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INTEGRATION ISSUES OF A PLASMA CONTACTOR POWER ELECTRONICS UNIT

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ABSTRACT

A hollow cathode-based plasma contactor is baselined on International Space Station Alpha (ISSA) for spacecraft charge control. The plasma contactor system consists of a hollow cathode assembly (HCA), a power electronics unit (PEU), and an expellant management unit (EMU). The plasma contactor has recently been required to operate in a cyclic mode to conserve xenon expellant and extend system life. Originally, a DC cathode heater converter was baselined for a continuous operation mode because only a few ignitions of the hollow cathode were expected. However, for cyclic operation, a DC heater supply can potentially result in hollow cathode heater component failure due to the DC electrostatic field. This can prevent the heater from attaining the proper cathode tip temperature for reliable ignition of the hollow cathode. To mitigate this problem, an AC cathode heater supply was therefore designed, fabricated, and installed into a modified PEU.

The PEU was tested using resistive loads and then integrated with an engineering model hollow cathode to demonstrate stable steady-state operation. Integration issues such as the effect of line and load impedance on the output of the AC cathode heater supply and the characterization of the temperature profile of the heater under AC excitation were investigated.

INTRODUCTION

Spacecraft potentials as high as -120 V, with respect to ambient plasma, have been predicted for the International Space Station Alpha (ISSA) due to its high voltage solar arrays, a negative grounding electrical configuration, and insulating exterior thermal control surfaces. This can lead to possible electric discharges between the ambient plasma and ISSA structure. These can damage surface coatings and/or cause possible electromagnetic interference (EMI) problems. To mitigate these problems, a hollow cathode based plasma contactor will be used on ISSA for charge control (Patterson, et al., 1993).

The plasma contactor system consists of a hollow cathode assembly (HCA), a power electronics unit (PEU), and an expellant management unit (EMU). NASA is currently developing a hollow cathode for the flight plasma contactor system (Patterson, et al., 1993). A breadboard PEU has also been fabricated and tested under the plasma contactor program (Hamley, et al., 1993 and Hamley and Patterson, 1994). The breadboard PEU, shown schematically in Figure 1, consists of a discharge, cathode heater, housekeeping, and auxiliary power supplies, an EMI filter, and a controller.

The plasma contactor is required to operate in a cyclic mode to conserve xenon expellant and extend system life. This was recently changed from a continuous operation requirement. Cyclic operation imposes a requirement of 18,000 on/off cycles over its three year lifetime and a qualification test requirement of 27,000 cycles. A DC cathode heater supply was originally baselined for the PEU (Hamley, et al., 1993), however, it was speculated that the electrostatic field produced by DC excitation can cause ion migration in the insulator material of the heater (Slutz, 1990). This can cause changes in the resistivity of the heater which can prevent the heater from attaining the proper cathode tip temperature for reliable ignition (Soulas, 1994). An AC cathode heater supply was baselined to mitigate this problem by eliminating the DC electrostatic field.

This paper summarizes the requirements and design considerations for the AC heater supply. The design and testing of the inverter are described. Finally, results from resistive and inductive load testing and integration with a hollow cathode are presented and discussed.

AC HEATER SUPPLY REQUIREMENTS AND DESIGN CONSIDERATIONS

Output Requirements

The AC cathode heater supply must provide three constant output current setpoints to the cathode heater. These setpoints of 3.85, 7.2, and 8.5 A_{RMS} (Patterson, 1994) were selected from an intensive research program. The first low current setpoint is needed for cathode activation prior to ignition to remove contaminants from the electron emitting insert surface. The second and third setpoint are used to raise the cathode insert temperature during the ignition process. The 7.2 A_{RMS} setpoint is nominally used. Long term cathode degradation can lead to a requirement for elevated ignition temperatures (Patterson, 1994). The third setpoint is thus included to insure successful ignition across the total mission profile.

Load and Line Impedance Considerations

Typical heater resistance ranges from 0.2 Ω for a cold heater up 1.4 Ω for a hot heater. The nominal operating resistance is 1.1 Ω, but with the accumulation of thermal cycles, the heater resistance tends to increase (Soulas, 1994). The cathode heater supply must be able to supply and regulate the three current setpoints throughout this range of heater resistance.

