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T. A. LaVIGNA

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GSFC
GODDARD SPACE FLIGHT CENTER
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ABSTRACT

This paper describes a novel high efficiency buck-boost voltage regulator for use in a solar-array battery space power system. The design approach for the switching regulator is presented, together with an analysis of its operation, definition of its characteristics, and functional performance.

The regulator uses a novel circuit which can step up or step down an input voltage from a dc source to achieve regulation. The circuit uses an inverter with an autotransformer to provide an additive or subtractive component of voltage which is impressed upon the dc input. The combined input and impressed ac is applied to a current transformer driven power transistor chopper circuit. Phase control of the chopper transistors relative to the inverter output will determine the operating mode; that is buck, boost, or neutral. The phase difference is variable and controlled to be that required to maintain the output at a fixed voltage for any change of line or load within the design range. The combining of a single current transformer with the power transistors to an inductive load produces a novel bucking function and provides efficient operation of the circuit at high frequencies.

This buck-boost regulation technique employing one series circuit offers increased efficiency as compared to previously used techniques. With such a circuit, the regulated bus voltage can be selected between the array and battery operating voltage levels. This flexibility allows optimization in the individual designs of both the array and battery.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

A BUCK-BOOST MAIN BUS VOLTAGE REGULATOR

FOR A SOLAR ARRAY BATTERY SPACE POWER SYSTEM

INTRODUCTION

As the state of the art in solar array-battery power systems advances, it is becoming more apparent that to obtain maximum system efficiency, it is necessary to optimize the individual designs of the solar array and battery. This optimization, however, can impose restrictions on the choice of the regulated bus voltage level as well as providing a wide voltage swing to be regulated by the main bus power conversion electronics. One separate buck or boost main bus regulator can not be well optimized for maximum efficiency over such a wide voltage swing. However, a combination of the two regulators, which could provide buck and boost regulation in one efficient conversion step, would be advantageous. With this in mind, a buck-boost regulator development was begun. This report documents the results of that development.

POWER SYSTEMS UTILIZING A BUCK-BOOST REGULATOR

Figure 1 shows a power system which employs a buck-boost regulator between the array and the main bus. The buck-boost regulator in this application eliminates constraints imposed on selection of the regulated main bus voltage by the solar array. When the solar array voltage is high, the buck-boost regulator operates in a bucking mode. This will happen at low array temperatures. When the solar array voltage is relatively low, the buck-boost regulator operates in a boosting mode. In this system, the bus voltage level can be chosen at a voltage consistent with the maximum power capability of the solar array at the critical design point. This system would find particular application to planetary missions where wide variations in solar array voltage occur due to operation at maximum and minimum AU (sun-spacecraft distance).

Figure 2 shows another system which uses a buck-boost regulator for bus regulation. In this system, the regulator must process the battery discharge power, as well as the array power, and provide a constant output voltage. The range of voltage over which the regulator must function is established from the minimum discharge voltage of the battery to the maximum operating voltage of the array. As mentioned previously with the optimized designs of the array and battery, a wide voltage swing results at the input of the regulator. However, use of a buck-boost regulator in this system allows the output voltage level to be chosen consistent with the load requirements.

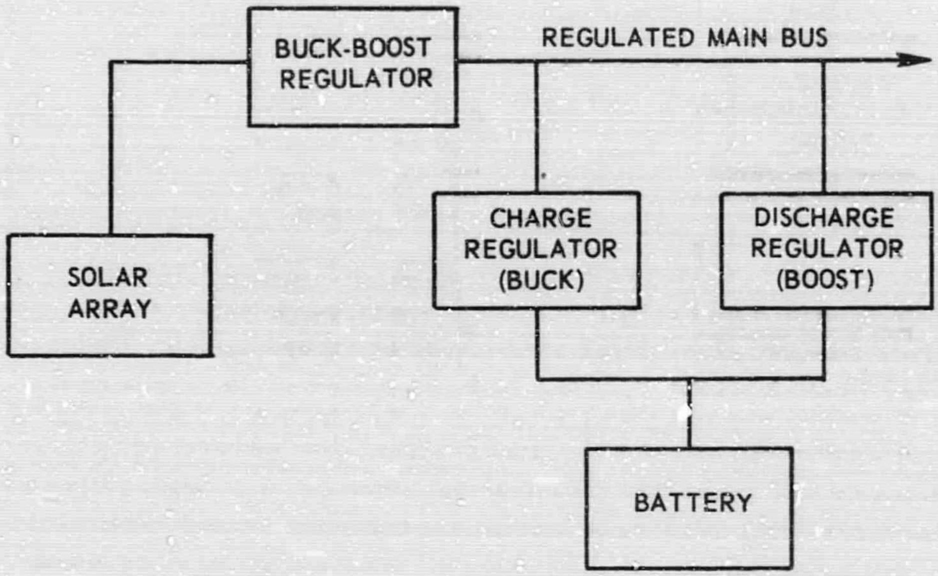

Figure 1. A Power System Using a Buck-Boost Regulator for Control of Array Power

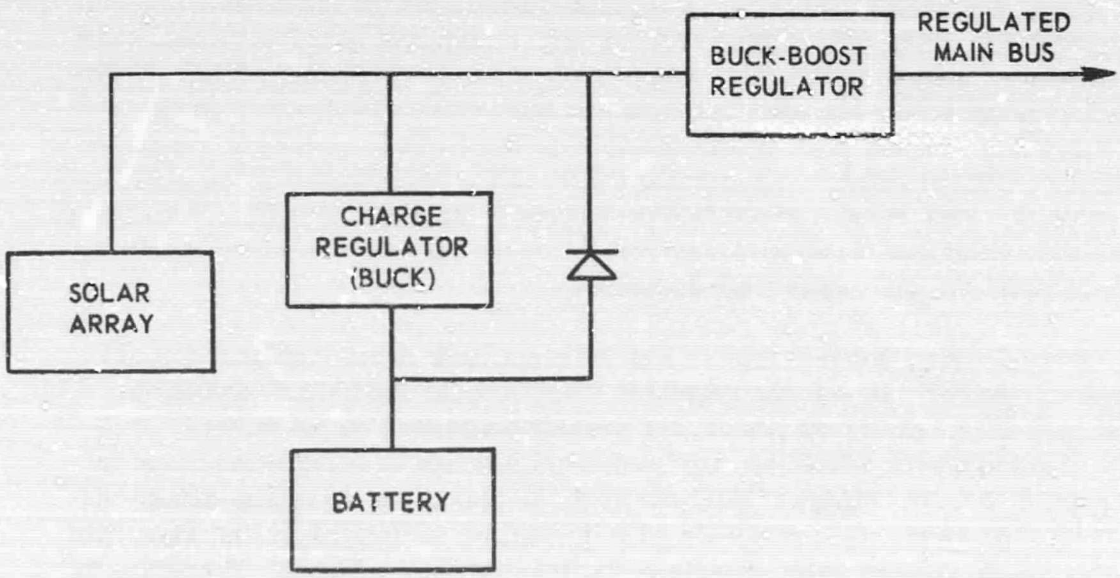

Figure 2. A Power System Using a Buck-Boost Regulator for Control of Array and Battery Power

DESCRIPTION OF THE BUCK-BOOST REGULATOR

Basic Buck-Boost Circuit

Highly efficient pulse width modulated boost regulators have been designed which use a power inverter with autotransformer in series with the main input to provide a voltage boost. Figure 3 shows such a circuit. The inverter must handle and switch only the boost power and not the entire load power. Compared with other boost circuit techniques, this method is more efficient. Thus, a development was undertaken to adapt this basic circuit configuration to provide a buck mode of operation in addition to the boost mode.

