NASA Technical Memorandum 88801

(NASA-TM-88801) A 20 KILOHERTZ SPACE
STATION POWER SYSTEM (NASA) 10 p
HC A02/MF A01
CSCL 10B
N86-28122
Unclas
G3/20 43359

20 Kilohertz Space Station Power System

Irving G. Hansen and Fredrick J. Wolff
Lewis Research Center
Cleveland, Ohio

Prepared for the
19th Annual Electronics and Aerospace Conference
sponsored by the Institute of Electrical and Electronics Engineers
Washington, D.C., September 8, 1986

NASA

E-3140

20 KILOHERTZ SPACE STATION POWER SYSTEM

Irving G. Hansen and Fredrick J. Wolff
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

The Space Station represents the next major U.S. commitment in space. The efficient delivery of power to multiple user loads is key to that success. In 1969, NASA Lewis Research Center began a series of studies with component and circuit developments that led to the high frequency, bi-directional, four quadrant resonant driven converter. Additional studies and subsequent developments into the early 1980's have shown how the high frequency ac power system could provide overall advantages to many aerospace power systems. Because of its wide versatility, it also has outstanding advantages for the Space Station Program and its wide range of users.

High frequency ac power provides higher efficiency, lower cost, and improved safety. The 20 kHz power system has exceptional flexibility, is inherently user friendly, and is compatible with all types of energy sources - photovoltaic, solar dynamic, rotating machines or nuclear. Lewis has recently completed development under contract a 25 kW, 20 kHz ac power distribution system testbed. The testbed demonstrates flexibility, versatility, and transparency to user technology as well as high efficiency, low mass, and reduced volume.

Background

In 1969, Lewis began a series of studies with component and circuit developments that led to the high frequency, bi-directional, four quadrant resonant driven converter. Additional studies and subsequent developments into the early 1980's (Fig. 1) have shown how the high frequency ac power system could provide overall advantages to aircraft secondary power systems. Because of its high efficiency, low EMI, and unusual versatility, it demonstrates marked advantages for the Space Station Program and its wide range of users.

Analysis performed during Phase B Space Station studies shows that a 20 kHz PMAD system is 5 to 10 percent more efficient than the 400 Hz alternative and, more importantly, is lighter and cheaper. Due to lighter transformers and significantly fewer parts, cost savings are substantial. The 150 Vdc distribution system was eliminated for reasons of safety, weight and cost. The 150 V transmission lines and the extra conversion steps required for a dc distribution would more than triple the system's weight compared to the 20 kHz alternative, and they would raise the costs substantially over those of even the 400 Hz system for the 300 kW Growth Station. An intermediate 2.4 kHz frequency system displayed no real advantages over any of the other alternatives.

The regulated high frequency sinusoidal distribution system has several other 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.

System Description

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. 2) 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 power conversion in general avoids the high frequency turn off loss term, and the capacitor output provides a suitable source for voltage distribution.

Another systematic advantage of the parallel converter is shown in Fig. 3. 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. A complete description of the converter circuitry together with full test data is contained in the final contract report (2).

For load conversion the second "half" conversion may be tailored to user specific requirements (Fig. 4). 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. This accepts dc or three phase ac power at any frequency up to 2.5 kHz, 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 required for motor operation may be synthesized. Control circuits, designed for their eventual incorporation into IC's, have been developed to perform the functions described as well as to control bi-directional power flow and to maintain converter status (4).

A unique regulation scheme has also been developed (5). Regulation is achieved by controlling a variable phase relationship between phasor summed, synchronized converters. This concept is particularly valuable when receiving energy from a multiphase 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. This results in the capability of accepting and transmitting low frequency energy without radiating electromagnetic energy at lower frequencies. Consider a voltage regulated, high frequency power system as shown in Fig. 6. In a low impedance or regulated power system, the voltage must remain constant. Therefore, if the system is to deliver only 400 Hz energy, 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. As a result of the translation of the power system spectrum to higher frequencies, the prime low-level instrumentation frequencies between dc and 15 kHz are undisturbed. This is of immediate benefit to plasma measurements, biological measurements, bolometer measurements, etc. Additionally, future high sensitivity instrumentation, although undefined at present, will also have great benefits. The narrowband magnetic radiation environment specified for the Space Station is shown in Fig. 7. This figure illustrates the large (70 dB) reduction below MILSTD-461 required if a 400 Hz power system were used.

