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ABSTRACT

Solid state remote power controllers (RPC's) are now available to control and protect all types of loads in both ac and dc power distribution systems. RPC's posess many outstanding qualities that make them attractive for most system applications. This paper reviews the present state-of-the-art and applications for solid state RPC's for both aerospace and terrestrial systems.

I. INTRODUCTION

With time, power generation and distribution systems have become increasingly complex and, in general, are increasing in power level. Many studies have shown that great advantages accrue when these systems are operated at higher voltages rather than at conventional 28 V dc and/or 115 V ac.(1,2,3,4,5) Savings in power distribution weight and I^2R losses at voltages up to 300 volts (dc or ac) have been projected at between 25 percent for the Space Shuttle Orbiter(2) and up to 50 percent for high power Space Stations(2) and for some military aircraft.(3) At equivalent voltage levels up to 300 volts, dc distribution systems have been shown to be lighter and more efficient than ac for most space flight and aircraft applications.(2,4,5) In addition, the simplicity of the dc system reduces paralleling and maintenance problems while minimizing corona and crew safety hazards.(5) As the power systems grow in power demand and size, there are continued efforts made to reduce system complexity, shorten power bus runs, and decrease the number of switching operations. Therefore, various multiplexed data bus systems with computer control have been proposed.

Critical to the realization of such power distribution systems, however, is the availability of remote power controllers (RPC's), which provide remote on-off switching, overcurrent protection, efficient operation, and maintain system power quality. Solid state RPC's are needed to provide well-defined, standard interfaces between power sources and loads for large, high voltage power systems. In addition, the RPC's are required to be compatible with the multiplexed data bus power management and control interfaces required for the larger power systems. In response to this need, considerable effort has been concentrated on the development of solid state RPC's that can be used for increased voltage dc and ac power distribution systems.

RPC's are solid state devices that combine in one unit the capability to perform all the needed functions of load switching, overload protection and a direct indication of whether the load is on or off. They provide total system protection of equipment and wires.

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RPC's are designed to be located near the load and communicate control and status information remotely via low level signals of a few milliwatts. Figure 1 shows a basic RPC in a typical application.

In addition, solid state RPC's possess several advantages that contribute directly to power system improvements. These advantages include:

- "Contactless" switching (no contact bounce, wear, or arcing)
- Controlled rates of current rise and fall
- Current limiting to provide protection from load transients
- Fast, precise, repeatable trip-out response
- Wide operating temperature range (-55° C to 100° C)
- Compatibility with all power sources, load types and computer control
- Electrical isolation of control/status signals from power bus
- Solid state reliability and ruggedness to vibration and shock

Internal dI/dt limiting in solid state RPC's provides essentially infinite surge capability without bulky inductors. This feature insures compatibility with most power sources and leads to compact, hybrid circuit packaging. Another feature of benefit to the power system is the demonstrated capability of solid state RPC's to meet all MIL-STD-461A requirements for EMI generation and susceptibility.

The capability of the solid state RPC's to provide superior control of load currents leads directly to reduced power system transients and improves power quality. The improved power quality reduces size and weight and increases reliability of power distribution equipment and loads. Small power sources, greater system manageability, and positive fault isolation are the result.

The purpose of this paper is to review the status of solid state RPC's, look at uses, and discuss technical perspectives. Some discussion of ac RPC's is included for completeness.

II. DESIGN AND OPERATION OF THE RPC

This section will describe some of the basic features of an RPC, its critical components and the two fundamental modes of operation of the device. As an introduction to the detailed design consideration, a brief description of the typical operation of an RPC is first presented.

A. Operation of an RPC

In the normal OFF state the control voltage is zero and all internal circuits in the RPC are powered down. There are no losses in the RPC unless bus voltage is applied. In this case the only loss is the product of bus voltage times the leakage current through the RPC, which is typically less than 1 milliampere.

To turn the RPC ON in a load circuit, bus voltage must exist at the power input terminal when a positive control voltage is applied to the control input. Refer to the block diagram of Figure 2 for this discussion. The control signal is optically coupled to the RPC logic circuits and an internal power supply. This supply steps down the high voltage from the bus to power the logic circuits at low voltage. With the trip and latch circuit and the "AND" and "OR" gates armed, the switch driver circuit is activated to turn-on the main power switch and energize the load in a controlled manner.

The time sequence of turn-on is the order of hundreds of milliseconds. The RPC sends back an "ON" signal for status indication. The magnitude of the load current is sensed to provide current limiting control and/or overload protection for the RPC and the wiring. In the event of a fault or overload condition the RPC senses the current values, compares it to a reference, and takes appropriate action. It may limit the current or integrate the current for a time and remain on if the overload is transient or short-term in nature. If the overload is large or long-term the RPC removes drive to the transistors, de-energizes the load, sends a "TRIPPED" status signal, and shuts down all circuits except the control/status. The RPC can be turned on again by applying another ON signal, but only after a preset time delay of several seconds.

B. RPC Power Switch and Drive Circuits

The greatest design challenge in the solid state RPC is the power switch, which must withstand applied faults at the load, i.e., between the power output terminal and ground. Under all turn-on, turn-off and fault conditions the power switch must maintain complete control of current to the load. For the worst case (shorted load) the power switch must handle power equal to maximum voltage times maximum allowable current for the time selected for current limiting or until a trip signal can be processed. Additionally, the switch must change quickly from the fully saturated state to a voltage blocking or current limiting state under overload conditions without passing transitional current spikes that would be damaging to the RPC. Therefore, because of their superior control capabilities under all load conditions, their faster switching speeds, and lower forward voltage drop, transistors are generally more desirable as power switches than any form of thyristor.

