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ANNUAL STATUS REPORT

TITLE: A SYSTEMS APPROACH TO DEVICE-CIRCUIT INTERACTION IN ELECTRICAL POWER PROCESSING

SUBMITTED TO: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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Annual Report NGR-33-008-090

I. Introduction

This is the first annual status report for NASA research grant NGR 33-008-090, covering the period June 1, 1967 to May 31, 1968. An itemized summary of research over this period appears in Section II. (Certain items appearing in our Semi-annual Report of January 1968 have been updated and carried over to this report for purposes of completeness.) Section III lists the publications which are, in effect, the end product of our research.

Although Section II and the publications listed in Section III contain all of the technical information on our research, it would be rather difficult to obtain from that material an overall view of how the individual items complement each other, resulting in an integrated effort whose effect is more than the sum of its parts. Therefore, we shall attempt in this introduction to point out very briefly the significance of the work and its potential usefulness in power processing applications. Some additional comments will be made on the educational value of the work and future projections.

1.1 Significance of our results

As was indicated in our proposal, progress in power-processing technology can benefit from research on a broad spectrum of problems, from semiconductor device design to system analysis and simulation. Our progress to date includes results over this whole range. For convenience we divide the range of topics into three parts, following our original proposal.

Analysis and Synthesis of Switched and Modulated Systems. Motivated by the fact that high efficiency power processing systems demand circuits composed of lossless elements and nonlinear switching devices, two basic theoretical studies have been undertaken: characterization and analysis of periodically switched lossless networks (See Section 2.1), and modelling of nonlinear resistive networks (2.3). A still more general study was made of larger classes of time variable systems (2.2). These studies have produced important new analytical tools as well as certain bounds on the theoretical limits of behavior of these classes of systems. Since they embrace such fundamental questions as maximum possible efficiency of power conversion, stability, validity of mathematical models, etc., these results have wide-ranging potential application in power processing systems.

Closely related to our analytical work is our effort in computer-aided analysis of networks producing discontinuous waveforms. These networks, typical of power processing systems, defy efficient analysis by conventional numerical methods. Our algorithms and computer programs, tailored to these applications, have shown impressive computational efficiency on several test problems.[2.4] Since improvements in power processing circuitry will require extensive computer simulation we plan to continue and, hopefully, expand our work in the area of computation and software development.

High power, high efficiency switched circuits. A thorough understanding of technological limitations on power processing circuits requires experience in the design and experimental realization of switched mode electronic circuits in integrated form. Our development of a tunable and bandwidth adjustable filter has given us valuable experience in these areas (not to mention providing a useful new circuit component). (2.5)

Characterization and Optimization of Power-Switching Devices. In view of the need for understanding the physical mechanisms that limit the speed and power of semiconductor devices, we suggested in our proposal the use of a small-signal analysis for investigating the speed of p-n-p-n devices. This approach has been successfully applied to a p-n-p-n tetrode. (2.6) Further application of small signal analysis in a double-diffused transistor is continuing and will be described in our next semi-annual report.

Our study of power field effect transistors (2.7) was motivated by the fact that these devices have some unique advantages in power processing systems for space applications. While certain information has now been obtained from a one dimensional analysis, a two dimensional study is required to obtain further results. This is now underway and will be reported subsequently.

1.2 Educational Aspects

Although this grant contributes to our educational program in various ways, one specific indication of this contribution is the fact that three doctoral condidates: L. Brandenburg, A.B. Glaser, and N. Voulgaris, all of whose research and/or research supervision was supported partially or completely under this grant, have now completed their research and received their degrees. The titles of their doctoral dissertations appear on the attached publication list.

1.3 Future Projections

Concerning the future course of our work, we were, of course, very gratified that the grant was renewed for the period June 1, 1968 - May 31, 1969. This has enabled us to continue some of the projects described in Sect. II, add several additional doctoral students to our research staff, and to initiate some new projects. The students at least partially supported under this grant are:

Sharad T. Sathe	Mebenin Awipi	Julius Oso
Choong-ki Kim	Amr Armanazi	
Young Kook Kang	Howard Eskin	

As is the case in any productive research effort our work has suggested many new avenues for future investigation.

Building upon some of the results described in this report, we are presently moving in certain new directions, some of the details of which were described in our renewal proposal dated April 1, 1968. Perhaps the most significant shift in our emphasis has been from analysis to design and optimization. For example, the possibility of applying techniques of mathematical programming and optimal control to the optimization of power systems is now under study. Our Systems Research Laboratory has recently acquired a time-shared computer terminal, primarily for the purpose of conducting design optimization studies involving very close interaction between man and machine at each step of the design process. If we can find the means for developing the necessary software support for this system, it should be an invaluable tool in our research effort.