Power Cable

As part of the advanced development effort, a low inductance cable was designed (5) to be compatible with the Lewis ac test bed program. Physically this particular cable was sized to our 25 kW breadboard, 100 m transmission distances, and was designed to bend with a 6 in. rad. This particular design (8) is a flat construction to allow flexure around one axis. Each conductor consists of flat braided individually insulated "Litz" wires which reduce 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. The electrical parameters of the preliminary 440 vrm, 20 kHz, 25 kW cable are:

$$R = \frac{0.83\ \text{m}\Omega}{\text{meter}} \quad L = \frac{0.035\ \mu\text{H}}{\text{meter}} \quad C = \frac{0.00137\ \mu\text{F}}{\text{meter}}$$

The physical length of the distribution system is such a small part of a wave length that the characteristic impedance has no great significance. However, the characteristic impedance of the 25 kW cable is only a few ohms. The low resistance of the cable represents an attempt to optimize cable weight against the weight of solar arrays to make up resistive loss. The low inductance is required to minimize "cross talk" due to load variations.

The power system specifications require that the worst case voltage variations due to loading and cross talk will be less than ±2.5 percent. A distribution system approximating one half of the Space Station is shown in Fig. 9(a). This system was computer modeled using the engineering analysis systems program "Easy 5". The results displayed in Fig. 9(b) indicate that for the conditions assumed in the model, the flat cable will meet the necessary electrical requirements. Alternate forms of low inductance cable will be developed during fiscal 1987.

Conclusions

The 20 kHz power system results from a bottom up design, designed specifically to meet aerospace system requirements. 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 control with zero crossing switching provides application flexibility and minimizes electromagnetic interference.

References

1. Mapham, N.: An SCR Inverter With Good Regulation and Sine Wave Output. IEEE Trans. Ind. Gen. Appl., vol. IGA-3, no. 2, Mar.-Apr. 1967, pp. 176-187.
2. Mildice, J.; and Waapes, L.: Resonant AC Power System Proof of Concept. NASA CR-175069, 1986.
3. Mildice, J.: AC Power System Test Bed. NASA CR-175068, 1986.
4. Mildice, J.: Bidirectional Power Converter Control Electronics. NASA CR-175070, 1986.
5. High Frequency Power Distribution System. NASA CR-175071, 1986.
6. Hoffman, A.C., et al.: Advanced Secondary Power System for Transport Aircraft. NASA TP-2463, 1985.
7. Hansen, I.G.; and Sundberg, G.R.: Space Station 20 kHz Power Management and Distribution System. NASA TM-87314.
8. Hansen, I.G.: Description of a 20 Kilohertz Power Distribution System. NASA TM-87346, 1986.

CRITICAL STEPS IN LeRC 20 kHz PMAD TECHNOLOGY

1963-1983 DEMONSTRATED 3 kW, 20 kHz RESONANT POWER FOR ION ENGINES
- GREATER THAN 33 000 hr OPERATION

1976-1979 20 kHz PMAD SYSTEM FREASIBILITY ESTABLISHED THROUGH DEMONSTRATION OF BI-DIRECTIONAL, 4-QUADRANT RESONANT CONVERTER

1969-1985 DEVELOPED SIGNIFICANT ENABLING COMPONENTS

- SEMICONDUCTORS: TO 1200 V, 100 kW, 50 kHz SWITCHING
- TRANSFORMERS - INDUCTORS (HEAT PIPE/CONDUCTION COOLED): TO 25 kW
- CAPACITORS - HIGH ENERGY DENSITY: TO 75 KVAR, 40 kHz
- SOLID STATE REMOTE POWER CONTROLLERS/CIRCUIT BREAKERS: TO 50 kW
- HIGH FREQUENCY TRANSMISSION LINE: 600 V, 60 A, LOW EMI, LOW LOSS
- ROLL RINGS (ROTARY POWER TRANSFER): TO 200 A, >100 YEARS EQUIVALENT LIFE TEST

