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An Automatically Controlled Power System for a Communications Buoy

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CONTENTS

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AN AUTOMATICALLY CONTROLLED POWER SYSTEM FOR A COMMUNICATIONS BUOY

INTRODUCTION

A communications system currently under development at the Naval Research Laboratory (NRL) will enable a submerged submarine to establish and maintain communications with surface and airborne craft. This system, imposing minimum restrictions on operating depth, employs a towable antenna buoy containing transceivers and a transponder. Control systems within the buoy and submarine maintain the desired operating modes through interconnecting wires in the tow cable. Several sophisticated methods are being employed to obtain maximum utilization of available tow-cable conductors, which are restricted both in size and number from a hydrodynamic standpoint. For example, digital commands are used for control, and frequency multiplexing is used for information. Likewise, system complexity has resulted in a need for a more advanced means of power transfer. This report deals with a new method for supplying power to the buoy electronics, resulting in improved performance over that of previous systems.

BACKGROUND

The AN/BRA-27 communications system was developed at NRL for use on conventional submarines. This system employed a UHF and an HF transceiver along with LF/VLF listening capability. Although frequency multiplexing was used for information transfer on the tow cable, system complexity was not great enough to require digital control. Similarly, due to relatively constant power requirements in the two modes, transmit and receive, the power system could be fairly simple. Essentially, it consisted of a two-voltage power source in the submarine and shunt zener diode regulation at the buoy end of the tow cable. In the receive mode, current drawn by the buoy electronics developed only a small voltage drop on the tow-cable conductor. The inboard power source was required to supply this drop plus the buoy operating voltage (30 V). In the transmit mode the inboard voltage was adjusted to supply enough current to the buoy to assure that the regulating zener diode never went out of conduction. Since operating current and changes in current due to modulation and load variation were comparatively low, the zener diode was required to dissipate only about 20 W. Thermal limitations were not excessive, since little additional power was dissipated; hence this system was quite acceptable.

In progressing from this communications system to the one presently being developed, several modifications and additions have resulted. Both transceivers, for example, have been increased in power. An IFF transponder has been added. The digital control system now used consumes a significant amount of power, and provision is being made for the addition of other capabilities; a video system for example, has been proposed. As a result of power consumed by each of these subsystems, there are as many as twelve different power states. Also, since current requirements for the transceivers have increased, the corresponding current variations under modulation and load have also increased. Finally, since the added electronics result in much more power being dissipated as heat in the buoy container, care must be taken to avoid adding any more heat than is absolutely necessary.

METHODS

In evaluating various methods for supplying power, certain assumptions are made on subsystem power consumption. First, all components use 28 Vdc, a standard operating voltage for state-of-the-art, solid-state designs. The digital control system uses 5 Vdc, which is derived from the 28-Vdc supply via a linear regulator. Although inefficient in operation, a linear regulator is preferred over a switching regulator within the buoy to avoid generation of noise which could completely mask LF/VLF reception. This regulator will dissipate approximately 16 W, supplying 5 V to the logic circuits at 0.7 A. The UHF and HF receivers will draw approximately 0.3 A. The UHF transmitter will draw 1.5 A with a peak current of 2 A. The HF transceiver under AM modulation will draw 2 A with a peak current of 3 A. In SSB operation the HF transceiver will require a somewhat lower average current. The IFF transponder will consume between 1.5 and 2 A. Allowing 0.5 A for additional equipment, the complete system under worst-case conditions will draw an average current of over 5 A. Under these conditions the electronics container will dissipate approximately 120 W. These values have been summarized in Table 1. A profile of the various operating points is shown in Fig. 1.

Table 1
Summary of Expected Operating Currents

Subsystems	Average Operating Current (A)	Peak Current (A)	Expected Deviation in Average Operating Current (mA)	Power Dissipation (W)
Logic	0.7	–	±10	20*
UHF + HF receivers	0.26	–	±20	7
UHF (AM)	1.5	2	±500	34
HF (AM)	2	3	±500	45
HF (SSB)	1.4	3	±500	≈30
IFF	1.8	–	±300	47
Auxiliary equipment	0.5	–	–	14

*Includes 5 V regulator.

The tow-cable power conductor is assumed to have a total resistance of 13 Ω and a ground-return resistance of 2.5 Ω. No limitation on current-carrying capacity is assumed, since the cable is in contact with a good heat sink and, in any case, can carry two to three times the proposed operating current.

