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THREE-PHASE, HIGH-VOLTAGE, HIGH-FREQUENCY DISTRIBUTED BUS SYSTEM FOR ADVANCED AIRCRAFT

Robert C. Finke
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

The NASA Lewis Research Center is developing higher voltage, higher frequency components for spacecraft. The technology is directly applicable to aircraft power-generating systems except that aircraft systems are about an order of magnitude larger than spacecraft systems.

For this paper the following assumptions were used: The system is generic. Everything is powered from the generators. If all the switches were turned on at once, the load would be 500 kVA. The distance from generator to load can be 250 ft. All generators and motors are inherently alternating-current machines. There is no such thing as a brushless direct-current motor. It's an alternating-current motor with electronic commutation. There is also no such thing as a direct-current generator. Alternating-current generators with rectifiers are used. All of the systems are inherently alternating current, and anything else requires hardware to be added to the system.

Figure 1 shows the system model. The model is simple: it has a generator and some level of current and voltage. The current and voltage multiply together to give the total power. All of the diodes, transistors, etc., are represented in the circuit by a forward voltage drop across the diode. There is also resistance of the line, connectors, etc. And finally, the load.

Forward voltage drop in semiconductors is relatively constant. It varies from about 1 to 2 V depending on whether the semiconductor is a silicon-controlled rectifier or a transistor and on what kinds of voltages and currents are going through it. But if there are many diodes in the line, as the system voltage goes down, the wattage lost through forward voltage drop goes up (fig. 2). In a system with a large number of semiconductors the loss curve begins to flatten out around 300 V. That is, the system losses due to all the semiconductors start getting appreciably lower.

For cable with a 2-percent loss, system weight increases significantly (fig. 3). At about 50 V it becomes excessive. For this reason, and because the semiconductor losses are lower there, high voltages would be preferred. To be able to use higher voltages in power systems, semiconductor devices with adequate ratings must be available.

The following components are available for use in aircraft power-generating systems:

(1) High-current power-switching transistor D7ST (fig. 4). The D7ST is the successor to the D60T, which Westinghouse is now producing under a NASA contract. The D7ST features are a voltage of 400 to 500 V at a current up to 150 A, with 400-A peak, and power of 50 kW. Its rise and fall times are 0.75 μsec with a 4-μsec storage time. It can therefore be used in a relatively high-frequency converter to switch high power levels. Although it is a fairly impressive device, it can be improved.

(2) Augmented power transistor. This transistor is in the development stage. The contract specifications are a voltage of 800 to 1000 V, current of 70 to 112 A (gain of 10) with a 400-A peak, power handling of 75 kW, power dissipation of 1.25 kW at 75° C, rise and fall times of 0.5 μsec, and storage time of 2.5 μsec. This device can also be used in power inverters or switches at high voltage and high power.

(3) Fast-recovery, high-voltage power diode. A 1200-V diode with a 50-A forward current (fig. 5) has been developed by Power Transistor Corp. under contract to NASA Lewis It is a fast diode, with reverse recovery time of 200 nsec. The applications in a system are myriad and include rectification, protection, filters, and clippers.

For higher-voltage systems, up to 1000 V, corona breakdown could be a problem. In a Boeing report done for Wright-Patterson AFB by William Dunbar, corona initiation voltages ranged from 1200 V at 40 000 ft to 400 V at 80 000 ft (fig. 6). With commercial aircraft flying around 40 000 ft, the higher voltages look pretty reasonable for power distribution.

Figure 7, produced by James Triner of NASA Lewis, shows efficiency and weight versus frequency for a 50-kVA transformer with advanced materials. As with voltage, as frequency increases there is a significant drop in weight and around 10 kHz the curve starts to flatten out. However, at that frequency the efficiency has alredy begun to decrease. A little under 10 kHz is a good frequency at which to do inversion and perhaps distribution because the magnetics are maintaining their efficiency but their weight is substantially reduced.