1980-1985 DEMONSTRATED 20 kHz PROOF-OF-PRINCIPLE BREADBOARDS AT 3, 5 AND 25 kW

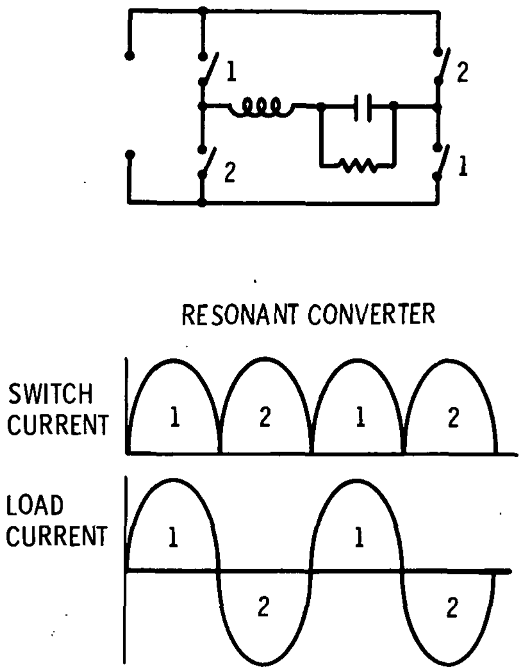
1984 ALL ELECTRIC AIRPLANE (767) STUDIES SHOWED 10 PERCENT FUEL, 10 PERCENT WEIGHT SAVINGS POSSIBLE USING 20 kHz PMAD

1984 TRANSFERRED TECHNOLOGY TO SPACE STATION

1985 DEMONSTRATED 25 kW TEST BED SYSTEM TO INDUSTRY

MAY 22, 1986 SPACE STATION ACCEPTED 20 kHz PMAD ARCHITECTURE

Figure 1.

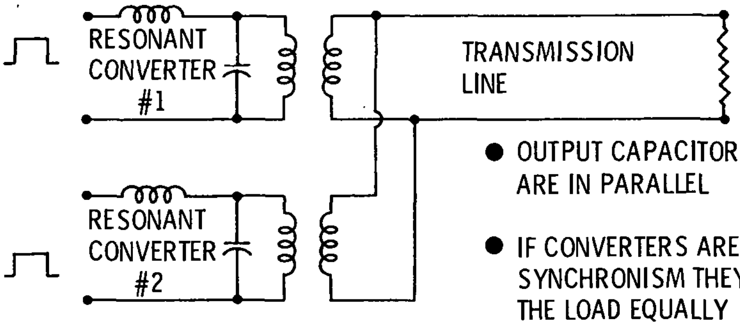


SWITCHED FULL BRIDGE
RESONANT LOAD
(LOW IMPEDANCE) OUTPUT

CURRENTS ARE HALF SINUSOIDS
ALL SWITCHING AT ZERO CURRENT

- NO FREQUENCY DEPENDENT SWITCH LOSS
- NO SECOND BREAKDOWN

Figure 2. - Parallel resonant conversion (MAPHAM).



- 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 3. - Parallel sources.

