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MODULAR SOLID-STATE INVERTER-CONVERTER SYSTEM

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16. Abstract

A modular approach for aerospace electrical systems has been developed, using lightweight high-efficiency pulse-width-modulation techniques. This report summarizes the basic system design and performance. With the modular approach, a required system power is obtained by paralleling modules. The modular system includes the inverters and converters, a paralleling system, and an automatic control and fault-sensing protection system with a visual annunciator. The output is 150 V dc, or a low distortion three-phase sine wave at 120 V, 400 Hz. Input power is unregulated 56 V dc. Each module is rated 2.5 kW or 3.6 kVA at 0.7 power factor.

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SUMMARY

The modular solid-state power conditioning approach to the design of aerospace electrical systems is discussed. An operating system using both dc-dc or dc-ac converters is described and the performance of these systems is summarized. Module output is either 150 volts dc or three-phase 120/208 volts, 400 hertz ac. The power rating is 2.5 kilowatts or 3.6 kilovolt-amperes at 0.7 power factor. An aircraft-type distribution subsystem, using mechanical contactors, is used. The module also includes an automatic control and fault-sensing protection system, paralleling circuits, and a control and monitoring panel which indicates operating conditions and faults and allows manual control. The circuits are forced air cooled breadboards. Efficiency, size, weight, and parts count are not optimized, but lightweight, high-efficiency techniques, such as high-frequency dc-dc conversion and pulse width modulation, were used.

INTRODUCTION

As the electrical requirements of spacecraft increase, the modular approach becomes a realistic solution to fulfilling the power conditioning requirements. Basically, the modular approach permits parallel operation of relatively low-power modules to form multikilowatt inverter or converter systems. The modular concept provides flexibility, reduced design time, and reduced cost through the use of standardized modules. Module replacement is also entirely feasible on manned missions.

A program was initiated to develop an experimental power conditioning system which could be used to study the modular concept. The power conditioner design was based on pulse-width-modulation and high-frequency conversion techniques.

Besides the basic power conditioners, a modular system includes a distribution subsystem, paralleling circuits, and a control and protection system. The power distribution system is based on aircraft electrical systems. A useful addition to the control and protection system, included in this program, is a control and monitoring panel which allows manual control and provides normal operation and fault monitoring. This report discusses the modular concept and summarizes the characteristics of this test system. References 1 to 3 discuss the individual subsystems in more detail.

The Westinghouse Aerospace Electrical Division designed and built two breadboard modules for the Lewis Research Center, under Contract NAS3-9429, which was technically directed by Francis Gourash. Each module contains an inverter-converter combination which produced either 2.5 kilowatts, 150 volts dc, or 3.6 kilovolt-amperes, 120-volt three-phase 400 hertz. The system was refined and tested at the Lewis Research Center.

MODULAR CONCEPT

The modular concept is essentially an advanced form of paralleling. Electric power generation in the past has relied heavily on paralleling because a single source could not provide the total power requirement. In aerospace power systems, paralleling is frequently used. Multiple generators are common, as well as multiple batteries where each battery typically contains many cells. Solar arrays and thermoelectric sources are often series-parallel connected.

In power conditioning, semiconductor limitations impose a limit on the power rating of a single power conditioner. Theoretically, series and parallel operation of individual devices can be used to obtain any desired power level, but there are practical limits to this approach. The modular concept as discussed in this report relies primarily on having a universal power conditioning module which can be easily adapted to construct many systems. Because it must be universal, the initial design and fabrication cost will be high. But relatively high production will reduce the average module cost. Also, design and development time is greatly reduced for new systems. System capacities can be altered without a major redesign by adding or deleting modules and in-flight replacement becomes feasible. System performance and reliability could also be improved because of the large number of modules being operated. And the long operating history of a standard module would result in continued improvement of the performance and reliability.

System power levels, performance, and particularly reliability are as dependent on the paralleling, and control and protection systems, as on the power conditioners. Reliability and power level are primarily dependent upon distributing the load among operating power conditioners and isolating defective components. In general, paralleling improves the power quality because the waveform and regulation characteristics of the power conditioners are averaged out.

