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Simplified Power Supplies for Ion Thrusters

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A clear need exists for lower cost, less complex ion thruster systems. This paper discusses the initial development and demonstration of power supplies with an order-of-magnitude reduction in parts count, which leads to increased reliability at lower weight while still maintaining thrust system performance. Two new self-regulating keeper power supply circuits were developed and tested. One supply comprises 14 parts and uses an input voltage of 18-36 V, the other operates at 200-400 V and requires 22 components. A new technique for controlling heater power is also demonstrated.

Nomenclature

a = empirical constant for a given transformer core
A_c = cross-sectional area of outer leg of transformer core, cm^2
A_L = inductance index for a given transformer core, mH/1000 turns
B_{max} = maximum flux density of outer leg of transformer core, G
f = oscillator frequency, Hz
I_L = load current, A
I_{SC} = short-circuit load current, A
L = secondary leakage inductance plus the reflected primary leakage inductance, H
n = transformer secondary-to-primary turns ratio
N_S = number of transformer secondary turns
V_{in} = input voltage, V
V_L = load voltage, V

Introduction

POWER processors for both 8 and 30 cm diam mercury (Hg) ion thruster systems[1-3] were designed to thruster requirements specified in the early 1970s.[1,3] The 30 cm Hg ion thruster requirements were specified to accommodate a broad spectrum of electric propulsion missions which 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% regulation specifications for the screen supply required closed-loop regulation techniques. 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 power processors is discussed in Ref. 4.

A program addressing less complex and potentially lower cost ion thruster systems has been started. The initial effort which reduced the number of power supplies necessary to operate a 30 cm diam Hg ion thruster was reported in Ref. 5. Continuation of this effort is discussed in a companion paper.[6]

Relaxing regulation tolerances and redefining required thruster load profiles expands the range of circuit techniques that can be evaluated for the purpose of using simpler circuits.

The work reported in this paper is the initial development of new power supplies with an order-of-magnitude reduction in parts count, leading to lower weight while maintaining thrust system performance.

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 half of the power processor components, while handling less than 4% of the thruster power (run condition at full power). There are about 1650 parts for the 9 low-power supplies. This parts count includes redundant control circuits and the multiple inverter power stage and excludes telemetry, set point and compensation circuits, and input filter.[7]

Of the low-power supplies, the keepers have the most unique requirements and were therefore chosen as the first supplies to be developed and demonstrated.

A development approach was taken that exploits modified thruster requirements, especially relaxed regulation, to achieve low parts count. This approach uses a variable frequency vs input voltage for self-regulation. Design equations are developed and detailed designs are discussed for the main and neutralizer keeper supplies of a 30 cm diam Hg ion thruster. Test results are compared to the design equations. Testing of both supplies with a 30 cm diam Hg ion thruster is also described. In addition, a new single-stage power supply technique for supply and control of heater power is demonstrated.

Keeper Supply Requirements

Neutralizer and cathode keeper supplies are required for both the 8 and 30 cm diam Hg ion thrusters as well as some inert gas thrusters. Ion thruster keeper loads have a unique requirement for an ignition potential greater than the operating potential.[8] A typical keeper discharge characteristic is shown in Fig. 1. Points a, c, and e are stable operating

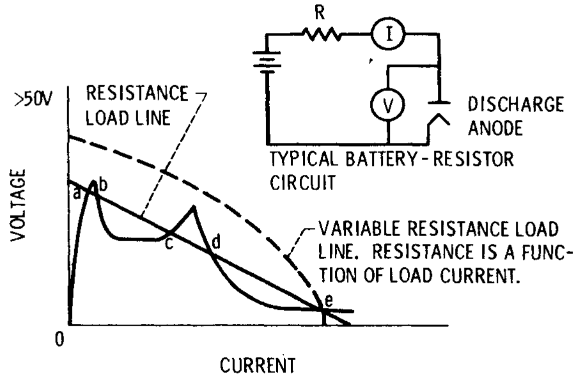

Fig. 1 Static discharge characteristics for typical glow-arc discharge (letters denote load line intersects).

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Table 1 30 cm diam Hg ion thruster keeper supply requirements

Item	Cathode keeper requirement	Neutralizer keeper requirement
Nominal operating point	5 V at 1 A	15 V at 2.1 A
Ignition	≥50 V at low source impedance	≥50 V at low source impedance
Current regulation	Nominally ±10% near operating current	Nominally ±10% near operating current
Input voltage	2/1 range, 18-36 V or 200-400 V	2/1 range, 18-36 V or 200-400 V
Input-output isolation	≥10 MΩ dc resistance, output return is tied to screen potential of 1.1 kV	≥10 MΩ dc resistance
Noise immunity	Immunity from transients induced by screen arcs	No special requirement
Operation into open circuit	Required	Required
Operation into short circuit or overload	Required	Required
Output ripple	Approximately 0.5 V peak-to-peak maximum	Approximately 0.5 V peak-to-peak maximum

points for the discharge. Points b and d are unstable. For the 30 cm diam Hg ion thruster point e is the desired operating point. It is desirable to avoid operation at stable points a and c.[9] This can be accomplished either by using a very high voltage together with a high series resistance or a voltage greater than 50 V[8,9] and a variable low-impedance load line as shown in Fig. 1.

