TESTING OF THE 30 kW ARCJET PCU STARTER USING THE SHORTING SWITCH APPROACH

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Abstract

Space Power, Inc. (SPI) has been developing 30 kW class arcjet Power Conditioning Units (PCU's) for space propulsion[1]. The objective is to design a high power, space qualified, flight-type PCU for orbit transfer applications. The design is a simple buck regulator with a built-in flyback starter circuit. The start circuits we used to generate the high voltage start pulse in these arcjet PCU's were different from what had been used in other arcjet PCU's (in the lower power systems). We believed that design was more suitable for high power systems. The starter recently was tested with arcjet thrusters in NASA LeRC[2], JPL[3] and RRC[4]. An accompanying paper will report the result of these tests. This paper will focus on the built-in starter circuit that is used to initiate the arc.

Arcjet Start-up Requirement

There are several techniques that one can use to start an arcjet such as: using argon gas; using an RF coil; using a sharp needle; or applying high voltage (D.C. or pulse). All these techniques are used to trigger, or help to trigger, a gaseous breakdown between the electrodes so that an arc is initiated. Among these possible approaches, the high voltage technique is most suitable for space application because multiple unattended starts must be performed in space The high voltage required is only in the order of several thousand volts.

High Voltage Start

Both high voltage D.C. and a high voltage pulse can be used to start an arc. High voltage D.C. requires a capacitor. If the capacitor is not de-coupled by a blocking diode, it may cause instability to the arcjet. Furthermore, another blocking diode will be needed to protect the power converter part of the arcjet PCU from the high voltage. On the other hand, no blocking diode will be required for high voltage pulse if the circuit is designed properly. Therefore, the high voltage pulse technique is more desirable.

Flyback Circuit For High Voltage Pulse

As far as we know, all arcjet PCU's have been designed to use high voltage start pulses. However, there are more than one approach to generate the high voltage pulse. Before we discuss the difference in the pulse generation, there are some commonality among the starters. For example, due to the impedance characteristics of the arc, all arcjet PCU's have an output inductor. And the output is also the best place to block the high voltage start pulse from the rest of the circuit. Therefore, most of the start circuits use the inductor, directly or indirectly, to generate the flyback high voltage pulse. A switch will be turned on momentarily to allow the inductor current to build up to a preset level and the switch opens abruptly to generate the start pulse.

Auxiliary Start-Up Winding Versus Shorting Switch

Previously, NASA LeRC had developed a start pulse generator that used the inductor indirectly[5]. They wound an additional winding on the output inductor. This additional winding is inactive except during the starting process. The additional winding acts as the primary winding of a transformer while the original winding of the inductor acts as the secondary winding. A flyback circuit is used to generate a pulse, which is stepped up to a higher voltage pulse across the output of the PCU. The step-up ratio equals the turns ratio between the additional winding and the main inductor winding. The introduction of the turns ratio allows freedom in selecting the switching voltage in the start circuit. The pulse voltage required to start an arcjet is on the order of several thousand volts. If a 10:1 turn ratio is used, the switch in the start circuit only needs to switch several hundred volts, which is within the operating range of a single semiconductor switch.

Despite the advantages of the auxiliary winding and the turns ratio, we decided not to use the extra winding approach for the high power arcjet PCU. The decision was

1. The arcjet PCU development was supported by Air Force and SDIO-SBIR funding and monitored by AFAL, AFWAL and NASA LeRC.

2. This test was a joint effort of NASA LeRC and SPI. SPI's effort was part of the SDIO-SBIR Phase II.

3. This test was supported by SDIO and operated by JPL. SPI was responsible for the preparation of the PCU.

4. This test was supported by a subcontract from Rocket Research Company.

5. Charles J. Sarmiento and Robert P. Gruber "Low Power Arcjet Thruster Pulse Ignition" AIAA-87-1951

based on the properties that are mostly unique to high power arcjet systems. As discussed below, the auxiliary winding is relatively easier to implement in a low power arcjet, where the current is smaller.

