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"The Control of Parameters in the Automatic Integration of Ordinary Differential Equations"

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IEEE Transactions on Circuit Theory
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IRE Transactions on Circuit Theory
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Series Editor's Preface

The "Benchmark Papers in Electrical Engineering and Computer Science" series is aimed at sifting, organizing, and making readily accessible to the reader the vast literature that has accumulated on both subjects. Although the series is not intended as a complete substitute for a study of this literature, it will serve at least three major critical purposes. First, it provides a practical point of entry into a given area of research. Each volume offers an expert's selection of the critical papers on a given topic as well as his views on its structure, development, and present status. Second, the series provides a convenient and time-saving means for study in areas related to but not contiguous with one's principal interests. Last, but by no means least, the series allows the collection, in a particularly compact and convenient form, of the major works on which present research activities and interests are based.

Each volume in the series has been collected, organized, and edited by an authority in the area to which it pertains. In order to present a unified view of the area, the volume editor has prepared an introduction to the subject, has included his comments on each article, and has provided a subject index to facilitate access to the papers.

This volume, *Computer-Aided Circuit Design: Simulation and Optimization,* has been edited by Professor S. W. Director of the University of Florida. It contains thirty-one papers that, he believes, represent the most significant results in those aspects of computer-aided design related to circuit simulation and optimal circuit synthesis. The volume should be invaluable to circuit designers and to other design engineers interested in computer-aided techniques. It can also be used as the basis for a first course in computer-aided design at a high undergraduate or first-year graduate level.

We believe that this series will provide a manageable working library of the most important technical articles in electrical engineering and computer science. We hope that it will be equally valuable to students, teachers, and researchers.

John B. Thomas

To my parents–Murray and Lillian Director

Preface

During the past decade, the digital computer has become an indispensable design tool. With the aid of a computer, the engineer can not only design larger and more complex systems in shorter periods of time, but, perhaps even more important, he can also remove many of the restrictive, and sometimes invalid, assumptions that are made when classical design procedures are used. Of all the engineering disciplines, it is probably electrical engineering, especially the area of circuit design, that has seen the greatest advances in computer usage.

These advances were partially due to the fact that computer-aided design was a virgin area with a great potential for providing many new research results. However, probably even more important was the fact that the computer had to be employed for the successful design of large-scale integrated circuits that were made possible by the breakthroughs in integrated circuit technology.

Computer-aided circuit design has become a broad field of specialization. Topics of interest in this field run the gamut from physics-oriented modeling, where one is concerned with predicting the performance of a device such as a transistor on the basis of knowledge of the processing steps used to fabricate the device, to layout, where one is interested in generating a set of masks that can be used to fabricate integrated circuits. As one might expect, the amount of literature that has been published in this field is overwhelming. It is desirable, for a number of reasons, therefore, to have a mechanism for tracing the important developments, or benchmarks, in the field of computer-aided circuit design. This volume is intended to serve that need. However, since important contributions in the entire field are too numerous to be included in a single volume, the present volume is limited to the most significant results in the development of the areas of circuit analysis, that is, the accurate simulation of circuit performance by the computer, and circuit synthesis, that is, the formulation of a circuit structure and optimization of circuit performance to meet given design criteria.

The papers in this volume have been separated into seven parts. The first three parts trace the progress in the area of circuit simulation; the second three trace the progress in the area of circuit optimization; and the last part contains papers that have had significant impact in the area of computer-aided circuit design, although they were not expressly intended for this purpose. I believe that this collection of outstanding work adequately illustrates the development of the field. This reference material should be useful not only to the circuit-design engineer, but to all those interested in general engineering design.

Finally, I wish to express my deep appreciation to the National Science Foundation for their research support, under Grant GK27615, in the area of computer-aided design.

S. W. Director

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Introduction

The initial effort to use the computer as a design tool was made in the well-established area of filter synthesis. By the middle of the 1950s a number of "theoretically" successful design techniques had been developed.[1] In these now-classical approaches, filter design was separated into two main steps. The first step was to approximate a given set of design specifications by a system transfer function. The second step was to realize this transfer function by a connection of ideal circuit elements. Typically, however, when physical elements were used to build the circuit, the actual performance deviated significantly from that which was desired.

In 1956, Aaron (Paper 15) suggested that the computer could be a useful aid in solving this problem. Aaron proposed using a least-squares approach for improving upon the design obtained in each step of the classical synthesis approach. Desoer and Mitra (1961: Paper 16), using Aaron's philosophy, proposed an iterative optimization method to adjust the element values of the physical nonideal elements of ladder filters to reduce the error between the magnitude of the desired and the actual transfer functions. This method was limited to a specific class of filters, owing to the lack of a general analysis capability. Calahan (1965: Paper 18), recognizing the cause of the limitation in Desoer and Mitra's work, proposed an iterative realization procedure that would work for any linear network. Calahan employed a topologically based analysis scheme that would later be abandoned because of the inherent limitation it placed upon the size of the network that could be handled.

A reasonably efficient computer solution to the approximation problem was proposed in 1965 by Smith and Temes (Paper 17). These authors described an iterative procedure for the synthesis of low-pass and band-pass filters that adjusted the pole frequencies of a transfer function to meet the design specifications.