A summary of the 30 cm diam Hg ion thruster relaxed requirements for the cathode keeper supply is given in Table 1. The input voltage was assumed to vary over a 2/1 range. Input power could be supplied from the standard unregulated 28 V spacecraft bus which is bracketed by the 18-36 V range chosen. Alternatively it may be desirable to power the 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 that option.[7] The cathode keeper has requirements similar to those required for the neutralizer keeper supply which was developed for an input voltage range of 200-400 V. For the purpose of this effort it was unnecessary to also develop a cathode keeper supply for the 200-400 V range.

A summary of the 30 cm diam Hg ion thruster requirements for the neutralizer keeper supply is given in Table 1. Since the neutralizer keeper load is the same type as the cathode keeper, the requirements are almost the same. However, the neutralizer keeper requires higher current and voltage.

Development Approach

A development approach was taken that exploited modified thruster requirements, especially relaxed regulation to achieve low parts count. A key to low parts count is the elimination of active voltage limiting as well as the closed-loop current control used in conventional thruster keeper power supplies. In addition, exclusion of multiple series stages of regulation and power conversion between the input power and output power to the thruster leads to reduced complexity. A single power stage is used for either input voltage range.

Further simplification is achieved through the use of dual-role components. A combined transformer-inductor and power MOSFET transistors with their intrinsic antiparallel diodes are used. Transformer leakage inductance has been used in the past for current limiting.[10]

Two new self-regulating circuits were developed to meet the keeper supply requirements. Both circuits use a modified Jensen[11] power oscillator. The oscillator frequency is directly proportional to the input voltage. The power oscillator transformer for both circuits is designed with a predetermined leakage inductance. 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 increased input voltage. Short circuit current is virtually constant over the 2/1 input voltage range. The cathode keeper circuit uses a parallel converter power oscillator for 18-36 V input and the neutralizer keeper supply incorporates a full bridge power oscillator to accommodate a 200-400 V input. Closed-loop regulation techniques using variable frequency are discussed in Refs. 12 and 13. The author could find no relationships describing the interaction of a variable frequency/variable voltage square wave with a series inductor and rectifier, so new relationships were developed. Details of these derivations are given in the original paper.

The expression for load voltage vs load current is

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

where

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

and the ratio of V_{in} to f is a constant.

To achieve a high value of leakage inductance a core with a magnetic shunt was used. The magnetic shunt diverts some of the magnetic flux from linking both the primary and secondary windings. This markedly increases leakage inductance compared to a standard transformer. For convenience, a pair of Ferroxcube EC series gapped cores were chosen for the power transformer.[14] For this transformer, windings were placed on each outer leg instead of the center leg. The center leg was used as a magnetic shunt. The primary was wound on one outer leg, the secondary was wound on the other outer leg.

Developing an accurate analytical expression for leakage inductance based on the core and winding geometry was not practical here. For this structure, leakage inductance calculations must take into account flux paths in addition to the center shunt, since the center shunt gap is large.[15] Therefore an approximate expression for the leakage inductance was developed

$$L \simeq aA_L N_S^2 \times 10^{-9} \tag{3}$$

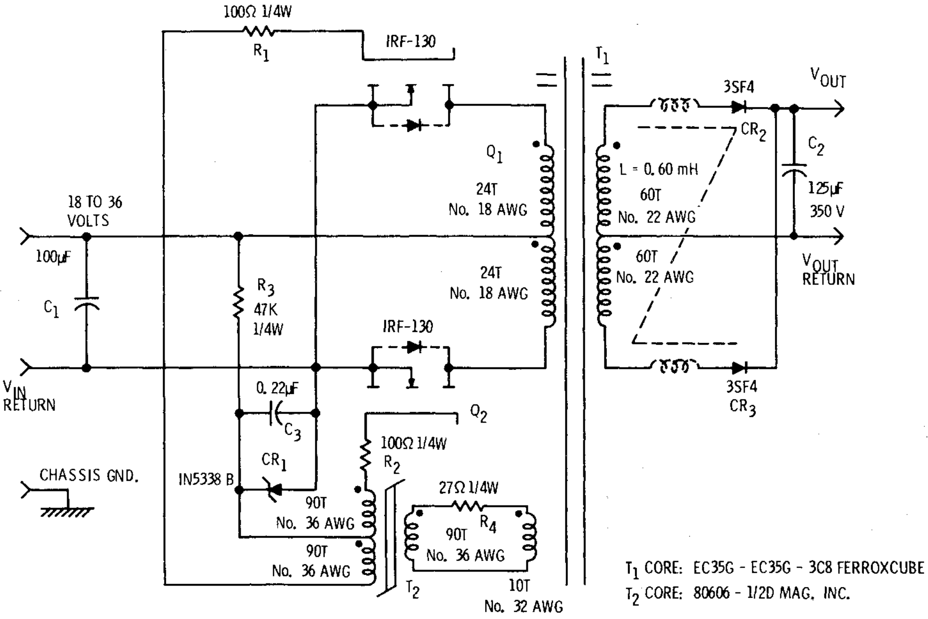

Fig. 2 Schematic of 30 cm Hg ion thruster cathode keeper supply.

