Simplification of Power Electronics for Ion Thruster Neutralizers

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A need exists for less complex and lower cost ion thruster systems. This paper discusses the design approaches and demonstration of the neutralizer power electronics for the relaxed neutralizer keeper, tip heater, and vaporizer requirements. The neutralizer circuitry is operated from a 200-400 V bus and demonstrates an order-of-magnitude reduction in the parts count. Furthermore, a new technique is described for regulating the tip heater power and automatically switching over to provide keeper power with only four additional components. A new design to control the flow rate of the neutralizer with one integrated circuit is also presented.

Nomenclature

C = output capacitance, F
f = oscillator frequency, Hz
i = small-signal capacitive and resistive load current, A
I = capacitive and resistive load current, A
I_L = load current, A
I_0 = load current at the lowest input voltage, A
I_{sc} = short-circuit load current, A
J_{NC} = neutralizer common current, A
J_{NK} = neutralizer keeper current, A
J_{NT} = neutralizer tip heater current, A
J_{NV} = neutralizer vaporizer rms current, A
K = open-loop gain, neutralizer volts per vaporizer ampere
L = transformer secondary leakage inductance plus the reflected primary leakage inductance, H
n = ratio of transformer secondary to primary turns
q = ratio of highest input voltage to lowest input voltage
R_L = load resistance, Ω
s = Laplace transform variable
v_{in} = small-signal sinusoidal input voltage, V
v_L = small-signal sinusoidal load voltage, V
V_{in} = input voltage, V
V_L = load voltage, V
V_{NK} = neutralizer keeper voltage, V
V_{NT} = neutralizer tip heater voltage, V
V_{NV} = neutralizer vaporizer heater voltage, V
ΔI = change in load current at constant resistive load from the lowest input voltage to the highest input voltage, A
τ = small-signal transfer function time constant, s

Introduction

POWER processors for mercury (Hg) ion thruster systems of 8 and 30 cm diameter were designed to thruster requirements specified in the early 1970s.[1,3] The 30 cm Hg ion thruster was to accommodate a broad spectrum of electric propulsion missions that had significantly different thruster operating requirements. The resultant power processor allowed great flexibility in thruster operation, but at a cost of power processor complexity. For example, 3% of the regulation specifications for the screen supply required closed-loop control techniques. The specified load characteristics of both the 8 and 30 cm diam Hg ion thrusters were based on the assumption that conventional closed-loop control techniques would be used for current and voltage regulation. The effect of other specifications on the power processors has been discussed.[4]

A program addressing less complex and lower cost ion thruster systems is continuing. The first efforts reduced the number of power supplies necessary to operate a 30 cm diam Hg ion thruster.[5,6] The initial demonstration of new keeper power supplies resulted in an order-of-magnitude reduction in the parts count.[7]

The low-power supplies required for thruster keepers and heaters provide the best opportunities for simplification. In the 30 cm diam Hg ion thruster system, the low-power supplies account for approximately one-half of the power processor components, while handling less than 4% of the thruster power (run condition at full power). There are about 1750 parts in nine low-power outputs. This parts count includes redundant control circuits, set point and compensation circuits, and the multiple inverter power stage, but excludes telemetry and the input filter. The neutralizer power electronics discussed in this paper comprises 65 components for three power supplies.

Another approach to simplifying the multiple ion thruster systems of the future may be to replace the individual thruster neutralizers with one- or two-system neutralizers. Recent tests with the SERT II spacecraft showed neutralization was more easily achieved from a distance of 1 m than by the immediate neutralizer.[9] The simplified circuits described in this paper show a design approach that lends itself to such a system neutralizer power circuit. Furthermore, the circuits are applicable to inert gas thrusters as well as Hg ion thrusters.

An approach was taken that exploits modified thruster neutralizer requirements, especially relaxed regulation tolerance and load profile requirements and reduced set points to achieve an order of magnitude reduction in parts count. The basis of this approach uses a variable frequency proportional to the input voltage for self-regulation.[7] Additional design equations are derived and detailed designs are discussed for neutralizer supplies and controls of a 30 cm diam Hg ion thruster. Test results are compared to the design equations. Testing with a 30 cm diam Hg ion thruster neutralizer is also described.

Neutralizer Supply Requirements

Although the following requirements are for a 30 cm diam Hg ion thruster, similar requirements exist for inert-gas thrusters.

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Table 1 30-cm-diameter Hg ion thruster neutralizer power electronics demonstration requirements

Item	Neutralizer-keeper requirement	Neutralizer tip heater requirement	Neutralizer-vaporizer heater requirement
Nominal operating point	15 V at 2.5 A	12 V at 4 A	3 V at 1 A rms with capability of 5.2 V at 1.7A rms
Regulation	±10% current	±10% current	Control loop regulates keeper voltage ±1 V nominal
Input voltage	2 : 1 Range, 200 to 400 V	2 : 1 Range, 200 to 400 V	2 : 1 Range, 200 to 400 V
Housekeeping power	Not needed	Not needed	Nominally 15 V at 0.05 A
Ignition	> 50 V at low source impedance	Not applicable	Not applicable
Input-output-control isolation	> 10 MΩ dc resistance	> 10 MΩ dc resistance	> 10 MΩ dc resistance
Load resistance	Not applicable	1 Ω cold, 3 Ω hot	3 Ω hot or cold
Operation into open circuit	Required	Required	Required
Operation into short circuit or overload	Required	Required	Required
On-off controls	Control logic port required	On with keeper, off is automatic with keeper ignition or with keeper off	On and off with keeper and separate control logic port for shutdown
Output ripple	Nominally 0.5 V peak-to-peak maximum	Nominally 1 V peak-to-peak maximum for f < 50 kHz	Not applicable

The neutralizer requires three power supplies: the vaporizer heater supply controls the propellant flow, tip heater power is required at startup for electron emission, and the keeper supply initiates and maintains the gaseous discharge.

