NASA/TM—2003-212514

# The Series Connected Buck Boost Regulator Concept for High Efficiency Light Weight DC Voltage Regulation

Arthur G. Birchenough
Glenn Research Center, Cleveland, Ohio

September 2003

## The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2003-212514

# The Series Connected Buck Boost Regulator Concept for High Efficiency Light Weight DC Voltage Regulation

Arthur G. Birchenough
Glenn Research Center, Cleveland, Ohio

Prepared for the
First International Energy Conversion Engineering Conference
cosponsored by the American Institute of Aeronautics and Astronautics (AIAA),
the American Society of Mechanical Engineers (ASME), and the Institute of
Electrical and Electronics Engineers (IEEE)
Portsmouth, Virginia, August 17–21, 2003

National Aeronautics and
Space Administration

Glenn Research Center

September 2003

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

# THE SERIES CONNECTED BUCK BOOST REGULATOR FOR HIGH EFFICIENCY DC VOLTAGE REGULATION

Arthur G. Birchenough
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## Abstract

Improvements in the efficiency and size of DC-DC converters have resulted from advances in components, primarily semiconductors, and improved topologies. One topology, which has shown very high potential in limited applications, is the Series Connected Boost Unit (SCBU), wherein a small DC-DC converter output is connected in series with the input bus to provide an output voltage equal to or greater than the input voltage. Since the DC-DC converter switches only a fraction of the power throughput, the overall system efficiency is very high. But this technique is limited to applications where the output is always greater than the input. The Series Connected Buck Boost Regulator (SCBBR) concept extends partial power processing technique used in the SCBU to operation when the desired output voltage is higher or lower than the input voltage, and the implementation described can even operate as a conventional buck converter to operate at very low output to input voltage ratios. This paper describes the operation and performance of an SCBBR configured as a bus voltage regulator providing ±50% voltage regulation range, bus switching, and overload limiting, operating above 98% efficiency. The technique does not provide input-output isolation.

## Introduction

DC-DC converter power loss and size and weight have decreased rapidly due to the improvements in semiconductors, and to a lesser extent due to improved passive components, topologies, and soft switching schemes. This is even true for linear regulators, where higher temperature components have reduced size and weight, and lower dropout voltage semiconductors and drive techniques have reduced the power loss. But these gains are evolutionary, and large step improvements are not likely.

The change from linear to switching regulators was revolutionary, and the power loss and therefore size of regulators made a large step decrease. Since then the single most significant parameter determining converter efficiency and size, for a given frequency, has been the kva rating. The size of components to switch, transform, and filter is relatively independent of the topology, as the same amount of power is switched, rectified, and stored in filter components. The technique of partial power processing, wherein only a small fraction of the total output power is required to buck or boost the input to the desired output voltage, can significantly reduce the converter size and power loss.

The boost mode of the partial power processing technique has been used previously, wherein the low voltage output of a small DC-DC converter is connected in series with the input voltage.[1,2] The output voltage can then be adjusted from essentially equal to the input voltage up to the input voltage plus the maximum output voltage of the DC-DC converter. For example, a regulator for a 100 volt 1 kw bus could be constructed with a DC-DC converter having a 100 volt nominal input, and a 0 to 10 volt output and a 100 watt, 10 amp, rating. The configuration would allow regulating the output to up to 10% higher than the input, and yet only use switching and filtering components sized for 10% of the total rating, and it therefore offers greatly reduced size and power loss. The technique is very useful in situations where the input/output voltage ratio is relatively small, the output is always greater than the input, and isolation between the input and output is not required.

The series connected buck boost technique expands the array of applications considerably by also allowing the output to be lower than the input. This allows essentially twice the regulation range for a given size converter. Additionally, a circuit enhancement allows operation of the same converter in the conventional buck mode, so that the output can be regulated down to zero volts, allowing operation as a current limiting voltage regulation remote power controller (RPC). The only major restriction on the use of this technique is that it does not offer input/output isolation.

The circuit concept and performance of a proof of concept circuit is described in this paper.

## Circuit Operation

The operation of the circuit will be described by separating the modes of operation and describing them individually, and then showing how they are combined. The simplest mode is the boost mode, which will be described first.

