A Basic Course in Network Analysis: Part I—Content, Results, Instruction

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***Abstract*—An introductory course to Electric Network Analysis is described. Both time domain analysis (differential equations, impulse response and convolution integral) and frequency domain analysis (harmonic eigenfunctions and system transfer function) are covered by this course. It is intended that students see these techniques within a global framework. This overview must enable the student to make a motivated choice for one of the methods in problems he has to solve. The passing rates of the course are quite poor. Students show a lack of insight. The presentation of the subject matter, the tutoring of students' exercises and the effort of students in connection with the examination system are discussed. A structural scheme of the subject matter, containing the methods of the course in their relations, is presented. It is concluded that the problems students have to solve as exercises require further analysis.**

I. Introduction

The CONTENTS of a rather unique course in Network Analysis are presented, together with a way to control the learning process of the students and the results. Network Analysis is a first-year course in our electrical engineering department. The subject of the course is input-output systems in electrical networks. Here a network is the idealization of an electrical circuit. The viewpoint that IO-systems carry out operations on input signals is stressed. In the course, developed by Prof. Gröneveld in the 1970's (cf. [1]), the properties of electrical networks are described by differential equations, impulse responses and system transfer functions. The relation between time domain and frequency domain is introduced here in the following way: harmonic output signals are considered as solutions to differential equations with harmonic input, as convolutions of harmonic input with impulse response, and as eigenfunctions of the circuits under consideration. These three views lead to three methods of calculation that are applicable to nonharmonic input signals as well.

To get an idea of the context of the course, our university system is sketched [2]. The Dutch law does not allow universities to select students; any student that has followed mathematics and physics in the highest level secondary school should be admitted. Education is offered in parallel, i.e., during each trimester of 9 weeks the students take 4 or 5 subjects and attend laboratory classes. A trimester is followed by a period of 4 weeks in which students prepare for examinations and take them.

Every year about 160 students attend the course. The course consists of three parts that run in parallel. The lectures (28 hours in all) are attended by all students. Tutoring hours (18 hours) are attended in groups of about 25 students, as are the laboratory sessions (9 half days of $3\frac{1}{2}$ hours each). Students are expected to spend about 55 hours of study at home. The ratio of students finishing the first year of the curriculum within one (physical) year is extremely low (around 20%). In the Network Analysis course the success rates are not high either (see Section III).

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II. Unique Course Design

The course is meant to be an introductory one in electric network analysis, given in the second trimester of the first year. The student is assumed to have completed first trimester courses in calculus and linear algebra. The student has also attended a first course in electronics. The main role of the course in network analysis is to provide for a basis to the subjects that follow in the curriculum.

The basic organization is rather unique with respect to the order in which the contents are presented (cf. Appendix). The course starts with an introduction of the elements that model electrical devices, with definitions pertaining to networks, and the formulation of the Kirchhoff equilibrium equations, leading to a set of linear differential equations relating network variables and element equations to each other (differentials and integrals are not mixed). The course is restricted to linear time-invariant networks.

Since networks are considered as operators on signals, one differential equation is derived from the above set of equations, relating one network output signal to the input signal (multiple input is allowed as well). This equation is then used to derive the unit step response, and the unit impulse response is introduced as the derivative of the unit step response.

The output signal of a network is calculated by convolution of the unit impulse response with the input signal. Network elements with nonzero initial state values must be modeled as elements with zero initial state and extra sources; these extra sources introduce extra inputs into the differential equation.

The system transfer function is introduced as the network response, calculated in the way described above (i.e., using the convolution integral) to a complex harmonic input signal. We do not yet introduce the complex s-domain. This means that the transfer function is restricted to the imaginary axis in the present course. The introduction of the transfer function is followed by easier ways to derive it from network structure equations and element equations, doing the calculations with impedances and admittances. Finally, some representation methods are introduced such as the phasor and Bode diagrams

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academical year:		85/86	86/87	87/88	88/89	89/90	90/91	91/92
all participants:	(%)	61	49	50	32	32	43	40
freshmen:	(%)					30	38	35

Fig. 1. Passing rates for Network Analysis.

and power and energy as applied to one and two-port networks operating in the sinusoidal steady state.

