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L5 SYSTEM:

Line-Power Feed

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The repeaters in a pair of L5 coaxial-carrier transmission lines are powered in a series loop with two dc-to-dc converters at each end of a power span. The loop is normally grounded at one end with the converter voltages balanced to minimize the voltage to ground at the floating end. As with the L4 system, automatic grounding of the floating point is provided to limit the line voltage to ground and to enable the two lines to be powered independently during turnup and under trouble conditions. A new dc-to-dc converter powered by a 140-V battery has been developed. It employs a single power stage to deliver 910 mA at output levels up to 1150 V. A dc-to-dc converter was also developed for operation on 24-V battery power for use at stations where installation of a new 140-V battery plant is not warranted. The dc-to-dc converters employ hybrid, thin-film, integrated circuits to achieve the needed level of precision without dependence on field adjustments. They also employ many new automatic control features that simplify operation of the four converters in a series loop and permit turnup by remote control via the E2 status reporting and control system. Another new feature is a spare converter with reversible polarity and a decentralized high-voltage patching arrangement.

I. INTRODUCTION

The repeaters and equalizers in the L5 coaxial-carrier transmission system are spaced at approximately one-mile intervals along the cable system. Dc-to-dc converters operating on station battery power and spaced up to 75 miles apart are employed to furnish a constant current of 910 mA at voltages up to 1150 V dc over the coaxial line to the series-connected repeaters and equalizers. This article describes the line-power-feed system and equipment with emphasis on the features that simplify (or automate) system operation and that minimize the effect of foreign voltages which may be injected into the system between stations.

II. BASIC POWER-FEED ARRANGEMENT

The L5 repeatered lines, like those of the L4 system, are powered in pairs using a series loop including two dc-to-dc converters at each end of a power-feed section (see Fig. 1).[1] For cables shorter than 37.5 miles, the pair of converters at one end is omitted. The system is permanently grounded at one station and the output voltages of the

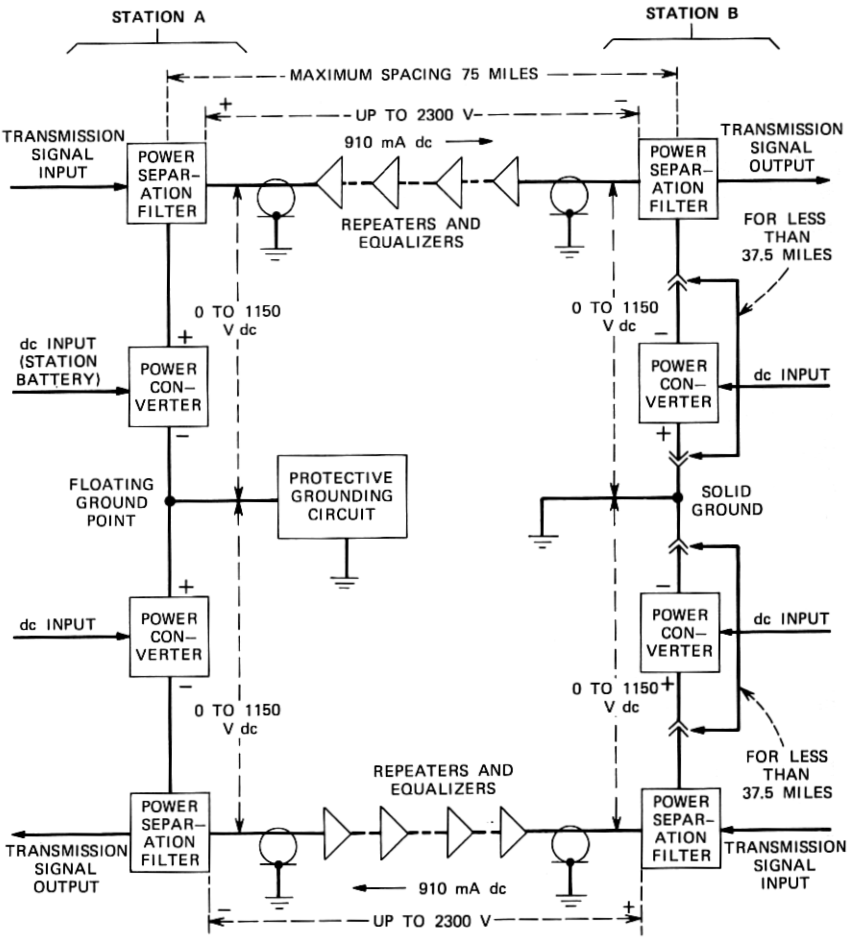

Fig. 1—Power-feed system.

four series-connected converters are balanced under normal conditions such that the voltage is near zero between the floating and local-ground points at the distant station. Therefore, the highest voltage to ground is 1150 V and no path exists for the flow of direct current through earth-metal interfaces between stations. This avoids electrolytic corrosion at such interfaces under normal steady-state conditions.

Under certain abnormal conditions, grounding of the floating point is desired. If, for example, a foreign longitudinal voltage appears between grounded points in the system, grounding of the floating-ground point may be needed to limit the peak voltage appearing between the center conductors and outer conductors of the coaxial cables. This arises from the tendency for such voltages to be superimposed on the output voltage of the converters connected to the floating ground point. A second abnormal condition which warrants grounding of the floating point is the appearance of a cable fault or a converter failure that would reduce the current in the power-feed loop below an adequate level. By detecting such a fault and automatically grounding the floating point, normal current (and transmission) can be maintained in one of the coaxial lines.

III. ELECTRICAL PERFORMANCE REQUIREMENTS

The principal electrical performance requirements that influenced the design of the line-power-feed system are summarized in Table I. The allowance for dc earth potentials as high as 15 V per mile is larger than that used in designing previous systems of this type. Such earth potentials are caused by geomagnetic storms that accompany solar flares. The effects are largest on east-west routes at high latitudes in areas with high soil resistivity. Large dc earth po-

Table I — System requirements

Nominal line-current	910 mA
Loop voltage drop	120 to 4600 V
Line-current variation (normal limit)	±40 mA for combined variations of ±100 V in loop drop, ±2 V per mile dc earth potential, 10–50°C ambient temperature, 120–152 V converter dc input voltage.
Line-current variation (during unusual geomagnetic disturbances)	±110 mA for earth potentials up to ±12 V/mile.
System-withstand capability (no protective shutdowns or equipment damage)	DC earth potential up to ±15 V/mile. 60-Hz induction up to 1500 V rms for 0.1 s.

tentials occur infrequently and persist only for a few minutes in a given locality. The design objectives of avoiding major transmission impairment up to 12 V per mile, and avoiding protective power shutdowns up to 15 V per mile are considered to be quite conservative, inasmuch as earth potentials approaching these levels are expected to occur only rarely and in limited areas of the United States.