Several practical limitations place constraints on the power switch design. For reasons of safety and fail safe operation, the hot or ungrounded side of the load must be switched. When the hot side is positive, as is usually the case, a PNP transistor is preferable to an NPN, since a simpler drive circuit is required. If the hot side is negative, an NPN transistor is preferable for RPC's. Figure 3 shows the main switch Q_1 as a PNP. At 28 V dc PNP's are available and conveniently used. However, at 120 V dc or higher, PNP devices that meet RPC requirements are not available at this time. Therefore, an NPN transistor in a Darlington configuration is used for the higher voltage RPC's.

The Darlington circuit has been demonstrated to reduce complexity, cost, EMI and increase reliability when compared with other drive circuits. The Darlington typically has a high forward voltage drop of 1.2 volts or higher. However, the higher conduction loss is offset by lower losses in the drive circuit. Therefore, efficiencies can be maintained around 99%.

A distinct bonus of the Darlington switch configuration is its ability to operate near peak efficiency even when conducting less than rated load current. This occurs because power dissipation in the Darlington switch and drive circuit changes in nearly direct proportion to any changes in load current and in required drive current. Thus, for a given system fewer RPC models with different current ratings would be required to handle all current ranges in the system. A second bonus is the capability to extend the RPC's operating voltage range down to about 20% of the rated voltage (with a loss of efficiency, however).

C. Control and Trip Circuits

The purpose of the control circuit is to interface with low power external signals to provide on-off control, logic for trip free operation, and status indication. Opto-couplers interface with the power circuit and provide dielectric isolation between the low power control side and the high power bus side of the RPC's. The trip circuit monitors the magnitude of the load current and provides a trip signal to the control circuit. The trip time delay for overloads is generated by a linear circuit that approximates an I^2t requirement. Essentially, there are two types of control/status circuits that have been demonstrated: constant voltage control with current-sinking status and Solid State Electric Logic (SOSTEL) type control. The current sinking type is basically digital requiring three wires for control and status indicating. This type tends to be simplest and most cost effective. It also conforms to MIL-P-81653 and is easily compatible with either manual or computer control.[9,10,11] The second type, SOSTEL or analog, requires a constant current control supply and needs only two wires for control and status indication.[6] It tends to be more complex, slower and requires additional opto-couplers. However, it can communicate more information both ways. The amount of available information is limited only by the number of sensors, the noise and the accuracy of the system.

D. Fail-Safe Devices

The fail-safe device is placed at the power input terminal to open the power circuit and remove bus voltage from the RPC should the RPC fail shorted. Although not an internal part of an RPC, the existence of such devices is usually essential for most distribution systems since it represents the last ditch means of protecting the power distribution system in the event that the RPC fails or does not remove a fault. This requirement for higher voltage dc RPC applications became difficult to meet, since initially there were no devices available. After extensive testing, some ceramic fuses were found to be acceptable for RPC applications up to 300 V dc. However, 300 volts is presently the limit of available small fuses.

E. RPC Overcurrent Protection

Basically there have been three philosophies of overcurrent protection developed for RPC's to accommodate high inrush currents and short term overloads without nuisance trip-outs.[7] Each philosophy has led to a basic type of overload protection in RPC's with different current vs. time trip-out characteristics as shown in Figure 4. Each type is described in some detail below.

1. Inverse Current-Time or I^2t Trip-out. - The simplest type of overcurrent protection is the inverse current vs. time or I^2t trip characteristic shown in Figure 4(a). This trip curve is very similar to a conventional circuit breaker response curve, however, the solid state RPC response is much more accurate and reproducible. The I^2t = constant trip curve may be chosen to best protect specific power system wiring from damage.

For certain systems applications (such as bus or feeder control) and load applications having little or no inrush currents, RPC's without current limiting may be used. In this case the RPC would be designed to trip out "instantaneously" at some current value, such as 500% of rated current. Or, if the overload were less than the ultimate trip current level the RPC would trip according to some inverse current curve such as shown on Figure 4(a).

The principal advantages of inverse current-time, I^2t trip-out are: circuit simplification, lower requirements on the main switching transitor, and therefore, lower cost. The disadvantages are: lack of compatibility with high inrush loads (such as capacitor input filter) and a coordination requirement for series or parallel operation of many RPC's.

Under short circuit faults the RPC is required to hold the rate of current rise within limits for a few microseconds until a trip signal can be processed. A convenient method of providing the dI/dT limiting has been demonstrated. A feedback capacitor is inserted between the input terminal of the current sensing shunt and the base of the drive transistor. This causes the main transistor to pull out of saturation and produces short term current limiting as the capacitor charges toward the source voltage at a rate proportional to the RC value.

2. Basic MIL-SPEC Current Limiting. - The second type of current limiting is defined in MIL-P-81653 and is shown in Figure 4(b). In this case all fault or overload currents are limited at 125 to 150% of the rated current for about 3 seconds. If the fault still exists after 3 seconds, the RPC trips out. This type of circuit protection is conveniently used at lower voltages and is specified for the Space Shuttle RPC's.

In many designs of this type the current limiting is done with the main power transistor alone. This places some rather severe power dissipation requirements on the transistor itself. The Shuttle RPC uses a unique form of current sharing in four transistors during current limiting.

This type of current limiting protects system wiring and prevents load transients from passing throughout the entire electrical system. The 3 second trip-out time protects the RPC from excessive heat generated during current limiting. At higher bus voltages, however, it becomes difficult to find transistors with sufficient safe operating area (SOA) to be used in this type of current protection. This fact plus certain load characteristics make a third type of protection attractive, one that combines advantages of both the first two types.