Load inductance can also affect the regulation of the cathode heater supply. The cathode heater consists of a sheathed heater with eight helical coils and insulation between the center conductor and the sheath (Soulas, 1994). The inductance of the heater was measured using an impedance analyzer and was in the order of 10^{-7} H. When the cathode heater is assembled with a hollow cathode, this inductance may increase because the contact between the hollow cathode and the sheath may provide the current an alternate return path through the hollow cathode which can preclude magnetic field cancellation.

Line impedance and contact resistance must also be considered. However, all these line effects can be minimized by twisting the conductors to reduce the loop area, using the minimum length of wire, and the minimum number of connections.

AC excitation forces skin effect to be considered. The skin depth of copper at a frequency of 20 KHz is approximately 0.5 mm (Cheng, 1985). Using a conductor with a diameter larger than 1 mm can increase the resistance of the line because of the reduction of the effective cross sectional area of the conductor. To avoid this effect Litz wire or multiple conductors with 1 mm diameter can be used.

To ensure that the load characteristics were understood, various cathode heaters were installed in a vacuum facility using twisted multiple conductors. Typical load impedances were measured at the input terminals to the facility. The resistance and inductances obtained for a cold heaters were in the order of 0.26 to 0.36 Ω and 0.9 to 2.2 μH, respectively.

PEU DESIGN

A breadboard PEU was previously built and successfully integrated with a HCA (Hamley, et al., 1993 and Hamley and Patterson, 1994). The new PEU, shown in Figure 2, was based to the greatest extent possible, on the old design. The main difference is in the cathode heater supply. Other minor changes were implemented to the output requirements, power transformer, and output filter for the discharge supply, and the controller's hardware and software to insure that the PEU met system demands.

AC Cathode Heater Supply

The cathode heater supply consists of a push-pull, DC to AC inverter with a switching frequency of 20 KHz. MOSFETs were used as switching devices in the power stage. This inverter regulates the root-mean-square (RMS) of the alternating output current using pulse width modulation (PWM) and current mode control.

There are some advantages when using an AC cathode heater supply. Only one secondary winding is needed for the AC heater supply because full wave output rectification is not used. This secondary winding was built using three strands of 18 AWG magnet wire to minimize skin effect. This design resulted in a smaller and lighter transformer than the one used in the DC cathode heater supply. The absence of output rectifiers increases power conversion efficiency and also eliminates the need of components to mitigate the effects of diode recovery. An output filter, which can account for a significant fraction of the component mass, is not required for this design. This can also lead to an increase in efficiency.

An RMS to DC converter circuit was implemented using an analog multiplier. This circuit generates a DC output signal proportional to the RMS value of the input signal and is used in the feedback loop of the inverter and for telemetry. This is a major complication compared to the DC heater supply. The AC output may cause possible EMI, and although hollow cathode heaters with AC excitation have been used in the past for ion propulsion flight programs (Low, 1990 and Herron, et al., 1976), this area is still being investigated.

TEST PROCEDURE

The AC heater supply was tested for proper operation using a non-inductive load bank to simulate the cathode heater and a series inductor was used to simulate the line inductance. The resistance value was varied between 0.4 to 2.4 Ω and the inductance was varied from 0.7 to 10 μH. The purpose of this test was to evaluate the effect of typical heater resistance and line inductance on the output of the AC cathode heater supply.

The AC heater supply was operated under the nominal output condition of 7.2 A_{RMS}. The load resistance was changed with no inductance on the load. Then, the inductance was added and changed with a 1.0 Ω resistance. A DC heater supply was built by adding a rectifier stage and an output filter to an AC heater supply. This unit was operated under the same output conditions as the AC heater supply to compare performance.