High levels of longitudinal 60-Hz induction can be caused by large unbalanced currents under fault conditions on major commercial power lines which parallel the cable route. The "system-withstand" capability of 1500 V is considered adequate for most applications. Where routes have unusual exposures to high levels of 60-Hz induction (i.e., more than 1500 V), additional measures, such as supplementary cable shielding, must be considered.

IV. SYSTEM DESIGN OBJECTIVES

A major factor affecting converter design was the desire for simplicity of system operation. In particular, it was desired to be able to turn up converters at unattended stations by remote control. This implied a need to design the converters and protective ground circuits to perform several functions automatically. These functions include:

(*i*) Soft start—To increase line current gradually over a period of about 15 seconds.

(*ii*) Converter voltage limiting—To avoid an excessive output voltage from the first converter turned on.

(*iii*) Automatic grounding—To ground the floating point during turnup.

(*iv*) Automatic ungrounding—To unground the floating point upon completion of turnup.

(*v*) Converter current limiting—To avoid producing excessive current into a short circuit.

(*vi*) High-impedance shutdown—To prevent turnup into an open circuit (avoids unnecessary personnel hazards).

To provide for faster power restoral after a protective shutdown caused by an unforseeable momentary transient, the converter would be designed to automatically make a single attempt to restart. To maintain the converter and to provide for fast restoral of power in the event of converter failure, a manually patchable spare converter and test-load facility would be available at each power-feed station.

Simple in-service pushbutton tests would be employed to verify that protective converter shutdown and grounding circuits are functioning. The need for adjustments to the system in the field would be minimized.

In summary, it was thought that the goal of high system reliability would be best served by accepting moderate increases in the complexity of the power-feed equipment to simplify its use in the field and permit remote control.

V. POWER CONVERTER DESIGN

5.1 Power conversion

The basic element in the converter is the power conversion section which changes the dc input voltage available from the station batteries to a higher voltage that is controllable and is isolated from the input. Power converters for the L5 system were designed to operate on 24-V and 140-V battery plants. The power conversion technique for 24-V input is similar to that developed for the L4 system,[1] and employs up to five pulse-width-modulated power stages. Each power stage employs power transistors switching at 20 kHz and delivers approximately 200 W at 230 V and 910 mA.

A new type of transistor-converter circuit[2–4] was developed for use with the 140-V battery plants that will be used increasingly in the Bell System.[5] The new converter circuit employs transistors rated at 200 V and 12 A and delivers approximately 1 kW from a single unit. The new circuit, illustrated in Fig. 2, separates the pulse-width-control function from the power-inversion function by employing a switching regulator (Q1, D1) operating at 40 kHz on the input side of a bridge-inverter circuit (Q2, Q3, Q4, Q5) that operates at 20 kHz. A principal feature of this circuit is the presence of the inductor which averages the voltage pulses at the input to the inverter rather than placing the inductor in the conventional position at the output of the rectifier bridge. This provides a number of advantages:

(*i*) Eliminates voltage and current surges that ordinarily appear in the transistors and diodes as a result of rectifier-diode recovery and/or transformer saturation.
(*ii*) Simplifies inverter base-drive circuits.
(*iii*) Reduces number of high-voltage rectifier and filter components.
(*iv*) Permits effective utilization of techniques to reduce switching loss.

By using nonlinear networks to improve the switching locus of the transistor, the switching losses were kept quite low even at a switching

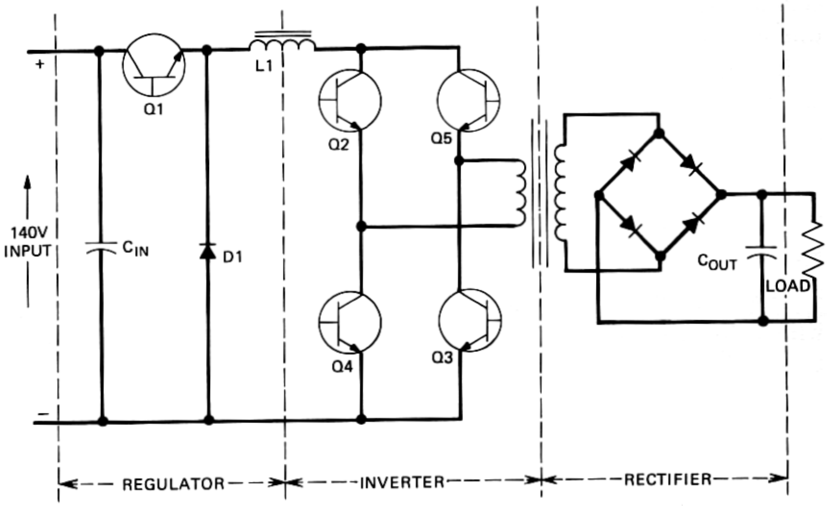

Fig. 2—Power-conversion circuit.

frequency of 40 kHz using transistors with 0.75-μs rise and fall times. These techniques are illustrated for the switching regulator section of the converter in Fig. 3. In Fig. 3a, the switching transistor operates into a highly inductive load (L1) with the inductor voltage clamped by fly-back diode D1. In the absence of the nonlinear loci-control networks, A and B, the adverse switching loci shown in Figs. 3b and 3c are obtained at turn-on and turn-off, respectively, of transistor Q1. The peak and average switching losses in transistor Q1 are 1500 W and 45 W, respectively. Inclusion of networks A and B yields the improvements in switching loci shown in Figs. 3b and 3c. This reduces both the peak and average transistor switching losses by a factor of 10. The total switching losses are reduced by a factor of 3, taking into account the losses in the added resistor, R1. The achieved conversion efficiency of 90 percent (96 percent for the switching regulator alone) is considered quite high at an operating frequency of 40 kHz.

5.2 Feedback control

The desired output voltage-current characteristic for a converter intended to feed a line of maximum length is illustrated in Fig. 4. There are three modes of regulation corresponding to the three linear segments of the voltage-current characteristic.

