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SG Undersea Cable System:

Undersea System Power

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The power-feed equipment for the SG cable system is of the type that regulates the output current and limits the output voltage. It energizes the serially connected repeaters in the TAT-6 undersea system. This paper describes the power-feed equipment in general terms and, in more detail, several new power techniques. These new techniques include inductive-input inverters in the main power train, pulse-position-modulation in the control and monitoring circuits, precise digital metering of output current and voltage, vacuum switch elements in the transfer switch, and special new components and design concepts in the power separation filter needed to achieve SG-wideband-transmission objectives in the presence of the high, TAT-6, power-feed voltages.

I. INTRODUCTION

The SG power-feed equipment is similar in system configuration to that which powers the SD[1] and SF[2] undersea cable systems previously developed and installed by the Bell System. As examples: (*i*) power-feed redundancy is achieved by connecting two load-sharing, independent, direct-current sources in series, with provision for the automatic assumption of the full load by the survivor should one current source fail, (*ii*) the cable is powered at each end with opposite polarities and a sea-ground power return, and (*iii*) the power supplies at both ends operate as current sources with their maximum output voltages restricted to be less than the voltage standoff capabilities of the repeaters.

Despite the conceptual similarities among the SD, SF, and SG power-feed systems, the techniques used to realize the system features have changed as the performance requirements have become successively more stringent and new circuit and physical design technologies have become available, or have been invented, to meet the performance requirements. Representative SG requirements are summarized in Table I.

In this paper, we describe the SG power-feed system as applied to TAT-6, emphasizing the following new circuit and physical design features:

(*i*) Inductive-input inverters in the power stages of the main power train.

(*ii*) Pulse-position-modulation in the control and monitoring circuits.

Table I — Representative SG power-feed performance requirements for TAT-6

Output current:	
Nominal	657.00 mA
Set point resolution	±0.10 mA (±0.015%)
Variation within 24 hours	±0.33 mA (±0.05%)
Variation resulting from a ±1000-V load change	±3.30 mA (±0.5%)
Variation resulting from the failure of one of the two converters	±3.30 mA (±0.5%)
Output voltage:	
Nominal voltage	5200 V/station
Maximum voltage	7500 V/station*
Tolerable earth potential	2300 V/station*
Shutdowns:	
Current	+6% of nominal current (circuit duplicated)
Voltage	9250 ± 750 V (static) 10800 V, maximum (dynamic)
Alarms:	
Cable current	±1% (minor), ±3% (major), fixed
Cable voltage	±5% (minor), ±15% (major), adjustable to bracket the cable voltage
Noise:	
Inverter harmonic tones	<0.17 μV in any 3-kHz band from 0.3 MHz to 30 MHz
Impulse (signal transmission path)	Maximum of one pop per 15-min period that exceeds −10 dBmO in any 48-kHz channel (requirement of the entire shore station including the power separation filter)
Power separation filter transmission requirement:	
Return loss	≥20 dB, 0.5 to 30 MHz

* In normal operation, the voltage-limiting-inception level would be set approximately 1000 V above the zero-earth-potential operating level, e.g., at 6200 V in TAT-6 stations. Hence, a readjustment is necessary to take advantage of the total voltage capability of the power supply.

(*iii*) Precise, digital metering of the current and voltage in the high-voltage output circuits.
(*iv*) Vacuum switches in the "hot transfer" switch circuits and vacuum relays in the wideband, signal-transmission path of the shore-station power separation filter.
(*v*) New, high-voltage, wideband, signal-transmission components and a low-pass, skin-effect filter in the power separation filter.
(*vi*) Physical design techniques to control radiated and conducted electromagnetic interference (EMI) within and from the power supply and into the power separation filter.

II. GENERAL DESCRIPTION OF THE POWER-FEED SYSTEM

Figure 1 displays the power-feed and signal transmission connections to the TAT-6 cable. The A terminal (Green Hill, Rhode Island) power supply provides a current of 657 mA at a nominal, positive voltage of 5200 V with a maximum capability of 7500 V. The 657 mA is joined to the signal transmission path within the power separation filter, and together they are routed into the center conductor of the cable. As the current passes through each repeater (as shown in Fig. 1), sufficient voltage is dropped to power its active circuits. At the B terminal (Saint Hilaire de Riez, France), the power-feed arrangements and equipment are identical to those at the A terminal, except that the power supply's output voltage is negative. The maximum end-to-end cable voltage capability of the SG power-feed equipment is 15,000 V. Maximum capability would be exercised only on long cables in the face of adverse earth potentials. Note also that the 7500-V capability of each power supply permits continuance of TAT-6 cable operation with a high-impedance, shunt fault, in the cable or in a repeater, as close as 2900 V to one station (7500 V from the other station) until a repair ship arrives and begins the repair operation.