A summary of the relaxed requirements for the neutralizer of a 30 cm diam Hg ion thruster is given in Table 1. The input voltage was allowed to vary over a 2 : 1 range. Input power could have been supplied from the standard unregulated 28 V spacecraft bus, but it was judged desirable to power all thruster power supplies from a dedicated unregulated high-voltage bus. Based on earlier work, a voltage range of 200-400 V was chosen to represent the higher-voltage bus.[8] More recent work suggests that the high-voltage bus maximum voltage be limited to 300 V due to space and thruster-induced plasma leakage currents.[10] In addition, near-Earth missions such as the orbit raising or stationkeeping of large space structures can require less than a 2 : 1 range in input voltage if the cold solar array voltage is limited or regulated. The basic circuits designed for the 200-400 V input bus requirement are applicable to a 150-300 V bus with little change in performance. However, if the input range is reduced, then regulation and power efficiency can be improved and mass reduced. A small amount of housekeeping power is required for the neutralizer closed-loop controller. The housekeeping power bus can vary in the 8-20 V range with only a single voltage needed.

Neutralizer Keeper

Ion thruster keeper loads have a unique requirement for an ignition potential greater than the operating potential.[11] Detailed power supply requirements for a keeper load (discussed in Ref. 7) are listed in Table 1. For this demonstration, the keeper current regulation tolerance with a 2 : 1 input voltage change was ±10%. Furthermore, the keeper voltage was allowed to vary ±1 V to simplify the vaporizer controls.

Neutralizer Tip Heater

The neutralizer tip heater operates for only a short time. Once the keeper discharge is established, the tip heater supply is turned off. Tip heater requirements are listed in Table 1. For this system, the keeper voltage is applied simultaneously with the tip heater power. When the keeper current begins flowing, the tip heater current can be proportionally reduced to zero at the keeper operating current. There was no requirement for a high-heat command (increase heater current by 10%), since this precaution may be made obsolete by further thruster development. However, high heat could be provided if necessary. For example, a small high-leakage inductance transformer-rectifier could be switched in parallel with the tip heater supply with a logic command.

Neutralizer Vaporizer Heater

The neutralizer vaporizer can control the Hg flow by controlling the temperature of the vaporizer. For this system, vaporizer heater power can be supplied as a train of 20 Hz pulse-width modulated dc pulses. The vaporizer thermal mass can average the power to provide the desired temperature and Hg flow. The many thruster operating conditions and possible keeper discharge modes makes open-loop vaporizer control, or even vaporizer temperature control, a difficult way to insure adequate thruster system performance. Therefore, the conventional closed-loop method of sensing and controlling keeper voltage by changing the Hg flow—using variable vaporizer power—was adopted as a requirement. In addition, the vaporizer platinum resistance thermometer (PRT) was used to limit the maximum vaporizer temperature as well as to prevent operation in undesirable modes. Control characteristics representative of the neutralizer requirements for this demonstration are given in Ref. 12. Neutralizer vaporizer heater requirements are summarized in Table 1. A control logic port is required to shut down the vaporizer during preheating of the thruster.

Approach

An approach was taken that demonstrates how the modified thruster requirements, especially the relaxed regulation tolerances, can achieve a low parts count. The basic avenues toward achieving a low parts count are the elimination of active voltage limiting and closed-loop current control, as well as simplification of certain sense, control, and logic functions used in conventional thruster neutralizer systems.

The circuit concept for the neutralizer keeper, tip heater, and vaporizer supplies is a new self-regulating technique.[7] The technique uses a modified full-bridge Jensen[13] power oscillator. A new start circuit as well as an on-off control were designed into the oscillator. One oscillator with three separate power output transformers was used to power each of the neutralizer loads. The oscillator frequency is directly proportional to the input voltage. The power transformers are designed with predetermined leakage inductances. Since leakage inductance current is reduced as frequency increases, output current going through the leakage inductance is automatically reduced as the oscillator frequency is increased. This interaction results in a first-order correction of the increase in output current due to the increased input voltage. The short-circuit current is virtually constant over the 2 : 1 input voltage range.

The expression for load voltage vs load current for each power supply is

$$V_L = nV_{in}\left(1 - \frac{I_L}{I_{sc}}\right)^{\frac{1}{2}} \tag{1}$$

where

$$I_{sc} = nV_{in}/8fL \tag{2}$$

and the ratio $V_{in}:f$ is a constant.

