A study on the teaching model of introducing modern network analysis tools into the electric network theory course

Shiwei Su[1], Wei Xiong[1*], Meixuan Su[2], Juan Xu[3]

[1]College of Electrical Engineering and New Energy, China Three Gorges University, Yichang, 443000, China
[2]China Three Gorges New Energy (Group) Co., Ltd. Construction Management Branch,Beijing, 100000, China
[3]Yichang No.2 Middle School, Yichang,443000, China
[*]Corresponding author: xwei@ctgu.edu.cn

Abstract: *The Electric Network Theory course suffers from difficulties in manual derivation of complex networks, a lack of visual support for abstract concepts, and a disconnect between algorithmic logic and theoretical principles. This study proposes a teaching model that systematically introduces modern network analysis tools. Based on the modular characteristics of knowledge, this model establishes a mapping relationship between the algebraic topological expressions of the tools and the theoretical content. It designs a coupling mechanism for tool integration and instruction, constructs an algorithmic path for network equations, a hybrid strategy of symbolic and numerical methods for dynamic circuits, and a visual derivation method for nonlinear networks. The model achieves efficacy optimization through multi-dimensional evaluation indicators, dependency constraint identification, and an iterative model of higher-order thinking. This model aims to achieve a deep integration of tool assistance and theoretical derivation.*

Keywords: *Electric Network Theory; Network Analysis Tools; Teaching Model; Knowledge Modularization; Higher-Order Analytical Thinking*

Introduction

The Electric Network Theory course covers a knowledge system including network graph theory, network equations, dynamic circuit analysis, and nonlinear solution methods, which places high demands on learners' abstract thinking and algorithmic understanding abilities. Traditional classroom teaching mainly relies on manual derivation and analytical computation. When dealing with multi-node networks, high-order dynamic systems, and nonlinear iterative solutions, the computational complexity exceeds the operable range in the classroom, which results in students' understanding of algorithmic essence and topological logic remaining at a superficial level. Modern network analysis tools possess functions such as symbolic computation, numerical simulation, automatic topology extraction, and visual feedback, which provide technical support for solving the above problems. However, the application of existing tools often stays outside theoretical instruction or exists as an independent simulation link, which lacks systematic integration with the knowledge structure of electric network theory. Therefore, it is necessary to study a model that embeds analysis tools into the main line of teaching, to clarify the positioning, operation strategies, and evaluation mechanisms of the tools within knowledge modules, and to improve cognitive efficiency while maintaining theoretical rigor. This paper expands from three aspects, namely the logic of tool integration, the construction of a teaching model, and the strategies for effectiveness evaluation and optimization, in order to provide a systematic teaching theory framework for introducing modern analysis tools.

1. The Integration Logic of Network Analysis Tools in the Electric Network Theory Teaching System

1.1 The Modular Characteristics of the Knowledge Structure of Electric Network Theory

The knowledge system of electric network theory can be decomposed into several relatively independent yet interconnected modules. The basic modules include the port constraints of ideal circuit elements (resistors, capacitors, inductors, controlled sources, and memristors, etc.), the topological constraints defined by Kirchhoff's laws, and the representations of the incidence matrix, loop matrix, and cutset matrix in network graph theory. On this basis, the higher-order modules cover the systematic construction methods of network equations (the nodal analysis method, the mesh analysis method, and the state variable method), the time-domain and frequency-domain response analysis of linear time-invariant networks, the parameter matrix description of two-port networks, and the synthesis theory of passive networks. This modular structure makes the dependencies among various knowledge points clear. For example, the teaching of the state variable method requires prior knowledge support from the graph theory and differential equation modules[1].

The modular characteristics provide a natural mapping interface for the introduction of modern network analysis tools. Each knowledge module can correspond to a type of tool function; for example, the graph theory module corresponds to the automatic generation algorithm of the incidence matrix, and the nodal analysis module corresponds to the symbolic assembly and numerical solution of sparse matrices. The clarity of module boundaries also reduces the teaching disturbance during tool integration, meaning that when a certain module adopts tool-assisted analysis, it does not cause structural interference to the knowledge transmission sequence of other modules. By identifying the data flow among modules (such as from component parameters to network equations and then to response waveforms), one can design a progressive teaching path supported by tools, thereby achieving precise alignment between tool functions and theoretical modules and avoiding a disconnect between tool application and theoretical content.

1.2 Algebraic and Topological Representation Functions of Modern Network Analysis Tools

The core capabilities of modern network analysis tools are reflected in their dual representation of the algebraic system and topological structure of circuits. At the algebraic level, such tools support efficient operations of symbolic variables (such as complex frequency and the Laplace operator) and numerical matrices, and they can automatically complete the filling of the nodal admittance matrix, determinant solving, and iteration of linear equation systems. Typical functions include the derivation of network functions (transfer functions and driving-point impedance) based on symbolic computation platforms and the simulation of transient responses based on numerical computing environments. At the topological level, the tools have built-in libraries of graph theory algorithms, which can extract node-branch incidence relationships from netlists, automatically generate the fundamental loop matrix and cutset matrix, and determine the connectivity of the network, the existence of a tree, and the presence of redundant components.