The power-return-current path is routed from the power supply through the power separation filter and the ocean-ground panel to specially constructed ocean-ground grids.[3]* Potential differences of as much as 2.7 kV have been observed between the ocean-ground grids in the TAT-1 system.[4] The power supplies at each end of the TAT-6 cable are adequately regulated to absorb potentials of similar magnitude while maintaining control of the cable current.

The manually operated transfer switch and adjustable test load, both located in the load transfer bay (Fig. 1), permit the cable to be transferred between power plants without taking the cable out of service. This simple, but important, circuit is also part of the interlock system where

* Although Reference 3 is related to an earlier British system, it provides details of the problems encountered in designing, installing, and operating ocean-ground grids.

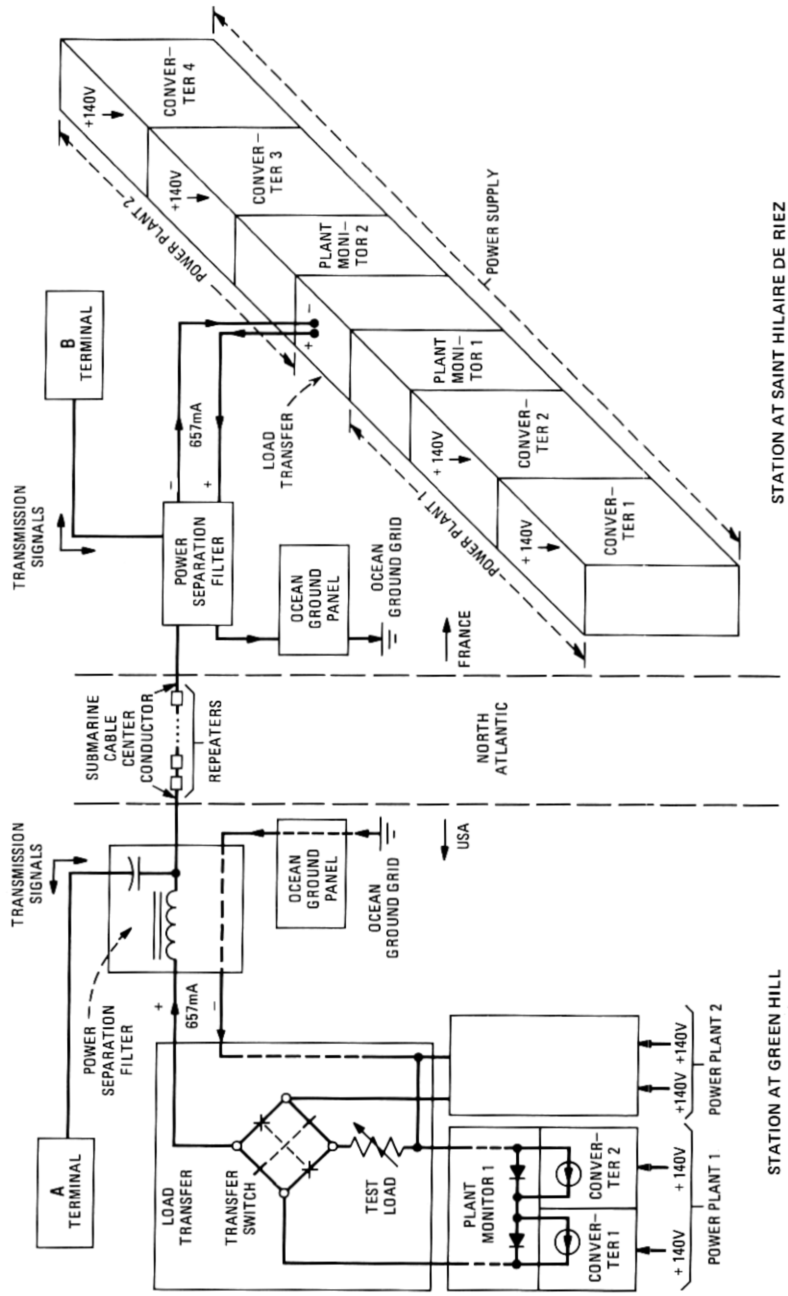

Fig. 1—Power-feed and signal transmission connections to the TAT-6 cable.

it differentiates between energized and unenergized high-voltage areas and permits access to the unenergized parts of the equipment for maintenance and inspection.