Using Eq. (1), design equations were developed for the tip heater and vaporizer resistive loads. The following equations provide expressions for the short-circuit current and open-circuit voltage as a function of resistive load current regulation tolerance for any input voltage range,

$$I_{sc} \simeq I_0\left[\frac{q^2 - 1 + 2(\Delta I/I_0)}{q^2 - 1 - 2(\Delta I/I_0)}\right] \tag{3}$$

$$nV_{in} \simeq \frac{I_0 R_L}{2}\left[\frac{q^2 - 1 + 2(\Delta I/I_0)}{\Delta I/I_0}\right]^{\frac{1}{2}} \tag{4}$$

Equations (3) and (4) were used to determine the requirements for the vaporizer, tip heater, and keeper power transformers that were designed as described in Ref. 7.

Vaporizer Heater Power and Control

Power is supplied to the 3 Ω vaporizer heater using a transformer-rectifier scheme similar to the keeper supply. The load characteristic is given by Eq. (1), so there is some automatic correction for input voltage changes. For control, power to the transformer is pulse-width modulated at 20 Hz using a power transistor as a switch. The vaporizer heater receives the pulsating direct current and the vaporizer thermal mass averages the power for constant-temperature operation.

The transfer function for the 30 cm Hg ion thruster neutralizer given in Ref. 12 is

$$\frac{V_{NK}}{J_{NV}} = \frac{K}{[(s/0.02)+1][(s/2)+1]} \tag{5}$$

Gain K varies widely with thruster operating conditions, but the break frequencies remain constant. The maximum gain measured in Ref. 12 was 50 or 34 dB, which was measured for the specified neutralizer keeper current of 2.1 A.

Within limits, the keeper voltage being regulated is not critical to the thruster performance or life and can vary ± 1 V.[14] This allows the use of a lower gain-control loop and the elimination of the compensation amplifiers, resistors, and capacitors necessary when 1% regulation is required. By reducing the phase margin from 60 to 50 deg, the worst-case gain can be increased from 34 to 42 dB. The power electronics gain can then be as high as 2.5. For this demonstration, the keeper was intended to run at a higher current then that used in Ref. 12. Furthermore, the thruster neutralizer used here was a later model than the neutralizer used in Ref. 12. Therefore, for this initial design and demonstration, the power supply gain near the nominal operating point of 3 W neutralizer-vaporizer power was conservatively chosen to be 0.7 at 200 V input and 1.2 at 400 V input.

Neutralizer Tip Heater

The tip heater power is supplied from a transformer-rectifier filter similar to the keeper supply. Power to the transformer primary is supplied from the full-bridge power oscillator. The tip heater is turned off once the keeper discharge is established. Heater turnoff has previously been accomplished by sensing the keeper current and shutting off the heater power supply when the logic circuits determine that the keeper current is above a certain level. Another method uses only one power supply for both a tip heater and a neutralizer keeper.[5] A relay is used to transfer power from the tip heater to the neutralizer keeper. The relay cycles the power supply output between the neutralizer tip heater and neutralizer keeper until a high enough discharge current is sensed, at which point only the keeper discharge is powered. The discharge ion bombardment then provides enough power to heat the electron-emitting tip.

Two separate approaches were considered for tip heater control and power. The first, a straightforward method, turns off the tip heater power when the keeper voltage drops below a preset value at the keeper ignition. A signal proportional to the keeper voltage, as well as a reference voltage, is already available from the vaporizer control circuit. A comparator with hysteresis turns off a power transistor in the primary of the tip heater power transformer (the same way the vaporizer is pulsed on and off) when the keeper voltage signal falls below the reference level. Comparator hysteresis prevents the power transistor from spending too much time in the active region where its power dissipation can be excessive. This approach requires 14 additional parts, but has the advantage of not consuming power once the keeper is ignited.

The second approach is shown in Fig. 1. Three versions of the technique provide regulated tip heater power as well as

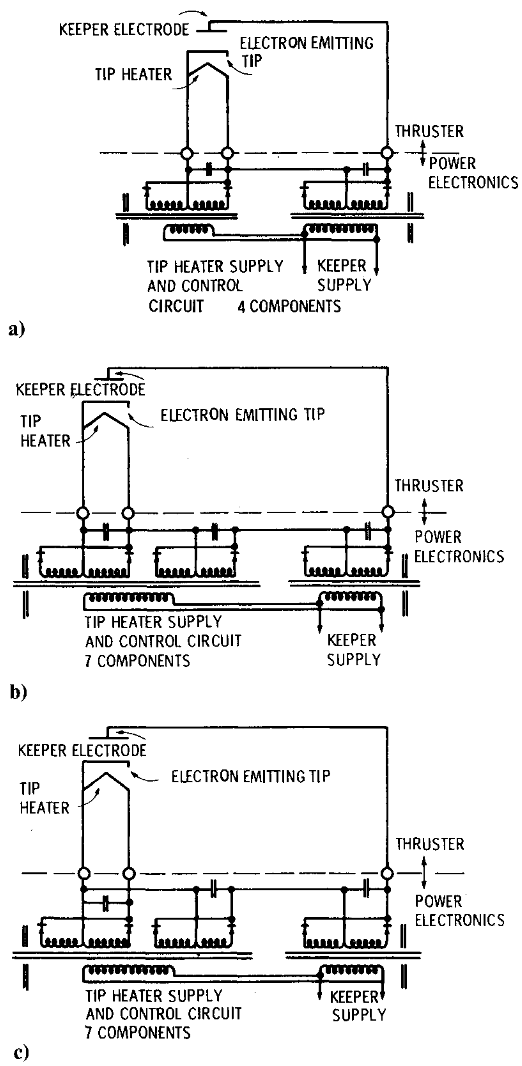

Fig. 1 Tip heater power, control, and sense circuits: a) tip heater power and control circuit for heater $I <$ keeper I; b) tip heater power and control circuit for heater $I >$ keeper I; c) tip heater power and control circuit for any heater current.