Figure 8 is a comparison of transformers for space and commercial uses. Both are 25-kVA, single-phase transformers. The commercial pole transformer weighs 400 lb, is 97.9 percent efficient, has a voltage of 120/240 V, and has a high voltage of 3850 V. The space transformer has the same power-handling capacity but at a frequency of 20 kHz instead of 60 Hz. That makes a sizeable difference. And it has also been designed extremely carefully from a thermal standpoint. The pie windings are shaped and fastened to aluminum plates for heat removal. Another paper in this conference, by Gene Schwarze of Lewis, describes this transformer technology and its characteristics. The weight difference is also significant - 400 lb at 60 Hz as compared with 7 lb at 20 kHz. The space transformer is also more efficient (99.2 versus 97.9 percent) and has a lower temperature rise.

The type of distribution system selected for an aircraft power system can have a substantial effect on the conductor weight as shown in table I. A two-wire, direct-current system has been selected as the base and allotted a weight of 100 percent. A very substantial weight reduction can be had by going to the three-wire Edison system. The two three-phase, alternating-current systems both exhibit a weight savings over the base. However, the three-phase, four-wire wye shows the largest gain even with a full-size neutral.

NASA Lewis has done research on remote-power-controller technology. The driver for this technology, however, is the semiconductor device, so we first need big enough, fast enough, semiconductors to make and break the circuit. Figure 10 shows early solid-state, remote power controllers (RPC's) developed for use in the space shuttle. These are 28-V RPC's at various sizes, 3 to 5 A up to 15 to 20 A. The next generation of remote power controllers (fig. 11) have voltages up to 120 V dc and currents to 30 A. They were developed by Westinghouse.

Figure 12 shows a Lewis-developed high-voltage, high-power circuit breaker. The figure shows the breadboard and a schematic of the system. The load-switching transistor has been the technology driver. Only recently have 1-kV transistors been developed to go into this circuit. But this circuit breaker has been built and tested. It has been used primarily with the electric propulsion systems. Ion thrusters use a 1-kV screen drive at several amperes. And this circuit breaker has been used as the main bus-interrupt for electrical propulsion systems. So it has been tested in that sort of application and now the technology is ready for other applications.

The following characteristics are recommended for aircraft power-generating systems:

(1) High voltage distribution. High voltage of about 200 to 300 V reduces conductor weight and reduces the effect of semiconductor drops. This provides a lighter and more efficient power system. Corona does not appear to be a problem at these voltages for any aircraft.

(2) Alternating-current distribution. Since all rotating machinery generates or consumes ac power, it appears to be most efficient and simple to distribute the power in that form. In addition, it is much easier to interrupt alternating current than direct current.

(3) High frequency distribution. Frequencies in the range of 10 kHz cause a substantial reduction in the weight of magnetics while still providing a relatively high efficiency.

(4) Multiphase distribution. A three-phase distribution system provides a substantial reduction in conductor weight. It can also be very low in radiation.

TABLE I. - EFFECT OF SYSTEM ARCHITECTURE ON CONDUCTOR WEIGHT

System	Weight, percent of baseline
Two-wire dc (baseline system)	100
Three-wire Edison	37.5
Three-phase delta	75
Three-phase, four-wire wye (neutral, full size)	33.3

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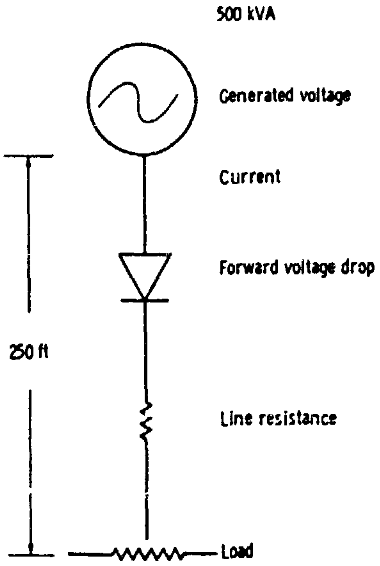


Figure 1. - System model.