RESULTS AND DISCUSSION

Inductive and Resistive Load Test

Figure 3 shows examples of the output current of the cathode heater supply for different load resistances. It can be seen that in order to regulate the effective value of the current at lower load resistance, the pulse width was short with high peak current. At higher load resistance, the peak current was lower with a longer pulse width. Examples of the output current with different load inductances are shown in Figure 4. It was found that the heater supply can maintain regulation of a nominal 7.2 A_{RMS} current into an inductive load of up to 6.7 μH. Figures 5 and 6 show plots for load regulation with various resistive loads and resistive loads with some series inductance. The load regulation for both cases was lower than 1 percent for nominal load resistance of 0.2 to 1.4 Ω and a load inductance lower or equal to 6.7 μH.

The maximum output power of the cathode heater supply was 101 W @ 8.5 A_{RMS}. The power conversion efficiency at nominal output current of 7.2 A_{RMS} into a 1.0Ω load was 0.92. This represent an 18 percent increase in power conversion efficiency when compared to the DC heater supply which has a power conversion efficiency of 0.74. This is due to the voltage drop in the rectifiers, which were a significant fraction of the output voltage, and to additional losses in the output filter.

PEU Integration

A test to quantify the temperature profile of the cathode heater under AC excitation and validate the equivalency of the AC and DC currents was conducted. Under nominal conditions, comparable cathode heater operation was observed.

The PEU was integrated with an engineering model hollow cathode to verify stable steady state operation. Hollow cathode ignition, discharge supply operation across the complete range of operation, automated operation using the controller, and the error procedures were demonstrated. No problems were identified during the test. Currently, more precise ignition specifications for the hollow cathode are being investigated and the design of a PEU input filter is underway.

CONCLUSION

A breadboard PEU for the ISSA plasma contactor system was fabricated and integrated with an engineering model hollow cathode. The design was based on a prior PEU and included an AC cathode heater supply to mitigate possible problems with ion migration in the insulator material of the heater due to DC excitation. After optimization of the magnetic components, in both the cathode heater and discharge supplies, lower component mass and higher power conversion efficiency were obtained compared to the prior PEU. Power conversion efficiency on the AC cathode heater supply increased 18 percent to 0.92 compared to 0.74 on the DC cathode heater supply. Issues such as load and line inductance and skin effect were addressed in order to reach specifications with AC excitation.

The PEU was integrated with an engineering model hollow cathode and proper overall performance of the PEU was verified. No significant differences were identified between heater temperature using AC and DC excitation. Also, steady-state operation and ignition of the hollow cathode with the discharge supply was demonstrated across a range of conditions bounding known operation requirements. Currently, efforts to finalize ignition specifications for the hollow cathode and to design of an input filter for the PEU are being developed.

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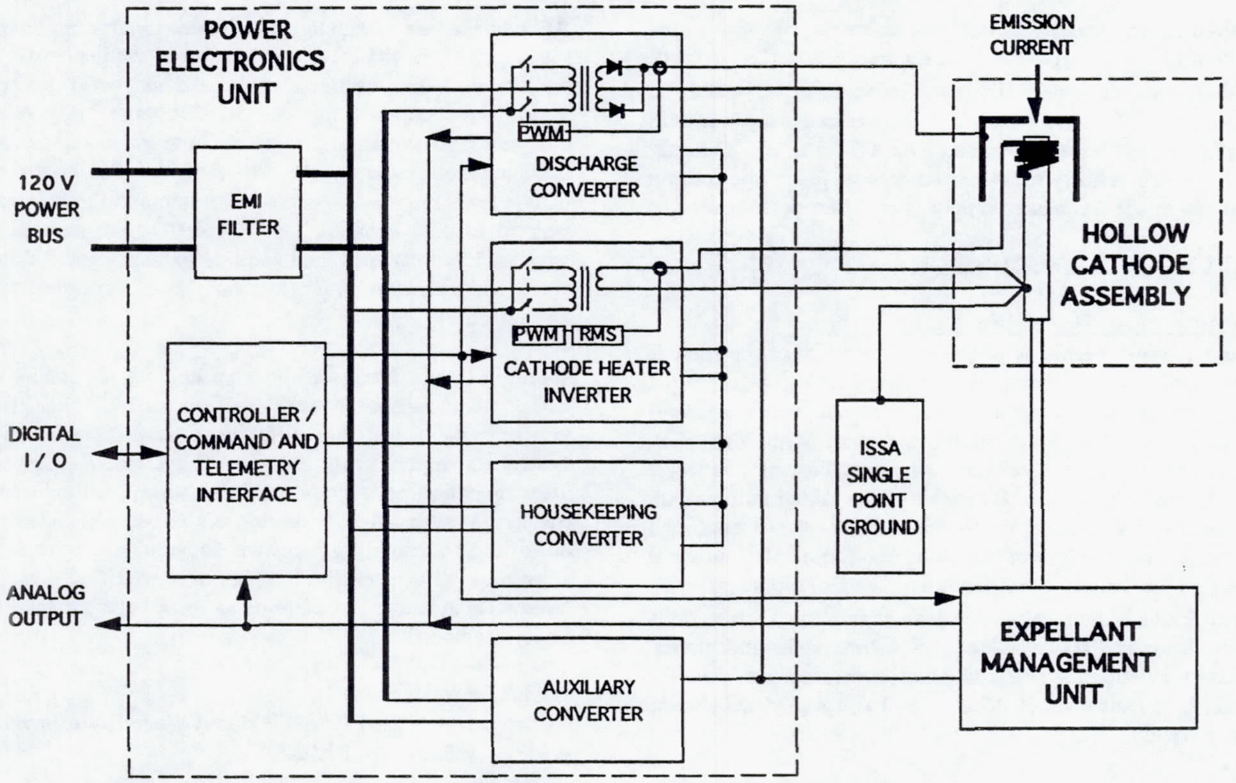