A power system similar to that used in the AN/BRA-27 equipment would require at least three operating voltages to assure good regulation and, in this case, would result in up to 50 W heat dissipation in the zener diode. With four switchable voltages, zener-diode dissipation could be kept below 30 W. With the addition of some logic to determine the switched line voltage, this method would supply the buoy with the proper operating voltage. The efficiency of the system from power supply to buoy would vary from 60% to 23% depending on the mode of operation. The dissipation contributed by the zener diode eliminates this system, however, since it would contribute significantly to the heat generated in the electronics container.

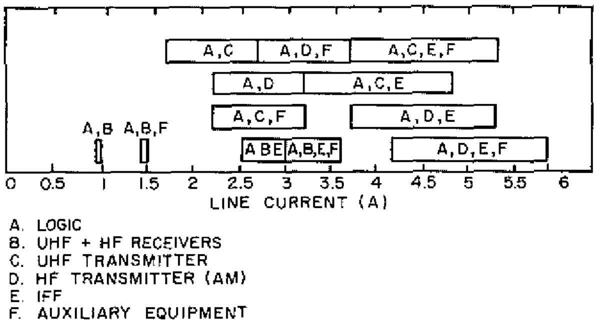

Fig. 1 - Expected range of line currents for various operating modes

The efficiency of the previous system is very poor, especially at high power levels. This is mainly due to line losses resulting from heavy currents. Another method, using a high ac voltage from submarine to buoy which is rectified and filtered at the buoy, could considerably improve system efficiency. If 250 Vac were supplied to the buoy, for example, line current would be only 0.7 A under full load with a resultant system efficiency of about 80%.

A similar approach could use a high dc voltage on the tow cable which would be converted to 28 Vdc at the buoy. This method could realize comparable efficiencies in a smaller space by using a dc-to-dc converter or switching regulator. Unfortunately, both of these would generate enough noise to make the LF/VLF system useless. Necessary filtering would make the physical size comparable to the ac system.

These two methods provide excellent system efficiencies by reducing line losses to an insignificant fraction of the total power consumed. In addition, no control of the inboard power supply is required. All the regulation necessary can be accomplished at the buoy, although not without some heat generation. Thus the power system can be very simple. Unfortunately, neither of these methods is adaptable to this application, due to the size and weight of the components which must be located within the buoy.

Perhaps it should be pointed out at this time that high efficiency for the total system, submarine to buoy, though desirable, is not an essential requirement as it would be in a system of much higher power. Of much greater importance is that the power system contribute little additional heat dissipation in the electronics container while achieving good regulation.

One method which would accomplish this employs a means for sampling line current. The line voltage would then be made a function of this sampled current such that the line voltage increases as the line current increases. With proper adjustment the voltage at the buoy would remain constant under any load. In fact, if the adjustment were exact, no zener-diode regulation would be required at the buoy; hence, no dissipation would be added to the electronics container. Since this is an open-loop system, however, there is no assurance that the balance thus obtained could be maintained under all environmental conditions. For example, under a full load, a 10-C-deg change in temperature on the tow cable would result in a 2.5-V change in buoy voltage, due to the rise in tow-cable resistance. Similarly, the ground-return resistance can cause a ±2.5-V variation, depending on the length of cable deployed and the salinity of the sea water. Finally, any change in tow-cable length would require readjustment of the balance.

Since closed-loop control will result in little additional complexity, this approach is adopted for the developmental system. By sampling the voltage at the buoy and feeding back an error voltage, any desired regulation can be obtained without dissipating any power at the buoy. The system will automatically adjust to any environmental condition within the control of the system.

INBOARD POWER SUPPLY

The inboard power supply must be able to supply the tow cable with a voltage variable from 40 to 110 V. Several methods may be used to accomplish this, including a linear regulator, a switching regulator, and SCR control.

A linear regulator, though capable of providing excellent transient response, must be rejected, due to excessive power dissipation under medium loads. This dissipation would be approximately 150 W for the system under consideration.

SCR control is the most attractive method, due to simplicity and low dissipation. However, to assure true SCR control, a large inductor must be used in the filter. The effect of this inductor on the transient response would be significant and would complicate the control-system design. Also, high-current, high-inductance chokes are not readily available.

A switching regulator, though more complex, can provide a variable voltage at high currents with a transient response quite adequate for this system. Filter inductors can be an order of magnitude smaller than for the SCR case and are readily available. Since space is not as restricted in the submarine, the noise generated can be filtered to a high degree, eliminating interference problems.