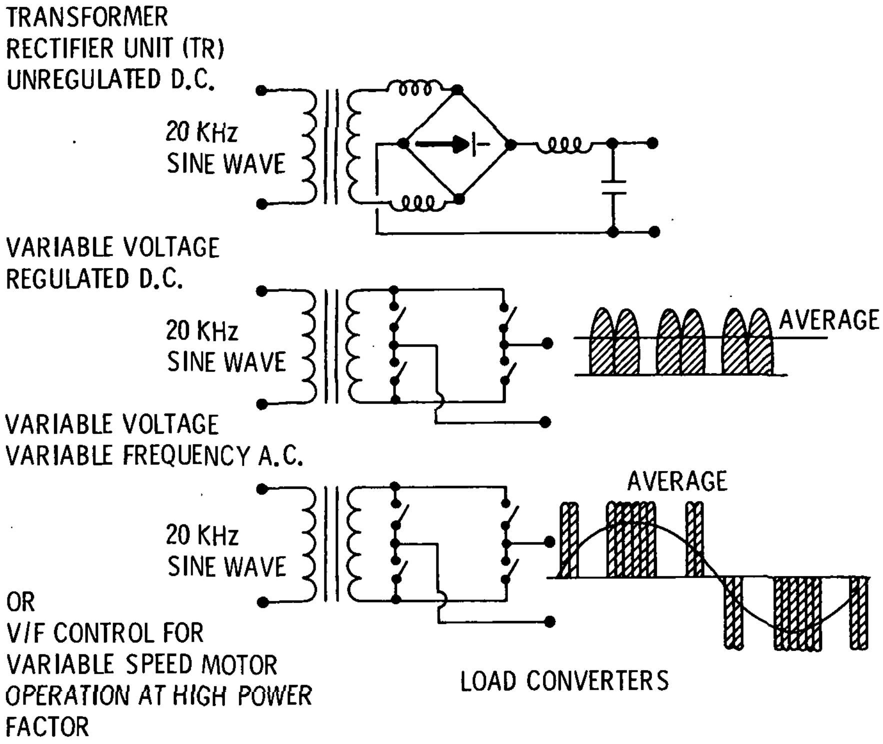


Figure 4. - Resonant converter output synthesis.

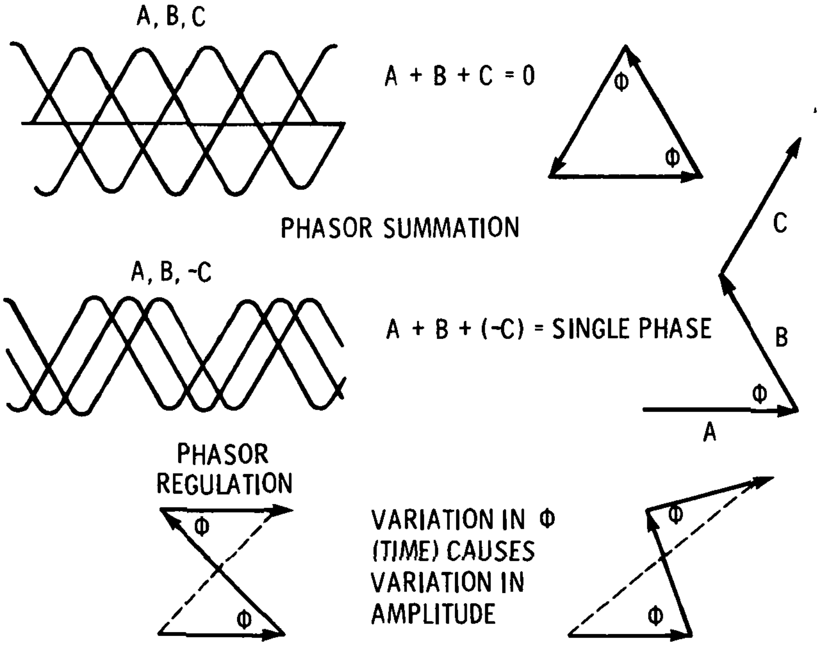
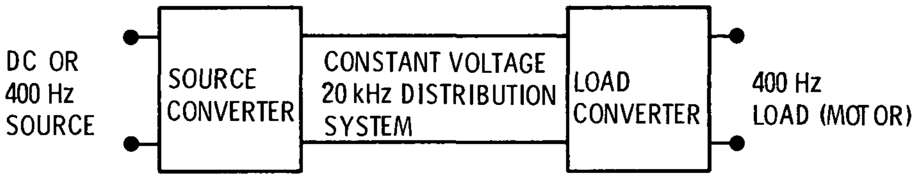
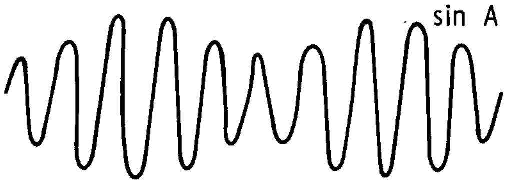


Figure 5. - Basic concepts.



- THE DISTRIBUTION VOLTAGE REMAINS CONSTANT
- THE DISTRIBUTION CURRENT WILL BE 20 kHz WITH A 400 Hz 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, 20.0 kHz AND 20.4 kHz
- THERE IS NO LOW FREQUENCY EMI SOURCE PRESENT IN THE DISTRIBUTION SYSTEM

Figure 6.

