This book is dedicated to the memory of

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Preface

The field of electrical and electronic engineering is vast and diverse. However, two topics hold the key to the entire field. They are 'Circuit Theory' and 'Signals and Systems'. Both these topics provide a solid foundation for later learning, as well as for future professional activities.

This undergraduate textbook deals with one of these two pivotal subjects in detail. In addition, it connects 'Circuit Theory' and 'Signals and Systems', thereby preparing the student-reader for a more detailed study of this important subject either concurrently or subsequently.

The theory of electric circuits and networks, a subject derived from a more basic subject of electromagnetic fields, is the cornerstone of electrical and electronics engineering. Students need to master this subject well, and assimilate its basic concepts in order to become competent engineers.

Objectives

Primary Objective:- To serve as a textbook that will meet students' and instructors' need for a two- or three-semester course on electrical circuits and networks for undergraduate students of electrical and electronics engineering (EE), electronics and communications engineering (EC), and allied streams. This textbook introduces, explains and reinforces all the basic concepts of analysis of dynamic circuits in time-domain and frequency-domain.

Secondary Objective:- To use circuit theory as a carrier of the fundamentals of linear system and continuous signal analysis so that the students of EE and EC streams are well-prepared to take up a detailed study of higher level subjects like analog and digital electronics, pulse electronics, analog and digital communication systems, digital signal processing, control systems, and power electronics at a later stage.

Electric Circuits in EE and EC Curricula

The subject of electric circuits and networks is currently covered in two courses in Indian technical universities. The introductory portion is covered as a part of a course offered in the first year of undergraduate program. It is usually called basic electrical engineering. About half of the course time is devoted to Introductory Circuit Theory covering the basic principles, DC circuit analysis, circuit theorems and single frequency sinusoidal steady-state analysis using phasor theory. This course is usually a core course for *all disciplines*. Therefore, it is limited very much in its content and depth as far as topics in circuit theory are concerned. The course is aimed at giving an overview of electrical engineering to undergraduate students of all engineering disciplines.

Students of disciplines other than EE and EC need to be given a brief exposure to electrical machines, industrial electronics, power systems etc., in the third semester. Many universities include this content in the form of a course called electrical technology in the third semester for students of other engineering disciplines. This approach makes it necessary to teach them AC steady-state analysis of RLC circuits even before they can be told about transient response in such circuits. The EE students, in fact, need AC phasor analysis only from the fourth or fifth semester since they start on electric machines and power systems only then. But the first year course on basic electrical engineering has to be a common course and hence even EE and EC students learn AC steady-state analysis before transient response.

The second course on circuits is usually taught in the third semester and is termed electric circuit theory for EE students and circuits and networks or network analysis for EC students. Few comments on these different course titles and course content are in order.

Traditionally, undergraduate circuit theory courses for the EE stream slant towards a 'steady-state' approach to teaching circuit theory. The syllabi of many universities in India contain extensive coverage on single-phase and three-phase circuits with the transients in RC and RL circuits postponed to the last module in the syllabus. The course instructor usually finds himself with insufficient contact hours towards the end of the semester to do full justice to this topic. The EE stream often orients circuits courses to serve as prerequisites for courses on electrical machines and power systems. This led to the EC stream preparing a different syllabus for their third semester circuit theory course—one that was expected to orient the student towards the dynamic behaviour of circuits in time-domain and analysis of dynamic behaviour in the frequency domain. But, in practice the syllabus for this subject is an attempt to crowd too many topics from network analysis and synthesise into what should have been a basic course on circuits.

Such a difference in orientation between the EE-stream syllabus and EC-stream syllabus for circuit theory is neither needed nor desirable. The demarcation line between EE and EC has blurred considerably over the last few years. In fact, students of both disciplines need good coverage of linear systems analysis or signals and systems in the third or fourth semester. Unfortunately linear systems analysis has gone out of the curriculum even in those universities which had introduced it earlier, and signals and systems has started making its appearance in the EC curriculum in many universities. But the EE stream is yet to lose its penchant for AC steady-state in many Indian technical universities.

The subject of electrical circuit theory is as *electronic* as it is *electric*. Inductors and capacitors do not get scared and behave differently when they see a transistor. Neither do they reach sinusoidal steady-state without going through a transient state just because they happen to be part of a power system or electrical machine.