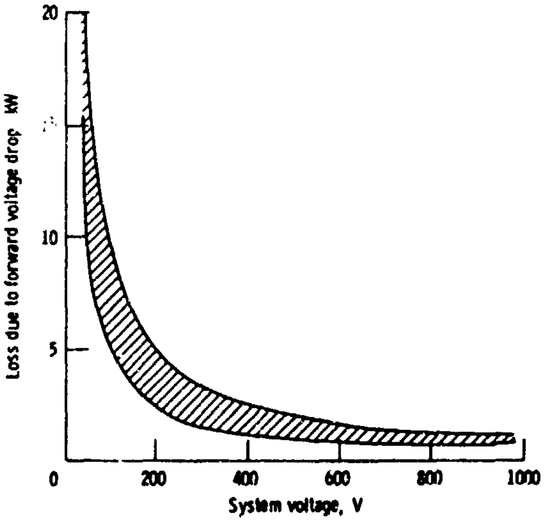


Figure 2. - Loss due to forward voltage drop as a function of system voltage.

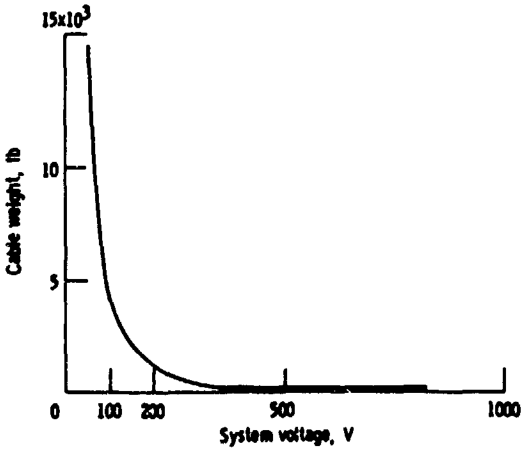
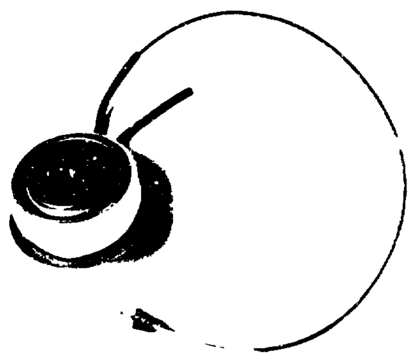


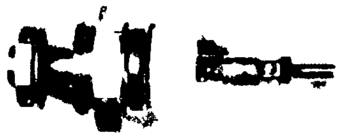
Figure 3. - Cable weight as a function of system voltage.

FEATURES

- VOLTAGE: 400 TO 500 VOLTS
- CURRENT: 100 TO 150 AMPERES @ GAIN OF 10
  400 AMPERES PEAK
- POWER HANDLING: 50 KILOWATTS
- POWER DISSIPATION: 2 kW @ 75°C
- RISE AND FALL TIMES: 0.75 MICROSECOND
- STORAGE TIME: 4 MICROSECONDS
  LOW SATURATION AND PER CYCLE SWITCHING LOSSES



POW-R DISC PACKAGE



STUD MOUNT PACKAGE

APPLICATIONS

- 25-50 kW HIGH FREQUENCY INVERTERS
- VSCF CONVERTERS IN MILITARY AIRCRAFT
- ELECTRIC VEHICLE MOTOR CONTROLLERS
- DC MOTOR CONTROLLER FOR SPACE SHUTTLE ACTUATOR
- 100 kW VLF TRANSMITTERS
- 50 kHz RF INDUCTION HEATERS
- POWER SUPPLIES FOR CONSUMER AND INDUSTRIAL APPLICATIONS

BENEFITS TO NASA

- DOUBLES CAPABILITY OF PREVIOUS IR-100 AWARD WINNING D60T TRANSISTOR
- COMMERCIALLY AVAILABLE IN QUANTITY AT REASONABLE COST
- MAKES POSSIBLE 50 kW SPACE POWER SYSTEM CONVERTERS AND POWER CONTROLLERS WITHOUT PARALLELLING OF TRANSISTORS
- EXPECT IMPORTANT USES ALSO IN AIRCRAFT POWER DISTRIBUTION AND CONTROL
- ESTABLISHES TECHNOLOGY FOR LARGER AREA, HIGHER POWER TRANSISTORS

Figure 4. - NASA Lewis high-current power-switching transistor (Westinghouse model D7ST, higher current version of D60T.)