perform the current sensing, logic, and heater supply turnoff functions with as few as four parts. The circuit in Fig. 1a adds four parts to the keeper supply and requires the heater current to be less than the keeper current. The tip heat supply is current limited and has the load characteristic given by Eq. (1). The tip heater and keeper supplies are connected so that any keeper current must also be supplied by the tip heater supply. Once the keeper discharge is established, the tip heater power is virtually zero since the tip heater supply of short-circuit current is exceeded. The tip heater voltage is clamped to about -0.7 V (one diode drop).

The circuit shown in Fig. 1b uses three more parts than the circuit of Fig. 1a. The extra winding on the heater supply adds enough ampere-turns to the secondary leg of the tip heater transformer, so that the tip heater is cut off even when the keeper current is less than the tip heater current.

The circuit of Fig. 1c allows complete cutoff of the tip heater, but requires more turns on the transformer secondary leg than the other two circuits.

The three circuits in Fig. 1 shut off the tip heater, but the heater supply is essentially operating into a short circuit and extra power is being dissipated after keeper ignition. These circuits require slightly more power, but this is partially offset because the tip heater supply also provides a large part of the open-circuit keeper ignition potential. The keeper supply open-circuit voltage then depends only upon the regulation requirements and the keeper supply can be designed for a lower open-circuit voltage that increases its efficiency. The circuit in Fig. 1b was chosen to demonstrate this technique.

Tip heater power, regulation, current sense, and turnoff can be accomplished with the addition of four or seven components, but slightly more power is consumed. Compared with the neutralizer keeper supply discussed in Ref. 7, it was found that circuit 1b uses an additional 6.5 W or decreases the power efficiency of the baseline J-series 30 cm Hg^{15} ion thruster system by 0.2%. The alternative straightforward approach discussed earlier does not increase power consumption, but requires more parts (14 total).

Neutralizer Keeper Supply

The neutralizer keeper supply is the same basic circuit described in Ref. 7, except that two voltages from the tip heater supply are added to make up the total keeper voltage. This changes the load profile at low keeper currents. However, after keeper ignition, the tip heater voltages go to nearly zero and the keeper supply operates as described in Ref. 7.

In addition, an on-off control logic port and a new start circuit has been designed into the keeper supply.

Audio Susceptibility Considerations

Spacecraft dc power system buses carry low-level noise as well as dc power. Most of the noise power spectrum is in the audiofrequency range (20-20,000 Hz); therefore, power circuit behavior with audiofrequency noise added to the dc input is important. The small-signal (about 1 V peak-to-peak) transfer function of the basic self-regulating power circuit[7] used for all of the neutralizer power supplies derived in the Appendix is

$$\frac{v_L}{v_{in}} = \frac{2n}{I_{sc}^{1/2}} \frac{(I_{sc} - I_L)^{3/2}}{(2I_{sc} - I_L)} \frac{1}{(\tau s + 1)} \tag{6}$$

where

$$\tau = \left(\frac{I_L}{2I_{sc} - I_L}\right) R_L C \tag{7}$$

From Eqs. (6) and (7), the maximum signal transfer occurs at dc (or very low frequency), where the natural regulation property of the circuit provides attenuation as the load current is increased. As the small-signal frequency is increased, the circuit behaves like a simple lag network, increasing attenuation 20 dB per decade after the corner frequency is reached.

Neutralizer Supply Circuit Design

The power circuit design shown in Fig. 2 is based on the full-bridge neutralizer keeper power supply design detailed in Ref. 7. The power transformers for the neutralizer loads have ferrite cores for convenience; the data are given in Table 2. One oscillator (Q_1 to Q_4) is used to power all three neutralizer loads. A new start circuit and an isolated on-off control logic port were designed and added to the original circuit.