The major components of this system are illustrated in figure 1. The power condi-

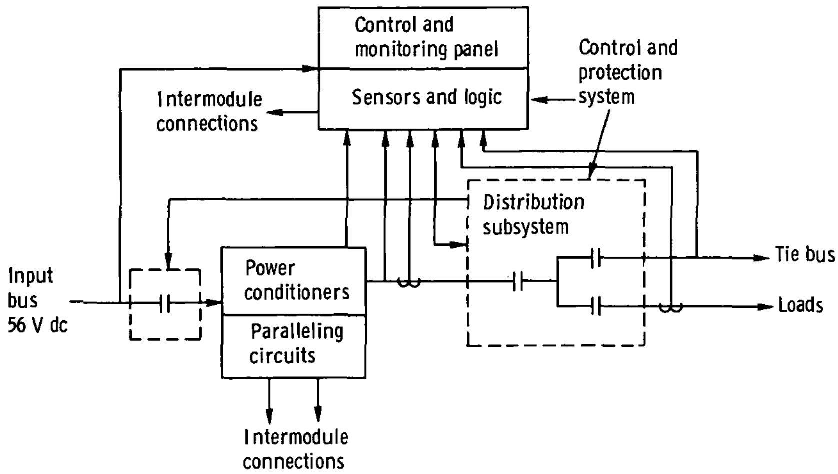

Figure 1. - Power conditioning module.

tioners produce either 150 volts dc or three-phase 400 hertz at 120 volts line-neutral. Much of the circuitry within the power conditioners and the control and protection system is used for either the ac or dc power system.

Power Conditioners

A block diagram of the power conditioner is shown in figure 2. Each three-phase inverter module (fig. 2(a)) consists of three identical single-phase inverters synchronized by a common clock signal. Each single-phase inverter consists of a dc-dc converter which provides voltage scaling and regulation, a dc-ac inverter, and control circuits.

For the dc-dc system, the inverter stages are not used, and the outputs of the converters are paralleled, as in figure 2(b).

Each converter is rated for 833 watts, and each inverter for 1.2 kilovolt-amperes. Therefore each module, consisting of three converters or three converters and three single-phase inverters, will supply 2.5 kilowatts at 150 volts dc, or 3.6 kilovolt-amperes at 0.7 power factor, 120 volts, 400 hertz. The design also allows for a 50 percent overload for 10 minutes.

Paralleling Circuits

The paralleling circuits, which are contained in the power conditioner control circuits, are connected into feedback loops of the power conditioners. The circuits sense

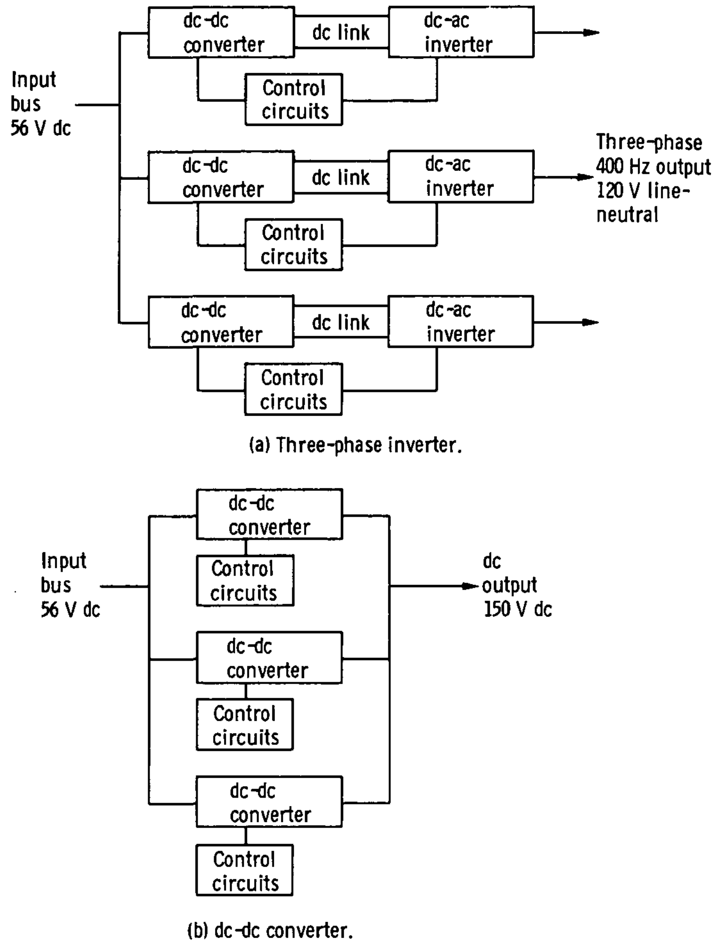

Figure 2. - Power conditioner block diagram.

output current unbalance and inject compensation signals into the voltage regulators. Each paralleling circuit requires only two connections between modules for sensing (six connections total for a three-phase module). Two synchronizing signals are also required in the ac system.

Control and Protection System

The control and protection system consists of a distribution subsystem, a sensor and logic subsystem, and a control and monitoring panel.