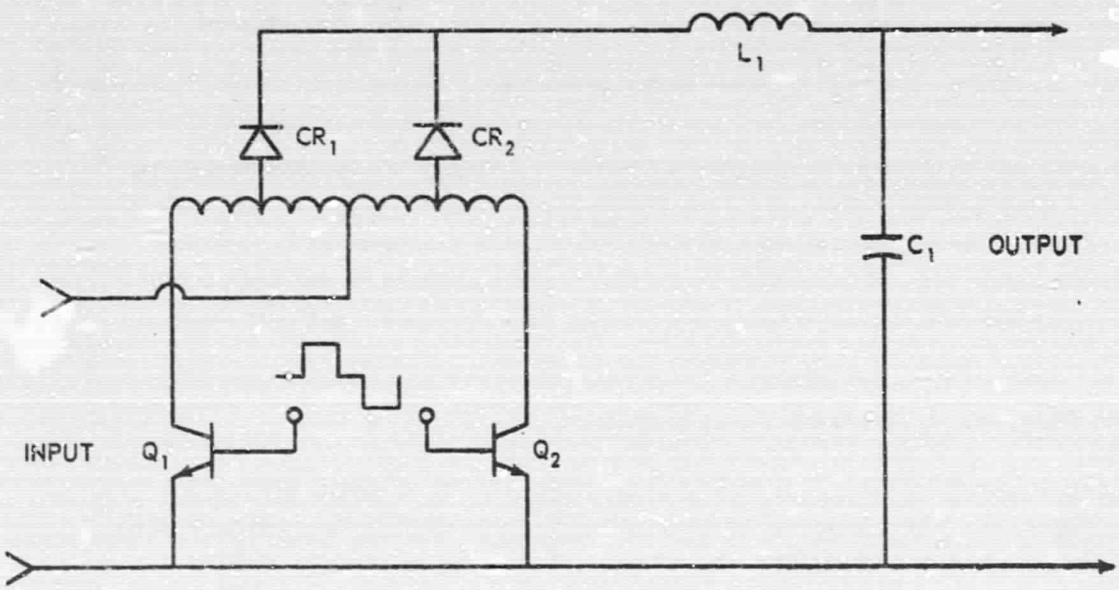

Figure 3. PWM Boost Transformer dc Regulator

The basic buck-boost circuit is shown in Figure 4. It includes a source of ac coupled in series with a dc source thru T_1, switches S_1 and S_2, and an averaging filter L_1-C_1. To explain the operation consider that the polarity of the transformer T_1 windings is as shown (the even numbered terminals of each winding are more positive than the odd terminals). Consider that switch S_1 is closed so current flow from the dc source will be thru winding 3-4 and switch S_1 to the filter and load. The instantaneous voltage appearing at the input of L_1 will be greater than the input since the polarity of winding 3-4 is such as to add to the source voltage. In this condition the circuit will be operating in the familiar boost mode.

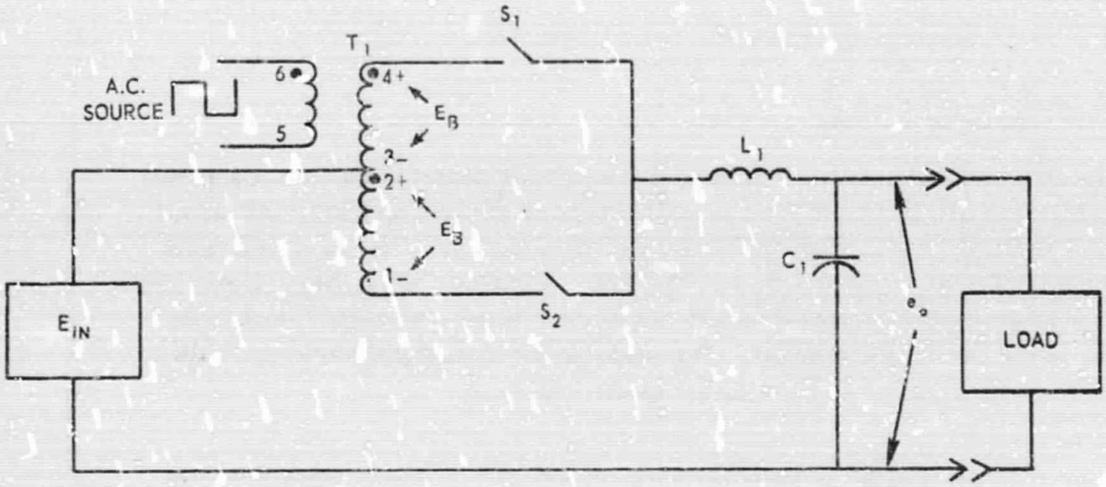

Figure 4. Basic Buck-Boost Circuit

Now consider that with the winding polarities as shown, S_1 is open and S_2 is now closed. Current flow from the dc source will be thru winding 1-2 and switch S_2 to the filter. The instantaneous voltage appearing at the input to L_1 will be less than the input since the polarity of winding 1-2 is such as to subtract from the source voltage. In this condition, the circuit will be operating in the buck mode.

Block Diagram of The Buck-Boost Regulator

A block diagram of the regulator implementing this buck-boost circuit is shown in Figure 5. The source of ac is internally generated by an inverter which is paralleled to the main dc input. The inverter switching is controlled by a master multivibrator. Conduction of either of the inverter transistors allows the main dc input to appear across the primary windings of an autotransformer. This input is coupled to the transformer secondary and provides an ac voltage which is combined with the input and then applied to a chopper circuit. Switching of the chopper power transistors is controlled by a slave multivibrator which is coupled in phase displaced relationship from the master multivibrator through a magnetic amplifier. This phase displacement, B, is variable and produces the required switching of the chopper power transistors between conducting and nonconducting states to cause the impressed voltage from the inverter to be either additive or subtractive. The output from the chopper circuit is applied to an averaging filter which smoothes the pulsating dc to the desired output level. The resultant output is sampled and compared to a reference to produce an error signal which is provided to a magnetic amplifier for control. In this manner, the resultant output relative to the input is controlled at a value larger, equal to, or less than the dc input.