The algebraic and topological representations implemented by the tools are not isolated from each other; instead, they achieve deep coupling through network equations. The tool first constructs a topological representation (the incidence matrix) from a netlist, then assigns branch admittances or impedance values to the algebraic structure according to component types, and finally forms nodal equations or state equations. This process completely reproduces the derivation chain of "graph theory → matrix → equation" in electric network theory. For nonlinear networks, the tool can utilize the linearized expression of the Newton-Raphson iteration, representing the Jacobian matrix of each iteration as a linearized approximation of the original network topology. This combined algebraic-topological representation mechanism establishes a correspondence between the abstract network matrix theory and the concrete computational process, thereby providing an operable medium for the transition "from concept to algorithm" in the teaching process[2].

1.3 The Coupling Mechanism between Tool Integration and Theoretical Instruction

The coupling mechanism between tool integration and theoretical instruction is established upon the control of teaching timing and cognitive load. The basic mode of coupling is "theory first, tool reproduction," which means that after teaching a certain theorem or method (such as Tellegen's theorem, the reciprocity theorem, and the calculation of the state transition matrix), the instructor immediately guides the students to reconstruct and verify the content using analysis tools. For example, during the instruction of the equation formulation steps of the nodal analysis method, the students first complete the manual derivation on the blackboard, and then the instructor demonstrates how the tool automatically performs the same steps from a netlist and outputs the results. This synchronized design prevents the tool from remaining outside the classroom; instead, it becomes an extended verification method for theoretical derivation, thereby strengthening the students' understanding of the algorithmic logic.

A deeper level of coupling is embodied as "concept reverse clarification driven by tools." Certain concepts in electric network theory (such as hybrid parameter matrices, sensitivity analysis, and network duality) are often simplified in traditional blackboard teaching due to the large amount of calculation involved, whereas analysis tools can fully demonstrate the computational processes and resulting forms of these concepts. Teachers can guide students to reversely analyze the correspondence between the tool outputs and the theoretical formulas based on the parameter matrices or frequency response curves generated by the tools. In addition, the graphical topology editing and real-time simulation functions provided by the tools allow for dynamic modifications of network structures and component parameters during class, which can display the theoretically predicted changes (such as pole movement and resonance peak shift) in real time. This real-time interactive coupling transforms theoretical instruction from static statement into an explorable dynamic deduction process, which significantly enhances the intrinsic cohesion between theoretical content and tool functions.

2. Construction of a Teaching Model Based on Network Analysis Tools

2.1 The Algorithmic Teaching Path for Constructing Network Equations

The formulation of network equations is the core step in electric network theory analysis. Traditional teaching mainly relies on manually deriving nodal equations or mesh equations, which is computationally tedious and error-prone when dealing with complex networks. The algorithmic teaching path breaks down the equation formulation process into a set of programmable logical operation sequences, and it guides students to start from graph theory representations and to use the incidence matrix or the loop matrix to automatically generate equation coefficients. This path begins with the component connection relationships in a circuit netlist. The tool extracts node-branch incidence information, automatically identifies the reference node, and constructs the sparse storage structure of the nodal admittance matrix. Each non-zero element in the matrix corresponds to the algebraic contribution of a branch admittance. Controlled sources and mutual inductance components introduce correction terms. The addition rules for these correction terms are expressed as a combination of conditional judgments and cyclic accumulations, thereby forming a complete equation assembly algorithm. In this process, students not only obtain the final equation expressions but, more importantly, understand the mapping rules from topology to matrices and the influence of the sparse matrix filling order on computational efficiency[3].

The algorithmic teaching path further emphasizes the preprocessing steps before solving the equations, including node renumbering to reduce the matrix bandwidth, detecting redundant equations, and performing singular value treatment. By comparing the equation forms generated under different algorithmic strategies, such as the difference between the direct application of the nodal analysis method and the modified nodal analysis method in handling voltage sources and controlled sources, students can observe the impact of algorithm selection on the equation size and the condition number. The tool allows step-by-step backtracking, which displays the intermediate matrix form after each operation, enabling students to map the algorithm flowchart to the mathematical expressions. This algorithm-driven rather than computation-driven approach transforms the construction of network equations from a manual craft into a reproducible systematic process, thereby laying a logical foundation for subsequent computer-aided analysis.

