Power Electronics in Space: A Review and Projection

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Power electronics has emerged as a distinct field of electrical engineering in recent years. This emergence is closely linked with the development of power control and conversion equipment for space application over the last 20 years. Development of switched-mode power conversion techniques has been the dominant activity in this field, spurred by both the improvements in solid-state power devices and the needs of space systems for light weight, highly efficient techniques for dc power regulation. This history is reviewed and projections are made in the four key areas of circuit fundamentals, components, circuit practice, and applications.

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I. INTRODUCTION

The new field of power electronics is an especially appropriate topic for the Aerospace and Electronic Systems Society in this centennial year of the IEEE for several reasons:

(1) The field, although new in its "label" and in the terms of the possibilities introduced by solid state power devices, still embraces the earliest applications of electricity: lighting, motive power, and regulation equipment.

(2) The development of power electronics technology has been intimately connected with the space program, i.e., the need to develop light weight, highly efficient devices for power regulation and control.

(3) The recognition of power electronics as a field has been enabled and promoted by the Aerospace and Electronic Systems Society in its Power Electronics Specialists Conference (now 15 years old) and most recently by the formation of a Power Electronics Council.

Power electronics technology, as it has been used for space application and what the future holds for this application, is reviewed here in terms of four key aspects:

(1) fundamental concepts—addressing the theoretical and analytical aspects of power conversion;
(2) component technology—addressing device performance as it relates to circuit application;
(3) circuit concepts and practice—addressing the types of circuits used;
(4) applications.

In what follows it will be helpful to refer to some fundamental power converter circuits by their common labels. Shown in Figs. 1 and 2 these serve to portray a sampling of the circuit technology which comprises the practice of power electronics. These are all switched-mode power converters which utilize controlled switch action to achieve power control and conversion. The switch control is most commonly (for space) pulsewidth modulation.

The single-ended regulator circuits of Fig. 1 are especially important. Although lacking transformers in their implementation, they nevertheless possess true transformer action subject to input/output voltage ordering restrictions. The second class of converters, some of which are shown in Fig. 2, are a much larger group and are at least as varied as are the possibilities for transformer designs and connections.

The history of power electronics for space applications, spanning more than 20 years, is virtually a chronicle of switched-mode power conversion development as will be seen in this review.

II. FUNDAMENTAL UNDERSTANDING

One measure of the maturity of a technical speciality is the degree to which the underlying general principles

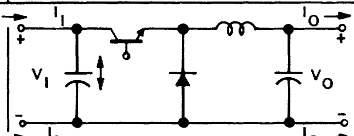
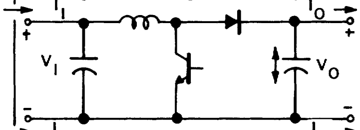
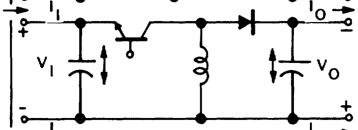
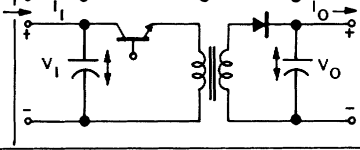
TOPOLOGY	SCHEMATIC	AC CURRENT	V_{CE}	$I_C(PK)$	LIMITING DC LOSS	L(WT)
BUCK		INPUT	$2V_O$	I_O	2/3 VD	XI
BOOST		OUTPUT	V_O	$2I_O$	$V_D + 2\ V_{CES}$	X1
BUCK-BOOST		INPUT OUTPUT	$2V_O$	$3I_O$	$V_D + 2\ V_{CES}$	X.6
BUCK-BOOST		INPUT OUTPUT	$2V_I$	$3I_I$	$V_D + 2\ V_{CES}$	X1.6

Fig. 1. Comparison of regulator types.