The values for A_L given in the core catalog[14] are minimum values. Measured values of A_L for the particular cores used were 10-20% higher than the minimum values listed. Measurements of a for EC41 cores ranged from about 1.8 for a 60 mil gap to 2.5 for a 120 mil gap.

Combining Eq. (2) for short-circuit current, Faraday's induction law,[16] and the leakage inductance relationship [Eq. (3)] an expression for secondary turns was developed

$$N_S \simeq \frac{5A_C B_{\max}}{aA_L I_{SC}} \tag{4}$$

Secondary turns are a function of short-circuit current and magnetic core characteristics. Equation (4) was used to select a transformer core for a given short-circuit current.

Cathode Keeper Power Supply

Design

The cathode keeper power supply schematic is shown in Fig. 2. The circuit is a modified Jensen power oscillator designed so that the oscillator frequency is directly proportional to the input voltage. The frequency is about 9 kHz at an input of voltage of 18 V and 18 kHz at 36 V. The transformer turns ratio n was 2.5 and the leakage inductance referred to the secondary was 0.60 mH.

The power MOSFET transistors, Q_1 and Q_2, have unique properties that make them well suited to this application. One property is the antiparallel diodes contained in these devices.[17] Since the current in the circuit is out of phase with the voltage, antiparallel diodes provide a conduction path for the inductive current. Another very important property for simplification is the field effect transistor transfer characteristics. The device turns full on with an ~6 V gate to the source voltage and can withstand a ±20 V gate to the source. This transfer characteristic easily allows a 2/1 variation in gate drive voltage. This in turn permits direct gate drive from the transformer where the voltage change is 2/1 for this circuit.

Starting this oscillator, even into a short circuit, is easy because the switch load is inductive, i.e., the initial load condition appears as an open circuit.

The start circuit comprises R_3, CR_1, and C_3. Q_1 and Q_2 have a gate-to-source threshold voltage of about 3 V. Voltage is applied to the Q_1 and Q_2 gates through R_3. The switch with the lowest threshold voltage turns on first. Input voltage is then reflected through transformers T_1 and T_2. This causes the opposite switch to be held off and an increase in drive to the transistor turning on. The on transistor remains on until T_2 saturates, removing drive to the on transistor. Inductive energy causes the transformer voltage to reverse and the opposite transistor is turned on. The cycle repeats and the circuit has started. The zener diode (IN5338B was chosen for convenience) limits the total gate-to-source voltage during normal operation. A resistor could have been used instead of the zener diode; but the zener allows a higher voltage to be applied to the gate-to-source terminals of the switches at high input voltage. This becomes important for large input voltage ranges since the upper limit on the gate-to-source voltage is specified at +20 V. About 6 V is required to turn on fully at the lowest input voltage. This limits the range of input voltages that can be used with this particular circuit. However, the range of input voltages could be extended by adding gate to source zener diodes. The capacitor C_3 provides a low-impedance path for gate-to-source currents during the switching interval and reduces switching losses.

This basic keeper circuit requires 14 components. However, it is desirable to include a high-voltage zener diode across the output, both to limit the voltage rating required for C_2 and to provide a safe path for high-pulse currents. High transient currents could occur if the keeper positive output is shorted to the screen power supply return.

The output winding of T_1, as well as the rectifying diodes and filter capacitor, is referenced to screen potential (1100 V); thus, the transformer secondary winding must be insulated for high voltages. Occasionally during normal thruster operation the screen shorts and arcs, which requires that the cathode keeper supply also be protected from these transients. The physical configuration of the transformer, with the secondary located far away from the primary, effectively reduces electrostatic coupling of quickly changing screen potentials during arcs. In addition, the high leakage inductance isolates the primary from rapid current changes in the keeper supply output.

Transistor switch and transformer waveforms are shown in Fig. 3 for both maximum and minimum input voltage. Q_1 voltage and current waveforms illustrate the large phase shift between voltage and current caused by the leakage inductance. Figure 3 also shows that the average rectified transformer secondary current increases only slightly when the input voltage is doubled and the frequency subsequently doubles. The load current is equal to the average rectified