A switching regulator is capable of achieving a conversion efficiency of up to 90%. Figure 2 is a plot of conversion efficiency as a function of load current for a prototype, lower power switching regulator. Such an efficiency is possible, since the pass transistor assumes only two states: saturation and cutoff. The only losses in the transistor are due to finite saturation voltage and finite switching times.

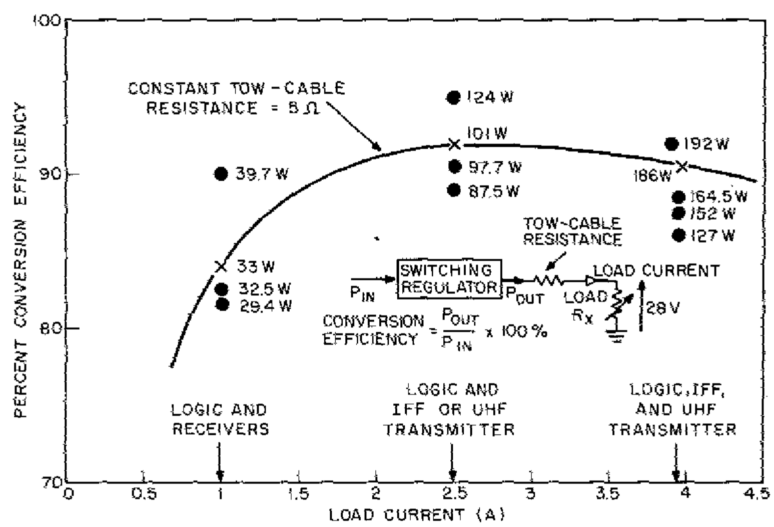

Fig. 2 - Conversion efficiency as a function of load current with delivered power as a parameter

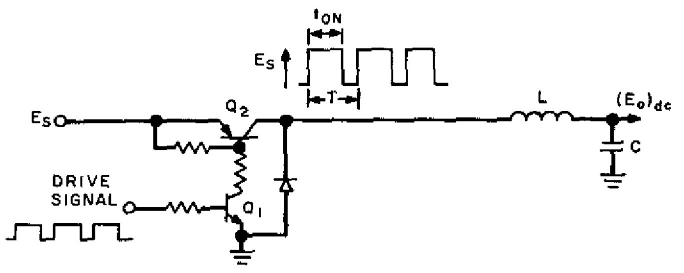

Fig. 3 - Simplified switching regulator

A variable output voltage is obtained by controlling the ratio of the time the transistor is conducting to the period of the drive signal. In Fig. 3 a drive signal is applied to Q_1 which in turn switches Q_2 on and off. The effective dc output voltage is given essentially by

$$(E_o)_{dc} = E_s \frac{t_{ON}}{T} \tag{1}$$

Voltage is controlled by varying either t_{ON} or T. Since varying the pulse width while keeping the frequency constant results in frequency-stationary harmonics which are easier to filter, this method is used here.

The filter input inductor is usually chosen to provide as small a current variation (Δi_L) as possible. This change in inductor current should be kept small to avoid excessive stress on the pass transistor. The maximum inductor current variation occurs when the effective output voltage is equal to one-half the source voltage and is given by

$$(\Delta i_L)_{max} = \frac{E_s}{4fL} \tag{2}$$

With a driving frequency of 15 kHz, an inductance of 10 mH, and a source voltage of 160 V, $(\Delta i_L)_{max}$ is equal to less than 0.3 A.

The requirement on the total filter is to provide as much high-frequency filtering as possible. If, for example, a noise voltage on the power line of less than 2 μV is desired, the filter must provide at least 160-dB attenuation at 15 kHz. A two-section filter with a cutoff frequency of 150 Hz will provide this while having little effect on the control system. In addition, a high-frequency filter is used to suppress transients coupled through the large inductors.