Previous Bell System power-feed equipment relies on conservatively designed, mechanically simple, transfer switch mechanisms. Although very rugged mechanically and proven reliable in many existing systems, these transfer switch mechanisms are physically large and cumbersome to operate. Hence, the SG-power-feed equipment makes use of a reliable, smaller, lighter, and simple-to-operate transfer switch.[5] The switch, shown in Fig. 2, has two cams that rotate with the handle of the switch. The cams operate plungers in four vacuum interrupters.

Figure 3 displays an annotated photograph of the seven-bay power supply. The bays are approximately 2.13 m (7 ft) high, approximately 0.71 m (28 in.) deep, and either approximately 0.79 m (31 in.) or approximately 1.14 m (45 in.) wide. The power supply ensemble is approximately 6.86 m (22.5 ft) wide.

Each of the seven bays contains low-voltage and high-voltage spaces. The low-voltage spaces contain alarm, monitoring, and control circuit components that are mounted in plug-in modules. Plug-in modules are

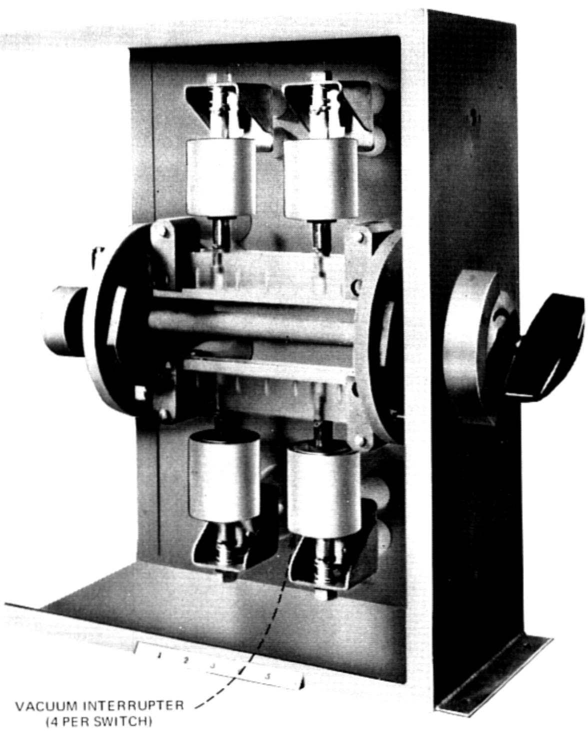

Fig. 2—Transfer switch.

