Power Supplies

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This article describes the power supply system and the equipment developed to supply power to the repeaters and equalizers spaced along the coaxial cable. Power is supplied as a constant direct current over the center conductors of each pair of coaxial tubes in a series circuit consisting of two or four current regulated converters and the cable system consisting of the repeaters and equalizers. The system is designed for high reliability, long life, ease of maintenance and repair, and unattended operation.

I. INTRODUCTION

This article describes the power feed system and the equipment used to supply dc operating power to the repeaters and equalizers spaced about every two miles along the cable system. Included is a description of the integral protection and monitoring features which protect the cable system components from damage by excessive currents or voltages and which aid in diagnosis of equipment malfunctions.

II. POWER FEED SYSTEM

2.1 *Basic Arrangements*

The power feed system shown in Fig. 1 is used for each pair of coaxial tubes.[1] For systems shorter than 75 miles, one pair of power converters may be eliminated.

Power for the repeaters and equalizers is supplied over the coaxial tubes by circulating a constant direct current through the series circuit comprising the coaxial tube center conductors, the repeaters and equalizers, and the power converters. Each repeater or equalizer contains a voltage regulating diode which determines its voltage drop. With this arrangement the power delivered to each repeater or equalizer is independent of its location in the system.

No power current flows through the coaxial tube outer conductors.

These are grounded at each repeater point for personnel safety as one of the many precautions taken in the system design to prevent personnel contact with high voltages. The power separation filters shown in Fig. 1, and other filters located in each repeater or equalizer, direct the transmission signal and the power current through their respective paths.

Input power is obtained from a −24 volt battery system which provides operating power for all equipment in the station. The −24 volt battery system is of conventional design, using lead acid storage batteries maintained in a fully charged state by rectifiers operating from commercial ac power or from reserve ac gas turbine or engine alternator equipment installed in the station.

2.2 *Reliability*

Reliability refers to the ability of the system to provide continuous transmission capability. This capability is achieved by the use of redundant transmission facilities which are rapidly and automatically switched into service whenever working facilities fail. The extent of the redundant facilities required depends upon both the failure rate and the repair time of the equipment making up the system. In the L-4 system, redundancy is limited to the provision of a single complete Fig. 1 arrangement for protection of one to nine working systems.

The power converter is designed with sufficient margins against failures resulting from normal aging of components so that a malfunction almost certainly indicates catastrophic failure of a component. Passive components have been selected to provide a useful life of 20 years at their normal working stress levels. Low power semi-conductors are operated at stress levels expected to give failure rates approaching 0.001 percent per thousand hours. Power transistors are subjected to screening tests designed to yield devices which have failure rates not exceeding 0.01 percent per thousand hours under normal circuit operating conditions.

Self-contained alarm and monitor circuits facilitate diagnosis when trouble does occur. Faulty subassemblies can be readily replaced with spares, thereby permitting the equipment to be quickly restored to an operable condition. A low inherent failure rate combined with rapid repair capability makes this approach to system reliability practical.

2.3 *Basic Design Considerations*

In a dc power system such as this, it is necessary to guard against electrolytic corrosion resulting from sustained flow of dc current

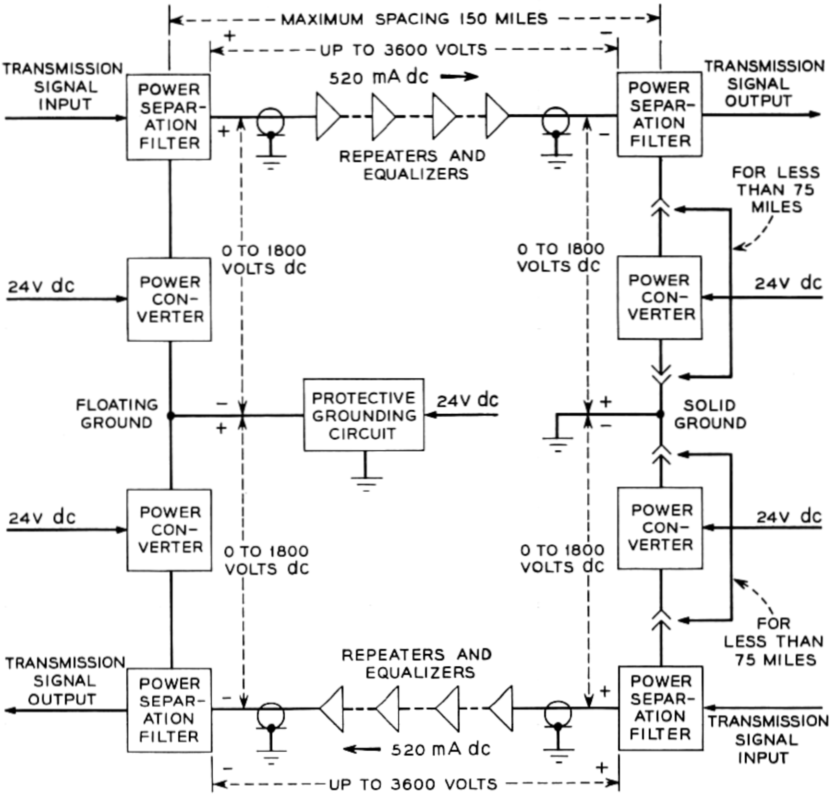

Fig. 1 — Power feed system block diagram.

through metal-earth interfaces. An ungrounded system would avoid the problem, but such a system has the disadvantage that the maximum spacing between power feed points can only be about one half that possible with a grounded system. The capability for maximum spacing between power feed points is desirable because the cost of the structure and facilities required at these points is a significant item in the overall system cost.

