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SCHOOL OF ENGINEERING
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**CENTER FOR SOLID-STATE
POWER CONDITIONING
AND CONTROL**



RESEARCH ON SPACECRAFT ELECTRICAL POWER CONVERSION

Final Report
Research Grant Number NGL-34-001-001
Supplement No. 17

Prepared for
National Aeronautics and Space Administration
Goddard Space Flight Center

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Prepared For
National Aeronautics and Space Administration
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January 31, 1983

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1. BACKGROUND

Research on this project began in the Department of Electrical Engineering at Duke University in May 1961. During the first years of the grant it was funded under Grant Number NSG 152-61. On June 19, 1968 the project was put on the three-year step-funding program of NASA, and the grant number was changed to Grant NGL 34-001-001. The final funding for the grant was Supplement No. 17 which spanned the period March 1, 1976 to February 28, 1979.

2. OVERVIEW

Over the almost eighteen-year period covered by this grant, the U.S. space program came of age. It was an exciting period as technology raced forward on many fronts. For those of us on the faculty at Duke University and our graduate students, it was a real pleasure and honor to have the opportunity to participate in and contribute to the shaping of events in the area of electrical power conversion. To see the design techniques, analyses, and understanding developed during this era being used today to power virtually every computer that is manufactured and every new communications installation is a continuing source of excitement and satisfaction. Much research and development still remains to be done to meet new applications calling for higher power, improved dynamic response, greater reliability and lower costs; but it is clear that acceptance of the new switching-mode approach to electronic power conditioning has firmly caught hold and that all products requiring almost any type of power supply will be the better for it.

Of lasting gratification to all at Duke who participated in the program is the remembrance of the many regular trips we made to Goddard Space Flight Center where we were always warmly welcomed, our results and ideas were critically examined in a constructive environment, meaningful suggestions

were made, clear goals and objectives were set, and we all returned to Duke with enthusiasm to meet the new challenge. Of particular significance and lasting impact on the lives of the graduate students who worked on this program is the high standards of professional performance set and the personal attention given by two of the technical monitors of our project, Mr. Fred Yagerhofer in the early years of the program and in more recent times by Mr. G. Ernest Rodriguez. Both gentlemen were exemplary in all respects.

In this final report, we undertake to summarize the project activities by briefly reviewing in Section 3 the personnel who have been associated in a significant way with the work of the grant. In Section 4, we list in chronological order all publications that were an outgrowth of this grant with the exception of Special Reports to NASA which are listed separately in Section 5. Invention disclosures submitted to NASA as a part of this project are listed in Section 6. Section 7 lists patents that were issued and Section 8 is the concluding section of the report.

3. PERSONNEL

Throughout the course of the grant Professor Thomas G. Wilson served as principal investigator. Bruce A. Wells, Associate Professor in the Department of Electrical Engineering, participated on a part-time basis during the years 1966 to 1970. In 1971, Professor Harry A. Owen, Jr. joined the project as Associate Investigator and continued to serve in that capacity until the end. Drs. Wilson and Owen are both full-time members of the faculty of the Department of Electrical Engineering.

Numerous students, graduate and undergraduate, were associated with the project in many different capacities over the lifetime of the grant. Table I lists the names of those graduate students who had a serious commitment to the project for a period of time greater than one year and contributed in a

meaningful way to one or more of the research publications. Also noted are the years covering their involvement and an indication if a M.S. thesis or Ph.D. dissertation resulted that was based on work related to the project. Some continued to serve for a period of time after completing their dissertations as Post Doctoral Research Associates. An interesting statistic is that eleven of the sixteen persons continue to work professionally in the area of power electronics in industry and in other universities.

TABLE I. GRADUATE STUDENTS WITH MAJOR COMMITMENT TO RESEARCH PROJECT

1. Edward Towson Moore	1961-67	Ph.D. Dissertation (1963)
2. Donald L. Hester	1964-66	Ph.D. Dissertation (1966)
3. William E. Hammond	1964-65	
4. Yuan Yu	1964-68	Ph.D. Dissertation (1967)
5. Ihsan M. H. Babaa	1962-67	Ph.D. Dissertation (1967)
6. Sam Y-M Feng	1966-72	Ph.D. Dissertation (1972)
7. William A. Sander	1966-70	M.S. Thesis (1967) Ph.D. Dissertation (1973)
8. Zen Chen	1968-70	M.S. Thesis (1970)
9. George Dakermadjji	1970-73	
10. Fred C-Y Lee	1971-74	Ph.D. Dissertation (1974)
11. Dan De Yu Chen	1972-75	Ph.D. Dissertation (1975)
12. William W. Burns, III	1968-69 1972-77	Ph.D. Dissertation (1977)
13. Anil K. Ohri	1972-77	Ph.D. Dissertation (1977)
14. Stephen D. Huffman	1975-77	
15. David D. Bahler	1977-78	M.S. Thesis (1978)
16. Ronald C. Wong	1978-79	

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4. PUBLICATIONS

Table II lists in chronological order eighty-one publications in the open literature which were supported in part by this research grant. To provide a complete and comprehensive record of this aspect of the project's activities, this list cites not only complete papers that were published but also abstracts and digests of paper of two or more pages in length that were published separately in the literature. In a number of instances, the same or a very similar manuscript was published in more than one location. These are noted by cross references.