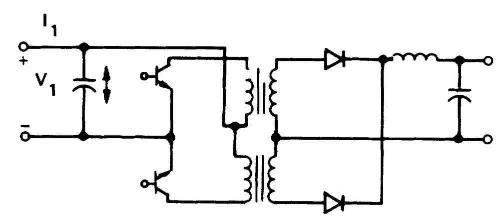
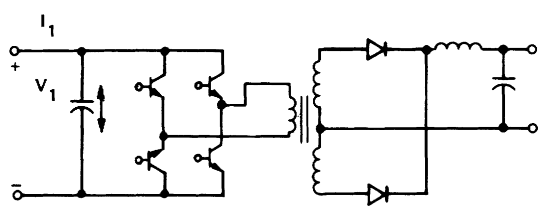
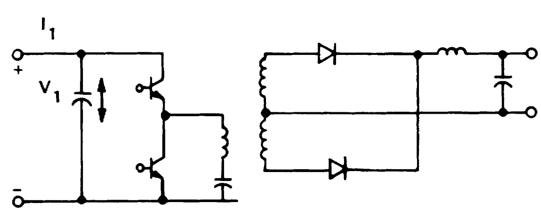
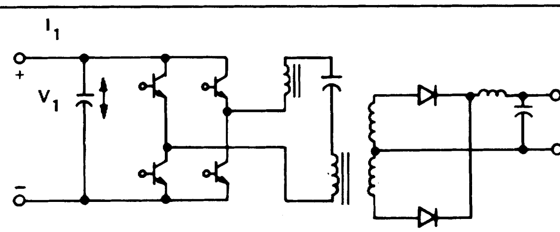
TOPOLOGY	SCHEMATIC	AC CURRENT	V_{CE}	$I_C(PK)$	V_1 LIMIT
PARALLEL			$2V_1$	I_1	200V
BRIDGE			V_1	I_1	400V
HALF BRIDGE			V_1	$2I_1$	400V
BRIDGE RESONANT			V_1	$1.6I_1$	400V

Fig.2. Comparison of regulator types, transformer coupling.

are understood. In the late 1950s power converter design was anything but mature. A handful of circuits were known along with empirical data on their behavior. There were also a number of outstanding mysteries. For example, why was the boost converter so much harder to stabilize than the buck converter?

The past 25 years have seen a gradual transition from an empirical to a reasonably generalized theoretical understanding. As is so often the case, as the theoretical understanding increased, the generalizations allowed variation matrices to be drawn and from the gaps in the matrices, new and useful circuit possibilities were recognized and created. Another gain from the theoretical work was a better understanding of the limits to performance and the means to approach these limits.

The first real breakthrough came from the small signal modeling initiated by Middlebrook and his colleagues [1]. Beginning in the early 1970s a series of papers discussed small signal modeling using the state-space averaging techniques to overcome the inherent modeling problem caused by the grossly nonlinear nature of switchmode converter circuits. One of the first fruits of this effort was an explanation of the boost converter problem. The control to output characteristic of the boost converter has a right-half plane zero which is a consequence of the switching action, not the component selection. Other modeling techniques were also being developed at the same time [2] in Europe.

Along with the modeling came another problem: how do you perform small signal measurements in the presence of the very high levels of noise due to the inherent switching action? This is necessary to verify the models and to demonstrate the adequacy of practical designs. Again, Middlebrook provided some solutions [3].

For a very long period of time most converters used a simple single loop control system, with the loop response crossover well below the switching frequency. Some empirical observations, coupled with the improving theoretical understanding, led to the use of multiple feedback loops and feedforward. These techniques have proved to be a powerful tool for increasing the performance of power converters and for solving numerous practical problems in their application.

The small signal modeling effort culminated in canonical models [4]. Rather than having a separate model for each converter, it was shown that all converters with the same number of states during a single switching cycle had the same topological model. The differences between converters lay in the branch element values, not the model topology. Most converters up to 1982 had two or three states during the switching cycle, corresponding to continuous or discontinuous inductor current. The state-space averaging canonical model approach indicated that converters could exist with more than three states [5], and this has opened up a whole new realm of circuit possibilities.

Until 1978 most converter circuits were reviewed as separate individuals with specific characteristics unrelated to each other. Severns [6] showed that existing circuits could be viewed as combinations of very basic circuits which retained most of the properties of the basic constituents. This allowed the grouping of converter circuits into families with similar characteristics which could be predicted from the basic constituents. This generalization also allowed the creation of combinatorial matrices that showed what circuit possibilities had not yet been created via the hit or miss empirical process. In particular, the boost family of converters was shown to have numerous new members.

In many applications a converter will experience step load or line changes which are very large compared with the small perturbations assumed in the small signal modeling. The circuit response is usually highly nonlinear and the small signal model is not adequate. In 1982 Erickson and Middlebrook [7] demonstrated a method of large signal modeling which allowed predictions of performance. The method also solved another of the empirical mysteries by predicting instabilities that are present only in the large signal dynamics case.

