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A SERIES-RESONANT SILICON-CONTROLLED-RECTIFIER POWER PROCESSOR FOR ION THRUSTERS

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16. Abstract

The interim status of a program to develop a power processing system for ion thrusters is presented. Basic operation of the silicon-controlled-rectifier series inverter circuitry is examined. The approach for synthesizing such circuits into a system which limits the electrical stress levels on the power source, semiconductor switching elements, and the ion thruster load is described. Experimental results are presented for a 2.5-kW breadboard system designed to operate a 20-cm ion thruster.

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SUMMARY

A series-resonant silicon-controlled-rectifier (SCR) power processing system is being developed to provide power in the various forms needed for a 20-centimeter mercury bombardment ion thruster. The approach to synthesizing circuits into a system which limits electrical stress levels on the power circuit components and simultaneously time regulates and controls power to the thruster during normal and overload conditions is described. Since the series-resonant inverter system acts as a current source, it is fault insensitive. An internal power transformer isolates the dc source from the thruster loads. The use of SCR's as switching elements permits construction of multikilowatt converters as single modules which reduces power processor complexity. Sinewave currents generated by the resonant power circuit assures SCR operation safely below the maximum di/dt rating of the device. It also minimizes the voltage current product or power loss during the initial switching interval.

Since the power circuit operates in a series-resonant mode, the SCR switching elements turn off automatically each time the resonant current passes through zero, separate commutating circuits are unnecessary, and miscommutation of SCR's is avoided.

A breadboard of the system was constructed and tested. It consisted of three separate inverters tied to a common input filter which suppresses the ripple generated by the inverters from being reflected back to the power source. Regulation of the output was implemented by using an analog signal to discrete time interval converter (ASDTIC) system which operated by controlling the internal inverter off time interval between successive resonant current pulses. For a 2-to-1 variation of source voltage coupled with a 6-to-1 range of output current, the output voltage was controlled to less than 0.1 percent total variation.

Efficiency of the overall system was 86 to 88 percent, depending on the particular SCR's used. The forward conduction loss of the off-the-shelf SCR's used contributed the greatest single loss in the system.

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INTRODUCTION

An ion thruster for space propulsion will require that raw power from a solar array source be properly conditioned to supply the multiple current and voltage needs of the thruster. The power processing system to accomplish this must convert voltage from the solar array, which can easily vary over a 2 to 1 range, to various regulated and controlled voltages for the thruster elements during all conditions including starting, running, and shutdown. It must protect the thruster from overcurrent damage during arcing on the one hand and on the other hand it must protect the source against transients during the various thruster operating modes.

Any power processing system which nondissipatively scales dc voltages to higher or lower levels will include current switching elements and inductive transformer and filter components. These will cause ripple currents and stray fields which the power processing system must control. It must be designed to prevent these ripple currents from being reflected back to the source and it must control stray fields to a level compatible with proper operation of spacecraft payloads and subsystems. It must also respond to external commands, by switching electric power to the functional elements in a thruster in controlled amounts for startup, normal and abnormal running conditions, and shutdown. While performing these functions for the source and thruster loads, the power processing system must at the same time protect itself against oscillations developing from interactions of thruster loads with the power processor, maintain isolation of electrical noise in the power circuits from the low level voltage control circuitry, and control electrical stresses on its internal components below rated values during all operating modes.

Such a power processing system must be durable, efficient, and lightweight, to be compatible with hardware requirements of future space missions. The series-resonant inverter circuit with silicon-controlled-rectifier (SCR) switching elements appears to be a very promising approach, meeting most of the aforementioned requirements. Acting as a current source, the series-resonant inverter circuitry provides isolation between the source and load. The semiconducting switching element is generally the most vulnerable circuit element in power processing system power circuits (ref. 1). An SCR is used in the system described in this report since it can have power handling and forward breakover voltage capacities well in excess of the maximum operational values impressed on the switching elements. Utilization of such devices permits construction of single module multikilowatt converters, which reduces power processor complexity.

This report presents a general description of the series resonant SCR-type power processing system with its key circuit features, system design interfaces, associated design problems and solutions being investigated. This is followed by a discussion of preliminary experimental results for a complete 2.5-kilowatt breadboard power processing system designed to operate a 20-centimeter ion thruster.

SYSTEM DESCRIPTION

The following sections present a description of the key features of the SCR series-resonant ion engine power processing system being designed to meet the system requirements outlined in the previous section. The basic circuits for this concept were initially conceived by Dr. Francisc C. Schwarz at the NASA Electronics Research Center (ref. 2). The subject system is being developed by TRW Systems Group under NASA Lewis Research Center Contract NAS3-14383.

System Block Diagram

A block diagram of the power processing system is presented in figure 1. The input source of power to the three converters is assumed to be a 200- to 400-volt solar array feeding through a common input filter. The input filter required by all nondissipative dc to dc power processing systems, prevents perturbations generated within the inverters, regulator controls, or thrusters, from being reflected back on the solar array.

Converter 1 provides the high voltage output required for the beam and accelerator supplies. Converter 2 provides a medium output voltage for the thruster arc supply. Converter 3 provides a variety of low voltage outputs for the remaining thruster loads. A detailed description of the operation of the 20-centimeter thruster for which this unit was designed is presented in reference 3. Converters 1, 2, and 3 produce nominal output powers of 2000, 300, and 200 watts, respectively.

Each converter has its own separate SCR control and regulator section, which includes sensing circuits to measure voltage buildup in the series capacitors, logic to determine when the auxiliary SCR's should be fired and circuitry to control the time interval between successive internal sinewave pulses. In addition, this circuitry also includes the necessary logic to control the functional interactions between the various ion thruster loads.