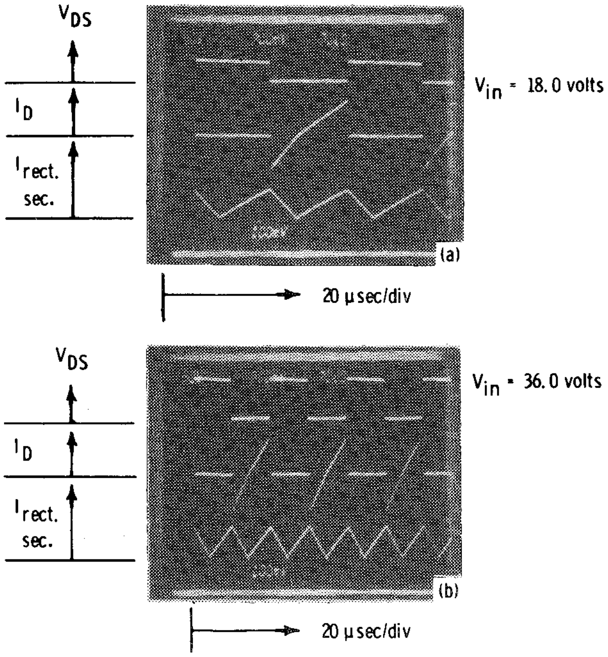

Fig. 3 Cathode keeper supply waveforms for Q_1 and the transformer-rectified secondary current under the condition of input voltages of 18 and 36 V with a 10 Ω load (vertical scale factors: V_{DS}, 50 V/div; I_D, 4 A/div; $I_{rect.sec}$, 2 A/div).

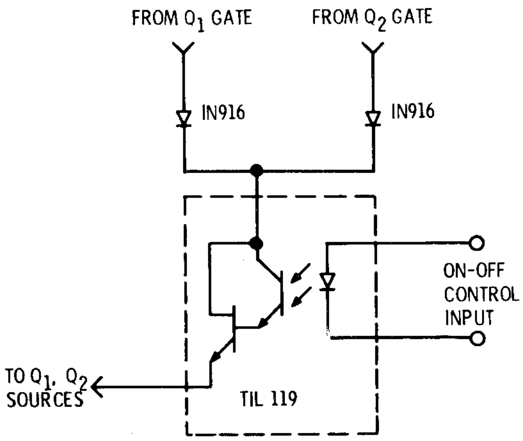

Fig. 4 Schematic of cathode keeper supply isolated on-off control circuit.

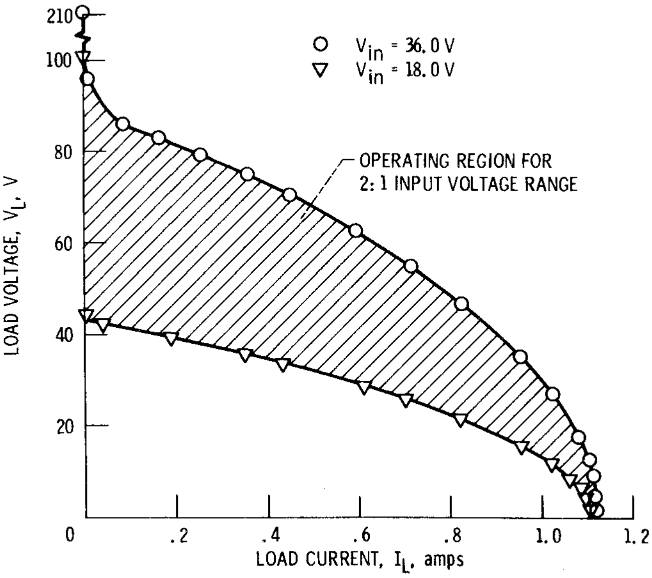

Fig. 5 Cathode keeper supply load characteristics.

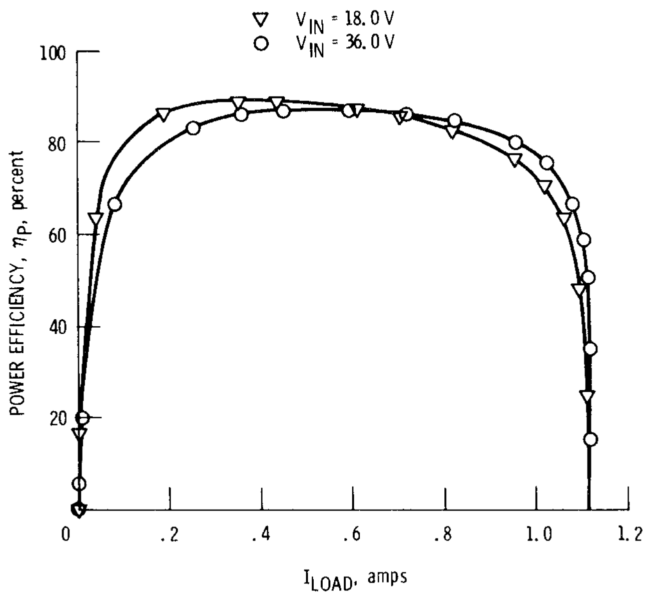

Fig. 6 Cathode keeper power supply, power efficiency vs load current.

transformer secondary current so it remains virtually constant.

