessment with multi-stakeholder input, is implemented. This paper provides actionable solutions for integrating multidisciplinary knowledge, e.g., electrochemistry, power systems, control theory, energy economics, to cultivate students' comprehensive ability in addressing complex challenges of storage integration and grid-storage synergy. It offers significant insights for reforming related interdisciplinary courses under new engineering education.

Keywords: New Engineering Education, Interdisciplinary Course, Teaching Design, Smart Grid, Energy Storage Technology

1. Introduction

1.1 Background

The new wave of technological revolution is reshaping the global industrial landscape. The deep convergence of artificial intelligence and new energy sources has given rise to emerging fields such as smart grids and quantum sensing. This trend poses dual-dimensional demands on technology R&D personnel and engineering professionals: cross-disciplinary integration capabilities and disruptive innovation capabilities.

However, traditional engineering education models face structural constraints in cultivating such talent. The curricula of mechanical, electrical, and computer engineering remain compartmentalized, resulting in an "isolation phenomenon" of knowledge. For instance, in robotics engineering programs, mechanical design courses typically exclude embedded programming content. This gap leads to disconnects between control logic and mechanical dynamics during mechatronic system integration projects. Simultaneously, the slow iteration of curricula content lags behind technological convergence, with updates to single-discipline textbooks progressing far slower than interdisciplinary advancements[1].

Under this background, interdisciplinary courses have become the core hub and key pathway for breaking through the structural bottlenecks in cultivating new engineering talent. Industry trends in talent recruitment show a clear preference for graduates with interdisciplinary integration capabilities, as their ability to solve systemic engineering problems aligns perfectly with the urgent needs of industry upgrading. China's Ministry of Education underscores this shift in its New Engineering Education Guidelines, explicitly advocating to "dismantle disciplinary barriers and establish cross-disciplinary course clusters," positioning interdisciplinary curricula as the core vehicle for engineering education transformation[2]. Empirically validated by top-tier global institutions, these curricula reconfigure knowledge architecture to cultivate the intellectual ecosystem for disruptive innovation[3].

1.2 The Proposal of Energy Storage Technologies for Smart Grids Course

With the in-depth advancement of the national strategy to build a new power system and the explosive growth of the new energy industry, energy storage technology, as a key supporting link, has an increasingly urgent need for high-quality, multi-skilled talent. Thus, the launch of the 'Energy Storage Technologies for Smart Grids' course has significant strategic necessity and urgency, aiming to cultivate the core forces capable of mastering future energy systems.

However, as a representative example of a deeply interdisciplinary field, this course faces rigorous and multifaceted challenges in its teaching design and implementation. Its defining characteristic lies not in being an extension of a single discipline, but rather in its deep integration of multidisciplinary knowledge systems. These encompass power system operation and control, electrochemistry and materials science, thermal energy engineering, advanced control theory, system simulation, and even project economic evaluation and market mechanisms, which forming a highly intricate and interconnected multidimensional knowledge framework.

This profound interdisciplinarity inherently gives rise to significant pedagogical challenges. The diversity and limitations of students' knowledge backgrounds pose the primary obstacle. Students from different disciplines, such as electrical engineering, automation, materials science, chemistry, and management, generally have significant 'knowledge gaps.' Teachers need to effectively bridge the huge cognitive gap between power electronics and electrochemistry principles, material structure and system control, and technical performance and economic models within a limited number of class hours. It is difficult to standardise the starting point of teaching, and there is a high risk of knowledge gaps.

The pace of technological iteration in the power grid and energy storage technology fields is astonishing, with new battery systems, advanced energy storage materials, and intelligent management algorithms emerging one after another. Industrial practices are evolving rapidly, leading to textbooks, experimental equipment, and case libraries easily falling behind the latest developments. Static knowledge transfer is unable to meet the demand for rapid response to new knowledge and trends, placing extremely high demands on the dynamic updating mechanism for teaching content.

To solve the above problems, this study proposes a new teaching design. It breaks through the limitations of the traditional teaching mode and systematically optimizes the teaching path for cutting-edge cross-disciplinary courses, such as Energy Storage Technologies for Smart Grids. The ultimate goal is to effectively improve the teaching effect and the quality of talent cultivation.

2. Energy Storage Technologies for Smart Grids Course Teaching Challenges

2.1 Course characteristics and objectives

"Energy Storage Technologies for Smart Grids" is a compulsory specialized course designed for senior undergraduates and graduate students majoring in Electrical Engineering and Automation, Energy Storage Science and Engineering, and related disciplines. This course systematically explores the pivotal role and application prospects of energy storage technologies in modern smart grid development.