Normal operation of the converter is in the middle section called the impedance mode. The slope resistance of this section, 3370 ohms,

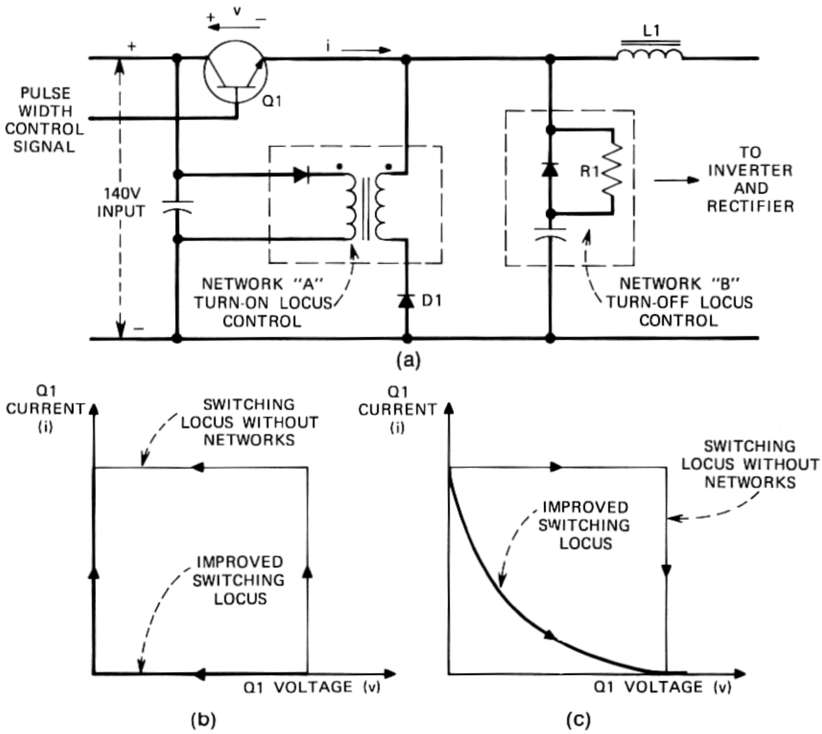

Fig. 3—(a) Switching regulator with locus-control networks. (b) Q1 switching locus at turn-on. (c) Q1 switching locus at turn-off.

is chosen to limit the variations in cable current to ±110 mA in the presence of dc earth potentials up to 12 V per mile. The "level" of the impedance segment is adjustable in the field to accommodate cables of various lengths and to provide means for balancing the voltages produced by the four converters in the series loop. None of the other output characteristics, alarm, or protective shutdown levels require adjustment in the field. Instead, the necessary precision (approximately ±2 percent) is built into the equipment using precise integrated voltage regulators, thin-film tantalum resistors, and integrated operational amplifiers.

At current levels above 1000 mA, the regulating mode automatically changes to the current-limiting segment, where the slope resistance increases to 24,500 ohms. This limits the output current to less than 1050 mA for any short-circuit fault on the line. Normal operation in a

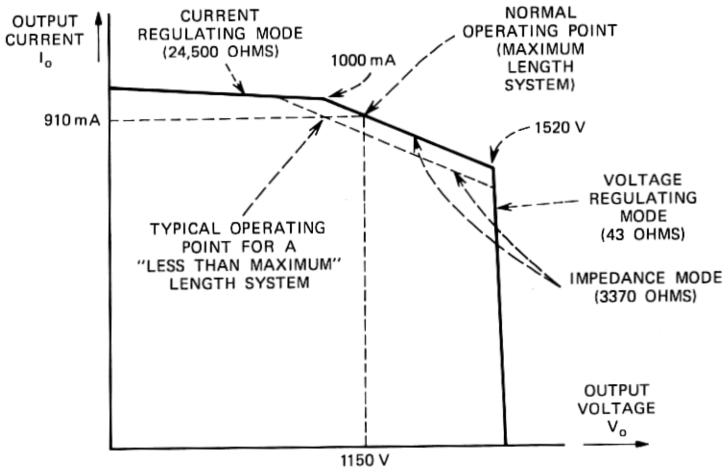

Fig. 4—Converter output voltage-current characteristic.

mode with such a flat (i.e., high-impedance) slope would be undesirable because of the difficulty of maintaining good voltage balancing between the four converters. At output-voltage levels above 1520 V, the regulating mode automatically changes to the voltage-limiting segment, where the slope resistance decreases to 43 ohms. This limits the converter output voltage to 1550 V while power is being turned up. Without this feature, the first converter turned on in the series loop would deliver higher output voltage in attempting to supply power to the complete loop. When the converter is turned on, the output voltage of the converter is increased slowly in the open-loop control mode over a period of 15 seconds to minimize the voltage and current transients applied to the system and to enable the feedback regulator to take control smoothly and restrict the output voltage and current levels not to exceed the characteristic shown in Fig. 4.

The circuit implementation of the triple-mode regulator is indicated in Fig. 5. The output voltage and current of the converters are sensed using saturable reactors to achieve dc isolation. A negative dc voltage proportional to converter output voltage is presented at point *a* and a negative dc voltage proportional to converter output current is presented at point *b*. These two voltages are compared to a reference voltage in three different ways at the inputs to each of three "current-summing" operational amplifiers. The outputs of the three operational amplifiers are combined via diodes D1, D2, and D3 to control the output of a 40-kHz pulse-width modulator which, in turn, controls the output voltage and current of the dc-to-dc converter. The three diodes assure that only one operational amplifier (the one with the highest level) controls the converter. In the current-limiting mode, operational amplifier No. 2 is controlling. Note that the output-current level is compared to a reference level at current summing point *c*. In the voltage-limiting mode, operational amplifier No. 1 is controlling with the converter output voltage compared to reference at current-summing point *d*. In the impedance mode, operational amplifier No. 3 is in control. In this case, a linear combination of the output voltage and current signals is compared to reference at summing point *e*. The slope of the converter output characteristic in the impedance mode is determined by the ratio of the combining resistors R1 and R2.