On-off control could be accomplished using a series switch or relay. Another method was developed which does not require a power handling component. The circuit takes advantage of the power MOSFET's high threshold voltage. The simple circuit is shown in Fig. 4. A TIL119 optocoupler is used in conjunction with two diodes to clamp the gates of Q_1 and Q_2 below the threshold voltage. Gate resistors R_1 and R_2 (Fig. 2) were changed from 100 to 180 Ω to accommodate the TIL119 worst case current limit. The circuit provides an on-off control that is electrically isolated from the power return.

Performance

The cathode keeper power supply regulation, power efficiency, and high- and low-temperature regulation and efficiency were measured. In addition the power supply was run with a laboratory 30 cm diam Hg ion thruster. Tests for input audio susceptibility and reflected ripple were not performed.

Although low component weight and adequate power efficiency were achieved, no effort was spent to maximize power efficiency or to reduce weight. The main purpose of this effort was to demonstrate the circuit concept and to obtain benchmark data.

The total component weight of the supply, substituting a flight-type capacitor for the output filter capacitor C_2, was approximately 150 g. The short-circuit current of the breadboard turned out to be 1.1 A instead of 1.0. No effort was made to readjust the current by increasing the frequency or increasing the leakage inductance by reducing the length of the magnitude shunt air gap.

The cathode keeper load characteristics for inputs of 18.0 and 36.0 V are shown in Fig. 5. The experimental data agree well with the values of load voltage predicted from Eqs. (1) and (2). Power efficiency vs load current appears in Fig. 6. Power efficiency is about 88% for optimal loading and 35-50% at the keeper operating point chosen for the 30 cm diam Hg ion thruster. This compares with the 30 cm diam Hg ion

Table 2 Change in cathode keeper supply short-circuit current and maximum flux capacity of the timing core with temperature

Temperature, °C	$\frac{I_{SC} - I_{SC} \text{ at } 25° \text{C}}{I_{SC} \text{ at } 25°} \times 100\%$ 18.0 V_{in}, %	36.0 V_{in}, %	Change in maximum flux capacity from capacity at 25°C for square Permaloy 80, %
−20	+2.6	+2.9	+3.1
+25	0	0	0
+51	−2.0	−2.0	−2.0
+71	−3.8	−3.8	−3.8

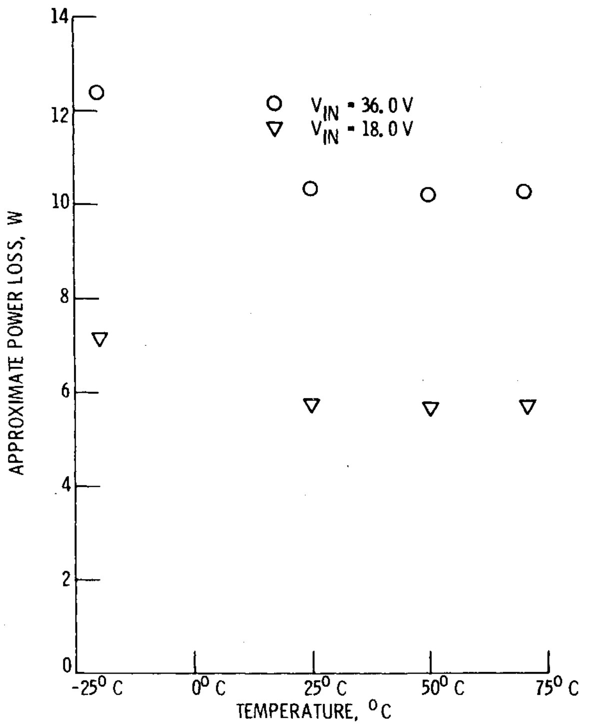

Fig. 7 Cathode keeper supply approximate power loss vs temperature for a 5.4 Ω load.

thruster thermal vacuum breadboard low-power supplies total full-load efficiency of about 75%, and 50% efficiency at the run condition.[18] Power efficiency would be much higher for a higher voltage load such as the neutralizer keeper.

The worst case output ripple is about 0.5 V peak-to-peak at room temperature when the output filter capacitor C_2 is the aluminum electrolytic capacitor used for convenience.

Temperature Tests

A temperature chamber was used to test the cathode keeper supply in an ambient temperature environment of −20 to +71°C. The automatically controlled chamber used liquid nitrogen for cooling and electric heaters for high temperatures. Test article temperature was maintained or changed quickly by convection from internal fans. Before electrical tests, the circuit was soaked for 1 h or longer after the desired chamber temperature was reached.

The upper temperature of +71°C was arbitrarily chosen since it is commonly used in military specifications. The lower temperature was limited by the output capacitor C_2 that was chosen for convenience. At −20°C the equivalent series resistance of the aluminum electrolytic capacitor increased so much that the output ripple increased to about 4 V peak-to-peak with a 5.4 Ω load.