CONTROL SYSTEM

General control-system requirements can be determined by referring to the block diagram in Fig. 4. In this diagram K is the gain of the inboard power supply, α is the attenuation of the cable, A is the gain of the sampling circuit in the buoy, and βE_B represents the error voltage developed on the ground return from the buoy to the submarine. From this diagram the closed-loop response is determined to be

$$\frac{E_B}{E_R} = \frac{AK\alpha}{1 + K\alpha(A+\beta)} \tag{3}$$

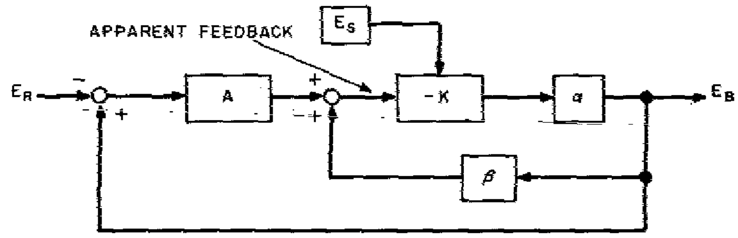

Fig. 4 - Mathematical block diagram of the control system

The regulation of the system is the ratio of the no-load voltage to the full-load voltage, which when system parameters have been substituted into Eq. (3) yields

$$\frac{E_{BNL}}{E_{BFL}} = \frac{5 + (17.5/AK) + (2.5/A)}{5 + (7.5/AK) + (0.5/A)} \tag{4}$$

Equation (4) can be used to determine control-system requirements. For example, if no gain is supplied at the buoy (E_B only is fed back to the submarine), the best regulation obtainable is approximately 36%. In general, for any given desired regulation, a certain gain A is required. On the other hand, perfect regulation can be approached by allowing A to become very large. In the developmental system, A is an integrator, thus providing very good regulation. The power-supply gain K has been chosen to be 20 to limit the necessary voltage excursions on the feedback line.

The following philosophy has been followed in the frequency-response design. No attempt is made to have the control system follow frequencies in the audio range encountered in modulating one of the transmitters. Instead, a fairly large capacitor is provided at the buoy. This capacitor has an impedance of 0.14 Ω at 500 Hz and provides adequately low source resistance for audio frequencies. The control system, however, is required to follow the varying power requirements caused by the syllabic content of speech. In this respect a frequency response from dc to 10 Hz is desirable. The control system will thus be able to respond to environmental load changes, such as are encountered when a transmitter is driving an antenna which moves in and out of the water. With a 10-Hz bandwidth the control system will be able to readjust the line voltage in response to an additional load (for example, turning on the IFF unit) within 30 msec. Finally, with this bandwidth, no problems should be encountered in the design due to the power supply filter.

In the frequency-response design, the equivalent feedback configuration shown in Fig. 5 is particularly useful. Frequency tailoring is accomplished within gain elements A and K to obtain the equivalent-circuit frequency response shown in Fig. 6.

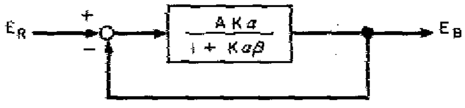

Fig. 5 - Equivalent circuit representation of the control system

Up to this point the power supply has been assumed to have a linear gain K. The inherent transfer characteristic for the pulse-width modulation system used conversely displays a quite nonlinear behavior, as shown in Fig. 7. Whereas the control system design could include this nonlinearity, it is more desirable to linearize the power supply. By employing feedback around the power supply, as shown in Fig. 8, the gain element K can be made linear, as shown in

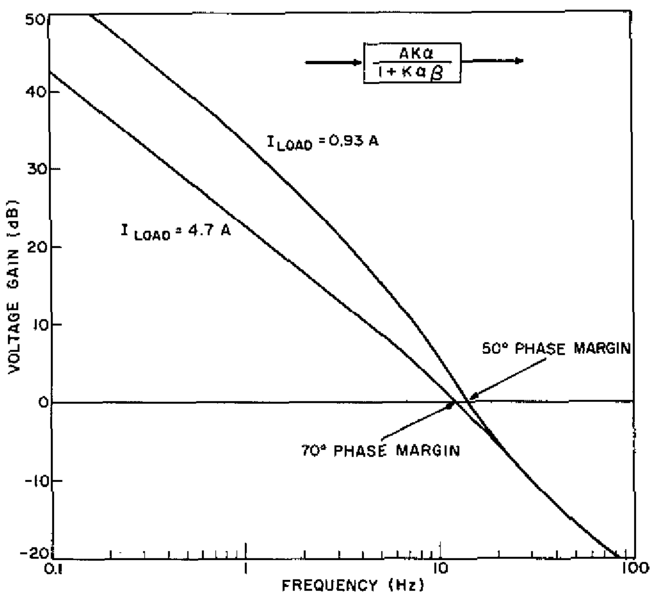

Fig. 6 - Frequency response of the equivalent-circuit open-loop transfer function