Although financial support under this grant terminated February 28, 1979, additional effort has been expended on the part of faculty members and some former graduate students associated with the project to further develop some of the concepts and ideas that were started during the tenure of the project. These efforts have resulted in seven additional publications over the past three years. These are listed as Items 75 through 81 in the list of publications.

Of particular note should be the fact that two of the papers reporting research results on this grant were singled out by the Aerospace and Electronics Society of the Institute of Electrical and Electronics Engineers to receive special IEEE awards. Paper No. 43, "Computer-Aided Design and Graphics Applied to the Study of Inductor-Energy-Storage DC-to-DC Electronic Power Converters," received the M. Barry Carlton Honorable Mention Award for 1974. It was authored by D.Y. Chen, H.A. Owen, Jr. and T.G. Wilson. Five years later, Paper No. 74, "A State-Trajectory Control Law for DC-to-DC Converters" by W. W. Burns, III and T.G. Wilson, was selected to receive the M. Barry Carlton Award for 1979 "for the best paper published in the Society Transactions in the previous calendar year".

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS

1. "A Self-Oscillating Inverter Using a Saturable Two-Core Transformer to Turn Off Silicon Controlled Rectifiers," E.T. Moore, T.G. Wilson, R.W. Sterling, AIEE Paper No. 62-1029 (June 17-22, 1962). [See also 2.]
2. "A Self-Oscillating Inverter Using a Saturable Two-Core Transformer to Turn Off Silicon Controlled Rectifiers," E.T. Moore, T.G. Wilson, R.W. Sterling, AIEE Transactions, Part I, Communications and Electronics, Vol. 81, pp 429-433 (Jan. 1963). [See also 1.]
3. "Multiple Cores Used to Simulate a Variable Volt-Second Saturable Transformer for Application in Self-Oscillating Inverters," R.W. Sterling, E.T. Moore, T.G. Wilson, Proceedings of the 1963 International Conference on Nonlinear Magnetics (IEEE Special Publication T-149), pp 13-5-1 to 13-5-7 (April 1963). [See also 6.]
4. "Regulated D-C to D-C SCR Converter Employing Nonlinear Two-Core Transformer," T.G. Wilson, E.T. Moore, I.M.H. Babaa, Institute of Electrical and Electronics Engineers Paper No. 63-1090, pp 1-19 (June 1963).
5. "Inverter For Use With Very Low Input Voltages," T. G. Wilson, E.T. Moore, IEEE Paper No. 63-1450 (Oct. 28-30, 1963). [See also 7.]
6. "Multiple Cores Used to Simulate a Variable Volt-Second Saturable Transformer for Application in Self-Oscillating Inverters," R.W. Sterling, E.T. Moore, T.G. Wilson, IEEE Transactions on Communications and Electronics, Vol. 83, pp 288-294 (May 1964). [See also 3.]
7. "Inverter For Use With Very Low Input Voltages," T.G. Wilson, E.T. Moore, IEEE Transactions on Communications and Electronics, Vol. 83, pp 424-428 (July 1964). [See also 5.]
8. "A-C to D-C Power Supply Using High-Frequency Techniques For Size Reduction," E.T. Moore, T.G. Wilson, Proceedings of the National Electronics Conference, Vol. 20, pp 118-123 (Oct. 1964).
9. "D-C to D-C Converter Using Inductive-Energy Storage for Voltage Transformation and Regulation," I.M.H. Babaa, E.T. Moore, T.G. Wilson, Y. Yu, W.E. Hammond, Proceedings of the 1965 International Conference on Magnetics (IEEE Publication 33C4), pp 13.4-1 to 13.4-7 (April 1965). [See also 11.]
10. "A D-C to D-C Converter Using Two Synchronized Complementary Converters," W.E. Hammond, T.G. Wilson, I.M.H. Babaa, E.T. Moore, Y. Yu, Supplement to IEEE Transactions on Aerospace, Vol. AS-3, No. 2, pp 201-209 (June 1965).
11. "D-C to D-C Converter Using Inductive-Energy Storage for Voltage Transformation and Regulation," I.M.H. Babaa, E.T. Moore, T.G. Wilson, Y. Yu, W.E. Hammond), IEEE Transactions on Magnetics, Vol. MAG-2, No. 1, pp 18-25 (March 1966). [See also 9.]

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS (Cont.)