The new start circuit comprises R_6 and R_7 and CR_2, CR_5, and C_2. Capacitor C_2 charges through R_7 until the firing voltage of CR_5 is reached (typically 32 V). The pulse from C_2 into T_1 starts the converter by momentarily turning Q_2 and

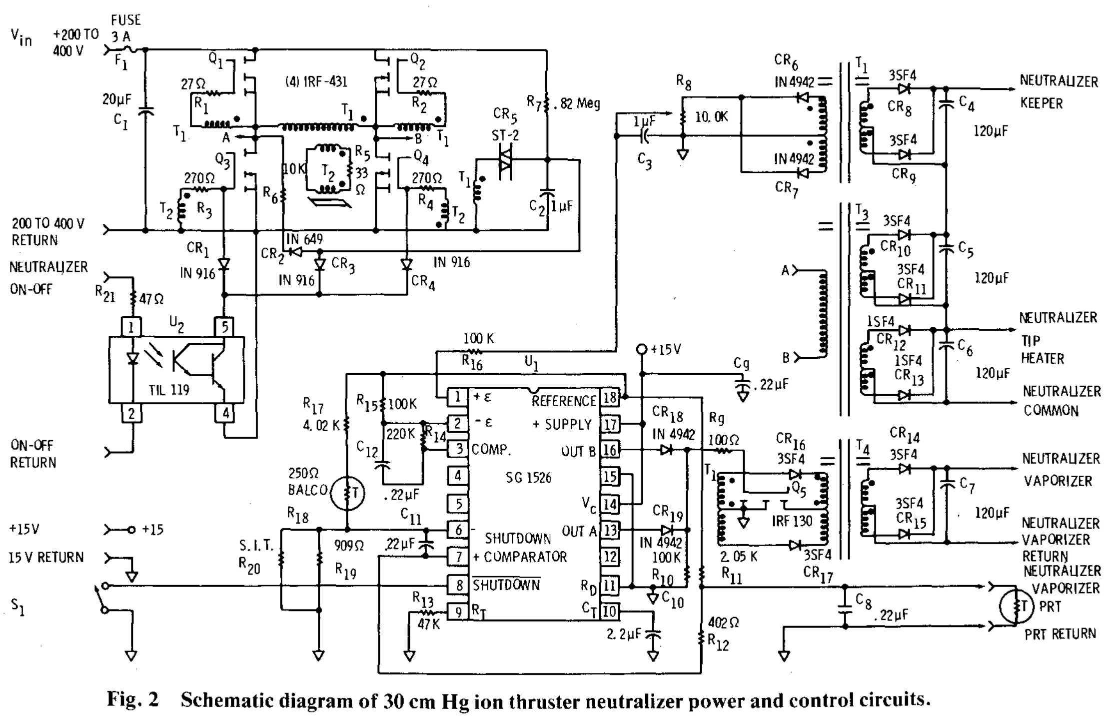

Fig. 2 Schematic diagram of 30 cm Hg ion thruster neutralizer power and control circuits.

Table 2 Transformer data

Transformer	Core	Windings
T_1	EC70-EC70G 3C8 material	Primary leg Primary: 130 turns no. 20 AWG Vaporizer power: 25 turns no. 22 AWG bifilar Feedback for Q_1 gate drive: 6 turns no. 26 AWG Feedback for Q_2 gate drive: 6 turns no. 26 AWG Feedback for Q_3 and Q_4 gate drive: 5 turns no. 26 AWG Pulse start: 2 turns no. 20 AWG Secondary leg Secondary: 22 turns no. 16 AWG bifilar Feedback for vaporizer control: 8 turns no. 26 AWG bifilar
T_2	80516-1/2D	95 turns no. 36 AWG trifilar
T_3	EC70-EC70 with center gap increased to 4 cm 3C8 material	Primary leg Primary: 130 turns no. 20 AWG Secondary leg Secondary 1: 27 turns no. 6 AWG bifilar Secondary 2 tip heater: 22 turns no. 16 AWG bifilar
T_4	EC52G-EC52G 3C8 material	Primary leg Primary: 54 turns no. 22 AWG bifilar Secondary leg Secondary: 18 turns no. 18 AWG bifilar

Q_3 on, while holding Q_1 and Q_4 off. Resistor R_6 and CR_2 limit the voltage on C_2 to prevent pulsing during normal operation. Turnoff is achieved by clamping the gate to the source voltage of Q_3 and Q_4, below the threshold voltage using U_2, an optocoupler, together with CR_1 and CR_4. Diode CR_3 prevents C_2 from charging.

The tip heater is powered from T_3 and operates as previously described. Vaporizer power is supplied through T_4 and is pulse-width modulated at a 20 Hz rate by Q_5 and the regulating pulse-width modulator U_1. The regulating pulse-width modulator integrated circuit contains the voltage reference (5.0 V), oscillator, error amplifier, pulse-width modulator, drivers, shutdown comparator, and vaporizer shutdown logic port. A signal proportional to the keeper voltage is taken from T_1. For convenience during testing, potentiometer R_8 was used as a voltage divider to set the ratio of feedback signal to keeper voltage. The feedback signal is compared to the reference in the low-gain error amplifier. Integrated circuit U_1 generates the pulse-width modulated 20 Hz Q_5 gate signal width that is proportional to the error signal. The resultant average current to the neutralizer is linearly proportional to the error signal. However, the rms current to the neutralizer is nonlinear, so the circuit gain increases at low current and changes with the input voltage, but not enough to be of any consequence. The change in the rms vaporizer current per volt change in the keeper voltage for the entire circuit at 1 A rms vaporizer current was 0.7 at 200 V input and 1.2 at 400 V input. A vaporizer overtemperature limit was implemented using the vaporizer platinum resistance thermometer (PRT). To save using an extra amplifier, the PRT signal was increased by using a higher PRT current. The higher current caused a negligible amount of self-heating. Room temperature tests of the PRT in a J-series 30 cm diam Hg ion thruster in a vacuum were run using a precision current source. Temperature rises measured were 0°C for 0.22 mW, 0.7°C for 2.0 mW, and 2.7°C for 5.5 mW. As a compromise between self-heating and signal level, the worst-case power dissipation was chosen to be 2 mW since an error as high as 2°C is not significant. The PRT was used in one leg of a bridge powered by the 5.0 V reference. The U_1 shutdown comparator was used as a detector and turns off all vaporizer power when the bridge signal exceeds about 100 mV. The comparator trip-level threshold change with U_1 temperature is about +0.2 mV/°C. A small positive temperature coefficient resistor R_{18} was used to compensate for most of this variation. Since the comparator signal is low level, noise filters comprised of C_{11}, R_{12}, and C_8 were used.