3. Current Limit with I^2t Trip-out. - The current limit with I^2t trip-out method of overcurrent protection shown in Figure 4(c) incorporates portions of the two methods previously described. Current limiting is provided at 300% of rated current for 0.1 second with trip-out. Overloads below 300% but above 120% of rated current trip-out according to an I^2t trip curve. Overloads just above 120% trip-out in a time usually less than 10 seconds. It should be noted that there are other parameters that could be chosen for current limiting depending on circuit needs and component limitations. The 300% for 0.1 second current limit matches most conceivable load types and inrush characteristics

As mentioned before, some form of current sharing is required during the current limiting interval, especially at voltages over 100 V dc. Of interest here is the technique of using a passive helper circuit to dissipate the excess energy and effectively boost the safe operating area (SOA) capability of the main switching transistor. Referring again to Figure 3, we illustrate a passive helper, SOA boost circuit. For purposes of discussion Q_1 and Q_2 are shown as PNP transistors, but as noted before represent Darlington switches in higher voltage RPC's. During normal operation Q_1 is fully saturated and carries essentially all of the load current. During current limiting Q_2 is saturated and as the voltage across Q_1 increases, current (and hence power) is diverted from Q_1 to the relatively low cost resistors, R_1 and R_2. This eliminates the need for one or more large, relatively expensive, transistors in parallel with Q_1 to absorb excess energy during current limiting. The circuit will limit load current to the desired level even though currents I_1 and I_2 may be changing. That is, at any instant in time, $I_1 + I_2 = I_{load}$ = constant, during the current limiting interval. Obviously, the lower the values of R_1 and R_2 the more effective the boost becomes.

III. RPC DEVELOPMENT STATUS

RPC development efforts have been carried out at a number of voltages for both dc and ac power systems. Several 28 V dc and 115 V ac RPC's have been fully developed and are operational. Since this paper is concerned primarily with higher voltage dc, primary emphasis will be placed on the 120 V dc and 300 V dc RPC development with the Shuttle RPC's at 28 V dc and the B-1 aircraft RPC's at 230 V ac discussed for comparison. For convenience, each RPC under development is presented separately.

A. 28 V dc RPC

The Space Shuttle Orbiter contains over 500 RPC's in six ratings from 3 to 20 amperes.[8] The RPC's are designed to operate from a nominal 28 V dc generated by fuel cells. The six ratings are constructed in three package sizes in a hybrid micro-electronic configuration and encased in hermetically sealed bolt down packages with stud-type terminal posts. Figure 5 shows a cut-away drawing of the Shuttle RPC. The Shuttle RPC's feature current limiting with controlled turn-on and turn-off rates. A special drive circuit responsive to load current reduces power dissipation especially at partial loads.

Of special interest is the fact that these RPC's are 4 terminal devices. The use of a common ground for power and control precludes an isolation interface between the control and power circuits. Status indication is not provided by the RPC itself. However, load voltage status signals are hard wired between loads and input/output interfaces for the computer. This monitoring is not done for all loads. All solid state power controls and higher control voltages with well defined hysteresis eliminates noise and transient susceptibility and generation without requiring the comlexity of isolation. Reference 8 discusses the RPC design, evaluation and results in considerable detail. A few of the more significant parameters are:

Operating Voltage: 24 to 34 V dc

Current Ratings: 3A, 5A, 7.5A, 10A, 15A, 20A

Current Limiting: 125 to 150% of rated current

Overload Trip Time: 2 to 3 seconds

Rise and Fall Times: 0.3 to 6 milliseconds

Control Voltage: 5-7 V (OFF) and 9-12 V (ON)

Control Current: 10 mA maximum

The packages range from 3.8 x 3.8 x 2.3 centimeters high weighing 77 grams to 4.8 x 4.8 x 3.1 centimeters high weighing 142 grams. They are mounted to a liquid cooled cold plate maintained between -4° C and 52° C. The RPC's are mounted in unsealed sections of the Orbiter and, therefore, are exposed alternately between space vacuum and atmospheric pressure on each mission.

B. 120 V dc RPC

Of significance for 120 V dc applications is the development of three types of RPC's with two types having 5 ampere current rating and one type a 30 ampere rating. All three types have a coordination of trip characteristics to permit series/parallel operation of the RPC's in a distribution system. They control and distribute power at 600 Watt and 3.6 kW levels with demonstrated efficiencies of 98.5 to 99.0 percent at rated loads. Hybrid versions of all three types have recently been manufactured and fully tested. They are hermetically sealed and fully capable of flight applications in space. Figure 6 is a cutaway of a 120 V dc RPC with current limiting. The package sizes range from 4.4 x 4.7 x 2.0 centimeters high weighing 100 grams for Type I to 5.5 x 7.1 x 1.9 centimeters high weighing 203 grams for the Type III.[9,10]

An NPN Darlington configuration is used as the basic switching and control element in the 120 V dc RPC's. The current limiting version (Type I) uses a passive helper circuit for an SOA boost as shown in Figure 3. The ultimate current, I^2t trip-out versions, Type II and Type III, rated at 5A and 30A, respectively, are similar but less complex since the helper circuit and associated sensing and logic circuits are eliminated. The 30 A RPC, however, has required 10 switching transistors in parallel to handle and dissipate the power under fault conditions in a hybrid package.

The Type I RPC is current limiting at 3X (three times rated current) for 0.1 second followed by an I^2t trip time. RPC Types II and III have instant trip current levels at 5X and 3X, respectively, and an I^2t trip current level for fault currents below the instant trip level. A very simple linear circuit was used to approximate the I^2t trip time functions.