12. Abstract of "Basic Considerations for DC to DC Conversion Networks," E.T. Moore, T.G. Wilson, 1966 Abstracts of the International Conference on Magnetics, p 16-2 (April 1966). [See 14 for full paper.]
13. Abstract of "Analytical Model for Describing the Operation of the Marzolf Tunnel Diode Inverter," D.L. Hester, T.G. Wilson, Y. Yu, 1966 Abstracts of the International Conference on Magnetics, p. 16.6 (April 1966). [See 15 for full paper.]
14. "Basic Considerations for DC to DC Conversion Networks," E.T. Moore, T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-2, No. 3, pp 620-624 (Sept. 1966). [See 12 for Abstract.]
15. "Analytic Model for Describing the Operation of the Marzolf Tunnel Diode Inverter," D.L. Hester, T.G. Wilson, Y. Yu, IEEE Transactions on Magnetics, Vol. MAG-2, No. 3, pp 632-638 (Sept. 1966). [See 13 for Abstract.]
16. "DC to DC Converter Controlled by a Magnetically-Coupled Multivibrator with Asymmetrical Output," Y. Yu, T.G. Wilson, I.M.H. Babaa, E.T. Moore, Proceedings of the National Electronics Conference, Vol. 22, pp 265-270 (Oct. 1966).
17. Abstract of "A Static DC to Sinusoidal AC Inverter Using Techniques of High-Frequency Pulse-Width Modulation," Y. Yu, T.G. Wilson, I.M.H. Babaa, S.Y.M. Feng, E.T. Moore, 1967 Abstracts of the International Conference on Magnetics, p. 3.7 (April 1967). [See 18 for full paper.]
18. "Static DC to Sinusoidal AC Inverter Using Techniques of High-Frequency Pulse-Width Modulation," Y. Yu, T.G. Wilson, I.M.H. Babaa, S.Y.M. Feng, E.T. Moore, IEEE Transactions on Magnetics, Vol. MAG-3, No. 3, pp 250-256 (Sept. 1967). [See 17 for Abstract.]
19. "Analog Computer Simulation of a DC-to-DC Flyback Converter," B.A. Wells, B.T. Brodie, I.M.H. Babaa, Supplement to IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-3, pp. 399-409 (Nov. 1967).
20. "The Nonlinear Theory of a Class of Transistor Oscillators," Donald L. Hester, IEEE Transactions on Circuit Theory, Vol. 15, No. 2, pp. 111-118 (June 1968).
21. "Analytic Solutions of Limit Cycles in a Feedback-Regulated Converter System with Hysteresis," I.M.H. Babaa, T.G. Wilson, Y. Yu, IEEE Transactions on Automatic Control, Vol. AC-13, No. 5, pp 524-531 (Oct. 1968).
22. "DC to DC Converter Regulated by a Constant-Frequency Duty-Cycle Generator," I.M.H. Babaa, T.G. Wilson, Y. Yu, Proceedings of the National Electronics Conference, Vol. 24, pp 291-296 (Dec. 1968).

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS (Cont.)

23. "Effect of Leakage and Source Inductances on the Switching Pattern of a Magnetically-Coupled Tunnel Diode Oscillator," D.L. Hester, Y. Yu, T.G. Wilson, 1969 Abstracts of the INTERMAG Conference, p. 11.4 (April 1969). [See also 25. See 30 for full paper.]
24. "Small-Capacitance Nondissipative Ripple Filter for DC Supplies," S.Y.M. Feng, W.A. Sander, III, T.G. Wilson, 1969 Abstracts of the INTERMAG Conference, p. 11.7 (April 1969). [See also 26. See 29 for full paper.]
25. "Effect of Leakage and Source Inductances on the Switching Pattern of a Magnetically Coupled Tunnel-Diode Oscillator," D.L. Hester, Y. Yu, T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-5, No. 3, pp 352-353 (Sept. 1969). [See also 23. See 30 for full paper.]
26. "Small-Capacitance Nondissipative Ripple Filter for DC Supplies," S.Y.M. Feng, W.A. Sander, III, IEEE Transactions on Magnetics, Vol. MAG-5, No. 3, pp 354-355 (Sept. 1969). [See also 24. See 29 for full paper.]
27. "The Influence of Circuit Parameters on the Harmonics of a PWM DC-to-Sinusoidal Inverter," Y. Yu, T.G. Wilson, I.M.H. Babaa, S.Y.M. Feng, W.A. Sander, III), Proceedings of 8th Annual 1969 IEEE Region III Convention, IEEE No. 69 C46-Reg. III, pp 232-239 (Nov. 1969).
28. "Optimum Toroidal Inductor Design Analysis," S.Y.M. Feng, T.G. Wilson, W.A. Sander, III, IEEE Proceedings of 1970 20th Electronic Components Conference, IEEE No. 70 C12-PMP, pp 337-347 (May 1970).
29. "Small-Capacitance Nondissipative Ripple Filters for DC Supplies," S.Y.M. Feng, W.A. Sander, III, T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-6, No. 1, pp 137-142 (March 1970). [See 24 and 26 for Abstract.]
30. "Effect of Leakage and Source Inductances on the Switching Pattern of a Magnetically Coupled Tunnel Diode Oscillator," D.L. Hester, Y. Yu, T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-6, No. 4, pp. 840-844 (Dec. 1970). [See also 23 and 25 for Abstract.]
31. "Very-High-Frequency DC-to-DC Conversion and Regulation in the Low-Megahertz Range," S.Y.M. Feng, T.G. Wilson, W.A. Sander, III, Power Conditioning Specialists Conference Record 1971, IEEE Publication 71 C15-AES, pp 58-65 (April 1971).
32. "Regulated DC-to-DC Converter for Voltage Step-Up or Step-Down with Input-Output Isolation," S.Y.M. Feng, T.G. Wilson, G. Dakermadjji, F.C.Y. Lee, Proceedings of the IEEE Fall Electronics Conference 1971, IEEE Publication 71 C64-FEC, pp 338-343 (Oct. 1971).
33. "A Computer-Aided Design Procedure for Flyback Step-Up DC-to-DC Converters," H.A. Owen, Jr., T.G. Wilson, S.Y.M. Feng, F.C.Y. Lee, 1972 Digest of the International Magnetics Conference, IEEE Publication CHO 592-6 MAG, p. 4.4 (April 1972). [See 38 for full paper.]