Distribution subsystem. - The basic distribution system, shown in figure 3, is based on existing aircraft systems. Associated with each power conditioner is a load bus contactor. Through this contactor, the power conditioner can be connected to an

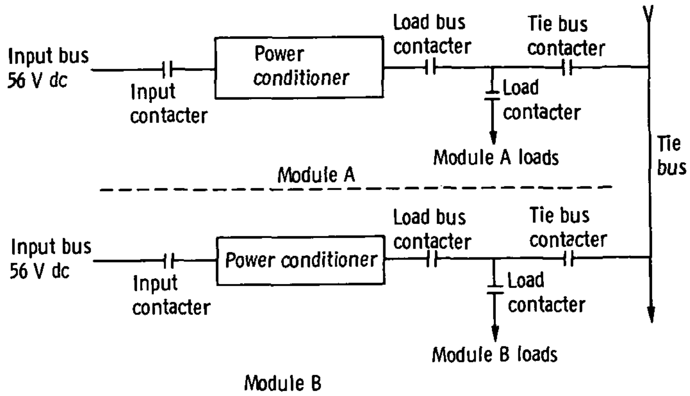

Figure 3. - Modular distribution subsystem.

independent load bus associated with each module. These load busses can be interconnected for parallel operation by closing the tie bus contactors. The loads are connected to the load bus so that they can be powered from the associated power conditioner or from the tie bus. The tie bus is used in both the ac and dc systems. The load contactor can be opened to disconnect nonessential or defective loads from the system. This general arrangement could be modified to provide multiple load busses, multiple tie busses, or critical load busses. A contactor is also located at the input of each power conditioner to disconnect it from the source if desired. The contactors can be controlled manually or automatically, as indicated later.

Sensors and logic. - A subsystem of the control and protection system, figure 4, consists of sensors and a logic system. Sensors used in a dc system detect overvoltage and undervoltage, load current and output current. Current unbalance among paralleled modules is also sensed, and an automatic parallel sensor determines if the tie bus voltage is within acceptable limits to allow switching the module onto the tie bus. Power conditioner output current and load current are both sensed so that power conditioner overloading and defective loads can be detected.

The ac system does not sense tie bus voltage. In addition to the other dc sensor functions, overfrequency, underfrequency, waveform distortion, and a synchronizing signal are detected.

The logic system is identical for the two systems. It accepts inputs from the sensors and from switches on the control and monitoring panel. An array of logic gates, flip-flops, and time delays determines the logic outputs. These outputs control the contactors, the paralleling circuits, and the monitoring panel. The proper sequencing of contactor closing to control startup, parallel operation, and fault isolation is completely automatic. A manual override is included to allow manual operation within the constraints of the protection system. A recycle circuit will reclose a tripped contactor

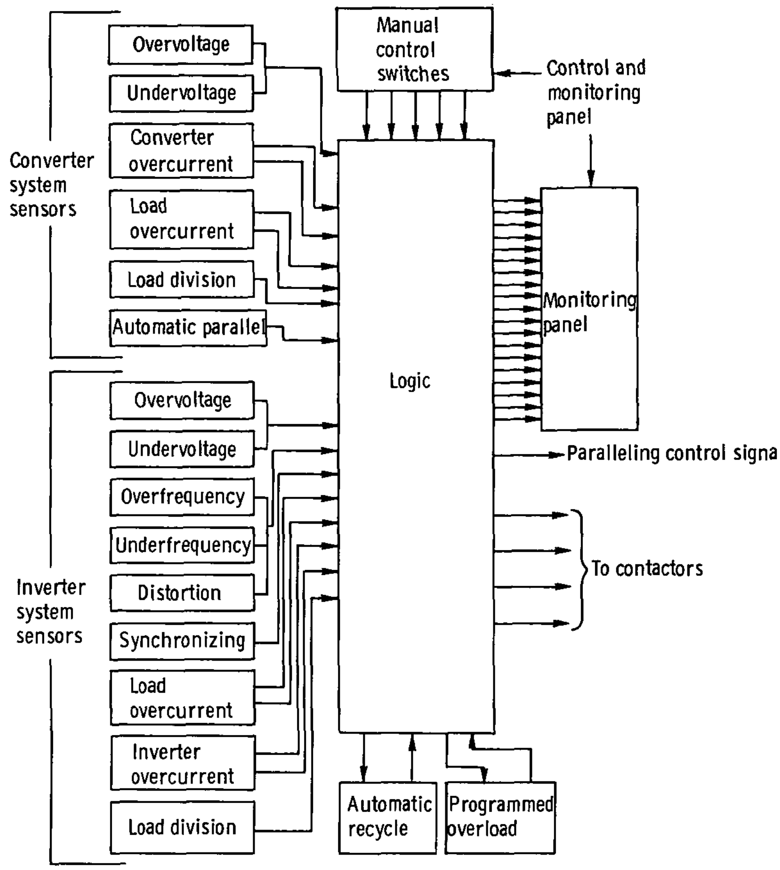

Figure 4. - Control and protection system.

twice to determine if the fault still exists before that contactor is permanently opened. Programmed transient overload tolerance is provided by delaying 10 minutes before tripping for overloads less than 150 percent, and 1.5 seconds for overloads greater than 150 percent. The power conditioners contain their own internal protection which limits the overcurrent to approximately 160 percent of rated current.