Each topic should be studied in sufficient depth to make it easy to bridge the gap to the next course. Thus the modeling of real circuits is not a course item, the impulse (response) is not discussed in a formal way, and students are not asked to derive network properties from phasor and Bode diagrams.

In many textbooks on network analysis (e.g. [3]–[5]) convolution is not introduced at all: the treatment starts with differential equations, then the system transfer function is derived in several forms, and convolution is probably postponed until a later course in linear systems. Other books treat convolution in a restricted sense (e.g. for first order systems only) or only in connection with the Laplace transform, in which case multiplication in the frequency domain is equivalent to convolution in the time domain (for instance [6]–[15]). A third category of textbooks treats convolution extensively as an independent subject on a rather advanced level (e.g. [16]–[18], [1]). This latter approach is preferred, but on an introductory level only.

It is most important that students get a good idea of the methods used in deriving the output signal for a given network and input signal. Furthermore, students must be able to make a choice among the three methods (differential equation, convolution integral, system transfer function).

The purpose of this introductory course is that students get an overview of the relations between equilibrium approach (differential equations), the operator-on-signal approach (convolution) and the eigenfunction approach (transfer function). Students are required to perform on two levels at the examinations. They have to master the formal methods (the calculations) and they have to show some insight: creativity, reflection, common sense, and reasoning capabilities with respect to the concepts of the course. These goals are reached to a limited extent only. The students have difficulties to meet the above requirements.

III. Poor Results and Educational Procedures

In Fig. 1 the percentage of the participants that pass the examinations in Network Analysis is shown. The results are not very stable over the years. This might have been caused by the Dutch educational system (no selection and a slowly declining level of capabilities on entrance), or partly by changes in lecturer or tutors. Since overall results are not satisfactory, a closer investigation of possible causes is executed.

Three parties interact in the course: the lecturer, the tutors, and the students. These act and interact in a process that must result in the students passing their exams. The lecturer is responsible for the contents of the course and the order in which these contents are presented. The tutors guide and assist students in problems solution. The students have to spend enough time studying the contents and solving problems in an effective way.

IV. Support for Getting an Overview: the Structural Scheme

The contents of the course have been analyzed with respect to levels of abstraction [19]. It was found that the highest levels can be represented in a structural scheme, displaying all methods of the course in their relations (see Appendix). The main structure of the scheme is presented in Fig. 2.

The starting point in this scheme is a representation of the circuit and the input signals under investigation. Several methods lead to the calculation of the output signal. In the frequency domain (left) the system transfer function represents the network (input-output system) and the input signal is decomposed into harmonics. In the time domain (right) the system is represented by its impulse response and the input signal remains as it is given: a function of time. In the center the network is represented by differential operators acting on input and output signals. In some problems all methods are applicable, in others only one or two. This scheme has been presented to the students since 1989, with special attention given to it by lecturer or tutors.

V. Influence of Tutor's Characteristics

Each tutor guides the students in his own way. Some tutors present problem solutions on the blackboard, others let the students solve the problems themselves. Thus the possibility that the results might strongly depend on the characteristics of the tutor was investigated in the academic year 1989–1990.

Students' appraisals of the teaching characteristics of the four tutors involved were measured. It turned out that the one superior tutor had no significantly better results in the average grades of his students, although the percentage of his students that failed was slightly lower.

From these data it was concluded that tutor characteristics are not very important with respect to student performance in this situation. Therefore, tackling the difficulties by changing the organization of the course (rather than raising the educational quality of teaching staff) is preferred.

