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DESCRIPTION OF A 20 KILOHERTZ POWER DISTRIBUTION SYSTEM

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ABSTRACT

The power distribution system to be discussed is a single phase, 440 VRMS, 20 kHz system, with a regulated sinusoidal wave form. The rationale for selecting each of these characteristics follows. A single phase power system minimizes the wiring, sensing, and control complexities required in a multi-sourced redundantly distributed power system. The single phase addresses only the distribution link, multi phase lower frequency inputs and outputs accommodation techniques are described. While the 440 V operating potential was initially selected for aircraft operating below 50 000 ft, this potential also appears suitable for space power systems. This voltage choice recognizes a reasonable upper limit for semiconductor ratings, yet will allow direct synthesis of 220 V, 3 power. A 20 kHz operating frequency was selected to be above the range of audibility, minimize the weight of reactive components, yet allow the construction of single power stages of 25 to 30 kW.

The regulated sinusoidal distribution system has several advantages. With a regulated voltage, most ac/dc conversions involve rather simple transformer rectifier applications. A sinusoidal distribution system, when used in conjunction with zero crossing switching, represents a minimal source of EMI. The present state of 20 kHz power technology includes computer controls of voltage and/or frequency, low inductance cable, current limiting circuit protection, bi-directional power flow, and motor/generator operating using standard induction machines. A status update and description of each of these items and their significance will be presented.

SYSTEM CONCEPTS

The 20 kHz power distribution system is somewhat like any ac utility power system. Distribution of ac power allows an easy adjustment of operating voltages to specific local user needs. Also voltage adjustment transformers provide the isolation of common mode potentials necessary to control electrical noise and cross talk. However, low frequency utility systems are rotating machine derivatives and are at best inflexible in accommodating varying voltage or frequency requirements. The 20 kHz system is based upon rapid semiconductor switching, low stored reactive energy, and cycle by cycle control of energy flow allowing the tailoring of voltage levels and wave shape by synthesis. The fundamental system concept is the "split" converter (Fig. 1) in which a conventional dc/ac/dc converter is split into a dc/ac section, an ac transmission line, and a ac/dc conversion section. The converter operating at 20 kHz is of parallel resonant Mapham configuration (1*) with the output load across the capacitor. Resonant conversion in general avoids the high frequency turn off loss term, and the capacitor output provides a suitable source for voltage distribution. A complete description of the converter circuitry together with full test data is contained in the final contract report (2). The systematic advantage of the parallel converter is shown in Fig. 2. Topologically the resonant inductors act as current sources which are "sunk" by a single (parallel combination) capacitor. If the converters are triggered in synchronism no further control is required for load sharing.

For load conversion the second "half" conversion may be tailored to user specific requirements (Fig. 3). Several generic load converter circuits have been designed and tested (3). These system concepts have been verified using a 25 kW, single phase, ac test bed system. The system accepts dc or three phase ac power at any frequency up to 2.5 kHz, converts the power to 20 kHz ac, transmits it over a 100 m line, and load converts it into variable or fixed voltage ac or dc, or variable frequency ac. All energy flow, and all set points are under computer control. Of particular note is the relative simplicity and ease with which variable voltage, variable frequency power, such as that required for motor operation may be synthesized. Control circuits designed for their eventual incorporation into integrated circuits have been developed to perform the functions described as well as controlling bi-directional power flow, and maintaining converter status (4).

A unique regulation scheme also has been developed (Fig. 4). Regulation is achieved by controlling a variable phase relationship between phasor summed synchronized converters. This concept is particularly valuable when receiving energy from a multi-phase low frequency source. When a dedicated resonant converter is employed in each phase, the source "sees" a continuous linear loading which in turn maintains the sinusoidal waveshape of both the voltage and the current. Maintenance of waveshape fidelity in turn maximizes conversion efficiency and reduces electro-magnetic interference.

ELECTROMAGNETIC INTERFERENCE (EMI) - In a high frequency power system the electromagnetic spectrum is limited to frequencies evenly clustered about the fundamental (carrier) frequency. The result is the capability of accepting and transmitting low frequency energy without radiating electromagnetic energy at the low frequencies. Consider a voltage regulated high frequency power system as shown in Fig. 5. In a low impedance or regulated power system the voltage must remain constant. If the system is to deliver only 400 Hz energy for example, the amplitude of 20 kHz current must then vary at a 400 Hz rate. This amplitude variation results in a class of modulation defined as double sideband suppressed carrier. Such modulation contains only an upper sideband located at 20 kHz + 400 Hz (20 400 Hz), and a lower sideband located at 20 kHz - 400 Hz (19 600 Hz). Translation of the low frequency energy to higher frequencies not only removes the source of low frequency EMI, but allows shielding to be accomplished much more efficiently at the higher frequencies.