II. Research Summary. (References in brackets refer to the publication list of Section III.)

2.1 Periodically Switched Lossless Networks

A study of networks of ideal inductors, capacitors and switches, with the constraint that no loss of energy occurs when the switches are operated periodically, is in progress [B5]. The analysis proceeds from a state-space formulation to give system function descriptions consistent with the general theory of linear networks of lumped, periodically time varying elements. Some properties of the system functions, especially those of one-port and two-port networks which are consequences of the lossless condition have been derived. These are observed as generalisations of analogous properties of linear time-invariant LC network functions. Frequency power formulas are also derived for the class of networks under consideration, and are used to demonstrate, in particular, the possibility of bypassing Page's inverse square law of harmonic generation. The ideal switch defined and used in the analysis is equivalent to the absolutely controlled, bilateral type discussed by Schwarz[1]. A possible solid state simulation of this device at medium power and frequency levels consists essentially of two gate-turn off switches connected in inverse parallel.

1. F.C. Schwarz, "A Class of Nonlinear Active Filters with Application to Electrical Energy Conversion," Ph.D. Thesis, Cornell University, 1965, pp. 6-9.

2.2 General Time Variable Systems

In connection with our more general studies of large and high order time-variable systems, a modelling technique utilizing stochastic processes has been devised. The work has produced a fairly complete theory of shaping filter models for nonstationary random processes. [B1, C1, D1, D2,D3].

2.3 Mathematical models of resistive networks.

Many network elements and devices can reasonably be described by purely resistive nonlinear models. However when a network is constructed by interconnecting these components, the overall network sometimes exhibits undesirable dynamic effects such as unbounded response or unwanted oscillations. This behavior can be traced to the stray inductance and capacitance introduced by the interconnections of the original components. Thus it seems reasonable to expect that we should be able to eliminate undesirable response by controlling the values of the stray elements even though their exact values and locations may not be known.

In fact, by using the theory of Lyapunov functions, we have shown this to be true for a certain class of nonlinear resistive networks. [B3] Work is continuing to extend these results to larger classes of networks.

2.4 Computational Algorithms for Highly Nonlinear Circuits

In the analysis of highly nonlinear circuits two related difficulties often appear: a) the existence of certain nonlinear constraints on the state variables and b) the appearance of widely separated time-constants. Most existing computer programs for network analysis cannot cope efficiently with these problems.

We have been developing a numerical technique that shows considerable promise in dealing with the aforementioned difficulties. It is based upon the computation of limiting solutions of a set of equations containing small parameters. Computational results comparing the method with more conventional approaches indicate a fifteen-fold saving in computation time on typical circuits. [B2, B4] Work is continuing in order to make the computational algorithm more reliable and more generally applicable. We are also planning to do more software development leading eventually to an interactive nonlinear circuit analysis program operating on a time-shared computer system.

2.5 Switched Mode Networks

In developing a unified systems approach to the classification, characterization and analysis of switched-mode electrical power processing networks, the outstanding problem relates to transient and stability analysis. In the literature analyses have not been rigorous, particularly where asynchronously switched electrical power processing networks are concerned. The central objective in the present research therefore is to develop structural and mathematical formulations that will allow complete analysis of such networks where the switching patterns are signal dependent and give rise to complex implicit equations. Using these formulations, suitable design criteria can be established relating to circuit-device parameter interaction in the networks under investigation.

Various pulse modulation techniques have been studied for eventual incorporation into the development of optimal power conversion circuits. This is done, with a view towards subsequent microminiaturization and integration. As part of this effort a tunable and bandwidth adjustable filter has been designed and realized as a switched linear network using integrated circuits. [A2]

2.6 Small Signal Models of Semiconductor Devices

In the course of this research, it was found that the p-n-p-n tetrode could be considered as a linear device. [A 6] The small-signal parameters and equivalent circuits for both low-frequency and high-frequency operation were obtained from the physical geometry, impurity profiles and lifetimes of a typical p-n-p-n tetrode. Novel applications of the tetrode as controllable gain amplifier, multiplier, variable negative-resistance device and carrier-switch modulator were realized. [C 3] Furthermore, a generalized turn-on criterion for a p-n-p-n tetrode was derived.

