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Power Conditioning Techniques

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POWER CONDITIONING TECHNIQUES (U)

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(U) Power level requirements for aerospace missions continue to increase (figure 1). Historically, aircraft have dominated their spacecraft counterparts in the need for electric power by an order of magnitude. For example, the power systems on board the Boeing 747 and DC-10 are rated for a few hundred kilowatts. The Space Shuttle power system, on the other hand, provides just a few tens of kilowatts. Currently, the Space Station Freedom baseline design calls for a modest 75 kW power system; a factor of two smaller than the jumbo airliners designed 20 years ago. Growth Station, projected for operation in 2010, will provide 150 kW to its users. When completed, spacecraft power levels will finally approach the size of today's aircraft power systems. Future missions, such as the National Aero-Space Plane (NASP), a Manned Lunar Base, and a Manned Mission to Mars are each expected to require about one megawatt. To date, the largest space type power system deployed is aboard the Space Shuttle and is rated for only 25 kW. Figure 1 also shows that the electric power requirements for SDIO missions, which include the Neutral Particle Beam, will exceed one megawatt with projections to 10 MW already envisioned.

(U) State-of-the-art power electronics technology is best demonstrated by considering the Space Station Freedom's 75 kW power system. Solar arrays provide DC power to a bank of inverters operating at 20 kHz which, in turn, supply regulated 440 VAC to the distribution bus. Each inverter module has a specific weight of 3.7 kg/kW and provides 12.5 kW. Since each module contains 8 active switches, each switch handles about 1600 W. A 1984 NASA contract with Hughes resulted in a resonant converter near 2 kg/kW supplying 25 kW at 1000 VDC from a 250-350 VDC input. It required only four D7ST switching transistors for the active switches, each handling just over 6 kW. Scaled to one megawatt, the Space Station design would require 640 switches and 80 modules, whereas the Hughes design would require 160 switches and 40 modules. The major differences between the two designs are topology and reliability. A conservative design approach is used for the Space Station due to the nature of the mission; while the goal of the Hughes design was to demonstrate the maximum power handling capability of state-of-the-art switches.

(U) If a 1 MW DC-to-DC converter were built using the Hughes 2 kg/kW technology, it would weigh two metric tons, roughly the equivalent of 26, 170-lb people. Assuming launch costs of $10,000/kg, the price of launching the converters alone into low earth orbit would exceed $20 million.

(U) A key to reducing power system weight is to understand the weight distribution among the various components. In most converters, the weight is shared among the capacitors, inductors, switching devices, control circuitry, and supporting structure. Capacitors, for example, are used as components in filters, resonant tanks, switch snubbers, and many other applications. Inductors are used as filters, current limiters, components in resonant tanks, and, when mutually coupled, as transformers. Transformers provide step-up, step-down, and isolation for AC voltages. Switching devices can be fully controllable (eg. BJT, FET, GTO, and SIT), partially controllable (eg. SCR and LASS), or uncontrollable (eg. rectifiers and flyback diodes). The switching device structure may be P-N junction, field-effect, or Schottky Barrier which give certain operating characteristics to the device. Finally, the supporting structure holds everything together, provides cooling, and possibly acts to furnish paths for electrical conduction. Since circuit topology limits the choice of components and vice versa, understanding the complex relationships between circuit operation and component selection will result in megawatt level power converters with very light weight.

(U) In a paper study performed at the NASA Lewis Research Center on a state-of-the-art 2 kg/kW, 500 kW, 20 kHz resonant converter, the weight contribution from each component type was determined. The results show that the weight distribution in the power circuit components is 63% capacitors, 30% inductors, and 7% switches. This seems to indicate a need for technology development in capacitors and, to a lesser extent, inductors to realize significant weight reductions. However, the circuit studied is a resonant circuit. This type of topology tends to have higher capacitor weight due to the resonant capacitor. From this example it can be determined that advances in both component technology and circuit topology are the key to reducing the specific weight of space type power systems.

(U) Since circuit topology is one factor affecting component weight distribution in a converter, the NASA Lewis Research Center has established programs with the University of Wisconsin and the University of Toledo to study converter circuit topologies. The goal of these studies is to survey the operational characteristics of a wide range of converter topologies. Among the characteristics under consideration are: efficiency, switch utilization, fault energy handling, component types required, and specific weight. From the survey results, promising circuit topologies are chosen for design, build-up and characterization. The circuits typically operate at a few kilowatts and consideration is given to potential difficulties in scaling the units to higher power levels. The work indicates that no single topology will meet every requirement for all space-based power systems; rather, the "right" converter topology is application specific.

(U) Power circuit topologies under consideration range form hard-switched to resonant with quasi-resonant types falling in between. A hard-switched converter chops DC directly into a transformer. It may not require capacitors provided that the switches can handle the voltage transients caused by the transformer leakage inductance. Fully controllable switches are mandatory in a hard-switch converter if one wishes to avoid the extra weight associated with forced commutation circuitry. Resonant converters require capacitors in their tank circuits but provide natural commutation to the switches. Circulating current is the major drawback in resonant topologies because the circuit Q forces the switches to handle more power than is being supplied to the load.

