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Simulating a 1-kW Arcjet Thruster Using a Nonlinear Active Load

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Arcjet thrusters are known to have distinctly nonlinear electrical characteristics with negative incremental resistance throughout their normal operating region. The 1-kW arcjet simulator proposed here is an electronic load bank which accurately mimics these characteristics statically and dynamically up to 40 kHz. A power-processing unit (PPU) was tested using a resistive load bank, the simulator, and a 1-kW arcjet. The simulator was found to be an accurate stand-in for the arcjet during system transient testing, while the resistive load was not. The simulator uses resistors and insulated-gate bipolar transistors to dissipate the PPU output power; a nonlinear feedback is applied to produce the desired *v-i* characteristics. This feedback is analyzed dynamically. This arcjet simulator allows the development of a new PPU design to a higher level of confidence before beginning testing at an arcjet facility.

Nomenclature

C = magnitude of arcjet incremental impedance, Ω
j = square root of -1
K_A-K_D = offset and gain coefficients of the analog multiplier
$L(s)$ = incremental loop gain of the arcjet simulator
R_{SOURCE} = internal incremental resistance of the arcjet PPU, Ω
r_d = arcjet low-frequency incremental impedance, Ω
s = Laplace transform complex frequency, rad/s
$z_d(s)$ = simulator incremental impedance, Ω
ω_H = simulator dissipative stage dominant pole frequency, rad/s
ω_{H1} = simulator impedance pole frequency, rad/s
ω_Z = proportional-integral compensator zero frequency, rad/s
ω_{Z1} = simulator impedance zero frequency, rad/s

Superscript
$\hat{}$ = incremental values of voltage or current

Introduction

THERE has been considerable interest in recent years in the use of the arcjet thruster to convert available electrical energy into additional thrust, thus reducing the mass of chemical propellants needed to accomplish a given mission.[1] Arcjets are known to have a distinctly nonlinear *v-i* characteristic, with a negative incremental resistance throughout the normal operating range.[2] This unusual characteristic of the arcjet as an electrical load impacts the design and testing requirements for the power processor unit (PPU). A discussion of conditions required for electrical stability of the arcjet-PPU combination may be found in Gruber's paper.[3] The intial testing and control system stability verification for the PPU is conveniently done using resistive load banks; however, the nonlinear and negative-resistance characteristics of the arcjet make it imperative that an additional round of testing be done using the arcjet itself. This causes practical difficulties, due to the need for a vacuum chamber, and appropriate handling and safety precautions for the propellants used. From the point of view of the PPU designer, it would be quite convenient to have an electronic load device programmed to simulate the arcjet *v-i* characteristics. Using an arcjet simulator, a PPU under development could be verified to a higher level of confidence before beginning the final testing using an arcjet.

The purpose of this article is the description of a load device which simulates the static and dynamic *v-i* behavior of a 1-kW arcjet. An analysis of the proposed design is presented, together with static and dynamic test data. These data are compared with experimental measurements made on a 1-kW arcjet.[2] In addition, an arcjet PPU[4] was tested in combination with the arcjet simulator, and also with the 1-kW arcjet itself. The behaviors of these two tests are then compared to show that the simulator closely simulates the arcjet statically and dynamically up to about 40 kHz.

Arcjet Electrical Behavior

Electrical behavioral data for a 1-kW arcjet have been taken by Hamley.[2] Static *v-i* characteristics from this source are reproduced in Fig. 1, in which a distinctly nonlinear behavior may be observed. The data displayed in this figure correspond to the normal operating range for the arcjet and show that the incremental resistance of the device is negative in this range. This immediately raises questions of stability for the arcjet-PPU combination. It has been shown[3] that stability of the arcjet-PPU system is obtained if the incremental output resistance of the PPU is positive and exceeds the magnitude of that of the arcjet. However, this analysis is limited by the fact that it only considers small-signal, low-frequency conditions.

