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Development and Buildup of a Stirling Radioisotope Generator Electrical Simulator

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Abstract

This paper describes the development of a Stirling Radioisotope Generator (SRG) Simulator for use in a prototype lunar robotic rover. The SRG developed at NASA Glenn Research Center (GRC) is a promising power source for the robotic exploration of the sunless areas of the moon. The simulator designed provides a power output similar to the SRG output of 5.7 A at 28 Vdc, while using ac wall power as the input power source. The designed electrical simulator provides rover developers the physical and electrical constraints of the SRG supporting parallel development of the SRG and rover. Parallel development allows the rover design team to embrace the SRG's unique constraints while development of the SRG is continued to a flight qualified version.

Introduction

The vision for space exploration calls for lunar exploration for a variety of reasons, such as bringing a human presence to the moon, pursuing scientific activities that explore the history of the solar system, and preparing further exploration technologies. Key to all of these themes is the ability to harness any useful resources found on the moon. This would require less mass to be transported to lunar orbit for use in future missions launched from the moon or in maintenance of a lunar outpost. A critical resource needed by humans and one that might be found on the moon is water. If water is found on the moon, it would most likely be in the form of ice (ref. 1) buried in a crater shielded from the sun.

The environment in a sunless crater presents too many unknowns to risk a human astronaut for a first mission to explore for ice. Instead, a robotic rover is expected to search for the availability of in-situ resources such as water. Exploring the moon in sunless craters presents many technical challenges. The surface temperature within a shadowed crater is expected to be near –233 °C (40 K). Compare this to sunlit areas of the moon like the Apollo landing sites where temperatures can vary 280 °C with a high of 101 °C (374 K) and a low of –181 °C (92 K) (ref. 1). While sunlit areas of the moon have a harsh temperature environment, the crater temperature is especially extreme. In addition to the extreme cold, the lack of light is an impediment to landing and navigation within a crater. Another significant challenge to operating a robot within a shadowed crater, in addition to the extremely cold temperatures, is the power source. Power in previous robotic platforms (Mars Exploration Rovers, Mars Pathfinder) and most earth satellites is generated by solar cells. Previous lunar platforms were powered by either battery power or a hybrid design using both solar and battery power. The Soviet Lunokhod rover charged its batteries with a solar panel, while the Apollo Lunar Roving Vehicle was battery powered with no means of recharging the onboard batteries (ref. 2). A rover designed to operate within a shadowed crater cannot rely on solar power to generate the needed power for mission operations. A solar charge followed by a run into the crater is one option for a power system, but the duration of crater operations would be limited by battery capacity. Other power systems may provide a more crater friendly power source, and are being explored by the Carnegie Mellon University and Glenn Research Center surface mobility team.

The power systems under consideration for a lunar robotic rover are the Stirling Radioisotope Generator (SRG), Thermophotovoltaic (TPV), Proton Exchange Membrane (PEM) Fuel Cells, and batteries. Both the SRG and TPV systems rely on General Purpose Heat Source (GPHS) (ref. 3) modules which consist of a radioisotope block that generates heat, while the PEM fuel cell uses oxygen and hydrogen as fuel. The radioisotope power sources are especially attractive for sunless crater operation because they produce heat as well as power. This paper will discuss the investigation of the use of an SRG on a robotic rover, and the NASA Glenn Research Center Optical Instrumentation Branch Flight Electronics Laboratory activities toward providing a clear path to the use of an SRG on robotic rover platform.

Why use a Stirling Radioisotope Generator?

The Stirling engine, capable of the highest efficiency of any type of heat engine is comprised of two heat exchangers, a closed cylinder filled with a working gas and a piston. The heat exchangers or reservoirs are used as a heat source and a heat sink respectively. Work is extracted from the engine by compression and expansion of the working gas within the cylinder, which in turn moves the piston providing mechanical work. The cold reservoir is usually the environment, while the hot reservoir is generated by combustion of fuel such as gasoline, sun light converted to heat, or a radioisotope such as plutonium.

The SRG developed at NASA Glenn Research Center is meant to be powered by a radioisotope GPHS (ref. 4). The radioisotope heat source has many advantages for use in space, one being the long life of the source, another is that it’s simply a block of hot material, from which heat not used by the Stirling engine can be used to warm onboard systems. Previous rover platforms have used resistive heating devices and radioisotope heating units (RHUs) (ref. 5). Resistive heating converts electrical power into heat, while RHUs transfer the heat of the radioisotope to the surroundings. Resistive heating would have an expensive electrical power overhead if used in a crater. The SRG provides a simple yet elegant solution to the heating problem, putting waste heat to use.

Why Build a Simulator for the Stirling Radioisotope Generator?

The SRG has been developed and is in the process of being flight qualified. The rover team is trying to leverage this available technology to eliminate the significant cost of re-engineering an SRG to suit the specific needs of a rover. To do this the rover must be designed around the SRG. To design the rover effectively with the SRG in mind, the rover designers must be thoroughly familiar with the power generator parameters including the volume, mass, power budget, support electronics, and center of gravity. The SRG volume and mass will dictate the rover volume. The SRG power budget will determine the rover’s mass, drive motor torque, drive speed, and duty cycle among other things. To support Carnegie Mellon University in the design of a rover, the NASA Glenn Flight Electronics Laboratory has designed an SRG simulator to embed in a robotics platform with the goal in mind to provide a power platform that will fit in the same volume and footprint as a flight version of the SRG, and will provide a similar power output. This will allow development of a robotic rover platform while development and testing of the actual SRG is ongoing.