The heart of the regulator is an analog signal to discrete time interval converter (ASDTIC) (ref. 4). This device employs two control loops as shown in figure 2. The first is a conventional direct current (dc) loop which senses the average output voltage or current to the load and compares the resulting signal with a reference level. Since the dc loop is located external to the output filter, its response is necessarily quite slow because of the inherently long time constant of the filter. The second loop is an alternating current (ac) loop which senses transients internal to the filter and hence its re-

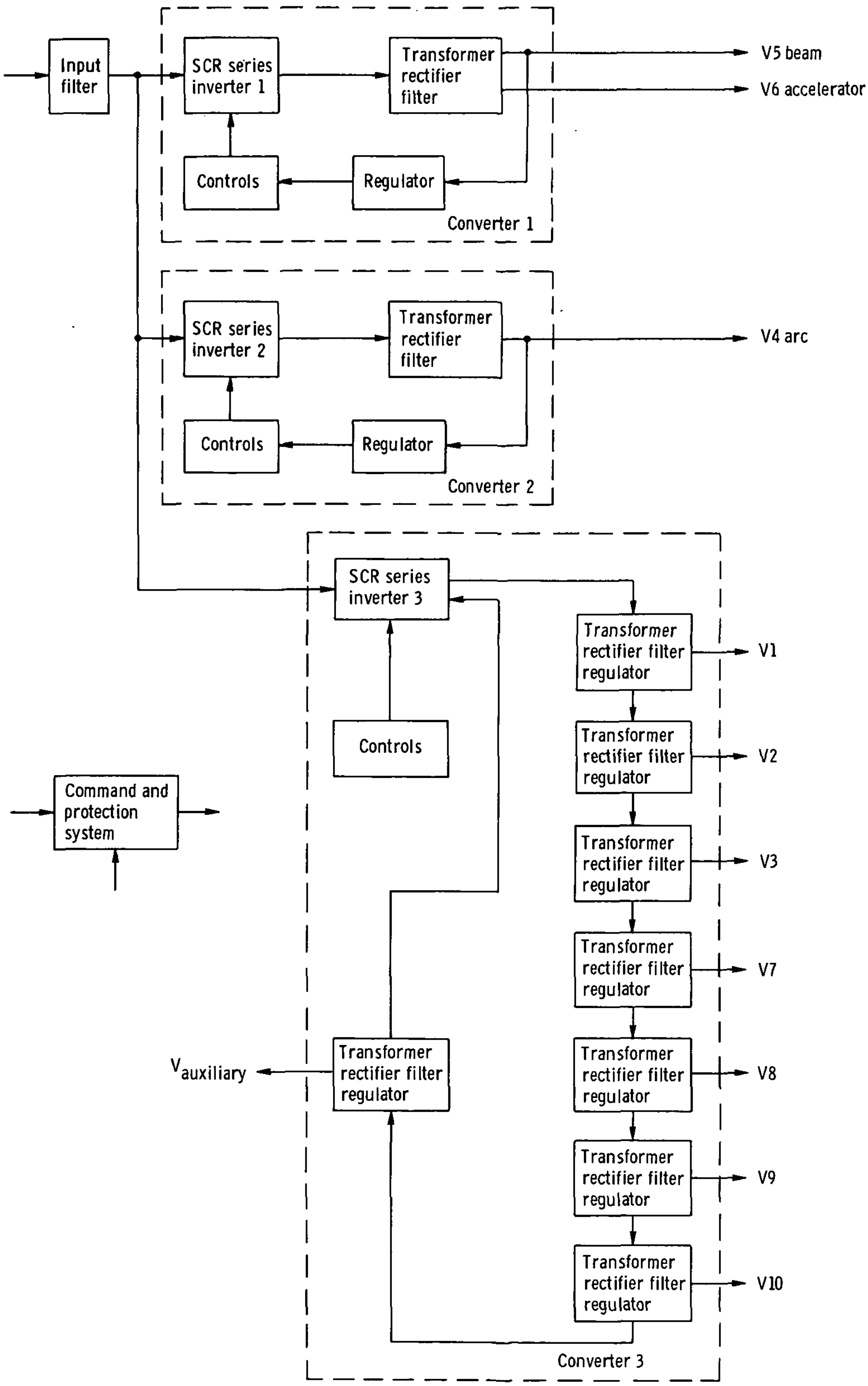


Figure 1. - Block diagram of development model of series-resonant ion engine power processing system.

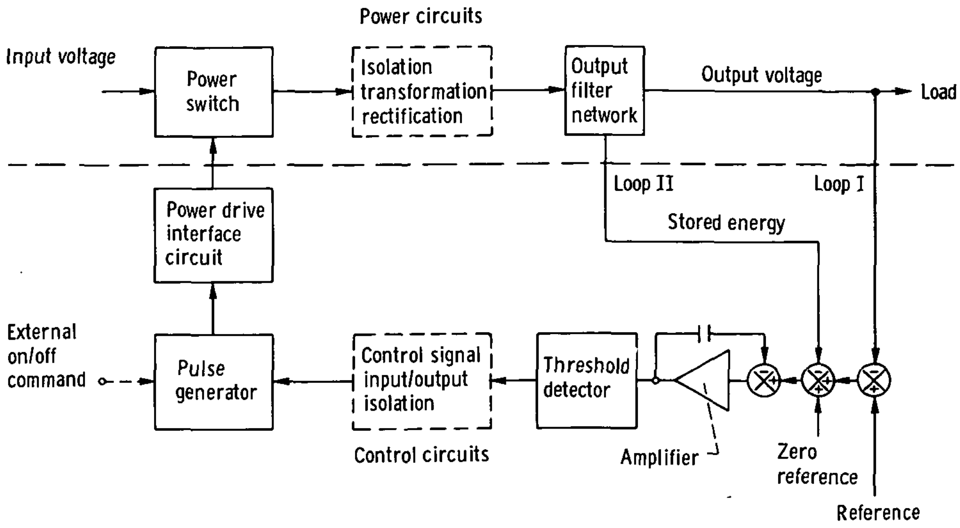


Figure 2. - Block diagram of ASDTIC control loop.

sponse is quite rapid. Specifically, the ac loop senses whether the ac energy internal to the output filter is increasing or decreasing during successive cycles and compares this information to a zero reference. The resulting information is combined in ASDTIC. A signal is generated to either increase or decrease the off time interval between the pulses of the SCR gate control section to maintain the necessary output voltage or current at a predetermined constant value. The ASDTIC provides precision output regulation and, because of its very fast response time, active filtering of line disturbances.