The stability characteristics of the arcjet-PPU combination may be complicated by the high-frequency output impedance of the PPU, which for a switching power converter will be distinctly frequency-dependent throughout a range starting well below the control system gain-crossover frequency. De-

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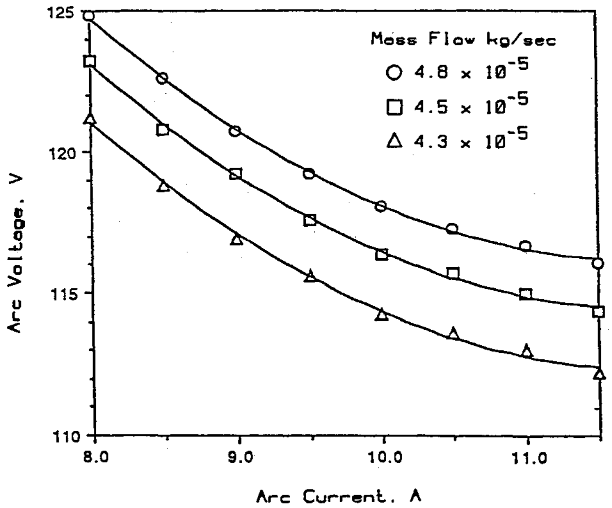

Fig. 1 Static *v-i* data for a 1-kW arcjet.[2]

pending on the design specifics of the PPU, this output impedance may exhibit sharp peaking (resonance). Therefore, a complete stability investigation requires knowledge of the frequency-dependent characteristics of the arcjet. Hamley also obtained high-frequency incremental impedance data from a 1-kW arcjet.[2] For the arcjet studied, the experimentally measured incremental impedance was summarized by

$$z_d(s) = -C \exp[-(1.5 \times 10^{-6})s] \ \Omega \qquad (1)$$

In this result, C was found to be a function of the operating point (the dc voltage-current pair and the propellant flow rate), but not a function of frequency. Data taken above 10 kHz suggest a 1.5-μS transport lag, also shown in Eq. (1). A typical value of C for the arcjet studied was found to be 3.76 Ω at $I = 10$ A.

The arcjet being studied was to be used with a PPU having a 40-kHz ripple frequency. It was therefore elected to simulate it with an electronic load having appropriate static *v-i* characteristics and an incremental impedance having an angle of 180 deg to beyond at least 40 kHz. This was expected to correctly simulate the interaction of the arcjet with the PPU output impedance throughout the range below 10 kHz, where impedance is primarily determined by the control design, and to approximately simulate the response of the arcjet to the switching-frequency ripple current. Above 10 kHz, the output impedance of the PPU was expected to be dominated by that of the PPU output inductor.

Hardware Description

Dissipative Elements

Because a 1-kW PPU had previously been built[4] for use with an existing 1-kW arcjet,[2] the electronic load was sized for 1 kW. The data taken on the arcjet throughout its normal operating current range showed a voltage drop of not less than 100 V. It might be assumed from the trends in this data that lower voltage drops could occur at higher currents, but these current densities were considered destructive and no attempt was made to simulate the arcjet beyond 15 A. Therefore, the electronic load was made of a resistor bank in series with a set of 16 paralleled insulated-gate bipolar transistors (IGBTs). This allowed the sharing of the dissipated power between the resistor bank and the IGBT bank, at the cost of restricting the voltage range over which the desired *v-i* characteristic could be obtained. The choice of a 4-Ω resistor bank allowed dissipation of 1 kW, provided the terminal *v-i* characteristic did not require voltage below 70 V. The IGBTs were operated in their active regions to obtain the wide bandwidth desired of the simulator. At the design operating point of 11 A and 115 V, 480 W is dissipated by the resistors and 780 W by the IGBTs. The resistor bank therefore considerably reduces the dissipation requirements on the IGBTs. It should be emphasized that the resistor bank functions as an internal component of this electronic load bank and is not intended to directly emulate any part of the PPU or arcjet.