These RPC's use the constant voltage, current-sinking signal for on-off control and status indication. Two opto-couplers interface with the power circuit and provide 1000 V ac, 60 Hz, dielectric isolation. ON, OFF, and TRIPPED status are identified on the status indication.

Since the Darlington power switch is used, these RPC's have excellent partial load efficiency with a steady state operating voltage range from 25 to 132 V dc. A most important benefit of the RPC switch design was that it permitted a universal circuit design that led to a standardization of the control and drive circuits for all types. From this point extensions of the design have been made to higher voltages, such as 270/300 V dc. Actually, in principal the design will accommodate any voltage for which transistors and other components are available. A few of the significant specifications are given below:

Operating Voltage: 25 to 132 V dc

Current Ratings: 5 A and 30 A

Current Limiting: 300% for 0.1 second

Load Protection: Inverse trip time, $T = 0.9(25-I)/(I-6)$ for Type I, $T = 0.011(150-I)/(I-36)$ for Type III where I is load current

Rise and Fall Times: 0.05 to 1 milliseconds

Control Voltage: 13 - 14 V (ON) and 12 - 13 V (OFF)

Control Current: 10 mA maximum at either 15 or 28 V dc

Efficiency: 98.5 to 99% with self power from 120 V dc power bus

Fail Safe: Compatible with load protection and a 4000+ A surge from source

Operating Ambient Temperatures: -55° C to 100° C

Table II shows a performance summary of two 120 V dc RPC designs.

C. 270/300 V dc RPC

Two ratings were selected for 270/300 V dc RPC's. The first (Type I) is rated at 1 A and provides fault current limiting at 3 A for 0.1 second. The second rating (Type II) is 2 A with instant trip out for fault currents of 5 A or more. Both types have I^2t overload protection. These RPC's have greater than 99% efficiency, controlled rise and fall times, use a Darlington NPN power switch and are compatible with both a current sinking and a SOSTEL type control/status indication.[11,12]

The significant performance requirements for the 270/300 V dc RPC's are listed below:

Type I:

- Voltage Rating: 80 V dc to 300 V dc continuous transients per MIL-STD-704B
- Current Rating: 1 ampere
- Voltage Drop: 1.5 V dc maximum at rated load
- Load Protection: Inverse tripping time, T, to the relationship $T = .09(5-I)/(I-1.2)$ seconds for $I > 1.2$ amps.

- Current Limiting: 300 ± 30% for .1 sec
- Efficiency: 99% with self power obtained from the HVDC power bus
- Control/Status: To conform to SOSTEL requirements.
- Fail Safe: To be compatible with load protection and with source capability of 4,000 amperes short circuit
- Operating Ambient Temperature: -55° C to + +100° C

Type II:

- Same as the Type 1 RPC with the following exceptions
- Current Rating: 2 amperes
- Load Protection: Inverse tripping time, T, to the relationship T = .025 (10-I)/(I-2.4) seconds for I > 2.4 A
- Control/Status: 28 V/10 mA dc control and sinking-type status

To accomplish these specifications required that special attention be focussed on three areas of development: power switch, power supply and fail safe devices. As mentioned earlier after an extensive search and evaluation program some acceptable ceramic body fuses were qualified.

Of significance, also, was the search for an NPN power transistor to meet the RPC requirements. There are none on the market capable of current limiting with 150 Volts and 1.5 amperes simultaneously with a 600 V rating. However, a large area power transistor(13) under development was found to be adequate with enhanced current gains, sufficient SOA capability, and a collector sustaining voltage of 600 V. An alternative version was constructed for the power switch using 5 or more transistors in parallel. The basic disadvantages in the parallel design were in complexity and some loss of current gain.

Another area of concern was a power supply for the internal circuitry. It was recognized that the passive series regulator approach used at 120 V dc was unusable if the 99% efficiency goal was to be met. Several circuits were considered with a pulse width modulator regulator selected.

Table III shows a summary of the 270/300 V dc Performance data with both versions of the power switch. The RPC has been demonstrated to be:

- Compatible with a diversity of sources and loads including resistive, lamp, motor, inductive and capacitive
- Compatible with electrical system power quality per MIL-STD-704B and ±1000 V spike transients
- Capable of providing either current limiting or instant trip fault protection
- Capable of interfacing with either current-sinking or SOSTEL controls
- Consistent with design practices leading to hybrid assembly capability

D. 230 V ac/400 Hz RPC

Flightworthy prototypes of power controllers rated at 1.5 A and 230 V/400 Hz for use on the B-1 aircraft electrical load distribution system have been built and evaluated. The RPC are designed to interface with the Electric Multiplex (EMUX) control system under development by the Air Force.(14,15) Two designs have been demonstrated, one using transistor switches and the other SRC's, which are competitive for ac applications using zero crossing turn-off. Tradeoff studies are still underway to select a design and adapt it to printed circuit card construction. Several controllers can be mounted together in a sealed case and installed on a B-1 aircraft.

Some of the significant performance specifications are listed below:

Operating Voltage: 208 to 244 V ac rms

Current Ratings: 1.0 or 1.5 A

Overload Protection: Ac per MIL-P-81653 limits

Turn-on Time: 5 to 15 milliseconds

Turn-off Time: 5 to 15 milliseconds

Control Voltage: 4.0 V (ON) and 2.0 V (OFF)

Control Current: 10.0 mA max. @ 6.0 Volts

Fail Safe: 640 amperes peak

Operating Ambient Temperatures: -54° C to 71° C

The RPC designs have been evaluated for EMI, temperature-altitude, random vibration, and load-life. Present effort is being directed to reduce the designs to flight hardware for installation on future B-1 test vehicles.

