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CHILLDOWN ELECTRICAL SYSTEM FOR S-IVB SPACE VEHICLE

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ABSTRACT

This paper presents the electrical system used to drive the chilldown motor pumps on the S-IVB space vehicle. This system consists of a 56 volt battery supplying power to the two three-phase solid state inverters which in turn drive two cryogenic motor pumps. Included in this paper is a short description of the overall chilldown system requirements. The advantages of the a-c system over the d-c system are discussed with emphasis on weight and reliability.

Two functionally identical 1.5kva inverters were designed. One inverter uses germanium transistors in the output stage while the other uses silicon transistors. Both inverters were designed to have a quasi-square wave output. The inverter circuitry is described and the advantages of each is discussed including a comparison of weight, size, operating temperature, efficiency and voltage rating.

INTRODUCTION

In the Saturn Program, the Douglas built S-IVB stage serves a rather unique role. The S-IVB is the second stage of the Saturn IB vehicle. In essentially the same configuration, it is also the third stage for Saturn V. In the Saturn IB mission, the S-IVB stage injects the payload into Earth orbit and provides attitude stabilization for the payload in orbit. In the Saturn V mission it must also provide escape velocity and initial control of the translunar trajectory, which requires restart of the engine during Earth orbit. The engine is a 200,000 pound thrust rocket engine built by Rocketdyne. Designated as the J-2 engine it uses liquid hydrogen (LH_2) and liquid oxygen (LOX) for propellants.

Prior to ignition, the J2 engine and its associated fuel lines must be chilled down to prevent gas bubbles from forming in the lines and engine during ignition. This gas formation, somewhat similar to a vapor lock in a car, would cause the main engine pump to cavitate and keep the engine from starting. To prevent this, liquid hydrogen and oxygen is pumped through the engine and feed lines. Figures 1 and 2 show the flow and pressure needed to chilldown the engine.

After careful consideration, it was decided that the most efficient way of performing the chilldown task was to develop a closed loop recirculating system where liquid oxygen and liquid hydrogen independently are pumped through the feed lines, the engine and back to the main tanks. A cryogenic motor pump would be used to recirculate the propellants.

LOX CHILLDOWN PUMP PARAMETERS

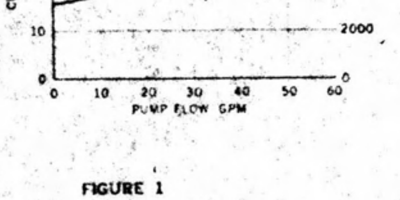

FIGURE 1

LH2 CHILLDOWN PUMP PARAMETERS

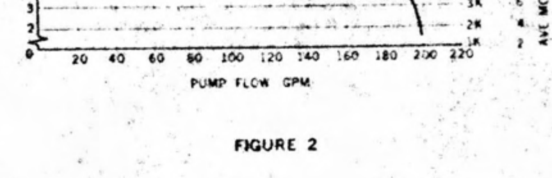

FIGURE 2

S-IVB 1410

SYSTEM WEIGHT

	2 CHILLDOWN PUMPS	BATTERY WEIGHT	2 INVERTERS	PRESSURE SYSTEM	TOTAL SYSTEM WEIGHT
A C SYSTEM	27 LB	40 LB	24 LB	6.5 LB	97.5 LB
D C SYSTEM	42 LB	40 LB	0 LB	13 LB	95 LB

FIGURE 3

The purpose of this paper is to describe the electrical system used to drive the recirculation motor pumps. The main features presented in this paper are:

1. The use of an a-c system utilizing solid state static inverters.
2. The use of a quasi-square wave driving an a-c motor without the use of an output transformer or filters.
3. Increasing the d-c battery voltage to 56 vdc.
4. The designing of two inverters, one with germanium transistors in the output stages and a "backup" unit using silicon transistors in the output stages.

Electrically there are two ways to drive the chilldown pump. One way is with an a-c motor and the other is with a d-c motor. At the time the project was proposed the state of the art in d-c brushless motors had not progressed to the point that a d-c brushless motor of the size needed was available. Therefore, all discussion of d-c motors will be of the conventional type. The advantages of both systems are:

D-C SYSTEM ADVANTAGES

1. More d-c experience than a-c/inverter experience (at non cryogenic temperature).
2. A d-c motor connects directly to the battery power source.