Against this background, I state the pedagogical viewpoint I have adopted in writing this textbook.

Pedagogical Viewpoint

- With a few minor changes in emphasis here and there, both EE and EC students need the same Circuit Theory course.
- 'Lumped Linear Electrical Circuits' is an ideally suited subject to introduce and reinforce 'Linear System' concepts and 'Signals and Systems' concepts in the EE and EC undergraduate courses. This is especially important in view of shortage of course time which makes it difficult to introduce full-fledged courses in these two subjects. This textbook is organised along the flow of Linear Systems Analysis concepts.
- Circuit Theory is a very important *foundation course* for EE, EC and allied disciplines. The quality of teaching and intellectual capability of students varies widely in different sectors of technical educational institutions in India. Therefore, a good textbook on circuit theory has to be written explaining the basic concepts thoroughly and repeatedly, with the average students in mind—not the brilliant ones who manage to get into ivy-league institutions. Such a textbook will supplement good teaching in the case of students of premier institutions and, more importantly, save the average students from life-long confusion.
- The pages of a textbook on Circuit Theory are precious due to the reasons described above. Therefore, all extraneous matter should be dispensed with. The first in this category is the so-called historical vignettes aimed at motivating the students. I have avoided them and instead, used the valuable space to explain basic concepts from different points of view.

- The pre-engineering school curriculum in India prepares the students well in mathematics and physics. Engineering students have not yet become impatient enough to demand examples of practical applications of each and every basic concept introduced in subjects like Circuit Theory or Newtonian Mechanics. There is no need to keep on motivating the student by citing synthetic-looking examples of complex electrical and electronic systems when one is writing on basic topics in Circuit Theory. The pages can be used for providing more detailed explanation on basic concepts. The first year or second year undergraduate student is far away from a practical engineering application! I believe that a typical engineering student is willing to cover the distance patiently.
- Circuit Theory is a foundation course. It is difficult to quote a practical application for each and every concept without spending considerable number of pages to describe the application and set the background. And the pedagogical impact of this wasteful exercise is doubtful. However, those applications that are within the general information level of an undergraduate student should be included. Thus, applications that require long explanations to fit them into the context must be avoided in the interest of saving pages for explanations on Circuit Theory concepts.
- Circuit Theory is a basic subject. Therefore, all other topics that the students are going to learn in future semesters will be anchored on it. Hence, it should be possible to set pointers to applications in higher topics in a textbook on Circuit Theory. Such pointers can come in the form of worked examples or end-of-chapter problems that take up an idealised version of some practical application. An example would be to use an idealised form of fly-back switched mode converter and to show how the essential working of this converter can be understood from the inductance v–i relationship. In fact, all well-known switched mode power converter circuits can be employed in the chapter which deals with the v–i relation of an inductor. Similarly, switched-capacitor circuits can be introduced in the section dealing with the v–i relation of a capacitor.
- Circuit Theory can be learnt well without simulation software. Circuit simulation packages are only tools. I am of the opinion that using simulation software becomes a source of distraction in a foundation course. A foundation course is aimed at flexing the student's intellect in order to encourage the growth of analytical capability in him/her.
- An argument usually put forth in support of simulation software as an educational aid is that it helps one to study the response of circuits for various parameter sets and visualise the effect of such variations. That is precisely why I oppose it in a foundation course. Ability to visualise such things using his/her head and his/her ability for mental imagery is very much essential in an engineer. Let the student develop that first. He/she can seek the help of simulation software later when he/she is dealing with a complex circuit that goes beyond the limits of mental imagery.

  After all, we do not include a long chapter on waveform generators and another one on oscilloscopes in every Circuit Theory textbook. In fact, some of the modern-day waveform generators and oscilloscopes have so many features, that a chapter on each of them will not really be out of place. Yet, we do not spend pages of a Circuit Theory textbook for that. The same rule governs simulation software too.

Pedagogy

- Each chapter begins with a list of chapter objectives outlining the relative emphasis of topics covered in that chapter.
- Detailed summary covering all the important points made in the chapter is provided at the end of each chapter.
- Boxed entries and pointer entries located on the wide side margins highlight important concepts and reinforce them. Additional information is provided within these boxed entries wherever relevant.