A diagram of the power flow in the boost mode is shown in Fig. 1. In the boost mode, the output of a low voltage converter is added in series with the input voltage to provide an output voltage equal to or greater than the input. Thus, power from the converter is added to the output to increase the voltage. The SCBBR implementation described uses a full bridge input stage and a center tapped transformer – rectifier output stage as shown in Fig. 2. When all the primary side switches are turned off there is no voltage across the transformer, and the input voltage is connected to the output thru the input filter, the secondary of the transformer, the rectifier diodes, and output filter. When the switches of the input bridge are conducting, a voltage is impressed on the secondary of the transformer. The instantaneous output at the rectifiers is the input voltage plus the transformer secondary voltage, which is equal to the input voltage divided by the transformer turns ratio. By varying the PWM duty cycle from 0 to 100% the average output can be controlled between a minimum of the input voltage, and a maximum of the input voltage plus the boost provided by the transformer secondary's output. The output filter smoothes the output and the average output voltage, ignoring conduction losses in the filters and rectifiers, will be:

Vout = Vin + Vin * PWM Duty Cycle/Turn Ratio

The turns ratio for the prototype design is 2:1, allowing the output to be boosted up to 150% of the input.

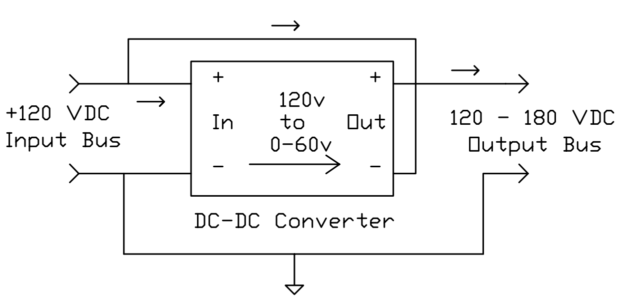


**Fig. 1. Boost Mode Power Flow Block Diagram**

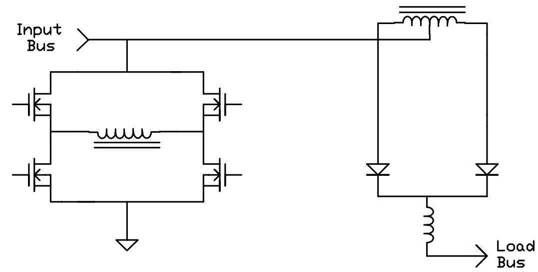


**Fig. 2. Boost Mode Schematic Diagram**

The buck mode of the SCBBR operates in a very different mode, but uses essentially the same components. The power flow is as shown in Fig. 3. The input voltage is greater than the desired output voltage. The concept of operation is that the input of a DC-DC converter is connected in series, with opposed polarity to the SCBBR input bus, and the output of the DC-DC converter is connected in parallel with the SCBBR input bus. The voltage drop across the input of the DC-DC converter reduces the SCBBR output voltage, and the power associated with this voltage drop is returned to the input bus by the DC-DC converter. The operation is similar to placing a battery in series with the input bus. Connected in one direction it increases (boosts) the output voltage. When it is connected "backwards" it decreases (bucks) the output voltage. In the boost case, the battery is discharged as would be expected, but in the buck case the battery is actually charged, and eventually overcharged. The use of a DC-DC converter allows a continuous process. A block diagram of the buck mode is shown in Fig. 3.

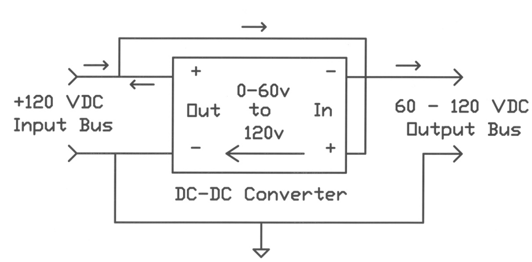


**Fig. 3. Buck Mode Power Flow Diagram**

It is important to note that the SCBBR input and output voltages are always positive[1] and that the SCBBR input and output currents are always positive.[2] However, in terms of the DC-DC converter within the SCBBR, the voltage on the input bus side is always positive and the current in the output bus side is always positive,[2] but the current into the input bus side of the DC-DC converter itself is positive in the boost mode and negative in the buck mode, and the voltage at the output bus side of the dc-dc converter itself will be positive for the boost mode and negative for the buck mode.