A-C SYSTEM ADVANTAGES

1. Safer - no spark generation. Will utilize a squirrel cage induction motor.
2. More cryogenic experience on a-c systems.
3. No brushes required (longer system life).
4. Higher calculated reliability.
5. No pressurization system on the LH_2 motor pump. The motor is run flooded in liquid hydrogen.
6. No shaft seal required on the LH_2 pump.
7. Higher system efficiency.
8. Smaller system transients - the inverter will limit in-rush currents.
9. A low current relay (1.5 ampere) can turn the inverter off and on instead of a high current motor relay (100 amperes peak starting).
10. Less EMI problems.

WEIGHT

The overall system weight comparison between the a-c and d-c system is shown in figure 3. While the weight of the two systems is almost identical, the reliability of the a-c system is almost double that of the d-c system (see figure 4). Combining the noted advantages with a longer operating life led Douglas to develop an inverter to drive the a-c motor pump for the S-IVB childown system.

BUS VOLTAGE

An analysis was performed of the electrical bus from which the chilldown system is supplied. It was found that substantial weight savings could be realized in both the inverter and the battery by using a 56 volt, rather than a 28 volt bus. It was subsequently decided to use a 56 volt electrical system on the S-IVB to supply power to the chilldown inverters.

In the final system it was decided to operate the LH_2 motor pump with the motor submerged in the cryogenic liquid. The LOX motor pump was operated with the motor in a pressurized helium container. The motor in both cases was an a-c cryogenic induction motor of approximately one-horsepower. The efficiency of the LH_2 motor is approximately 88% while the efficiency of the LOX is 82%. The motors drive the pumps at approximately 11,500 rpm, while operating from the 30, 400 cps quasi-square wave output from the inverter. While a

SYSTEM RELIABILITY

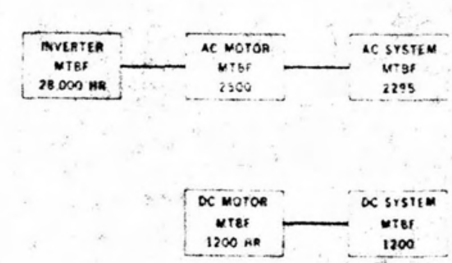

FIGURE 4

detailed description of the motor performance is beyond the scope of this paper it should be noted that theoretical and experimental investigations have shown that this type of voltage wave-form causes only slight additional losses in the motor.

INVERTER DESIGN

Design criteria for the inverter followed the standard for any component on a space vehicle. The unit was required to be of minimum size and weight with maximum efficiency and reliability. The design which fulfilled these four essentials utilized germanium transistors in the power stages. However, the environmental conditions in which the inverter would be required to operate had not been accurately established. Therefore, NASA requested a unit with silicon transistors in the power stages also to be designed. This inverter will be used for the flight vehicle if the temperature conditions are beyond the extremes in which the germanium transistors will operate.

These two inverters were developed simultaneously. Both are solid state devices employing a modular type of construction (see figure 5). The inverters are functionally identical, with the output capability of 1.5 kva at a frequency of 400 cycles per second. The weight of these inverters are 12 pounds for the germanium and 22 pounds for the silicon.

The quasi-square wave output voltage waveform which can be developed using switching techniques, has no even harmonics, and its lowest odd harmonic is the fifth (see figure 6). When the waveform is used to drive a wye connected motor, the quasi-square wave is combined to form a line-to-neutral waveform, also shown in figure 6. The lowest harmonic in this waveform is also the fifth harmonic.

CHILLDOWN INVERTERS

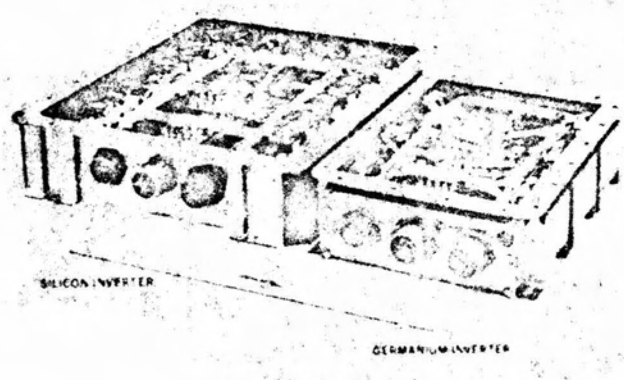

FIGURE 5

The inverters differ only in the output stages. The silicon unit uses eighteen 30-ampere silicon transistors. While the germanium inverter uses twelve 50-ampere transistors. A comparison of the two inverters is given below showing the advantages of each unit.