The control and monitoring panel interfaces only with the control and protection logic system. It indicates operating conditions (parallel or isolated, manual or automatic control), contactor positions, and faults. This panel is primarily a diagnostic tool, but it also serves as a control panel for manual operation.

In the manual override mode, the contactors in the distribution system may be opened at will, but the manual override will not allow a contactor to be closed unless the proper conditions are met for automatic closing of that contactor.

APPARATUS AND PROCEDURE

There are many important parameters required to evaluate a power system. Among these are size, weight, efficiency, output voltage distortion for ac systems, output ripple for dc systems, transient response, regulation, and reliability. Another important system parameter is continuity of power to critical loads, expressed in terms of voltage dips and overshoots, and complete power dropout during switching and fault clearing.

Tests were run on the breadboard modular system to determine some of these parameters. The two modules, rack-mounted and forced-air-cooled as shown in figure 5 were tested. The modules included the paralleling, control and protection, and distribution systems. A summary of the results is presented in this report. Additional data and the individual circuit analysis are available in references 1 to 3.

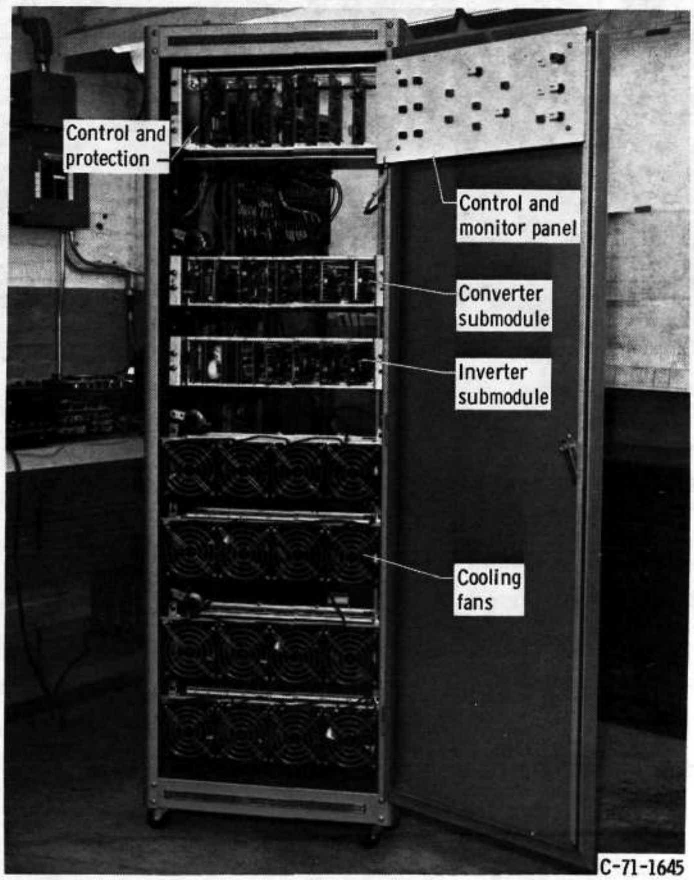

Figure 5. - Inverter module.

RESULTS AND DISCUSSION

Power Conditioner Performance

The primary advantage of high-frequency pulse-width-modulated conversion systems is the waveform purity which can be obtained without extensive filtering. Theoretically, all the large amplitude harmonic components in the output voltage of these inverters would occur in the area of 40 kilohertz or greater. Distortion at these frequencies can be reduced with small, lightweight, and efficient filters. The filtered output waveform shown in figure 6 contains three-quarters of a percent distortion. The