2.2 Main issues

The course is still in its early stages of development and does not yet have a systematic teaching design framework, resulting in a rather scattered organization of teaching content. Teaching methods are still dominated by one-way lectures, with insufficient discussion-based and project-driven teaching. Students passively absorb knowledge and lack opportunities for active exploration, resulting in generally low levels of classroom participation. The course evaluation system is in urgent need of restructuring. The current assessment system places too much emphasis on concept memorization and formula derivation in written examinations, and lacks effective means of assessing core competencies such as system design ability, technological innovation thinking, and team collaboration efficiency.

3. Teaching design

3.1 Principles

This course fundamentally transcends traditional disciplinary boundaries by integrating knowledge

from power electronics, electrochemistry, materials science, energy economics, and control systems into a coherent interdisciplinary framework. This course equips students with the foundational knowledge required for energy storage solutions in grid application. Course content dynamically incorporates cutting-edge developments in storage technologies, evolving industry trends, and critical policy standards, ensuring consistent alignment with technological frontiers.

3.2 Course content

This course centers on the application of energy storage systems in smart grid to establish a four-tiered knowledge architecture spanning fundamental theories, technological platforms, grid integration strategies, and value-chain realization. Vertically integrating power system operations, storage core technologies, and control-economic decision-making, it horizontally converges four disciplinary pillars: Electrical Engineering, Control Science, Materials Chemistry, and Energy Economics.

3.2.1 Chapter 1 : Power System Overview

This chapter delineates the closed-loop architecture of electric power systems spanning generation, transmission, distribution, and consumption, while chronicling China's remarkable evolution from fragmented local grids to the world's largest and technologically advanced unified grid through quantum leaps in technology and regulatory reforms. The curriculum exhaustively examines diversified generation technologies, includes conventional thermal and hydroelectric power alongside burgeoning wind and solar renewables. In transmission, particular attention is given to ultra-high voltage AC/DC technologies enabling massive long-distance power delivery, with empirical analysis of the nationally strategic West-East Power Transfer Project. Distribution systems are explored through the points of intelligent equipment enhancing grid flexibility and reliability. The consumption segment conducts in-depth analysis of inherent attributes across diverse load types, alongside emerging interactive and diversified trends exhibited by load characteristics within modern power systems. According to China's energy frontier, this chapter shows the nation's world-leading status in renewable energy capacity expansion and ongoing innovations toward a nationwide electricity market underpinned by ultra-high voltage networks for comprehending energy storage's critical enabler role.

3.2.2 Chapter 2 : Basic grid modelling and regulation method

This chapter systematically introduces fundamental concepts and constituent elements of electric power loads, detailing the characteristics and practical applications of load curves. The daily and annual load curves reflect temporal demand patterns. Key metrics such as peak-valley differentials and load factors are also introduced. Then, this chapter dissects static and dynamic load response characteristics and their mathematical modeling methodologies.

The curriculum then converges on the critical physical constraint in power system operations. The real-time active power balance operation feature is introduced. This encompasses optimal unit commitment strategies for thermal, hydro, and renewable generation units based on load curve attributes. By combining specific examples, the course provides an in-depth analysis of the economic allocation problem between power plants from the perspective of mathematical modelling and solution. It rigorously derives the core criterion for minimising fuel consumption costs across the entire system, namely the principle of equal incremental consumption.

Finally, the theoretical framework extends to the more sophisticated Optimal Power Flow (OPF) problem, underscoring its pivotal role in modern grid security and economic operations. This progression establishes essential theoretical foundations for subsequent exploration of energy storage integration in optimal dispatch paradigms, demonstrating how storage technologies interact with economic dispatch constraints and OPF frameworks to enhance grid flexibility while maintaining operational efficiency under high renewable penetration scenarios.

3.2.3 Chapter 3 : Fundamentals of energy storage technology

This chapter commences with a multidimensional analysis of energy storage applications across generation, grid, and consumer domains. At generation-side, storage mitigates renewable output fluctuations, provides frequency regulation ancillary services, and optimizes unit operations. For grid applications, core functions include deferring transmission and distribution devices upgrade, delivering peak-shaving, frequency support, and enhancing system security. Consumer-side implementations focus on energy arbitrage, power quality enhancement, and critical load protection. Concurrently, economic perspectives are integrated to examine cost structures and revenue mechanisms across these scenarios.

This chapter also introduce operational principles of mainstream storage technologies. For example, electrochemical storage like lithium-ion batteries involving chemical-to-electrical energy conversion, physical storage like pumped hydro and compressed air systems are operated based on potential energy and electricity transformations, electromagnetic storage like supercapacitors enabling direct field-to-electricity conversion. Through systematic comparison of critical performance metrics, e.g., energy density, power density, response time, cycle life, cost structures, and safety profiles—the course delineates application thresholds for distinct storage classes. This comprehensive technical foundation enables scientific technology selection for subsequent storage system deployment, establishing robust cognition of operational boundaries and performance trade-offs essential for grid-integrated storage solutions under evolving energy paradigms.

