A Study on the Teaching Model of Introducing Modern Network Analysis Tools into the Electric Network Theory Course

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Abstract: *The Electric Network Theory course has problems with the manual construction of complex networks, lacks visual aids for abstract concepts, and there is a disconnect between algorithmic logic and theoretical ideas. A Teaching Model for Introducing Modern Network Analysis Tools is Proposed in This Paper. Given that one knows that knowledge is modular, a map is built from the algebraic topological expressions of the tools to their theoretical contents in this way. It is to build a coupling mechanism for tool integration and instruction, to create an algorithmic path for network equations, to use a hybrid strategy of symbolic and numerical methods for dynamic circuits, and to develop a visual derivation method for nonlinear networks. Based on the above indicators, improve the efficiency of the model, find the dependency constraints, and then use iteration for high-level reasoning. The two will be combined to achieve the aim of exploration and research.*

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

Introduction

The knowledge system of the Electric Network Theory course includes network graph theory, network equations, dynamic circuit analysis and nonlinear solution methods, etc.; strong abstract thinking and algorithmic ability are required of the students. Traditional classroom teaching is mainly manual derivation and analytical calculation. High-order dynamic systems and nonlinear iterative methods for multi-node networks have very high computational costs; therefore, it is not feasible to teach them in class, and students will fail to grasp the basic ideas and topological logic of the algorithms. Now, many network analysis tools have been developed that can carry out calculations of symbols, numerical simulations, automatic extraction of topology and visualisation, etc., to solve the problems mentioned above. However, the use of the current tool is often not covered in the theoretical teaching or only appears as a separate simulation link; it has not been systematically included in the knowledge structure of electric network theory. Therefore, it is necessary to build a model that integrates analysis tools into the main flow of teaching, clarify the position, operation strategies and evaluation mechanisms of the tools in the knowledge modules, improve cognitive efficiency and maintain theoretical rigor. The three parts of this paper are: Reasons for Tool Integration; Construction of a Teaching Model; and Strategies for Assessing the Effectiveness of Teaching and Improving It, and together they will present an organised system of teaching theories for introducing modern analytical tools.

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

1.1 Modular Features of the Knowledge Structure in Electric Network Theory

The parts of the knowledge system in electric network theory are relatively independent but also cooperate. The first few components are the port constraints of ideal circuit elements (resistors, capacitors, inductors, controlled sources, memristors, etc.), the topology constraints given by Kirchhoff's laws, and the representations of the incidence matrix, loop matrix and cutset matrix in network graph theory. Therefore, the high-order modules will cover the systematic construction methods of network equations (nodal analysis method, mesh analysis method and 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. The modules are independent and do not need the other knowledge points. For example, in order to teach the state-variable method of teaching, students should have already learned some content in graph theory and differential equations[1].

A module structure is a good place to add new network analysis tools in a modern way. Each knowledge module can be mapped to a type of tool function; for example, the graph theory module is the automatic generation algorithm for the incidence matrix, and the nodal analysis module is the symbolic assembly and numerical solution of sparse matrices. Separate these modules so as not to disrupt the teaching progress of tool integration; that is to say, when using a tool for the study of a particular module, the general organisation of knowledge dissemination in other modules should not be disturbed. Identify the flow of data among the modules (e.g., from component parameters to network equations and then to response waveforms) to design a progressive teaching path with the help of tools, ensure that the functions of the tools are consistent with the theoretical modules, and prevent any mismatch between the application of tools and theoretical content.

1.2 Algebraic and Topological Representation Functions of Modern Network Analysis Tools

The main features of the modern network analysis tools are that they can be expressed in both algebraic systems and topological structures of circuits. Algebraically, the above tools can be employed to carry out operations on symbolic variables (such as complex frequency and the Laplace operator) and numerical matrices efficiently, and they can automatically perform the filling of the nodal admittance matrix, determinant solving and iteration of linear equation systems. First, the Symbolic Computation Tool is employed to obtain the derivation of the network function (transfer function and driving-point impedance), and then numerical simulation of the transient response is carried out in a computing environment. The above tools have built-in libraries of graph theory algorithms at the level of topology, can extract node-branch incidence relationships from netlists, automatically generate the fundamental loop matrix and cutset matrix, determine the connectivity of the network, check for the existence of a tree, and find redundant components.