At the same time that the synthesis procedure was being computerized, work was being carried out in the area of circuit simulation. In order for the computer to be an effective design tool, a good general-purpose analysis capability was required. As in the case of synthesis, the initial attempts at computerized circuit simulation were limited to more or less directly implementing standard analysis methods. In the early 1960s the state-variable approach to network analysis[2,3] was very popular and was used as the basis for many of the first general-purpose circuit analysis programs, such as TAP (Branin, 1962: Paper 1), CORNAP (Pottle, 1965 and 1969: Papers 2 and 3), AEDNET (Katzenelson, 1966: Paper 4), and SEPTRE.[4] Although it was originally thought that the state-variable formulation was the best approach for the time domain analysis of networks, it was found that the computational effort required to set up the state equations was excessive and unnecessary. However, the state-variable method did yield pole and zero information required by the classical synthesis methods.

One of the early programs that did not employ a state-variable formulation was ECAP.[5] ECAP, an outgrowth of TAP, used a node equation formulation and was probably the first widely available general-purpose circuit analysis program.

There were two major problems with early analysis programs that caused them to use exorbitant amounts of computer time, especially when they were used to analyze large nonlinear networks in the time domain. The first problem was that the procedure used to solve sets of simultaneous equations, a routine fundamental to all analysis schemes, did not take advantage of the fact that the matrices involved were highly sparse. Typically less than 15 per cent of the elements in the matrices of interest were nonzero. Thus a considerable amount of machine time was wasted performing trivial operations, such as multiplying by zero. Moreover, large amounts of storage were wasted in storing the zero-valued elements. This situation motivated an interest in the application of the sparse matrix methods that were originally proposed for solving linear programming problems (Markowitz, 1957: Paper 29). Significant contributions in the application of sparse matrix methods were made by Tinney and Walker (1967: Paper 5), Gustavson, Liniger, and Willoughby (1970: Paper 6), and Lee (1968: Paper 7) among others.[6-8] The papers reprinted in this volume are believed to have had the greatest impact in the area of circuit analysis.

The second major problem of the early analysis programs has been called the *minimum time constant problem.* For stability purposes, the numerical integration schemes used by these programs required a step size that was smaller than the smallest time constant of the network. However, many networks are stiff; that is, the time constants are widely separated. In such a network, the response due to the smaller time constants dies out rapidly while the response due to the large time constants dominates. By requiring a small time step, an excessive amount of computer time was needed to predict the dominant response.

This problem was solved by Gear (1968: Papers 8 and 9), who proposed a variable-step-size, variable-order predictor-corrector method that was not troubled by the minimum time constant problem. Gear's method, which could be used to solve arbitrary sets of first-order differential equations, also had an outstanding error control feature. In 1971, Calahan (Paper 10) discussed the implementation of Gear's method in a nodal-based analysis program.

Although Gear's method was a vast improvement over previous techniques, it could become numerically unstable if the step size was changed rapidly. Recently, Brayton, Gustavson, and Hachtel (1972: Paper 11) proposed an alternative method that was less likely to become unstable when the time step changed rapidly.

While these advances in circuit analysis were being made, significant progress in the area of network design was also being reported. In 1965 and 1966, three papers appeared that described the use of mathematical programming for circuit design. Schiebe and Huber (1965: Paper 19), Lasdon and Waren (1966: Paper 20), and Athanassopoulos, Schoeffler, and Waren (1966: Paper 21) all recast the network design problem into a nonlinear programming problem that was solved by using an optimization technique such as the Fletcher and Powell method (Fletcher and Powell, 1963: Paper 30) or the conjugate gradient method (Fletcher and Reeves, 1964: Paper 31). In each of these papers, the artificial boundary between approximation and realization was removed.

The advances described in Papers 19 through 21 were still limited in that a general-purpose analysis program was not used and calculation of the gradient required by the optimization algorithm was costly. In 1967, Rohrer (Paper 22) described a highly efficient technique, which has become known as the adjoint network method, for computing the gradient. It was shown that the gradient of the performance function with respect to all the elements of an arbitrary linear passive network could be computed after only two network analyses. Moreover, a general-purpose analysis program such as ECAP could easily be employed for the gradient computation. And in Paper 23, by Hachtel and Rohrer (1967), the adjoint network technique for gradient computation was extended for use in nonlinear switching circuit design by using a state-variable analysis approach.

The adjoint network approach for gradient computation was completely freed from a particular analysis scheme by Director and Rohrer in 1969 (Papers 24 and 25). In these papers, Tellegen's theorem (Tellegen, 1952: Paper 28) was used to derive gradient and sensitivity expressions for arbitrary elements in both the frequency and time domain. These expressions could be evaluated after only two network analyses: one on the original network and one on the adjoint network. [It was later shown (Director, 1971: Paper 25) that, in fact, not even two complete analyses were necessary for the gradient computation.]

With the advances in sparse matrix methods, numerical integration techniques, and sensitivity calculation methods, as well as the tremendous strides made in modeling, [9,10] the scene was set for the appearance of the third-generation simulation program. Three such programs were described in the special issue on computer-aided circuit analysis and device modeling of the *IEEE Journal of Solid-State Circuits* in August 1971. ECAP-II, by Branin et al. (Paper 12), was the first widely available nonlinear transient analysis program that incorporated the latest sparse matrix and numerical integration methods. CANCER, by Nagel and Rohrer (Paper 13), which could perform small-signal ac as well as nonlinear transient analysis, included a capability for computing network sensitivities and the effects of thermal and shot noise. Finally, SLIC, by Idleman et al. (Paper 14), was a rather complete linear integrated circuit simulator that incorporated the latest device models and could compute the poles and zeroes of a specified transfer function.

However, the advances in numerical techniques had an impact far greater than that of merely improving the standard approaches to analysis. These advances allowed Hachtel, Brayton, and Gustavson to propose (Paper 27), an entirely new approach to analysis, as well as design. In this approach, all network equations, that is, Kirchhoff's voltage and current law equations and branch relationships, along with