- Large number of solved examples illustrating the concepts explained in the text is included. Simple formula-substitution kind of examples are avoided. There are about 250 such worked examples in the book.
- Numerous questions designed to provoke analytical thinking and to reinforce major concepts are included at the end of chapters. These questions may be short numerical problems or qualitative ones. There are about 270 such questions in the book.
- Ample number of problems included at the end of every chapter test the student's understanding. Section-wise organisation of these problems is *avoided intentionally*. I expect the student to assimilate the entire chapter and use all the concepts covered in that chapter (and from earlier chapters) to solve a problem if necessary. After all, no one tells him which concepts are relevant in solving a particular problem in the examination hall or in practical engineering. There will be about 450 such problems in the book. Answers to most of the problems are provided at the end of the book. A detailed solution manual is available at *www.pearsoned.co.in/kssureshkumar* for the course instructors.

Outline and Organisation

The book contains 17 chapters divided into 6 parts. The first three parts are intended to be used for basic electrical engineering course in the first year of undergraduate program. The remaining three parts are to be used for electric circuit theory for EE students and circuits and networks or network analysis for EC and allied disciplines. It may not be possible to cover these three parts entirely in one semester. A selection of sections to suit the course requirements is recommended.

Part I 'Basic Concepts', contains three chapters. The first chapter delves into the physics of two-terminal circuit elements briefly and deals with element relations, circuit variables, and sign convention. It also addresses the concepts of linearity, time-invariance and bilaterality properties of two-terminal elements. This chapter assumes that the reader has been introduced to the basic physics of electromagnetic fields in pre-engineering high-school physics. The chapter attempts to explain the important assumptions underlying circuit theory from the point of view of electromagnetic fields. The treatment is qualitative and not at all intended to be rigorous.

The second chapter covers the two basic laws – Kirchhoff's voltage law and Kirchhoff's current laws – in detail. Emphasis is placed on the applicability of these two laws under various conditions.

The third chapter looks into the v–i relationship of the resistor, the inductor and the capacitor. Series-parallel equivalents are also covered in this chapter. This chapter analyses the v–i relations of inductor and capacitor in great detail. The concept of 'memory' in circuit elements is introduced in this chapter and the electrical circuits are divided into two classes – *memoryless circuits* and *circuits with memory*. Circuits with memory are termed as *Dynamic Circuits* from that point onwards.

Part II 'Analysis of Memoryless Circuits', contains three chapters. Chapter 4 takes up the analysis of memoryless circuits containing independent voltage and current sources, linear resistors and linear memoryless dependent sources using node analysis and mesh analysis methods. An argument based on nodal admittance matrix (or mesh impedance matrix) and its cofactors is used to show that a memoryless circuit comprising memoryless linear two-terminal elements will be a *linear system* and that it will obey superposition principle.

The discussion then moves on to Chapter 5. This chapter systematically develops all important circuit theorems from the properties of a linear system.

The abstraction called a *linear dependent source* is given a concrete shape in Chapter 6 by introducing the Operational Amplifier (Opamp) as a memoryless circuit element. However, the reader will be given an introduction to feedback and stability *i.e.*, dynamics of Opamps at this stage itself. This chapter is an optional chapter in the syllabus for 'Basic Electrical Engineering'. It is a self contained chapter that can be suitably be shifted to some other course in a higher semester.

After the analysis of memoryless circuits, the book moves on to **Part III**, 'Sinusoidal Steady-State in Dynamic Circuits. This part of the book starts with a detailed look at power and energy in periodic waveforms in Chapter 7. The periodic sinusoid is introduced and the principles governing its amplitude, frequency, and phase are made clear. The concept of cycle-average power in the context of periodic waveforms is covered in detail.

Chapter 8 begins with a qualitative description of the transient response and the forced response taking an RL circuit as an example, and illustrates how the sinusoidal steady-state can be solved by using the complex exponential function. It goes on to expound on phasor theory, transformation of the circuit into phasor domain, solving the circuit in phasor domain, and moving back to time-domain. It also introduces active power, reactive power and power factor and presents the basic ideas of frequency response.

Chapter 9 takes up three-phase balanced and unbalanced circuits and includes symmetrical components as well. Unbalanced three-phase circuits and symmetrical components may be optional in 'Basic Electrical Engineering' course.