The command and protection system processes all the input commands to control the turn-on and turn-off sequence. In addition, it provides protection for the engine during fault conditions.

Series-Resonant Inverter

The series-resonant inverter is used as the basic ac inversion stage and as a means of matching the 200- to 400-volt dc input power to the output current and voltage requirements of the ion thruster.

Basic inverter stage. - The basic SCR switched series resonant converter circuit is shown in figure 3. It consists of two SCR's, SCR1 and SCR2, two identical inductors (L), two identical capacitors (C), an output transformer (T), a diode bridge, and a current-averaging capacitor filter (C1). When an SCR is turned on, an oscillatory current flows through the series combination of L, T, and C. The sinusoidal current flow, occurring at a frequency determined by the L-C components, is zero when an SCR is initially turned on, builds up to a maximum determined by the circuit design, and then

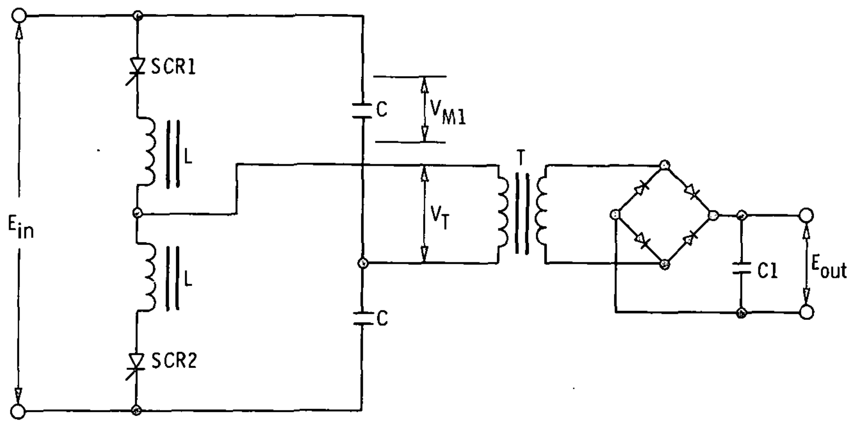


Figure 3. - Basic series inverter.

returns to zero. As the current passes through zero, the capacitor is charged to a voltage higher than the supply voltage and the inductor voltage drops to zero. The sum of the capacitor voltage and transformer voltage appears as a reverse voltage on the conducting SCR during its recovery to a blocking state. The L and C circuit elements, therefore, provide a natural commutation circuit which is an integral part of the power circuit. No auxiliary transformer windings or capacitors are necessary as additional elements to generate commutating pulses to turn off the SCR's. This feature is unique to this type of converter.

The sinewave current insures SCR operation below the maximum di/dt rating and minimizes the voltage-current product during the initial switching interval to reduce the disadvantage of slow SCR switching. In parallel inverter transistor circuits used for this application, high switching losses and high stress may occur if both high voltage and high current exist at the same time (ref. 5).

The sinewave current amplitude is changed by the turns ratio of transformer T before it is rectified and filtered by capacitor C1. The transformer also provides isolation between the dc source and the dc output. The transformer turns ratio may be quite large in the case of ion thrusters to produce the high voltages required for the beam and accelerator supplies. The distributed capacitance of the windings of such transformers can be considerable. This is no problem in the design of series inverters since the reflected capacitance of the large filter capacitor C1 is much greater than the winding capacitance so that the latter may be neglected.

By neglecting the small resistive component inherent in L, T, C, and the source, the current flowing through the inductor and transformer, upon closure of SCR1, is given by

$$i = \frac{V_{M1} - V_T}{\sqrt{\frac{L}{2C}}} \sin \frac{t}{\sqrt{2LC}} \tag{1}$$

where V_{M1} is the voltage across the upper capacitor C in figure 3 at time $t = 0$, when SCR1 is turned on, V_T is the amplitude of the squarewave voltage across the transformer primary. The latter voltage is clamped at a value established by the low-ripple voltage across the output capacitor C1. In equation (1), the current through the system will still be limited if the output transformer voltage is reduced to zero due to an output short.

A functional subtlety regarding voltage V_{M1} can be illustrated by the extreme case of an output short circuit. When $V_T = 0$, there can be no output power. However, each sinusoidal current pulse represents an increment of energy derived from the power source. Since energy not dissipated by the load is stored in the series capacitor C, voltage V_{M1} across C can build up quickly. To avoid excessive voltage buildup across C, all energy not consumed by the load must be dissipated or returned to the source.

The energy buildup is now analyzed to gain insight into the series-inverter operation. Let V_{01} be the initial voltage across the upper C at the beginning of the first half-cycle of conduction through SCR1. It can be shown that, during this first half-cycle, the voltage across the upper capacitor C is

$$\left(V_c\right)_1 = V_T + (V_{01} - V_T) \cos \frac{t}{\sqrt{2LC}} \tag{2}$$

After a half-cycle of conduction by SCR1, it is turned off. Following a controlled time interval, SCR2 is turned on. During this second half-cycle, voltage across upper capacitor C can be shown to be

$$\left(V_c\right)_2 = E_{in} - V_T - (E_{in} - V_T - V_{02}) \cos \frac{t}{\sqrt{2LC}} \tag{3}$$

where V_{02} is the initial voltage across the upper capacitor at the beginning of the second half-cycle (or the end of the first half-cycle).