IV. RPC APPLICATIONS

The Navy's SOSTEL (Solid State Electric Logic) and the Air Force's EMUX (Electric Multiplex) systems are examples of emerging control and management techniques for power distribution systems. As previously stated these system concepts are depending on the use of solid state (RPC's) to provide remote on-off switching, overcurrent protection, maintain system power quality, and interface with computers.

A. Distribution Systems

Various studies have examined the benefits of RPC's for distribution systems. A British study evaluated the redesign of a large civil aircraft, the VC10, using solid state RPC's and solid state logic.(16) They concluded that 91 kg or 14% of the wire weight could be eliminated just by changing to RPC's. An additional 78 to 113 kg could be trimmed by redesigning equipment to match solid state RPC's and using a multiplexed data transmission system. Total weight savings were estimated at 25 to 30% in the transmission system on the aircraft.

A Navy study(3) compared a standard 115 V ac, 3 phase transmission system with a higher voltage dc system. They determined that a 345 V dc transmission system using a ground return would give a reduction in weight of wiring, number of wires, and in I^2R losses to one third their present value. Even compromising to

230 V dc because of some disadvantages at 345 V dc would result in roughly 50% savings in both wire weight and I^2R losses on the WF-2 and F4J aircraft. The utilization equipment at high voltage dc appeared to give very little improvement in either weight or efficiency, but the simplicity of the dc system would reduce paralleling and maintenance problems.

As part of the NASA space vehicle technology development, TRW systems performed a comprehensive study of power distribution systems.(2) Their results pointed to many significant advantages for 115 V dc systems when compared to either 28 V dc or 115 V ac. Specifically, they showed that for the Space Shuttle a 25 to 30% reduction in I^2R losses and total power distribution weight could be made if 115 V dc were used rather than either 28 V dc or 115 V ac. For a large Space Station (80 kW total power) the I^2R losses and weight could be reduced by 50%.

B. AC Applications

There have been many RPC's developed for 115 V ac and as previously discussed two designs developed explicitly for 230 V ac.(14,15) Of interest is the fact that both the 120 V dc and the 300 V dc RPC's with minor modifications offer significant advantages for ac systems. These advantages have been demonstrated to provide subcycle control and current limiting of inrush transients and overloads. The dc RPC is connected within a bridge rectifier. With the addition of as few as seven parts to the dc RPC's, ac RPC's are available for 115 V ac and 230 V ac systems. Therefore, one basic RPC could be built for both ac or dc at a given voltage rating with suitable terminals provided externally.

C. Other Applications

1. Solid state RPC's have great potential for assembly lines and process controls where millions of operations are required. Their load compatibility, immunity to transients, low EMI susceptibility, and potential use for ac as well as dc are unique benefits.

2. Solid state RPC's provide "contactless" switching with no arcs or sparks for use in volatile environments with explosive gases present such as in mining operations.

3. In both terrestrial and spaceflight use of solar power generation with battery storage RPC's could be used to control and protect loads and improve power quality.

V. RPC PERSPECTIVE

It is useful at this stage in the development of solid state RPC's to evaluate present technology limitations and indicate what improvements in components, circuits and design approaches could extend the technical limits and reduce cost. An evaluation has been completed to address these questions and define areas of development yielding RPC's with increased ratings or other improvements and lower cost.(12) The effort was directed to assess the factors that limit further increases in voltage, current and power ratings. In addition all items that affected efficiency, reliability, parts-count, cost, size and weight were also evaluated. The primary areas of consideration included:

- Circuit Approaches
- Components
- Interfaces
- Fabrication Techniques
- Packaging

Circuit approaches and components are obviously the most critical areas that affect voltage, current and power ratings.

The basic component setting technical limits for the RPC is the NPN transistor power switch. With NPN transistors now becoming available at 600 V with adequate safe operating areas, 300 V dc RPC's could handle 2 A with current limiting and up to 7.5 A with instant trip. This assumes one switching transistor and the RPC meeting MIL-STD-704B surge and transient voltage requirements. Voltage rating could be raised to 400 V dc. Higher current and power ratings could be obtained by paralleling transistors, however, a single transistor improves efficiency and reliability while reducing parts count and cost.

Several other improvements have been noted that raise some of the limitations on RPC's:

- Refinement of circuit techniques and a grouping of RPC's with a common internal power supply would improve power ratings and increase efficiency by 0.2 to 0.3%.
- Increased use of monolithic IC's for the control, sensing and logic functions decreases parts-count, improves reliability, and reduces cost.
- Optical isolators need improvement especially for use in hybrid packages giving increased reliability.
- Improved fabrication and packaging techniques both with hybrid assembly and PC board construction using monolithic IC's are needed to reduce cost substantially.

Finally, solid state RPC's could be used with solar array power sources up to 400 V dc with the simple additions of a hold circuit and a trip lock out circuit with under voltage detection. These circuits are required to preserve operational capability should the array voltage drop to zero under a short circuit. Consideration of 5 A and 10 A are possible with one or more large NPN's under development, with paralleling of PNP's in the driver circuit, and finding fail safe devices compatible with system requirements.

VI. CONCLUSIONS

The development of solid state RPC's has progressed systematically to the applications state at various voltage levels for aircraft and space flight. On a system basis today, an all solid state power electronics distribution system appears to be competitive or better than its electromechanical counterparts in efficiency, weight, reliability and cost. The soft turn-on and turn-off of solid state RPC's give significantly improved power quality and better equipment reliability. This, coupled with their high efficiencies, reduces source power requirements and eliminates additional EMI and transient protection components.