Part IV, 'Time-Domain Analysis of Dynamic Circuits' contains three chapters. Chapter 10 is one of the key chapters in the book. It takes up a simple RL circuit and uses it as an example system to develop many important linear systems concepts. The complete response of an RL circuit to various kinds of inputs such as unit impulse, unit step, unit complex exponential, and unit sinusoid is fully delineated from various points of view in this chapter. Further, the need for, and sufficiency of initial current specification is thoroughly dealt with, and the concepts of time constant, rise and fall times, and bandwidth are clearly explained.

The response of a circuit is viewed as the sum of ***transient response*** and ***forced response*** on the one hand and as the sum of ***zero-input response*** and ***zero-state response*** on the other. The role of various response components is clearly spelt out. The application of superposition principle to zero-state and zero-input components is examined in detail.

Impulse response is shown to be an all-important response of a circuit. The equivalence between impulse excitation and non-zero initial conditions is established in this chapter. The chapter also shows how to derive the zero-state response to other inputs like unit step and unit ramp from impulse response in detail. The tendency of inductance to keep a circuit current smooth is pointed out and illustrated.

The notions of DC steady state, AC steady state and periodic steady state are explained in detail and illustrated through several worked examples. The chapter ends with a general method of solution to single time constant RL circuits in 'transient response + forced response' format as well as in 'zero-input response + zero-state response' format. This chapter places emphasis on impulse response as the key circuit response, keeping in mind the discussion on convolution integral in Chapter 12.

Chapter 11 takes up a similar analysis of RC and RLC circuits. Further, this chapter gradually introduces the concept of sinusoidal steady-state frequency response curves through RC and RLC circuits and sets the background for Fourier series in a later chapter. Specific examples where the excitation is in the form of a sum of harmonically related sinusoids containing three to five terms are used to illustrate the use of frequency response curves and to illustrate linear distortion. The conditions for distortion-free transmission of signals are briefly hinted at in this chapter and taken up for detailed study in Chapter 14.

Inconvenient circuit problems like shorting a charged capacitor, opening a current-carrying inductor, connecting two charged capacitors together, and connecting an uncharged capacitor across a DC supply require the inclusion of parasitic elements for correct explanation. Parasitic elements are emphasised at various places in chapters dealing with time-domain analysis.

Chapter 12 extends the differential equation based time-domain analysis to multi-node and multi-mesh circuits containing dependent sources. The issue of stability is brought out through illustrative examples containing dependent sources. The criterion for stability in linear circuits is hinted at and developed fully in later sections.

This chapter generalizes the time-domain approach and introduces the concept of 'signal space'. Every point in the complex signal space is viewed as a possible transient response term of some linear circuit in complex exponential format or as a possible excitation function. The idea that a linear circuit can be represented as a set of points in the signal space is introduced to the reader in this manner. This will be a precursor to pole-zero representation in Chapter 15.

Impulse response is generalised for an n^{th} order system and circuit stability criterion is translated into absolute summability of impulse response in this chapter. The reader is reminded of the relation between step and ramp responses to impulse response and is prompted to ask the question: Can the zero-state response to any arbitrary input be determined from impulse response? The question is answered through the development of expansion of any input signal into a sum of delayed and scaled impulse functions, and convolution integral follows.

Two important results that follow from convolution integral are explained in detail. The first one is the relation between area of impulse response and steady-state value of step response. The second is the frequency response function in terms of impulse response. Once the sinusoidal steady-state frequency response is seen to be completely decided by impulse response, the question that arises is: Can the zero-state response to any arbitrary input be found out using frequency response function? The answer to this question defines what is meant by frequency-domain analysis and makes up Part V of the book.

Part V, 'Frequency-Domain Analysis of Dynamic Circuits', starts with Chapter 13 which answers the question posed in the previous paragraph, for a specific class of inputs – periodic inputs. This chapter expands a periodic waveform along the imaginary axis in signal space at discrete points. Fourier series in trigonometric and exponential forms are covered in detail in this chapter.