Starting with V_{01} and using equations (1) and (2) alternately, with their respective proper initial voltages, the voltage V_C at the end of the n^{th} cycle can be shown to be

$$\left(V_c\right)_n = 2nE_{in} - 4nV_T + V_{01} \tag{4}$$

or

$$\frac{d\left(V_c\right)_n}{dn} = 2(E_{in} - 2V_T) \tag{5}$$

Equation (5) indicates that

(1) For $E_{in} < 2V_T$, $\left(V_c\right)_n$ would decrease with each cycle n (i.e., voltage across C cannot build up). In steady-state inverter operation, $E_{in} < 2V_T$ is possible.

(2). For $E_{in} = 2V_T$, $\left(V_c\right)_n$ would be identical for each n (i.e., steady-state operation can result). While this is true academically, it is nevertheless not recommended due to its similarity to case (1).

(3) For $E_{in} > 2V_T$, $\left(V_c\right)_n$ would increase with n (i.e., voltage across C will build up indefinitely until limited be dissipative inverter elements). The rate of increase is maximum at $V_T = 0$, as evident from equation (5).

It can be concluded, from the three previous cases that, for a series inverter to operate reliably, the following two conditions must be met: (1) V_T must be designed to be less than one-half the minimum nominal input voltage E_{in}, and (2) a means must be implemented to limit the energy buildup in the series resonant capacitor C.

Methods to limit energy buildup in resonant capacitor. - There are two basic methods for limiting the capacitor buildup: (1) Transfer of the stored energy in the inductor to the load or to the source at a point during the half-cycle when a particular capacitor voltage level has been reached. (2) Transfer of the excess energy stored in the capacitor to the load or to the source between the end of a half-cycle power pulse and the start of the following pulse.

Figure 4 shows the basic power circuit schematic of the aforementioned method (1). SCR1 and SCR2 are the main line SCR's. When the main SCR1 is fired, a sinewave current is passed until the series-resonant capacitor, C1, in figure 4 reaches a predetermined value. The capacitor voltage sensor then fires the auxiliary SCR3 which terminates the current flow into the series capacitor, C1, and allows the inductor energy of L1 to transfer into the power transformer T. With the firing of SCR3, SCR1 is turned off as a result of a reverse bias voltage derived from C1. Current decays approximately linearly to zero in inductor L1 and transformer T. SCR3 then turns off, completing one switching event and the first half-cycle of operation. In the following half-cycle of operation, a similar switching event occurs starting with the firing of the alternate main SCR2. This allows a sinewave current to flow through the series-

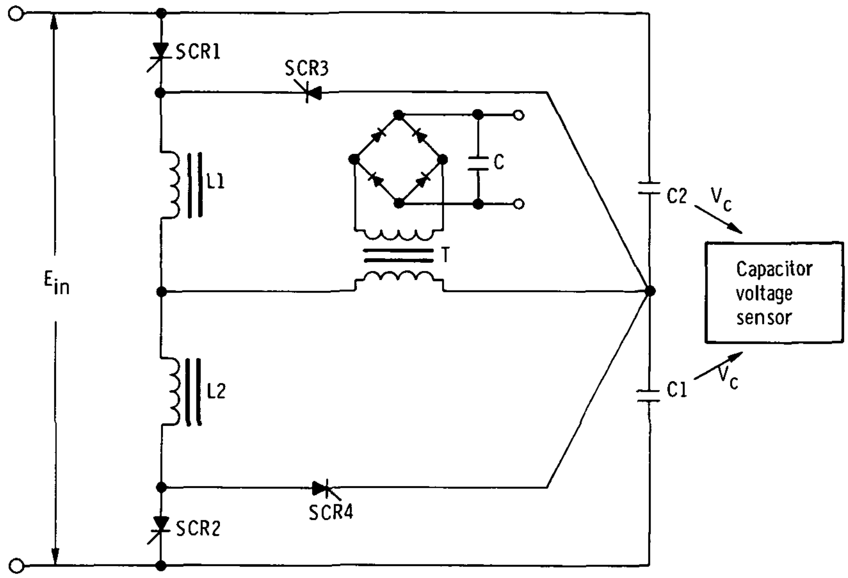


Figure 4. - SCR series-resonant inverter with excessive inductor energy returned to load.

resonant capacitor C2, transformer T, inductor L2, and SCR2 until the series-resonant capacitor reaches the predetermined limit value. The capacitor voltage sensor then fires the auxiliary SCR4, terminating current flow into C2 and allowing the inductor energy to transfer into the power transformer. This then completes one full cycle of operation.

The basic problem with this design is that the main SCR was forced commutated off and thereby produced switching losses which limits its operating frequency.

Method (2) was developed to circumvent this problem by TRW Systems Group under NASA Lewis Research Center Contract NAS3-14383. Figure 5 illustrates method (2),

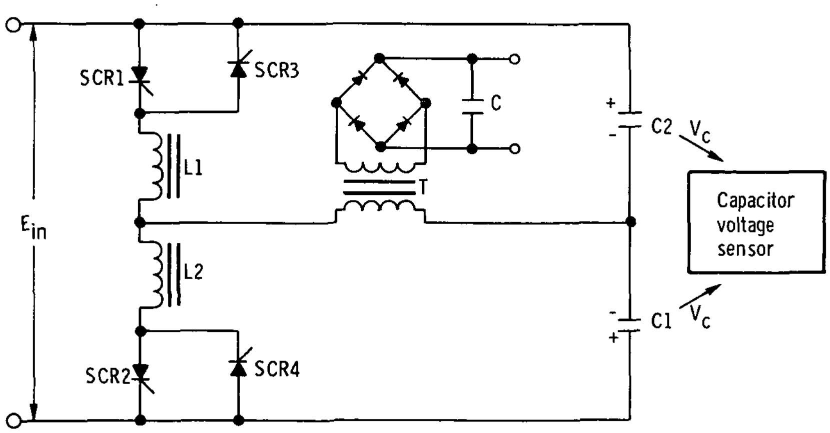


Figure 5. - SCR series-resonant inverter with excessive capacitor energy transfer to source and load.

where excess capacitor energy is transferred to both the load and the source. Sinewave currents are passed through both main (SCR1 and SCR2) and auxiliary SCR's (SCR3 and SCR4). At the start of a switching cycle, the capacitor voltage sensor determines the energy level in a series capacitor. If this level is too high, the appropriate auxiliary SCR is fired. Assuming the polarity as shown on the two resonant capacitors, SCR4 is turned on, circulating current from the lower capacitor through transformer T and current from the upper capacitor back to the source. When the upper capacitor voltage reaches the preset value, SCR1 is turned on. By controlling the firing of the main line SCR's, the peak current in the inductors and main line SCR's is limited.