The schematic for buck mode operation is shown in Fig. 4. Many of the same components used for the boost converter are used for the buck converter, although in different roles. The center-tapped side of the transformer, which was the secondary in the boost mode, becomes the primary, and FET switches replace the rectifier diodes of the boost converter. (In the actual application the buck mode FETs are placed in series with the boost mode rectifiers.) The FETs which switched the primary of the transformer in the boost mode now function as a full wave bridge rectifier using the body diodes (, or synchronous rectification with the FETs).

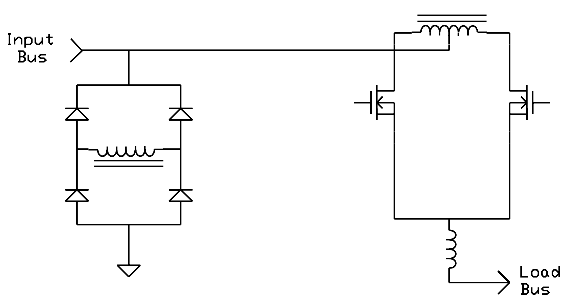


**Fig. 4.** **Buck Mode Schematic Diagram**

The output voltage of the DC-DC converter is recirculated back to the input bus of the SCBBR. Varying the duty cycle of the switches controls the ratio between the input and output voltage of the converter. Since the input bus voltage fixes the output voltage of the DC-DC converter, the effect of varying the duty cycle is to vary the voltage drop between the input bus and the SCBBR output voltage.

The switching action of the two switches in the primary of the buck converter might also be considered unusual in that either one or both switches are always turned on, they are both never off simultaneously, even during the switching cycle. It is a current fed mode of operation. When both switches are conducting there is no voltage drop (except the small conduction losses) across the input of the DC-DC converter, so the output voltage of the SCBBR is equal to its input voltage. When one switch is open, the voltage across the transformer output will be equal to the SCBBR input bus voltage since the bridge rectifiers clamp it to that value. Therefore the input voltage of the converter will be equal to the input bus voltage divided by the transformer turns ratio. Varying the duty cycle controls the average voltage dropped across the DC-DC converter, and therefore the SCBBR output voltage.

The SCBBR output voltage in the buck mode can be computed as:

Vout = Vin - Vin * PWM Duty Cycle/Turn Ratio

Where a PWM Angle of 0 corresponds to the switches being closed all the time and an angle of 100% corresponds to each switch being closed 50% of the time. Except for the sign in the equation, this equation is identical to the one for the boost mode. If the duty cycle is redefined such that the duty cycle for maximum buck is –100%, the equations become identical and for a 2:1 turns ratio transformer, the output can be varied from 50% to 150% of the input voltage.

The third mode of operation, the Current Limiting (CL) mode, uses many of the components used in the boost and buck modes, as well as some additional components. It is again a completely different mode of switching, and allows operation down to 0 output voltage to allow an increased operating range, and particularly an OFF mode and turn-on/overload limiting function. In the CL mode the primary or full wave bridge side of the converter switches serve no purpose, and they are all tuned off. The FET switches used for the buck mode on the output bus side of the converter are switched simultaneously, effectively as

[1]If the transformer voltage was less than 1:1, a negative output voltage could be generated, and the net power flow in the SCBBR would be back to the input. Considering this would add confusion and contribute little to an understanding or appreciation of the capabilities of the SCBBR concept and won't be discussed further.

[2]The SCBBR can operate in a mode where the power flow is from the output to the input if synchronous rectification is used at all points, and it makes some sense as a "regenerative" sort of application. This ability will be discussed later in the paper.

one switch and the transformer has no voltage across it. A diode is added between the FET switches and common, and the FET switches, the diode, and the output inductor function as a conventional buck converter as shown in Fig. 5. The transformer has no function in this mode, and is in fact shorted by an auxiliary FET to reduce voltage transients.