3.2.4 Chapter 4 : Energy storage grid integration control and technical specifications

This chapter systematically deconstructs operational units of representative energy storage, e.g., battery-based systems, detailing functionalities of core subsystems. The battery arrays serving as electrochemical storage media whose characteristics dictate fundamental performance. Battery Management Systems performing real-time monitoring of cell or module state including voltage, current, and temperature, executing precise charge-discharge control with state balancing, and implementing critical protection against overvoltage, overcurrent, and overtemperature conditions. Power Conversion Systems operating as bidirectional energy hubs that enable efficient, controllable AC/DC conversion while regulating active/reactive power. It is supported by multiple converter topologies including two-level or triple-level Voltage Source Converters and Modular Multilevel Converters for high-voltage and high-capacity applications. The control systems functioning as the "central nervous system" that coordinate BMS and PCS operations through dispatch command execution and grid-connection strategies, e.g., constant power or voltage/frequency control.

The curriculum introduces critical technical metrics for system evaluation, including rated power and capacity, response time, round-trip efficiency, cycle life, energy retention rate, self-discharge rate, and safety ratings. This chapter analyzes the economic indicators that measure the value of its application, such as the initial investment cost, the cost of kilowatt-hour, the operation and maintenance cost, and the payback period. This integrated technical-economic framework establishes comprehensive quantitative foundations for engineering design, technology selection, and commercial deployment of grid-scale storage systems, enabling lifecycle optimization from component specification to grid interoperability validation under dynamic operating regimes.

3.2.5 Chapter 5 : Participation of energy storage in grid regulation and its new application forms

This chapter comprehensively examines core grid regulation mechanisms essential for maintaining dynamic supply-demand balance, focusing on peak shaving which manages substantial daily and seasonal load fluctuations, frequency regulation involving rapid correction of system frequency deviations through primary and secondary control layers, and voltage regulation that ensures nodal voltages remain within prescribed operational limits.

The analysis subsequently establishes energy storage systems distinctive value proposition within these domains via dynamic operational models incorporating charge-discharge power constraints, millisecond-scale response capabilities, capacity boundaries, and sophisticated state-of-charge management strategies. These models enable precise execution of grid dispatch commands, demonstrating how storage effectively reduces peak-valley differentials through strategic valley-period charging and peak-period discharging during peak shaving operations, stabilizes frequency via instantaneous power injection or absorption in frequency regulation scenarios, and supports localized voltage profiles through reactive power modulation for voltage control applications.

Advancing to emerging technology-driven paradigms, the curriculum explores virtual power plants which utilize advanced communication and control architectures to aggregate distributed storage resources, generation assets, and flexible loads into dispatchable portfolios participating in electricity markets and ancillary services. Concurrently, cloud-based and shared storage models innovate business frameworks by enabling multiple users to share centralized or distributed storage capacity on demand, thereby enhancing resource utilization efficiency while reducing individual investment thresholds. Vehicle-to-grid systems further unlock transformative potential by leveraging electric vehicle batteries as mobile distributed storage units, examining their substantial flexibility contributions through managed charging strategies and bidirectional energy exchange capabilities. These paradigms illustrate storage technologies pivotal role in fundamentally reshaping power system operational topologies and commercial structures, transitioning conventional passive assets into active grid participants that facilitate renewable integration while ensuring stability through multi-timescale controllability,

ultimately catalyzing the evolution toward adaptive, market-responsive, and resilient modern grids.

3.2.6 Chapter 6 : Energy storage configuration and operation method

This chapter establishes modeling framework addressing energy storage deployment through strategic investment planning models and real-time operational dispatch models. The planning model focuses on determining optimal storage siting, technology selection, power ratings, and energy capacities while accommodating future grid development requirements and investment cost constraints. The dispatch model resolves how to dynamically optimize charge-discharge strategies under given configurations by responding to real-time electricity prices, load profiles, renewable generation forecasts, and grid conditions to minimize operational expenditures or maximize revenue streams. The curriculum particularly emphasizes storage's pivotal role in low-carbon transition pathways, analyzing its carbon reduction mechanisms via displacing higher-carbon marginal generation units and facilitating renewable energy integration, with dedicated exploration of carbon-constrained planning and scheduling methodologies. Simultaneously, the course dissects critical parameters influencing storage configuration and operational decisions, encompassing techno-economic characteristics of storage technologies, grid operational behaviors, electricity pricing structures, and policy incentive frameworks.

