A STANDARD LOAD CENTER CONVERTER POWER SUPPLY

J. R. Graves, H. L. Lenox, J. R. Lanier, Jr., and R. E. Kapustka

NASA/George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

ABSTRACT

This paper presents a discussion of a modular, multiple output power converter developed for a wide range of space applications and selected as NASA standard hardware. The unique packaging concept, advanced heat removal techniques, and electrical design and characteristics are presented in detail.

INTRODUCTION

The development of a modular, multiple output Standard Load Center Converter (SLCC) has been completed by NASA's Marshall Space Flight Center. The SLCC was designed for use in a wide range of space applications and can be tailored to meet specific user requirements with minimum development cost and risks.

Development of the SLCC began with studies to identify potential applications, candidate circuitry, and packaging concepts. These studies determined the feasibility of standardization and resulted in trade studies and development activities leading to the present design. Follow-on packaging refinements, including the use of heat pipes for thermal control, has produced a flight qualified, efficient, lightweight power converter which was selected as NASA standard hardware in 1977 (NASA Standard Hardware Catalog No. 6.001). Flight units have been delivered for use in the Induced Environment Contamination Monitor (IECM) to be flown as part of the instrumentation package for all the Space Shuttle Orbital Flight Tests (OFT 1-9) and the Spacelab 1 mission.

A general description of the SLCC including specifications, characteristics, and its electrical and mechanical designs are presented in detail in the following sections.

Fig. 1. Four module SLCC.

The SLCC is designed to convert a bus or distributed voltage to various regulated voltage levels required by a user. It consists of a mainframe with interchangeable, plug-in modules. The mainframe serves as a common support base and distribution chassis for the plug-in modules and contains the housekeeping power supply, heat sink, and input filtering. Mainframes are available to accommodate one, two, and four plug-in modules. A four module SLCC is shown in Figure 1.

The plug-in modules contain the output regulator including the power switching elements and the associated drive and control circuitry. Each output regulator module is capable of up to 100 W of output power at a specified voltage level of 4 to 80 Vdc. All output modules are identical with the exception of the power transformer and a resistor divider network in the comparator and failure detection circuitry. These components are selected as a function of the output voltage level required.
The output regulator design utilizes a dc-to-dc converter incorporating regenerative current feedback with a time-ratio controlled duty cycle to achieve high efficiency and tight regulation over wide variations in input voltage, output load, and temperature. Efficiencies of a typical production unit are shown in Figure 2. Although this compares favorably with the 50 percent efficiency of nonswitched mode multiple-output converters and 60 to 70 percent for typical switched mode multiple output converters, design modifications are presently being made to improve these efficiencies by 4 percent on future production units.

A summary of the pertinent electrical specifications for the SLCC are listed in Table 1. Note that the voltage regulation of 0.25 percent is worst case for production units and may be adjusted to less than 0.1 percent if desired. The SLCC also has remote start-up/shutdown capability, over-voltage and short circuit protection, and remote sensing capability for output regulation at the load terminals.

**TABLE 1. SLCC SPECIFICATIONS**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Input Voltage</td>
<td>21 Vdc to 36 Vdc</td>
</tr>
<tr>
<td>Output Power</td>
<td>1 to 4 discrete voltage levels (4 to 80 Wdc)</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>100 W to 400 W (Selectable)</td>
</tr>
<tr>
<td>Voltage Regulation</td>
<td>±0.25% (Adjustable to ±0.1%)</td>
</tr>
<tr>
<td>Output Ripple</td>
<td>1.0% Maximum Peak-to-Peak</td>
</tr>
<tr>
<td>EMI</td>
<td>Per SL-E-0002 and MIL-STD-461A</td>
</tr>
<tr>
<td>Isolation</td>
<td>Input/Output — 50 Megohm Minimum</td>
</tr>
<tr>
<td></td>
<td>Common/Case — 50 Megohm Minimum</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20°C to +85°C</td>
</tr>
<tr>
<td>Weight</td>
<td>400 W Unit — 6.6 kg (14.6 lb)</td>
</tr>
<tr>
<td></td>
<td>200 W Unit — 4.1 kg (9.0 lb)</td>
</tr>
<tr>
<td></td>
<td>100 W Unit — 2.7 kg (6.0 lb)</td>
</tr>
</tbody>
</table>