Overvoltage limiting was included in the simulator, but it did not need to operate until the terminal voltage approached the 500-V rating of the devices used, thus minimizing its interference with the normal function of the simulator. No attempt was made to simulate the arcjet ignition process, which would require breakdown at about 1.6 kV. Forced-air cooling of the IGBTs was employed, the IGBTs being mounted on an air duct with sufficient airflow to maintain a case temperature of 100°C at the design operating conditions.

Load Controller

A feedback controller was used with the dissipative portion of the arcjet simulator to obtain the desired *v-i* characteristics. A reduced schematic diagram of the arcjet simulator appears in Fig. 2. In this figure, $Q1$ represents the composite of the 16 paralleled IGBTs; R_D is the resistor bank. The analog multiplier forms the product of the sensed load terminal voltage (v) and the load current (i). This product, represented by the voltage $-v_a$, is compared with a reference voltage V_{REF}, and the resulting error signal is processed by a proportional-integral (PI) compensator which in turn controls the gate voltage on the IGBTs. Constant-power *v-i* characteristics might be expected, assuming stability of the system formed by the PPU and the simulator. This would be true if the multiplier had all of its offsets trimmed; however, the input and output offset adjustments provided by the MC 1496 multiplier were found convenient for shaping the *v-i* characteristics, and are therefore included in the following analysis.

Figure 3 shows a typical set of simulator *v-i* characteristics. It can be noted that these *v-i* characteristics are bifurcated, as are those of an arcjet. Curve no. 1, which corresponds to

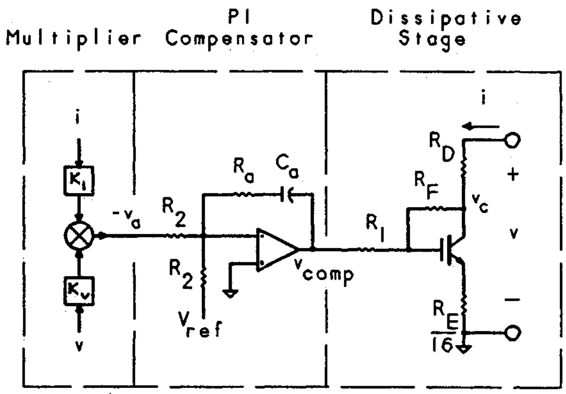

Fig. 2 Block diagram of the arcjet simulator.

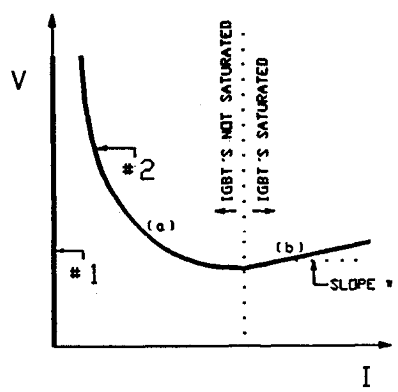

Fig. 3 Arcjet simulator *v-i* characteristics.