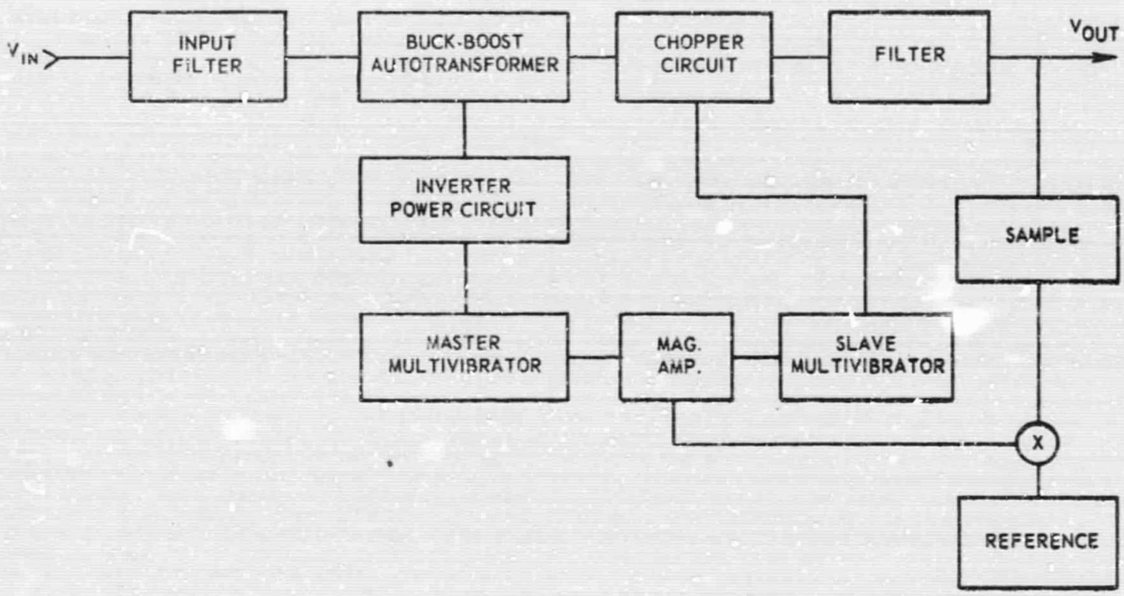

Figure 5. Block Diagram of the Buck-Boost Regulator

Detailed Description of the Regulator

Figure 6 is a circuit diagram of the buck-boost regulator. A detailed description of the major functions of the circuit follows:

(1) Filters

A pi filter consisting of C_2, L_2 and C_3 is used at the input to the regulator to maintain low ripple voltage and current and prevent feedback onto the input power line.

A filter consisting of L_1 and C_1 is used at the output to average the buck-boost voltage waveform and smooth it to a dc voltage of low ripple. In the design of this filter, the inductance is chosen to maintain continuous current flow for the minimum load to insure proper bucking operation.

(2) Inverter

An inverter with autotransformer composed of Q_1, Q_2, D_1, D_2, T_1, CT_2, R_5, R_6, and R_7 is used to generate the ac voltage buck-boost component which is combined with the input. When either transistor switch Q_1 or Q_2 closes, the input is impressed across the primary of T_1 for the duration of the closure. This voltage is coupled by autotransformer action to the secondary and added to or

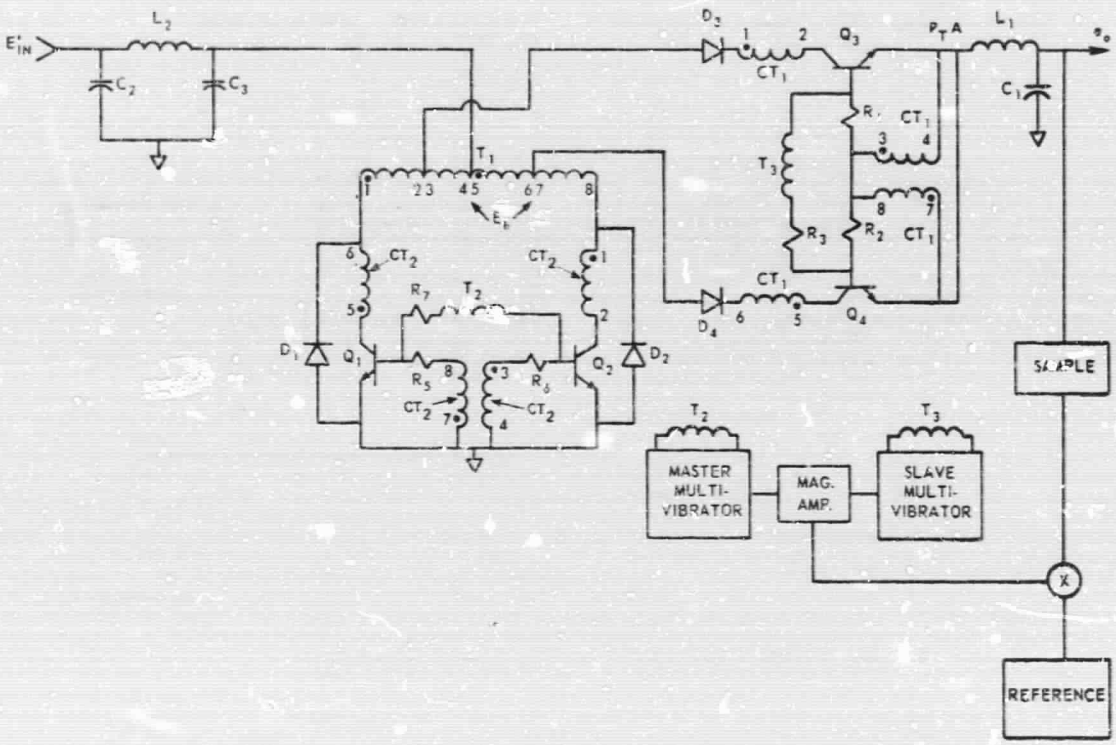

Figure 6. Circuit Diagram of the Buck-Boost Regulator

subtracted from the input. The primary inverter current required is the magnetizing current plus the load current coupled back to the primary by the turns ratio. The switching action of Q_1 and Q_2 from conducting to nonconducting states and vice versa is accomplished by signals from the master multivibrator; while, CT_2 is used to maintain conduction of the turned on transistor. Diodes D_1 and D_2 are used to provide a path for reactive energy pumpback which occurs during the bucking portions of the cycle. For operation in the bucking mode, the inverter must be designed to handle lagging power factor loads.

(3) Power Chopper Circuit

The power chopper circuit is composed of Q_3, Q_4, D_3, D_4, CT_1, R_1, R_2, and R_3. To explain its operation assume that the power transistor Q_3 is turned on by the slave multivibrator during the time interval when terminal 3 of the autotransformer T_1 is more positive than terminal 4. The voltage across winding 3-4 of T_1 is thus added to the input, creating a boosted voltage or the positive portion of the voltage swing appearing at the collector of Q_3. When Q_3 is turned on, the boosted voltage is then applied to the averaging filter L_1-C_1. Conduction of Q_3 is maintained by the base drive supplied by the 3-4 windings of CT_1. At some time later in the time interval, the master multivibrator switches state, causing the polarities of the autotransformer windings to change. Terminal 3 of the windings 3-4 of T_1 now becomes more negative than terminal 4. Thus the voltage across winding 3-4 is opposite in polarity to the input dc voltage applied to the transformer primary windings. Accordingly, the voltage across winding 3-4 represents a bucking voltage or the negative portion of the voltage swing to the input. Conduction of Q_3 is maintained by the 3-4 windings of the current transformer CT_1, and a voltage less than the input voltage is applied to the averaging filter. The power chopper circuit remains in this condition until the slave multivibrator changes state. At that time, base drive to transistor Q_3 is removed and after complete turn off of Q_3, base drive is applied to turn on Q_4. Switching off of the conducting transistor Q_3 takes place instantaneously through the action of the drive circuit and Q_4 cannot be biased to a conducting state until Q_3 has turned completely off. The operation of transistor Q_4 and its associated circuitry is identical to that of Q_3.