In an ungrounded system, the voltage to ground at any point around the loop depends upon leakage resistances which are not controllable in a working system. In extreme resistance unbalance, the voltage to ground at one of the power separation filters, for example, could be nearly equal to zero. In this case the maximum voltage point is at the other power separation filter located at the same end of the system.

The magnitude of this voltage is equal to the sum of the output voltages of two power converters and is twice what it would be if leakage resistance was balanced.

The corona threshold level of the coaxial tubes determines the safe upper working limit on voltage to ground. If leakage resistance is the only means for controlling voltage to ground, allowance must be made for the effects of resistance unbalance which, in the limit, requires a two-to-one margin. Since the required operating voltage is proportional to system length this two-to-one voltage margin necessitates a two-to-one reduction in the spacing between power feed points. If means are provided to limit the voltage excursions, then the spacing limitation can be eliminated.

After careful study, it was concluded that the best approach was to ground the system at one point as shown in Fig. 1. The required voltage limiting means is provided by the protective grounding circuit.

DC ground current can flow when the protective grounding circuit operates. This condition generates an alarm which serves to remind personnel that abnormal conditions exist and to stimulate action to return the system to the normal condition. The rate of corrosion when the floating ground is grounded is small; the total corrosion is not significant unless the abnormal condition exists continuously for several years.

III. PROTECTIVE GROUNDING CIRCUIT DESIGN

3.1 *Floating Ground Voltage*

The floating ground voltage consists of two components. The first is a low frequency (essentially dc) component resulting from variations in the individual converter output voltages, in the load voltage of the cable system and from earth potentials. The second is an ac component resulting from induction into the coaxial cable from nearby power lines and to transients arising from faults in the cable system.

When the grounding circuit operates, the resulting transient can momentarily affect transmission. It is desirable, therefore, that such grounding not occur except when there is real trouble in the system. Studies have shown that substantial ac voltages in the order of 800 volts can be induced, as a series (longitudinal) voltage, into the center conductors of the buried coaxial tubes when single phase faults occur on commercial power transmission lines which run parallel for distances as short as 15 miles to the cable route. The induced voltage is of similar magnitude and phase in each coaxial tube and therefore affects the instantaneous floating ground voltage. This induced voltage is troublesome only if its presence causes a malfunction such as insulation breakdown. The protective grounding circuit is designed to ignore this voltage unless it carries the instantaneous floating ground voltage and in turn the coaxial tube center conductor voltage beyond levels which will significantly reduce component life. A level of 2600-volts peak has been set as the maximum safe instantaneous voltage limit. This corresponds to a peak floating ground voltage of 800 volts. When the instantaneous floating ground voltage is carried above 800 volts it is necessary to follow the lesser of two evils and ground the floating ground. The resultant fluctuations in cable current caused by the induced voltage must then be tolerated.

In contrast to the maximum allowable short duration voltage of 2600 volts, is the maximum long term overvoltage which the system can withstand without jeopardizing system life. This voltage is about 2200 volts which corresponds to a floating ground voltage of 400 volts. If the low frequency component of the floating ground voltage exceeds 370 volts the protective grounding circuit responds and grounds the floating ground.

3.2 *Protective Grounding Circuit Description*

Figure 2 is a simplified schematic diagram of the protective grounding circuit. Cold cathode gas tubes, in a relaxation oscillator circuit, provide the low frequency threshold voltage sensing capability. Gas tubes were used because of their low leakage current at voltages below breakdown. A 20-millisecond time constant is provided by elements R1–C1 to make this part of the circuit respond only to the low frequency component of the floating ground voltage.

Protection for the ac component is provided by a carbon block protector with an 800-volt nominal breakdown voltage.

The output pulses from the relaxation oscillator are coupled through transformer (T1) to a transistor pulse stretching circuit which will operate the grounding relay (P) and alarm relay (A) with a single pulse from the relaxation oscillator. The alarm relay locks the circuit in the grounded state in addition to signaling the external alarm system. The ground and alarm are released by operation of the manual reset switch which opens the alarm relay lock-up path.

A long-life incandescent lamp, mounted adjacent to the gas tubes, provides illumination which results in rapid ionization of the gas tubes when the applied voltage exceeds their breakdown level. Loss of illumination can result in ionization times of up to a few seconds which is a tolerable but undesirable long-term operating condition.