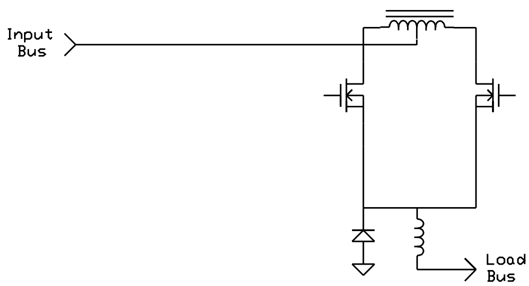


**Fig. 5. Current Limiting Mode Schematic Diagram**

In this paper this mode will be referred to as the CL mode to avoid confusion with the SCBBR buck mode previously described. In this mode the output voltage can be computed as:

Vout = Vin * PWM Angle

Although the form of this equation is quite different from the boost and buck mode equations given previously, the output voltage is still defined only by the input voltage and PWM angle, and the output can be controlled between 0 volts and the input voltage. Actually the range in this mode overlaps completely the range in the SCBBR buck mode, but with lower efficiency and higher ripple currents in the filters. In the prototype the switching frequency is increased for operation in the CL mode to reduce the current ripple. The current limit mode is used only during turn on and overload conditions, or if the output voltage must be lower than that that can be obtained with the SCBBR buck mode. Also, the equation is only valid for continuous conduction where the inductor current never goes to 0.

Essentially overlaying the boost, buck, and current limit mode schematics reveals the complete SCBBR schematic, as shown in Fig. 6.

This discussion has assumed that the input and output currents of the SCBBR are always positive. But if synchronous rectification is used on both sides of the

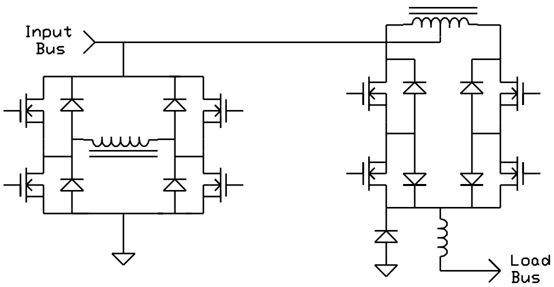


**Fig. 6. SCBBR Schematic**

DC-DC converter then current flow can be either direction. This is very useful because the magnetizing current of the transformer can be supplied from the input source, otherwise there would be a minimum output current, the current required to magnetize the transformer, below which the SCBBR buck mode would not operate. Switches that can conduct in both directions are already required on two of the switches on the SCBBR output. The logic to control the primary switches is straightforward, and provides the magnetizing current discussed above. By also using active switches in the other two positions of the output the efficiency will increase (synchronous rectification), and the SCBBR will operate in a regenerative mode wherein power is actually returned to the source from the load. The regenerative operation in the CL mode is possible if the free wheeling diode was replaced with a switch, but this has not been done in the prototype.

## Efficiency

High efficiency was the primary driver for developing the SCBBR technique; therefore the breadboard circuit was optimized for low losses. As such the design uses rather large semiconductors and magnetic components, and a relatively low switching frequency, but it clearly indicates the potential. Figure 7 shows the efficiency as measured for a constant input voltage and load current as the buck or boost ratio is varied. Plots are shown for a 5-amp load, the design full load for the converter; for a 2-amp load where the efficiency peaks; and for a 0.5-amp load, where switching losses dominate. These plots show the high efficiency over a wide range of buck/boost ratios and load currents. The DC resistance of the series connected components (the input filter, the transformer secondary, the secondary switches, and the output filter) is 0.15 ohms, accounting for 0.25% loss at 2 amps, and 0.6% loss at 5 amps load. Two-thirds of the loss at full load is due to switching losses or resistive losses in the primary and magnetic components core losses.