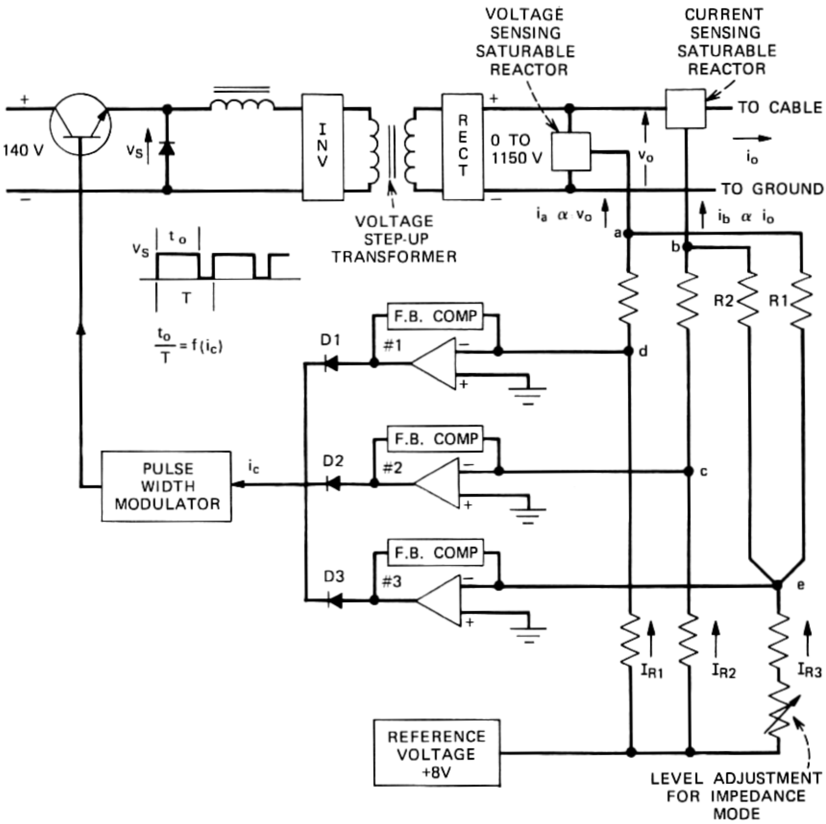

Fig. 5—Triple-mode feedback-regulator circuit.

The feedback regulator circuit and the ramp generator (used for soft starting) were realized as a hybrid integrated circuit using beam-lead operational amplifiers, thin-film tanalum resistors, and ceramic-chip capacitors. The resistors in the current-summing networks are matched to 0.25 percent using an anodizing process.

5.3 *Alarm and protection functions*

General alarm and protective features were included in the converters as follows:

Low-current alarm (−5%)	High-current shutdown (+32%)
High-current alarm (+7%)	High-voltage shutdown (1750 V)

A circuit is also employed to detect line-circuit fluctuations resulting from an arcing fault in the repeatered line and to activate converter shutdown. As a supplementary measure to protect personnel from high-voltage hazards, a circuit is provided which prevents turn-up of the converter if the coaxial line has an open circuit. These functions are realized with three additional hybrid integrated circuits. The precision of these circuits (±2 percent end of life) is such that no field adjustments are needed. Means are provided for simple (pushbutton) go, no-go in-service tests of these protection and alarm functions.

VI. GROUND PROTECTOR CIRCUIT

The function of the ground-protector circuit shown in Fig. 1 is to automatically ground or unground the system's floating-ground point under appropriate conditions. When the converters are turned down, the floating point is grounded. The ground is automatically opened after two conditions are satisfied: (*i*) the sum of the magnitudes of the two line currents exceeds 1500 mA and (*ii*) the difference between the magnitude of the two line currents is less than 34 mA. This assures that all four converters have been energized and that the opening of the ground connection will not produce a voltage at the floating ground greater than 129 V.

The floating point is automatically grounded after a short delay if the voltage exceeds 250 V to ground or instantaneously if the voltage exceeds 800 V ±15 percent to ground. Possible causes of voltages sufficient to actuate the automatic grounding circuit are a converter failure, a line fault, the appearance of an abnormal dc earth potential between stations, a nearby lightning strike, or abnormal 60-Hz induction. As in the case of other automatic features, a pushbutton, in-service test is provided to verify the proper functioning of these features.

VII. SYSTEM RESPONSE TO DC EARTH POTENTIALS BETWEEN POWER-FEED STATIONS

As noted earlier in this paper, abnormal solar-flare activity can cause the appearance of earth potentials up to 12 V per mile. Such an earth potential appears as a voltage between station grounds as shown in Fig. 6. The effect of earth potential will be discussed for the case of a maximum-length system where the effect is maximum. Until the earth potential reaches 3.33 V per mile (250 V for 75 miles), the earth potential appears at the floating ground point. The line currents are not affected since the system is grounded at only one point. As the earth potential increases further, the threshold for the automatic grounding circuit is exceeded and the system becomes grounded at both stations. The earth potential now appears as an aiding voltage in one loop (cable plus two converters) and as a bucking voltage in the other loop (see Fig. 6). Thus, in a pair of cables, the cable current increases in one cable and decreases in the other.

Upon taking into account the nonlinear output characteristic of the converters and the major nonlinearities in the repeaters, the overall effects of dc earth potentials are shown in Fig. 7. The hysteresis effect is the result of the margins purposely designed into the automatic

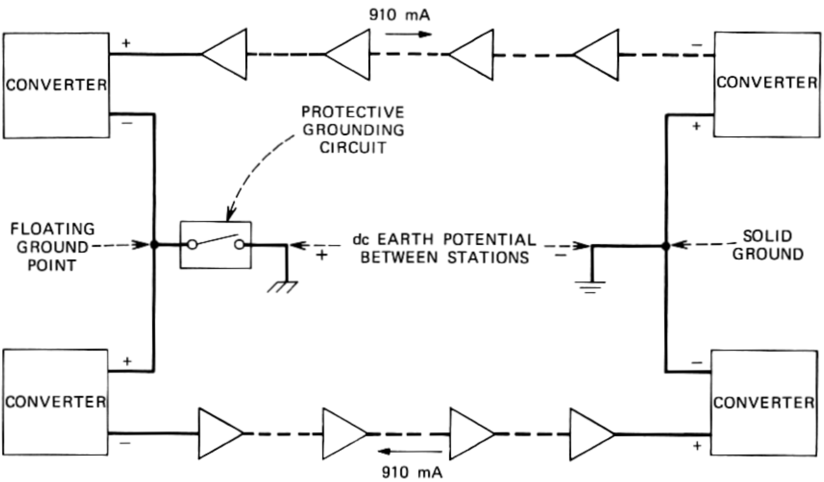

Fig. 6—Appearance of dc earth potential between stations.