FIGURE 1. PLASMA CONTACTOR SYSTEM BLOCK DIAGRAM

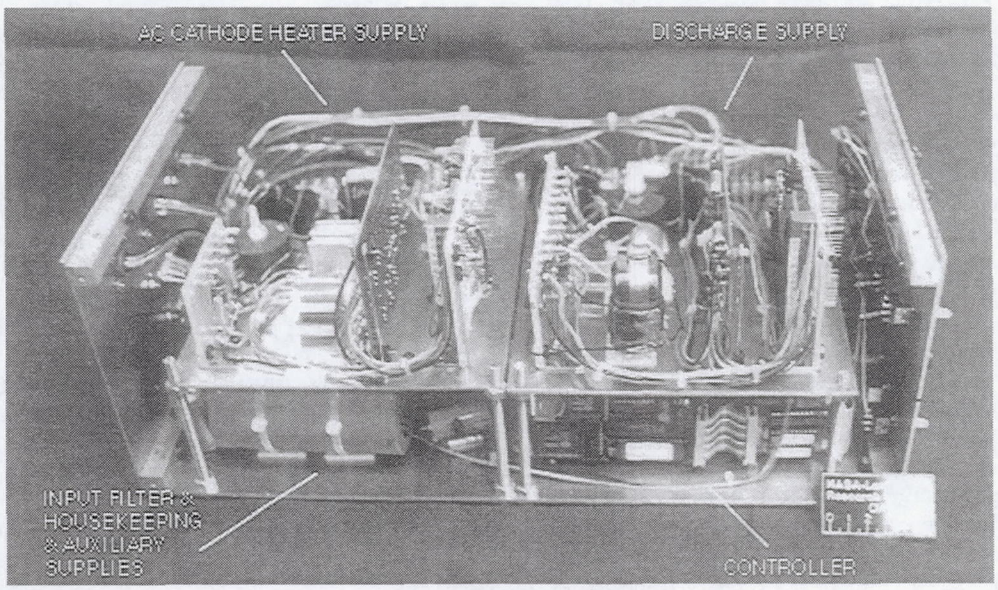

FIGURE 2. POWER ELECTRONICS UNIT

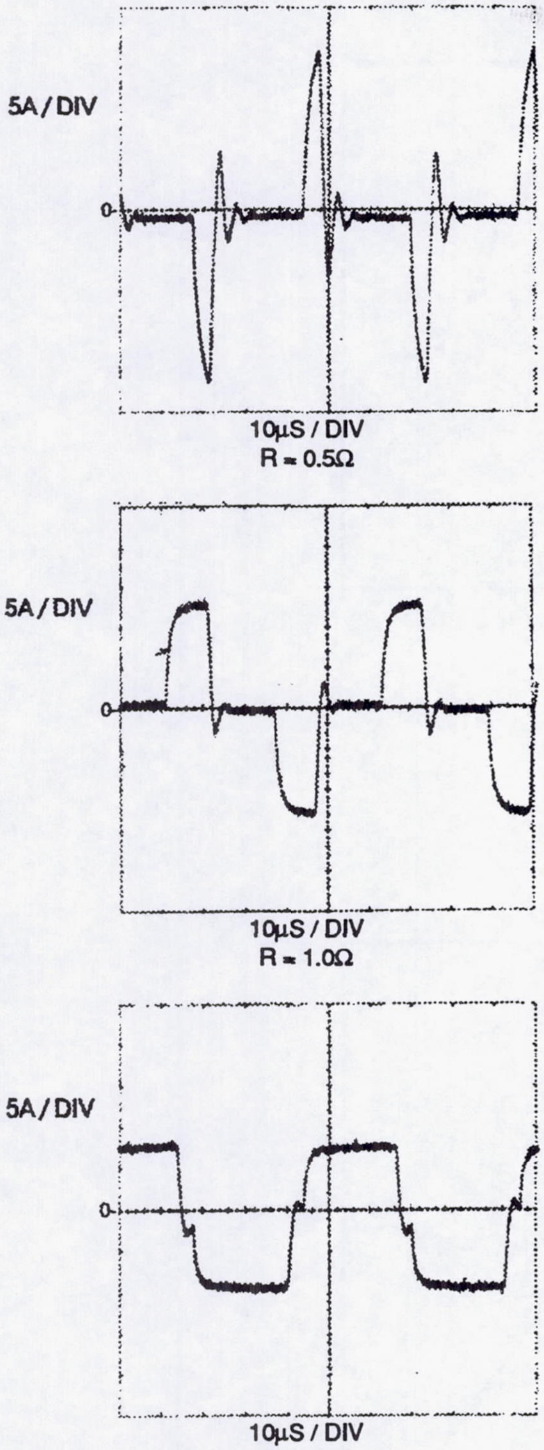

FIGURE 3. OUTPUT CURRENT OF 7.2 