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS (cont.)

34. "Analysis of Limit Cycles in a Two-Transistor Saturable-Core Parallel Inverter," F.C.Y. Lee, T.G. Wilson, S.Y.M. Feng, Proceedings IEEE Power Processing and Electronics Specialists Conference, IEEE Publication 72-CHO-652-8-AES, pp 36-47 (May 1972). [See also 42.]
35. "Computer-Aided Design and Graphics Applied to the Study of Inductor-Energy-Storage DC-to-DC Electronic Power Converters," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, Proceedings IEEE Power Processing and Electronics Specialists Conference, IEEE Publication 72-CHO-652-8-AES, pp 59-70 (May 1972). [See also 43.]
36. "Phase-Plane Analysis of a Nonlinearly Controlled Self-Oscillating Step-Up or Step-Down DC-to-DC Converter," T.G. Wilson, S.Y.M. Feng, H.A. Owen, Jr., Proceedings IEEE Workshop on Applied Magnetics, IEEE Publication 72-CH-629-6-MAG, pp 68-69 (May 1972).
37. "Development of a Continuous Linear Model of a DC-to-DC Flyback Converter," Bruce A. Wells, Proceedings of Workshop on Applied Magnetics, IEEE Publication 72 CH 629-6-MAG, pp. 62-67 (May 1972).
38. "A Computer-Aided Design Procedure for Flyback Step-Up DC-to-DC Converters," H.A. Owen, Jr., T.G. Wilson, S.Y.M. Feng, F.C.Y. Lee, IEEE Transactions on Magnetics, Vol. MAG-8, No. 3, pp 289-291 (Sept. 1972). [See 33 for Digest.]
39. "Computer-Aided Design of Two-Winding Voltage-Step-Up/Current-Step-Up Constant-Frequency DC-to-DC Converters," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, 1973 Digests of the International Magnetics Conference, IEEE Magnetics Society, p. 10.1 (April 1973). [See 44 for full paper.]
40. "Analysis, Modeling, and Normalization of a Group of Two-Transistor Parallel Inverters," F.C.Y. Lee, T.G. Wilson, 1973 Digest of the International Magnetics Conference, IEEE Magnetics Society, p. 20.5 (April 1973). [See 45 for full paper.]
41. "Analysis of Starting Circuits for a Class of Hard Oscillators: Two-Transistor Saturable-Core Parallel Inverters," F.C.Y. Lee, T.G. Wilson, PESC-73 Record IEEE Power Electronics Specialists Conference 1973, IEEE Publication 73 CHO 787-2-AES, pp 118-129 (June 1973). [See also 46.]
42. "Analysis of Limit Cycles in a Two-Transistor Saturable-Core Parallel Inverter," F.C.Y. Lee, T.G. Wilson, S.Y.M. Feng, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-9, No. 4, pp 571-584 (July 1973). [See also 34.]
43. "Computer-Aided Design and Graphics Applied to the Study of Inductor-Energy-Storage dc-to-dc Electronic Power Converters," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-9, No. 4, pp 585-597 (July 1973). [See also 35.]

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS (Cont.)