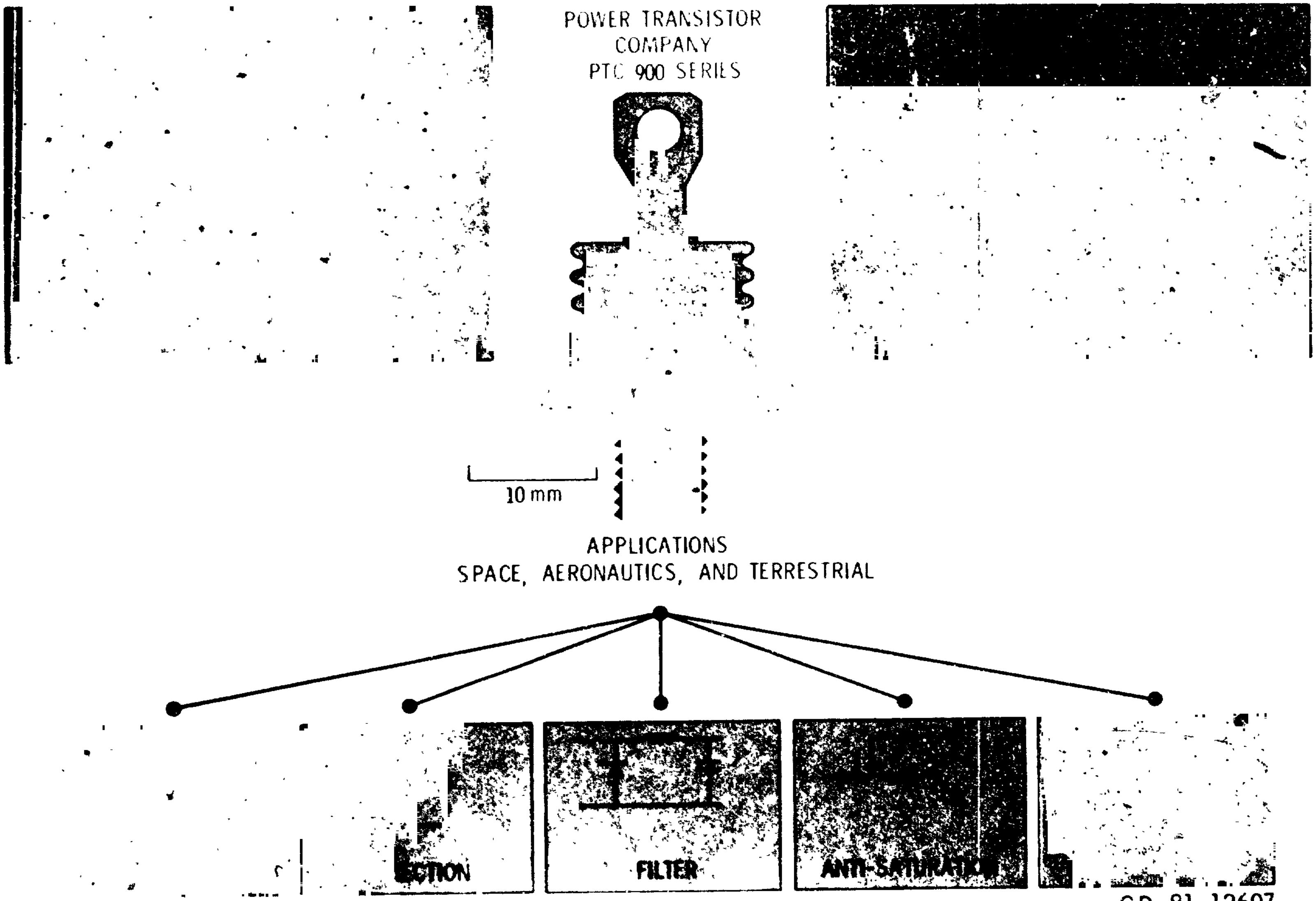


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Figure 5. - NASA Lewis fast-recovery, high-voltage power diode.