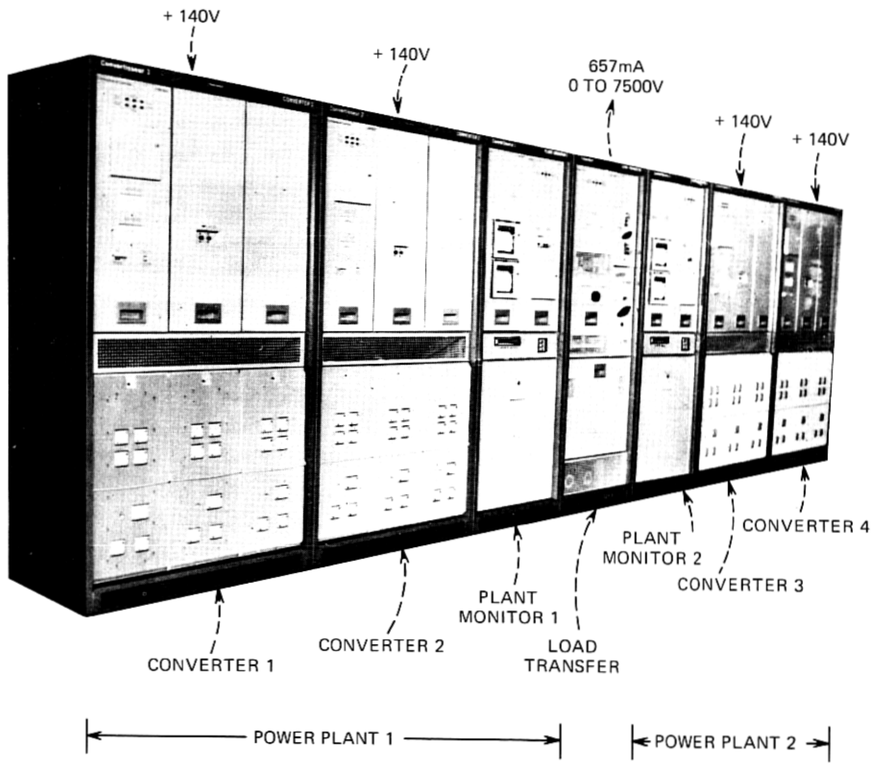

Fig. 3—SG power supply for one end of a long-haul, undersea cable.

located in pull-out slides to provide easy access for both normal operation and maintenance. The high-voltage circuits in the seven bays of the power supply and the high-voltage circuits in the power separation filter are contained in compartments that can be accessed only after appropriate manipulation of the key-controlled, safety-interlock system to assure the disconnection of the input power to the high-voltage space being accessed.

All interbay wiring in the seven-bay power supply is routed through connectors, except for the high-voltage leads, to minimize installation effort and errors. The center conductor and inner shield of a triaxial (shielded coax) cable provide the high-voltage and power-return paths, respectively, between the power supply output and the power-separation-filter bay. The outer shield is useful in reducing EMI conduction from the power supply to the power-separation-filter bay.

The power conversion systems are powered from +140-V battery systems.* In addition, 115-V, 50/60-Hz power is required by the digital meters in the plant monitor and load transfer bays and the test load cooling fans. The 115-V inputs are not shown in Fig. 1.

III. POWER CONVERSION TECHNIQUES

The process of converting power from the +140-V source into a precisely controlled, 657-mA, constant-current level suitable for energizing SG-type cables, at up to 7500 V, is accomplished in the converter bay. The cable-powering requirements are far more demanding than those of previous cables. For example, the 5.0-kW, nominal output capability of each SG converter bay represents a more than eight-fold increase over the capability of the most recent, previous, comparable Bell System converter. The power-train circuits follow the SF system practice of switching at ultrasonic frequencies† to:

(*i*) Minimize the stored energy in filter capacitors.
(*ii*) Avoid generation of high-level, audible noise.
(*iii*) Minimize the physical size of magnetic apparatus.

The increase in power level and the more demanding regulation requirements prompted the use of a pulse-width-control technique instead of the saturable-reactor-type power control used in several previous undersea cable systems. The pulse-width-control technique is used to control switching-regulator transistors in the power path.

The increase to 5.0 kW of converter output power required efficient utilization of the state of the art in power transistor technology. High current (25 A), medium voltage (200 V), and fast switching speed (0.75-μs

* A description of the primary power arrangements inluding the commercial power connections, the rectifier-floated battery systems, and the automatic-or-manual-start, standby engine-alternator systems is beyond the scope of this article.

† The SF power-feed equipment was the first to use static converters switching at ultrasonic frequencies to power long-haul underseas cables.

rise-and-fall times) devices were selected as appropriate to operate with the +140-V input voltage and to minimize the number of required power stages. The +140-V input was selected to minimize current levels. The nominal current drain from the +140-V input for a converter bay is less than 36 A instead of over 100 A if a 48-V input had been used. The lower input current results in:

(*i*) Less I^2R losses, thereby providing greater efficiency in the primary power path.
(*ii*) Lower-strength magnetic fields emanating from the inverter's switching circuits.

The basic dc-to-dc power conversion unit, referred to as a "power stage," operates at 20 kHz (inverter) and 40 kHz (switching-regulator) to develop an output current of up to 690 mA at voltages of up to 2500 V from the +140-V input. Each converter bay contains up to three of these power stages with their outputs connected in series to obtain up to a 7500-V output. During normal operation in a TAT-6 station, six power stages (three in each converter bay) are powering the cable with each power stage operating at less than half its power capability. Figure 4 shows a converter bay with one power stage extended from the bay on its slide and with its EMI-containment covers removed.