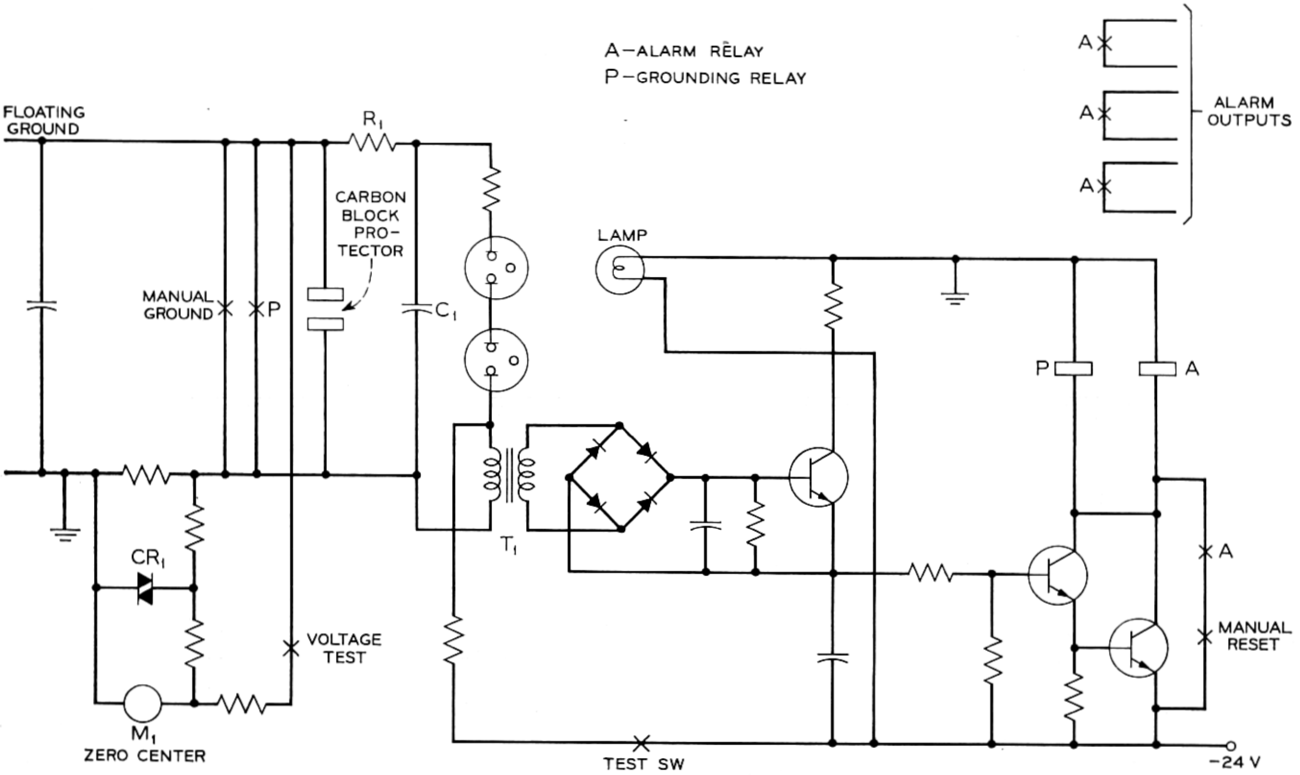

Fig. 2 — Ground circuit simplified schematic.

Two gas tubes that have a nominal breakdown voltage of 185 volts are connected in series to obtain the 370-volt low-frequency threshold voltage.

When the cable system is being energized or de-energized the floating ground is manually grounded. This permits power to be applied or removed on one coaxial tube at a time.

Meter M1 serves both as a milliammeter and a voltmeter. When energizing the system, a milliammeter null indicates that the currents in the two coaxial tubes are equal and the floating ground can be ungrounded without introducing power current transients. Likewise, when testing the ground circuit or when preparing to turn down power, if the floating ground voltage is zero, ground can be applied without introducing transients.

The pulse stretching circuit may be tested by operating the test switch. Before making this test the floating ground voltage is brought to zero by adjusting a power converter until a voltage null is indicated on the meter.

Diode CR1 serves to protect the meter against excessive current and permits a metering circuit having an expanded scale near null.

IV. POWER CONVERTER DESIGN

4.1 *General Considerations*

The power converter provides power to the cable system as well as providing a portion of the overall cable system automatic protection and alarm system. The latter function permits the cable system to be operated with a minimum of human supervision with the knowledge that the system will automatically protect itself from damage if abnormal conditions develop.

It was desirable, for both economic and technical reasons, to be able to tailor the power converter output capability to the requirements of the various cable lengths to be powered. Excessive output capability can cause system damage if the power converter regulator malfunctions and causes the power converter to deliver its maximum possible output into a short length system. This objective was readily achieved by the subdivision of the power conversion circuit into several identical modules or power stages and by arranging the circuit so that one or more power stages could be provided as needed to meet load requirements. A maximum of five modules are used, the number being dictated by the power handling capability of the available power transistors.

The voltage drops of the cable, the repeaters, and the equalizers are well controlled in manufacture but have only a small percent variation principally because of operation of auxiliaries such as the monitoring oscillators.[2] The load voltage sharing between the series connected power converters depends upon the magnitude and stability of their equivalent output resistances and the dc stability of their regulators. A lower bound on dc output resistance of 6000 ohms for a full length system is required to accommodate normal load voltage variations without exceeding the cable current deviation limits.