The small-signal approach was also applied to the thermally-stabilized integrated devices that have a diode-connected transistor. [A 4] It has been shown that the diode-stabilized device is operated with a built-in current-shunt feedback. It has low input impedance, high output impedance and small internal-feedback factor. The frequency response of the device with bias-diode is superior to that without the bias-diode. The device takes advantage of the close matching and thermal coupling of temperature sensitive components in an integrated circuit. Because of the good thermal stability it is a useful basic building block for the processing of the control signal in power systems.

2.7 Design of Power FET's.

In considering the power limitations of semiconductor devices for space applications, our attention has turned to the design of power field-effect transistors (FET). Since the transconductance of the FET decreases with increased temperature it should not be prone to thermal runaway and second breakdown. Furthermore, as a majority-carrier device, its transconductance is insensitive to radiation damage. The basic limitation of a power FET is the channel width and current density in the channel. Various one-dimensional analyses have been used to show the non-zero channel width at pinch-off. However, the current density distribution cannot be obtained by a one-dimensional approach. A two dimensional study is now in progress.

In our investigation of the theory of the FET, we found that a four-terminal junction FET has the property of an analog multiplier. An experimental amplitude modulator was built to verify the multiplification of the two transconductances of the device. The results demonstrated good linearity from low modulation index to 90% modulation. [A5]

III. LIST OF PUBLICATIONS

A. Journal Articles

*1. Stern, T.E., and H.D. Eskin, "State-of-the-Art Oriented Review of CIRCUS," Electro-Technology, October 1967, p. 110.

*2. Glaser, A.B., C.C. Halkias, and H.E. Meadows, "A Tunable Bandwidth Adjustable Filter Using Integrated Circuits," submitted for publication to the Journal of the Franklin Institute.

*3. Stern, T.E., "Reciprocity in Nonlinear Networks," in Aspects of Network and System Theory, N. DeClaris and R.E. Kalman (ed.), Holt, Rinehart, and Winston, 1968.

4. Yang, E.S., "Small-Signal Characteristics of the Diode-Stabilized Linear Integrated Devices," IEEE Journal of Solid-State Circuits, vol. SC-3, pp. 190-193, June 1968.

5. Yang, E.S., "Four-Terminal Field-Effect Transistors for Amplitude Modulation," IEEE Journal of Solid-State Circuits, April 1969

6. Voulgaris, N.C. and Yang, E.S., "Linear Operation of a p-n-p-n Tetrode," IEEE Trans. Electron Devices, May, 1969

B. Meeting Papers

*1. Brandenburg, L.H., and H.E. Meadows, "Generation and Description of a Class of Random Processes," Presented at the 1st Annual Asilomar Conference on Circuits and Systems, November 1-3, 1967.

2. Stern, T.E., "Computer-aided Analysis of Nonlinear Networks," presented at the Summer Seminar on Network Theory, Technion, Israel, August 1968. (Columbia University Technical Report No. 107).

*Five copies of these items forwarded with our semi-annual reported dated January 1968.

3. Sathe, S., and T.E. Stern, "The Effect of Stray Parameters on the Stability of a Class of Nonlinear Networks," presented at the 6th Annual Allerton Conference on Circuit and System Theory, September 1968. (Columbia University Technical Report No. 108.)

4. Stern, T.E., "Computer-aided Analysis of Nonlinear Networks Described by Constrained Differential Equations," presented at the International Symposium on Network Theory, Belgrade, Yugoslavia, September 1968.

5. Awipi, M. and H.E. Meadows, "Periodically Switched Lossless Networks: System Functions and Power Relations" Proceedings of the 2nd Annual Asilomar Conference on Circuits and Systems, November 1, 1968.

C. Theses

1. Brandenburg, L.H., "Shaping Filter Models for Nonstationary Random Processes," 1968.

2. Glaser, A., "A Tunable, Bandwidth Adjustable Filter using Integrated Circuits," 1968.

3. Voulgaris, N.C., "Non-switching Operation of Four-Terminal p-n-p-n Devices," 1968.

D. Technical Reports

1. Brandenburg, L.H., "Shaping Filter Models for Nonstationary Random Processes," (No. 104), June 1968.

2. Brandenburg, L.H., and H.E. Meadows, "Stability Properties of Shaping Filter," (No. 105), July 1968.

3. Brandenburg, L.H., and H.E. Meadows, "Shaping Filter Representation of Colored Noise," (No. 106), July 1968.

4. No. 107. (See paragraph B above.)

5. No. 108. (See paragraph B above.)

E. Technical Memoranda

1. Armanazi, A., and C.C. Halkias, "Switched-Mode Electrical Power Processing Networks," October 1968.