44. "Design of Two-Winding Voltage Step-Up/Current Step-Up Constant-Frequency DC-to-DC Converters," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-9, No. 3, pp 252-256 (Sept. 1973). [See 39 for Digest.]
45. "Analysis and Modeling of a Family of Two-Transistor Parallel Inverters," F.C.Y. Lee, T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-9, No. 3, pp 414-418 (Sept. 1973). [See 40 for Digest.]
46. "Analysis of Starting Circuits for a Class of Hard Oscillators: Two-Transistor Saturable-Core Parallel Inverters," F.C.Y. Lee, T.G. Wilson, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-10, No. 1, pp 100-112 (Jan. 1974). [See also 41.]
47. "Voltage-Spike Analysis and Suppression for a Free-Running Parallel Inverter," F.C.Y. Lee, T.G. Wilson, 1974 Digest of International Magnetics Conference INTERMAG, IEEE Magnetics Society, p. 36.4 (May 1974). [See 51 for full paper.]
48. "Digital Computer Simulation of Inductor-Energy-Storage Converters with Closed-Loop Regulators," A.K. Ohri, H.A. Owen, Jr., T.G. Wilson, G.E. Rodriguez, Spacecraft Power Conditioning Seminar Abstracts, European Space Research Organization, ESRO, Frascati, Italy, pp 1-4 (May 1974). [See 52 for full paper.]
49. "Nonlinear Analysis of a Family of LC Tuned Inverters," F.C.Y. Lee, T.G. Wilson, PESC-74 Record IEEE Power Electronics Specialists Conference 1974, IEEE Publication 74 CHO 863-1 AES, pp 223-231 (June 1974). [See also 53.]
50. "Relationships Among Classes of Self-Oscillating Transistor Parallel Inverters," T.G. Wilson, F.C.Y. Lee, W.W. Burns, III, H.A. Owen, Jr., PESC-74 Record IEEE Power Electronics Specialists Conference 1974, IEEE Publication 74 CHO 863-1 AES, pp 233-236 (June 1974). [See also 54.]
51. "Voltage-Spike Analysis for a Free-Running Parallel Inverter," F.C.Y. Lee, T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-10, No. 3, pp 969-972 (Sept. 1974). [See also 47 for Digest.]
52. "Digital Computer Simulation of Inductor-Energy-Storage Converters with Closed-Loop Regulators," A.K. Ohri, H.A. Owen, Jr., T.G. Wilson, G.E. Rodriguez, Spacecraft Power-Conditioning Electronics Seminar, ESRO SP-103, European Space Research Organization, pp 245-251 (Sept. 1974). [See also 48 for Summary.]
53. "Nonlinear Analysis of a Family of LC Tuned Inverters," F.C.Y. Lee, T.G. Wilson, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-11, No. 2, pp 169-179 (March 1975). [See also 49.]

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS (Cont.)

54. "Relationships Among Classes of Self-Oscillating Transistor Parallel Inverters," T.G. Wilson, F.C.Y. Lee, W.W. Burns, III, H.A. Owen, Jr., IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-11, No. 2, pp 238-244 (March 1975). [See also 50.]
55. "Design of Air-Gapped Iron-Core Inductors for Superimposed Direct and Alternating Currents," A.K. Ohri, T.G. Wilson, H.A. Owen, Jr., 1975 Digest of International Magnetics Conference and INTERMAG, IEEE Magnetics Society, p II.7 (April 1975). [See 64 for full paper.]
56. "Design of Energy-Storage Transformers for Two-Winding Voltage Step-Up/Current Step-Up Converters with Constant On-Time and Constant Off-Time Controllers," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, 1975 Digest of International Magnetics Conference INTERMAG, IEEE Magnetics Society, p. II.1 (April 1975).
57. "Analysis and Design of a Rectifier LC-Filter Circuit for Continuous- and Discontinuous-Conduction Modes," A.K. Ohri, T.G. Wilson, H.A. Owen, Jr., 1975 Proceedings of Applied Magnetics Workshop, IEEE Publication 75 CHO 964-7MAG, pp 3B2.1-3B2.15 (June 1975).
58. "Energy Balance Constraints Affecting the Design of Energy-Storage DC-to-DC Converters," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, 1975 Proceedings of Applied Magnetics Workshop, IEEE Publication 75 CHO 964-7MAG, pp 3B4.1-3B4.22 (June 1975).
59. "Table-Aided Design of the Energy-Storage Reactor in DC-to-DC Converters," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, PESC-75 Record IEEE Power Electronics Specialists Conference 1975, IEEE Publication 75-CHO 965-4 AES, pp 113-125 (June 1975). [See also 61.]
60. "A Digital Computer Simulation and Study of a Direct-Energy-Transfer Power-Conditioning System," W.W. Burns, III, H.A. Owen, Jr., T.G. Wilson, G.E. Rodriguez, J. Paulkovich, PESC-75 Record IEEE Power Electronics Specialists Conference 1975, IEEE Publication 75-CHO 965-4 AES, pp 138-149 (June 1975).
61. "Table-Aided Design of the Energy-Storage Reactor in DC-to-DC Converters," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-12, No. 3, pp 374-386 (May 1976). [See also 67.]
62. "Energy Transfer and Storage in a Voltage Step-Up DC-to-DC Converter," W.W. Burns, III, T.G. Wilson, 1976 Power Electronics Specialists Conference Preview and Digest of Conference Papers, pp 59-60 (June 1976). [See 63 for full text of modified paper.]
63. "State-Plane Trajectories Used to Observe and Control the Behavior of a Voltage Step-Up DC-to-DC Converter," W.W. Burns, III, T.G. Wilson, PESC-76 Record IEEE Power Electronics Specialists Conference 1976, IEEE Publication 76CH 1084-3 AES, pp 212-222 (June 1976). [See 62 for Digest. See also 65.]