Table I contains a tabulation of the power converter electrical requirements and performance characteristics. The largest single variable to be accommodated is the input voltage variation. Open loop compensation is used to reduce the effects of this major variation and in

TABLE I — ELECTRICAL REQUIREMENTS AND PERFORMANCE CHARACTERISTICS

Converter input current	65 amperes maximum
Converter output current	520 milliamperes, working smoothly adjustable from zero
Converter input voltage	20–29 volts dc
Converter working output voltage range	40–1800 volts dc
Output current regulation and stability	±5.8% for combined variations in: temperature of: 40°–80°F input voltage: 20–29 volts output voltage: ±3.5%
AC component superimposed on dc output current	10 milliamperes rms maximum
AC component superimposed on dc input current	50 milliamperes rms maximum
Automatic shutdown limits	If output current decreases below 390 to 350 milliamperes or increases above 645 milliamperes after 1/2 to 1 second delay or if the output current decreases by more than 250 milliamperes in 1/2 second or fluctuates at an amplitude of 125 milliamperes at anywhere from a 4 Hz to a 2 kHz rate.
DC output resistance	1200 ohms per power stage 6000 ohms total

combination with a simple low-gain (3.5 dB) closed-loop regulator is sufficient to meet performance requirements.

4.2 *Power Stage Design*

Figure 3 shows a simplified schematic diagram of a power stage. Output control is achieved by controlling the pulse width of the "on" time of the power transistors which operate in the switching mode at a fixed repetition rate.[3] Pulse width is controllable from zero to virtually 100 percent duty cycle. Waveshape V_o is representative of the output from diode bridge CR5. This pulse train is filtered by the L1–C1 filter elements to produce the desired dc output.

Reliable operation of this circuit requires that simultaneous conduction of transistors Q4 and Q5 does not occur. The application of forward base current to an "on" going transistor is prevented until the off going transistor has fully turned "off." This requires that there be a time interval, defined as dead time, when no forward base current is applied to either transistor. This dead time must be greater than the difference between the actual circuit operating transistor turn-off and turn-on times.

Dead time is provided by the action of diodes CR3 and CR4. These diodes are designed to store a greater charge in response to a given forward current than the transistors. Consider current *ib*4, which for the moment is assumed to have the waveshape designated base drive current. When positive it passes in the forward direction through both the base-emitter junction of transistor Q4 and through diode CR4. When *ib*4 reverses polarity, at the beginning of a new half cycle of the base drive current, the charge stored in diode CR4 prevents reversal of its voltage until the stored charge has been removed. Until this occurs there is insufficient base voltage available to result in forward base current in transistor Q5.

The base drive current also passes through the base terminal of transistor Q4. This reverse polarity base current accelerates removal of the charge stored in the transistor reducing its turn-off time. When the transistor recovers, *ib*4 transfers to diode CR3. When diode CR4 recovers, *ib*4 transfers to the base of transistor Q5 and it turns "on." Thus the required dead time is provided. The process is similar for transistor Q5 and diode CR3.

Duty cycle control of transistors Q4 and Q5 is obtained by terminating forward base current prior to the end of each half cycle of the base drive current. Transformer T2 and the CR1 diode-transistor Q3

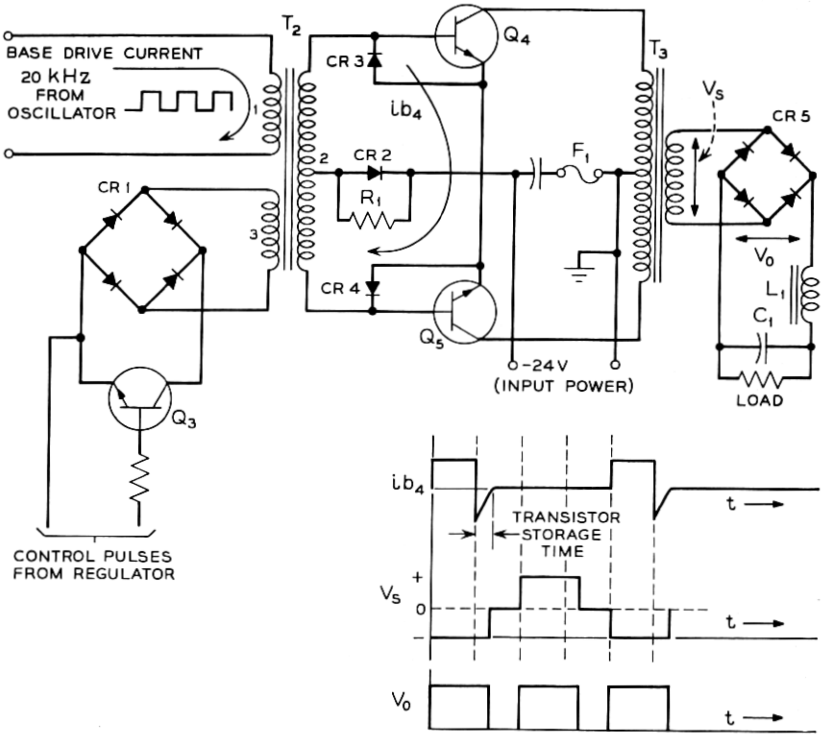

Fig. 3 — Power converter simplified schematic.

combination may be thought of as a current gate. When transistor Q3 is in the "off" state the gate is open and the base drive current passes through to the power transistors. When transistor Q3 is in the "on" state the gate is closed and base drive current is blocked.