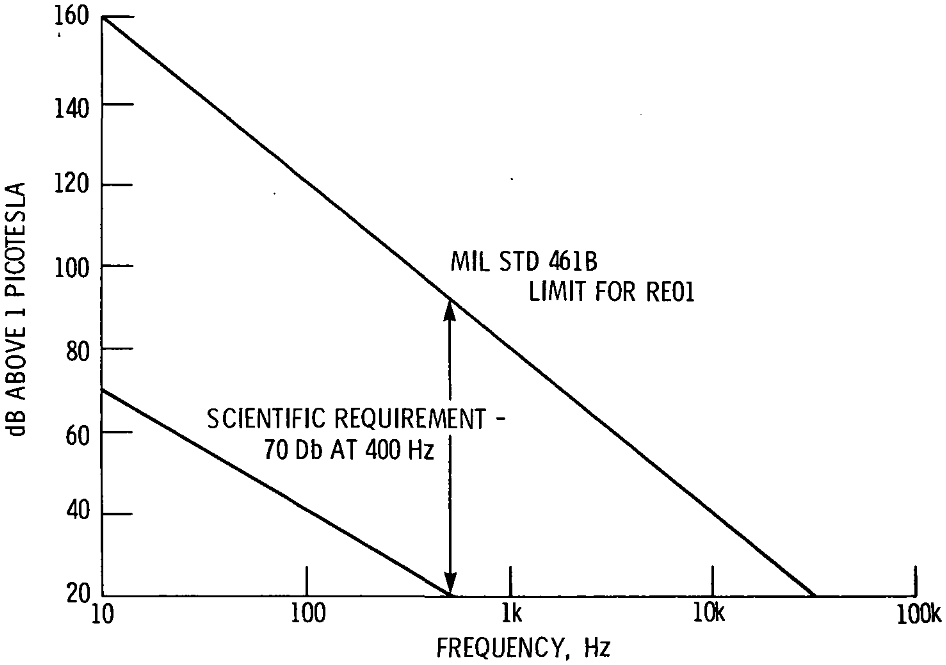
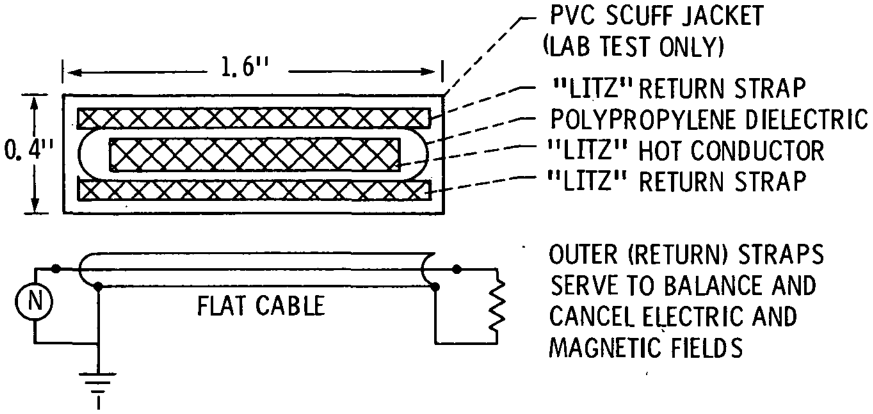


Figure 7. - Narrowband magnetic radiation.



OUTER (RETURN) STRAPS
SERVE TO BALANCE AND
CANCEL ELECTRIC AND
MAGNETIC FIELDS

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 8. - Flat cable.