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS (Cont.)

64. "Design of Air-Gapped Magnetic-Core Inductors for Superimposed Direct and Alternating Currents," A.K. Ohri, T.G. Wilson, H.A. Owen, Jr., IEEE Transactions on Magnetics, Vol. MAG-12, No. 5, pp 564-574 (Sept. 1976). [See 55 for Digest.]
65. "State Trajectories Used to Observe and Control DC-to-DC Converters," W.W. Burns, III, T.G. Wilson, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-12, No. 6, pp 706-717 (Nov. 1976). [See also 63.]
66. "Design of Type-C Core Single-Winding Energy-Storage Reactors for DC-to-DC Converters", A.K. Ohri, T.G. Wilson, H.A. Owen, Jr., 1977 Digest of International Magnetics Conference INTERMAG, IEEE Magnetics Society, p. 7.3 (June 1977). [See 71 for full paper.]
67. "Analytic Derivation and Evaluation of a State-Plane-Trajectory Control Law for DC-to-DC Converters," W.W. Burns, III, T.G. Wilson, 1977 Power Electronics Specialists Conference Preview and Digest of Conference Papers, pp 44-46 (June 1977). [See 69 and 74 for full paper.]
68. "Fast-Response Free-Running Frequency-Stabilized DC-to-DC Converter Employing a State-Plane-Trajectory Control Law," S.D. Huffman, W.W. Burns, III, T.G. Wilson, H.A. Owen, Jr., 1977 Power Electronics Specialists Conference Preview and Digest of Conference Papers, pp 94-97 (June 1977). [See 70 for full paper.]
69. "Analytic Derivation and Evaluation of a State-Trajectory Control Law for DC-to-DC Converters," W. W. Burns, III, T.G. Wilson, PESC-77 Record IEEE Power Electronics Specialists Conference 1977, IEEE Publication 77CH 1213-8 AES, pp 70-85 (June 1977). [See 67 for Digest. See also 74.]
70. "Fast-Response Free-Running DC-to-DC Converter Employing a State-Plane-Trajectory Control Law," S.D. Huffman, W.W. Burns, III, T.G. Wilson, H.A. Owen, Jr., PESC-77 Record IEEE Power Electronics Specialists Conference 1977, IEEE Publication 77CH 1213-8 AES, pp 180-189 (June 1977). [See 68 for Digest.]
71. "Design of Single-Winding Energy-Storage Reactors for DC-to-DC Converters using Air-Gapped Magnetic-Core Structures", A.K. Ohri, T.G. Wilson, H.A. Owen, Jr., IEEE Transactions on Magnetics, Vol. MAG-13, No. 5, pp 1214-1216 (Sept. 1977). [See 66 for Digest.]
72. "Synthesis and Implementation of a State-Trajectory Control Law for DC-to-DC Converters," W.W. Burns, III, S.D. Huffman, T.G. Wilson, H.A. Owen, Jr., Third ESTEC Spacecraft Power Conditioning Seminar Abstracts, Noordwijk, The Netherlands, pp 95-96 (Sept. 1977). [See 73 for full paper.]
73. "Synthesis and Implementation of a State-Trajectory Control Law for DC-to-DC Converters," W.W. Burns, III, S.D. Huffman, T.G. Wilson, H.A. Owen, Jr., Proceedings of the Third ESTEC Spacecraft Power Conditioning Seminar, ESA SP 126, European Space Agency, pp 281-296 (Sept. 1977). [See 72 for Abstract.]

TABLE II. CHRONOLOGICAL LISTING OF PUBLICATIONS (Cont.)