A_{RMS} FOR VARIOUS LOAD RESISTANCES

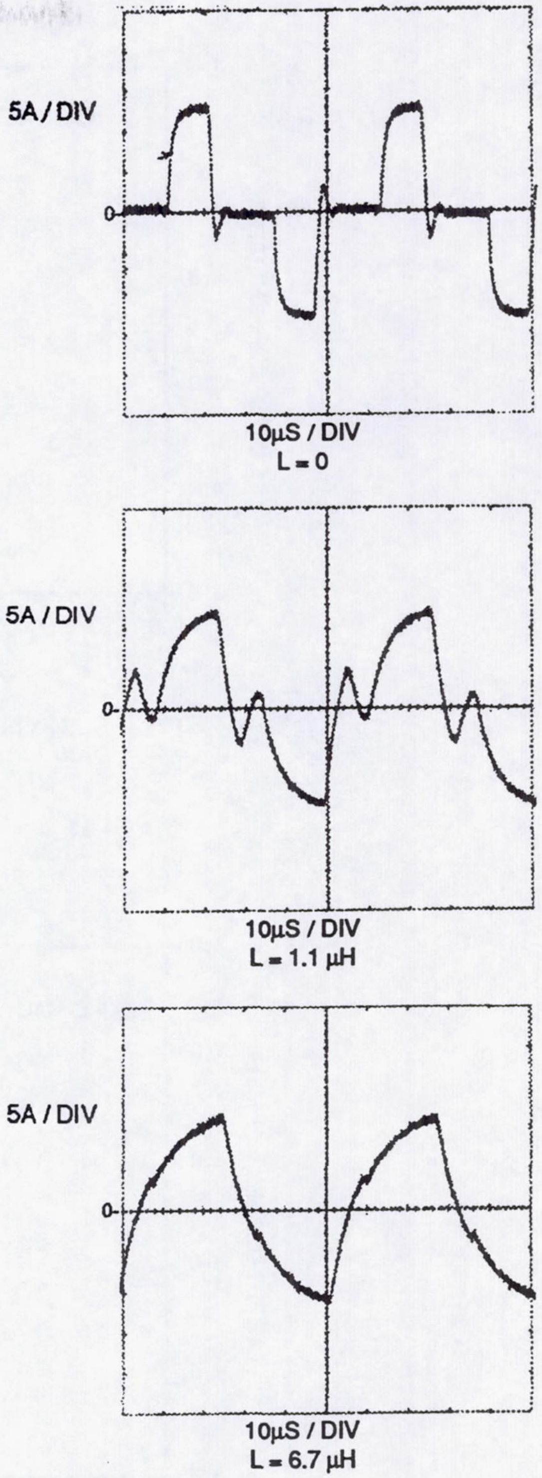

FIGURE 4. OUTPUT CURRENT OF 7.2 A_{RMS} FOR VARIOUS LOAD INDUCTANCES AND 1.0 Ω LOAD RESISTANCE

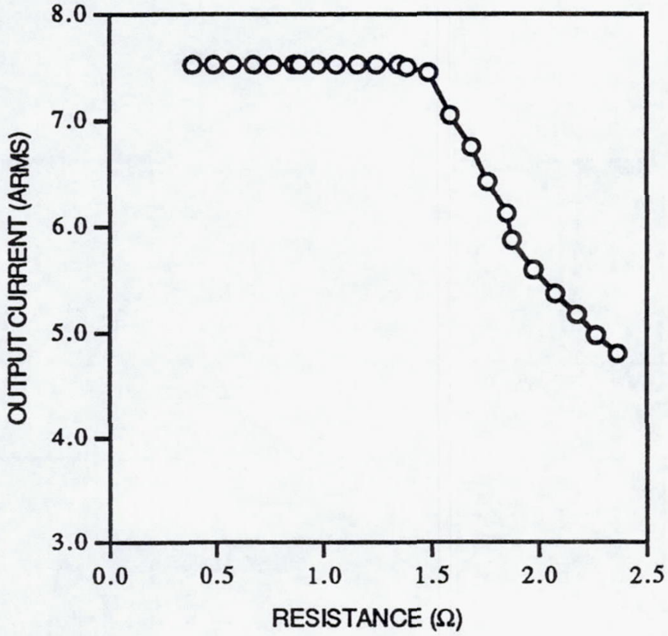