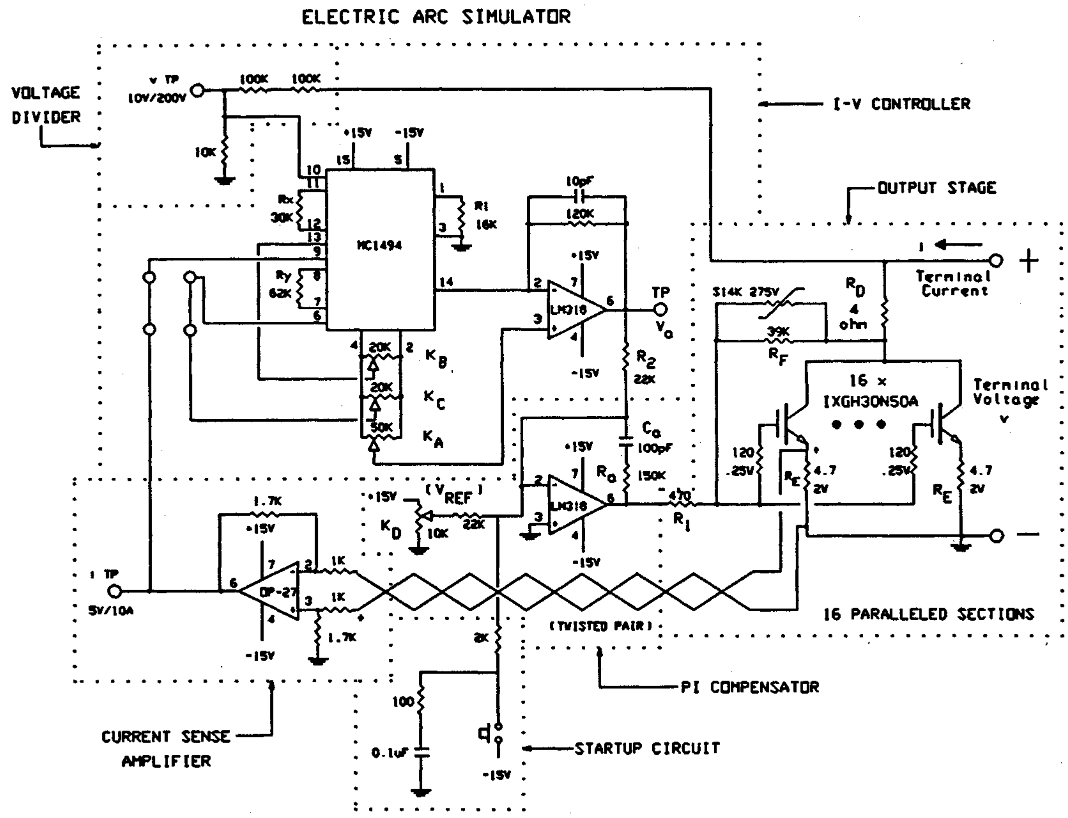

Fig. 4 Detailed schematic diagram of the arcjet simulator.

the nonionized condition, occurs prior to ignition of the arcjet. Curve no. 2 corresponds to the ignited condition. These characteristics are current-controlled; i.e., for a given value of terminal current there is a unique voltage, but the converse is not true. This also corresponds to a characteristic observed in the arcjet and many other types of electrical arcs. Operation of the simulator from a voltage-limited high-impedance current source is bistable, with initial operation at startup on curve no. 1. In the arcjet, transition from the nonionized condition to the ignited condition may be triggered by a high-voltage pulse.[5] Although the simulator could also be adapted to simulate this pulse ignition, it was not done, primarily because of the IGBT breakdown voltage requirement that would result. Transition from the un-ionized to the ignited curve in the simulator was instead triggered by a push button which directly caused the IGBT bank to go to a low-impedance state. After the push button is released, the arcjet simulator-PPU system finds an operating point on curve no. 2, if the system is stable.

The large-signal behavior along the negative-slope portion of curve no. 2 of the simulator is next derived from Fig. 2. The voltage- and current-sensing circuits and multiplier can be described by

$$v_a = K_A + K_B i + K_C v + K_D v i \tag{2}$$

If a stable operating point is found, the input signal to the PI compensator is zero. Thus $v_a = V_{\mathrm{REF}}$, and curve no. 2 is described as follows:

$$v(i) = \{[(V_{\mathrm{REF}} - K_A) - K_B i]/(K_C + K_D i)\} \tag{3}$$

The low-frequency incremental resistance of the proposed simulator is readily derived from Eq. (3):

$$r_d = \left.\frac{\mathrm{d}v(i)}{\mathrm{d}i}\right|_I = \frac{-K_B - K_D V}{K_C + K_D I} \tag{4}$$

This incremental resistance is seen to be negative-signed for positive coefficients $K_B - K_D$.