Along with switchmode converters, resonant converters were being developed for space applications. The drastically increased power levels projected for future missions have brought resonant converters to the fore. Unfortunately, our basic understanding of this converter lags well behind that of switchmode circuits and is presently an area of active investigation.

Vorperian and Cuk [8] have demonstrated dc and small signal analysis for a series resonant converter and it is expected that this work will be generalized in the future for other types of resonant converters.

Another current development is the work by Bloom and Severns [9] on the generalization of unified magnetic structures and zero ripple conditions to include all switchmode converters. This will allow significant reductions in weight and volume for airborne and space power conditioning.

Looking to the future, many questions still must be answered. In particular, generalized large and small signal modeling and generalized topological possibilities for resonant converters are needed. A resolution of the relative advantages to the different multiloop control schemes and the generalization of large signal analysis in switchmode converters are also needed.

Our understanding of power converter circuits is by no means fully mature, but compared with our understanding as recently as the late 1960s, it is clear that giant strides have been and continue to be made.

III. COMPONENT DEVELOPMENT

The performance of power electronic equipment in general and power conversion equipment in particular is fundamentally limited by the capabilities of the components used in the power portions of the circuits.

Advances in components have been a major part of the progress made in power converter design and continue to be a pacing item. In particular, the ability to operate at very high switching rates (20–200 kHz), which has done so much to reduce the weight and volume of power processors while improving efficiency, is due in large part to the advances in power component technology.

In the 1950s and early 1960s true power bipolar junction transistors (BJT) were just becoming available as silicon technology was evolving. The power BJT, along with the silicon controlled rectifier (SCR), were the key elements which allowed solid-state power processing to proceed. Along with the development of these devices came the understanding of how they work and how to use them in real circuits. The process of understanding these devices still continues.

As is so often the case, improvements in one component highlight the inadequacies of other components. As BJTs began to switch faster and at higher power levels, the rectifier diodes became limiting factors. This prompted the development of the fast recovery epitaxial diodes (FRED) with abrupt junctions and lifetime killing dopants. A variation of FRED, the ion implant diode, has proved even faster so that we have gone from microsecond recovery times to nanosecond recovery times: three orders of magnitude improvement.

With the rise of TTL logic loads, much of the power consumed was at +5 V. Because of its relatively high offset voltage, the usual silicon diode makes an inefficient rectifier at such low voltages. The need to improve rectification efficiency drove the development of the Schottky barrier diode in the late 1960s and early 1970s. While hardly a painless development, the Schottky now dominates low voltage rectification. There is a potential usurper of this position in the wings, however, as we shall see in a moment.

Having developed fast diodes, the spotlight of criticism fell next on the filter capacitors. Except for bulk energy storage, the size of a filter capacitor in a power converter is determined more by its ripple current capability than by the value of capacitance. The early capacitors suffered from many ills: high equivalent series resistance (ESR) and inductance (ESL), poor reliability, silver migration in wet slug tantalum capacitors, etc. Many designs in the late 1960s and early 1970s were dominated by the volume of their capacitors, a very frustrating situation for a designer. Since that time, a great deal of progress has been made to produce reliable, low ESR, low ESL, light-weight filter capacitors. The progress in capacitor technology, while much less heralded than semiconductors, has been crucial to the development of power converters.

Just about the time (1976) we thought we had begun to understand BJT switches, along came the power MOSFET. This new device promised to provide much faster switching times (2 orders of magnitude), better reliability due to increased safe operating area (SOA), efficient rectification for low voltage outputs because of a zero offset voltage, etc. These benefits did not come as easily or as quickly as initially projected, but today the promises are being realized and MOSFETs are beginning to predominate in aerospace power converters at power levels up to 5 kW. While very high frequency switching (1000 kHz) had been demonstrated [10] with BJTs, it is the MOSFET which has driven switching frequencies higher and weight and volume down. The use of the MOSFET and higher switching frequencies has stimulated yet another cycle of component improvements.

Most power conversion equipment has a fair amount of control, protection, and/or telemetry circuitry associated with it. In many cases the weight, volume, power consumption, and cost of this auxiliary circuitry is significant and in some designs dominant. The development of large scale integration (LSI) and very large scale integration (VLSI) technology has provided the means to reduce this problem. Many different first generation control integrated circuits (ICs) are presently in use.

Today, the cutting edge of the technology has taken monolithic ICs to the point where both the control circuitry *and* the power semiconductors can be integrated on a single substrate. This leads to much smaller volumes and makes much more complex control and protection logic feasible. This process is referred to as D/CMOS, a combination of DMOS and CMOS.