Fig. 9. Moreover, this feedback accomplishes another purpose. The switching-regulator input voltage E_s is obtained from an isolation-transformer/bridge circuit with a single-capacitor filter. As such, E_s possesses a strong 120-Hz component, especially at higher currents. The feedback arrangement shown in Fig. 8 has a frequency response wide enough to suppress this 120-Hz component by modulating the drive signal to the pass transistor. Since the LC filters are not within the feedback loop, no stability problems are encountered. Although the LC filters affect the frequency response above 100 Hz, the only significant effect on the frequency response of the complete system by the element K comes from frequency-tailoring elements represented by γ in Fig. 8.

The closed-loop response for the complete system is shown in Fig. 10. Figure 11 is the theoretical time response of the system to a step change of the reference voltage E_R. The buoy voltage E_B and effective load R_x are related by a complex nonlinear equation. No attempt is made here to solve for

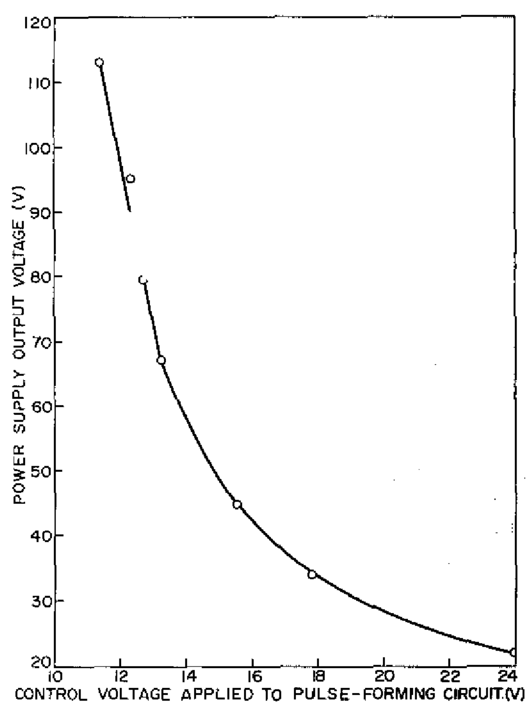

Fig. 7 - Power-supply output voltage as a function of the control voltage

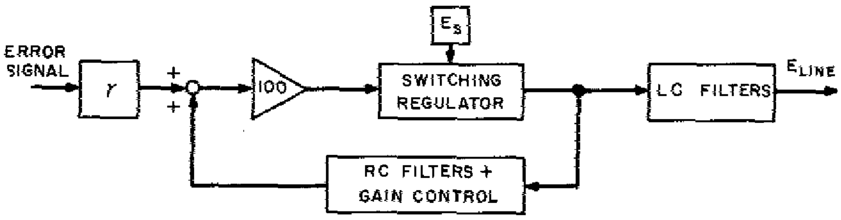

Fig. 8 - Expanded diagram of power-supply amplifier

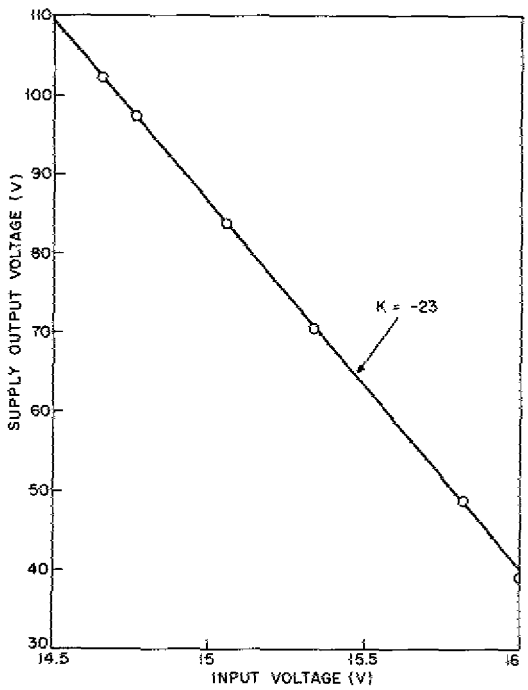

Fig. 9 - Power-supply output voltage as a function of the control voltage with feedback

the response of the system to load variations. Figure 12 is a block diagram of the complete system.