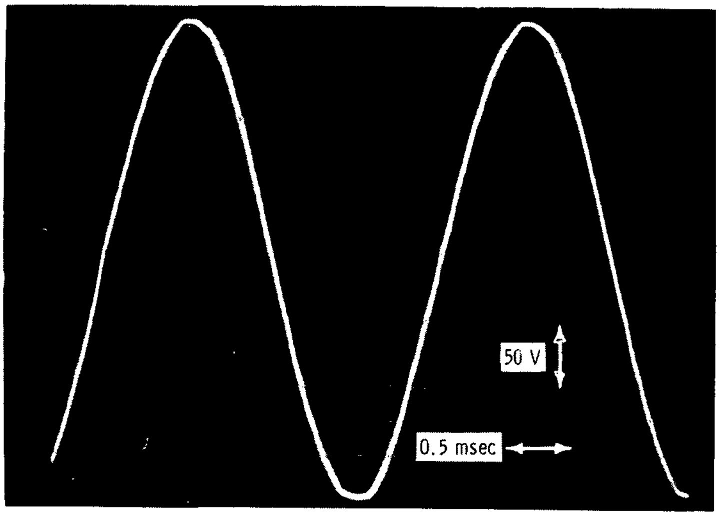

Figure 6. - Inverter line-neutral output voltage.

level of distortion is essentially independent of the load or power factor. The harmonic content of this wave is shown in figure 7.

The no load to 150 percent rated load voltage regulation of a single-phase inverter is shown in figure 8. The regulation is approximately $\pm 2\frac{1}{2}$ percent, and is essentially independent of power factor and input voltage. The independence of input voltage variation is obtained by injecting a signal proportional to the input bus voltage into the regulation loop which compensates for the inherent tendency of the output voltage to increase with increasing input voltage.

The dc-dc converter is overcompensated for input voltage changes, resulting in a decreasing output voltage at high input voltage. However, the no load to 150 percent rated load regulation is only ±1 percent. The regulation for line and load variations is $\pm 1\frac{1}{2}$ percent, as shown in figure 9. Both the inverters and converters have internal cur-

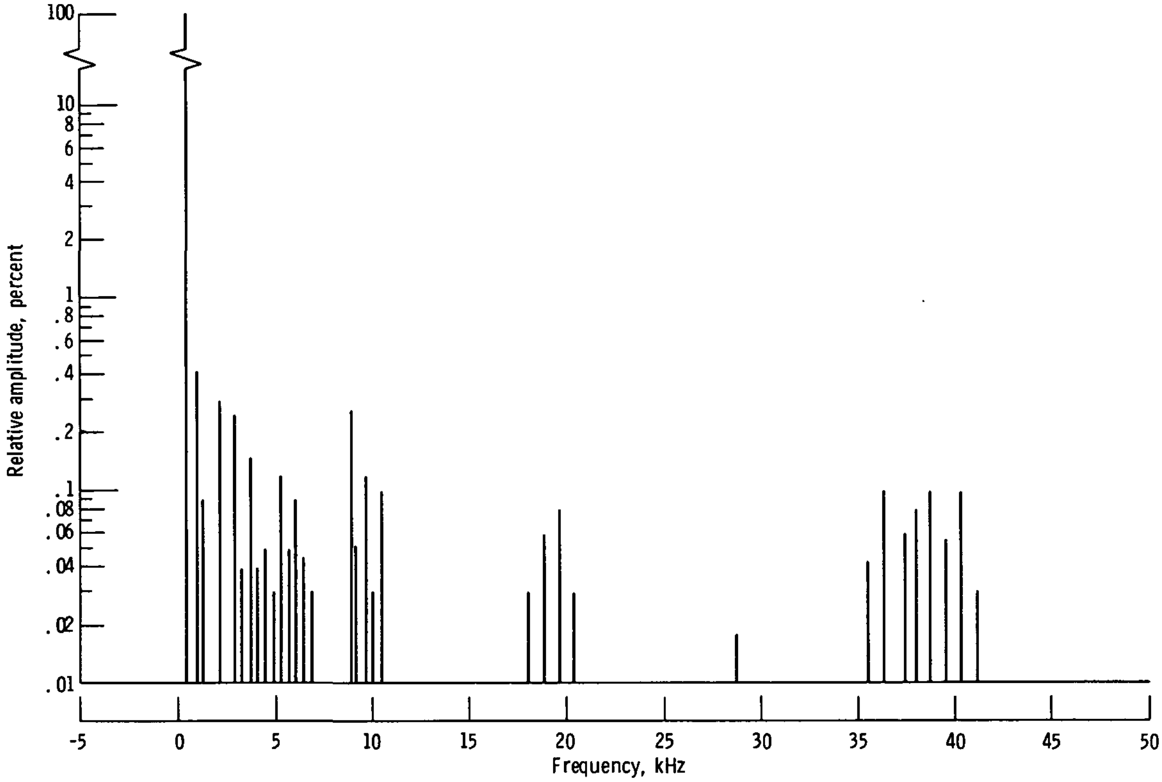

Figure 7. - Harmonic content of inverter line-neutral output voltage.