A power stage is self-starting and requires only +140-V power, an oscillator-synchronizing signal, and the pulse-width-control signal as inputs for normal operation. Both high-power switching and low-level-control-and-monitoring circuits are incorporated in this plug-in package. Each power stage contains its own base-drive generator rather than receiving base-drive from an external, common generator in the converter bay. This feature assures that the loss of a base drive generator will not cause multiple power train damage. Also, the distribution of switching currents, and the resultant EMI noise radiation within and from the bay, is minimized.

Operation of the power switching transistors to near their maximum current capability requires the use of fast-responding, monitoring-and-protection circuits to prevent damage during load transients. Among the monitoring circuits are those that detect excessive switching currents and sense the high-voltage-output level.

3.1 Description of the power path

The interconnections among the principal elements in the power stage are shown in Fig. 5. The regulator transistor (Q5) switches at 40 kHz to control the power flow from the +140-V input to the inductive-input inverter (Q1, Q2, Q3, and Q4), using a conduction range from 0 to 90 percent. The ratio of Q5 "on" time to the time of a single switching period provides the required average output voltage from the regulator in response to one of the current or voltage control systems in the power plant.

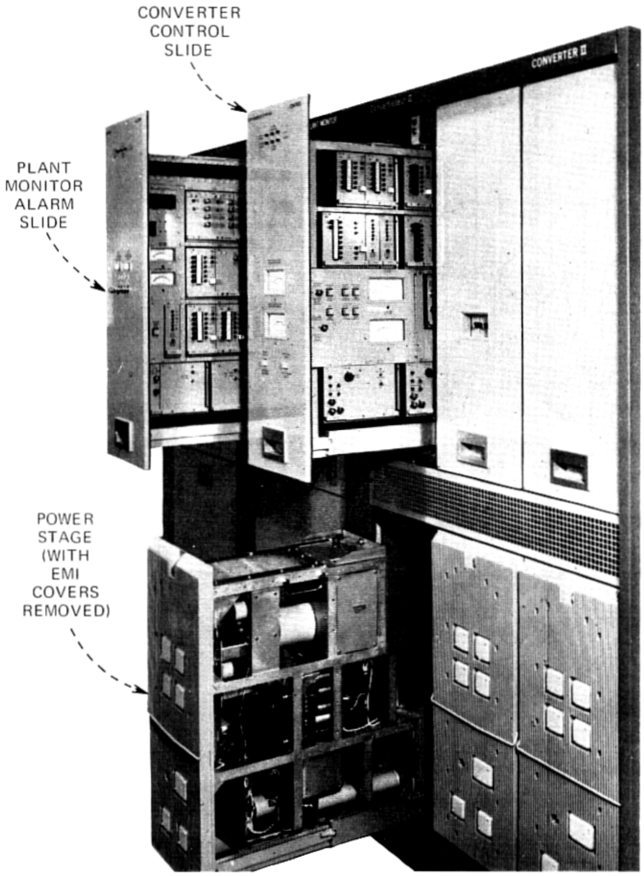

Fig. 4—Power stage extended on its slide from a converter bay.

Identical pulse-width-control signals are applied to all power stage regulators in a converter bay to force each power stage to support an approximately equal share of the load voltage.

The inductor L1, located between the regulator's output and the inverter's input, smoothes the voltage pulses from the regulator to establish a regulated direct-current flow into the inverter. This current flow is inverted into a regulated-amplitude, alternating current by the 20-kHz commutation of the Q1-Q2-Q3-Q4 bridge circuit. The bridge output is applied to a step-up transformer, full-wave rectified, filtered, and applied toward the external load. The inductor L1 is strategically located in the power path to limit the rate of rise of the current in the power semiconductors. The advantages of this special connection between the regulator and inverter in the power path are that it:

(*i*) Permits safe operation of all power semiconductors close to their maximum ratings.