The positive-sloped portion of curve no. 2 in Fig. 3 occurs when the IGBT bank is saturated. The controller is ineffective over this portion of the v-i characteristics, and the slope is simply R_D, the value of the resistor bank. The simulator is designed such that this portion of its v-i curves does not correspond to any normal condition of operation for the arcjet being simulated. However, this portion of the v-i curves could be usefully applied to an arc-producing device operating at high current density, a case in which it appears that the v-i curves revert to a positive slope.[6]

Simulator Dynamics

The frequency response portion of the incremental impedance of the simulator is derived from Fig. 4, its detailed schematic diagram. The 16 paralleled IGBTs in the dissipative stage are incrementally modeled as shown in Fig. 5. The PPU incremental output resistance is modeled by R_{SOURCE}. The dissipative stage transfer function $\hat{v}_c/\hat{v}_{\mathrm{COMP}}$ can be derived directly from Fig. 5, although the calculation is tedious. However, it was observed that for reasonable IGBT and circuit values, this transfer function is characterized by a single dominant pole, and that the gain-bandwidth product of the stage is almost completely unaffected by R_{SOURCE} values ranging from zero to infinity. Comparison of an exact frequency response function and an approximate one showed that the dynamics of this stage were accurately modeled by considering only the effects of the feedback capacitance $16C_{rss}$.

At this point it is noted that the simulator internally forms a two-loop feedback system. Because the arcjet simulator is to be used to simulate a potentially unstable system (the arcjet and its PPU), its own internal stability must be assured to provide dependable results. The loop gain of the simulator can be calculated by breaking the loop at the output of the PI compensator, a location where both feedback paths are touching. The loop gain is found using Figs. 4 and 5, and the

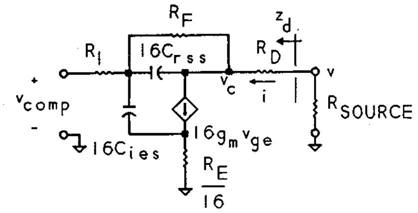

Fig. 5 Incremental equivalent of the dissipative stage.

approximation of single-pole behavior in the dissipative stage

$$L(s) = \frac{-\hat{v}'_{\text{COMP}}}{\hat{v}_{\text{COMP}}} = \left[\frac{R_a}{R_2}\frac{s + \omega_z}{s}\frac{A_0}{1 + (s/\omega_H)}\right] \cdot \left[\frac{(K_C + K_D I)R_{\text{SOURCE}} - (K_B + K_D V)}{R_{\text{SOURCE}} + R_D}\right] \tag{5a}$$

where

$$A_0 = \frac{R_F(R_D + R_{\text{SOURCE}})}{(R_F R_E/16) + R_1(R_D + R_{\text{SOURCE}})} \tag{5b}$$

$$\omega_H = (1/16 R_1 C_{rss} A_0) \tag{5c}$$

The strategy used in designing the PI compensator of Fig. 4 was the location of ω_z at the lowest frequency that ω_H could take. Both the values of ω_H and A_0 are functions of R_{SOURCE}; however, their product is nearly constant. For the component values used, the change in A_0 and ω_H for R_{SOURCE} between zero and infinity is only 17 dB (7:1). It is interesting to note that $L(s)$ will reverse its sign if R_{SOURCE} is too low. This corresponds to an instability known to be exhibited by the arcjet-PPU combination,[3,7] and is equivalent to the condition for stability that PPU output resistance exceed the arcjet incremental resistance.

The incremental impedance presented by the arcjet simulator to the PPU is also derived from Figs. 4 and 5. The following result assumes a complete cancellation of ω_z and ω_H:

$$z_d = \frac{\hat{v}}{\hat{\imath}} = r_d \frac{1 - (s/\omega_{z1})}{1 + (s/\omega_{H1})} \tag{6a}$$

where

$$\omega_{H1} = (A_0/R_2 C_a)(K_C + K_D I) \tag{6b}$$

$$\omega_{z1} = (A_0/R_2 C_a)[(K_B + K_D V)/R_D] = \omega_{H1}(|r_d|/R_D) \tag{6c}$$

The presence of a left-half-plane pole and a right-half-plane zero can be noted in the simulator impedance. For the component values selected, R_D and r_d have comparable magnitudes, although r_d varies with operating point. Therefore, the magnitude of z_d is not strongly frequency-dependent, but it does show decreasing phase for frequencies approaching ω_{H1}. The "upper cutoff frequency" of the simulator was defined to be the frequency at which z_d departs from its low-frequency value by 45 deg. The experimentally measured upper cutoff frequencies ranged from 40 to 60 kHz when the simulator was driven from source resistances near to the boundary of stability with current levels from 6 to 14 A. The simulator behavior is therefore found to be frequency independent up to the ripple frequency of the PPU it was tested with.