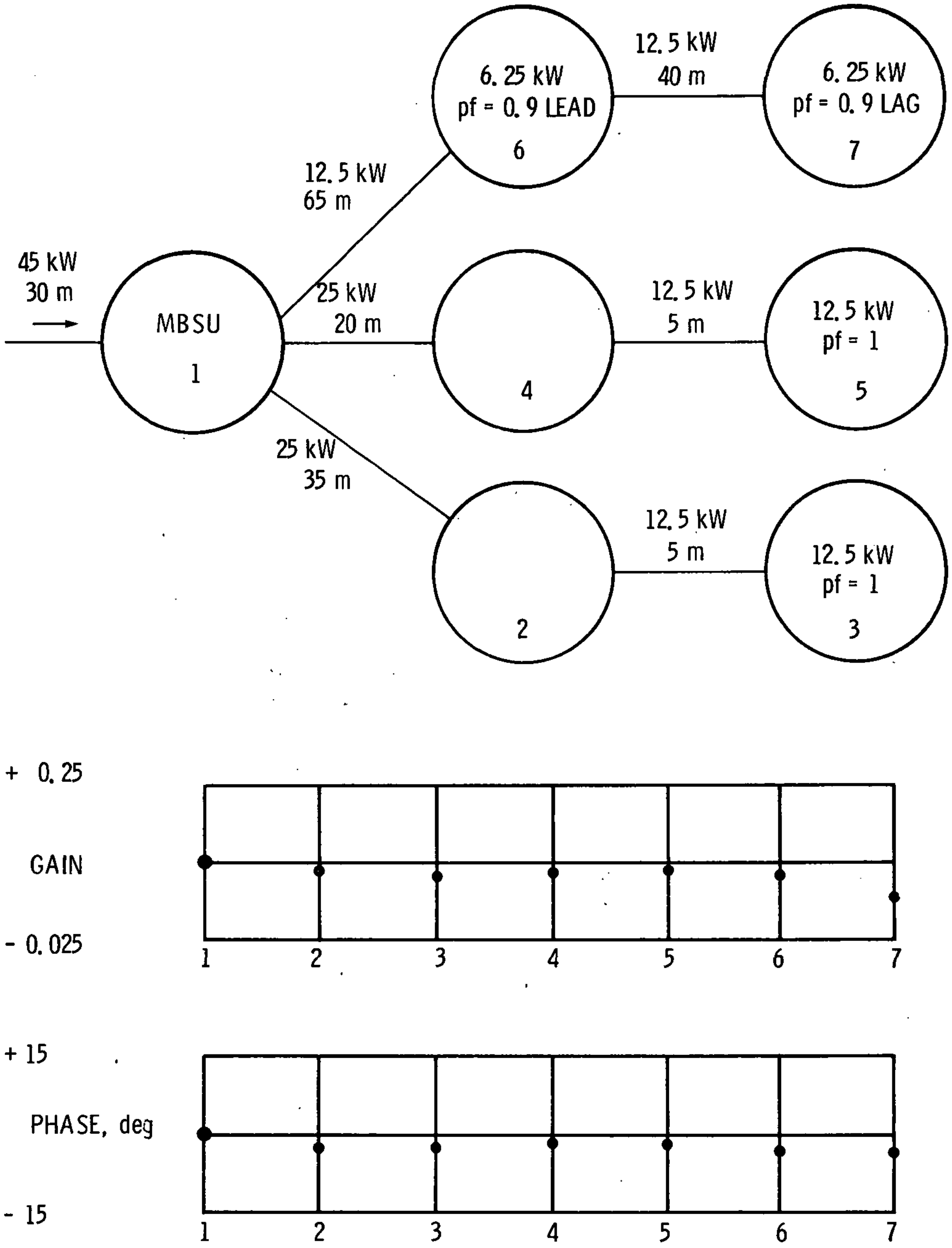


Figure 9. - System regulation.

1. Report No. NASA TM-88801	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle 20 Kilohertz Space Station Power System		5. Report Date
		6. Performing Organization Code 481-54-02
7. Author(s) Irving G. Hansen and Fredrick J. Wolff		8. Performing Organization Report No. E-3140
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135 ND315157		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 19th Annual Electronics and Aerospace Conference, sponsored by the Institute of Electrical and Electronics Engineers, Washington, D.C., September 9, 1986.

16. Abstract

The Space Station represents the next major U.S. commitment in space. The efficient delivery of power to multiple user loads is key to that success. In 1969, NASA Lewis Research Center began a series of studies with component and circuit developments that led to the high frequency, bi-directional, four quadrant resonant driven converter. Additional studies and subsequent developments into the early 1980's have shown how the high frequency ac power system could provide overall advantages to many aerospace power systems. Because of its wide versatility, it also has outstanding advantages for the Space Station Program and its wide range of users. High frequency ac power provides higher efficiency, lower cost, and improved safety. The 20 kHz power system has exceptional flexibility, is inherently user friendly, and is compatible with all types of energy sources - photovoltaic, solar dynamic, rotating machines or nuclear. Lewis has recently completed development under contract a 25 kW, 20 kHz ac power distribution system testbed. The testbed demonstrates flexibility, versatility, and transparency to user technology as well as high efficiency, low mass, and reduced volume.

17. Key Words (Suggested by Author(s)) 20 Kilohertz power system Space station Power system	18. Distribution Statement Unclassified - unlimited STAR Category 20

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135

NASA