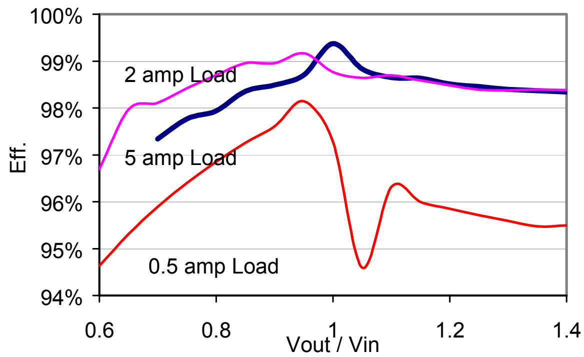


**Fig. 7. SCBBR Efficiency**

The current development of the SCBBR is for an application as a fuel cell regulator. The prototype SCBBR is being tested with a simulated fuel cell scaled at 50% of the voltage and 10% of the current rating of the intended fuel cell. The target fuel cell is rated at 10kw, 340 volts no load (170 for the simulator), 200 volts full load (100 volts for the simulator), at 50 amps (5 amps for the simulator). The intended load is a 270-volt (135 volts for the simulated system) bus. The input voltage variation and SCBBR efficiency is shown in Fig. 8. The efficiency doesn't fall badly until about 10% load. The power loss is a relatively constant 2 to 3 watts below 50% power. These efficiencies are for the power stage only, the control power requirement, including gate drive, of the prototype is 3 to 4 watts.

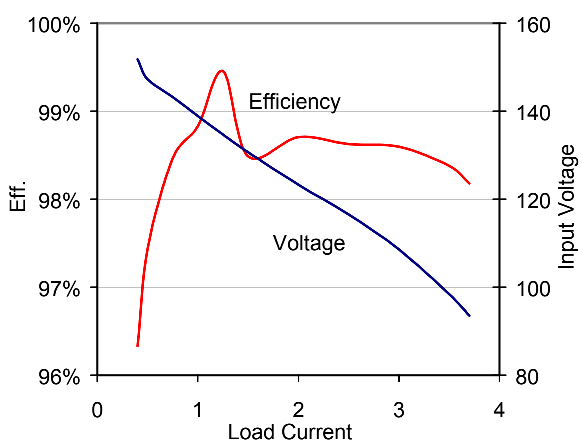


**Fig. 8. Efficiency as a Fuel Cell Regulator**

Voltage Regulation and Stability

Voltage regulation in a converter is primarily a measure of the performance of the voltage regulation feedback loop. The regulation can be as good as the regulator, independent of the transfer characteristics of the converter. However, the preceding discussions discussed the transfer functions of this converter and the similarity of them throughout the three different modes, and implied that the output voltage could be determined based on the input voltage, the transformer ratio, and the PWM angle. Figure 9 shows the open loop regulation of the SCBBR as a function of input voltage and output current. The open loop regulation generally continues into the current limit mode also, but not as accurately, and this region is not shown in the figure. A closed loop regulator is also included on the prototype SCBBR. Its only function is to trim out the remaining error shown in the figure, so its control range is limited to altering the output voltage a few percent, and it uses only the integral of the voltage error. Transient response, and damping, is provided by the open loop path, which simplifies the design of the integral controller path.

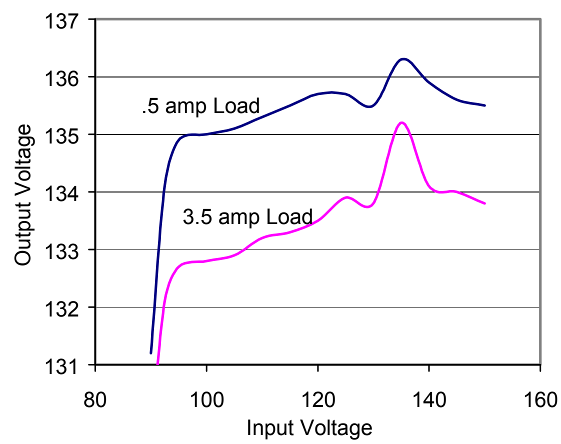


**Fig. 9. Open loop Voltage Regulation**

As discussed so far, the SCBBR is a stiff voltage source, and to be useful in a real system the ability to limit currents into an overload is required. Two circuits were added to accomplish this. The first an instantaneous overcurrent sense at twice rated current to shut off all switches and limit the peak current into the output filter. The second is a linear proportional pus integral current regulation loop at 1.5 times rated current to control the PWM angle until the output voltage recovers and the voltage regulator takes over. Implementation of these loops was successful as illustrated in Fig. 10, which shows the recovery from applying a large capacitor as a transient load while running at rated current. The capacitor is 100 times the output filter capacitance so the output voltage collapses almost completely. The instantaneous overcurrent sensing limits the initial spike of current (into the filter), and then the SCBBR runs under current limit until the capacitor is charged. The current sensing and the data plotted are the current into the output filter.