74. "A State-Trajectory Control Law for DC-to-DC Converters," W.W. Burns, III, T.G. Wilson, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-14, No. 1, pp 1-20 (Jan. 1978). [See 67 for Digest. See also 79.]
75. "Nonlinear Analysis of Voltage-Spike Generation and Suppression for a Free-Running Parallel Inverter," F.C. Lee, T.G. Wilson, Industry and Applications Society Conference Record, 1979 Annual Meeting, IEEE Publication 79CH 1484-51A, pp 414-420 (Sept. 1979).
76. "Design of Energy-Storage Reactors for Single-Winding Constant-Frequency DC-to-DC Converters Operating in the Discontinuous-Reactor-Current Mode," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, 1980 Digest of International Magnetics Conference INTERMAG, IEEE Magnetics Society Publication 80CH1541-2 MAG, p 20-3 (April 1980). [See 77 for full paper.]
77. "Design of Energy-Storage Reactors for Single-Winding Constant-Frequency DC-to-DC Converters Operating in the Discontinuous-Reactor-Current Mode," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, IEEE Transactions on Magnetics, Vol. MAG-16, No. 6, pp 1422-1426 (Nov. 1980). [See 76 for Digest.]
78. "Design of Reactors for Single-Winding Constant ON-Time and Constant OFF-Time Converters Operating in the Discontinuous Mode," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, T.G. Wilson, Jr., 1981 Digest of International Magnetics Conference INTERMAG, IEEE Magnetics Society Publication, p 35-8 (May 1981). [See 79 for full paper.]
79. "Design of Reactors for Single-Winding Constant ON-Time and Constant OFF-Time Converters Operating in the Discontinuous Mode," D.Y. Chen, H.A. Owen, Jr., T.G. Wilson, T.G. Wilson, Jr., IEEE Transaction on Magnetics, Vol. MAG-17, No. 6, pp 3290-3292 (Nov. 1981). [See 78 for Digest.]
80. "State-Plane Analysis, Classification, and Duality Relationship of Several Classes of Self-Oscillating Parallel Inverters, Part I - State-Plane Representation," F.C. Lee, T.G. Wilson, IEEE Transactions on Circuits and Systems, Vol. CAS-29, No. 6, pp 355-365 (June 1982).
81. "State-Plane Analysis, Classification, and Duality Relationship of Several Classes of Self-Oscillating Parallel Inverters, Part II - Model Extension, Classification, and Duality Relationships," F.C. Lee, T.G. Wilson, IEEE Transactions on Circuits and Systems, Vol. CAS-29, No. 6, pp 366-374 (June 1982).

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5. SPECIAL REPORTS

In addition to articles in the open literature which served as the principal means of reporting significant research results accomplished during the course of the project, fourteen special reports were prepared and submitted. These reports, which are listed in Table III, often constitute longer documents with greater detail of information than could be accommodated in a paper in some journal. Some of these special reports are M.S. theses or Ph.D. dissertations prepared by graduate students working on this grant.

6. INVENTION DISCLOSURES

During the course of the grant some twenty-one invention disclosures were submitted to NASA. The titles and dates of these disclosures are given in Table IV.

7. PATENTS

Of the twenty-one invention disclosures, four resulted in the issuance of U.S. Patents. These are enumerated in Table V. In the case of items 1,2 and 4, waivers were requested by the University and/or the inventors and the costs of obtaining a patent were borne by them. In the case of item 3, the patent was obtained by NASA-engaged attorneys.

8. CONCLUSION

To the best of the Principal Investigator's knowledge, this final report represents an accurate and complete summary of all technical aspects of the research carried out under this grant.

TABLE III. SPECIAL REPORTS

1. ELECTRICAL SYSTEM PROTECTION, J.T. McKee1, E.T. Moore, C.D. Parker, R.W. Sterling, T.G. Wilson (October 30, 1961).
2. STATIC ELECTRICAL-TO-ELECTRICAL ENERGY CONVERSION FROM DIRECT CURRENT SOURCES, Edward Towson Moore, Appendix J of Fourth Report (June 30, 1963).
3. REPORT ON FEASIBILITY STUDY OF LIQUID-METAL SWITCH, E.T. Moore, T.G. Wilson (July 1964).
4. ANALYSIS OF THE MARZOLF TUNNEL DIODE INVERTER USING TECHNIQUES OF NONLINEAR MECHANICS, D.L. Hester, T.G. Wilson, Yuan Yu (April 15, 1966).
5. A STUDY OF THE VOLTAGE STEP-DOWN DC-TO-DC REGULATED CONVERTER WITH HYSTERETIC BISTABLE TRIGGER: ANALYSIS WITH EMPHASIS ON DESIGN, Ihsan M.H. Babaa (January 31, 1967).
6. ANALYSIS OF PERFORMANCES FOR STATIC POWER-CONDITIONING SYSTEMS: INVERSION, CONVERSION, AND REGULATION, Yuan Yu (January 31, 1967).
7. A STATIC DC-DC REGULATED CONVERTER USING A TWO-CORE OUTPUT TRANSFORMER, William August Sander, III (August 31, 1967).
8. LIMIT CYCLE ANALYSIS OF A TRANSISTOR OSCILLATOR, Zen Chen (August 25, 1970).
9. STATIC DC TO DC POWER CONDITIONING-ACTIVE RIPPLE FILTER, 1 MHZ DC TO DC CONVERSION, AND NONLINEAR ANALYSIS, William August Sander, III (March 23, 1973).
10. ANALYSIS OF TRANSIENT CHARACTERISTICS AND STARTING OF A FAMILY OF POWER CONDITIONING CIRCUITS: TWO-TRANSISTOR SATURABLE-CORE PARALLEL INVERTERS, Fred Chai Yan Lee (April 16, 1974).
11. DESIGN OF ENERGY STORAGE REACTORS FOR DC-TO-DC CONVERTERS, De Yu Chen (August 18, 1975).
12. A THEORY OF CONTROL FOR A CLASS OF ELECTRONIC POWER PROCESSING SYSTEMS: ENERGY-STORAGE DC-TO-DC CONVERTERS, William W. Burns, III (April 25, 1977).
13. AIR-GAPPED STRUCTURES AS MAGNETIC ELEMENTS FOR USE IN POWER PROCESSING SYSTEMS, Anil Kumar Ohri (July 6, 1977).
14. MEASUREMENT TECHNIQUES FOR THE CHARACTERIZATION IN THE FREQUENCY DOMAIN OF REGULATED ENERGY-STORAGE DC-TO-DC CONVERTERS, David Dean Bahler (August 16, 1978).