VI. System of Assessment and Results

The system of assessment was changed in the academic year 1990–1991 [20]. The contents of the course were divided into blocks that were appraised separately. The students therefore knew what would be asked (differential equations, for instance), and no mixed problems were given. To appraise the overview of the students, in the last partial examination a special question was designed to evaluate this point. It was

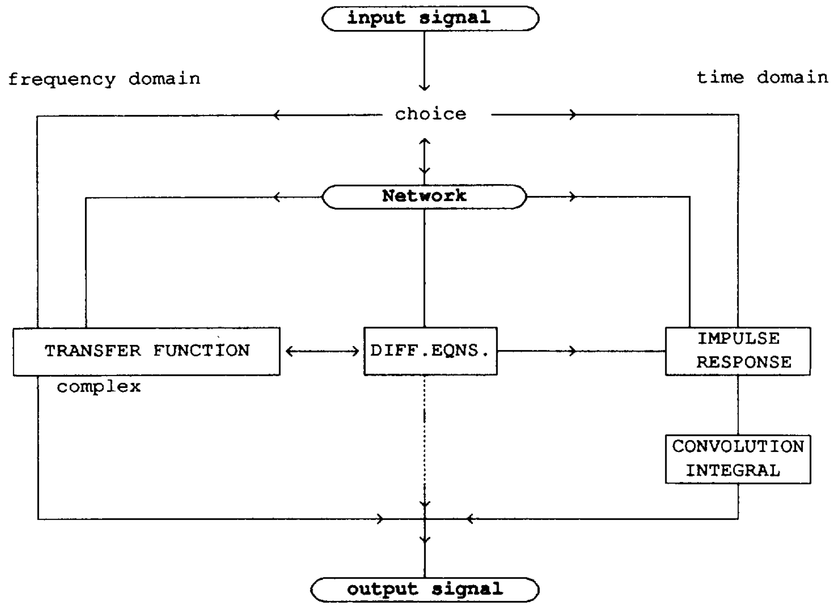

Fig. 2. Basic structure of network analysis. On the left: the frequency domain where the system is represented by its transfer function. In the center: the differential equations where the system is represented by differential operators acting on input or output signals. On the right: the time domain, where the system is represented by its impulse response.

part.examination:	A	B	C	D
number of part.:	145	126	123	126
passed:	83	60	55	33
rate (%):	**57**	**48**	**45**	**26**

Fig. 3. Results of partial examinations in 1990–1991.

expected that grades and passing rates improve when students are stimulated to keep up with the subject matter lectured. The results were as follows:

There are slight indications that students study more regularly in this system. According to the passing rates (cf. Fig. 1) an improvement in results was clearly visible. Students who took the examinations for the first time perform a little bit less than all students (including some last year's freshmen who took the exam a second or third time). The educational effort of lecturer and tutors did increase because of the new system. On a long term, rather great fluctuations of passing rates are visible. Therefore, it is not sure that the improvements will hold. The conclusion is nevertheless that partial examinations contribute to a rise in the passing rate.

The results for the partial examinations in 1990–1991 are presented in Fig. 3. The number of students in this year was 157. All students participated in at least one partial examination. For the examinations A, B, and C a second chance was given at the same time as the overview examination (partial examination D).

With respect to overview (cf. Fig. 3, partial examination D), it can be seen that only 33 students out of 126 (26%) perform satisfactorily. Overview was tested by posing the following problem as one of the examination questions.

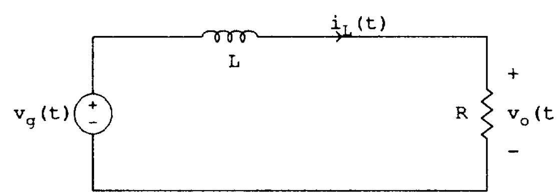

Fig. 4. An input-output system in a linear network. The output signal is the voltage $v_o(t)$ across the resistor R, and $v_g(t)$ is the input signal.

Problem: Choice between Three Methods for Calculation: Given the linear, time invariant network of Fig. 4, calculate the output signal values $v_o(t)$ for $t > 0$, if $v_g(t) = A\cos(\omega t)u(t)$ volt and the network is in zero-state at $t = 0$ (i.e., $i_L(0) = 0$ Amp.). Here $u(t) = 0$ for $t < 0$ and $u(t) = 1$ for $t \geq 0$.

About 74% of the students failed to solve this problem, 58% got zero points for the problem. Students failed mostly because they used a wrong method. Students tend to overlook the fact that the input signal differs from zero for $t > 0$ only. Therefore the answer cannot be found by using the modulus and argument of the system transfer function, but a convolution can easily be made. Other students try to derive and solve a differential equation, in which case they encounter trouble.