(U) Switch utilization, which is defined as the converter output power divided by the total volt-ampere product of the switches, represents how well a circuit topology uses the capability of its switches to achieve the output power. Resonant circuits have low switch utilization due to high circulating currents. Hard-switched converters can have high switch utilization provided that the switching voltage transients, due to transformer leakage, can be snubbed; but snubbering leads to the inclusion of capacitors in the circuit.

(U) Operating a converter at a fixed frequency allows filters to be tuned; thus eliminating the need to design wide band filters and further reducing weight. Yet, tuned resonant filters require inductors and capacitors which are the heaviest of all the components to choose from. Some topologies require less output filtering but at the expense of additional input filtering. One consideration would be to match the filtering requirements to the load and the source.

(U) Source and load limitations impose the boundary conditions within which the power management and distribution (PMAD) system must function. An electric power source provides some output voltage range, output impedance, and other restrictions that must be matched by the PMAD system to a load having a certain voltage range, ripple voltage, and other power requirements. If power is supplied by a 100 VDC source, it is likely that switches having very low forward voltage drop will be used in the converter. Every 1-volt drop in a 100 VDC system results in decreasing efficiency by 1%. In full bridge configurations for DC-to-DC conversion, two 1-volt switch drops in the chopper and two more in the output rectifier translates to a 96% efficiency and this is before losses contributed by other components and cables are taken into account. Another consideration is radiation effects on the switches. Nuclear reactor powered systems, which use thermoelectric or thermionic devices, provide high power at low voltage. Efficient transmission of this power to the user requires converters, located near the reactor, to step up the voltage for transmission. We have a program at the Lewis Research Center where radiation effects on BJT's, FET's, and other switches are being studied.

(U) Finally, fault tolerance ensures that the power management and distribution system will be able to withstand load shorts or arcs. Ideally, stored energy within the power system should be low to protect the load from catastrophic failure by preventing burnouts. In a neutral particle beam system this amount to only a few tens of joules.

(U) If we can develop the technology to build a 0.1 kg/kW converter operating at a megawatt, it would weigh 0.1 metric tons, about the weight of a 220-lb man. Launch costs would decrease dramatically from $20 million, for the 2 kg/kW converter, to $100K. The cost savings represent an order of magnitude decrease in converter specific weight and an order of magnitude increase in power level over state-of-the-art systems.

(U) The approach will require new circuit topologies, the development of very light weight capacitors and inductors, and new switching devices capable of handling large currents with low forward voltage drop. Potential circuit topologies under consideration are resonant, soft-switched, square wave, voltage multiplication or some combination. The NASA Lewis Research Center has in-house and university grant work already underway in these areas. Light weight capacitors are being studied in-house and at the State University of New York at Buffalo. The MOS Controlled Thyristor (MCT), a new controllable switch with low forward voltage drop, is under development at GE.

(U) Ultra-lightweight converter technology can meet the needs of many users. The Strategic Defense Initiative Office is planning on orbiting platforms for systems such as the Neutral Particle Beam and Free Electron Laser systems. The Air Force and commercial aircraft industry could replace heavy and leak prone hydraulic systems with electric control surface actuator systems to reduce weight and minimize down time. Two weeks time is spent on the Space Shuttle in preparation for its next launch due to checking and qualifying its hydraulic actuator systems. NASA needs lightweight converter technology for a Manned Lunar Base, Space Based Manufacturing, interplanetary travel, and a Manned Mission to Mars. The Army could have large mobile power systems capable of powering electromagnetic launchers. Finally, the Navy could increase the payload on board its ships by decreasing the weight of its electric power systems.

(U) The goal of a joint development program between NASA, the Air Force, and the Strategic Defense Initiative Office, is to build a 1 MW DC-to-DC converter with a specific weight of 0.1 kg/kW for a total converter weight of 100 kg. The output voltage will be 100 kV DC developed from an input voltage of 500-5000 VDC. The system will be fault tolerant and store only a few tens of joules to prevent burnouts during fault conditions. We project that the system will be completed in a 3-5 year time span with a demonstrable 1 MW hardware as an output. NASA is currently in the procurement stage through a NASA Research Announcement (NRA).

(U) In conclusion, a 1 MW, 0.1 kg/kW 100 kV DC-DC converter seems to be attainable in 3 to 5 years. Circuit topology and light weight component technology are key factors in achieving ultra-lightweight, high power converters. The goal of this work is to demonstrate a 0.1 kg/kW converter operating at the one megawatt power level.