Figures 7, 8, and 9 show some ideal waveforms of the circuit for boost, neutral, and buck modes respectively. Analyzing the ideal output waveform of the power chopper circuit, the output voltage e_o, as a function of the phase control angle β can be obtained as follows:

$$e_o = \left[\frac{1}{T}\int_o^{\alpha} E_B\, dt + \int_{\alpha}^{T} - E_B\, dt\right] + E_{IN}$$

where:

e_o = average output voltage

E_{IN} = input DC voltage

E_B = secondary voltage of T_1

T = time of one full voltage swing cycle

β = phase control angle and correspondingly the time of negative portion of voltage swing cycle

α = time of positive portion of voltage swing cycle

since

$$\alpha = T - \beta$$

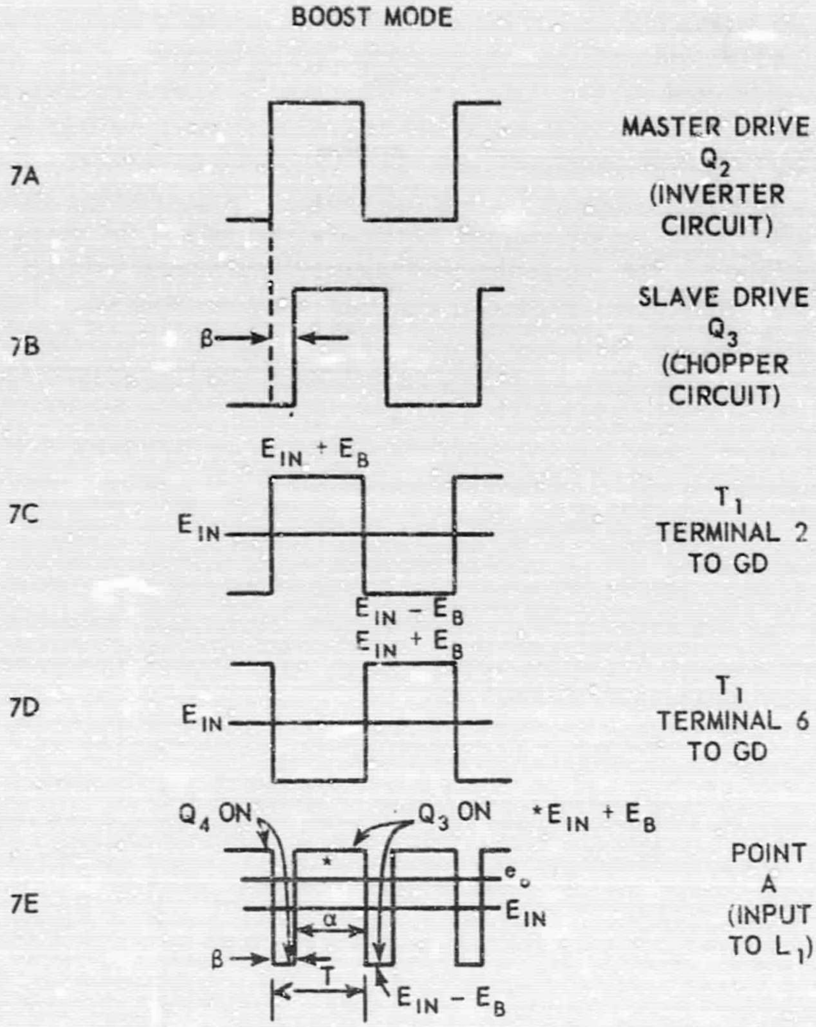

Figure 7. Ideal Waveforms of the Regulator Operating in the Boost Mode

substituting gives:

$$e_o = \left[\frac{1}{T}\int_0^{T-\beta} E_B\, dt + \int_{T-\beta}^{T} - E_B\, dt\right] + E_{IN}$$

integrating gives:

$$e_o = \frac{E_B(T - 2\beta)}{T} + E_{IN}$$

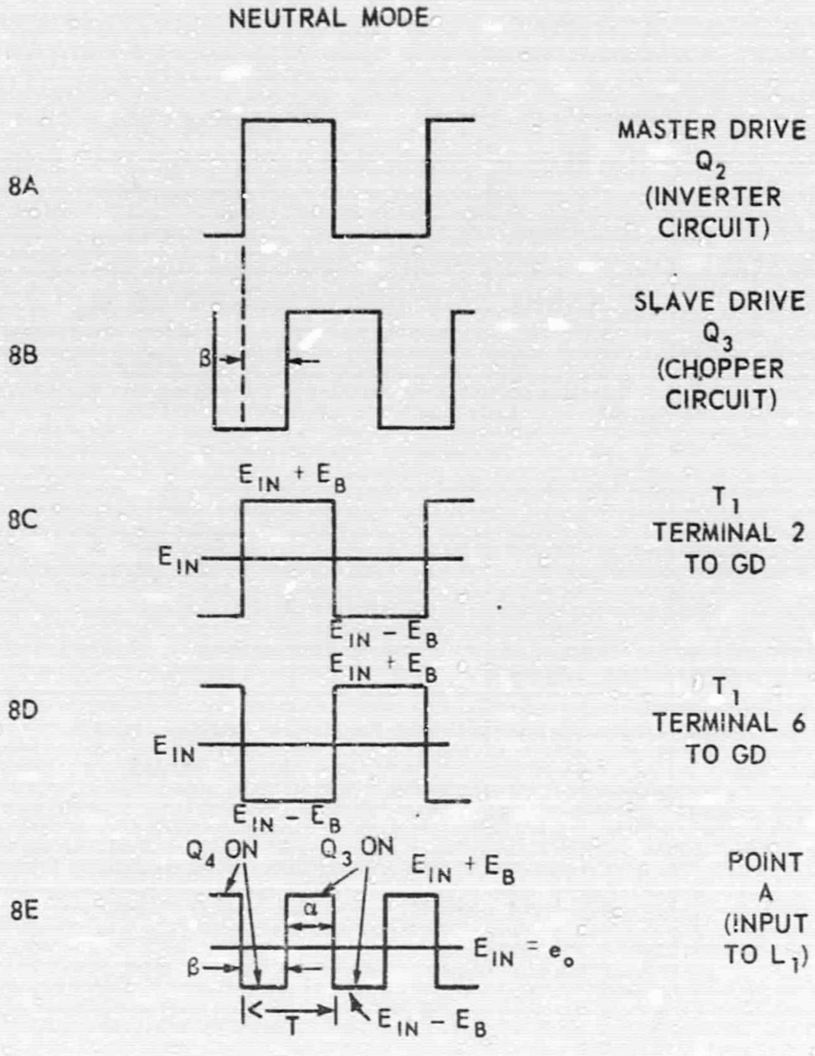

Figure 8. Ideal Waveforms of the Regulator Operating in the Neutral Mode

since

$$E_B = E_{IN} \frac{N_s}{N_p}$$

wherein:

N_p = primary turns of T_1

N_s = secondary turns of T_1

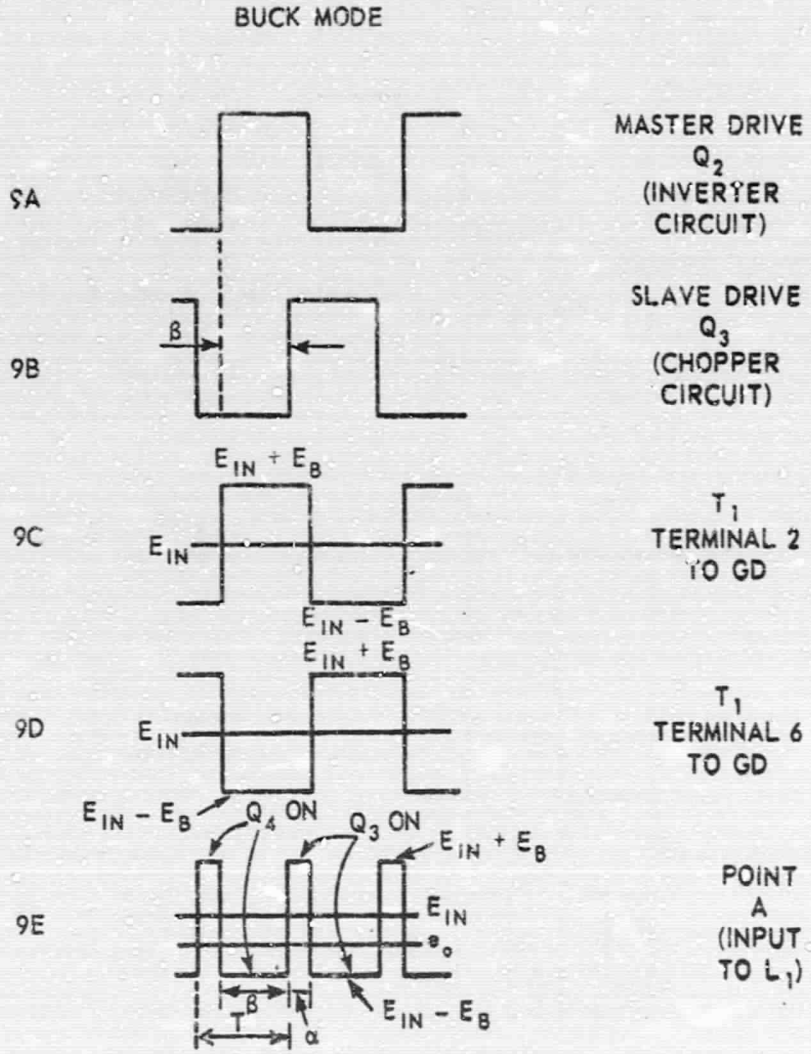

Figure 9. Ideal Waveforms of the Regulator Operating in the Buck Mode

then:

$$e_o = \frac{E_{IN} \frac{N_s}{N_p} (T - 2\beta)}{T} + E_{IN}$$

simplifying gives:

$$e_o = E_{IN}\left[\frac{\frac{N_s}{N_p}(T - 2\beta)}{T} + 1\right]$$

Thus the output is seen to be a direct function of the phase control angle β. For phase control angles less than $T/2$, the average output voltage e_o will be greater than the input E_{IN} with the maximum boost occurring when β equals zero. The buck-boost regulator will operate in this boost mode when the output waveform of the chopper circuit has the shape illustrated in Figure 7E. As shown in the figure, for β less than $T/2$, the time intervals that transistors Q_3 and Q_4 provide a bucking voltage to the input is less than the time intervals that Q_3 and Q_4 provide a boosted voltage to the input. Accordingly, this waveform will have longer duration positive voltage swing portions than negative portions. The average of this waveform will provide an output which is greater than the input.

If the phase control angle β is selected to be equal to the time inverval $T/2$, the outputs from Q_3 and Q_4 to the junction A will have the wave shape shown in Figure 8E. This waveform has equal positive and negative voltage swings and when averaged, the resultant output voltage e_o will equal the dc input voltage E_{IN}.

The regulator will operate in its bucking mode if the outputs from Q_3 and Q_4 have the wave shape illustrated in Figure 9E. In such case, the phase control angle β is greater than the interval $T/2$, and the waveform will have longer duration negative voltage swing portions than positive. Accordingly, the output voltage e_o will be less than the input voltage E_{IN} with maximum buck occurring when β equals T.

A special feature of the chopper circuit is the manner in which the voltage bucking function is accomplished. The inductor L_1 of the averaging filter is specifically designed to maintain continuous current through either Q_3 or Q_4 which is in its conducting state. The windings of CT_1 will continue to supply drive to the conducting transistor during the time interval when the active secondary winding of T_1 is opposite in polarity to the input. Thus the bucking function is achieved by maintaining conduction of either of the power transistors by utilizing a single current transformer and a filter inductor.

In addition to providing the novel bucking function, the current transformer and power transistors of the switching circuit permit operation of the buck boost regulator at high frequencies since fast switching is achieved. This is desirable since high frequency operation permits a substantial reduction in the size and weight of the autotransformer and averaging filter. Further, no long commutation time between the switching transistors is required. The manner in which this fast switching is achieved without undesired simultaneous conduction is as follows:

Referring to the diagram of Figure 5, Q_3 is assumed as conducting and its turn off is desired. Its base drive as supplied from the current transformer winding 3-4 is instantaneously removed by detouring it through the controlling slave drive winding T_3, through R_1, R_3 and R_2, and winding 7-8 of CT_1 and back to terminal 4 of CT_1. The ratio of R_3 to the sum of R_2 and R_1 is selected such that Q_4 cannot be biased into conduction during this time. Once Q_3 turns off and the polarity of the windings of CT_1 reverses, a forward bias is applied to Q_4 by the slave multivibrator thru T_3. Q_4 then conducts forward current and is maintained in conduction by winding 7-8 of CT_1. Q_4 cannot be turned on until Q_3 has turned completely off. Thus, no short circuit is applied to the power transformer T_1 and the inverter. Accordingly, there is no interval of high power dissipation which would otherwise limit the operational frequency of the regulator.

Modified Buck-Boost Regulator with Overload Protection

With only minor modifications to the power chopper circuit, a highly desirable current overload protective function can be added to the regulator. Figure 10 shows the modified switching circuit. Operation of the circuit is as follows:

Assume Q_3 is conducting and CT_1 is providing base drive for Q_3 through winding 3-4. The current produced by winding 3-4 causes a voltage drop across R_4 which under normal load conditions is not sufficient to gate on SCR_1. When the load current increases through winding 1-2 of CT_1, a corresponding current increase will be reflected in winding 3-4. When the load current increases to a preselected level where overload protection is desired, the increased current through winding 3-4 produces a voltage drop across R_4 to a level which gates SCR_1 to a conducting state. This applies a low impedance to CT_1 through winding 9-10. By using a high turns ratio of winding 9-10 to winding 1-2, the effects of the voltage drops across the bridge rectifier diodes and SCR_1 are minimized. Now when SCR_1 turns "on" the current which was coupled to winding 3-4 is reduced to zero, since, it is now coupled to winding 9-10, which offers the lowest impedance path. Base drive to Q_3 is thus reduced to zero causing Q_3 to turn off. The slave multivibrator drive through R_3 cannot provide drive to Q_3 or Q_4 to render them conducting since the low impedance path through CT_1 windings 7-8 and 3-4 is present.

Upon turn off of Q_3 current flow through winding 1-2 of CT_1 and, correspondingly, winding 9-10 is extinguished. As a result, the current flow through