To obtain satisfactory circuit operation it is necessary to minimize the time delay between the transistor Q3 control pulse and the power transistor Q4 or Q5 turn-off time. Power transistor storage time, the principal time delay, is minimized by taking further advantage of the charge stored in diodes CR3 and CR4. The transformed base drive current flowing through transistor Q4 and diode CR4, for example, results in stored charge in the forward biased junctions. Until this charge is removed these junctions have a definite open circuit voltage. When transistor Q3 turns on, the terminals of diode CR4 and the base and emitter terminals of transistor Q4 become parallel connected through the low impedance of winding 2. The resulting circulating current is in the reverse direction through the transistor base terminal. This accelerates the removal of the transistor stored charge. With this effect included current *ib*4 has the waveshape shown in Fig. 3. The decay in *ib*4 with time is caused by the increase in the transistor base-emitter impedance as the transistor stored charge is removed.

The time delay, resulting from the power transistor turn-off time, adds distortion between the control signal applied to transistor Q3 and the output pulse width. This is troublesome in applications such as this where the power stage functions as a pulse width modulator. Fortunately, as the output pulse width is narrowed, the finite power transistor response time results in less transistor stored charge making control down to zero output possible. This extreme control range is necessary to permit cable power turn up from zero.

Transistors Q4 and Q5 have specifications which limit the maximum in circuit turn-off time to 1.5 microseconds. Typically measured circuit turn-off time, at normal power output, is 1.0 microsecond.

Resistor R1 provides a path for collector-base junction saturation currents of transistors Q4 and Q5 during time intervals when transistor Q3 is "on" and no external base current is provided. Diode CR2 protects resistor R1 against excessive voltage if either transistor Q4 or Q5 develops an internal collector-to-base short circuit. The low impedance of the diode insures that this current will be large enough to blow the input protective fuse F1.

4.3 *Regulator Circuit Design*

To obtain open loop compensation against input voltage variations, the regulator circuit must develop a control signal for the power stage which results in generation of constant area pulses. This requires that the output pulse width V_o vary inversely with the magnitude of the input voltage. To obtain closed loop regulation it must be possible to vary, in response to a feedback signal, the area of the pulses held constant by the open loop compensating circuit.

The required control characteristic can readily be achieved by a magnetic amplifier. The magnetic amplifier contains two square hysteresis loop cores with windings arranged on these cores so that the magnetic flux swing in the cores can be controlled in response to currents and voltages impressed on the various windings.

Each core has an individual winding designated the gate winding. The two cores are then stacked and two additional windings wound around both cores. These windings are designated control windings. One of the control windings, further designated the bias winding, is current is in the reverse direction through the transistor base terminal. This accelerates the removal of the transistor stored charge. With this effect included current *ib*4 has the waveshape shown in Fig. 3. The decay in *ib*4 with time is caused by the increase in the transistor base-emitter impedance as the transistor stored charge is removed.

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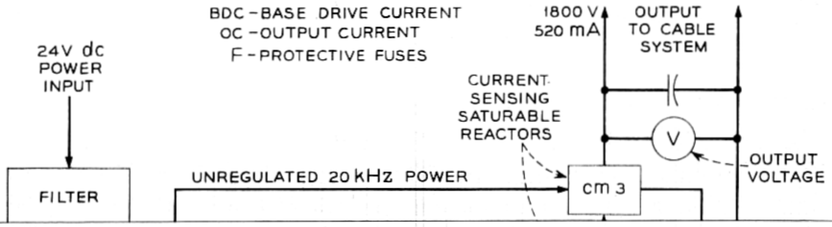
tem resulting in a virtually constant loop gain.