Short-circuit current changed slightly with temperature as shown in Table 2. This was due mainly to changes in frequency with temperature since short-circuit current is inversely proportional to frequency [see Eq. (2)]. Frequency is determined by the input voltage and the characteristics of transformer T_2. As the flux capacity of the T_2 core is decreased with rising temperature, the frequency increases and the short-circuit current is reduced. Short-circuit current is directly proportional to the flux capacity of the timing core. Table 2 shows the observed correspondence between short-circuit current and the change in flux capacity of square Permaloy 80.[19]

Cathode keeper supply approximate power loss vs temperature for a 5.4 Ω load is shown in Fig. 7. Power loss changes slightly for temperatures between 25 and 71°C. The power measurement accuracy at −20°C is adversely effected by a 4 V peak-to-peak ripple voltage caused by the equivalent series resistance increase in C_2, the aluminum electrolytic capacitor used for convenience. The increased equivalent series resistance of C_2 also results in about a 0.7 W increase in power loss.

Ion Thruster Test

The cathode keeper supply was operated with the 30 cm diam Hg ion thruster and test facility described in Ref. 5. As a precaution against excessive supply currents caused by thruster arcs, an antiparallel diode was connected across the power supply output terminals. For one test the input voltage to the cathode keeper supply was set at 18.0 V. Initially the keeper output voltage measured 58 V before the thruster was started. Full open-circuit voltage was not reached due to high-resistance loading in the thruster or in the test setup. After keeper ignition the cathode keeper voltage remained at 5.5 V. The corresponding cathode keeper current was 1.09 A. The thruster was run at the baseline conditions listed in Ref. 5. During startup the thruster screen arced, demonstrating keeper supply transient isolation capability as well as high-voltage isolation.

The thruster was shut down and allowed to cool, after which another test was started. The input voltage to the cathode keeper supply was set at 36.0 V and the output no load voltage was about 170 V. After startup the keeper voltage varied between 5.6 and 5.8 V, corresponding to a keeper current of 1.12 A. Again screen arcs were observed. The thruster tests demonstrated power supply and ion thruster compatibility since the cathode keeper operated in a stable mode and no component overstresses occurred during thruster arcing.

Neutralizer Keeper Supply

Design

The neutralizer keeper supply was developed to demonstrate the high-voltage input capability of the new self-regulating single-power-stage approach for keeper supplies. A full-bridge oscillator version of the Jensen oscillator was developed. The circuit schematic is shown in Fig. 8. Transistors Q_1 and Q_2 were driven from windings on the power transformer T_1 instead of from the timing transformer T_2. This was done for convenience since electrostatic shields and 400 V insulation would have been required in a tiny transformer wound by hand. The electrostatic shields were added

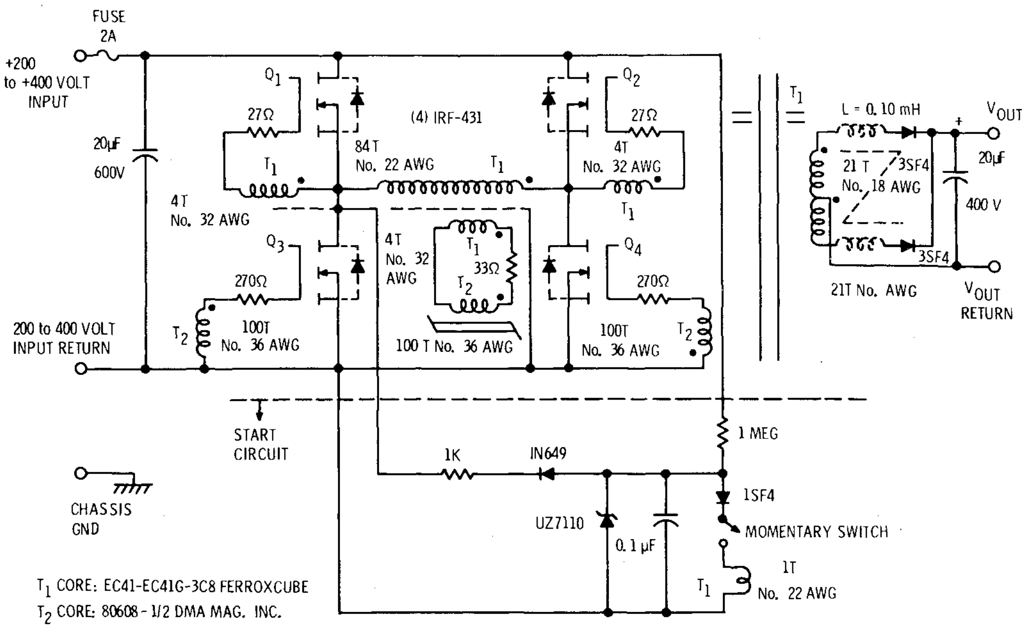

Fig. 8 Schematic of 30 cm Hg ion thruster neutralizer keeper supply.