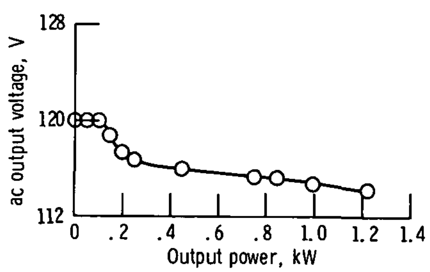

Figure 8. - Inverter voltage regulation.

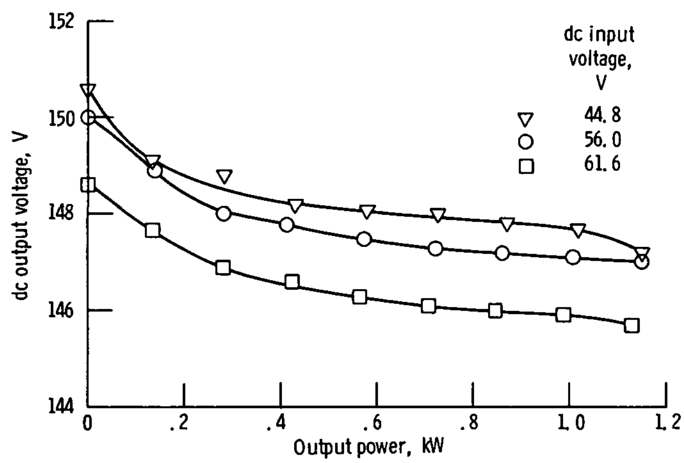

Figure 9. - Converter voltage regulation.

rent limits providing protection from overloads.

The full load efficiency of a single converter is 85 percent. A single-phase inverter consists of a converter and an inverter as shown in figure 2. The combined efficiency is 74 percent at full load.

As a complete module, including the control and protection system and the paralleling circuits, the inverter system has a full load efficiency of 72 percent at unity power factor. The converter system is 80 percent efficient. Figure 10 shows the module and power conditioner efficiencies as a function of load.

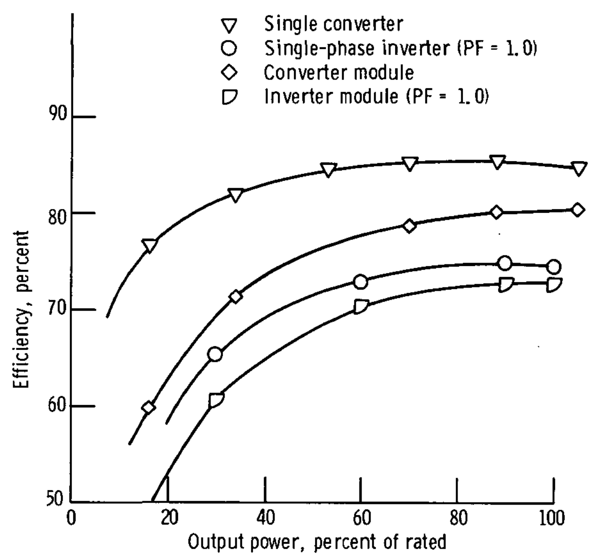

Figure 10. - Power stage and module efficiency.

Transient response of the power conditioners was determined for step load changes and recovery from short circuits. Figure 11 shows the application t_1 and removal t_2 of a 0.7 power factor full rated load on an inverter. The undershoot on load application was 60 volts rms, but recovery to within 10 percent was about 10 milliseconds. Load removal caused a 40 percent (to 170 V rms) overshoot and required 100 milliseconds to recover to within 10 percent. Recovery from a short circuit takes approximately 1 second, and has a 20 percent overshoot.

Control and Protection System Characteristics

The sensors in the control and protection system are required to sense only major faults. The sensors were therefore relatively inaccurate but simple. Major fault sens-