Experimental Results

Simulator Behavior

The static *v-i* characteristics of the simulator were plotted using laboratory power supplies with series resistors. It was immediately demonstrated that the series resistance must exceed the magnitude of the incremental resistance of the *v-i* curve for the system to be stable. It was also found that the constant-current mode of the available power supplies did not produce a high output impedance. This is believed to be due to the large output filter capacitors invariable used in these power supplies, and the limited bandwidth of their internal regulators. The characteristics of Fig. 3 were readily obtained; with all the multiplier offsets zeroed, a constant-power characteristic ($vi = 1$ kW) could be obtained with a single-adjustment procedure. Iterative adjustment of the multiplier offsets was used to match the arcjet data more closely, but this was found to be a tedious process. A curve tracer would be helpful, but was not available due to the power levels involved.

The real and imaginary portions of the incremental impedance of the arcjet simulator were measured with the simulator set for a constant-power characteristic ($vi = 1$ kW). A dc power supply was used to bias the simulator to operating points ranging from 6 to 14 A while a dynamic signal analyzer performed a swept-frequency measurement of its incremental impedance. A typical result for the operating point 102 V, 10 A was a low-frequency impedance of $z_d = -8.7 + j0\ \Omega$, which compares well with the expected value of $-V/I = -10.2\ \Omega$. The upper cutoff frequency measured under these conditions was 58.9 kHz. It was also noted that the simulator invariably had a positive imaginary component of impedance as the upper cutoff frequency was approached, indicating an inductive characteristic. However, the imaginary component was generally insignificant below 10 kHz.

Arcjet-Simulator Comparison

Experimental observations were made of the performance of the 1-kW PPU loaded by the simulator, a resistor bank, and also the arcjet. It was established that the arcjet static *v-i* characteristic could be accurately reproduced over its normal range of operating currents, given sufficient care in setting the coefficients $K_B - K_D$ and V_{REF}. Examination of the 40-kHz ripple current and voltage at the arcjet and the simulator showed that the negative-resistance characteristics of the arcjet were retained to at least this frequency, and that they were accurately reproduced by the simulator. However, an additional concern was the interaction of the PPU's regulator with the negative resistance characteristic of the arcjet.

Figures 6–8 show three experimental waveforms, each obtained from the PPU with a large disturbance injected into its current reference. Figure 6 is for the PPU with a resistive load. The response to the pulse disturbance appears well-damped, indicating a satisfactory control compensation. Figure 7 was taken from the PPU-arcjet combination. The negative incremental resistance of the arcjet is apparent in the

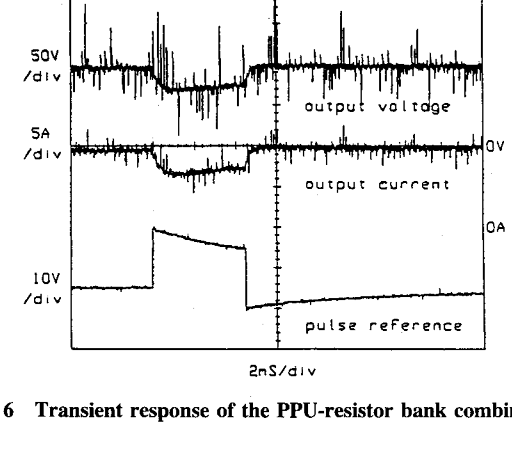

Fig. 6 Transient response of the PPU-resistor bank combination.