TABLE IV. INVENTION DISCLOSURES SUBMITTED TO NASA

1. "A New Method for Turning Off the Silicon Controlled Rectifier," Edward T. Moore, Thomas G. Wilson, NASA Disclosure No. 277, January 12, 1962.
2. "A New D-C to A-C Parallel Inverter," Edward T. Moore, Thomas G. Wilson, NASA Disclosure No. 276, January 12, 1962.
3. "A New Transistorized D-C to A-C Converter," Edward T. Moore, Thomas G. Wilson, NASA Disclosure No. 275, January 12, 1962.
4. "An Electrically Controlled Liquid Switch," Edward T. Moore, NASA Disclosure No. 487, June 29, 1962,
5. "Simultaneous Reverse Bias of Converter Transistors," Robert W. Sterling, Edward T. Moore, Thomas G. Wilson, NASA Disclosure No. 542, August 10, 1962.
6. "A Regulated Converter Employing Simultaneous Reverse Bias," Robert W. Sterling, Edward T. Moore, Thomas G. Wilson, August 10, 1962.
7. "A Simple and Efficient Regulated D-C to D-C Converter with Constant Average Output Voltage Employing a Reverse Biasing Method," Robert W. Sterling, Edward T. Moore, Thomas G. Wilson, August 10, 1962.
8. "A Closed Loop D-C to D-C Regulated Converter Employing a Reverse Biasing Method," Robert W. Sterling, Edward T. Moore, Thomas G. Wilson, August 10, 1962.
9. "Overload Protection Obtained by a Reverse Biasing Method," Robert W. Sterling, Edward T. Moore, Thomas G. Wilson, August 10, 1962.
10. "Frequency Controllable Trigger Circuit," Edward T. Moore, NASA Disclosure No. 668, November 19, 1962.
11. "Circuitry for Controlling Transient Voltages and Currents at the Input and Output of Averaging Filters," Edward T. Moore, Thomas G. Wilson, NASA Disclosure No. 669, November 19, 1962.
12. "Variable-Frequency Transistor Inverters Using Multiple-Core Transformers," Robert W. Sterling, Edward T. Moore, Thomas G. Wilson, NASA Disclosure No. 748, January 22, 1963.
13. "Inverter for Use with Very Low Input Voltages," Edward T. Moore, Thomas G. Wilson, NASA Disclosure No. 1,006, June 3, 1963.
14. "A Transistorized Regulated Converter," Edward T. Moore, NASA Case No. 2465, October 23, 1963.
15. "A Constant-Frequency Voltage to Duty Cycle Generator," Ihsan M. H. Babaa, August 24, 1967.

16. "An Unconventional Magnetically-Coupled Multivibrator," Yuan Yu, Edward T. Moore, March 11, 1968.
17. "A Small-Capacitance Nondissipative Passive Ripple Filter for DC Supplies," Sam Y.M. Feng, William A. Sander, III, Thomas G. Wilson, June 22, 1970.
18. "A Small-Capacitive Nondissipative Active Ripple Filter for DC Supplies," William A. Sander, III, Sam Y.M. Feng, Thomas G. Wilson, June 22, 1970.
19. "Bistable-Voltage to Duty-Cycle Encoder," Sam Yun-Ming Feng, Thomas G. Wilson, August 30, 1971.
20. "Regulated DC-to-DC Converter for Voltage Step-Up or Step-Down with Input-Output Isolation," Sam Yun-Ming Feng, Thomas G. Wilson, August 31, 1971.
21. "A System State and Operating-Condition Sensitive Control Technique for Electronic Power Processing Systems," William W. Burns, III, Thomas G. Wilson, NASA Case No. GSC 12,233-1, December 22, 1976.

TABLE V. U.S. PATENTS

1. "Inverter Circuitry Using Controlled Rectifiers," E.T. Moore, T.G. Wilson, U.S. Patent No. 3,281,644 (October 25, 1966).
2. "Turn-Off Circuitry for Silicon Controlled Rectifiers and Other Thyatron-Like Devices," E.T. Moore, T.G. Wilson, U.S. Patent No. 3,299,279 (January 17, 1967).
3. "Regulated DC-to-DC Converter for Voltage Step-Up or Step-Down with Input-Output Isolation," S.Y-M Feng, T.G. Wilson, U.S. Patent No. 3,771,040 (November 6, 1973).
4. "System-State and Operating Condition Sensitive Control Method and Apparatus for Electric Power Delivery Systems," W.W. Burns, III, T.G. Wilson, U.S. Patent No. 4,084,103 (April 11, 1978).