The major advantage of the shorting switch approach is its simplicity. The major disadvantage is the requirement of a high voltage switch. In the start-up winding approach, the switching voltage can be made lower by selecting a step-down turns ratio on the start-up winding. However, a *voltage step-down* transformer is also a *current step-up* transformer. Instead of switching high voltage at moderately high current (2000V, 100A), we can design in the start-up winding approach to switch lower voltage at much higher current such as 400V at 500A or 200V at 1000A. Because the inductors need to use gapped ferrite cores or molypermalloy powder cores, the coupling between the windings will not be very high. Therefore, the switching current in the start-up winding design will be even higher. If we use MOSFETs, a set of multiple switch devices is inevitable. The shorting switch approach requires a combination of series and parallel of MOSFETs while only parallel connections will be sufficient for the start winding approach. However, the total number of MOSFETs should be about the same.

Why does the high power system need to switch a higher current? Even though the high power arcjet thruster is physical bigger, the energy to initiate an gaseous breakdown may not be much higher in a bigger thruster. Depending on the value of p•d (pressure times distance), the breakdown is likely to be easier for a bigger thruster. The reason is the low inductance of the output inductor. For same percentage of acceptable current ripple, the high power system can tolerate high d_I/d_t. The arcjet voltage is about the same for both low and high power arcjet. Therefore, the high power system only requires a low inductance output inductor. The three phase high power arcjet PCU design allows even lower output inductance. In order to produce a given amount of energy in the start pulse, a higher inductor current is required to compensate for the low output inductance (Energy = $L \bullet I^2$). Therefore, the switch in the starter is required to switch a higher current in the high power systems.

With respect to the concern of high voltage design, we need to design the output inductors and the output terminals to withstand the same breakdown voltage no matter which approach we choose. High voltage design practice and precaution is inevitable. The additional high voltage design requirement in the shorting switch approach is the isolation capability of the gate drive transformer for the MOSFETs in the higher end of the series transistors.

Another important consideration is the transition from start-up to steady state operation. With the shorting switch, the current of the output inductor is delivered through the power switch for the steady state operation, all the power components as well as servo-control operational amplifiers needed to operate the arcjet in steady state are in their active state during start-up. The transition is very smooth once the arcjet is started. On the other hand, the energy of the start pulse in the start-up winding approach is coming from an external source. After the arcjet is started, the power stage must pick up the operation. The transition may be more complicated.

The 30 kW class arcjet PCU uses three power phases to minimize the ripple of the arcjet current. This raised an additional issue for the start-up winding approach. If a start-up winding is used on all three inductors, three additional windings will add significant cost and weight to the PCU. If only one winding is used, the inductors of the other two phase will become available alternate current paths and compromise the effectiveness of the flyback circuit.

Arcjet Starter Used In High Power PCU

Figure 1 shows the schematic of the arcjet starter. This starter, when operating with the SPI built 30 kW arcjet PCU, is capable of generating a 2000 V pulse with about half μsec pulse width. A starter of this design has successfully started arcjets in several arcjet integration tests. However, it seemed to be somewhat marginal under some operating conditions. A revised version of the starter has been built and the schematic is shown in Figure 2. The new starter allows the inductor current to build up to a significantly higher level so that the start pulse has higher stored energy.

Even with the modification in the newer start circuits, we expected the open circuit voltage of the starter to remain unchanged because the voltage should be held down by the protection Zener diodes. Incidentally, the Zener diodes were inadvertently opened by the high pulse energy not long after the test began. The opening of the Zener diodes had no significant effect on the circuit except the output voltage was then allowed to increase from about 2000 V to about 3000 V. Therefore, the modified starter turned out to be more powerful than what we originally planned. This newer starter has generated pulses up to 3-4 kV after its internal voltage limiter (Zener diodes) was opened.

Test Data

Figures 3 and 4 show start voltage waveforms of the original starter. Figure 3 shows the waveform of the start pulse without breakdown. Figure 4 shows the waveform of the start pulse at breakdown. Both of these waveforms were taken at an arcjet integration test held in Jet Propulsion Laboratory. The starter was the original design. From the small difference between the open circuit voltage and the breakdown voltage, one can tell that the start pulse was marginally performing its function. The breakdown occurred at near the peak of the start pulse.

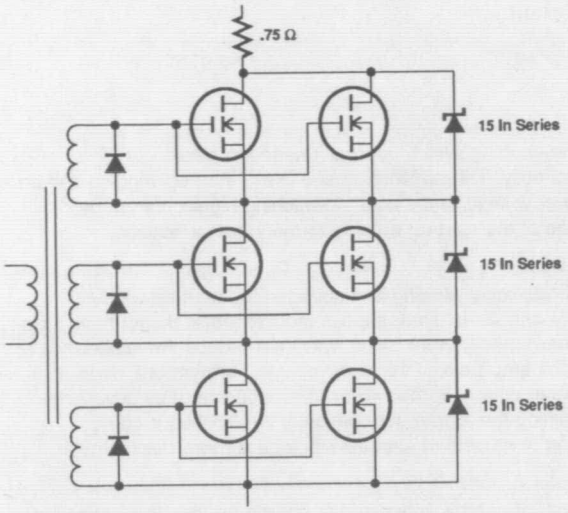


Figure 1. Original Starter.