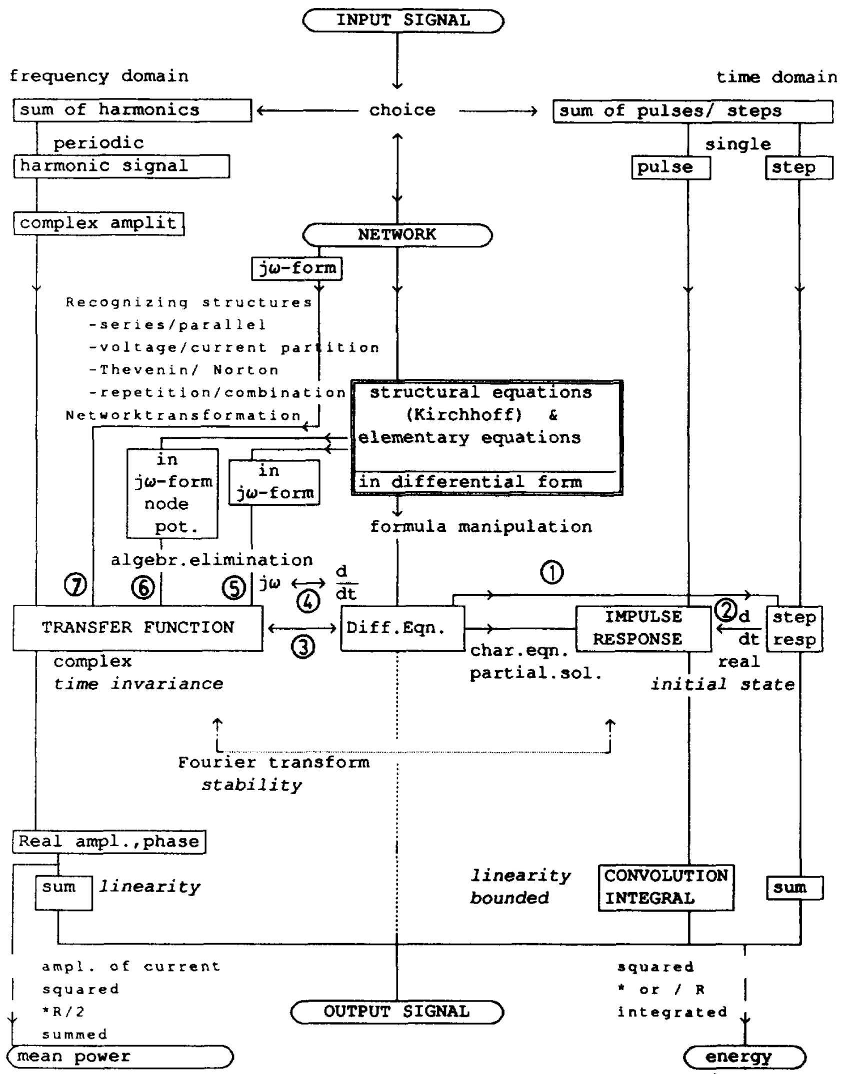

Fig. 5. Scheme of methods for solving problems in Network Analysis.

About 60% of the students do not make a conscious choice between several possible methods of solution. They are not aware of the choice possibilities and conditions for a right choice. In other words, they have no strategy to tackle this kind of overview problems. They show no insight in the conditions of applicability of the methods, and thus show a lack of overview. So at least one goal of this course is not met.

VII. Conclusion and Discussion

The passing rates in the course are rather low. Students show a lack of insight related to lack of overview. The structural scheme that was presented did not change this. Furthermore, better tutors do not necessarily have better passing rates. Partial examinations did not lead to entirely satisfactory results.