Another vaporizer control circuit configuration using fewer parts, where CR_{18} and CR_{19} are eliminated, was examined but had the disadvantage that the vaporizer could not be completely turned off. Some newer integrated circuits being designed especially for single-ended outputs may further reduce the parts count.[16]

Neutralizer Supply Circuit Performance

The neutralizer power supply regulation, power efficiency, and other circuit functions were tested at room temperature using resistive loads. For convenience, the audio susceptibility tests were run on the keeper supplies described in Ref. 7. These supplies exhibit the same general behavior as all of the neutralizer circuits used for this demonstration. Tests with the J-series 30 cm Hg ion thruster neutralizer were run using only the neutralizer assembly with a collector plate to simulate operation of a neutralizer.

Resistive Load Tests

The neutralizer circuits shown in Fig. 2 were tested over the input voltage range with resistive loads. The circuit was turned on and off into a short circuit and various resistive loads at 400-200 V input using the isolated on-off control logic port provided by the opto-coupler U_2. In addition, the circuit was also turned on and off into a short circuit and various loads at input voltages of 200-400 V by turning the input power on and off. Load transients, including short circuits, were also induced at the 200 and 400 V inputs. No failures or degradation occurred in any of the tests, which accumulated about 80 h of data.

The neutralizer keeper load profile is shown in Fig. 3. The short-circuit current is 0.15 A higher at 400 V input than at 200 V input and results in wider regulation limits than given

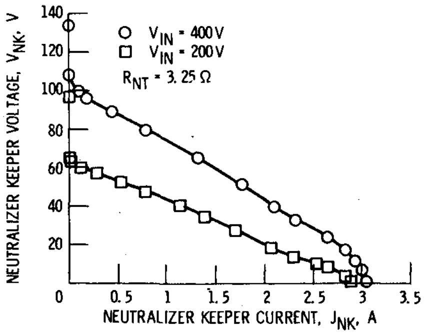

Fig. 3 Neutralizer keeper voltage as a function of neutralizer keeper current.

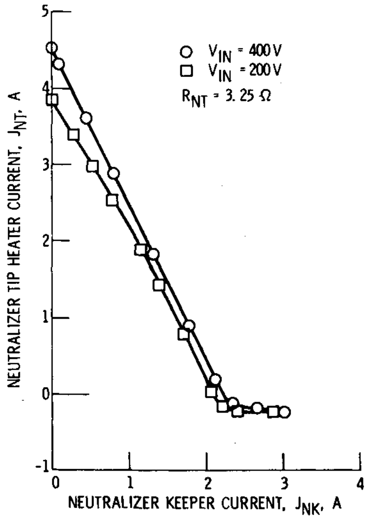

Fig. 4 Neutralizer tip heater current as a function of neutralizer keeper current.

by Eq. (3), which assumes a constant short-circuit current. The keeper load profile represents the addition of two tip-heater-rectified transformer secondary voltages to the keeper supply voltages until about 2.2 A is reached; then from 2.2 A to short circuit, the neutralizer keeper load profile is represented by Eq. (1). The keeper supply ripple was 0.8 V peak-to-peak at nominal loading.

The neutralizer tip heater current vs the neutralizer keeper current is shown in Fig. 4 for a tip heater load of 3.25 Ω. At zero keeper current, the tip heater current line regulation boundaries are slightly higher than given by Eq. (3). The tip heater current is slightly negative at 2.1 A keeper current for a 200 V input and at 2.2 A keeper current for a 400 V input. About 0.2 A of keeper current flows through the 3.25 Ω simulated heater. This increases to about 0.6 A for a 1 Ω heater and represents 0.3 W heater power when the heater is off. This is not significant and, therefore, the circuit was not changed to the more efficient circuit shown in Fig. 1c. The power efficiency measured with a 3.25 Ω heater load was 52.3% at 400 V input with a keeper voltage of 14.51 V and 64.1% at 200 V input and keeper voltage of 15.30 V. This compares with the neutralizer-keeper supply (detailed in Ref. 7), which exhibited a power efficiency of 60% for a keeper voltage of 15 V at 400 V input and 76% at 200 V input. Another indirect comparison is the 30 cm diam Hg ion thruster engineering model power supply. The low-power supply efficiency was about 50% at the full beam run condition.[17] The neutralizer vaporizer supply was tested with a 3 Ω load and met the requirements listed in Table 1.