The system cannot be any better than the reference voltage it must follow. In the developmental system, a 0.25-W zener diode is used as the reference. The buoy voltage will be governed by the temperature coefficient of the zener diode voltage. The use of a temperature-compensated zener diode as a reference will provide excellent voltage stability.

PROTECTION CIRCUITS

The power system includes several protection circuits to prevent failure of components. Overcurrent protection, for example, shuts off the system when a current of greater than 6 A is being drawn. The supply will recover within 1 sec, and if the overcurrent condition persists, it will shut off again. In the presence of a short circuit, it will remain off until the short circuit is removed. A temperature-sensing circuit supplies a warning light when the power-supply temperature exceeds 70°C.

The feedback signal from the buoy is fed to the tow cable as a dc voltage. The conductor is shared with the communications information signals, and thus no efficiency is lost in tow-cable conductor use. If this conductor should become open or shorted, the feedback signal would be lost, but the information would likewise be lost. Hence, this feedback line is continuously monitored, and in the case of an open or short circuit, the power supply is shut down.

Finally, heavy-duty zener diodes rated at 31 V are shunted across the power line at the buoy. These diodes do not conduct under normal conditions. They provide protection against overvoltage situations such as overshoot.

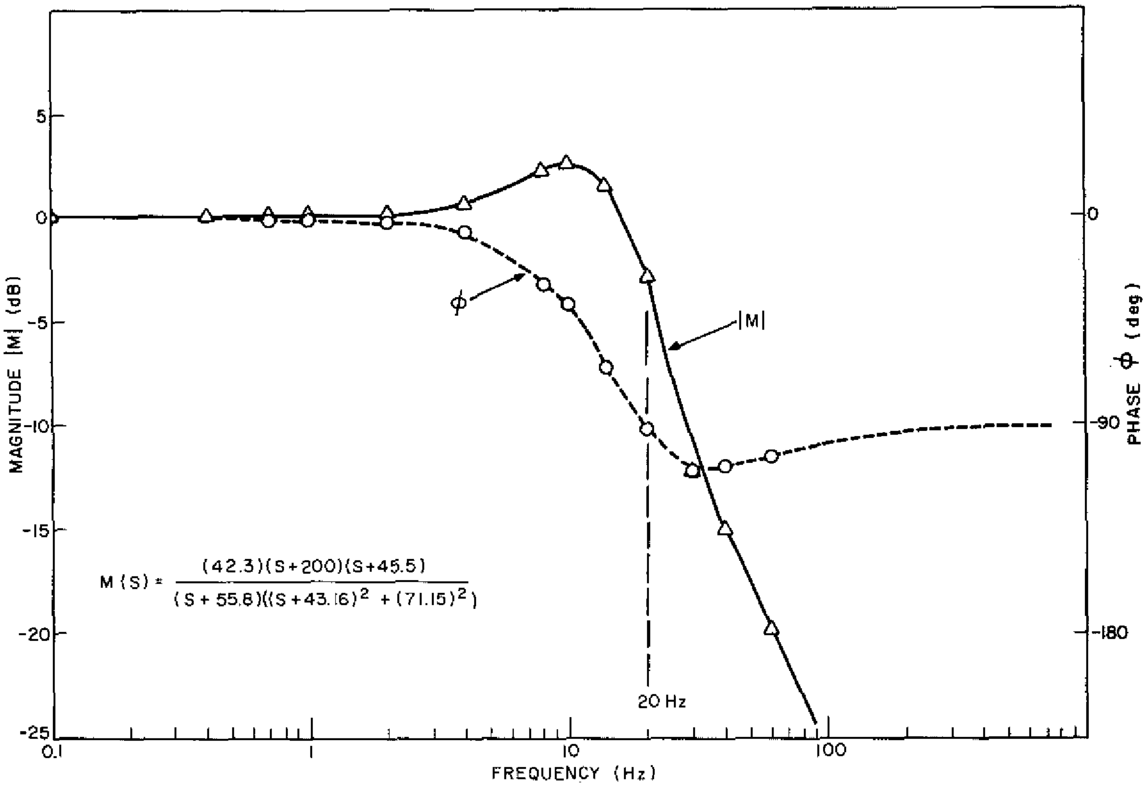

Fig. 10 - Closed-loop frequency response for the control system with a load current of 0.93 A