DESIGN COMPARISON

Physical Characteristics

Germanium	Silicon
Length: 12.0 inches	Length: 15.5 inches
Width: 8.5 inches	Width: 12.75 inches
Height: 3.5 inches	Height: 3.25 inches
Weight: 12 pounds	Weight: 22 pounds

Efficiency
(see figures 7 & 8)

Germanium	Silicon
96.0%	91.6%

Transistors
(see figure 9)

Germanium	Silicon
Output Stage: 12 each	Output Stage: 18 each
50 amps - 170 watts 3500 watts peak at V_{ce} = 70V T_j maximum = 110°C	30 amps - 250 watts 4500 watts peak at V_{ce} = 150V T_j maximum = 175°C

Operating Temperature Range
(Rated)

Germanium	Silicon
-65°F to 135°F	-65°F to 165°F
Breadboard tests have been performed over a range of -65°F to 165°F without a failure.	Breadboard tests have been performed over a range of -65°F to 195°F without a failure.

WYE CONNECTED WAVEFORM

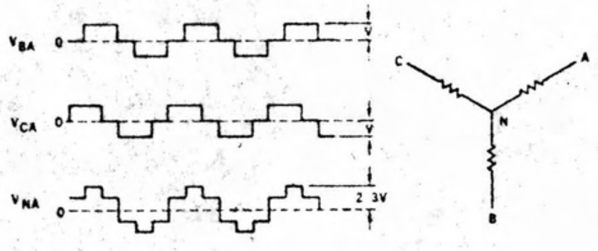

FIGURE 6

GERMANIUM INVERTER EFFICIENCY

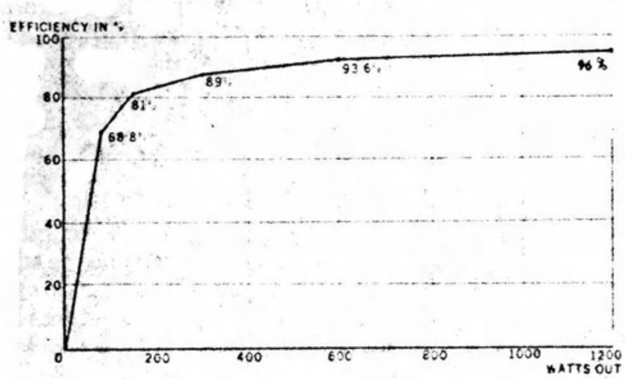

FIGURE 7

SILICON INVERTER EFFICIENCY

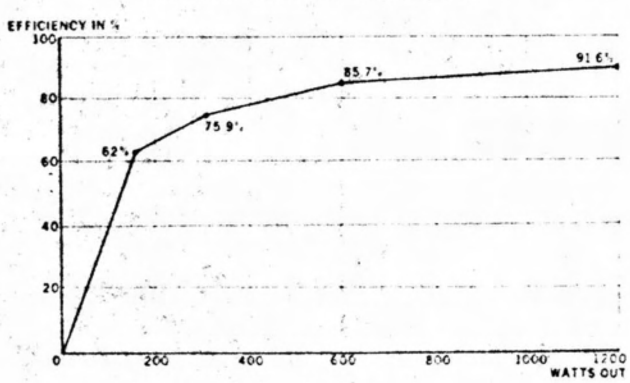

FIGURE 8

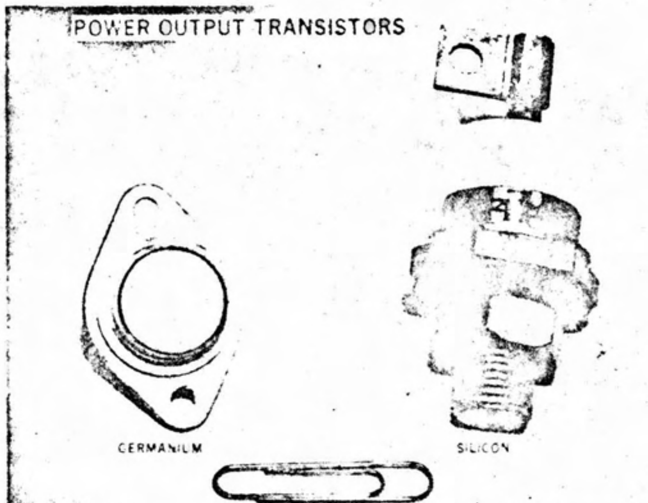

FIGURE 9

The block diagram of the two inverters is shown in figure 10. The following is a brief discussion of the function of each of the blocks.

INPUT FILTER

The input filter was incorporated in the chilldown inverter to suppress radio frequency interference. It is made up of ceramic capacitors connected to both the positive and negative input leads of the control and power lines, and terminated to the case of the inverter. These capacitors are used to attenuate the high frequency interference. There is a tantalum capacitor across the input power lines for suppression of low frequency interference.

