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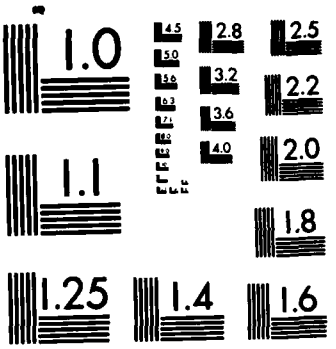

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CALIFORNIA INSTITUTE OF TECHNOLOGY

POWER ELECTRONICS GROUP

EE 116-81

Pasadena, CA 91125

SPONSOR: ONR/NOSC

CONTRACT: N00014-78-C-0757

TITLE: GENERALIZED THEORY AND OPTIMAL TOPOLOGICAL STRUCTURES IN POWER PROCESSING ELECTRONICS

FINAL REPORT

Submitted by: Slobodan Ćuk, Principal Investigator

RESEARCH SUMMARY — ONR/NOSC FINAL REPORT

Period 1980 — 1983

The research performed under the ONR/NOSC contract is summarized in greater detail in the three enclosed progress reports. Each progress report covers approximately one year's research effort.

During the period of the contract and to a large degree inspired directly by it, a large number of papers have been presented at power electronics conferences. Those which directly relate to the work sponsored by ONR/NOSC are included with this report. These and other papers have resulted from other government and industry sponsors and have been included in the 3 volume book "*Advances in Switched-Mode Power Conversion*" and proper acknowledgment of the source of funding was made with each paper.

Research work performed under this contract also resulted in some patent applications which were appropriately listed in the references.

In conclusion, all of the objectives stated in the original 3 year Proposal have been successfully met and in fact, in many instances, substantially surpassed.

CALIFORNIA INSTITUTE OF TECHNOLOGY

POWER ELECTRONICS GROUP

Sponsor: ONR/NOSC

Contract: N00014-78-C-0757

Title: Generalized Theory and Optimal Topological Structures in Power Processing Electronics

PROGRESS REPORT NO. 1

Submitted by: Slobodan Ćuk, Principal Investigator

CONTENTS

RESEARCH SUMMARY - ONR

The first year of the proposed three-year research program has been very successful in completing a number of the proposed tasks, as well as in initiating research in several areas designated for full development in the second and third years.

First, in the area of integrated magnetics analysis and optimization, several new magnetics configurations have been proposed and an anlaysis approach developed for the optimization of these complex magnetic structures.

Second, in the area of dc-to-dc inverters, a new switching amplifier concept has been used to verify its usefulness for variable speed drive of induction (Tesla) motors by use of a single-phase demonstration model at low power level (100W). A new switching technique taking full advantage of the three-phase system has been conceptualized, and is currently under investigation in a higher power (1kW) variable speed drive system for a three-phase induction motor.

Third, research in the area of resonant switching converters, which are at the present time very poorly understood, has resulted in some new analytical results and much better understanding of their operation.

RESEARCH SUMMARY - NOSC

Through the additional support from the Naval Ocean Systems Center in San Diego (NOSC), our modeling and analysis technique (state-space averaging method) has been successfully implemented on a desk-top computer. A companion measurement technique has been implemented on the same desk-top computer resulting in a powerful tool for fast, efficient and very accurate, automated prediction as well as measurement of frequency response of virtually any switching structure (including those yet to be invented).

A manual describing these two software packages is currently in development and will shortly be made available to our sponsors and to industrial users.

Our paper presentation on the same subject at the POWERCON 8 Conference in Dallas (March 1981), and our exhibit of this computerized system at the same conference, convinced us of the tremendous need in industry for such a system.

PAPER PRESENTATIONS

Five papers have been presented at a number of major conferences in the Power Electronics area, such as the Power Electronics Specialists Conference in Boulder, Colorado (June 1981), the Eighth International Solid-State Power Electronics Conference (Powercon 8) in Dallas, Texas (March, 1981), and the IEEE Circuits and Systems Society Conference in Chicago (March 1981). One paper is yet to be presented, at the International Power Conversion Conference in Munich, Germany (September 1981). In addition, several papers have been exclusively written for the two-volume book Advances in Switched-Mode Power Conversion, as introductory papers, in order to bring the reader to the level of the remaining high-level scientific papers contained in the book. One of these papers is appearing in a three-part series in the highly popular Power Conversion magazine, widely used by design engineers.