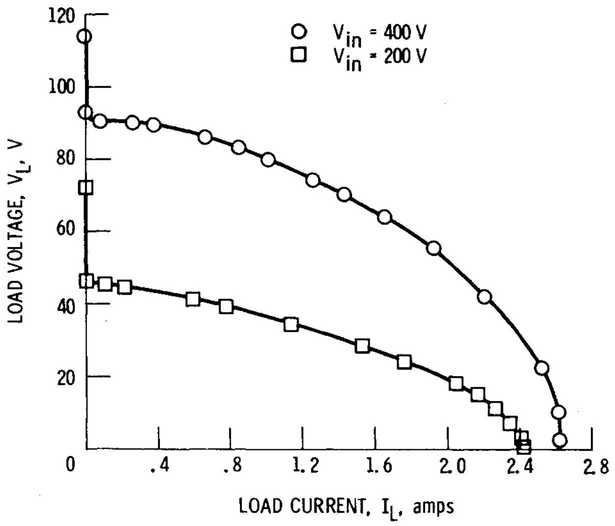

Fig. 9 Neutralizer keeper supply load characteristics.

to T_1 as a precaution because 400 V is switched in only about 300 ns. The resulting high dV/dt could couple charge-through stray circuit capacities and possibly cause difficulties.

The start circuit was not fully developed for the neutralizer keeper supply. The start circuit shown in the schematic requires closing a momentary switch to pulse T_1. This turns on Q_2 and Q_3 simultaneously and oscillation begins. If all four transistors were driven from T_2, the start circuit would have different requirements. However, better performance might be obtained by driving all transistors from T_2, which means that a different start circuit would be needed. When the circuit was first tested it was found that the lower transistors (Q_3 and Q_4) turned on slightly before transistors Q_1 and Q_2 turned off, resulting in the undesirable condition that Q_1 and Q_3 as well as Q_2 and Q_4 were on simultaneously for a short time. It was desirable to correct the condition quickly without a major redesign of the circuit. This was done by adjusting the time constants formed by the gate source capacitance and drive resistors. Q_1 and Q_2 were driven by 27 Ω resistors, whereas Q_3 and Q_4 have gate resistors of 270 Ω. This allowed operation over the full input voltage range of 200-400 V without the simultaneous turn on of Q_1 and Q_3 or Q_2 and Q_4.

At 200 V input the frequency of oscillation was 20.6 kHz and at 400 V input the circuit oscillated at 38.5 kHz. The frequency of oscillation was not quite proportional to the input voltage, resulting in an 8% higher short-circuit current at 400 V input than at the 200 V input condition. The slight nonproportionality of frequency vs input voltage was due to approximately 3 μs fixed frequency independent delay that occurred during each cycle. The transformer turns ratio n was 0.25 and the leakage inductance referred to the secondary was 0.10 mH. The value of short-circuit current predicted by Eq. (2) was about 20% high for this circuit. But Eq. (2) does not account for power loss or voltage drops in the circuit.

Circuit operation is very similar to the cathode keeper supply. Output current for heavy loads is maintained nearly constant for changes in input voltage. Waveforms are similar to those shown in Fig. 3. For an 8 Ω load the drain to the source off voltage of Q_3 is 200-400 V and the peak drain and the T_1 primary current is 1.4 A.

Performance

Power Regulation and Efficiency Tests

The neutralizer keeper power supply regulation and power efficiency were measured over the full range of load currents and voltages for both 200 and 400 V input. Regulation data are plotted in Fig. 9. Output ripple measured 0.6 V peak-to-peak worst case. Temperature tests and tests for input audio susceptibility and reflected ripple were not performed. As with the cathode keeper supply, no effort was spent to maximize power efficiency or to minimize weight. The weight of the components is estimated to be about 200 g compared to about 150 g measured for the cathode keeper. The power efficiency of the neutralizer keeper supply at the nominal operating voltages of 15 V is about 60% at 400 V input and 76% at 200 V input. Power efficiency vs load current is similar to the cathode keeper supply shown in Fig. 6. The efficiency at the operating point is much higher than the cathode keeper because the output voltage is 15 instead of 5 V. The neutralizer keeper supply is operated nearer its maximum power capability.

Ion Thruster Tests

The neutralizer keeper power supply was run with the 30 cm diam Hg ion thruster and test facility described in Ref. 5. Only the neutralizer was operated for this test since the screen supply was inoperable when the test was run.

In the first test the power supply input was set below the specified 200 V, to 150 V to check lowest voltage ignition. The neutralizer Hg vaporizer was run open loop. The neutralizer ignited and started running at 12.1 V and 2.1 H, then the voltage drifted to 9.7 V at 2.17 A. The voltage was lower than 15 V because the neutralizer was running Hg rich. The power supply input voltage was then increased to 200, 300, and 400 V. The corresponding measured neutralizer keeper operating points were 9.6 V at 2.31 A, 9.7 V at 2.49 A, and 9.8 V at 2.63 A. The input voltage to the supply was set at 200 V and the Hg flow and tip heat were turned off. As the Hg flow decreased, the keeper voltage increased and current decreased until 46 V was reached. Two data points taken near the nominal operating voltage were 14.3 V at 2.18 A and 18.2 V at 2.05 A. After this test the input of the neutralizer keeper supply was increased to 400 V. The voltage prior to ignition was 101.7 V. After ignition the operating point was 13.5 V at 2.6 A. Then fuel flow and tip heat were shut off. The test was stopped when the operating point reached 25.6 V at 2.53 A.