REGULATOR

The regulator supplies a voltage to the pulse generator, timing circuitry, and bias winding of the current limit sense transformer.

CHILLDOWN INVERTER BLOCK DIAGRAM

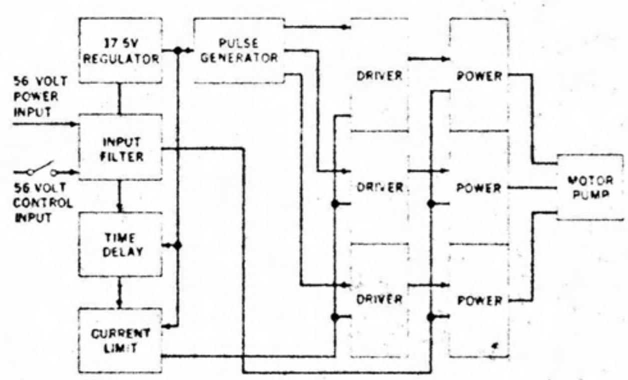

FIGURE 10

The regulator is a common dissipating type circuit. It includes a temperature sensitive device that is embedded in the oscillator transformer which varies the voltage output proportional to the temperature change of the cores. The oscillator frequency is maintained at 400 cps ± 1% due to the closed loop operation of the temperature device and the regulator circuitry.

THREE PHASE MAGNETIC PULSE GENERATOR

The pulse generator is a magnetic coupled multivibrator with a multi-core transformer. Its outputs are three push-pull square waves, 120° out of phase with each other, operating at a frequency of 400 cps. The explanation of its operation has been previously presented,[1] with the exception that the pulses are magnetically gated within the core instead of in a diode gate circuit.

CURRENT LIMIT

During the motor start condition, the inverter is required to drive approximately four times the nominal load. The current limit is needed to limit the peak current to a level below the maximum capabilities of the output power transistors. The output current is magnetically sensed and the inverter is turned off when a pre-determined level is reached. The inverter can be made to turn on when the current drops below this level or the off time can be set for a pre-determined length of time.

Figure 11 describes the transistor voltage and phase current waveforms during a typical motor start. The effects of the current limit circuit is clearly shown. Figure 12 shows the same waveforms after the motor has achieved running speed.

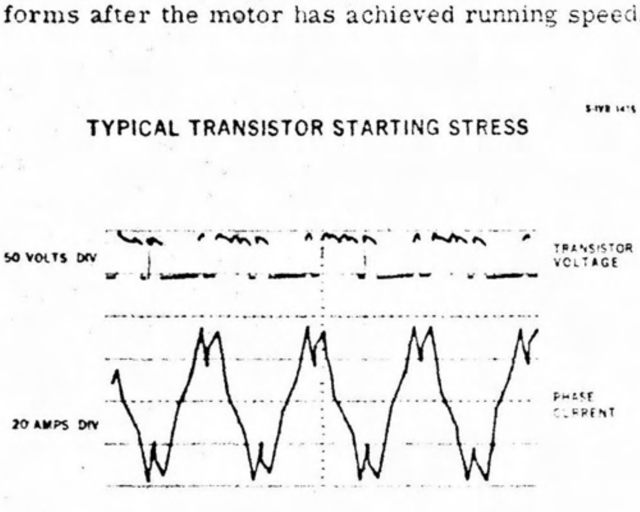

FIGURE 11

[1] D. W. Tesdall, P. E. Lorentzen, "MAGNETIC PULSE GENERATOR" A.I.E.E. summer session on June 17, 1962 at Denver, Colorado.

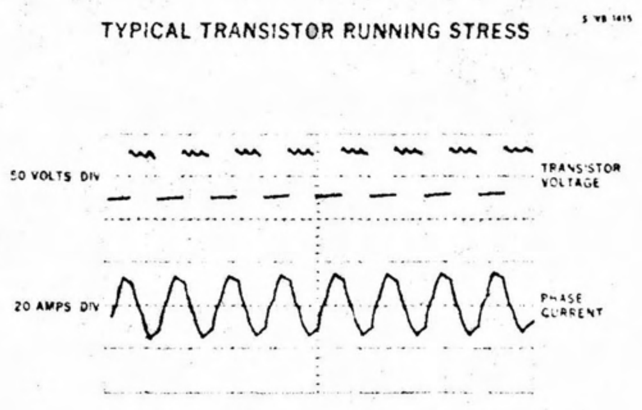

FIGURE 12

TIME DELAY

During the motor starting condition additional base drive is required for the output transistors. When the motor reaches operating speed the base drive can be decreased, thus reducing dissipation and increasing overall efficiency. The method chosen to accomplish the varying base drive requirements for motor starts and motor run condition is as follows.