The algebraic and topological representations obtained by the tools are not independent but are connected in a network of equations. First, build the topological representation (the incidence matrix) of the netlist; then, based on the type of component, add branch admittances or impedances to the algebraic structure, and finally form nodal equations or state equations. Therefore, we can reproduce the derivation chain of "graph theory → matrix → equation" in the theory of electric networks. For nonlinear networks, one can use the linearized form of the Newton-Raphson method and approximate the Jacobian matrix linearly at each iteration based on the structure of the original network. Together, the algebraic-topological representation method has established a link between the abstract world of network matrix theory and practical computation and provided a specific way to connect the concept with the algorithm in teaching[2].

1.3 Coupling Mechanism of Tool Integration and Theoretical Instruction

The link between tool integration and theoretical teaching is based on the control of teaching time and cognitive load. The first kind of teaching is "theory first, tool reproduction"; that is, after teaching a particular theorem or method (such as Tellegen's theorem, the reciprocity theorem and the calculation of the state transition matrix), the teacher immediately has the students reconstruct and verify the content using analysis tools. For example, in the instruction for the equation formulation step of the nodal analysis method, students can first manually derive it on the blackboard, and then the teacher can show that the tool can automatically carry out the same steps from a netlist and output the results. The synchronous Design will not be left out of the classroom; instead, it will be used to expand the theoretical derivation and help students better grasp the logic of the algorithm.

At the most basic level of coupling, this is called "tool-driven concept reversal clarification". Some 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 number of calculations, but analysis tools can show the computational process and the resulting forms of these concepts in full. Teachers can have students work backward from the output of the tool to determine which parameters or frequency response curves of the tool were used in the calculation. With the graph topology editing and real-time simulation functions of this tool, one can change the network structure and component parameters dynamically during class time, and the resulting changes in theory (such as pole movement and shift in resonance peaks) will be seen in real time. Interactive coupling has changed the form of theoretical teaching from one-way transmission of knowledge to joint construction, and the link between theoretical content and tool functions has been strengthened.

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

2.1 The Algorithmic Teaching Path for Constructing Network Equations

First, there is the construction of network equations in the study of electric networks. Traditionally, one has to manually derive the nodal equations or mesh equations, and these methods are too complicated and prone to errors in large-scale networks. The algorithmic teaching path breaks down the process of equation formulation into a set of programmable logical operation sequences, and students start with graph theory representations and then automatically obtain the equation coefficients via the incidence matrix or the loop matrix. The first is the component-connection relationship graph of a circuit netlist. A tool can be employed to obtain the node-branch incidence information, automatically find the reference node, and construct the sparse storage structure of the nodal admittance matrix. Each non-zero element of the matrix is the algebraic contribution of a branch admittance. Controlled Sources and mutual inductance elements add correction terms. The addition rules for these correction terms are in the form of conditional judgments and cyclic accumulations, and thus they form a complete equation assembly algorithm. At the same time, students can also learn how to obtain the final equation expressions, as well as the mapping rules from topology to matrices and the effect of sparse matrix filling order on computation efficiency[3].

First, renumber the nodes and reduce the matrix bandwidth in the algorithm for teaching paths; then, one needs to find redundant equations and handle singular values before solving these equations. By comparing the forms of the equations obtained from different algorithmic strategies, for example, the difference between directly applying the nodal analysis method and using the modified nodal analysis method to handle voltage sources and controlled sources, students can see how the choice of algorithm affects the size of the equations and their condition numbers. There is a step-by-step backtracking function, and after each operation, the corresponding matrix form will be shown to help students connect the algorithm flowchart with the mathematical expression. Do not write the network equation by hand; instead, have the algorithm automatically construct it in an organised way and provide a basis for the following computer-aided analysis.

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

Dynamic Circuit Analysis includes Laplace Transforms, Transfer Functions, Pole-Zero Plots, Transient Response Analysis, etc. The two have been taught separately in traditional classes. The two modes of computation are combined in a single system, and all steps of the process can be carried out in the same place, from the start of analysis to the calculation of numerical results. At the level of symbols, one can employ strategies to handle rational functions with complex frequency variables, carry out partial fraction decomposition, polynomial division and find the roots of polynomials, and automatically obtain the closed-form time-domain solution for voltage or current. The same circuit is employed at the level of numbers, but a particular set of parameter values is used and an implicit numerical integration algorithm (such as the Trapezoidal Rule) is applied to calculate the time-domain response waveform. The two computation modes are connected by a parameter binding mechanism; the symbolic parameters in the symbolic expression can be given values to form a numerical model, and then the waveform features obtained from numerical calculation can be used to verify the correctness of the symbolic derivation.