*Numbers in parenthesis designate References at end of paper.

COMPONENT TECHNOLOGY STATUS

POWER CABLE - As part of the advanced development effort a low inductance cable was designed (5) to be compatible with the Lewis Research Center ac test bed. This particular design (6) is a flat construction to allow flexure in at least one axis. Each conductor consists of flat braided individually insulated "Litz" wires which control the ac resistance at 20 kHz. The flat conductors comprise a double sided stripline having very low inductance and as a direct consequence the radiated magnetic field about the cable is also very low. Alternate cable configurations, having similar electrical characteristics are being evaluated for possible advantages in terms of ease of termination, additional flexibility, or better adaptation to inline splicing.

REMOTE POWER CONTROLLER (Leach Corp.) - Contract No. NASA3-24660 - A current limiting remotely setable power controller is under development. In addition to its current limiting protection and power system programming capabilities this device also provides current sensing and status required for power system management. All functions, other than current limiting, are controlled by a computer interface with the power system controller. the current limiting characteristics of the controller provides not only fault protection but also protects the power system from inrush upon load turn on.

BI-DIRECTIONAL CONTROL ELECTRONICS - A high frequency power distribution system involves source conversion, transmission and user load conversions. In the assemblage of such a system there occurs many replications of identical circuit functions. This contract (4) divided the necessary control functions into basic blocks which could then be fabricated as dedicated integrated circuit chips. The following applications were examined; variable voltage dc input, and multiphase variable voltage/variable frequency inputs. Identical outputs were also accommodated and bi-directional power flow between any combination of the various inputs and outputs was examined. This effort resulted in the definition and design of only seven chips which when properly combined will perform all the control functions of a multi-kilowatt power system and provide computer control interfaces. All voltage set points, current limits, input and output frequencies, and energy flow are under computer control. In this capability the computer supplies only set points, the cycle by cycle control is handled by the dedicated chips. In case of computer failure the power system reverts to a "dumb" system status and controls to the last or other prearranged setpoint.

SEMICONDUCTOR PACKAGING (contract No. NASA3-24622 - Allen Bradley) - This contract will result in the development of an improved semiconductor packaging for high power space environments. The package will provide long term hermetic sealing of semiconductor packages. The package also supplies the necessary electrical/thermal interface separation. Performing this separation internal to the package provides major benefits; it allows all electrical connections to be made at a single surface allowing low inductance connections. Also the electrically "hot" surfaces which radiate an electric field are held to minimum dimensions and contained within the metallic package. It is expected that control of the connection inductance and the common mode capacitance will allow relief of some parasitic elements and their interference effects which are common in all power converters.

DEVELOPMENT OF FAST SWITCHING HIGH POWER SEMICONDUCTORS (RFP 3-170905) - At this writing proposals have been received to develop high power semiconductors which are tailored specifically to 20 kHz resonant converter applications. The goal of this work is a device which allows direct offline conversion from a 440 V, 20 kHz power bus. The semiconductor will be a bilateral conducting device which is controlled directly from logic power. Functionally the device will resemble an extremely fast (nanosecond) triac being controlled (off and on) by a logic gate. This particular device has application in power converters, load converters and remote power controllers. This device will have a dramatic impact on reducing the system parts count even further with the usual attendant improvement in cost and reliability.

20 kHz SYSTEM APPLICATIONS - Two power system design studies involving 20 kHz technology have been completed thus far. The first concerned the application of high frequency power to an "all electric" secondary power system for a Boeing 767 (6). In this study all existing secondary power system functions were performed by electrically powered systems operating from a dual redundant 20 kHz power distribution system. In this application the high frequency power system resulted in both a significant weight reduction and an increased efficiency. Overall the aircraft dry weight was reduced by 10 percent and the fuel consumption was reduced by 9 percent. The second system design was evaluated as the power distribution system for the NASA Space Station currently in the study phase (7). As presently planned, the Space Station power system will have an initial power capability of 75 kW and allow eventual growth to 300 kW. Both photovoltaic and solar dynamic power sources are accommodated with high voltage (440 V) high frequency power being transmitted station wide. Again evaluations of this particular design showed that the intrinsic low weight and high efficiency of the 20 kHz system would result in an initial cost savings of about 100 million dollars. Several other applications for high frequency power are under consideration at this time. Among these are the Naval Air ship program, electrically operated flight controllers for Shuttle II, the SP 100 power system (both the thermoelectric and Stirling cycle cases), spacecraft 2000 and the newly proposed transatmospheric vehicle.

CONCLUSIONS

The 20 kHz power technology is rapidly approaching technical maturity. It represents a "clean sheet" end to end system concept and is based upon proven technology and was designed specifically for aerospace applications. When the high frequency system is viewed from a total end to end perspective it requires a minimum number of power conversion steps. High efficiency together with low parts count and weight result in the highest reliability and lowest cost. In addition, the sinusoidal cycle by cycle energy control with zero crossing switching provides application flexibility and minimizes electromagnetic interference.