**ELECTRICAL DESIGN**

A detailed description of the SLCC electrical design can best be presented by describing its individual elements and their relationship to the operation of the supply. Figure 3 is a simplified block diagram of the SLCC showing the mainframe and output regulator module circuitry. The mainframe circuitry consist of the input filter and the housekeeping supply. The output regulator module is basically a push-pull switching regulator and operates as follows. The output load current is monitored at the primary winding of the power transformer via a current transformer. This current is compared with an error feedback voltage which is proportional to the difference between a scaled output voltage and a precision reference voltage. When the load current exceeds this error voltage, a pulse is generated by the comparator and supplied to the control logic. This pulse causes the control logic to inhibit the power switch drive for the rest of the cycle. The control logic is then reset by the next clock pulse and the cycle repeats, providing pulselength modulation. In essence, the control loop forces the load current to be that value necessary to produce a scaled output voltage equal to the reference voltage.

**Fig. 2. SLCC efficiencies.**

**Fig. 3. Block diagram.**

A detailed description of the operation of the key elements in the power train and control feedback loop is given as follows.

**Control Logic**

The control logic circuitry consists of basically eight nand gates and two J-K flip-flops as shown in Figure 4. The circuit operation is dependent upon a positive-going clock pulse at the input of U1. Upon receipt of the clock pulse, the output of U1 goes to 0 V, coupling a negative-going pulse through C1. U2 output responds by providing a positive-going pulse, approximately 1.0 μs wide, to U3 resetting its output to 0 V.
and causing the outputs of U4 and U5 to become high, inhibiting the base drive to the predriver transistors. Concurrently, C2 discharges through R2 until the threshold voltage of U6 is reached at which time its output goes high. The time required for this to occur is approximately 3 ms. This represents the time delay necessary before the inverter transistor may be turned on, assuring that both power transistors will not be on at the same time due to storage time.

When U6 goes high, it clocks J-K flip-flop U3, toggling U7 and enabling gates U4 and U5 such that either may go to 0 V (depending on the previous status of U7), enabling drive to the inverter power transistors. Upon receipt of a zero level command from the regulating loop comparator, U8 goes high resetting U3 to 0 V which inhibits drive to the power transistors for the rest of the clock cycle. This process is repeated each clock cycle, alternating drive to the two power transistors.

The cross coupled gates U9 and U10 provide the latching function necessary to shut down the regulator when an over- or under-voltage command is received from the failure detection circuitry. When U9 is in the zero state, the output of U4 and U5 are latched high, thus inhibiting the drive to the power transistors. This gating is accomplished through CR5 and requires a reset command for normal operation to continue.

Power Switch and Drive

A simplified schematic of the pulse-width-modulated (PWM) power switch and drive circuitry is shown in Figure 5. Since this element contains two identical and independent circuits, explanation of only the circuits consisting of Q1, T1, Lm (representing the magnetizing inductance of T1), and Q3 will be given, thus simplifying the discussion.

Initially, with transistor Q1 conducting, the secondary winding is essentially an open circuit, since the base-to-emitter terminals of transistor Q3 are reverse biased. The current flow in primary winding N1, assuming zero initial conditions, increases at a rate determined by the inductance of the primary winding and the circuit resistance, i.e.,

\[ i_m(t) = \frac{V_{cc}}{R_1} \left(1 - \exp\left(-\frac{R_1}{L_m}t\right)\right) \]

where

\[ i_m(t) = \text{the magnetizing current flowing in the primary winding N1, when Q1 is conducting} \]

\[ V_{cc} = \text{input voltage to drive circuit} \]

\[ t = \text{time.} \]

When Q1 is turned off, which open circuits the primary winding, the energy stored in the primary magnetizing inductance \( L_m \) discharges into the secondary winding. This may be represented as a current flowing out of \( L_m \) into the primary winding N1 (into point 1), which causes current in the secondary winding \( N_2 \) to flow into the base of Q3. This current decays at a rate proportional to the base-to-emitter voltage of Q3 and can be expressed as

\[ i(t) \approx \left[I_m - \left(\frac{V_{BE} N_1}{N_2 L_m}\right)\right] \times t \]

where

\[ I_m = \text{value of the magnetizing current immediately before transistor Q1 is turned off} \]
**Error Amplifier and Comparator**