Short-Circuit Current Adjustment

For production, a method of adjusting power supply short-circuit current is necessary. Tolerances in the flux capacity of the timing core as well as winding tolerances in the transformer inductor determine short-circuit current. One way to adjust short-circuit current is to change the gap length in the magnetic shunt of T_1. This requires stocking a variety of core halves. However, this is an easy adjustment since the gap length is not critical. Doubling the gap length of T_1 in the neutralizer keeper supply reduced the leakage inductance by only about 20%.

Heater Power Supplies

Several resistance element heaters are used in ion thrusters. The heaters all have a high thermal mass so the heaters can time average odd-shaped voltage and current waveforms to provide an even temperature. This property can be used to develop simplified heater supplies. For example the vaporizer heater time constant is on the order of 10 s.[20] So if the vaporizer power supply can be cycled on and off rapidly with an adjustable duty ratio, then variable power can be supplied to the vaporizer heater.

The cathode keeper power supply (Fig. 2) together with the on-off control circuit (Fig. 4) can be turned on and off very rapidly because the circuit starts easily. A supply similar to the cathode keeper supply, but designed with a lower open-circuit voltage, can be turned on and off rapidly enough to supply a continuously varying rms current to the heater. For controlling vaporizer heaters the duty ratio could be varied with one of several integrated circuits used for pulse width modulation in power supplies.

To demonstrate feasibility of the concept, the cathode keeper circuit with the on-off control circuit was pulse-width modulated using a variable-duty ratio pulse generator. A fixed period of 58 ms was arbitrarily chosen. Very rapid on-off control of this circuit is possible because the switching transistor load is inductive and starting drain currents are virtually zero. The input voltage to the supply was set at 28 V and the load was approximately 6 Ω. The duty ratio was varied continuously from full off to full on. Figure 10 shows load current I_L and Q_1 drain to source voltage V_{DS} for a duty ratio of about 50%. Note that the output filter capacitor rounds off the output waveform and reduces electromagnetic interference.

The test shows that it is possible to control heater power by on-off duty ratio control of a circuit similar to the cathode keeper power supply.

Conclusions

Relaxing ion thruster power supply regulation tolerances and redefining load profile requirements expands the range of circuit techniques that can be evaluated for the purpose of using simpler circuits.

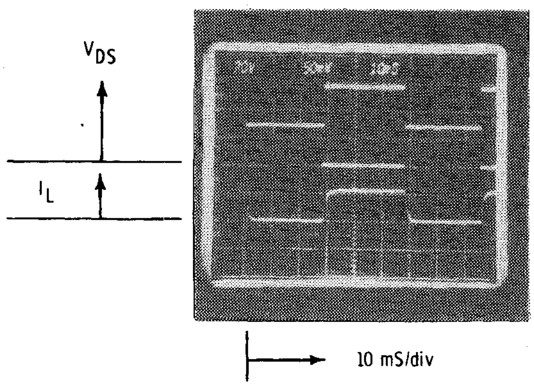

Fig. 10 Cathode keeper supply on-off pulse width modulation under conditions of 28 V input, approximately 6 Ω load (vertical scale factors: V_{DS}, 20 V/div; I_L, 1 A/div).

A key to achieving a low parts count is the elimination of active voltage limiting as well as closed-loop current control used in conventional ion thruster power supplies. In addition, a single self-regulating power stage between the power source and thruster eliminates the need for a preregulator circuit. The incorporation of dual-role components such as a transformer-inductor and power MOSFET transistors with their intrinsic antiparallel diodes results in further simplification.

Two new, single-power-stage, self-regulating power supplies were developed and demonstrated for the main and neutralizer keepers of a 30 cm diam Hg ion thruster. These keeper supplies have an order-of-magnitude reduction in parts count from contemporary supplies leading to increased reliability at lower weight, while still maintaining thrust system performance.

The keeper power supplies provide: 1) an ignition potential greater than 50 V at low source resistance, 2) input-output isolation, 3) operation into short circuits and overloads, and 4) output current regulation.

The cathode keeper power supply demonstrated operation from a low-voltage bus (18-36 V) and thruster compatibility, as well as high- and low-temperature operation. The neutralizer keeper power supply demonstrates operation from a high-voltage bus (200-400 V). Thruster compatibility was also demonstrated.

A new, single-stage technique for supplying and controlling heater power was demonstrated. The self-regulating cathode keeper supply has the capability of being turned on and off very rapidly. This property was used to pulse width modulate heater power. The high thermal mass of the heater averages the pulsed energy to provide a nearly constant temperature. Further work is needed to fully implement this circuit technique for ion thruster use.

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