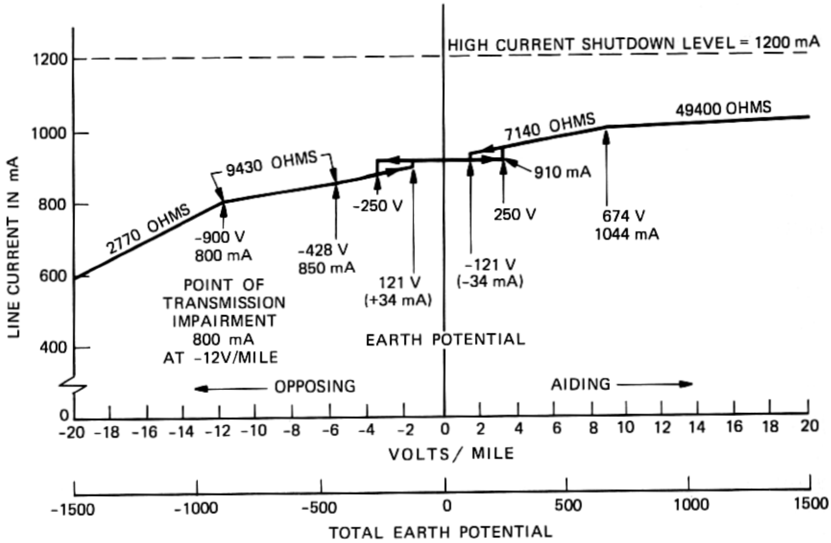

Fig. 7—Effect of earth potential on L5 cable currents.

grounding and ungrounding circuits to avoid unstable operation. The current variations in the cables are less than 110 mA for earth potentials less than 12 V per mile (900 V in a 75-mile power-feed section).

VIII. SYSTEM RESPONSE TO LONGITUDINAL, 60-Hz INDUCTION

The appearance of a burst of 1500-V, longitudinal, 60-Hz induction near a power-feed station will cause a peak line voltage to ground of 2300 V and a peak line current of 2.2 A. If the 1500-V, 60-Hz induction is closer to the center of a power-feed section, the peak voltage will be less, but the peak current can increase to 3.5 A.

The action of the diodes in the converter output rectifiers is such that the effect on the converter is similar to the application of an alternating series of open and short circuits. Fast current-limiting circuits are included in the converter to reduce the peak currents in the switching transistors. A delay is included in the high-current shutdown circuits to avoid an unwanted power shutdown during such bursts of 60-Hz induction, which are expected to be less than 100 ms in duration.

IX. HIGH-VOLTAGE PATCHING ARRANGEMENT FOR SPARE CONVERTER AND TEST LOAD

A spare converter is provided for use in quickly restoring power to a line in the event of failure of a regular line-feed converter. A manual high-voltage patching arrangement is provided to permit connecting the spare converter to substitute for the original converter for any coaxial line and, at the same time, connecting the original converter to the test load contained within the spare converter. To achieve this, the output of the spare converter and the test load are multipled to jacks in a protected area at the top of each converter, as shown in simplified form in Fig. 8. There are two types of plugs shown in Fig. 8, P1 and P2. The plugs are shown in their normal positions in Fig. 8. Note that there is a P1 type plug for each converter normally associated with a particular coaxial line, but only one P2 type plug which is normally associated with the spare converter. In the normal state, each individual converter feeds a particular line and the spare converter is connected to its internal test load. Under this condition, the spare converter may be exercised into the test load to assure its operability should it be needed to substitute for an individual converter. The spare converter also provides a means for checking operation of the spare converter plug-in units at each station.

When an individual converter fails, the P1 plug from the failed converter is manually interchanged with the P2 plug from the spare converter. As can be seen from Fig. 8, the failed converter will connect to the test load and the spare converter to the coaxial line. After the failed converter has been repaired and tested, power is turned off on the line and the patch plugs are restored to their normal positions.

The patching is somewhat more complex inasmuch as there are both positive and negative converters for the individual lines and the converter output polarity of the spare converter is reversible. The

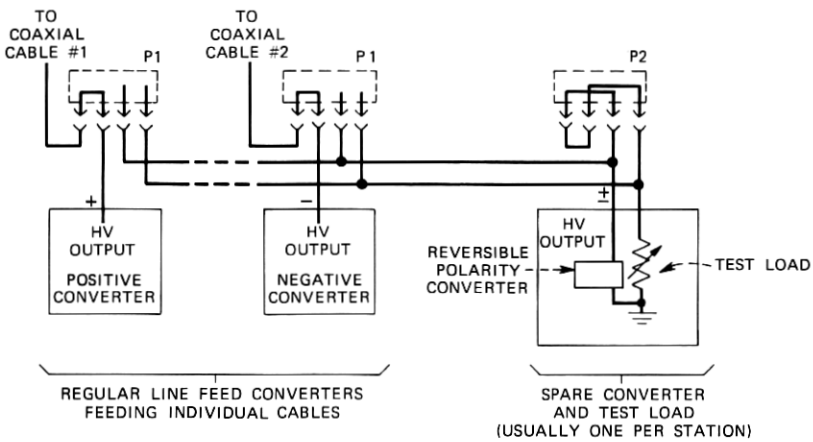

Fig. 8—High-voltage patching arrangement.

P1 plugs from positive converters are slightly different from P1 plugs from negative converters and this difference is used to control the output polarity of the spare converter when it is used to power a coaxial line. There are safety interlock features built into the patch plugs to assure that converters cannot be energized unless the plugs are in valid positions and the covers over the patch panels are closed. Major design objectives for the patching arrangement were to keep it simple and safe for use by the telephone craftsperson in the field and to facilitate the addition of converters without requiring a power shutdown on all cables at a station.

X. PHYSICAL DESIGN

10.1 Design considerations

The physical design of the line-power-feed equipment for the L5 system was based on the following factors:

(*i*) Two power sources (converters) and their associated ground panel are always provided as a group to power a pair of repeatered lines (see Fig. 1), and thus can be manufactured and subsequently installed in the field as a single entity.
(*ii*) The two paired power sources (converters) have the same output voltage magnitudes but different polarities.
(*iii*) The required line-feed voltages can be predetermined and the power-feed equipment can be ordered from the factory with the proper output-voltage capability.

These factors resulted in a physical design which integrates two power sources (converters) and a ground panel into a single structure (see Fig. 9). While the structure has well-partitioned volumes for each function—converters and ground panel—they are not distinct, separable, physical entities.

10.1.1 Specific design considerations

The physical design of the line feed has been influenced, in detail, by other factors. For instance, the L5 line-feed equipment had to be compatible with L4 line-feed equipment in some respects to facilitate station rearrangements when L4 lines were converted to L5. The height and width had to be the same as in L4 or some rational submultiple thereof. The depth of the L5 equipment was designed to be approximately one-half the depth of the L4 power-feed equipment.