The drive stages are normally operating at maximum output immediately upon the application of power. The full line voltage is applied to all the drive stages through a saturated series transistor, paralleled by a zener diode. After a predetermined period the timing circuitry activates and removes the base supply from the series transistor placing the zener diode in series with the source of voltage for the drive stages. The voltage applied will then be the original source voltage minus the zener voltage. This reduces the supply voltage to approximately one half of the value supplied through the transistor, and provides sufficient drive to saturate the output transistors in the run condition.

DRIVERS

The drive stages are straight forward transformer coupled push-pull square wave amplifiers, driven directly by the three phase magnetic pulse generator. The drive transformer is a "C" core design, operating in a nonsaturating mode. The "C" core design has an air gap which eliminates the possibility of the transformer saturating due to a voltage unbalance.

SILICON POWER STAGES

The output stage of the silicon inverter is a three phase bridge (see figure 13). Three transistors are paralleled at each position in the bridge to switch the load current. In this configuration the manufacturer specified a maximum of 25% current unbalance. The base drive is designed to saturate the power transistors for this worst case condition.

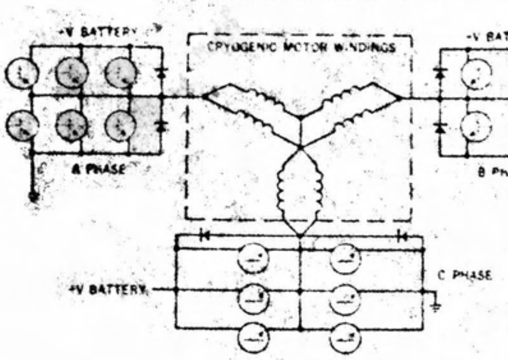

FIGURE 13

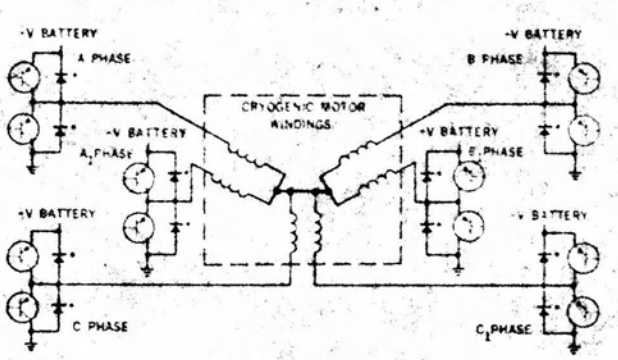

FIGURE 14

Diodes are connected across each set of transistors. Their function is to protect the transistors from the inverse voltage caused by reactive currents created in the load.

GERMANIUM POWER STAGES

The germanium power output stages of the chilldown inverter consists of two parallel three phase bridges driving the parallel wye motor (see figure 14). During the start condition the motor will draw a peak current of 80 amperes per phase at the nominal input voltage. This current is divided between the two windings in each phase. The transistors in the bridge circuits are thereby required to carry only half of the phase current. There are zener diodes connected across each power transistor. These diodes perform a two-fold function. In the forward direction, they handle the inductive currents, in the reverse direction or zener direction they protect the power transistors from an over voltage condition, which could cause a failure of the transistor.

The output transistor in the germanium inverter are all 100% tested, to remove early failures by acceleration of potential failure modes. The first test is a clamped inductance switching test to simulate the actual usage in the inverter, where the transistor must withstand average power pulses of 1400 watts for 100 microseconds, at a case temperature of 80°C. This power pulse is applied at 400 pulses per second for 5 second periods. After the transistors have successfully passed this test with the allowable changes in parameters, they are tested with a reverse bias to stress the junction surface conditions. Successful completion of this test is verified by parameter stability. After this test the transistors are put on a short life test to determine if degradation has occurred. Only when the transistor passes these tests, will it be used in the Germanium chilldown inverter.

CONCLUSION

The overall chilldown system as well as the advantages of an a-c and d-c system have been discussed. It was found that while the a-c system was slightly heavier in weight the reliability of such a system was almost double. It was found that a weight saving could be accomplished if the battery voltage was raised from 28 to 56 volts. To realize this saving, the battery voltage was increased to 56 volts.

Of the two inverters designed to drive the motor pump, the following was found, the inverter using the germanium transistors was approximately 45% lighter and 5% more efficient than the inverter using silicon transistors. The silicon unit will operate over a wider temperature range and has higher voltage rating than the germanium unit.

ACKNOWLEDGEMENT

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