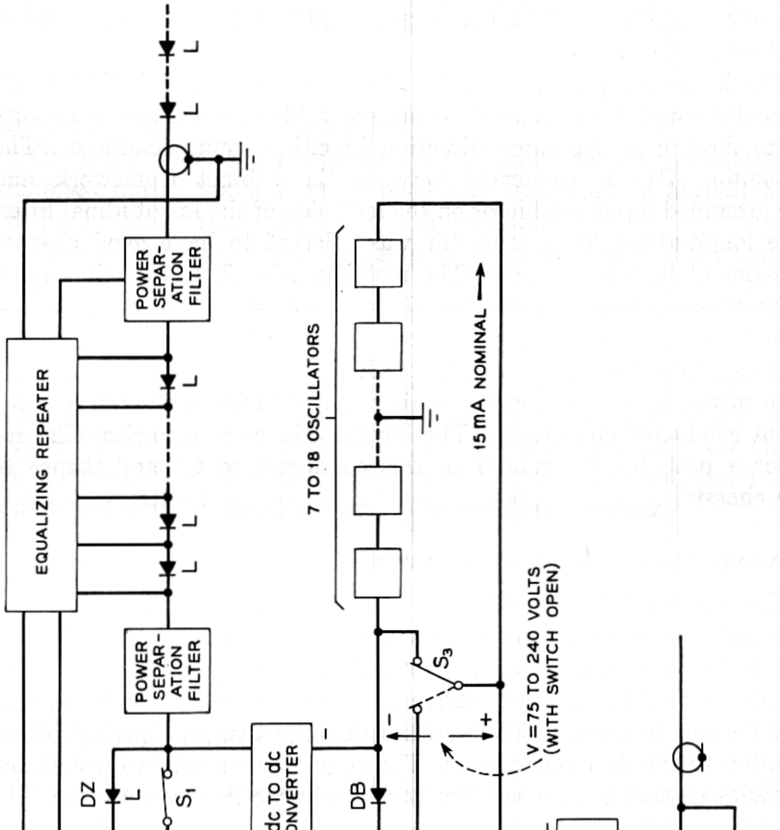
The required output resistance is, therefore, automatically obtained supplied a constant current and acts to bias or set the control characteristic for current in the other control winding at a convenient level and the required polarity.

In the absence of external gate winding voltage, the flux density



of 125 milliamperes or more in the frequency range of 4 Hz to 2 kHz.

All shutdown circuits



Monitoring oscillator power arrangements.

converter by diodes DB of Fig. 6. On-off control of these converters is provided from the transmission equipment acting through switches S1 or S2. A pair of converters, for redundancy, is provided at each equalizing repeater and is arranged to mount in manhole housings along with the transmission equipment.

Only one converter is energized at a time. Because of an upper limit (for personnel safety), of 120 volts to ground on the cable pairs feeding the monitoring oscillators, only 18 monitoring oscillators can be powered at one time. Switch S3 makes it possible to power a total of 36 monitoring oscillators in two groups of 18 each from one converter.

VI. PHYSICAL DESIGN OF THE POWER FEED CONVERTER

6.1 *Objectives*

The objectives of the physical design of the L-4 carrier power feed dc-dc converter power supply were to achieve compactness consistent with high voltage and heat dissipation requirements and to incorporate maintenance features to afford ease of rapid repair.

6.2 *General Description*

The complete converter power supply, seen in Fig. 7, is approximately 30 inches high, 21 inches wide, and 15 inches deep. The structure houses six large plug-in units, that is, up to five converter (power stage) units and one oscillator; and three smaller plug-in units, that is, the alarm sending unit, the alarm shutdown unit, and the regulating unit. Some of the plug-in units have been partially removed and are identified in the figure.

When less than five power stages are required, patch units, which provide circuit continuity through the connector and which prevent access to high voltages, are inserted in the unused positions. The converter power supply is suitable for use in a seven-foot-high standard power cabinets and nine-foot-high duct bays.

6.3 *Maintenance Feature Considerations*

Plug-in units, shown in Fig. 8, contain all of the active components, such as semiconductors and relays, to permit rapid repair of a power supply by replacement. Two extender designs for the plug-in units are available for maintenance and repair. Status lamps for alarm conditions, which remain lighted to retain a record of the fault cause if the unit is shut down, are furnished. Lamps, switches, and adjustments

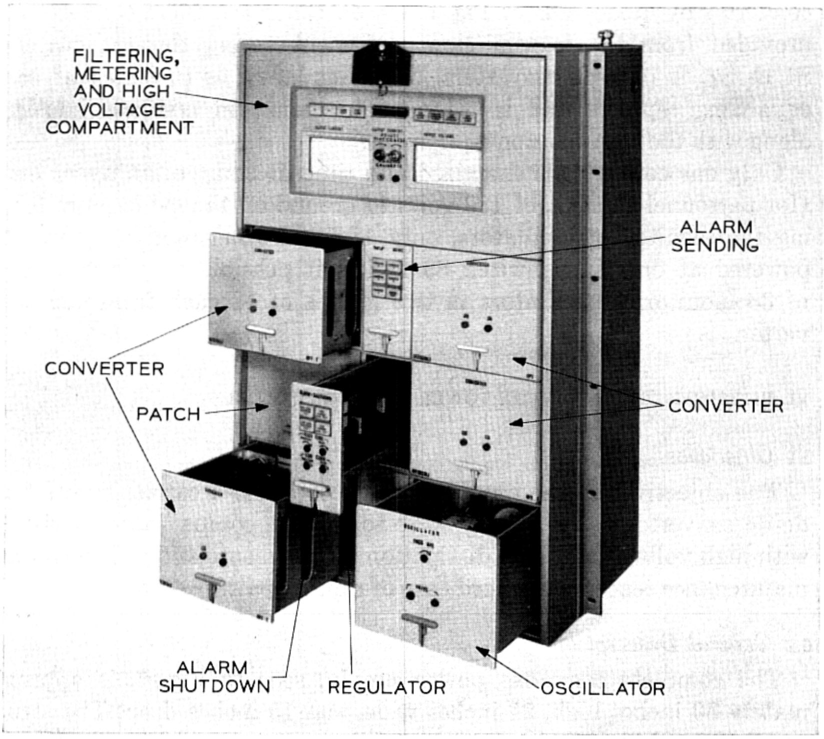


Fig. 7 — Power feed converter: Front view—plug-in units partially removed.