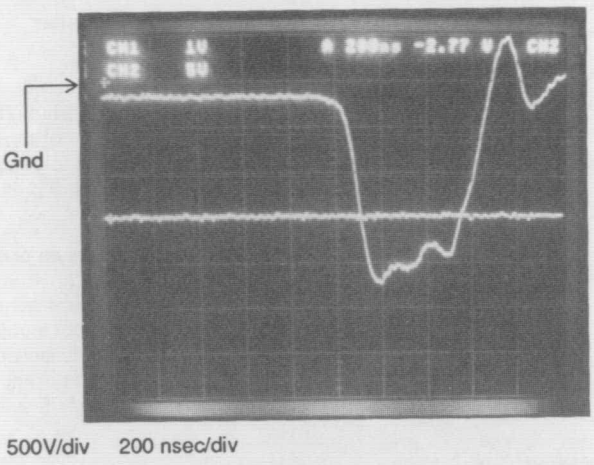


Figure 3. Start Pulse (No Breakdown).

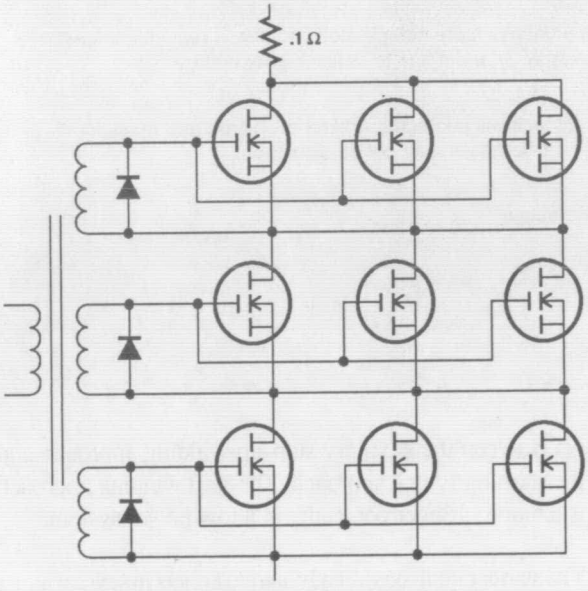


Figure 2. Modified Starter.

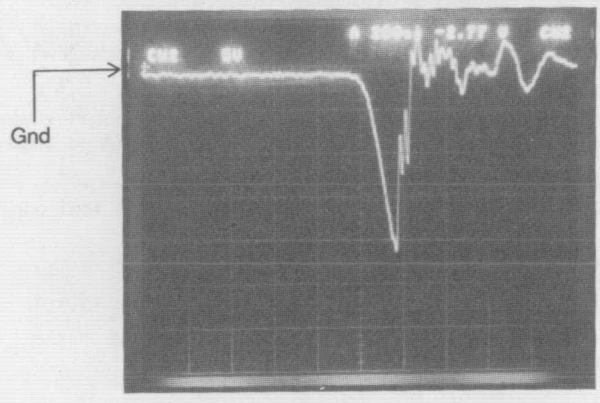


Figure 4. Start Pulse (Breakdown).

Figures 5 and 6 show start voltage waveforms of the improved starter. Figure 5 shows an open circuit start pulse waveform. The peak voltage was about 2.9 kV, which was higher than the original design. Figure 6 shows the start pulse waveform at breakdown. The breakdown voltage was about 2000 V. The waveforms were taken at the integration test held in Rocket Research Company. If breakdown voltage is consistently at around 2000 V, the new starter, that generates a 2900 V pulse, should be a reliable design. However, the breakdown voltage depends on factors such as thruster design, propellant flow, thruster surface condition, and pulse width. There is not yet sufficient data to conclude that the new starter design could cover all reasonable arcjet operating conditions.