BOOK PUBLICATION

A two-volume book, Advances in Switched-Mode Power Conversion has just been published, which contains research results and contributions of the Caltech Power Electronics Group for the last ten years. The first volume covers our research in the area of modeling, analysis, and measurement techniques, while the second volume covers our contributions to new converter and inverter topologies.

The book is really a research monograph although, because of additional background and introductory material, it could also be used an an introductory text. It will be used as a textbook in Dr. Ćuk's two-quarter Power Electronics course (EE117), one volume for each quarter. There are some indications that it may be adopted as either a textbook or reference book at some other universities. Springer-Verlag has expressed an interest in republishing the book

for European and Far East areas.

CONFERENCE EXHIBIT

The Power Electronics Group has prepared an exhibit booth at the POWERCON 8 Conference in Dallas, Texas, in which a number of new demonstrations have been shown for the first time. This is the fourth successive time that we have attended this conference in a dual capacity (both as exhibitor and presenting scientific papers), which is unique since there is no other university which has done that in the past.

In addition to the automated computerized system for plotting predicted and measured frequency response of any switching converter, we demonstrated a number of new results: a variable-speed drive of a single-phase induction motor using the Ćuk amplifier; a new B-H loop tester capable of showing material magnetic properties up to 1MHz (also a demonstration of hybrid cores, and gapped magnetic structures); a state of the art, high frequency (500kHz) switching audio amplifier based on the buck power stage and a novel flux sensing technique in a push-pull driven converter preventing its saturation; and a zero-ripple Ćuk converter.

Again, this year as in the past, our presence in the exhibits was one of the main attractions, and gave our students an opportunity to interact and convey many of the research results to the attendees. The actual construction of demonstration equipment was much facilitated by significantly improved laboratory equipment.

LABORATORY FACILITIES

The theoretical work in the Power Electronics area goes hand-in-hand with its complement, experimental work. A significant effort has been expended this year to upgrade our laboratory facilities. In particular, mechanical construction capability and some specialized tools have been developed in order to precisely gap ferrite pot cores and investigate various gapped magnetic structures. Upgrading of the electronic equipment (digital sampled scope) and computer facilities

(new plotter, etc.) is currently underway.

IR AWARD

For contributions to the Power Electronics field, and in particular for the invention of the Ćuk switching converter and a number of its extensions, the IR 100 Award given by Industrial Research magazine for the 100 most significant industrial inventions in 1980 has been given to Drs. Ćuk and Middlebrook on September 18, 1980 in Chicago at the special Awards Banquet. Also a specially prepared exhibit with a Ćuk converter model was on display for a month in the Museum of Science and Industry in Chicago.

A NASA Award for innovation of the high efficiency, light weight DC/DC Ćuk Switching Converter, and its publication in NASA TECH BRIEFS, has been given to Drs. Ćuk and Middlebrook.

REVIEW PRESENTATIONS

Two presentations of our research results have been given so far to our sponsors, IBM and ONR, and several invited talks have been given at the International Power Conversion Society in Los Angeles (November 1980, April and May 1981), and at the IEEE Magnetics Society meeting in Pasadena (April 1981).

STUDENT PROGRESS

During this year several members of the Power Electronics Group accomplished important goals. One of them, Dr. Art Brown, has successfully defended his PhD Thesis, "Topics in the Analysis, Measurement, and Design of High-Performance Switching Regulators," and so became the seventh PhD emerging from our group. Two other members have successfully passed a very difficult PhD oral exam. Two more members will take this exam in the near future. In the coming year we will have three or four new members who have been admitted to the Caltech graduate program.