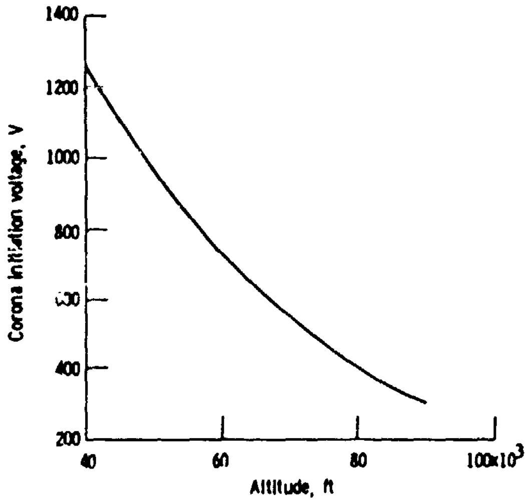

Figure 6. - Corona initiation voltage as a function of altitude.

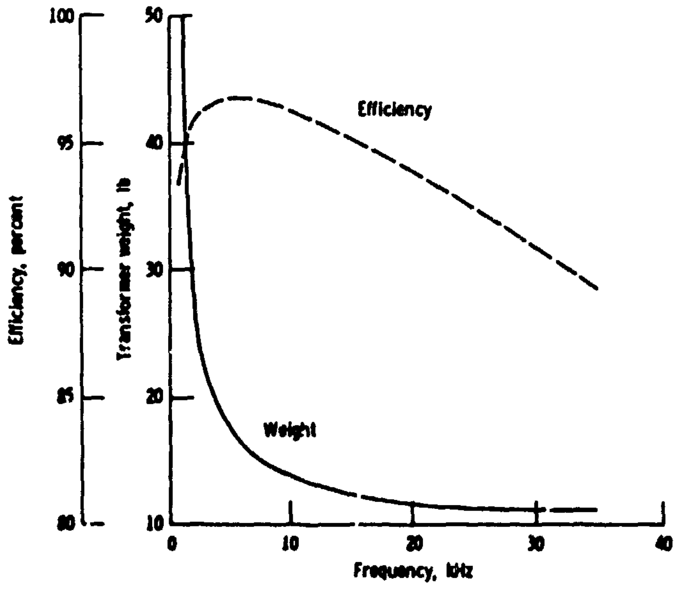

Figure 7. - 50-kVA transformer design for constant flux density. Primary voltage, 440 V; secondary voltage, 1 kV.

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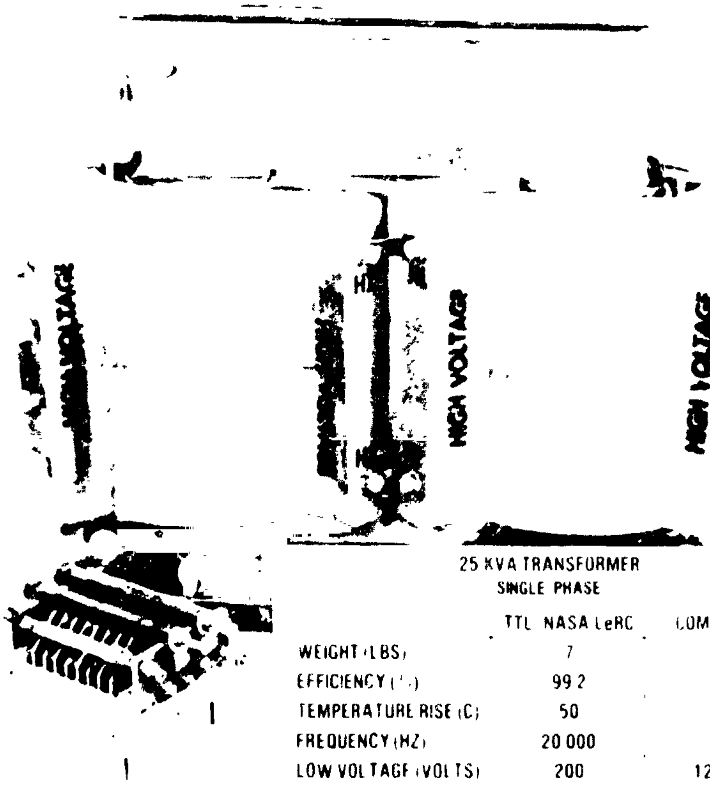