The main purpose of this effort was to demonstrate the circuit concepts and to obtain benchmark data. No effort was made to raise efficiency or to reduce weight. As a start, lighter weight and higher efficiency could be achieved by using higher flux density transformer core material, core configurations that minimize copper weight, and more efficient power MOSFETS.

Audio Susceptibility

The two keeper circuits detailed in Ref. 7 are representative of the power circuits used for the neutralizer system. For convenience, tests and analyses were run on these two supplies instead of the neutralizer supplies described in this report. Only the neutralizer vaporizer supply with its controller is significantly different, but only because of the control circuit. It was judged that this difference would not present serious difficulties because the vaporizer time response is very long compared to the periods of audio frequencies.

For the audio susceptibility tests, a 1 V peak-to-peak sinusoidal signal was added to the dc input voltage. This was accomplished by using an audio isolation transformer with the secondary in series with the positive dc input line. An oscilloscope was used to measure peak-to-peak voltages so accuracy was limited. Equations (6) and (7), which are derived in the Appendix, were used to calculate gain vs frequency for various load resistances. Figure 5 shows test data and calculated values of gain vs frequency for the 18-36 V input parallel converter detailed in Ref. 7. Data for line voltages of 18 and 36 V show the same general trend. Attenuation is greatest at the lowest resistance loads and falls with frequency at about 20 dB per decade. For heavy loads, where attenuation is greatest, the equations predict more attenuation. However, under heavy loads, very accurate measurements of I_{sc} and I_L are needed because the small-signal transfer function depends upon the difference between the two currents, which are almost equal and are measured in the presence of some ripple current. In addition, the short-circuit current for this converter depends slightly on the input voltage, which is not accounted for in the model. Figure 6 shows calculated and measured values of the small-signal transfer function for the 200-400 V converter detailed in Ref. 7. For this converter, there is a much greater shift in the short-circuit current with the input

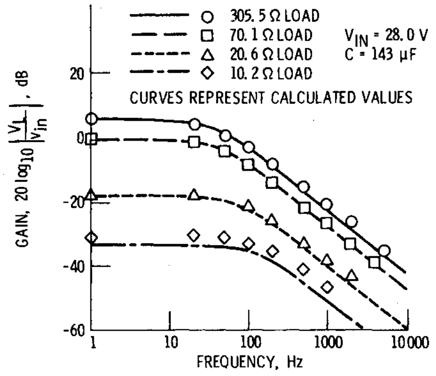

Fig. 5 Parallel converter (V_{in} = 18-36 V) small-signal gain vs frequency.

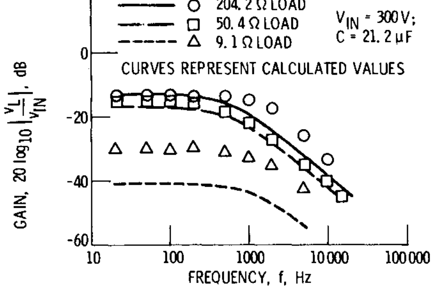

Fig. 6 Full bridge converter (V_{in} = 200-400 V) small-signal gain vs frequency.

voltage, so the measured values for gain at heavy loads are greater than predicted by the model. However, attenuation is always greater than or equal to the dc line regulation. In addition, the corner frequencies at light loads are higher than those predicted by the model. The corner frequencies for the full-bridge converter are an order of magnitude higher than the corner frequencies for the parallel converter. This difference is due mainly to the output capacitors used in each supply.

The test results and transfer function show that the self-regulating power circuit concept has desirable properties that should ease dc bus filter requirements.

Neutralizer Tests

The J-series 30 cm Hg ion thruster neutralizer was tested in a port in the facility described in Ref. 18. A perforated collector plate connected to a current-regulated power supply and mounted about 6.5 cm in front of the neutralizer orifice was used to simulate beam extraction.

For convenience, some of the current measurements recorded with the strip-chart recorder were made with a dc clip on the current probes. The neutralizer common current was measured using a 0.01 Ω shunt, but this measurement did not include the collector (simulated beam) current. A 100,000 Ω bleeder resistor was connected across the keeper supply to insure that the keeper supply capacitor voltage rating (125 V used for convenience) would not be exceeded by peak charging when the keeper was at open circuit.

Several tests were run with the neutralizer. The preheat phase was demonstrated by turning on the tip heater and keeper while the vaporizer was shut down by closing S_1. The system was run closed loop with the collector off for two periods of approximately 15 h each with no instabilities or anomalies. The following neutralizer operating sequence was demonstrated. Initial input voltage was set at 300 V. About 200 s later, the logic on command was given and the tip heater power keeper ignition voltage and the vaporizer power were applied simultaneously. The tip heater voltage increased as the tip heater resistance increased. Tip heater resistance of this particular neutralizer overshoots and then stabilizes. The keeper ignited about 400 s after power was applied. At ignition, the tip heater voltage changed from +9.5 to −0.7 V. The keeper current was about 2.75 A and the neutralizer common current was 2.35 A. About 0.4 A was flowing through the tip heater. The tip heater power after ignition was about 0.3 W.