LIST OF NEW PUBLICATIONS

Papers

[1] R. D. Middlebrook, "Power Electronics: An Emerging Discipline," IEEE International Symposium on Circuits and Systems 1981 Record, Chicago, April 1981. pp. 225-229, (IEEE Publication 81CH1635-2).

[2] R. D. Middlebrook, "Power Electronics: Topologies, Modelling, and Measurement," IEEE International Symposium on Circuits and Systems 1981 Record, Chicago, April 1981. pp. 230-238, (IEEE Publication 81CH1635-2).

[3] R. D. Middlebrook, "Predicting Modulator Phase Lag in PWM Converter Feedback Loops," Proc. Eighth National Solid-State Power Conversion Conference (Powercon 8), Dallas, Texas, April 27-30, 1981. pp. H-4.1-6.

[4] Farhad Barzegar, Slobodan Ćuk, and R. D. Middlebrook, "Using Small Computers to Model and Measure Magnitude and Phase of Regulator Transfer Functions and Loop Gain," Proc. Eighth National Solid-State Power Conversion Conference (Powercon 8), Dallas, Texas, April 27-30, 1981. pp. H-1.1-28.

[5] Arthur R. Brown and R. D. Middlebrook, "Sampled-Data Modeling of Switching Regulators," Power Electronics Specialists Conference, 1981 Record, Boulder, Colorado, June 1981, pp. 349-369, (IEEE Publication 81CH1652-7).

[6] Slobodan Ćuk, "Basics of Switched-Mode Power Conversion: Topologies, Magnetics, and Control," Parts I, II and III, to appear in Power Conversion Magazine, August, September, and October 1981 issues.

Books

[7] R. D. Middlebrook and Slobodan Ćuk, *Advances in Switched-Mode Power Conversion, Vol. I: Modelling, Analysis, and Measurement.* TESLAco, July 1981.

[8] Slobodan Ćuk and R. D. Middlebrook, *Advances in Switched-Mode Power Conversion, Vol. II: Switched-Mode Topologies.* TESLAco, July 1981.

Patents

[9] Slobodan Ćuk, "Dc-to-Dc Switching Converter with Zero Input and Output Current Ripple and Integrated Magnetics Circuits," U.S. Patent Application, March 30, 1979.

[10] Slobodan Ćuk and R. D. Middlebrook, "Dc-to-Dc Converter Having Reduced Ripple Without Need for Adjustments," U.S. Patent Application, June 15, 1979.

CALIFORNIA INSTITUTE OF TECHNOLOGY

POWER ELECTRONICS GROUP

Sponsor: ONR/NOSC

Contract: N00014-78-C-0757

Title: Generalized Theory and Optimal Topological Structures in Power Processing Electronics

PROGRESS REPORT NO. 2

For 1981 – 1982

Submitted by: Slobodan Ćuk, Principal Investigator

RESEARCH SUMMARY – ONR/NOSC 1981 – 1982

In the second year of the research effort, the main effort was directed toward the generalization of the switching topological structures useful for dc-to-dc conversion into their 3-phase equivalents. The original objective of implementing these new switching configurations for variable speed motor drives (such as induction motors) as outlined in Section 5 of the original 3 year Proposal, was successfully completed.

A new polyphase switched-mode amplifier which produces clean 3-phase power was synthesized in a most general way. It's topology consists of 3 current bidirectional switching dc-to-dc converters. Any of the basic dc-to-dc converters may be utilized as it's building blocks, for example, the buck, boost, flyback or Ćuk converter.

A practical demonstration of the newly proposed general polyphase amplifier configuration was made by use of 3 dc-to-dc current bidirectional buck type switching converters, and by use of a 1 hp induction motor. The voltage feedback loop is closed around each output and loop gain compensation appropriately designed.

The motor drive obtained exhibited a very smooth torque, free of torque pulsations, even at a very low speed, mainly due to the high quality (clean sine wave) of the driving waveforms. The comparison with a commercially available 1 hp motor drive, which exhibited torque pulsation and high noise level in its operation, clearly demonstrated the advantage of the new drive method.

Two papers have been presented at the leading power conversion conferences [1,2]. Also a patent has been filed on this new polyphase amplifier configuration.