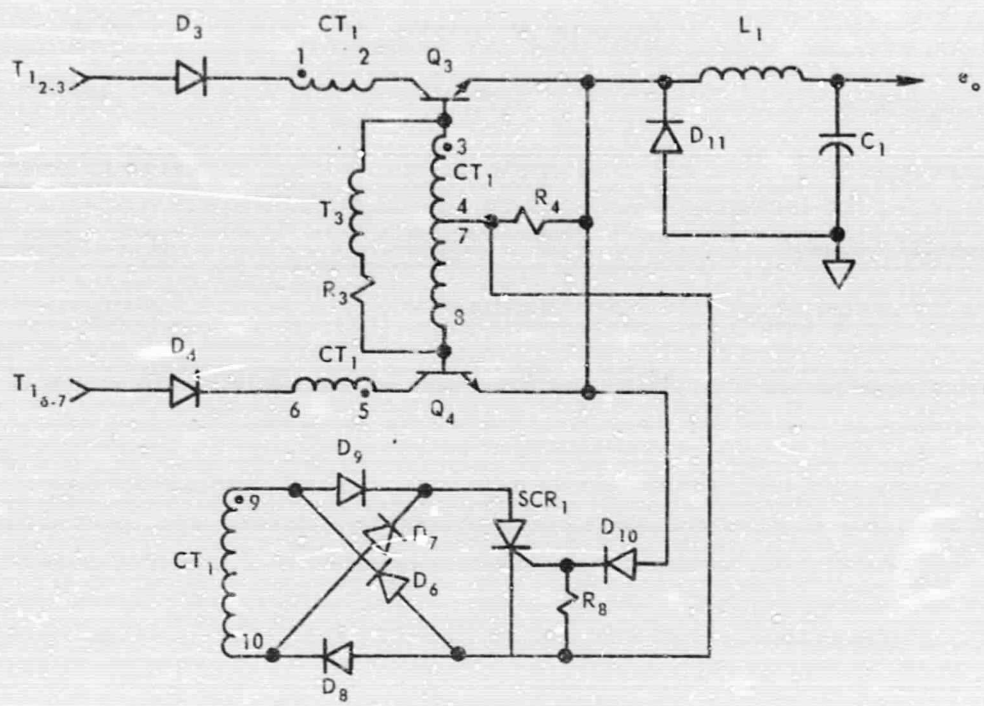

Figure 10. Modified Power Chopper Circuit to Provide Buck-Boost Regulator with Overload Protection

SCR_1 drops below its holding current level and it returns to a blocking state. This enables the power switching circuit to resume its normal operation with Q_3 or Q_4 turned on by a signal from the slave multivibrator. Such resumed operation permits the load current to be sampled for the overload condition.

PERFORMANCE

The operating requirements for the Buck-Boost regulator were chosen to coincide with those required of the RAE main bus regulator in order that a comparison of performance could be made. The RAE regulator is a boost regulator using the highly efficient autotransformer circuit described previously. The following are those requirements:

	Buck-Boost Development	RAE
1. Input Voltage Range	12 to 24 volts	12 to 17 volts
2. Output Voltage Level	18 volts	18 volts

	Buck-Boost Development	RAE
3. Static Regulation	±1%	±2%
4. Power Output	9 to 100 watts	4.5 to 45 watts
5. Temperature Range	-20 to +50°C	-20 to +50°C
6. Frequency of Operation	5 Khertz	5 Khertz

The performance characteristics of the Buck-Boost regulator are shown in Figures 11 thru 13 and 15 thru 17. The voltage regulation and efficiency are plotted as a function of load current from 0.5 to 5.55 amperes. The voltage levels chosen for these plots; 12, 15, 18, and 24 volts; represent possible operating points on a solar array battery composite characteristic curve. Also plotted for