By controlling the firing of the SCR's as a function of the series capacitor voltage, electrical stresses on the power components can be maintained within limits during normal load operation, and for abnormal input line and load conditions. By controlling the current flow in the inverter components, load transients are isolated from the power source and provide surge protection of the power source. The LC resonant circuit controls the instantaneous current during the conduction period of the SCR's.

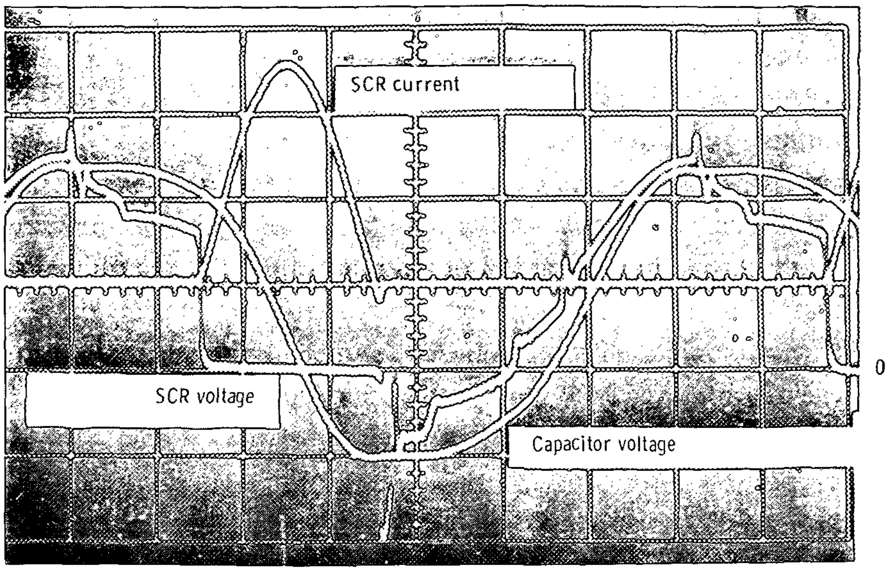
SYSTEM PERFORMANCE

Transient Performance

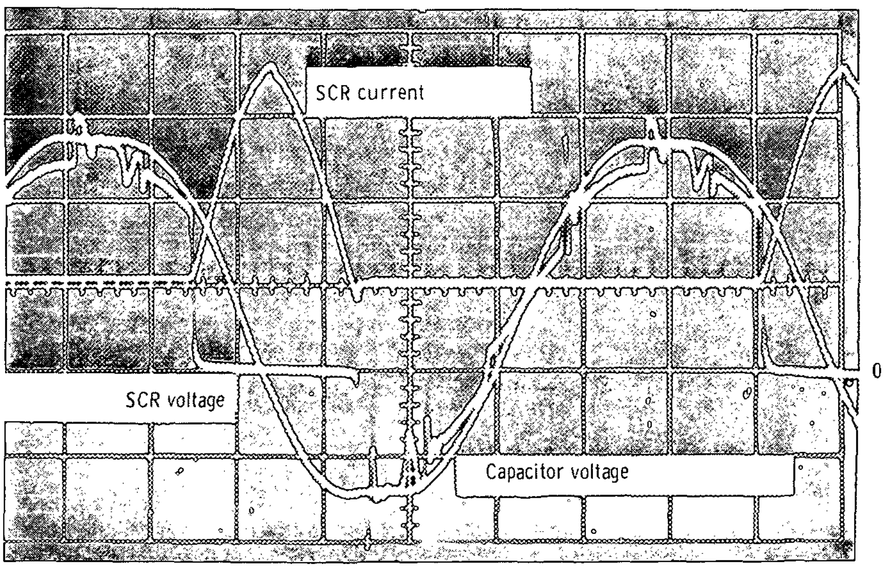
Figure 6 shows a typical voltage and current waveforms for a main line SCR, and the voltage waveforms for the series-resonant capacitor for the beam supply during (1) normal and (2) short circuit operation at 300-volt dc input. The photographs show that the main SCR peak current did not increase from normal output to short circuit operation. Only slight waveform changes occur. The series capacitor peak voltage changes from 480 to 520 volts and the SCR blocking voltage changed from 560 to 600 volts during the peak transients.

Figure 7 illustrates the input current limiting during normal start and turn-off for the 2-kilowatt beam supply. The initial rise on the input current waveform in figure 7(a) is due to the interaction of the input filter with the starting transient of the beam power supply. Figure 8 illustrates the input current during shorting and removal of shorts. The current oscillation is caused by the bounce of the mechanical switch used to simulate an ion engine short. The important thing to note from the results in figures 7 and 8, is that there are no input current transients that exceed the steady state maximum power level and cause collapse of a current limited solar array input bus.