The SRG simulator is designed to be an electrical stand-in for the SRG. It will provide a power output curve similar to that of the SRG. The current design will be ac wall powered. Initial plans for the rover called for a hanging tether to simulate lunar gravity for the rover. With this tether already in place, the decision was made to power the SRG simulator from wall power. The tether provided a means to wire the simulator to an ac power source, providing constant power to the rover with no charging duty cycle. This simplified the electronics (no need for a battery charger) and also resulted in a lighter package (batteries are heavy). An ac powered system will not be limited by a charging duty cycle, which will allow longer rover tests.

Simulator Buildup

The simulator power supply was designed with simplicity and durability in mind. The simulator is expected to be used in extreme environments: in hot areas such as deserts and definitely in dusty, sandy areas which will mimic lunar environments. The simulator is also expected to operate continuously with no impact on rover test operations. The circuit shown in figure 1 was the simplest design found to provide the most realistic power output curve.

The Design consists of

1. A transformer to step down the input of ac wall voltage to approximately 30 V ac (peak)
2. A Bridge rectifier to rectify the ac into dc
3. A Smoothing Capacitor to filter out ripple from the rectification process
4. The linear pass transistor section, which monitors the output and adjusts the pass transistor's current to control the output voltage and current

This circuit worked effectively to provide the correct output, but heat dissipation through a single pass transistor (Q2 in figure 1) was a major concern, as it allowed a single point of failure. For the case of a short circuit load the single transistor may be forced to dissipate 160 W. The heat developed inside the simulator from the current sense resistors, rectifying bridge, and losses in the transformer could be enough to raise the interior ambient temperature to a point which would push the transistor junction temperature toward the maximum operating temperature point which could result in component failure. To lower the heat dissipation in the pass transistor and provide robustness during a single transistor failure, the pass transistor section (section 4 of figure 1) of the circuit was duplicated 4 times, to spread the current out through parallel paths of transistors, as shown in figure 2. To further increase the heat dissipation, the pass transistors were mounted to the aluminum housing with electrically insulating, heat conducting material. This allowed the Simulator case to act as a heat sink.

Figure 3 shows the assembled SRG simulator provided to CMU. The housing was built from Aluminum sheet metal. This allowed the housing to be used as a heat sink, and provided a chassis ground for safety. To provide a safer circuit, a circuit breaker switch was installed at the ac power input which limits the input current to 2 A. This provides circuit protection in case the transformer develops a short circuit.

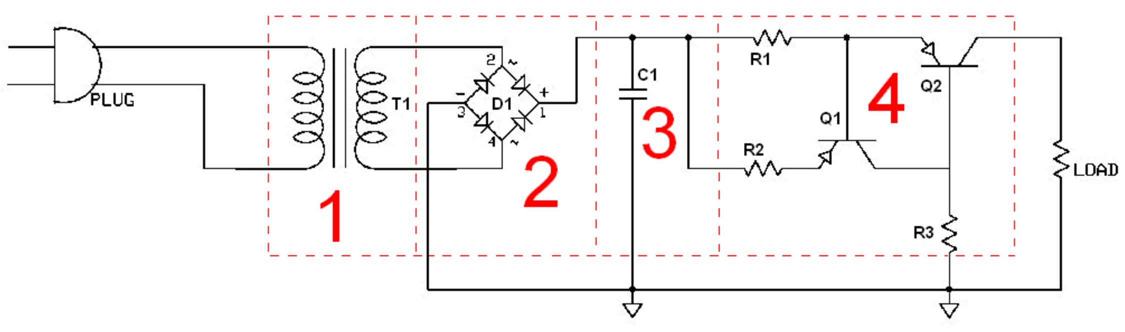

Figure 1.—Initial simulator circuit for testing.