The complete compatibility of the RPC's with all sources, types of loads, and multiplexed computer control is a distinct asset. Compliance of the RPC's with the power quality of MIL-STD-704B makes them ready for system applications. Their overall system compatibility clearly opens doors for a wider range of applications at increasingly higher power levels in aerospace and in nonaerospace systems as well.

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TABLE I. - DESIGN GUIDELINES FOR SOLID STATE REMOTE POWER CONTROLLERS

Characteristic	Requirement	Advantage to system
"Contactless" switching with positive control	Solid state/transistor	Reliability, long life, fast response, low EMI, and transient voltages
Darlington switch (used at higher voltages)	Eliminate transformer-oscillator; simplify power circuit	Fewer parts, lower costs, weight, EMI, higher partial load efficiency, wider operating voltage range
Current limiting	3X for 0.1 second plus I^2T limit or 1.5 x for 1 to 3 seconds	Reduce wire size, lower EMI, handle loads with high inrush currents
Non-current limiting	5X instant trip plus I^2T limit	Simpler, less costly, compatible with many load types
Controlled rate turn-on and turn-off, dI/dt limiting	Rate of rise less than 0.35 A/μsec (2.5 V/μsec) with no inductors	Reduce transient voltage and EMI generation, less weight and volume, adaptable to hybrid circuits
Trip response	Fast, accurate, and repeatable over temperature extremes	Smaller wire size, smaller power sources, improved power quality
Low level remote control/status;	5, 15, or 28 Vdc control, current sinking status, or SOSTEL control with dielectric isolation	Shorter power bus runs, compatible with computer control, excellent transient voltage isolation
Series/parallel operation	Coordination of trip characteristics	System compatibility, controlled startup and load shedding

TABLE II. - PERFORMANCE SUMMARY OF THE 120 VDC REMOTE POWER CONTROLLERS

	A. Original design, transformer-oscillator drive			B. Simplified design, Darlington drive			
Item	Type I	Type II	Type III	Type I	Type II	Type III	Units
Current rating	5.0	5.0	30.0	5.0	5.0	30.0	Amperes
Voltage rating	120.0	120.0	120.0	120.0	120.0	120.0	Volts dc
Operating voltage range	80 to 132	80 to 132	80 to 132	25 to 132	25 to 132	25 to 132	Volts dc
Turn-on voltage	7.5	7.5	7.6	13.5	13.9	13.4	Volts dc
Turn-off voltage	7.4	7.4	7.5	12.6	12.0	12.2	Volts dc
Turn-on time	105	120	150	700	900	1400	Microseconds
Rise time	85	35	145	50	50	90	Microseconds
Turn-off time	80	270	112	1450	660	2000	Microseconds
Fall time	65	35	50	600	260	900	Microseconds
Voltage drop at rated load	0.39	0.50	0.72	1.15	1.16	1.3	Volts dc
Power dissipation at rated load	8.62	6.63	36.5	7.83	6.84	41.8	Watts
Efficiency at rated load	98.55	98.85	98.96	98.7	98.7	98.8	Percent
Current limit level	15.0	N.A.	N.A.	14.5@120 Vdc	N.A.	N.A.	Amperes
Current limit ripple	0	N.A.	N.A.	0	N.A.	N.A.	Amperes
Incandescent lamp start capability	775	275	635	700	300	---------	Watts
Fault response time	1.0	3.0	5.0	3	3	5.0	Microseconds
Peak fault current	18.0	68	140	53	60	111	Amperes, peak
Number of electrical components	138	117	120	81	78	86(96)	Parts
Cost of electrical components, based on 1974-100 piece quantities	225	103	119	79	57	75(108)	$

TABLE III. - PERFORMANCE SUMMARY OF 270/300 VDC REMOTE POWER CONTROLLERS

Item		Temp. °C	Type I 1A/270V	Type II 2A/270V	Units
Dielectric Test		25	OK	OK	
"On" Dissipation	A B	-55 to 100	1.98 - 2.67 1.65 - 2.05	4.29 - 5.27 3.73 - 3.96	Watts
"On" Efficiency	A B	-55 to 100	99.0 - 99.3 99.2 - 99.4	99.1 - 99.3 99.3 - 99.4	%
"Off" Dissipation	A B	-55 to 100	.38 - .47 .39 - .47	.34 - .44 .34 - .43	Watts
Turn-On Time	A B	-55 to 100	370 - 770 300 - 470	300 - 500 50 - 60	μsec
Rise Time	A B	-55 to 100	85 - 110 75 - 90	70 - 80 270 - 340	μsec
Turn-Off Time	A B	-55 to 100	540 - 2100 500 - 1450	800 - 3700 450 - 2200	μsec
Fall Time	A B	-55 to 100	490 - 1450 400 - 1050	650 - 2700 370 - 1900	μsec
S.C. Peak Let-Thru Current	A B	-55 to 100	27 20	33 33	Amps
+1000V Spike Test		25	OK	OK	----
-1000V Spike Test		25	OK	OK	----
OV Transient Test		25	OK (350V, 400V & 470V)	OK (350V, 400V & 470V)	----
UV Transient Test		25	OK (275V, 175V)	OK (275V, 175V)	----
Incandescent Load Capability		25	100% Rating (1A S.S.)	40% Rating (.8A S.S.)	----
Motor Load Operation		25	1.5A S.S./7A peak in rush	1.5A S.S./7A peak in rush	----
Breaker Load Operation		25	.6A/.1 Sec in rush OK	.6A/.1 Sec in rush OK	----
Maximum Load Capacitance		25	740 (Calc'd)	7	MFD

Note: The "A" designation refers to the version using several NPN transistors in parallel and "B" refers to the version using one large NPN power switch.