Expanding to market-driven contexts, the curriculum examines how electricity market designs, ancillary service market regulations, price volatility patterns, investor risk preferences, and potential revenue stacking mechanisms collectively impact commercial feasibility assessments and strategic investment timing for storage projects. This multifaceted market analysis equips students with robust theoretical foundations for comprehending storage's evolving positioning within modern electricity markets.

3.3 Refinement of teaching objectives

This course cultivates interdisciplinary professionals proficient in energy storage system integration and grid coordination through a modularized competency development framework.

Chapter one establishes foundational knowledge, requiring students to systematically master the architecture of generation-transmission-distribution-consumption systems and China's power grid evolution, thereby developing panoramic insights into modern power systems and strategic energy perspectives. Chapter two deepens theoretical modeling capabilities, focusing on load characteristic modeling, active power balance constraint derivation, and economic dispatch algorithm implementation to strengthen mathematical problem-solving proficiency in engineering optimization. Chapter three develops technological discernment, enabling students to interpret multi-scenario storage applications and select appropriate solutions through performance parameter comparisons, fostering techno-economic tradeoff analysis. Chapter four cultivates system integration competencies by mastering power conversion system topologies, battery management system control logic, and techno-economic evaluation metrics, while establishing engineering safety standards awareness. Chapter five emphasizes innovative applications, guiding students to implement storage control strategies for peak shaving, frequency regulation, and voltage support, while comprehending systemic values of emerging paradigms like virtual power plants, cloud-based storage, and vehicle-grid integration to nurture cross-disciplinary thinking. Chapter six enhances system decision-making proficiency through planning-dispatch coupling model construction and market-based investment factor analysis, forming comprehensive judgment capabilities balancing low-carbon objectives with economic viability.

These chapters form a tripartite progression framework. Chapters one and two constitute the foundational tier for system cognition and grid modeling. Chapters three and four build the core competency layer covering storage principles and grid integration. Chapters five and six extend into the applied frontier of regulation functions and optimization strategies. Collectively, they construct a multidimensional knowledge architecture supporting complex engineering solution development, where each tier vertically reinforces conceptual understanding while horizontally integrating cross-modular technical synergies to achieve holistic professional formation aligned with energy transition imperatives.

4. Innovation and practice

4.1 Diversified Teaching Methods

This course integrates the three strategies of in-class and out-of-class teaching, case study teaching and seminar teaching. In classroom teaching and extracurricular learning, students complete the

independent construction of basic knowledge through online micro-teaching videos and selected literature, and release classroom time and space resources for in-depth collision of core issues. During the teaching, targeted seminars and typical scenarios are organized, and students are required to write course reports in teams. This strengthens students' practical ability in energy storage system integration, economic analysis and market mechanism, and cultivates their forward-looking vision and complex engineering decision-making skills to cope with technological iterations and policy changes.

4.2 Improvement of the teaching evaluation system

This course establishes a teaching evaluation system centered on diversified and process-oriented assessment. This framework not only evaluates students' mastery of foundational knowledge but also emphasizes the development and enhancement of higher-order thinking skills, engineering application capabilities, and holistic professional competencies. It integrates teacher evaluations, student self-assessments, and peer reviews within group settings to create a multidimensional feedback mechanism.

Process-oriented assessment permeates the entire instructional journey, meticulously examining students' classroom engagement and depth of critical thinking, collaborative spirit and research abilities demonstrated in seminars and course paper writing, as well as knowledge comprehension and application levels reflected in regular assignments. The final examination adopts a limited open-book format, primarily assessing students' understanding of interdisciplinary concepts in energy storage technology and their capacity for comprehensive analysis, solution design, and decision-making when addressing complex real-world engineering challenges. This evaluation system achieves a paradigm shift from knowledge-testing to competency-based evaluation, thereby providing robust support for the attainment of pedagogical objectives.

5. Conclusions

The Energy Storage Technology for Smart Grid course cultivates interdisciplinary professionals proficient in integrated storage system deployment and grid coordination control through a systematically modular curriculum design that progressively deconstructs competency requirements. Course content establishes a tripartite competency hierarchy spanning foundational knowledge, technological principles, and advanced applications. It integrates diverse pedagogical strategies including flipped classrooms complemented by intensive seminars, case study analysis, and collaborative workshops. It implements multidimensional assessment centered on process-oriented evaluation that incorporates instructor appraisal, student self-assessment, and peer review mechanisms to comprehensively validate knowledge internalization, skill acquisition, and professional literacy development.

This course design not only addresses the critical demand for cross-disciplinary talent in modern power system development but also establishes a replicable pedagogical paradigm for cultivating high-caliber specialists in the energy storage domain, effectively bridging theoretical mastery with practical implementation challenges while advancing industry-academia synergy within evolving energy landscapes.

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