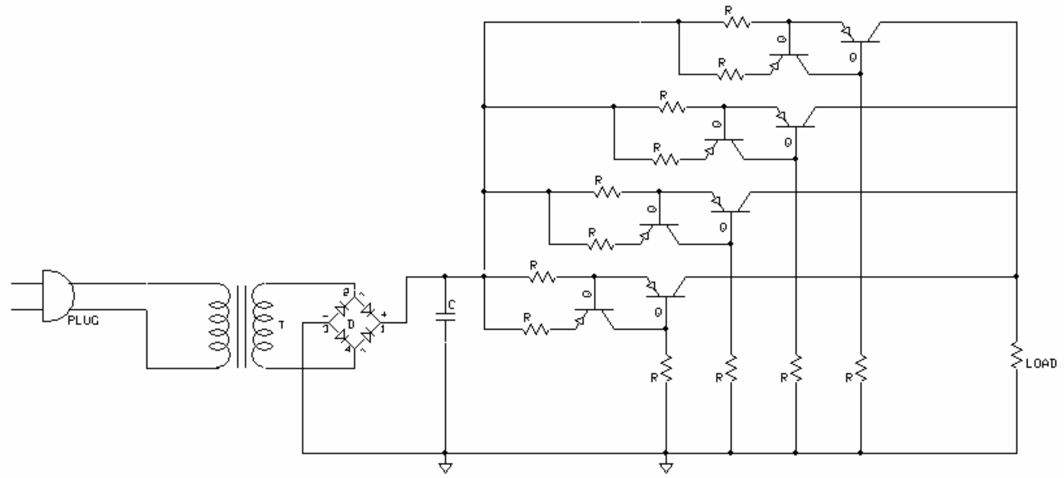

Figure 2.—Simulator circuit provided to Carnegie Mellon University.

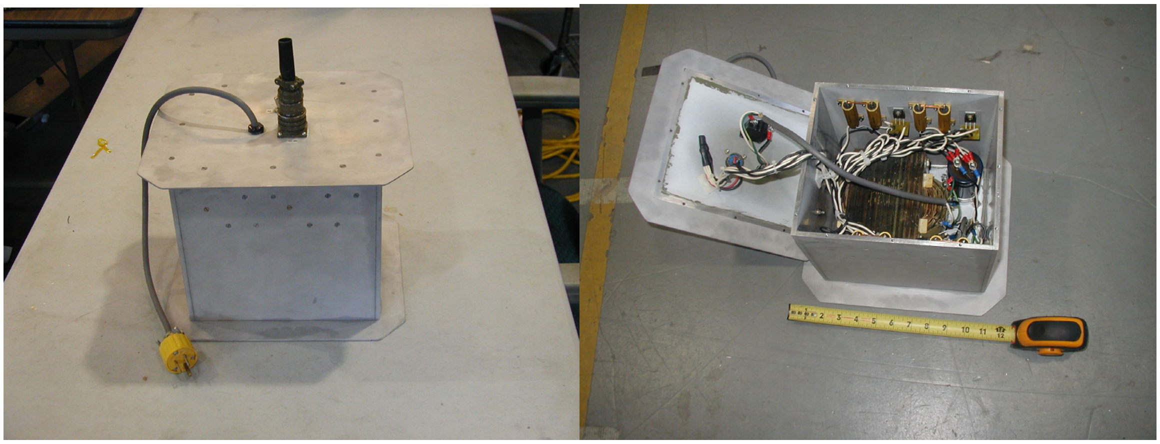

Figure 3.—Assembled simulator.

Testing and Results

The simulator was bench tested using four configurations loads of 50 Ω, 20 Ω, an open circuit measurement, and a short circuit measurement. Output current was measured using a ammeter in series with the test load and voltage was measured across the load using a voltmeter. To measure the short circuit current, the ammeter was connected across the output power connectors, in effect short circuiting the power supply. A thermocouple was used to measure the air temperature inside the enclosure as well as to monitor the enclosure's exterior temperature. The test load was applied for an hour for each test to monitor heat build up in the simulator, the case temperature, as well as output voltage and current. Neither meter used was calibrated with a NIST standard, but subsequent meter readings were compared with other NIST calibrated sources. These readings resulted in accuracy within the one percent tolerance of circuit components used.

Output voltage and current results are shown in table 1. Figure 4 shows the output power curve from a SPICE (ref. 5) simulation of the circuit using models provided by the electronic component manufacturers. Actual Test Points are plotted on figure 4 in green dots and are also shown in table 1. At short circuit, the current measurement was 5.7 A. At open circuit the voltage was measured at 29 V. During maximum current draw (short circuit load), the simulator enclosure became warm to the touch, but stayed at a safe-handling temperature. Temperatures within the simulator enclosure stayed well within the operating limits of the electronics used.

TABLE 1.—OUTPUT POWER TEST POINTS

Output voltage, V	Output current, A	Load, Ω
29	0	∞
0.5	5.7	~0
28	1.4	20
28.6	0.561	50

Figure 4.—SPICE simulation output power curve (red). Circuit test points (green).

Conclusion and Future Work

A Stirling Radioisotope Generator Simulator power supply was designed and delivered to Carnegie Mellon University for integration into the Highlander rover platform. Figure 5 shows the simulator mounted on the Highlander rover platform. The simulator power supply was designed to physically simulate the mass and volume of the SRG. The output power curve of the simulator complied with the specifications provided to the NASA Glenn Flight Electronics Laboratory; limiting current to 5.7 A at 28 Vdc nominal output voltage.

Future designs for a series of radioisotope generator simulators will introduce more Stirling like functionality, such as a constant power output and constant power consumption with conversion of unused power to heat. This will allow experimentation with heat regulation within the robot. Future simulators may also need to output greater power than a flight model for earth use. Because Earths gravity is 6 times that of the moon, rover trials on earth may require up to 6 times greater power. Future Stirling simulators may need to provide this greater supply of power for demonstrations. Other simulator utilities may also be needed, such as power tracking, power limiting, and adjustable power levels.

Figure 5.—The simulator mounted on the Carnegie Mellon University Highlander rover platform.

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