Durability of the SCR series converter was demonstrated by the fact that repeated short circuiting of the output terminals produced no abnormal electrical stresses on the

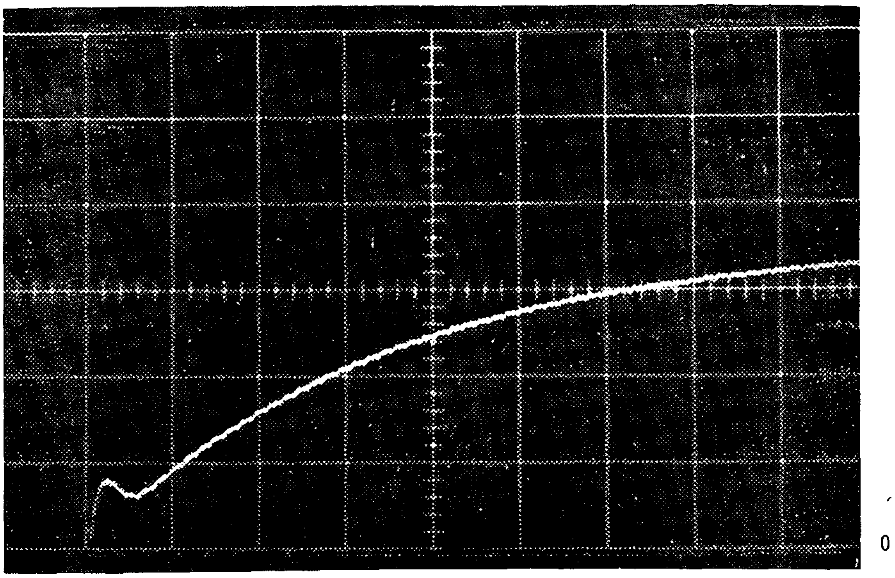


(a) Full load with 300-volt input.

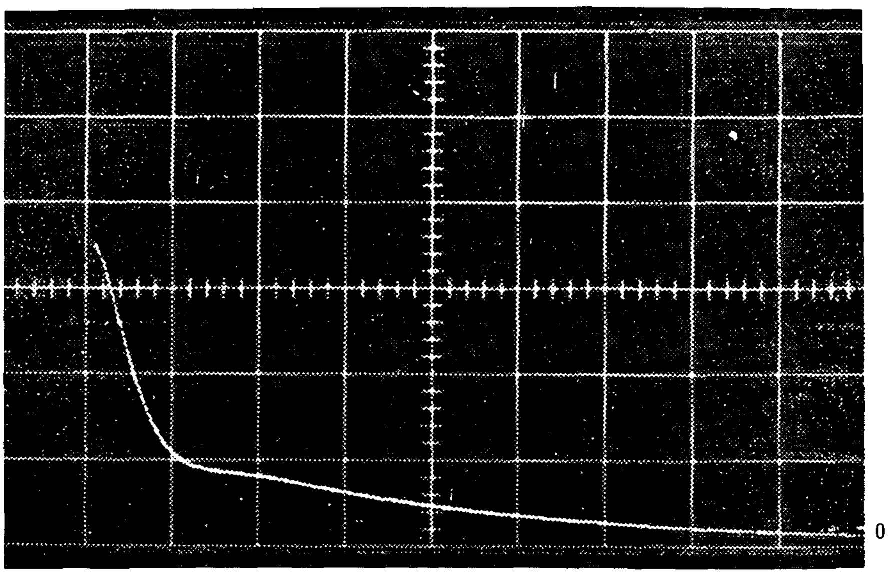


(b) Short circuited output with 300-volt input.

Figure 6. - Typical mainline SCR and capacitor voltage and SCR current waveforms during normal full load and short circuit operation. Voltage, 200 volts per grid division; current, 20 amperes per grid division; time, 10 microseconds per grid division.

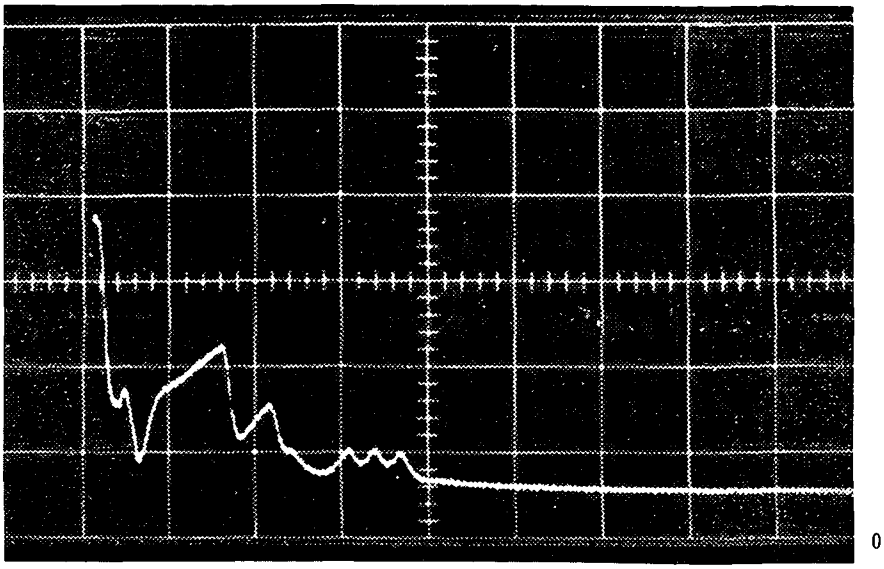


(a) Turn-on. Current, 2 amperes per grid division; time, 500 microseconds per grid division.

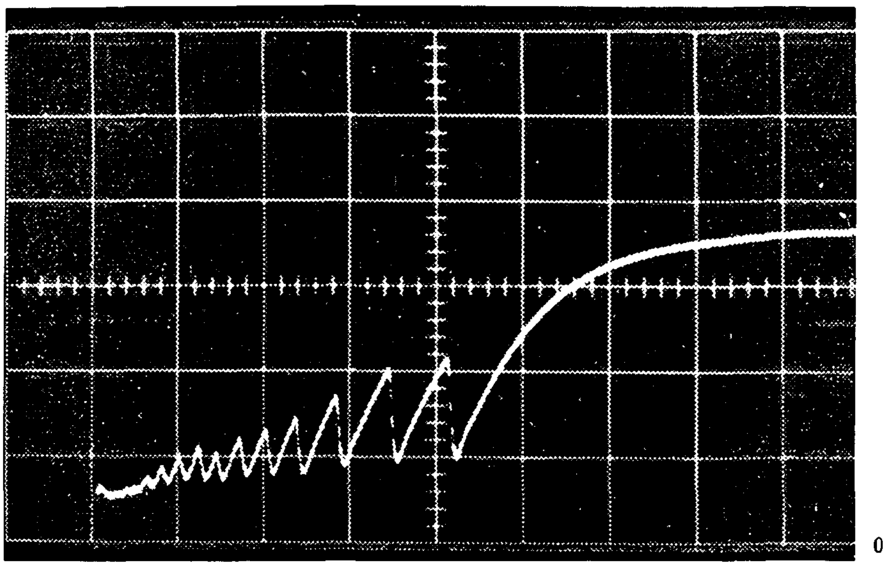


(b) Turn-off. Current, 2 amperes per grid division; time, 200 microseconds per grid division.