The general direction of the combined symbolic and numerical approach is to determine when to use each way and how to switch between them in teaching. Symbolic computation can find the structure of the system response for linear time-invariant dynamic networks, such as the relationship between the damping ratio and the real part of the poles and how to match the resonant frequency with the imaginary part; numerical computation is used for non-ideal parameters or small perturbations. First, obtain the general form of the output in symbolic mode with the tool, and then switch to numerical mode to change the parameters of the components and observe how the Bode plot or step response change continuously. The other way is to use symbolic differentiation to obtain the transfer function of the reduced-order model and then apply numerical methods to calculate the time difference between the original system and the reduced-order system to determine how much the model has been simplified[4].

2.3 The Visualised Auxiliary Derivation Method for Solving Nonlinear Networks

A typical method for solving nonlinear networks is the Newton-Raphson method; that is, at the current approximate solution, the nonlinear equations are linearised, and then this process of correction is repeated several times. A graph of the auxiliary derivation method can show the path of iteration and reduce the mystery of the algorithm. For a network with a single nonlinear resistor, the tool is used to plot the error function curve in a two-dimensional plane, dynamic markers show the estimated position at each iteration, and it can be observed that as the markers move in the direction of the tangent, an inverse operation effect of the Jacobian matrix takes place, so it can be seen intuitively that the estimated points converge to the zero point of the curve. Contour maps or three-dimensional surface plots can be used to show the distribution of error energy in multivariable networks; arrow sequences are used to present iteration steps, and the tortuosity of the convergence path is related to changes in the condition number of the Jacobian matrix.

In fact, the two functions are parameter tuning and convergence checking of the iteration. Manually change the initial guess of the student and observe whether the sequence of iterations converges or diverges for all starting points. At the same time, show the residual norm, step size and convergence criterion threshold in real time, and if it does not converge, inform the user that there is oscillation or divergence. If there are several solutions to a circuit problem, the visualisation method can display all the stable equilibrium points that can be obtained from different starting positions. Students know why the algorithm is sensitive to the starting value because they have seen how much it changes when the tangent slope is too steep. In this way, the abstract numerical iteration can be presented as an intuitive geometric path, and it will be easier for people to learn the steps of the theory for nonlinear network analysis and grasp the general idea of the algorithm more deeply.

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

3.1 Set Several-dimensional Evaluation Indicators for Knowledge Transfer Effectiveness

The efficiency of knowledge transfer is the degree to which the knowledge acquired by learners in one situation can be applied to solve problems in another situation. For the course on the theory of electric networks after the introduction of network analysis tools, the three levels of transfer efficiency are cognition, operation and integration. The index of the cognitive dimension shows how well students can present the main ideas clearly, for example, deriving network equations, matrix transformations and frequency response analysis without the help of tools. The two indices in this index are the degree of concept map matching and the correct rate of theorem application. Indicators of the operational dimension refer to how smoothly the theoretical steps can be mapped onto a sequence of tool commands, such as the speed of netlist generation, the correspondence accuracy among different types of analysis and tool functions, and the rationality of parameter sweep settings. The index of integration dimension is the level at which students can independently plan the use of tools in the presence of irregular circuit structures, such as multi-port networks with controlled sources and nonlinear components. This index refers to the extent of inclusion in the structure of the output results[5].

The weights of the three-dimensional indicators are varied according to the time of teaching. The first stage is learning; that is to say, students need to learn the manual construction logic of the nodal admittance matrix before they are introduced to the automatic generation function of tools, and the evaluation of transfer efficiency is based on how well theoretical knowledge can be replicated in a tool-free manner. The middle stage will be at the operation level; students need to complete the whole process of describing the network topology and outputting the response curve without referring to the operation manual, and evaluation will be based on the completion time and step redundancy. The latter stage will be about integration, and whether students can independently design an analysis plan for untaught circuit forms and compare the output waveform with theoretical predictions will be the main indicator of transfer efficiency. The old Index System for Teaching Effect was based on feelings; now it can be quantified.