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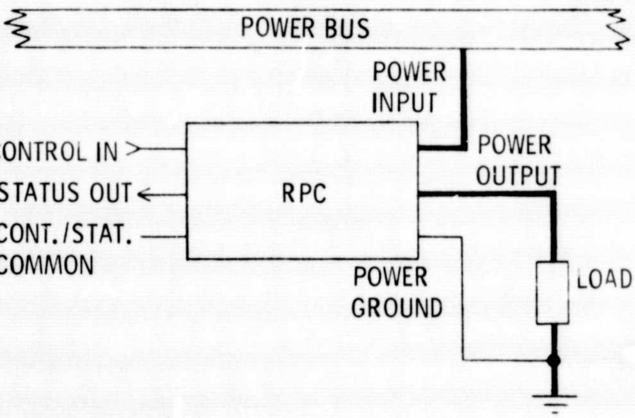

Figure 1. - Basic RPC in a typical application.

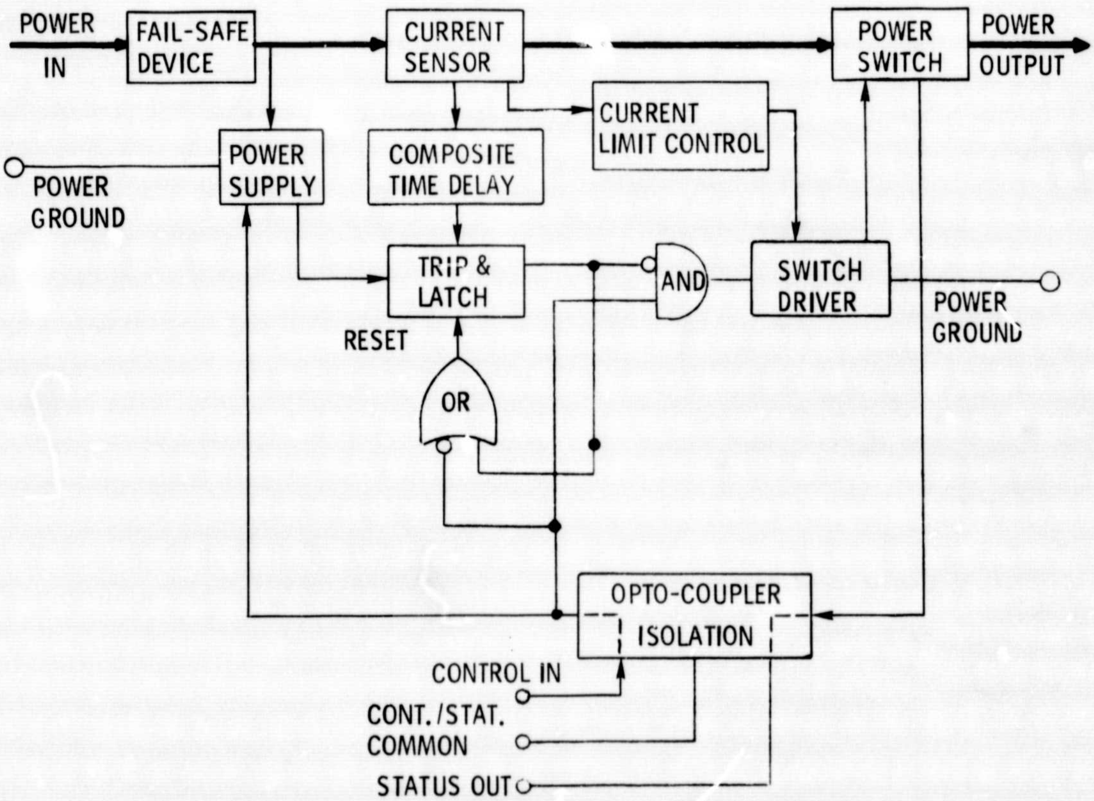

Figure 2. - Block diagram of an RPC showing each basic function.

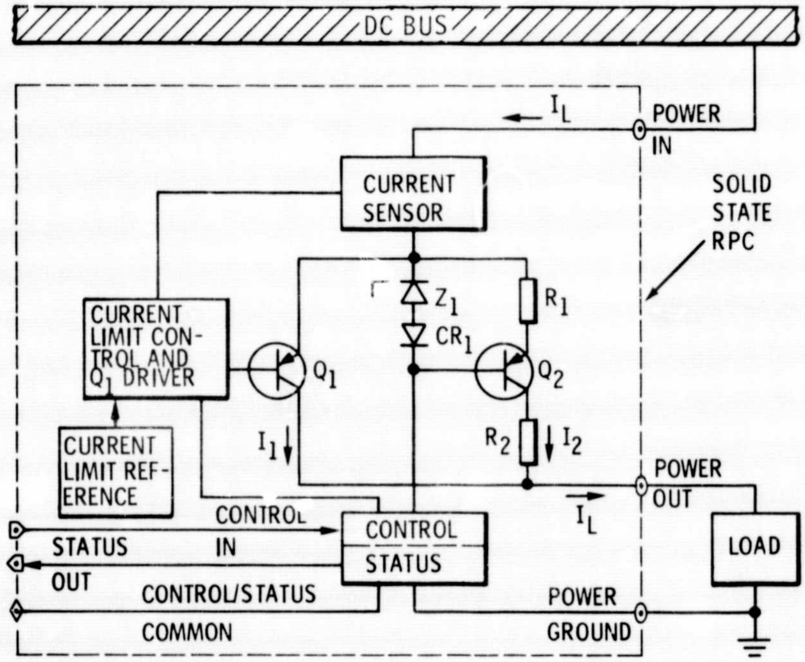

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Figure 3. - Basic RPC in a typical application using a Safe Operating Area (SOA) booster circuit for current limiting.