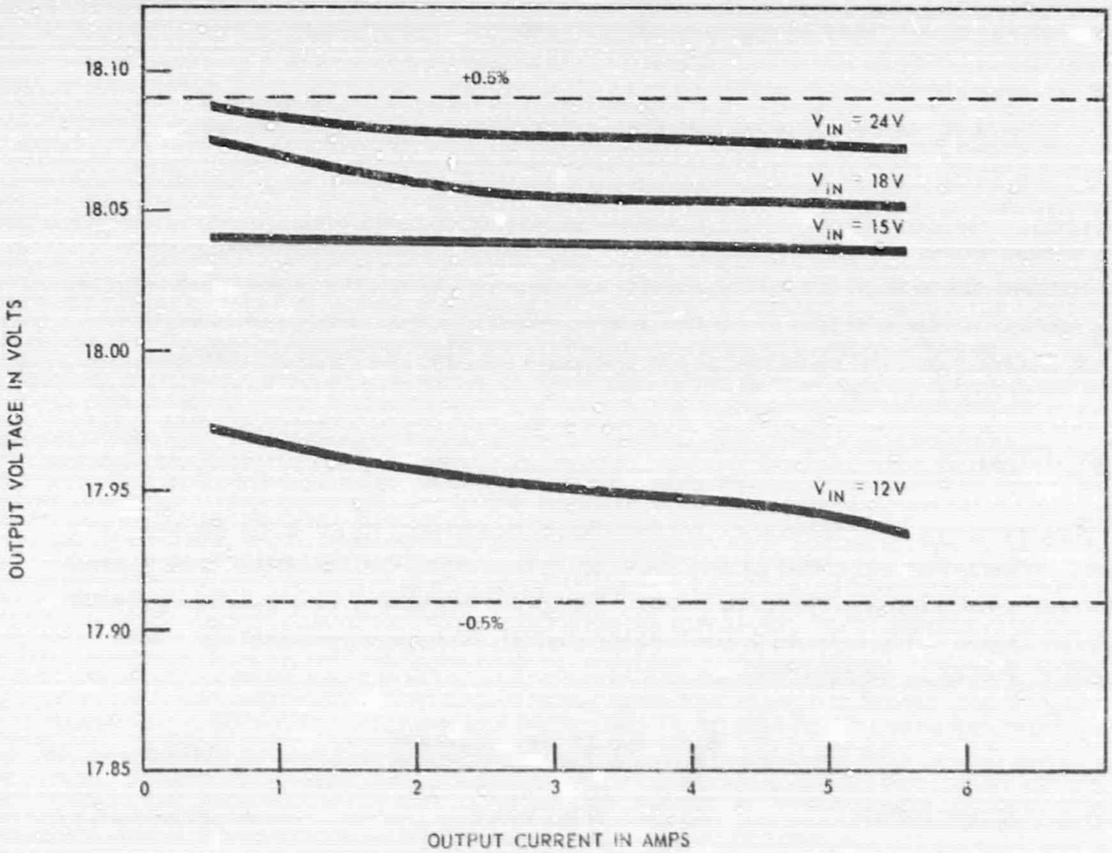

Figure 11. Regulation Plots of Buck-Boost Regulator at 25°C

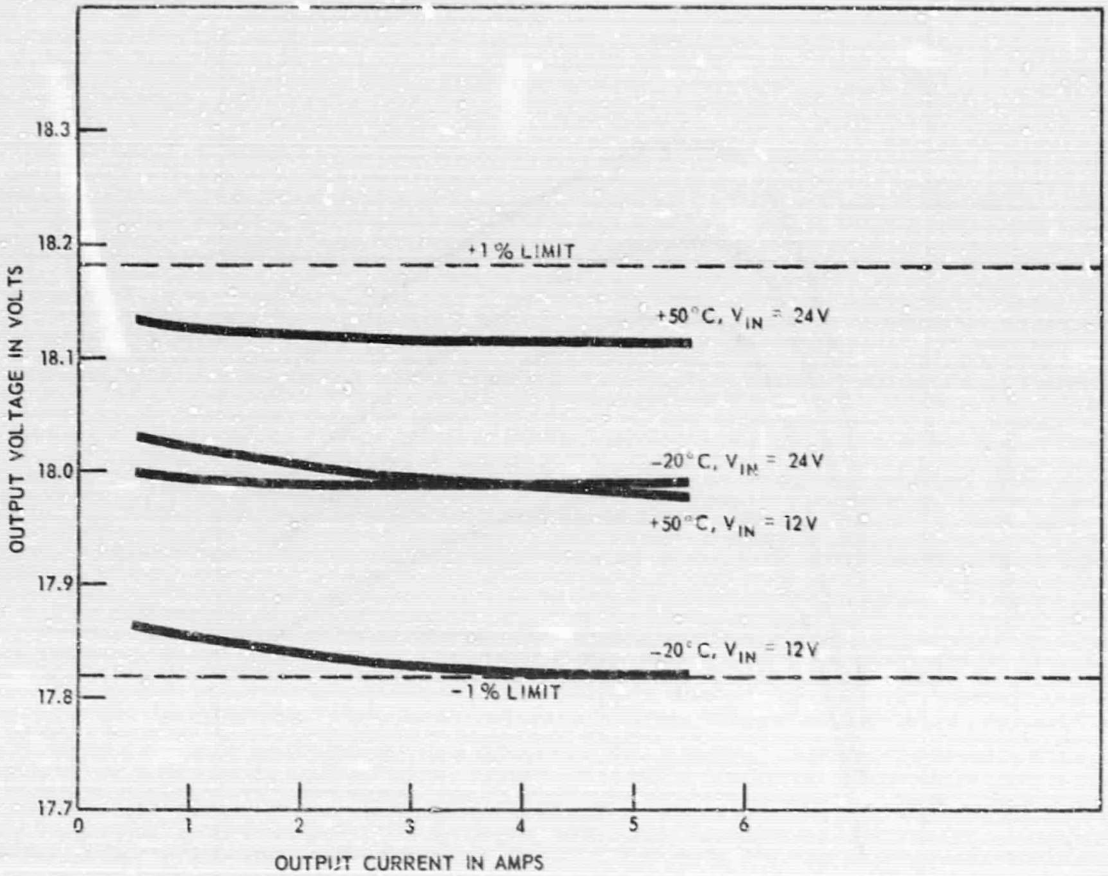

Figure 12. Regulation Plots of Buck-Boost Regulator at T_A = 20°C and +50°C

comparison purposes is a graph of efficiency versus load current for the RAE main bus regulator. Photos of the transient response of the regulator to step load change are shown in Figures 15 thru 17.

Static Regulation

From the curves of Figures 11 and 12, it can be seen that the regulator has excellent load regulation, less than 0.2%; while the change due to input voltage is about 0.75%. Temperature variation produces the greatest change, approximately 0.9%. The total overall regulation due to all specified conditions is quite good at 1.85% which is within the limit band of 2% (±1%).

Efficiency

The regulator efficiency varies from a minimum of about 84.5% at a load current of 0.5 amperes and an input voltage of 24 volts to a maximum of 90.5%

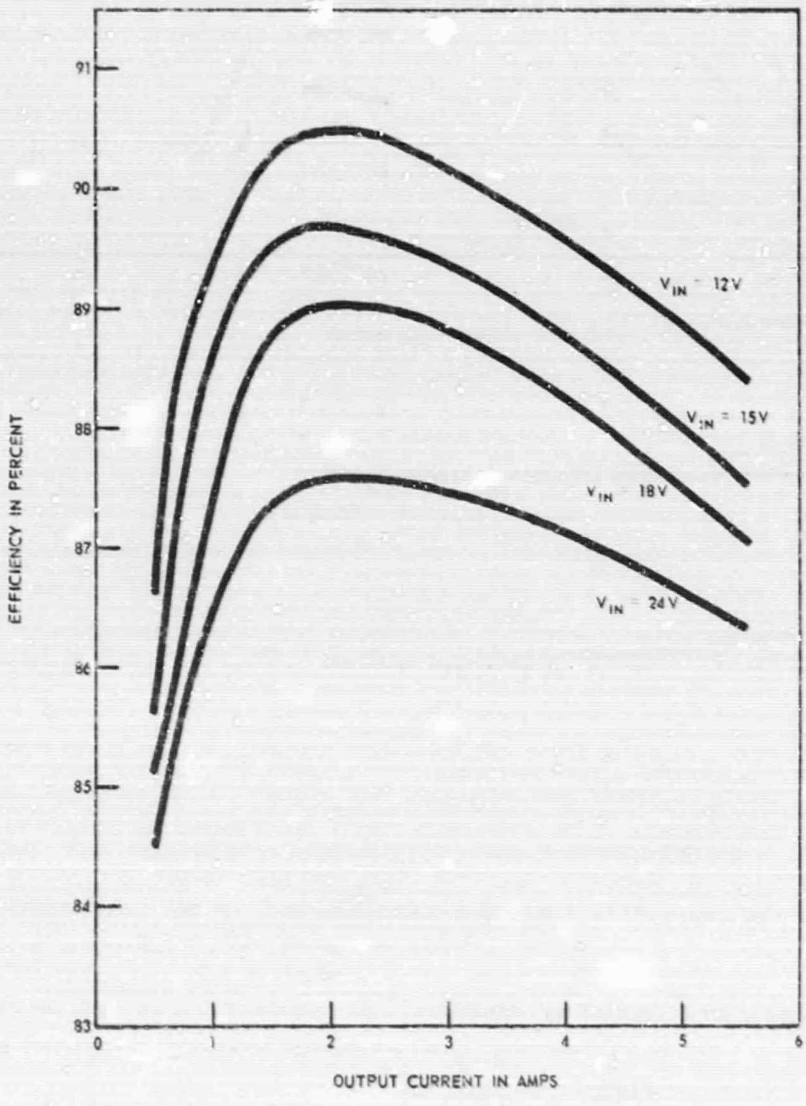

Figure 13. Efficiency Plots of Buck-Boost Regulator

at a load current of 2 amperes and input voltage of 12 volts. From a close look at the efficiency curves of Figure 13, it can be seen that the lowest efficiency occurs at the minimum load of 9 watts since the no load power loss, which varies from 0.9 watts at 12 volts to 1.5 watts at 24 volts, is now significant. At loads from 20 watts to 80 watts, the efficiency ranges from 88 to 90.5%.

For any given load, maximum efficiency occurs at the minimum input voltage of 12 volts, where the regulator is operating in the boost mode. As the input voltage increases, the efficiency decreases, with minimum efficiency occurring at the maximum input voltage of 24 volts where the regulator is operating in the buck mode. This efficiency decrease is due in a large part to the increased losses in the power inverter when it must handle lagging power factor loads. This condition occurs for the duration of the buck interval.

Figure 14 shows an efficiency plot of the RAE main bus regulator. A comparison of these efficiency curves to those of the buck-boost regulator (Figure 13)