25 KVA TRANSFORMER
SINGLE PHASE

	TTL NASA LeRC	COMMERCIAL
WEIGHT (LBS)	7	400
EFFICIENCY (%)	99.2	97.9
TEMPERATURE RISE (C)	50	85
FREQUENCY (HZ)	20 000	60
LOW VOLTAGE (VOLTS)	200	120 240
HIGH VOLTAGE (VOLTS)	1500	3850 4160 4470

Figure 8. - Comparison of space and commerical transformers.

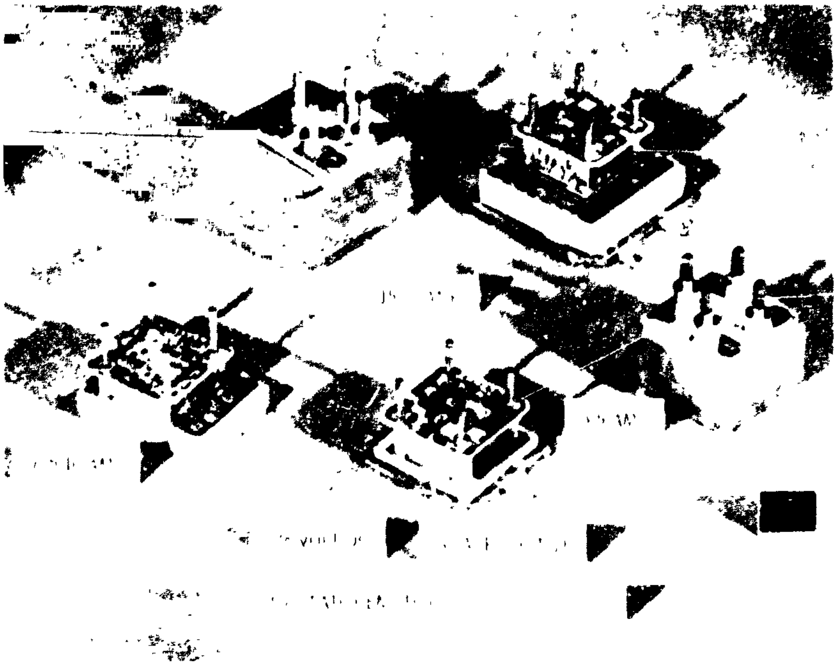

Figure 9. - Solid-state remote power controllers developed for use in space shuttle.

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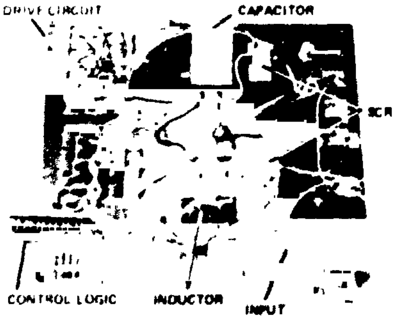
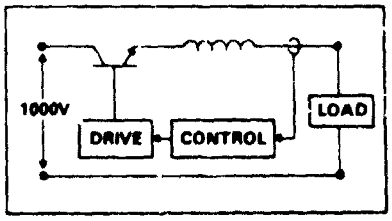
Figure 10. - Next generation of remote power controllers.

1 KV, 25 A D.C.
SOLID STATE CIRCUIT
BREAKER BREADBOARD





- **OPTICALLY ISOLATED**
- **PROGRAMED TRANSIENT PROTECTION**
- **CAPABLE OF WITHSTANDING SHORTS**

CIRCUIT REQUIRED FOR MULTI HUNDRED KILOWATT POWER MANAGEMENT

Figure 11. - High-voltage, high-power circuit.