Figure 7. - Input current to beam supply during turn-on and turn-off with 300-volt input and full load output.



(a) Short on. Current, 2 amperes per grid division; time, 1 millisecond per grid division.



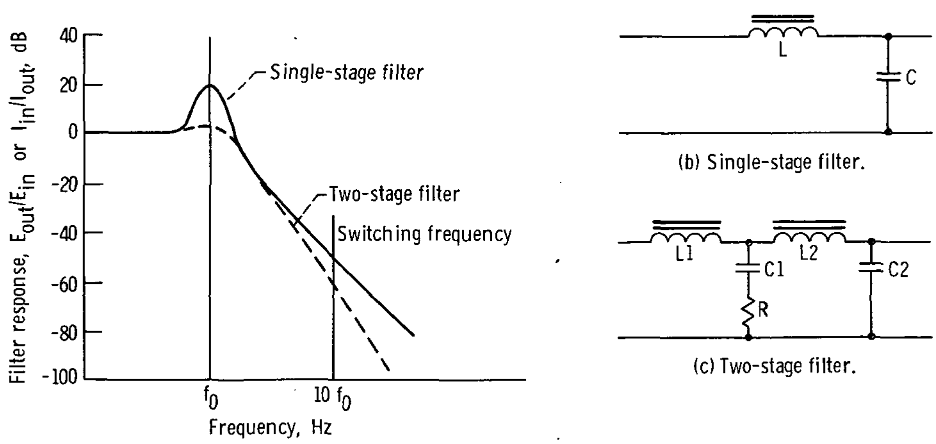
(b) Short off. Current, 2 amperes per grid division; time, 2 milliseconds per grid division.

Figure 8. - Input current to beam supply upon applying and removing output short with 300 volt input.

energy source or internal power processor components and had no effect on subsequent performance.

Input Filter

The input filter must isolate the inverter system from input bus voltage variations and transients generated by other spacecraft loads operating from the same source as well as suppress the ripple current generated by the inverter from being reflected into the power source. Generally, multiple loads require that compromises be made to obtain best overall performance. The conventional single stage LC filter shown in figure 9(b) can exhibit peaking or amplification at the resonant frequency (below the inter-



(a) Input filter response characteristics where f_0 is natural resonant frequency of filter.

(b) Single-stage filter.

(c) Two-stage filter.

Figure 9. - Input filter characteristics of single- and two-stage filters.

nal operating frequency) due to its very low damping properties (ref. 6). As shown in figure 9(a), amplification factors of +20 decibels (gain of 10) or higher at resonance can easily be obtained from such a circuit. Also line current perturbations on the relatively high impedance of the solar array bus will cause sizable voltage variations which must be attenuated. Figure 9(c) shows a two-stage filter design which reduces the severity of these problems. The first stage, consisting of L1, C1, and R, controls the resonant peaking of the filter. The second stage (L2 and C2), supplies most of the pulse current demanded by the series-resonant power circuit. Reduced amplification factors of only 3 to 4 decibels (gain of 1.4 to 1.6) will result at the filter resonant frequency as shown in figure 9(a). It can also be seen in figure 9(a) that the two-stage filter design has better attenuation characteristics than the single stage unit for filtering the high frequency power switching currents drawn by the power processor.

Command and Protection System

The power processor must process spacecraft commands for the operation of the thruster subsystem. It must also provide protection for the power source, power processor, and ion thruster.

The series inverter is inherently self protecting and provides effective isolation between thruster loads and solar array energy source. As a result, no additional control electronics are required in the command and protection system for protection of the internal elements of the power processor or the energy source during transient conditions. It is necessary, however, to provide the following functions in the command and protection system:

(1) Process the input commands for normal thruster startup and shutdown

(2) Protect the power processor from abnormal input voltage

(3) Protect the thruster during faults.

To perform the first function, input commands from the spacecraft are processed and internal commands implemented to turn the thruster on or off. The second function is performed by continuously sensing the input voltage to the power processor, and automatically sending a command signal to turn the unit off if the voltage falls out of the range of 180 to 400 volts.

Protection of the ion thruster during thruster arcing is provided by reducing the discharge current when the beam potential is below a given set point, indicating an overload condition.

During integration testing with a 20-centimeter ion engine it was discovered that, if the discharge current is reduced upon an undervoltage condition on the screen or accelerating electrodes, thruster startup, shutdown, or recovery from arcing can be accomplished without requiring any recycling of the other power supplies or variation in propellant flow rate. Briefly, it was found that upon an electrode overload condition, the reduction in discharge plasma density with decreased discharge current increased the interelectrode impedance by pushing the plasma sheath back into the engine. As a result, the screen and electrode power supplies did not experience a current overload condition and were able to return to their normal operating voltage. During these tests, an SCR series inverter power supply was utilized. This device operates as a current limited source. When a current overload condition occurs, the output voltage drops to zero with about a 25 percent increase in current above the current overload set point. This current rise can be reduced, if desired, by redesign of the circuit parameters.

Tests of Complete Breadboard

Evaluation testing was performed on a three converter breadboard model of a complete power processing system. This system was designed to operate a 2.5-kilowatt ion thruster. In order to perform these tests, a resistive load bank was utilized to simulate the range of static loads impressed by the thruster. A picture of the subject system is presented in figure 10; a description of the block diagram was presented previously.