2.2 The Hybrid Symbolic and Numerical Computation Strategy in Dynamic Circuit Analysis

Dynamic circuit analysis involves the Laplace transform, transfer functions, pole-zero distribution, and transient response solving. Traditional teaching often separates symbolic derivation from numerical simulation. The hybrid computation strategy incorporates both symbolic computation and numerical calculation into a unified tool framework, which enables students to complete the entire operation from analytical expressions to numerical waveforms in the same environment. At the symbolic level, the strategy handles rational functions containing complex frequency variables, performs partial fraction expansion, polynomial division, and polynomial root solving, and automatically outputs the closed-form time-domain solution of voltage or current. At the numerical level, the strategy applies specific parameter values to the same circuit and uses implicit numerical integration algorithms (such as the trapezoidal method) to calculate the time-domain response waveform. The two computation modes are linked through a parameter binding mechanism; the symbolic parameters in the symbolic expression can be assigned values to be transformed into a numerical model, and the waveform features obtained from numerical calculation can, in turn, verify the correctness of the symbolic derivation.

The key of the hybrid symbolic and numerical strategy lies in clearly distinguishing the applicable boundaries and conversion conditions between the two modes during the teaching process. For linear time-invariant dynamic networks, symbolic computation can reveal the structural characteristics of the system response, such as the relationship between the damping ratio and the real part of the poles, and the correspondence between the resonant frequency and the imaginary part; whereas numerical computation is used to handle cases with non-ideal parameters or small perturbations. The tool allows students to first obtain the general form of the output using the symbolic mode, and then switch to the numerical mode to modify component parameters and observe the continuous changes in the Bode plot or the step response. This hybrid strategy also supports the evaluation of the effect of order reduction for high-order systems: symbolic derivation provides the transfer function of the reduced-order model, and numerical calculation compares the time-domain differences between the original system and the reduced-order system, thereby strengthening the understanding of the model simplification criteria[4].

2.3 The Visualized Auxiliary Derivation Method for Solving Nonlinear Networks

The solution of nonlinear networks relies on iterative algorithms such as the Newton-Raphson method, and its core lies in linearizing the nonlinear equations at the current estimated point and gradually approaching the true solution. The visualized auxiliary derivation method visualizes the iteration trajectory, which breaks the abstractness of the algorithm black box. For a network containing a single nonlinear resistor, the tool plots the error function curve on a two-dimensional plane, uses dynamic markers to indicate the estimated position at each iteration, and the movement of the markers along the tangent direction reflects the inverse operation effect of the Jacobian matrix, so that students can intuitively observe the estimated points approaching the zero point of the curve. For multivariable networks, the tool uses contour maps or three-dimensional surface plots to represent the error energy distribution, displays the iteration steps as arrow sequences, and the tortuosity of the convergence path corresponds to the change in the condition number of the Jacobian matrix.

This method introduces the parameter adjustment and convergence diagnosis functions of the iterative process. Students can manually modify the initial estimate and observe the convergence or divergence behavior of the iteration sequence from different starting points. The tool displays the residual norm, step size, and convergence criterion threshold in real time, and it highlights the oscillation or divergence mode when convergence fails. For circuits with multiple solutions, the visualization method shows multiple stable equilibrium points reached from different initial points. Students understand the source of the algorithm's sensitivity to initial values by observing the jump phenomenon caused by an excessively steep tangent slope. This approach, which transforms abstract numerical iteration into an intuitive geometric trajectory, provides visual verification for the theoretical derivation steps of nonlinear network analysis, reduces the cognitive threshold, and strengthens the understanding of the algorithm's essence.

3. Theoretical Evaluation and Optimization Strategies for the Effectiveness of the Teaching Model

3.1 Setting Multi-Dimensional Evaluation Indicators for Knowledge Transfer Efficiency

Knowledge transfer efficiency reflects the extent to which knowledge acquired by learners in one context serves to solve problems in another context. For the electric network theory course after the introduction of network analysis tools, the evaluation of transfer efficiency covers the cognitive dimension, the operational dimension, and the integration dimension. The indicators of the cognitive dimension focus on the clarity of students' representation of core concepts (such as network equation generation, matrix transformation, and frequency response analysis) when they are not supported by the tools. This dimension uses the degree of concept map matching and the correct rate of theorem application as quantitative bases. The indicators of the operational dimension focus on the fluency of mapping theoretical steps to sequences of tool commands, including the speed of netlist writing, the matching accuracy between analysis types and tool functions, and the rationality of parameter sweep settings. The indicators of the integration dimension examine the students' ability to autonomously adjust their strategies for using the tools when facing non-standard circuit structures (such as multi-port networks with controlled sources and nonlinear components). This dimension determines the integration level through the structural completeness of the output results[5].