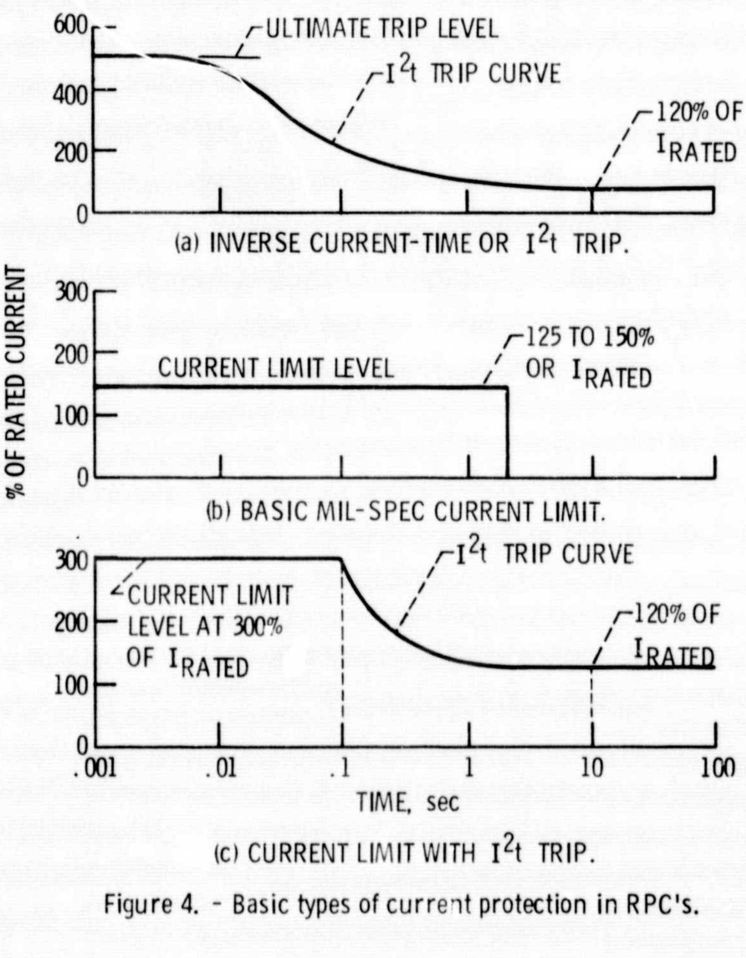

Figure 4. - Basic types of current protection in RPC's.

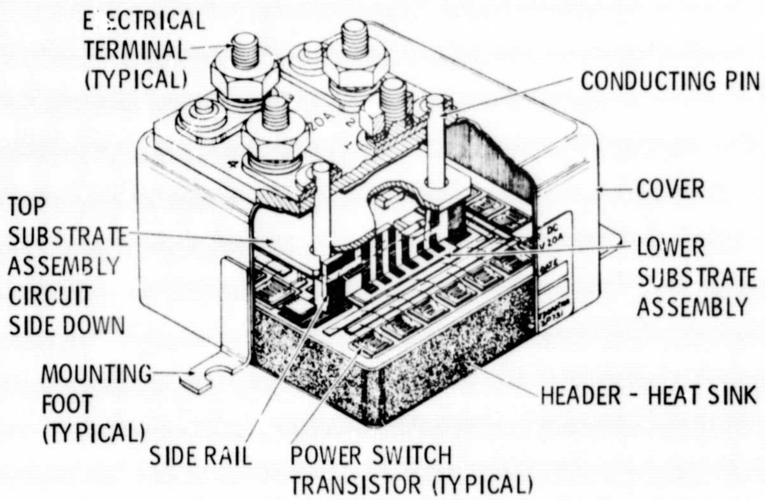

Figure 5. - Cutaway view of a Shuttle Orbiter 28 V dc remote power controller.

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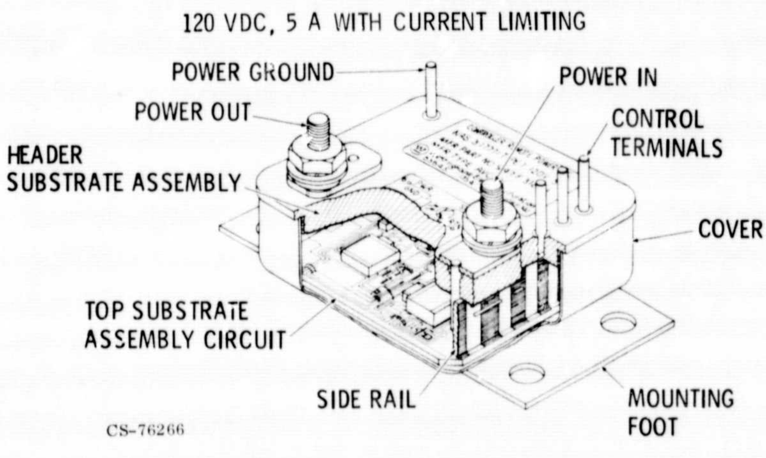

Figure 6. - Cutaway view of a packaged, hybrid 120 V dc remote power contrcller.