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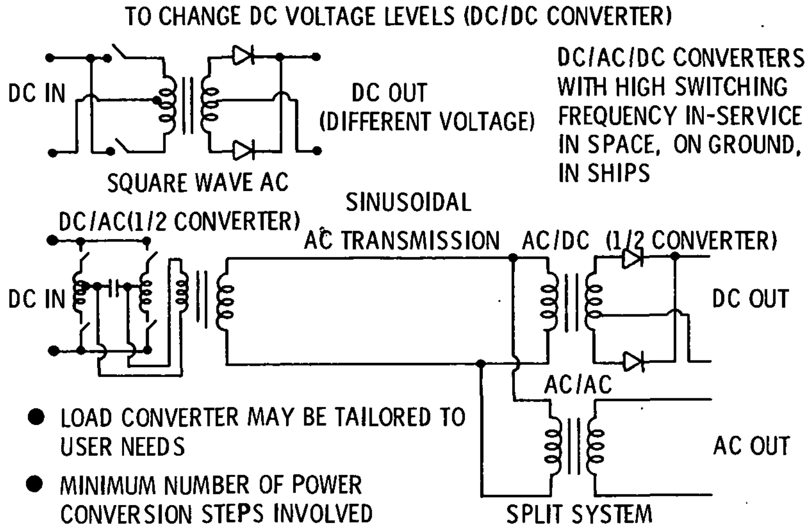
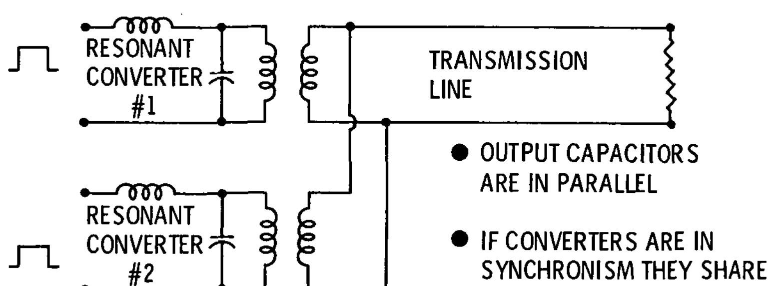


- LOAD CONVERTER MAY BE TAILORED TO USER NEEDS
- MINIMUM NUMBER OF POWER CONVERSION STEPS INVOLVED
- SAME PIECE PARTS AS IN DC/AC/DC CONVERTER, SEMI-CONDUCTORS, CAPACITORS, MAGNETICS ETC.

Figure 1.



- OUTPUT CAPACITORS ARE IN PARALLEL
- IF CONVERTERS ARE IN SYNCHRONISM THEY SHARE THE LOAD EQUALLY
- BY CONVERTING TO HIGH FREQUENCY, ANY SOURCE MAY ADD ENERGY TO THE TRANSMISSION LINE BY ONLY A 1/2 CONVERSION STEP
- MAXIMUM ENERGY AVAILABLE TO A SYSTEM FAULT IS THE CHARGE STORED IN THE CAPACITORS

Figure 2.