The weights of the three dimensional indicators are dynamically adjusted according to the teaching stage. The initial stage emphasizes the cognitive dimension, ensuring that students master the manual construction logic of the nodal admittance matrix before they are exposed to the automatic generation function of the tools, and the evaluation of transfer efficiency focuses on the reproduction rate of theoretical knowledge under tool-free conditions. The mid-stage shifts to the operational dimension, requiring students to complete the entire process from network topology description to response curve output without referring to the operation manual, and the evaluation is based on the completion time and step redundancy. The later stage takes the integration dimension as the core, and whether students can independently design an analysis plan for untaught circuit forms and compare the output waveform with theoretical predictions serves as the key criterion for measuring transfer efficiency. This indicator system transforms the evaluation of teaching effects from subjective perception to quantifiable description.

3.2 Constraint Identification for Balancing Tool Dependency and Derivation Ability

Tool dependency manifests as learners relying predominantly or even solely on the black-box output of the tools, which weakens manual derivation and logical verification. Constraint identification aims to identify the controllable boundary conditions that maintain a balance between tool usage and derivation ability. The first type of constraint comes from the time interval between the tool output and the theoretical derivation. When students view the results immediately after completing the tool operation without going through the step of derivation anticipation, the tendency of dependency increases. The establishment of a delayed feedback mechanism, which inserts a manual derivation step between the tool operation and the result display, constrains the formation of dependency behavior. The second type of constraint involves the granularity of tool operations. Compared with highly integrated complete analysis functions (such as directly calling a frequency response function), a modular and disassemblable sequence of functions (executing matrix filling and equation solving separately) is more conducive to maintaining derivation ability, because the latter requires an understanding of the data formats of the intermediate steps.

The third type of constraint is related to the degree of problem structure. Well-structured problems (with clearly defined component types and network topology) easily induce a passive acceptance mode; ill-structured problems (with uncertain parameters of components and variable connection relationships in the topology) force learners to return to basic principle derivation and translate them into tool commands. By introducing parameterized networks and non-ideal component models, one increases the proportion of ill-structured problems, thereby forming a positive constraint on derivation ability. The undo and history functions of the tools serve as constraint adjustment variables, which allow for backtracking and correction of intermediate states and reduce the sole reliance on the final output. The above constraint identification provides a parameter adjustment basis for designing a balanced teaching model[6].

3.3 A Teaching Iteration Model for Higher-Order Network Analysis Thinking

Higher-order network analysis thinking manifests as the ability to identify topological dualities and transformation relationships among network structures, to construct equivalent circuit simplification schemes, and to judge the physical credibility of numerical solution results. The teaching iteration model divides the course content into several analytical task units, and each unit follows a four-stage cycle of derivation anticipation, tool verification, discrepancy backtracking, and concept correction. The derivation anticipation stage requires students to predict the analysis results based on theory, without relying on tools to generate numerical values. The tool verification stage uses analysis tools to compute and output precise results. The discrepancy backtracking stage guides students to compare the deviations between the derivation anticipation and the tool output, and to check in turn whether the modeling simplifications in the manual derivation are reasonable and whether the tool algorithm options match the task characteristics.

The concept correction stage addresses the cognitive gaps identified during backtracking, re-teaches the relevant principles of electric network theory, and adjusts the presentation method and exercise configuration of those principles in the next iteration. The entire iteration model replaces single-instance knowledge indoctrination with multiple cycles; units form a progressive relationship, and the correction results of the previous unit provide more accurate assumptions for the derivation anticipation of the next unit. This model transforms the tool output from a final answer into a cognitive feedback signal, thereby making the analytical strategy approach higher-order thinking. The model incorporates a built-in convergence criterion: when the difference between the derivation anticipation and the tool output in two consecutive iterations falls below a set threshold, the teaching objective is deemed achieved, and the course proceeds to the next content module.

Conclusion

Starting from the knowledge structure characteristics of the electric network theory course, this study proposes a systematic teaching model for introducing modern network analysis tools. By analyzing the mapping relationship between the modular characteristics of knowledge and the algebraic and topological representation functions of the tools, this study establishes the coupling mechanism between tool integration and theoretical instruction. On this basis, this study constructs the algorithmic path for constructing network equations, the hybrid symbolic and numerical strategy for dynamic circuit analysis, and the visualized auxiliary derivation method for solving nonlinear networks, thereby forming a teaching operation framework covering the main content of the course. Furthermore, from the three dimensions of multi-dimensional evaluation of knowledge transfer efficiency, constraint identification for balancing tool dependency and derivation ability, and the higher-order thinking-oriented teaching iteration model, this study provides theoretical evaluation and optimization paths for the effectiveness of the teaching model. The above research results offer a logically self-consistent theoretical basis for the teaching design of the electric network theory course. Future research directions may include an adaptive adjustment mechanism for the granularity of tool operations for learners with different academic backgrounds, a personalized iteration path generation based on cognitive diagnosis, and the embedding of deep learning surrogate models into analysis tools to achieve real-time derivation suggestions and error pattern recognition.

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