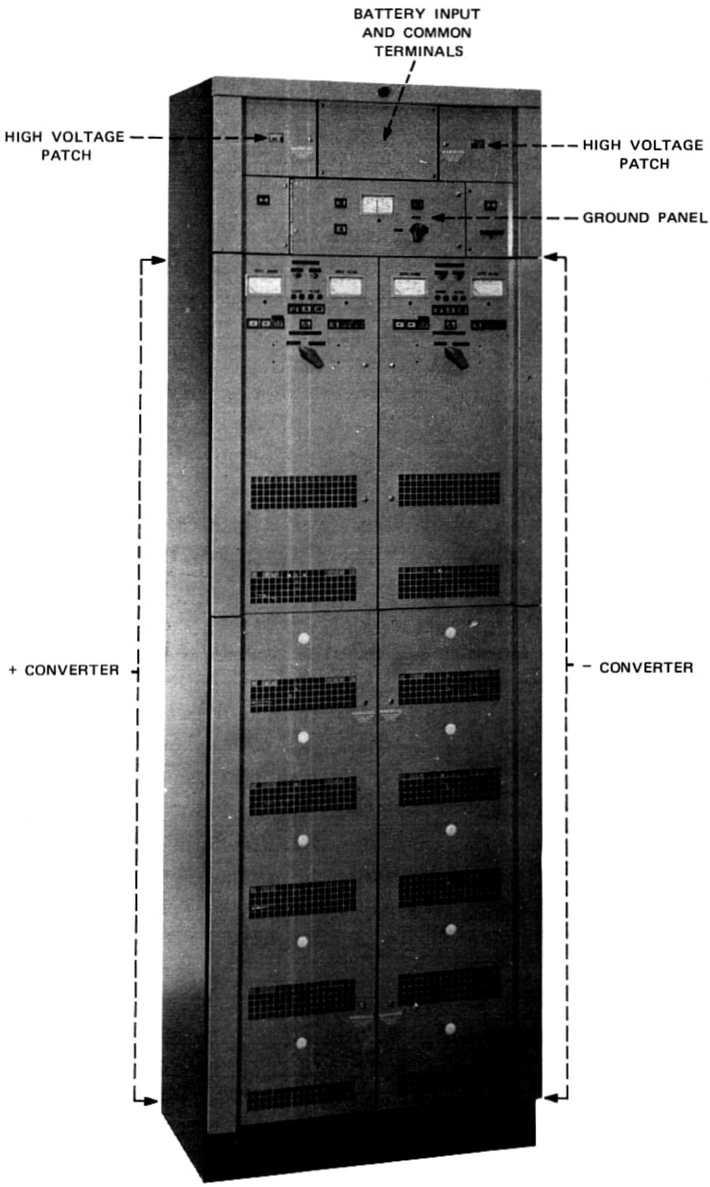

Fig. 9—Line-feed power supply (24-V-battery input).

To facilitate service restoral and maintenance, replaceable plug-in modules and a spare converter were included in the design. Personnel protection was required because of the high-voltage potentials present.

Other design factors were the usual requirements for (*i*) means for heat removal, (*ii*) convenient cabling design, (*iii*) human engineering features, and (*iv*) esthetic considerations.

10.2 Physical design realization

The line-power-feed equipment cabinet shown in Fig. 9 contains two converters and a ground panel. High-voltage patching compartments and a common area for battery input and alarm connections are also provided. Figure 9 shows the 24-V-battery input design, which is 27 inches wide, $13\frac{1}{2}$ inches deep, and 7 feet high. The 140-V-battery input version, designed for stations with the new 140-V dc distribution system shown in Fig. 10, is narrower. The same partitioning pattern has been followed in the 140-V design. Three 140-V cabinets placed side by side are equivalent to two 24-V-input designs and are thus compatible with floor plans.

Normal operating controls are mounted on the front panel. No other facilities for adjustments are provided within the equipment. Trouble indicators are a lamp at the top of the cabinet, and a lamp for each converter.

Figures 11 and 12 show the regular line-feed cabinets with their doors open to illustrate the plug-in modules. The lower doors are interlocked to deactivate the equipment (one converter at a time) since the high voltages are generated in this area. Access doors to other high-voltage areas, including the patching area, are also interlocked and protective covers are furnished.

The cabling plan is designed to minimize cable installation within the cabinet. Field-connected cable terminates at the top of the cabinet. The high-voltage outputs and the connections to the spare converter are protected by flexible conduit and enclosed metal ducts.

10.2.1 Replaceable plug-in modules

Replaceable plug-in modules, which contain the critical electronic circuits, are used to facilitate rapid field repair and manufacture. The modules for a 24-V input converter are shown in Fig. 13. The active electronic circuits for each converter, except for the power stages and oscillator, are contained on five printed-wire boards which provide the plant automatic features described earlier. Each board consists of a double-sided epoxy-glass board assembly with a standard plastic face

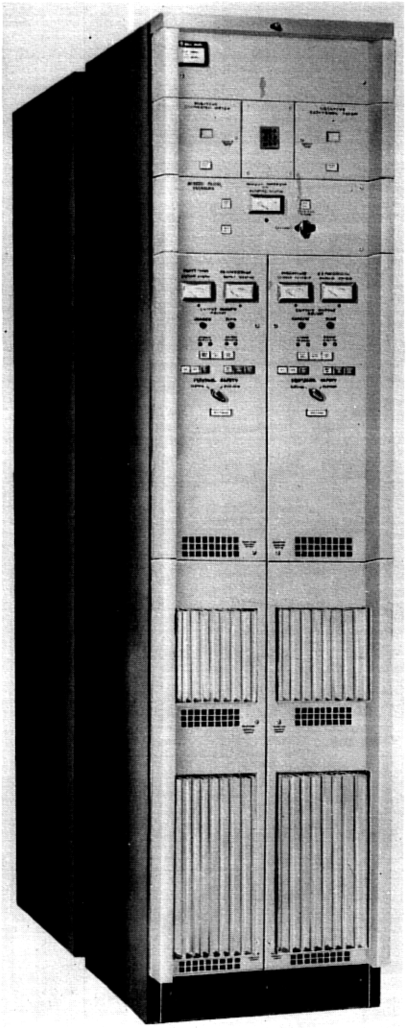

Fig. 10—Line-feed power supply (140-V-battery input).

plate. Connection to the unit is through printed-circuit contact fingers which plug into connectors mounted on the housing for the five boards. Each converter has an identical complement of five boards. Although the boards were initially designed for application in the 24-V-input version, they were applied without change in the 140-V-input version to simplify manufacture and repair. Other printed-wire-