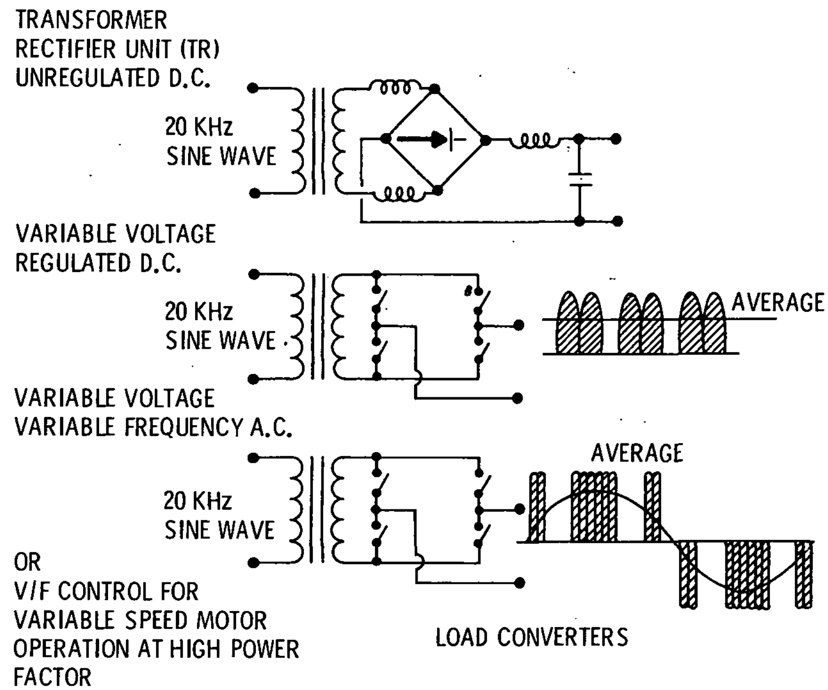
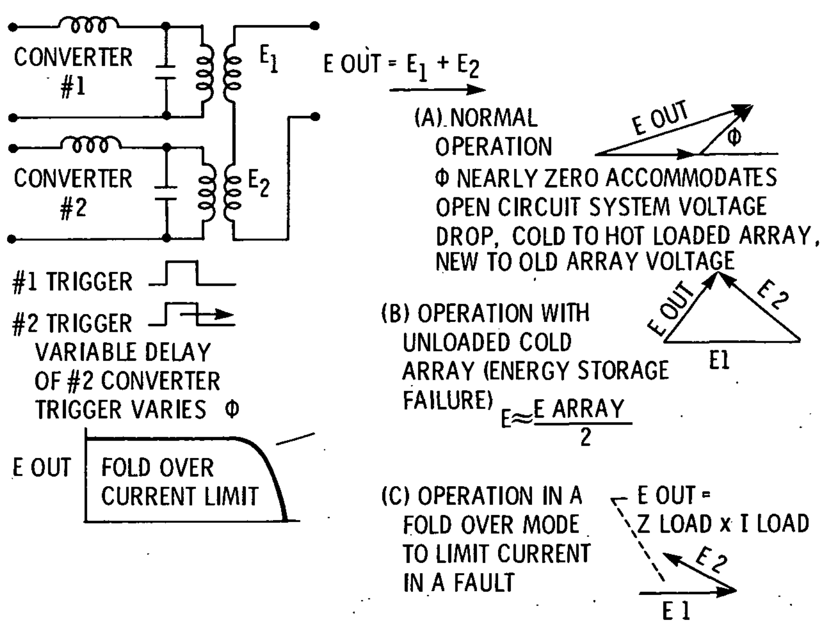
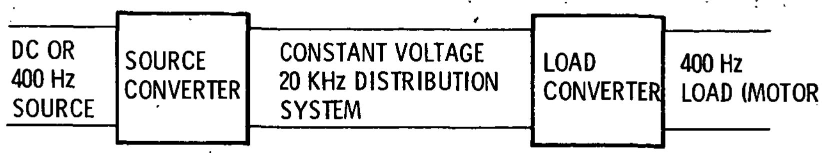


Figure 3.

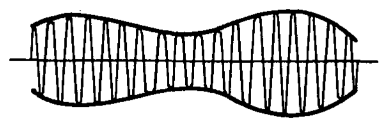


PHASOR REGULATION

Figure 4.



- THE VOLTAGE REMAINS CONSTANT
- THE DISTRIBUTION CURRENT WILL BE 20 KHz WITH A 400 KHz AMPLITUDE VARIATION

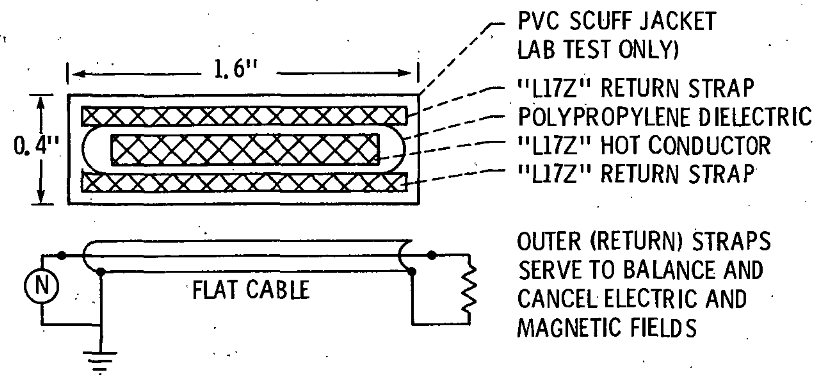


$\sin_A \sin_B = 1/2 \cos(A-B) - 1/2 \cos(A+B)$

(19.6 KHz) (20.4 KHz)

- THE ENERGY SPECTRUM OF THE DISTRIBUTION SYSTEM CONTAINS ONLY 19.6 KHz, 20 KHz AND 20.4 KHz
- THERE IS NO LOW FREQUENCY EMI SOURCE PRESENT IN THE DISTRIBUTION SYSTEM

Figure 5. - System EMI spectrum.



MEASURED DATA ON CABLE

R = 0.83 MILLIOHMS/METER
L = 0.035 μ HENRY/METER
C = 0.00137 μ FARAD/METER
CORONA INCEPTION: 1400 VOLTS

440 VRMS
(60 AMPERE RATING)

Figure 6.

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