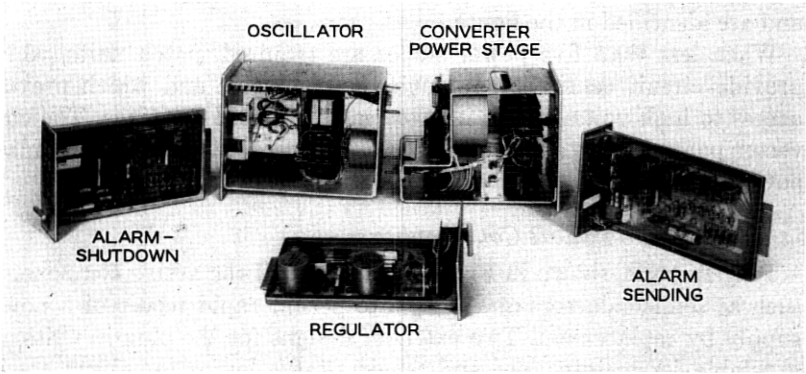


Fig. 8 — Converter plug-in packages.

for controlling and monitoring the power supply are located adjacent to the output meters to facilitate maintenance and adjustment.

6.4 *Personnel Protection Features*

The power supply's relatively high voltage of 1800 V requires adequate personnel protection features and mechanical design for long life operation. Certain parts of the equipment are protected by covers so that maintenance personnel are not exposed to hazardous potentials. The power supply series electrical interlock, described in Section 4.6, is an integral part of the personnel protection scheme. The converter (power stage) connector has interlock circuit pins which are shorter than those pins which carry high voltage, so that removing the converter plug-in will interrupt the interlock loop before the high voltage pins are disconnected.

6.5 *Detailed Mechanical Design of Plug-In Units and Extenders*

6.5.1 *Converter Power State and Oscillator*

The converter unit (power stage), shown in Fig. 7, is the basic building block module. The front panel latch, also shown, is used to eject the unit from the frame and to overcome the high contact forces of the high voltage connector at the rear of the unit. The power transistors are mounted on two heat sinks insulated from the chassis. Rectification is performed by a molded high voltage diode block assembly.

The 20 kHz driving frequency for the converter units is developed in the oscillator, also shown in Fig. 7. The oscillator has the same general profile as the converter unit. It uses the same type connector although different pins are used for the interlock loop, so that there will be no damage arising if a converter unit is plugged into an oscillator position or vice versa.

6.5.2 *Low Voltage Plug-In Units*

The three smaller plug-in units which may be seen in Fig. 7 are used for the basic regulating, alarm, and shutdown features of the power supply. These units have a die-cast frame and double-sided printed circuit boards with printed contact fingers to mate with the connectors mounted in the inner frame of the power supply.

6.5.3 *Extenders*

Two extender designs have been developed for this power supply for use when it may be necessary to repair the power supply or check various waveshapes in the field. The extender, for use with either the converter or oscillator unit (Fig. 9), is designed so that only the low voltage parts of the converter unit are accessible. These may be checked with proper maintenance tools when the extender is inserted in the power supply. It permits access to almost all of the components of the oscillator unit.

The extender unit for the three low voltage units is of much simpler design and incorporates a printed circuit board with a metal framework.

6.6 *Converter Main Chassis*

The power converter has a snap-in front cover which, when removed, exposes an inner hinged panel. Behind this panel are fixed components which include the 24 V battery input filter, a battery input fuse block with individual fuses for each power stage plug-in unit, and the battery input contactor.

Five combinations of voltmeters and associated multipliers are

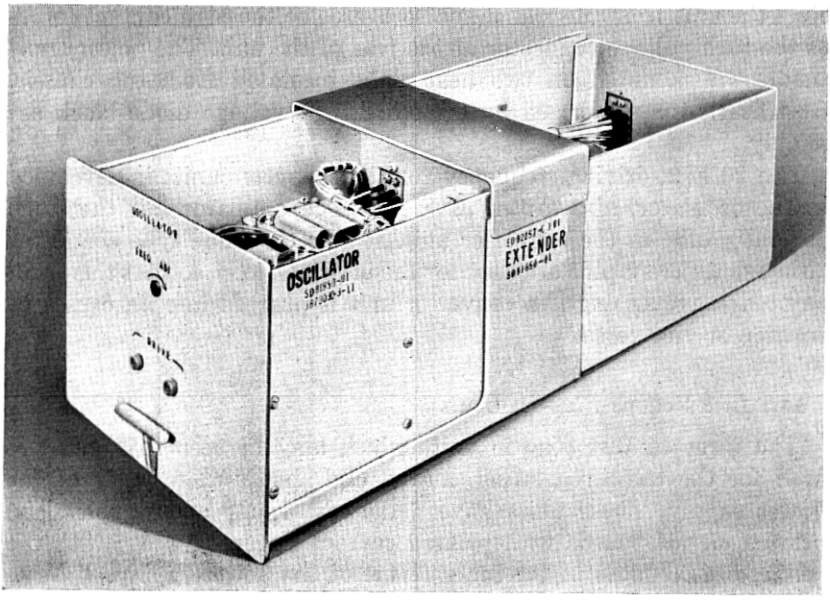


Fig. 9 — Extender for oscillator and converter (power stage) units—oscillator in position.