Under active development are radiation hardened MOSFETs and MOSFETs with very low (10 mΩ) on resistance [11]. In the next two to three years these devices should find wide applications as synchronous rectifiers and may supplant diode rectifiers.

For the future there are many tantalizing possibilities such as new semiconductor devices (insulated gate thyristor (IGT/COMFET)), power ICs, and second generation, multiple loop, control ICs.

IV. CIRCUIT PRACTICE

A great variety of power circuits have been developed to meet the needs of various power regulation, conversion, and switching applications. The available switched-mode converter topologies comprise the greatest part of this resource. The literature is full of specific applications and recent interest in power electronics has promoted the review of these circuit options [6]. While all of these switched-mode converter topologies can be modeled as transformers in the network sense, there is an important class of these which do not utilize a hardware transformer. These include the buck, boost, and buck-boost single-ended regulator circuits shown in Fig. 1. The buck converter or chopper has been widely used in spacecraft power control [12–14] and voltage regulation because of its simplicity, low component voltage stress and high efficiency at low voltage transform ratios. The boost converter circuit has been widely used to regulate the output of spacecraft batteries having source regulation on the order of ± 20 percent. In this case also, a low voltage transform ratio is required. For applications where the voltage transform ratio is 3 to 5 or greater, a transformer type converter has been used to maximize the conversion efficiency. These are also used where electronic isolation from input to output is desired. Circuit improvements in switched-mode converters for space application have emphasized weight reduction and efficiency improvement. Weight reduction is achieved by increasing the switching frequency, thereby decreasing the mass and volume of energy storage components. Efficiency improvements have resulted from the development of bipolar transistors specifically designed for switched-mode application, use of proportional (transformer) drive techniques, and the use of energy conserving "snubber" networks to reduce power lost in the switching event.

Although the majority of low and medium power converters have utilized pulsewidth modulation wherein proportional control of switch duty is obtained by varying the on time of a switch operating at constant frequency, the interest in resonant switching converters has introduced other alternatives. Resonant converters enable use of regenerative type switches such as silicon-controlled rectifiers (SCRs) and related devices. Such converters are capable of higher operating voltage levels, consistent with SCR performance while being limited in switching frequency for the same reasons.

In addition to switched-mode technology, a number of other more specialized component and circuit techniques have been widely used in space power electronics. Shunt regulation of spacecraft solar arrays has been in use for nearly 20 years as a "zero-loss" power control technique. The earliest such units which were voltage-regulating, proportionally controlled loads on the spacecraft power source have evolved into multisegmented, multireferenced shunt controllers which reject a small fraction of their power control capability as heat while maintaining low effective bus source impedance through control loop response.

Even more widespread and more broadly applied is the use of the power control circuits based on use of magnetic-latching relays. These have been used in voltage limiters, battery charging circuits, and power system reconfiguration applications (redundant equipment switching, for example). The wide application of these devices is due to the fact that they are highly efficient, compact and self-contained, and usually require no special drive circuitry.

With the scaling of power levels in spacecraft (from 500–1000 W to 5000–10 000 W), switched-mode power conversion will become more efficient, made practical by development of transistors of 500–1000 V breakdown voltage ratings. They will become lighter and more compact by use of progressively higher operating frequency—this enabled by use of power MOSFET devices. Use of dissipative regulating devices will be rendered less practical due to both the safe-operating area limitations of high power devices for this type of application and the difficulty of thermal control at these lowered component efficiency levels.

The higher voltage (100–200 V) space power systems will eliminate the use of magnetic latch relays for such power control applications as battery charge control and solar array switching. These will continue to be widely used in low voltage (e.g., 28 V and 5 V) load circuits. For these higher voltage dc systems, solid-state switchgear will need to be used for many source bus applications. The increased power loss (1–2 V drop) and significant weight of the switchgear developed to date suggests that these components cannot be applied as widely as magnetic-latch relays have been. At least motivated by the potential simplification of solid state switchgear is the investigation of alternating current (ac) power distribution [16]. Such an approach, which has been studied for space power systems of multihundred kilowatt scale would utilize 10–20 kHz sine wave ac. Square wave ac power distribution has been utilized both in the U.S. space program and in Europe to facilitate the provision of the variety of special power requirements for multipayload missions.

The continuing studies of large-scale power systems, such as the NASA Space Station, will provide the vehicle for comparative evaluation and development of the advanced power control and regulation techniques discussed above.