FIGURE 5. RESISTIVE LOAD REGULATION

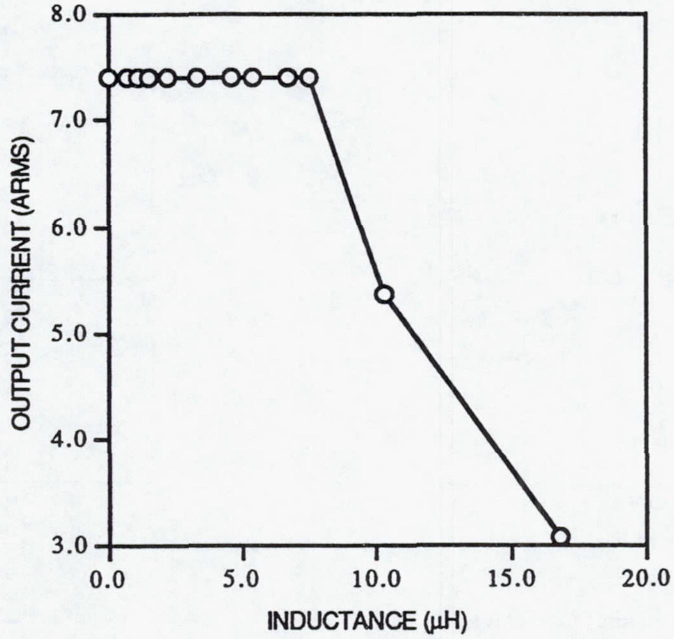

FIGURE 6. INDUCTIVE LOAD REGULATION WITH 1.0Ω HEATER RESISTANCE

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