The vaporizer control-loop response after the step change, caused by ignition, appeared stable and overdamped. Next, the collector simulating beam extraction was turned on. The vaporizer current settled to a lower level after the collector step change. The keeper voltage stabilized about 0.3 V lower since the control-loop gain was low. When the collector was turned off, the neutralizer voltages and currents approached the previous levels in a stable manner. With the collector off, step changes were introduced into the input from 300 to 200 V, 200 to 400 V, and 400 to 200 V. Step input voltage changes were repeated with the collector on. The system responses to these step changes were stable. The range of keeper voltage recorded during these tests was 13.9-15.4 V. The keeper current varied from about 2.2 to 3.0 A.

The vaporizer overtemperature limit was demonstrated by changing R_8 (Fig. 2) to force the neutralizer vaporizer temperature to reach the upper limit of 357°C. Limit cycles are recorded for 300 and 400 V inputs with the collector off. Sustained limit cycles at 200 V were not possible because R_8 was already set at a maximum value. To achieve limit cycle operation at 200 V input, the feedback ratio would need to be decreased further by adding turns to the feedback winding on T_1.

Approximate Hg flow measurements were made at 300 V input. The equivalent Hg flow was about 44 mA at 0 A collector, 29 mA at 2 A collector, and 58 mA average during high-temperature limit cycling with the collector off. Flow measurements taken during limit cycling were complicated by the Hg expansion and contraction during temperature cycling.

For this neutralizer under the conditions of the previous tests, the neutralizer keeper extinguishes when the collector current changes from 2 to 0 A (representing beam recycle), but automatically restarts once the tip heater is reheated. This keeper extinguishing did not occur at the 300 V input. One possible explanation is that the vaporizer temperature was 307°C at 200 V input, and the flow may not be adequate to sustain the keeper discharge when the collector beam is off for this particular neutralizer, under the operating parameters chosen for the test. If this neutralizer characteristic is undesirable and the neutralizer cannot be modified, then a lower temperature limit function may be considered as one possible way to prevent the neutralizer from extinguishing.

Conclusions

Simplification of the power electronics for ion thruster systems can be achieved by reducing the parts count, leading to less complexity and lower cost. New concepts and approaches for simplification were demonstrated with the neutralizer power electronics, which comprises the keeper, tip heater, and vaporizer power supplies and controls. The neutralizer power electronics simplification results from relaxing the ion thruster neutralizer power supply regulation tolerances, redefining load profile requirements, and reducing set points. A key to achieving a low parts count is the elimination of active voltage limiting, as well as the closed-loop current control used in conventional ion thruster power supplies.

A new neutralizer power and control system was demonstrated for a 30 cm Hg ion thruster. The system has an order-of-magnitude fewer components than contemporary neutralizer systems. In addition, based on neutralizer tests, power efficiency and thruster propellant utilization are virtually unchanged.

The self-regulating power circuit concept small-signal transfer function, as well as test data, show that the desirable attenuation properties of the circuit can simplify power source filtering. The neutralizer power electronics, operating from an unregulated high-voltage bus (200-400 V), demonstrated compatible operation with an ion thruster neutralizer.

Appendix: Derivation of Small-Signal Transfer Function

The purpose of this Appendix is to develop an expression for the small-signal transfer function of the self-regulating dc-to-dc converter from fundamental circuit properties.

For this derivation the converter output filter capacitor is considered to be part of the load. Therefore, the converter capacitive plus resistive load current is now represented by I instead of I_L. From Eq. (1),

$$I = I_{sc}\left(1 - \frac{V_L^2}{n^2 V_{in}^2}\right) \tag{A1}$$

The differentials of V_L and V_{in} are used to approximate the converter small-signal input and output voltages. Small-signal capacitive and resistive load current is approximated by the total differential of I,

$$i \approx \left(\frac{\partial I}{\partial V_L}\right) v_L + \left(\frac{\partial I}{\partial V_{in}}\right) v_{in} \tag{A2}$$

Therefore

$$i \approx \frac{-2I_{sc}}{V_L}\left(1 - \frac{I}{I_{sc}}\right) v_L + \frac{2I_{sc} n}{V_L}\left(1 - \frac{I}{I_{sc}}\right)^{3/2} v_{in} \tag{A3}$$

Since I is nearly equal to I_L, Eq. (A3) becomes

$$i \simeq \frac{-2I_{sc}}{I_L R_L}\left(1-\frac{I_L}{I_{sc}}\right)v_L + \frac{2I_{sc}n}{I_L R_L}\left(1-\frac{I_L}{I_{sc}}\right)^{3/2} v_{in} \tag{A4}$$

Small-signal capacitive and resistive load current is also given by

$$i = Csv_L + v_L/R_L \tag{A5}$$

Combining Eqs. (A4) and (A5) results in

$$\frac{v_L}{v_{in}} \simeq \frac{2n}{I_{sc}^{\frac{1}{2}}}\frac{(I_{sc}-I_L)^{3/2}}{(2I_{sc}-I_L)}\frac{1}{(\tau s+1)} \tag{A6}$$

where

$$\tau = \left(\frac{I_L}{2I_{sc}-I_L}\right)R_L C \tag{A7}$$

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