In summary, switched-mode converter technology has been adapted to a variety of power electronic applications, as is discussed in Section V. This broad application is motivated by their theoretically lossless performance and enabled by the flexibility of the technique. This flexibility derives from the many circuit topology, power switch drive, and control options available.

V. POWER ELECTRONICS APPLICATIONS IN SPACECRAFT

The applications of power electronics to space systems may be classed generally as being associated with the spacecraft electrical power system or with the variety of possible payloads.

The majority of spacecraft power systems, dating to the earliest programs in space, have supplied direct current power at approximately 28 V. These systems are termed regulated if power is supplied at a controlled voltage and "unregulated" when power is distributed throughout the spacecraft directly from a battery. In this case battery regulation may be ± 15 to ± 25 percent of nominal voltage. Solar photovoltaic arrays (solar arrays) have powered most spacecraft to date (with the exception of some early primary battery or radioisotope thermoelectric generator (RTG) powered systems) and this has posed some unique requirements for equipment designers. Solar arrays (as photo diodes) have a junction voltage which is inversely proportional to temperature while their current is a function of illumination.

Depending on their structural mounting arrangement, operating voltage can vary over a 3:1 range from the maximum power point to open circuit. A solar array for a 28 V system might reach 70 or 80 V peak. With application of component derating requirements, transistors of 150 V breakdown voltage would be required. Some early lower power systems used avalanche diodes to limit voltage. Later, the equivalent performance was obtained by controlled shunt load elements consisting of a resistive load and a proportionally controlled transistor operating as a voltage regulator. As power levels increased, excessive power dissipation was dealt with by placing the resistive load in a remote location on the spacecraft, by regulating at a "tapped" level on the solar array, and most recently by use of multilevel modular load elements which saturate rather than operate at full voltage [15]. These shunt regulators were found attractive because they had no power throughput loss and thermally dissipated only unwanted power. Such systems also had the advantage that closely regulated (± 0.2 V, e.g.) voltage could be provided for power distribution, during the Sun-lit portion of the spacecraft orbit. This approach proved especially attractive for higher orbit satellites such as geosynchronous "comsats" where the spacecraft is in the Sun 99 percent of the time.

By applying a battery voltage regulator, usually a single-ended "boost" switchmode type, a highly efficient regulated system is obtained. Voltage control bands are allocated to the solar array shunt regulator and battery regulator to minimize battery use and insure stable power transfer. Battery charging power for this system would be provided by dedicated solar array elements or a current regulating power supply.

Another approach has been widely used for low orbit satellites which does not require the extent of power equipment (i.e., 2 or 3 power control elements) that does the shunt approach. The battery-regulated approach utilizes the battery terminals as the main power connection while the solar array is connected to the battery through a series connected controller, usually a magnetic-latch relay. Since the bus voltage is virtually at battery voltage, bus voltage regulation is suitably bounded and the solar array is similarly voltage limited. There is no significant heat dissipated within the control equipment which itself can be a hysteresis type of voltage control switch, similar to an oven controller.

With the advent of the higher power, longer life systems it became apparent that more effective use of the spacecraft solar array and minimization of spacecraft heat dissipation was important. With the recognition of the battery as a cycle life limited and spacecraft life limiting element, elimination of the unnecessary battery cycling involved in battery regulated systems was desired.

These issues were confronted more than 15 years ago in the development of the two spacecraft which composed the Skylab system, the Orbital Workshop and the Apollo Telescope Mount. Both power systems used switched-mode power conversion for power control and voltage regulation functions in a multichannel dc power system.

Skylab was "ahead of its time" in application of switched-mode power conversion to spacecraft power control [17], but a number of current spacecraft designs are comparable to or exceed those of Skylab. For these systems, and those presently on the drawing board, switched-mode power conversion has emerged as the technique of choice, and equipment has been developed which anticipates higher power systems at 100–200 V levels [12–14]. Work continuing on this type of equipment has as its goal improved weight and efficiency figures.

In addition to these unique power control applications, many hundreds of power supplies have been developed which utilize switched-mode converters as voltage regulators. These are used to power control electronics, data equipment and computers, and a host of scientific instruments at voltages of $+5$, ± 15, 28, 100 Vdc, etc. Such units are also commonly used as preregulators for high-voltage TWT power supplies on space communications systems.