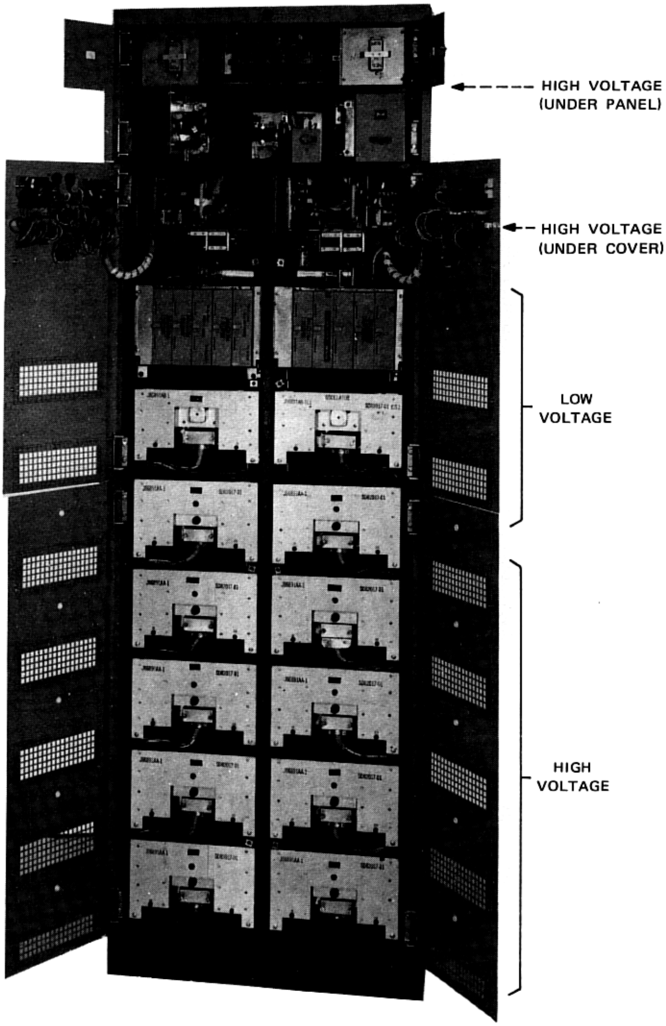

Fig. 11—Interior view of line-feed cabinet (24-V-battery input).

board assemblies are component parts of the power stages, oscillators, and ground panels.

10.2.2 Integrated circuits

The feedback regulation, alarm, and protective features incorporated in the converters utilize four specially developed hybrid integrated

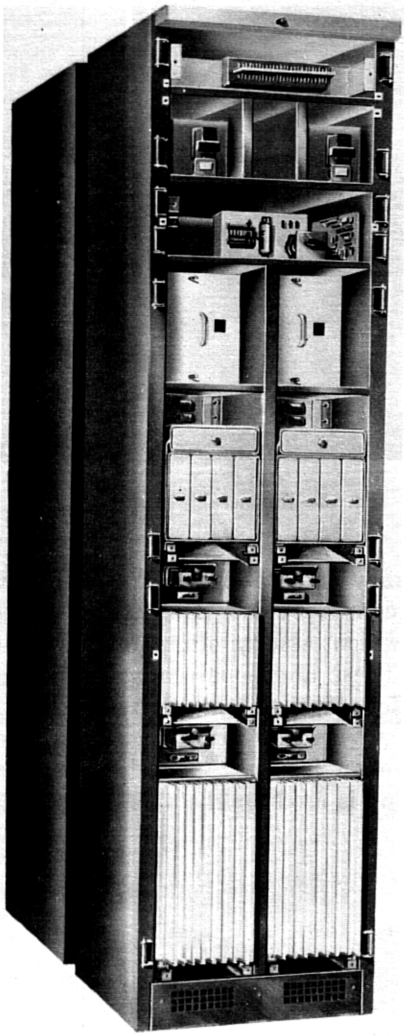

Fig. 12—Interior view of line-feed cabinet (140-V-battery input).

circuits shown in Fig. 14. The hybrid circuits include thin-film tantalum resistors with precise ratios (0.25 percent initial) to provide long-term stability and eliminate the need for adjustments over the anticipated life of the equipment. The resistors, positioned in close proximity on a ceramic substrate, are aged prior to final trim anodization to achieve

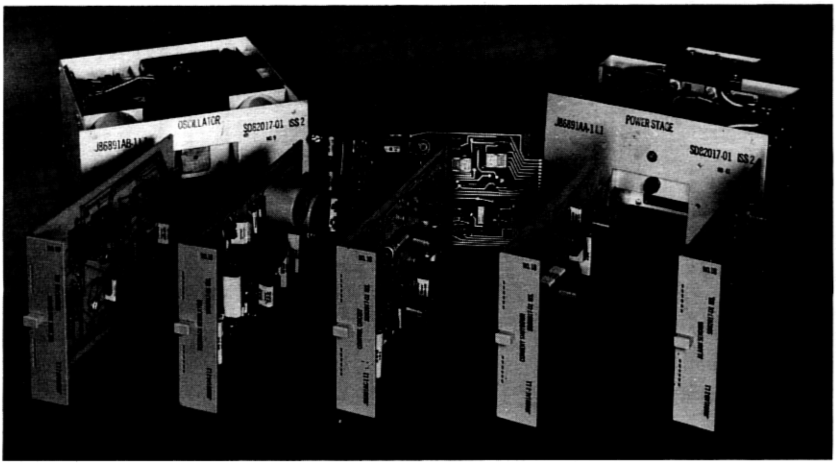

Fig. 13—Replaceable plug-in modules.

the required accuracy and stability. Additional advantages in circuit performance are realized by including associated components on the same substrate, which assures minimum-length paths for critical interconnections. These additional components include beam-leaded operational-amplifier chips, ceramic-chip capacitors, and beam-leaded diodes. Stitch crossovers are also used for interconnections on the substrate. Solder reflow is used to attach the capacitors and thermo-compression bonding is used for the operational amplifiers and diodes

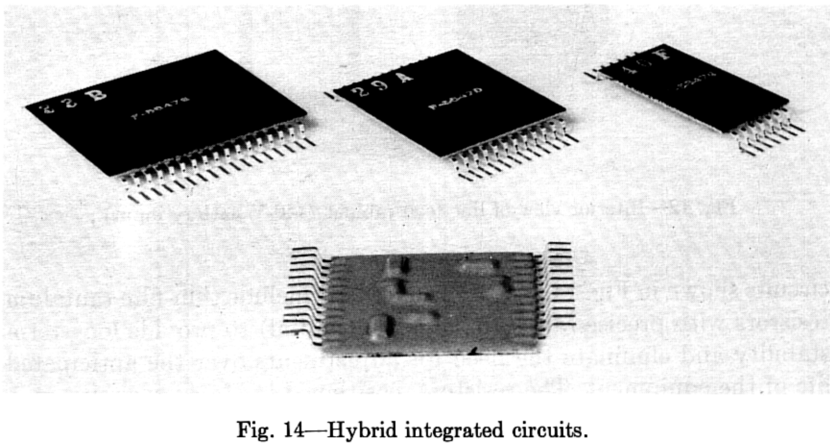

Fig. 14—Hybrid integrated circuits.