The error amplifier and comparator circuitry is shown in Figure 6. Error amplifier U2 is operated in the inverting mode. The gain of U2 is determined by the ratio of the impedance of the feedback network, R5 and C1, and the input resistor R1 which is selected as a function of the output voltage desired. This amplifier compares the reference voltage, conditioned by resistors R3 and R4, with the regulator module output voltage, which is conditioned by resistor network R1 and R2, and provides an error feedback voltage. The error feedback voltage is applied to the comparator amplifier U1 which compares it with the primary current in the power transformer, measured by current transformer CT1. When this current exceeds the error voltage, the comparator output goes low and provides the signal to the control logic to inhibit the drive to the inverter power transistors.

![Fig. 6. Error amplifier and comparator.](image)

**Mechanical Design**

After design, fabrication, and testing of a development unit, special efforts were directed toward reducing weight and volume of the SLCC. Analytical work had already shown some over-design in the structural area and marginal design in the thermal area. The thermal analysis also showed that approximately 86 percent of the total thermal energy dissipated in a typical output regulator module comes from the output power semiconductors and output magnetics. It became evident that some other-than-usual scheme for heat transport was highly desirable — thus, heat pipe technology and application were explored, and ultimately incorporated into the SLCC design. A brief discussion of heat pipe operation follows.

The basic heat-pipe structure (Fig. 7) consists of a sealed tubular container enclosing a wick structure for capillary flow of the liquid added to saturate the wick. With the application of heat, some liquid vaporizes and flows to a cooler region, where it condenses.
The wick returns the condensate through capillary pumping action. Evaporation, condensation, and pumping of the liquid in a capillary wick are used to continuously transfer latent heat of vaporization from one region to another without external aids. Furthermore, due to the heat pipe's uniform construction, it does not matter which region is used for evaporation or condensation.

The process is essentially isothermal for moderate lengths because the vapor pressure drop between the evaporator and condenser is small. With a properly designed heat pipe, the temperature gradient between the heat source and heat sink can be very low, especially when compared with solid-metal conduction methods. Conduction of the 0.64-cm (0.250-in.) diameter heat pipe used in the SLCC is about 20 times greater than that of a solid copper rod of the same size, yet weighs only about one-fourth as much.

Depending largely on the compatibility of materials employed, heat pipes are potentially very reliable devices. For the SLCC application, a heat pipe constructed of 300 series stainless-steel felt wicking structure, and methanol working fluid was selected. Heat pipes using this combination of materials have been successfully life tested for continuous periods of more than 22,000 h at 110°C.

The heat pipe extends from the top of the output regulator module down through the base and into a grooved boss in the mainframe adjacent to the mounting boss that is the primary thermal interface for the SLCC.

To reduce the thermal gradient at the interface, a quick-release pivoted clamping device (Fig. 8) is provided in the mainframe to increase contact pressure between the heat pipe and mainframe chassis. The clamp is actuated by tightening the cam screw adjacent to the output regulator module mounting screw. To distribute forces more uniformly and preclude damage to the heat pipe, the heat-pipe clamp is faced with an elastomer.
deformation of the bracket and provide good thermal contact between the mounting bracket and chassis structure.

Application of heat pipe technology, careful considerations in locating thermal dissipators, and improved thermal interfaces have resulted in significant reductions in size and weight of the SLCC. Temperature reductions of up to 12°C in some critical areas has been realized and component hot spot temperatures have been minimized, resulting in increased converter reliability and life.

CONCLUSIONS

Development of the SLCC provides users with a flight qualified power converter which can be tailored to meet specific requirements by simple selection of the proper transformer and feedback resistor networks. The regenerative current feedback dc-to-dc converter, unique modular packaging concept, and advanced heat removal techniques all contribute to making the SLCC a lightweight, repairable, highly efficient, tightly regulated power converter.