The improved power-to-weight figures for space electrical power systems and the greater payload capability of the Space Shuttle and other delivery systems will enable new space missions with unique power electronic requirements. The use of space-based lasers for communication and other applications will require megawatts of pulse power delivered at tens of kilovolts. Improved, solid-state radars will require hundreds of kilowatts delivered at 15 or 28 V. Power conditioning requirements will range from the need for ultra high quality regulation for radars to very low duty ratio pulses for laser communication systems. As always, weight and reliability will be paramount development considerations for this equipment.

As has been the case for two decades, the challenges of the space program will continue to drive power electronic technology in components, circuits, and systems.

REFERENCES

[1] Middlebrook, R., and Wester, G. (1972)
Low frequency and characterization of switched dc-to-dc converters.
In *IEEE PESC Record*, 1972.

[2] Prajoux, R., Marpinard, J.-C., and Jalade, J. (1976)
Etablissement de modeles mathematiques pour regulateurs de paiisance a modufation de largeur d'impulsions (PWM); 2 modeles continus.
ESA Scientific and Technical Review, *2*, 1 (1976), 115–129.

[3] Middlebrook, R. (1975)
Measurement of loop gain in feedback systems.
International Journal of Electronics, *38*, 4 (1975), 485–512.

[4] Cuk, S., and Middlebrook, R. (1976)
A general unified approach to modeling switching-converter power stages.
In *IEEE PESC Record*, 1976, pp. 18–34.

[5] Mahadevan, R., El-Hamamsy, S., Polivka, W., and Cuk, S. (1983)
A converter with three switched-networks improves regulation, dynamics, and control.
In *Proceedings of POWERCON 10*, 1983.

[6] Severns, R. (1980)
Switchmode converter topologies.
Application Note A0-35, Intersil Inc., Jan. 1980.

[7] Erickson, R., Cuk, S., and Middlebrook, R. (1982)
Large signal modeling and analysis of switching regulators.
In *IEEE PESC Record*, 1982.

[8] Vorperian, V., and Cuk, S. (1982)
A complete dc analysis of the series resonant converter.
In *IEEE PESC Record*, 1982.

[9] Bloom, E., and Severns, R.
Magnetic integration methods for transformer-isolated buck and boost dc–dc converters.
In *POWERCON 11 Conference Record*.

[10] Severns, R., and Sommers, D. (1978)
Design of high efficiency off-line converters above 100 kHz.
In *Proceedings of POWERCON 5*, May 1978.

[11] Blanchard, R., and Severns, R. (1983)
MOSFETs move in on low voltage rectification.
Applications Note, Siliconix, Inc., Santa Clara, Calif., Nov. 1983.

[12] Glass, M.C. (1980)
A six kilowatt transformer-coupled converter for space shuttle solar power systems.
In *IECEC-15 Record* (Aug. 1980).

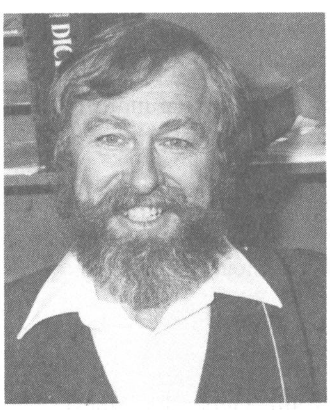
[13] Lukens, F.E. (1981)
Advanced development of a programmable power processor.
In *IECEC-16 Record* (Aug. 1981).

[14] Speer, J.H., Jr. (1981)
Microprocessor control of power sharing and solar array peak power tracking for high power (2.5 kW) switching power converters.
In *1981 PESC Record*.

[15] Kimble, S., Barany, F., and Brooker, R. (1982)
Design concepts and performance characteristics of a high performance linear/digital shunt regulator.
In *IECEC-17 Record* (Aug. 1982).

[16] Study of power management for orbital multi-100 kW applications.
Final Report (vol. 3), General Dynamics Convair Division, NASA CR159834, GDC-ASP-80-015, July 1980.

[17] Woolsey, A. (Ed.) (1974)
MSFC Skylab electrical power system mission evaluation report.
Technical Memo NASA-TM-X-64818, June 1974.



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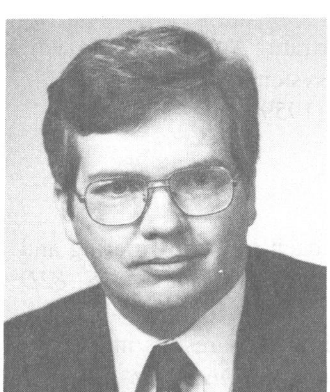

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