Chapter 14 extends the expansion of input functions along the imaginary axis in signal space for aperiodic waveforms through Fourier transforms. It also explains clearly how even periodic waveforms can be brought under the Fourier transform theory. The properties of Fourier transforms are explained and illustrated in detail. Significant insight into time-limiting and band-limiting of signals is provided in this chapter. This chapter introduces the notion of the system function and clearly shows that it is the same as the frequency response function. It thus answers the question raised earlier in the affirmative. This chapter also introduces the reader to continuous-time signal analysis.

Chapter 15 expands an arbitrary input signal along a line parallel to the vertical axis in a signal plane, that is, in terms of damped sinusoids of different frequencies rather than in terms of undamped sinusoids of different frequencies. This expansion is illustrated graphically in the case of a simple waveshape to convince the reader that an aperiodic signal can indeed be obtained by a large number of exponentially growing sinusoids and that there is nothing special about the expansion of a waveshape in terms of undamped sinusoids. This expansion of signals leads to the Laplace transform of the signal. Properties of the Laplace transform, use of the Laplace transform in solving differential equations and circuits, transfer functions, impedance functions, poles, and zeros follow. This chapter also includes a graphical interpretation of frequency response function in the s-plane. Stability criterion is re-visited and circuit theorems are generalised. This chapter winds up the section on frequency-domain analysis.

Part VI, 'An Introduction to Network Analysis comprises two chapters. Chapter 16 deals with two-port networks and develops various two-port parameter sets. It also deals with passive constant-k and m-derived filter sections for four basic filtering functions. A study of active filters cannot be treated as part of circuit theory and is better covered in an analog electronics course. Hence it is not included in the text. However, standard active filter circuits are included in worked examples and problems in earlier chapters dealing with frequency response studies.

Chapter 17 provides an introduction to the study of topological properties of electrical networks. The reader is taken through an introduction to linear graphs, incidence matrix, circuit matrix and cut-set matrix and KCL/KVL equations in terms of topological matrices followed by nodal analysis, loop analysis and node-pair analysis of networks. This chapter and the book end with a brief exposure to Tellegen's theorem.

Prerequisites for Students

The student-reader is expected to have gone through basic level courses in electromagnetism, complex algebra, differential calculus and integral calculus. These are covered in the pre-engineering school curricula of all boards of senior/higher secondary school education in India.

Material for Further Study

The following books may be used as reference material for gaining further insight into the subject:

[1] William H. Hayt, Jr. and Jack E. Kemmerly, *Engineering Circuit Analysis*, New York: McGraw-Hill, 1962
[2] M. E. Van Valkenburg, *Network Analysis*, PHI, 1974
[3] K. V. V. Murthy, M. S. Kamath, *Basic Circuit Analysis*, Tata McGraw-Hill Publishing Company, 1989
[4] Charles A. Desoer, Ernest S. Kuh, *Basic Circuit Theory*, New York: McGraw-Hill, 1962
[5] Ernst A. Guillemin, *Introductory Circuit Theory*, New York: Wiley, 1953
[6] Ernst A. Guillemin, *The Mathematics of Circuit Analysis*, New York: Wiley, 1949
[7] N. Balbanian, T. A. Bickart, *Electric Network Theory*, New York: Wiley, 1969

To the Engineering Teacher

This is my first book, and I have tried to minimise errors as far as possible. However, there may be a few that escaped my attention. I request you to point out them to me so that I can incorporate suitable corrections in the future impressions of this book.

I would be grateful to you for any suggestion to improve the content or presentation of this book. Please send your suggestions directly to me at sureshks@nitc.ac.in or to the publisher.

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I learnt electric circuits and networks as an undergraduate at Indian Institute of Technology Madras, Chennai during 1976 –'83. The credit for the good things the reader finds in this book goes to my esteemed professors – Dr. Venkataseshaiah, Dr. V. Bappeswara Rao, Dr. P. Sankaran, Dr. M. Anthony Reddy, Dr. S. S. Yegnanarayanan, Dr. K. Ramar, Dr. G. Sreedhara Rao, Dr. B. Venugopal and Dr. R. Parthasarathy who taught me well. The faults, if any, in this book are mine.

I am indeed fortunate that my wife, Asha D, and my three children – Gayathri S, Gautham Suresh and Archana Suresh allow me considerable personal space that is very much essential for a venture like writing a textbook. I couldn't have written this book if they had not allowed me to be myself (with all my imperfections) over the past years.

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