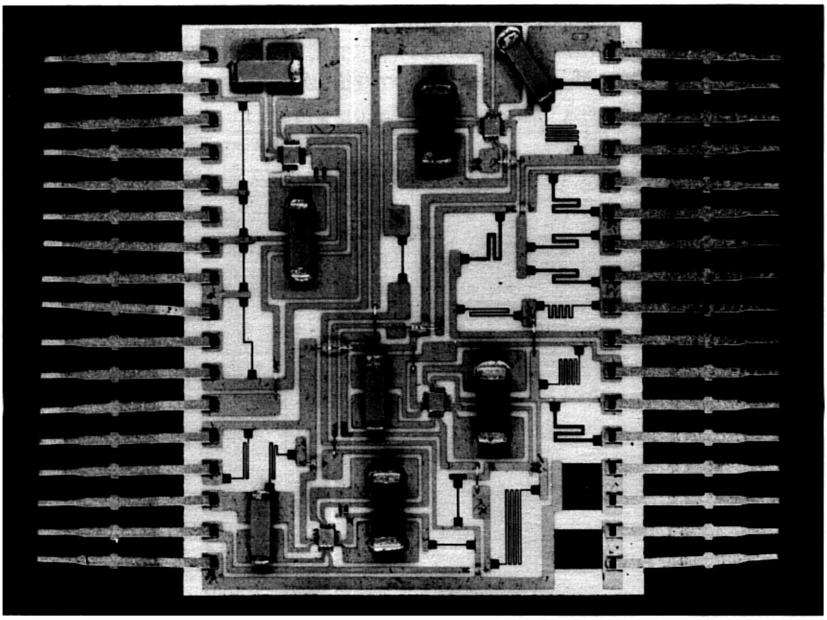

Fig. 15—Unencapsulated development model of feedback regulator with hybrid integrated circuitry.

as well as the substrate lead frame. An early development model of the feedback regulator hybrid, unencapsulated, is shown in Fig. 15. The hybrid circuit is mounted to the printed-wire board by reflow soldering the lead frame to presoldered terminal areas on the boards. The use of hybrid integrated circuitry eliminates a significant number of soldered connections, which would have been required in a discrete realization and thus should enhance reliability.

10.2.3 High-voltage patching and spare converter

The spare converter and the test load used in the high-voltage patching arrangement described earlier are housed in a cabinet similar to a regular line-feed cabinet (see Fig. 16). The spare converter occupies the left half of the cabinet and a resistive test load with its controls, including metering facilities, occupies the right half. Natural convection is used for disposal of heat from the test load.

Each converter (line and spare) has an associated high-voltage patch compartment containing the patch plug and mating receptacle. Access to the patch plug is gained by opening an interlocked hinged panel, as shown in Fig. 16. A small window in the line-feed converter panel is provided for visual observation of the patch status, i.e., to determine whether the normal plug or the spare plug is in place in the line-feed converter. A status lamp is provided at each line-feed con-

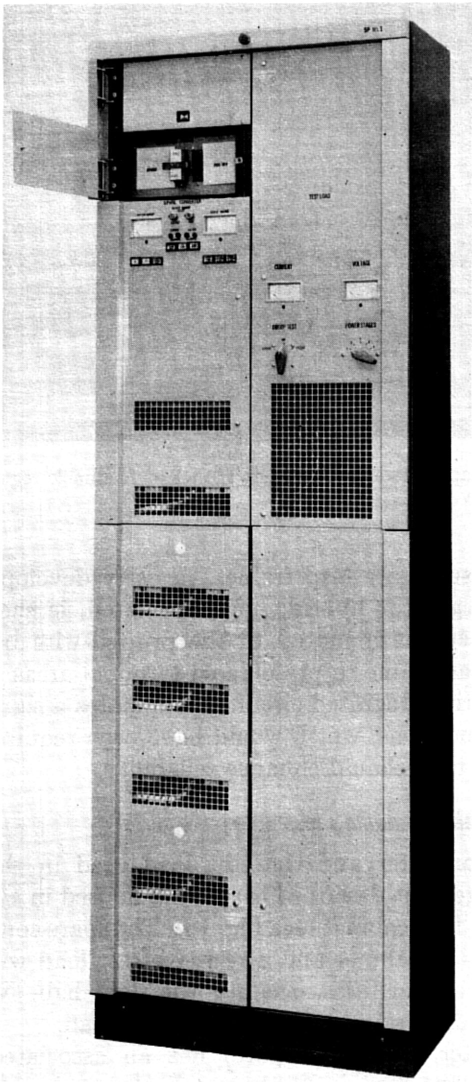

Fig. 16—Spare converter (24-V-battery input) with patch compartment open.

verter and indicates whether the spare converter has been placed in service as a substitute for a regular line feed or is available for assignment.

The spare converter services a number of line-feed converters, the quantity being a function of the acceptable system repair time. It should be noted here that the transmission-system-protection switching facility maintains service in the event of a converter failure. Arrangements are available to provide a multiplicity of spare converter systems for regular line feed within a single office if system-reliability requirements warrant.

Spare converters are available for −24-V and 140-V input voltages. The cabinet sizes are identical to those of the regular line-feed converters.

XI. SUMMARY

The precision obtained through the use of hybrid-integrated-circuit technology permitted the inclusion of many automatic control features in the power-supply system for the L5 repeaters. It is expected that the resulting simplification of system operation and the minimal number of adjustments required in the field will contribute significantly to overall system reliability.

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A. P. Walsak was responsible for physical design, and circuit design responsibilities were shared by R. Ostapiak, P. P. Untamo, R. E. Schroeder, and J. R. Meszar.

REFERENCES

1. J. D. Bishop and S. Mottel, "Power Supplies for the L4 System," B.S.T.J., *48*, No. 4 (April 1969), pp. 1041–1064.
2. E. T. Calkin and B. H. Hamilton, "Circuit Techniques for Improving the Switching Loci of Transistor Switches in Switching Regulators," IEEE Conf. Record of 1972 Seventh Annual Meeting of IEEE Industry Applications Society, pp. 477–484.
3. Ibid., "A Conceptionally New Approach for Regulated dc to dc Converters Employing Transistor Switches and Pulse Width Modulation," pp. 485–494.
4. U. S. Patents 3,736,495; 3,737,755; and 3,745,444.
5. J. J. Suozzi, W. J. Morrison, and J. J. Stockert, "A New 140 Volt Power System," Bell Laboratories Record, *51*, No. 2 (February 1973), pp. 41–47.