3.2 Identification of Constraints for Balancing Tool Dependency and Derivation Ability

Tool dependence is too high; learners are reliant on the black-box output of tools and have not learned how to derive or logically verify it manually. Determine the constraints of the boundary conditions that will keep the equilibrium of tool use and derivation ability. The first type of constraint is the time interval from the tool output to the theoretical derivation. When students see the results immediately after carrying out the tool operation and do not go through the step of anticipation derivation, their dependence will be relatively high. Late feedback is added to have a manual derivation step after the tool runs and before showing the results, so dependency behaviour has been limited. The second kind of constraint is the size of the tool's working area. A very integrated and complete analysis function (such as directly calling the frequency response function) is not ideal for retaining the ability to derive; otherwise, one needs to be familiar with the data format at the intermediate stage, so a modular and disassemblable sequence of functions that separately carries out matrix filling and equation solving is preferred.

The third type of constraint is due to the structure of the problem. Well-structured problems have clear types of components and network topology, are easy to learn passively, and ill-structured problems have uncertain parameters for components and variable connections in the topology, so learners need to return to the basic principle derivation and translate it into tool commands. Introduce a Parametrisation Network and a Non-ideal Component Model to increase the proportion of ill-structured problems and thus put a positive constraint on derivation ability. The undo and history functions of the tools are used to save the constraint adjustment variables, and one can go back and correct intermediate states without being tied to the final result. Given the above shortcomings, some parameters will be taken to design an ideal teaching model[6].

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

High-order network analysis thinking is the ability to find topological dualities and transformation relationships in the structure of a network, build equivalent circuit simplification schemes, and verify the physical plausibility of the results obtained by means of numerical calculations. The Teaching Iteration Model divides the course content into a small number of analysis task units, and each unit has a four-stage cycle of derivation anticipation, tool verification, discrepancy backtracking and concept correction. Anticipation of the derivation should be a prediction of the analysis results based on theory and should not use tools to obtain numerical values. The first is the tool verification step, and then the results will be displayed. The discrepancy backtracking stage has students compare the deviation between the derivation anticipation and the tool output, and then determine whether the modelling simplifications in the manual derivation are reasonable and whether the tool algorithm options are suitable for the characteristics of the task.

The concept correction stage will address the cognitive deficiencies in backtracking, re-teach the relevant knowledge of electric network theory, and modify how these principles are presented and applied in the next round. The whole iteration model is a multi-cycle way of knowledge induction that connects several units in sequence; that is, the correction results of a previous unit can be taken as more accurate assumptions for deriving the anticipation of the next unit. Use the tool to obtain the answer in the last step, then convert it into a cognitive feedback signal to direct the direction of analysis for higher-order thinking. A convergence condition is set in the model; that is, when the difference between the derivation anticipation and the tool output of two consecutive iterations is less than a small value, the teaching objective has been achieved, and the course moves on to the next section.

Conclusion

Based on the knowledge-structure features of the electric network theory course, an organised teaching model for introducing modern network analysis tools is put forward in this paper. Based on the analysis of the mapping relationship among the modular features of knowledge and the algebraic and topological representation functions of the tool, this paper puts forward a coupling mechanism for tool integration and theoretical instruction. Based on the above, this paper has built an algorithm for building network equations, developed a hybrid symbolic-numerical method of dynamic circuit analysis, created a visualized auxiliary derivation method for nonlinear networks, and thus established a teaching operation framework that covers the main contents of the course. According to the three dimensions of the multi-dimensional evaluation of knowledge transfer efficiency, constraints will be placed on the dependency of tools and the ability to derive knowledge, and a high-order thinking-oriented teaching iteration model will be introduced to improve the effectiveness of the teaching model. Based on the above research results, a reasonable theoretical foundation has been established for the teaching design of the electric network theory course. In the future, we will develop an adaptive adjustment mechanism for the granularity of tool operation based on the different academic backgrounds of learners, generate personalised iteration paths according to cognitive diagnosis, and embed deep learning surrogate models in the analysis tool to provide real-time derivation suggestions and error pattern recognition.

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