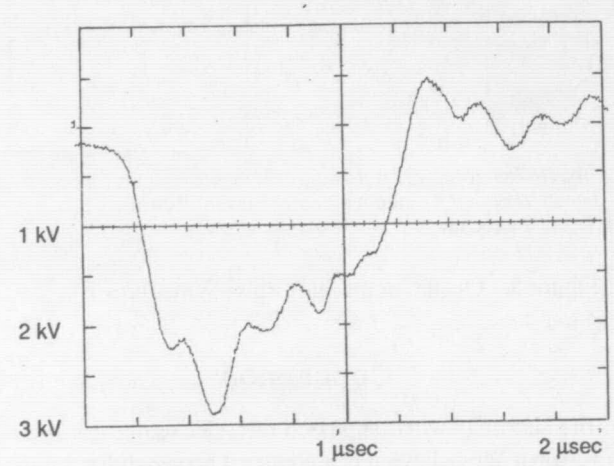
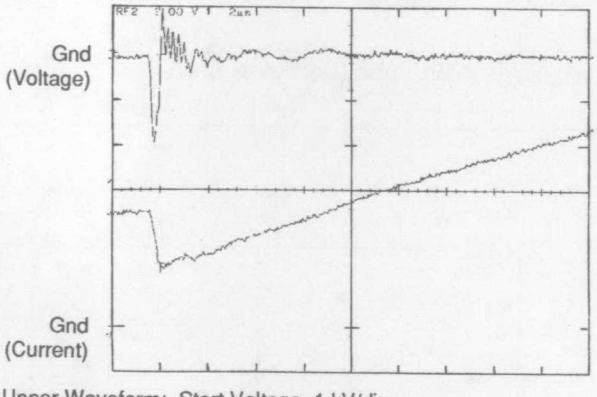


Figure 5. Open Circuit Start Pulse Waveform.

Table 1. Comparison of the Two Approaches to the Starter Circuit.

	Start-Up Winding	Shorting Switch	Discussion
Switch Requirement	Low voltage, high current	High voltage, high current	The switch(es) used in the shorting switch approach needs to block ~2000 V of start voltage directly. The switch(es) used in the start-up winding can be arrange to switch at a lower voltage at the cost of switching higher current by manipulating the turns ratio of the start-up winding to the inductor winding.
Additional Winding	1 or 3	0	A minimium of one set of additional winding is required in the start-up winding approach. However, if only one set is used, the two inductors that do not have start-up winding will serve as unwanted current paths which will reduce the impedence at the output terminal, thus the amplitude of the high voltage. Furthermore, even after the arc is ignited, the reverse current in the two passive inductors may adversely affect the chance of sustaining the arc. In our opinion, if the start-up winding approach is selected, using three sets of start-up windings is more desirable.
Stored Energy	Higher	Lower	Assuming the same amount of energy is required to charge up the stray capacitance between the cathode and the anode of the arcjet thruster, and the connecting cables. The energy stored in the inductor(s) of the start-up winding approach will be higher due to the coupling loss of the start-up winding. The coupling coefficient of a heavily gapped core will not be very high. This means the power switches are required to switch more energy.
Simplicity	More complicated	Simpler	The start-up winding approach is more complicated because it requires at least one additional winding (preferably 3) and it has to switch higher energy.
Size and Mass	Bigger and heavier	smaller and lighter	The start-up winding approach will add some additional volume and mass for its additional winding(s). The differences may not be significiant.
Chance of Sustaining the Arc	Not as good if only 1 winding is used	Good	See discussion in Item 2 above.



Upper Waveform: Start Voltage, 1 kV/div
Lower Waveform: Output Inductor Current, 10A/div
Time: 2 µsec/div

Figure 5. Open Circuit Start Pulse Waveform.

Conclusion

The shorting switch approach of arcjet starter has been verified. We believe it is a preferred approach for multi-phase high power arcjet PCU's. Table 1 shows the trade-off between the auxiliary start-up winding approach and the shorting switch approach. The start winding approach is a much stronger contender in a low power system.

The starter circuit has already started arcjets in several arcjet integration tests. The improved version started the arcjet much more consistently. However, it is still not completely flawless. It failed to start a thruster that had not been used for long time; but it did work very consistently after the same thruster had been seasoned. The exact cause is not known. Factors such as thruster design, propellant flow, thruster surface condition, and pulse voltage and width all affect the arcjet breakdown. In order to design a reliable and consistent arcjet starter, more effort needs to be spent in defining the breakdown condition.

Acknowledgment

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