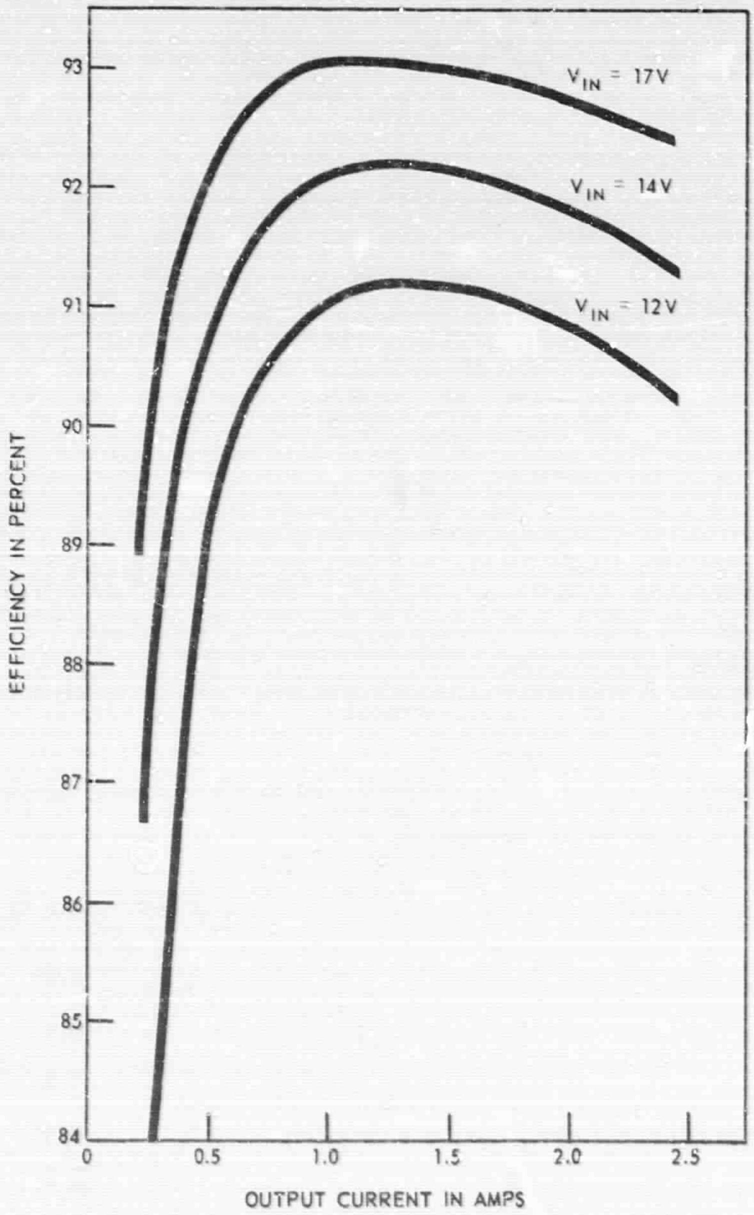

Figure 14. Efficiency Plots of RAE Pre-Regulator Efficiency vs. Output Current, $T_A = 25°C$

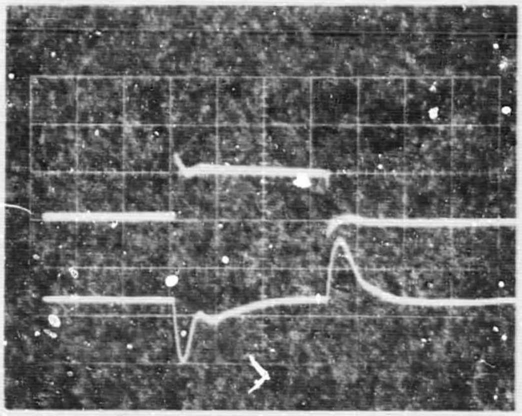

Figure 15. Photograph of the Transient Response of the Buck-Boost Regulator to Step Load Change

$V_{IN} = 12V$ $I_{LOAD\ STEADY\ STATE} = 2A$

Upper Trace: $I_{LOAD} = 2A/cm$

Lower Trace: $V_{OUT} = 2V/cm$

$T/cm = 5ms/cm$

shows that for the maximum boost condition (12 volt input), the regulators are within 1% in efficiency. However as the input voltage increases requiring less boost, the RAE regulator becomes more efficient, since it must switch less power; while the buck-boost regulator becomes less efficient since the buck interval increases.

A breakdown of the losses of the regulator at the maximum input of 24 volts and maximum load of 5.55 amps. is shown below:

Item	Power Loss in Watts
Filters	5.2
Inverter	3.5
Chopper Circuit	7.2
Master and Slave Multivibrator and Control Circuitry	0.6
Total Loss	16.5

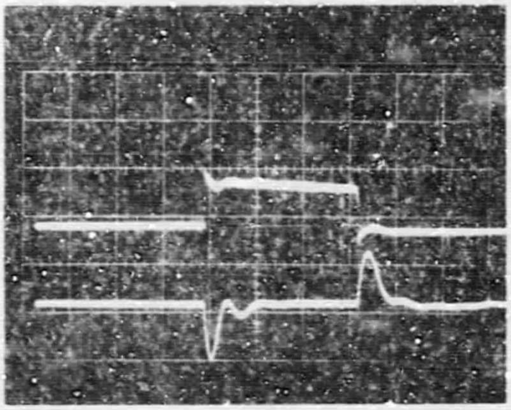

Figure 16. Photograph of the Transient Response of the Buck-Boost Regulator to Step Load Change

V_{IN} = 18 V $I_{LOAD\ STEADY\ STATE}$ = 2A

Upper Trace: I_{LOAD} = 2A/cm

Lower Trace: V_{OUT} = 2V/cm

T/cm = 5ms/cm

The primary areas of loss are in the input filter and power chopper circuit. Significant loss in the filter results from the high rms currents which flow thru the effective series resistance (E_{SR}) of the input capacitor C_3. This capacitor must handle the ac forward and pumpback current of the inverter. The highest loss results in the chopper circuit from load current flow through D_3 and D_4. This loss is directly proportional to load current and can be reduced if the output voltage level is increased, since for a given power requirement, the load current would be reduced. Calculations indicate that an efficiency increase of about 2% could be realized by raising the output from 18 to 28 volts.

Transient Response

The transient response of the regulator to instantaneous load change is shown in the series of photos of Figures 15, 16, and 17. For the response to load change, a steady state load of +2 amperes was chosen, while a step of 2 amperes with rise and fall times less than 5 microseconds was the dynamic load applied to the output. The application of this load resulted in an undershoot of 2.6 volts (14.5%) with recovery to within the regulation range taking 5 milliseconds. The removal of this load resulted in an overshoot of 2.4 volts (13.3%) with recovery

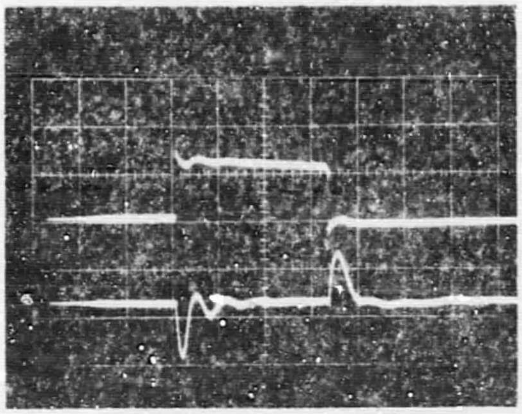

Figure 17. Photograph of the Transient Response of the Buck-Boost Regulator to Step Load Change

$V_{IN} = 24\,V$ $\quad I_{LOAD\ STEADY\ STATE} = 2A$

Upper Trace: $I_{LOAD} = 2A/cm$

Lower Trace: $V_{OUT} = 2V/cm$

$T/cm = 5ms/cm$

to within the regulation range taking 6 milliseconds. These maximum over and undershoots and response times occur at full load (5.55 amps) and at 12 volts input where the regulator is operating in the maximum boost mode as shown in Figure 15. For 18 and 24 volt input conditions, Figures 16 and 17 show that over and undershoots are about 2 volts in magnitude with response times of about 3 milliseconds.

SUMMARY

Optimization of the individual designs of the solar array and the battery is desired to achieve maximum system efficiency. The use of a buck-boost main bus regulator can provide added flexibility to make this optimization possible, since it can operate over a wide range of voltage above and below the desired output level.

This report has presented the design and development of a buck-boost regulator which uses a novel circuit to step up or down an input voltage from dc source. The buck-boost circuit is simple consisting of a power inverter with autotransformer, power chopper circuit, filters, and the necessary controls. The design approach was based on a highly-efficient PWM boost regulator in which only the boost power is switched. This basic circuit configuration was adapted to provide a buck mode in addition to the boost mode. The combining of a single current transformer with the power chopper transistors to an inductive load provided a novel bucking function and efficient operation of the circuit at high frequency.

With this approach, a buck-boost regulator was designed which exhibited good static regulation, high efficiency, and good transient response.

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