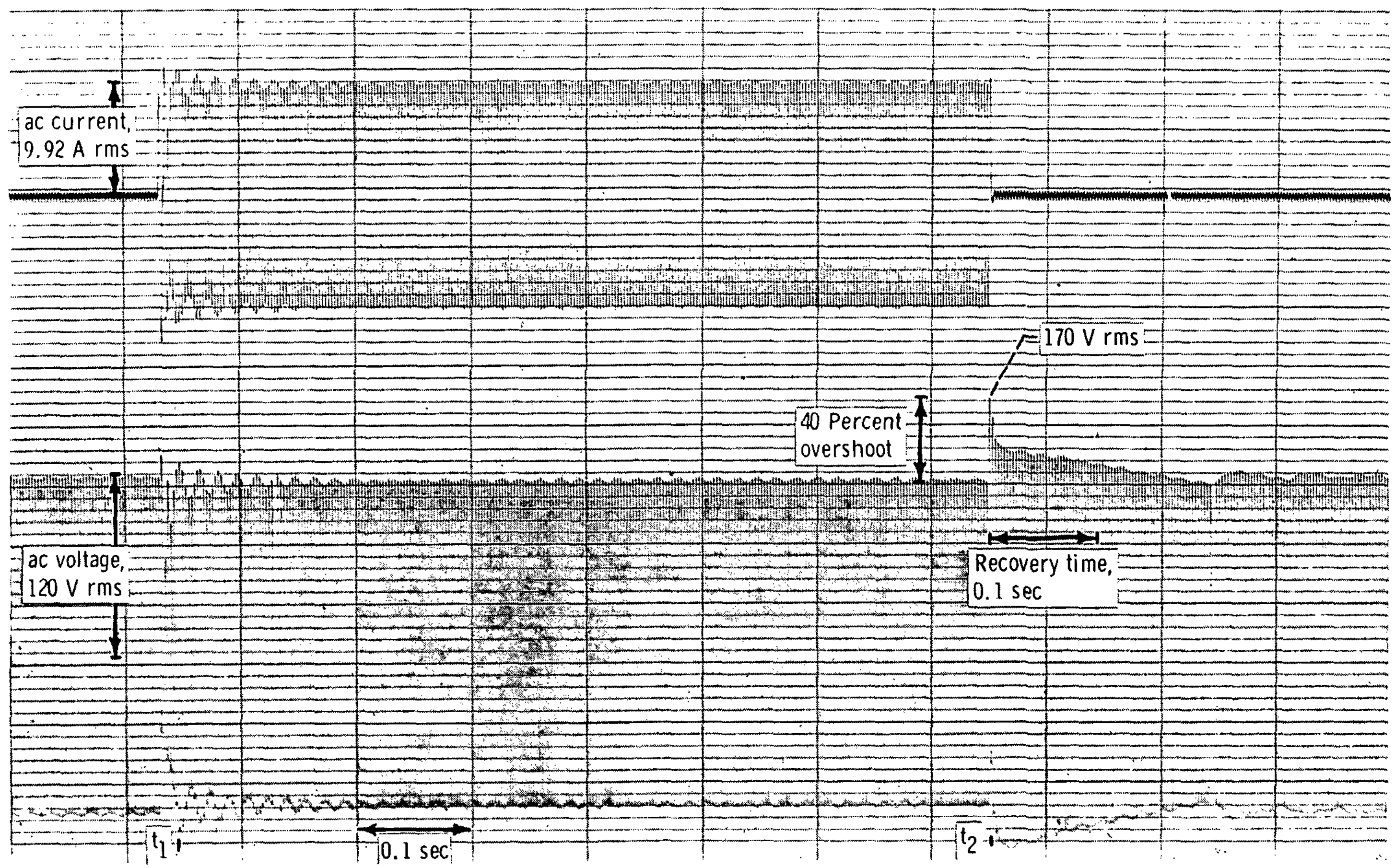

Figure 11. - Transient response trace of single-phase inverter module for step load changes of full rated load at 0.7 power factor.

TABLE I. - TRANSDUCER TRIP POINTS

Sensor	Trip setting	Difference from power conditioner design operating point
Inverter sensors		
Frequency reference protection	25 kHz	-35 percent
	40 kHz	+4 percent
Excessive ripple	42 V rms	Maximum 9.6 kHz ripple, 1.2 V rms
Abnormal frequency	388 Hz	-4 percent
	493 Hz	+20 percent
Abnormal voltage	135 V rms	+12 percent
	85 V rms	-29 percent
Inverter overcurrent		
110 percent sensor	11.5 A rms	+15 percent (+5 percent sensor error)
150 percent sensor	14.5 A rms	+45 percent (-5 percent sensor error)
Load overcurrent		
110 percent sensor	11.5 A rms	+15 percent (+5 percent sensor error)
150 percent sensor	14.5 A rms	+45 percent (-5 percent sensor error)
Load division protection	1.15 A rms	+17 percent load unbalance (+7 percent sensor error)
Converter sensors		
Abnormal voltage	135 V dc	-10 percent
	168 V dc	+12 percent
Converter overcurrent		
110 percent sensor	16 A dc	-4 percent (-14 percent sensor error)
150 percent sensor	21 A dc	+36 percent (-24 percent sensor error)
Load overcurrent		
110 percent sensor	17 A dc	+2 percent (-8 percent sensor error)
150 percent sensor	27.5 A dc	+65 percent (+15 percent sensor error)
Load division protection	1.5 A dc	+11 percent load unbalance (+1 percent sensor error)
Automatic parallel	168 V dc	+12 percent
	135 V dc	-10 percent
	22 V dc	-----------

ing is sufficient to protect the power conditioners. Table I lists the trip points of the inverter and converter sensors.