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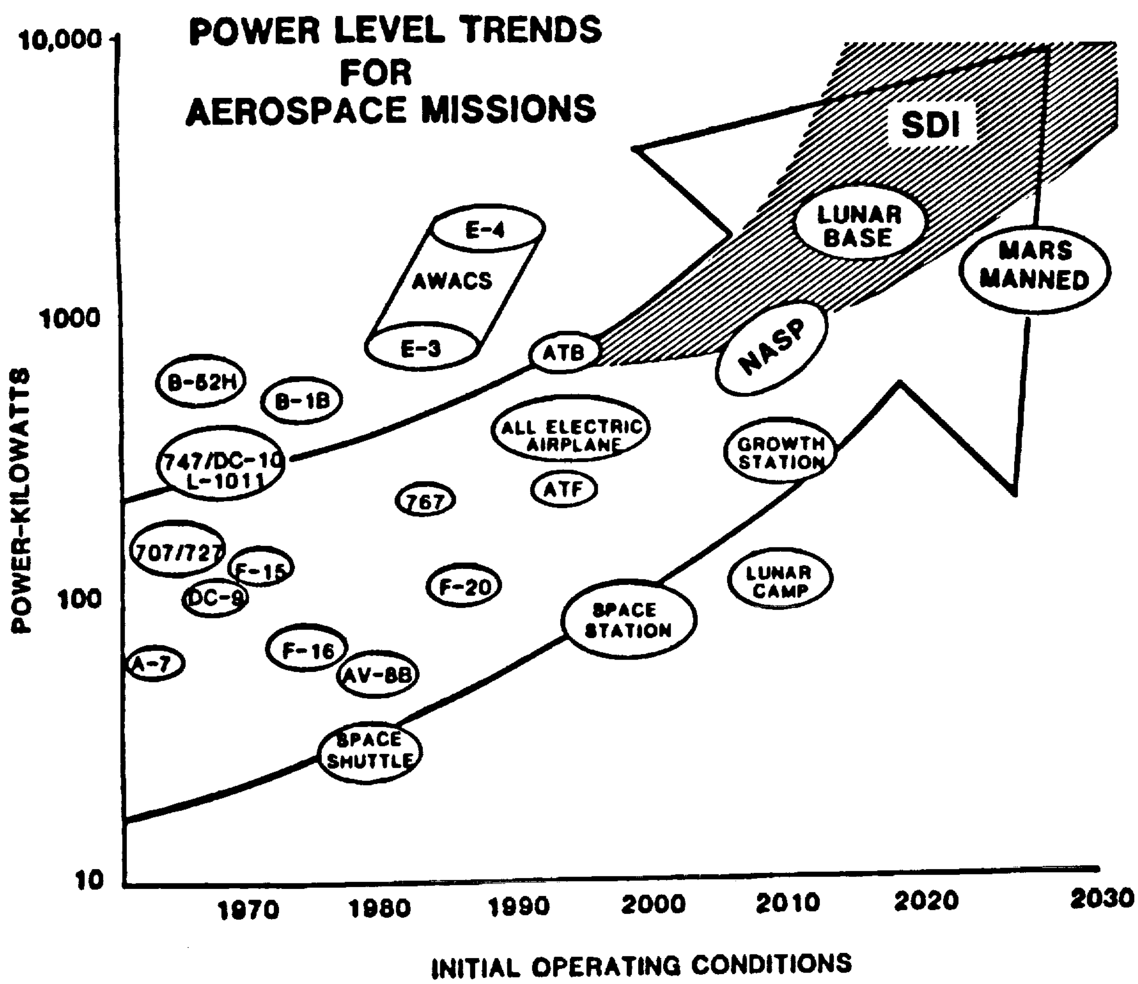
POWER LEVEL TRENDS
FOR
AEROSPACE MISSIONS
10,000
1000
100
10
POWER-KILOWATTS
1970
1980
1990
2000
2010
2020
2030
INITIAL OPERATING CONDITIONS
SDI
LUNAR BASE
MARS MANNED
NASP
E-4
AWACS
E-3
ATB
B-52H
B-1B
747/DC-10
L-1011
ALL ELECTRIC AIRPLANE
GROWTH STATION
ATF
767
707/727
F-15
DC-9
F-20
LUNAR CAMP
SPACE STATION
A-7
F-16
AV-8B
SPACE SHUTTLE

FIGURE 1.

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16. Abstract

This paper discusses the technological developments required to reduce the electrical power system component weights from the state-of-the-art 2.0 kg/kW to the range of 0.1-0.2 kg/kW. Power level requirements and their trends in aerospace applications are identified and presented. The projected weight and launch costs for a 1MW power converter built using state-of-the-art technology are established to illustrate the need for reliable, ultralight-weight advanced power components. The key factors affecting converter weight are given and some of the tradeoffs between component ratings and circuit topology are identified. The weight and launch costs for a 1MW converter using 0.1 kg/kW technology are presented. Finally, the objectives and goals of the Multi-Megawatt Program at the NASA Lewis Research Center, which is funded by the SDIO through the Air Force, are given.

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