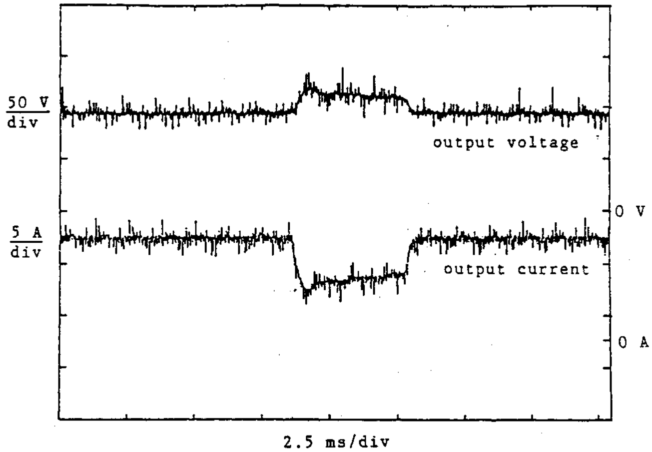

Fig. 7 Transient response of the PPU-arcjet combination.

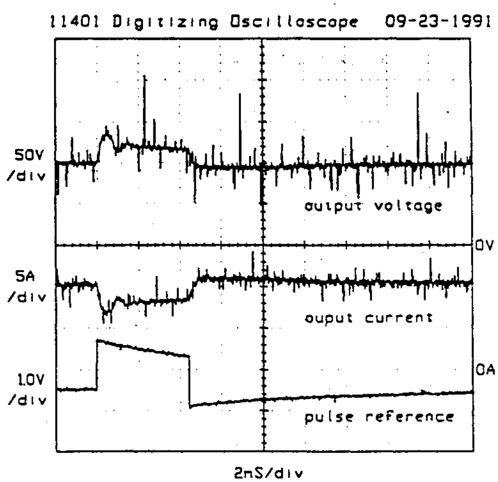

Fig. 8 Transient response of the PPU-simulator combination.

voltage and current waveforms, as is a decrease in the margin of stability, as evidenced by the underdamped pulse response. Figure 8 shows the pulse response of the PPU-simulator combination under the same circumstances. The simulator is seen to correctly reproduce the negative resistance character of the arcjet and to simulate the relative stability of the PPU-arcjet combination more accurately than the resistive load.

Summary

It has been shown that the nonlinear and negative-resistance characteristics of an arcjet have an influence on the design and compensation of its PPU. Initial laboratory testing of a PPU can be conveniently done using a resistive load bank, but does not give complete assurance of stable behavior when the arcjet itself is used as the load. Access to an arcjet for the initial testing of a PPU may well be inconvenient due to the facilities needed to handle the propellant and produce the operating vacuum. An arcjet simulator is presented here which functions as a conveniently adjustable load for the PPU, tracking the static *v-i* curves of the arcjet quite closely, and more importantly, having the negative resistance characteristics of the arcjet. This simulator allows the PPU to be more thoroughly proven before beginning tests with the actual arcjet.

A 1-kW arcjet simulator was built and experimentally tested, comparing its behavior with that of a corresponding arcjet. The simulator was found to predict the stability margin (as revealed by a large-signal transient response) of the PPU-arcjet system more accurately than a resistive load bank. The simulator was also found to reproduce the incremental impedance characteristics measured on the corresponding arcjet up to approximately 40 kHz. The simulator was found to be convenient in that it automatically produced the correct voltage response as the PPU output current setting was changed; a resistive load bank would have needed readjustment at each operating point.

It is anticipated that the simulator described here may be useful in simulating other types of electrical arcs. Applications might include development and testing of welding power supplies or gas-discharge lamp ballasts. Also, the success of this electronic load bank at the 1-kW level paves the way for its application to arcjet development in the 10–30 kW range. The main problem would be the dissipation of about one-half of the arcjet power in the IGBTs (the other half is dissipated in the resistor bank R_D). This would probably require water-cooled heat sinks, and 4–5 of the present devices per kilowatt of arcjet power.

Acknowledgments

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