The logic used to control the contactors was sufficient to isolate any faults. In the case of multiple faults, however, some faults would be isolated without the correct recycle sequence. This is a safe mode of operation and the module could be restarted to recheck the faults.

Table II indicates the faults for which contactors are opened to clear the fault and the fault indicating bulb that is lit.

TABLE II. - PROTECTION SYSTEM RESPONSES

Fault	Corrective action	Indication
Frequency reference protection	Transfer reference to next module	Frequency reference protection light
Excessive ripple	Open input contactor and load bus contactor	Abnormal frequency light
Abnormal frequency	Open input contactor and load bus contactor	Abnormal frequency light
Abnormal voltage	Open input contactor and load bus contactor	Abnormal voltage light
Inverter or converter overcurrent without load overcurrent	Open tie bus contactor	Tie bus fault light
Load overcurrent	Open load contactor	Load bus fault light
Load division protection	Open tie bus contactor	Load division paralleling light

Besides the fault indicators, lights monitor all contactor positions and operating modes, such as isolated or parallel, automatic or manual, and inverter or converter operation.

Response time of the control and protection system is limited by time delays required to prevent unnecessary tripping because of noise or transients faults, and time delays are used to accomplish some logic functions. Therefore, time lags between the occurrence of a fault and corrective action are 1 to 4 seconds. Also, a 10-minute delay is incorporated for overcurrent faults of less than 150 percent of rated load to take advantage of the thermal capacity of the power conditioners. The power conditioners are internally self-protected so these relatively long response times are harmful only in terms of voltage dropout at the load.

Paralleling Circuit Performance

Transient response of the power converters is unaffected by the paralleling circuits because of the low gain and fast response of the paralleling circuits. Therefore, a large number of modules should be able to be paralleled. Three inverters or six converters were paralleled successfully. The load unbalance among power conditioners is less than 10 percent. Therefore, 90 percent of the rating of each module is used in figuring the system power rating. Each module in a paralleled system would be assumed to be able to produce 90 percent of its nominal 2.5 kilowatt rating or 2.25 kilowatts.

Physical Characteristics

The power conditioners for the 2.5-kilowatt breadboard dc-dc converter weighed 22 kilograms (48 lb) and occupied approximately 0.034 cubic meter (2100 cu in.). A three-phase inverter breadboard including the dc-dc converters weighed 48 kilograms (105 lb) and occupied 0.064 cubic meter (3900 cu in.). The figures include the heatsinks but not the fans. Considering the contactors, control and protection and paralleling circuits, a flight three-phase inverter module, with the converters, would presently weigh on the order of 50 kilograms per kilowatt (100 lb/kW). A converter module would be approximately 30 kilograms per kilowatt (60 lb/kW).

Breadboard parts count per single converter was nearly 400, and 750 total for a single-phase inverter. A three-phase inverter module, with the paralleling, control and protection, and distribution system is about 2900 parts. The parts count, size, and weight are for the first breadboard and could all be reduced significantly in an optimized design.

SUMMARY OF RESULTS

An operational modular solid-state power conditioning system has been described. The power conditioning modules, operating from 56 volts dc bus, produce either 150 volts dc, 2.5 kilowatts, or three-phase 400 hertz at 120 volts ac, 2.5 kilowatts, 3.6 kilovolts-ampere (0.7 power factor). The paralleling system included ensures load sharing within 10 percent. The control and protection system senses five parameters for the dc system and seven parameters for the inverter system. Startup, parallel operation, recycle capability for fault clearing and programmed overload tolerance are automatically controlled. A control and monitoring panel indicates normal operating conditions and faults and allows manual control of the distribution system. The distribution system isolates defective loads, power conditioners or buses, and maintains power to all functional loads despite individual inverter failures.

Voltage regulation was $\pm 2\frac{1}{2}$ percent for the inverter module, and $\pm 1\frac{1}{2}$ percent for the converter modules. The full load efficiencies were 72 and 80 percent, respectively, for the inverter and converter modules. Harmonic distortion was 0.75 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 19, 1973,
503-35.

REFERENCES

1. Gourash, Francis; Birchenough, Arthur G.; Pittman, Paul F.; Ravas, Richard J.; and Hall, William G.: Development and Performance of Pulse-Width-Modulated Static Inverter and Converter Modules. NASA TN D-6511, 1971.

2. Birchenough, Arthur G.; and Gourash, Francis: Analysis and Performance of Paralleling Circuits for Modular Inverter-Converter Systems. NASA TN D-6713, 1972.

3. Birchenough, Arthur G.; and Gourash, Francis: Control and Protection System for a Paralleled Modular Inverter-Converter Power Conditioner. NASA TN D-7279, 1973.

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