Regulation. - Exceptionally high regulation was obtained on all outputs of the power processor demonstrating the capability of the ASDTIC control system. For a 2-to-1 variation in input voltage and 6-to-1 variation in output power the output functions were regulated to better than 0.1 percent of the nominal design values.

Efficiency. - The system was tested utilizing several different off-the-shelf SCR devices. Overall system efficiency obtained at a switching frequency of 20 kilohertz ranged from 86 to 88 percent, depending on the SCR device utilized. The major loss was due to the SCR's (5.8 percent of the loss in the beam supply, 1.76 percent of the loss in the arc supply). This loss was composed of forward conduction loss and reverse current loss due to stored charge. The forward current conduction loss occurred because the SCR did not approach minimum saturated forward voltage drop until very near the end of the sinewave current conduction cycle at the 20-kilohertz frequency. Tests at 10-kilohertz switching frequency improved overall efficiency by 1 to 2 percent,

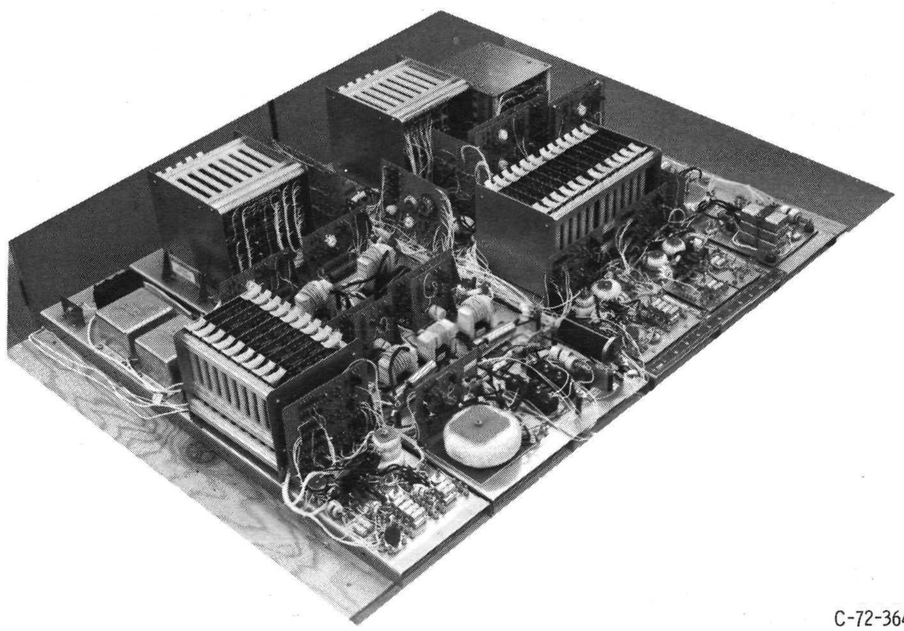


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Figure 10. - Power processing breadboard model.

largely due to the longer current conduction time period which afforded more time for the SCR's to turn on and reach the minimum forward voltage drop condition. This improvement of efficiency was at the cost of greater weight required in reactive components needed at the lower frequency. Projected improvements in SCR's, together with improvements in the design of the series capacitors, are expected to boost the overall system efficiency without increasing weight. This, together with circuit simplifications, is expected to boost the overall system efficiency to greater than 90 percent.

Weight and reliability. - Based upon component weights, the total weight for the overall 2.5-kilowatt nonredundant three-converter flight packaged power processing unit is projected to be between 11 and 13 kilograms. It has been calculated that the achievement of a 0.94 reliability goal for 10^4 hours of operation would entail an added weight penalty of 3 kilograms. This weight penalty is associated with the incorporation of majority voting in all regulator control circuits.

CONCLUSIONS

A power processor for providing power in the forms needed for a 2.5-kilowatt ion thruster having the following characteristics, has been developed:

1. The series-resonant power processing system provides for natural commutation of the silicon-controlled-rectifier (SCR) power switching elements. With natural commutation, there is no need to generate separate commutating pulses within the circuit, and losses associated with forced commutation are eliminated. Reliability is enhanced because fewer circuit components result from no commutating pulse circuits and natural commutation assures that a previously conducting SCR will be turned off before the next one is fired.

2. The sinewave current wave form generated in the resonant power circuit assures SCR operation safely below the maximum di/dt rating of the device. It also minimizes the voltage current product during the initial switching interval.

3. The series converter provides complete isolation between the dc power source and loads.

4. The series converter is inherently self-protecting against output overload transients. No additional control electronics are required for protection of the internal components, or the energy source during load transients. Repeated short circuiting of the output terminals of the converter produced no unusual stress levels on the energy source or the internal power processor components and had no effect on subsequent performance.

5. Input current transients are maintained under control during startup and turnoff by the series-resonant converter characteristics.

6. The high quality output regulation provided by ASDTIC control was typified by the fact that the output voltage was controlled to less than 0.1 percent variation with a 2-to-1 variation of source voltage coupled with a 6-to-1 range of output current. Similar control of output current can be maintained when it is necessary to provide a constant current output over a wide voltage range.

7. The overall system efficiency was 88 percent. SCR's used contributed the largest single loss in the system. An increase in efficiency to greater than 90 percent is projected when identified modifications to several components and circuit simplifications are incorporated.

8. Calculated weight for the complete 2.5-kilowatt nonredundant flight packaged power processing unit, based on known weights of the breadboard components, is 11 to 13 kilograms. If redundant components are included, for a calculated 0.94 reliability for 10^4 hours of operation, the weight would be increased by 3 kilograms.

9. The input filter needed with nondissipative dc to dc power processing systems to prevent an internally generated ripple from being reflected back to the source as well as to isolate source variations generated by other connected spacecraft loads from the power processing system, was a two-stage design filter. The two-stage design effectively damped peaking at the resonant frequency with more attenuation than a single-stage unit in the higher frequency range.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 18, 1972,
758-57.

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