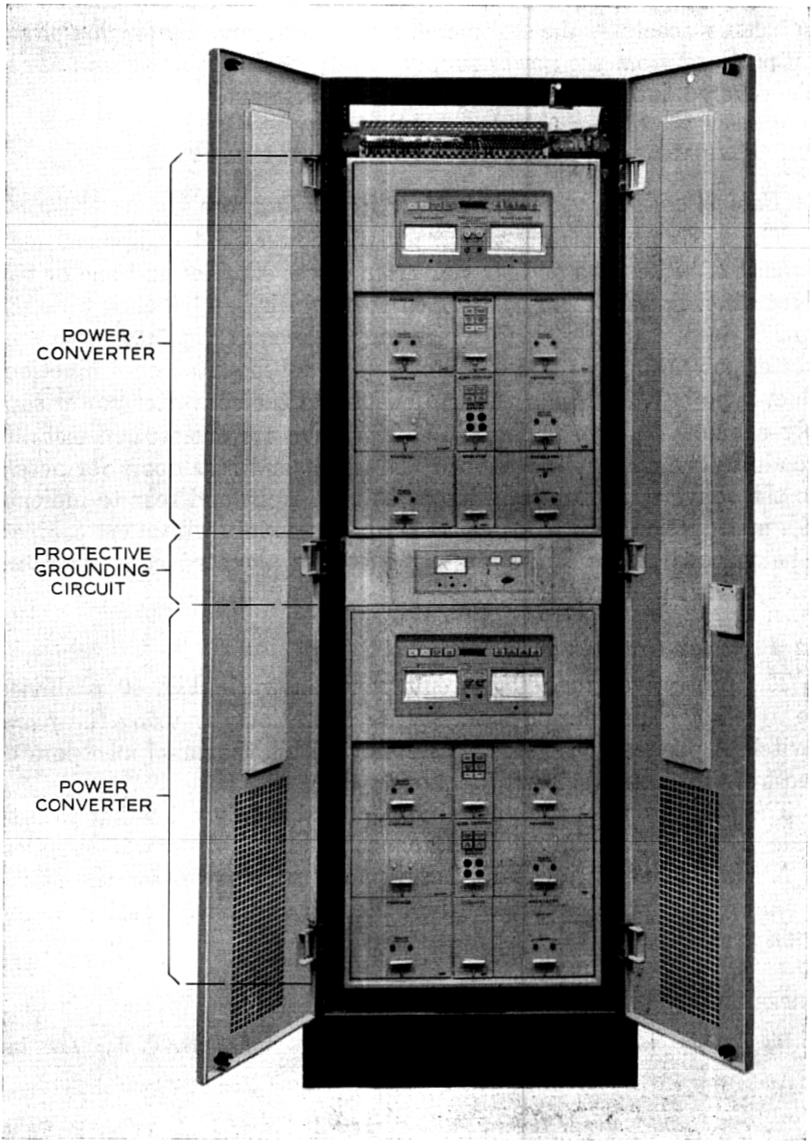


Fig. 10 — Power feed system equipment cabinet.

available consistent with the number of power stage units used. High voltage apparatus such as the output filters, the output current sensing saturable reactors, the voltmeter multipliers, and the high voltage output lead from the power supply to the coaxial cable system are in the covered, interlocked high voltage compartment.

VII. PHYSICAL DESIGN OF POWER FEED SYSTEM EQUIPMENT

7.1 *Cabinet and Bay Arrangements for Power Supplies*

The equipment arrangements for the power feed equipment may consist of either two or four converter power supplies and one or two protection panels enclosed in a cabinet which is 27 inches wide, 32 inches deep, and 7 feet high, which may be seen in Fig. 10, or two converter power supplies and one protector panel mounted on a nine-foot duct type bay. The high voltage leads from the converter power supply cabinets or bays to the L-4 carrier bays are enclosed in metallic conduit. The cabinet is equipped with front and rear doors for access to the converters and alarm lamps at both front and rear to indicate if a malfunction occurs in a converter power supply within the cabinet. The various status lamps on the duct-bay mounted converters are easily viewed.

7.2 *Protective Grounding Circuit Panel*

The protective grounding circuit panel shown in Fig. 10 is shifted to a solid ground during maintenance operations by using the panel switch. A printed wiring board assembly within the panel incorporates most of the essential circuit functions.

The solid ground panel, not shown, contains only a bus bar to provide a solid ground for series connected converter power supplies.

A supplementary jack and lamp panel, not shown, for the maintenance order wire circuit can be added to either the floating or the solid ground panel.

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