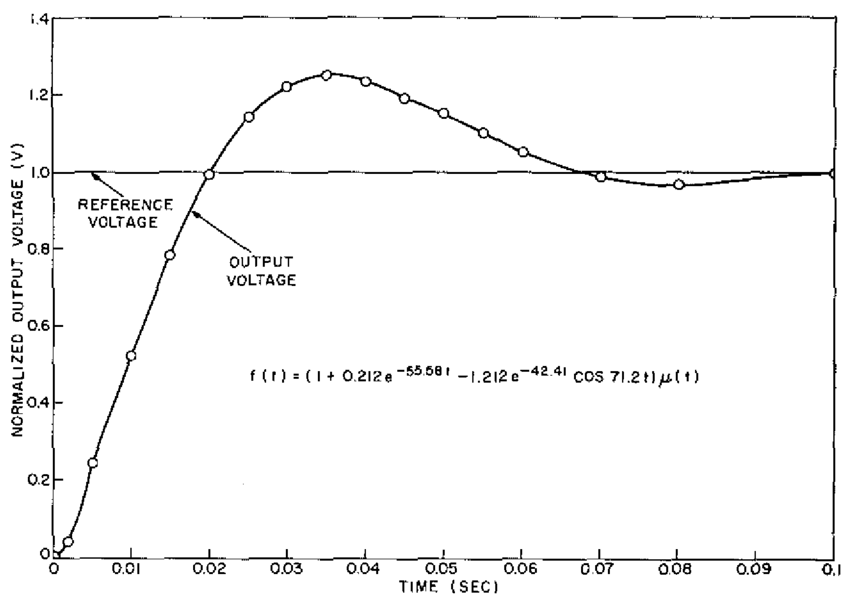

Fig. 11 - Time response of the control system to a step change of the reference voltage

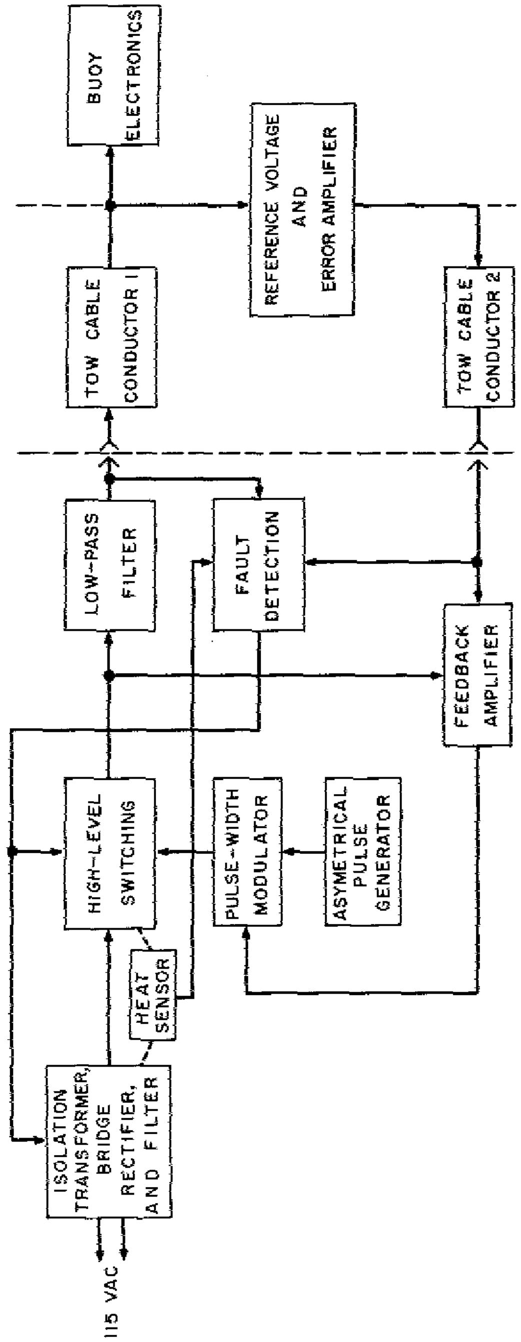

Fig. 12 - Control system

CONCLUSION

A new approach for supplying power to a communications buoy has been described. The system is completely automatic, requiring no periodic readjustment. It includes certain fail-safe features which prevent catastrophic failure either by exercising control over the system or by warning the operator. The system displays a considerable improvement over previous power-supply systems and should be adequate for future intermediate power applications.

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