The work accomplished during this period is also reported in the PhD thesis by Farhad Barzegar [4]. Dr. Barzegar has accepted a research position at Bell Laboratories, where he has continued work on motor drives.

REFERENCES

[1] Farhad Barzegar and Slobodan Ćuk, "Solid-State Drives For Induction Motors: Early Technology to Current Research," IEEE Region 6 Conference, 1982 Record, pp. 92-102 (IEEE Publication 82CH1738-4).

[2] Farhad Barzegar and Slobodan Ćuk, "A New Switched-Mode Amplifier Produces Clean Three-Phase Power," Proc. Ninth International Solid-State Power Conversion Conference (Powercon 9), pp. E3.1-E3.15, July 1982.

[3] Farhad Barzegar and Slobodan Ćuk, U.S. Patent applied for, "A New Polyphase Switching Power Amplifier."

[4] Farhad Barzegar, *Problems in Switched-Mode Dc and Ac Power Conversion*, PhD thesis, California Institute of Technology, May 1983.

CALIFORNIA INSTITUTE OF TECHNOLOGY

POWER ELECTRONICS GROUP

Sponsor: ONR/NOSC

Contract: N00014-78-C-0757

Title: Generalized Theory and Optimal Topological Structures in Power Processing Electronics

PROGRESS REPORT NO. 3

For 1982 – 1983

Submitted by: Slobodan Ćuk, Principal Investigator

RESEARCH SUMMARY – ONR/NOSC 1982 – 1983

The thrust of the research effort in the third year was directed toward yet another class of converter topologies distinct from the Pulse Width Modulated (PWM) type analyzed in the past. They are so-called *resonant converters*. The conventional PWM converters operate with "square" waveforms. Although there are many advantages to this approach, there are also two significant disadvantages: high stress levels on the semiconductor switching devices, and high conducted and radiated electromagnetic interference (EMI) resulting from the large harmonic content of the square waveforms.

With increasing concern about interference problems, and the need to develop an efficient approach at ultra high frequencies (100 kHz to 1 Mega Hz and higher), the resonant converters were studied.

Until the work performed by Caltech's Power Electronics Group, almost no analytical work had been done on resonant converters. Even the complete analytical understanding of its steady-state (dc) properties was lacking. This void was filled with the publication of our paper [1] on the complete Dc Analysis of Series Resonant Converters. In the natural extension which followed shortly thereafter, the state-space averaging technique, developed originally for PWM converters, was appropriately modified and extended to include dynamic (ac) analysis of the resonant converters. The results were reported at the Power Electronics Specialists Conference [2].

This work has also resulted in a PhD thesis by Vatche Vorperian [3]. After completing his doctoral work, Dr. Vorperian was appointed Assistant Professor of Electrical Engineering at Virginia Polytechnic Institute, where he is continuing the research work in the power electronics field, and more specifically, in the area of resonant converters.

During the period of 1981 – 1983, the tremendous productivity of the Power Electronics Group resulted in publication of 21 papers at conferences

and in journals. These were collected in the 3 volumes of "*Advances in Switched-Mode Power Conversion*" published in December 1983.

In conclusion, the original objectives stated in Section 6 of the original 3 year contract have been successfully realized.

REFERENCES

[1] Vatche Vorperian and Slobodan Ćuk, "A Complete DC Analysis of the Series Resonant Converter," IEEE Power Electronics Specialists Conference, 1982 Record, pp. 85-100 (IEEE Publication 82CH1762-4).

[2] Vatche Vorperian and Slobodan Ćuk, "Small-Signal Analysis of the Series Resonant Converter," IEEE Power Electronics Specialists Conference, 1983 Record, pp. 269-282 (IEEE Publication 83CH1877-0).

[3] Vatche Vorperian, *Analysis of Resonant Converters*, PhD thesis, California Institute of Technology, May 1984.

[4] Slobodan Ćuk and R. D. Middlebrook, *Advances in Switched-Mode Power Conversion*, vol. III, TESLAco, Pasadena, CA, 1983.

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