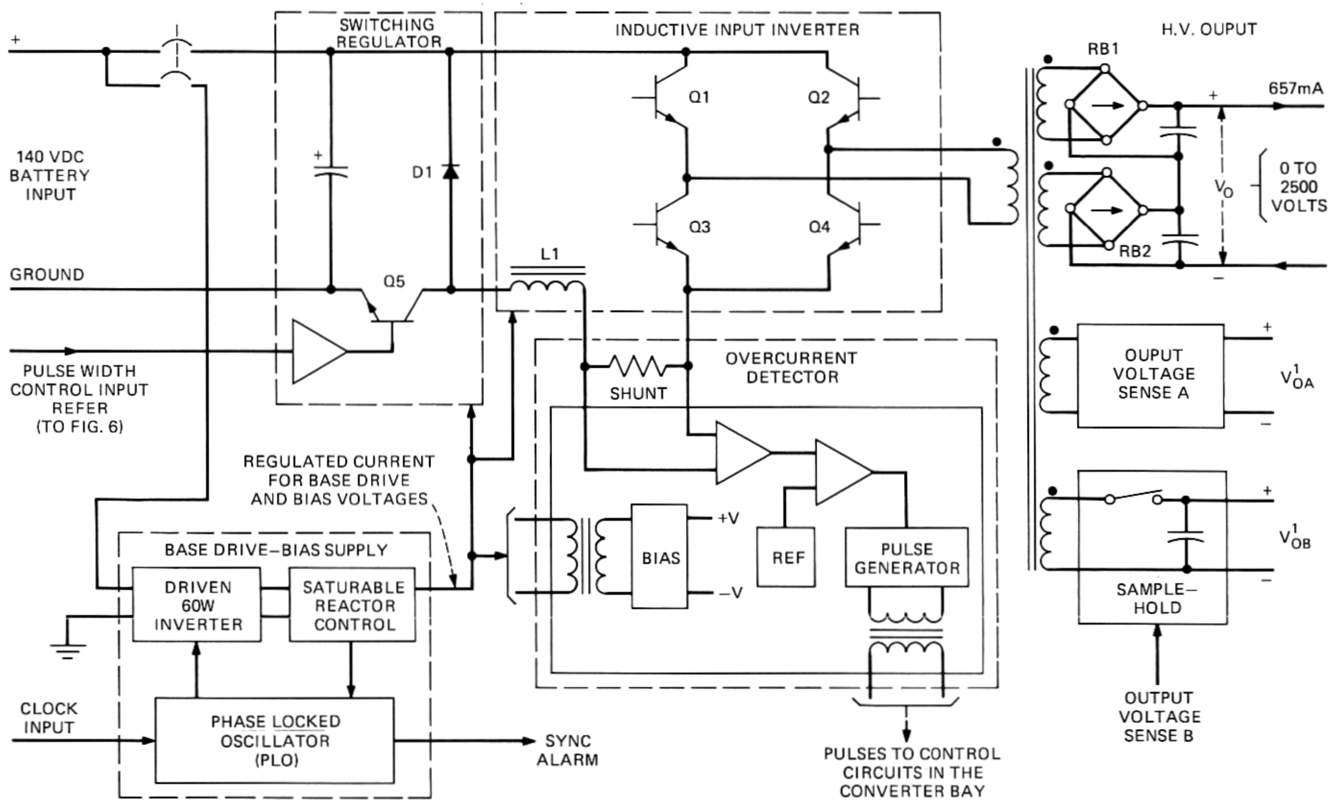

Fig. 5—Principal elements of a power stage circuit.

(*ii*) Controls peak currents in the bridge inverter even during commutation.
(*iii*) Allows easy adaptation of switching-loss-reduction networks which greatly reduce the transistor-peak-power dissipation and improve the efficiency by reducing the average switching loss.

The design and operational details of the basic power circuit topology, described above in general terms, have been documented.[6–10] Hence, the following discussion is concerned primarily with describing the overcurrent protection, the voltage sensing, the base-drive and bias supply, the physical realization, and EMI suppression.

3.2 Overcurrent protection

A fast-responding, overcurrent detector monitors the L1 inductor current that is the input current to the inverter (Fig. 5). The L1 inductor controls the rate of change of current in all semiconductors in the main power path. Thus, only a single overcurrent detector is required in each power stage. The overcurrent detector works in conjunction with the converter bay's control system. This combination limits the peak current in all power switches to be no more than 20 percent above normal under transient conditions, including those occurring in response to the application of a direct short circuit on the output.