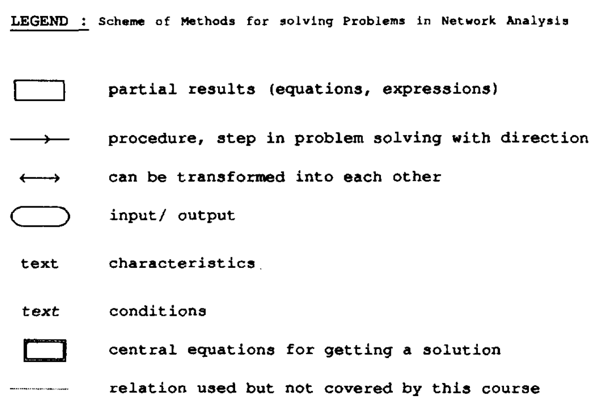

Fig. 6. Legend to scheme of methods in Network Analysis.

Faced with a problem in which a choice must be made from the three methods discussed above (differential equation, convolution, transfer function), students easily choose a wrong method. Not only should students develop a strategy to choose right in these cases, they should also have something to choose from. Therefore the methods and procedures appropriate to solve this kind of overview problems should be readily available to them. This can only be the case if they have successfully applied these methods and procedures before, preferably in situations in which they learn that a wrong choice can be made. Therefore it is concluded that the kind and order of problems given to the students should be considered more carefully in order to reach the goal of overview.

Moreover, students should become aware of this educational goal [21]. This awareness might partly be stimulated by the structural scheme presented. But, even if a map of a town shows the road to the town hall, most people may drive along several roads, wrong ones included, before they do reach that town hall. People should have practice not only in driving a car, but also in driving in an unknown town with the aid of a map. Likewise, for quite a number of students, the relation between the structural scheme and the examination problems is not clear. Overview problems should be given to the students, and they should be tackled by the students themselves, not by the tutors. To be able to make a choice, whether correct or incorrect, students should have practiced themselves several methods and procedures before.

These ideas sound logical and have been realized in a course of laboratory sessions [22] but not yet in a theoretical course. It is possible that students could be better prepared to have insight into questions, but insight could also be a matter of time. In the first case tutoring should be more directed toward this kind of difficult questions and more attention should be given to a global view of the subject matter. In the last case it would be more appropriate to leave out insight questions from the examinations. In our opinion the first possibility should be preferred if one takes education seriously.

Partial examination can be considered to be an external motivation for the students to study more continuously, but they should learn to study regularly themselves. Internal motivation, based on a gradually increasing notion that one can learn step by step new concepts and to use the related skills, should get consideration too. Therefore the students' difficulties in solving problems will be analyzed more carefully in a following paper [23], in which several kinds of problems are distinguished and a specific order of setting problems is proposed.

APPENDIX

A. Overview of Methods in Network Analysis

All problem solving methods covered in the course are represented in a coherent scheme (see Fig. 5 and 6). In the upper part of the scheme the problem is represented. The input signal can be a sum of harmonics (left) or a function of time (center and right). The network can be represented in j-omega form (complex impedance or admittance, left), in differential equation form (center) or as an impulse response (right). In some cases a step response is useful (utmost right). The required output signal is represented in the lower part. The middle part contains the partial results (equations or factors) that can be used in the solving process.

The order of treatment is indicated in the scheme by numbers. In each step it is shown that two methods give the same output signal for rather general cases. First, the step response is derived from a differential equation. Then the impulse response is introduced as the derivative of the step response. Third, the transfer function is derived from the convolution of impulse response and pure harmonic input signals. Next, it is shown that the differential equation can be represented in $j\omega$ form and that this form can be derived algebraically from a representation of complex impedances. Then the node voltage method is introduced, and finally several ways of structural transformations of the network are considered (like single equivalent element replacement or Norton's theorem).

Usually several of these methods represent alternative ways to solve one given problem. In general an alternative method provides for a check on the answer.

For each method rather general conditions of validity can be given as represented in the scheme. However, it is also possible to imagine networks that give inconsistent results when solved by different methods, e.g., two charged capacitors connected by a switch that is closed at $t = 0$.

The scheme can be used by the lecturer to indicate the order of treatment, by the tutor to indicate the relation between the methods, and by the students to integrate their knowledge about the various methods. The scheme can provide anchoring points for new knowledge.

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