This is the same as the currents that is in the output switches, and it is the critical current to be controlled for protection of the SCBBR.

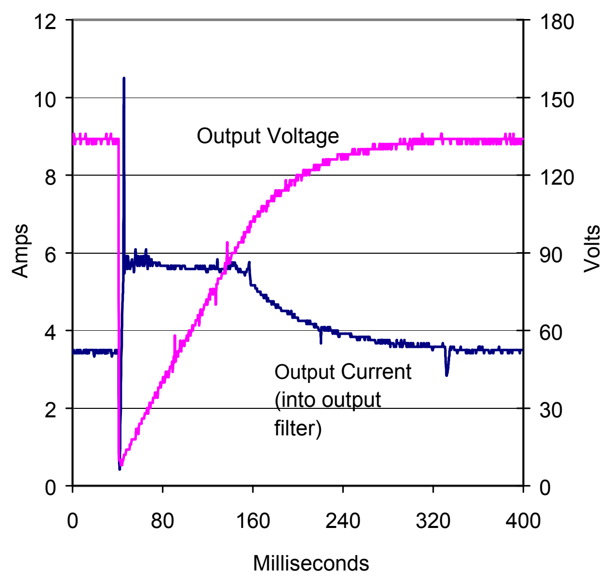


**Fig. 10. Transient Overload Response**

## Summary


The SCBBR concept has been developed as a breadboard to demonstrate its capabilities as a combined bus regulator and remote power controller incorporating switching and current limiting functions. The breadboard operates at over 98% efficiency over a broad input-output voltage and load range.


## References


1. Button, Robert M., 1998, "A Modular PMAD System for Small Spacecraft," NASA Technical Memorandum 1998–206628, NASA Lewis Research Center, Cleveland, OH.

2. Button, Robert M., 1996, "An Advanced Photovoltaic Array Regulator Module," NASA Technical Memorandum 107304, NASA Lewis Research Center, Cleveland, OH.

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY (*Leave blank*) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | September 2003 | Technical Memorandum |

**4. TITLE AND SUBTITLE**

The Series Connected Buck Boost Regulator Concept for High Efficiency Light Weight DC Voltage Regulation

**5. FUNDING NUMBERS**

WBS–22–706–21–03

**6. AUTHOR(S)**

Arthur G. Birchenough

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

**8. PERFORMING ORGANIZATION REPORT NUMBER**

E–14074

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

National Aeronautics and Space Administration
Washington, DC 20546–0001

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

NASA TM—2003-212514

**11. SUPPLEMENTARY NOTES**

Prepared for the First International Energy Conversion Engineering Conference cosponsored by the American Institute of Aeronautics and Astronautics (AIAA), the American Society of Mechanical Engineers (ASME), and the Institute of Electrical and Electronics Engineers (IEEE), Portsmouth, Virginia, August 17–21, 2003. Responsible person, Arthur G. Birchenough, organization code 5450, 216–433–6331.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**

Unclassified - Unlimited
Subject Category: 20 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** ***(Maximum 200 words)***

Improvements in the efficiency and size of DC-DC converters have resulted from advances in components, primarily semiconductors, and improved topologies. One topology, which has shown very high potential in limited applications, is the Series Connected Boost Unit (SCBU), wherein a small DC-DC converter output is connected in series with the input bus to provide an output voltage equal to or greater than the input voltage. Since the DC-DC converter switches only a fraction of the power throughput, the overall system efficiency is very high. But this technique is limited to applications where the output is always greater than the input. The Series Connected Buck Boost Regulator (SCBBR) concept extends partial power processing technique used in the SCBU to operation when the desired output voltage is higher or lower than the input voltage, and the implementation described can even operate as a conventional buck converter to operate at very low output to input voltage ratios. This paper describes the operation and performance of an SCBBR configured as a bus voltage regulator providing ±50 percent voltage regulation range, bus switching, and overload limiting, operating above 98 percent efficiency. The technique does not provide input-output isolation.

**14. SUBJECT TERMS**

Series connected regulator; Series connected boost regulator; DC to DC converter topologies

**15. NUMBER OF PAGES**

12

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102