The overcurrent detector consists of a shunt, an amplifier to raise the shunt's voltage level by 21 dB, a stable, direct-voltage reference, and a fast-slew-rate comparator that switches a pulse generator to the "on" state if the shunt current exceeds a predetermined threshold. The overcurrent detector has transformer isolation both in the output-pulse signal path and bias-power input path. This is required because the entire overcurrent detector circuit experiences common mode voltage excursions of 200 V at a 1000 V/μs rate during power switching. More details of the overcurrent detector can be found elsewhere.[11]

When the overcurrent detector's pulses are issued from a power stage, the control system in the converter bay halts conduction in the regulators in all power stages in the bay. This blocks further energy flow from the +140-V source to the inverters. Once this control loop becomes active, the cutoff intervals of the regulators are controlled to the proper duration to allow excess stored energy in the power path's magnetic components to be dissipated into the load. As a consequence, the switching currents in the inverter are reduced to normal levels before further regulator conduction is permitted.

3.3 Isolated output voltage sensing

Precise determination of a power stage's output voltage is required by the converter bay's regulation, alarm, and shutdown circuits. Each power stage contains sensing circuits that monitor the output transformer's voltage with sense windings. Direct sensing of the high voltage output is not desirable, since the secondary circuits may operate at several kilovolts above common. (This is a consequence of the series connection of the high-voltage outputs of the power stages.)

Unfortunately, a sense winding does not provide a voltage signal that has an ideal rectangular waveform, but one with large ringing transients and voltage notches at each polarity transition during inverter commutation. These aberrations vary considerably with load. They typically occur in power inverter circuits and cannot be completely avoided.

These disturbances excluded the use of conventional rectifier and passive filter circuits in this accurate, linear, sensing application. Instead, a unique application of a zero-order type sampling circuit is used to synchronously sample the voltage during a brief interval of the positive half-cycle of the sensed waveform midway between the commutation events. The sample switch is then held "off" to ignore the voltage ringing notches associated with commutation and the complete negative half-cycle. The charge stored on the "hold" capacitor maintains a relatively constant voltage across the high impedance load during the nonsampling part of the cycle.

Using this sampling scheme, tracking accuracy between the sense output and high-voltage output is better than ±1 percent of full scale over the 2500-V output range. The sensing circuits are duplicated in each power stage for improved reliability.

3.4 Internal base drive and bias supply

An efficient, 60-W, saturable-reactor-controlled, 20-kHz, quasi-rectangular-wave current source operates from the +140-V input to provide a ±2-A, regulated current to the inverter power transistors for base drive, to the regulator driver as a source for its base drive, and to the bias voltage supply in the overcurrent detector (Fig. 5). This ±2-A source determines the inverter commutation but not the regulator switching, since that is controlled by the converter bay's control circuits through the pulse-width-control input.

A phase-locked oscillator (PLO) operates with the base-drive source in a feedback system to minimize the variable, phase-shift error introduced by the saturable reactor. The PLO synchronizes the inverter's noisy commutation interval to the converter bay's clock with a phase-shift error of less than ±0.2 radian. The commutation transient always occurs during the "off time" of the regulator transistor and therefore does not contribute jitter to either the leading or trailing edge of the conducting period. An alarm is issued if synchronization fails to occur.

This synchronization feature prevents beat frequencies from appearing in the converter bay's output and other anomalous effects. Synchronization of all high-power switching also reduces the possibility of random noise tones exceeding the stringent power-plant-output-noise requirement of less than 0.17 μV for any single frequency in any 3-kHz band from 0.3 MHz to 30 MHz. Note, however, that loss of synchronization would not necessarily result in an increase in EMI.

3.5 Physical realization of and EMI control in the power stage

The power stage is physically realized as a completely shielded plug-in module that has input and output, hand-operated connectors and weighs approximately 56.7 kg (125 pounds). It is also key-interlocked and cannot be removed from its location at the bottom of the converter bay (Fig. 4) unless the high-voltage circuits within the modules are de-energized.

Shielding is utilized to minimize the effects of the radiated EMI noise produced by power-switching semiconductors within the unit. The shielding includes individually shielded compartments within the power stage as well as solid heat sinks on the front and rear of the unit, solid side covers with EMI gasketing, and honeycombed shields on the top and bottom of the unit.

The switching semiconductors, which are the main heat sources, are mounted on a heat sink that serves as the front panel of the unit. This takes advantage of both natural convection and radiation modes of heat transfer. Top and bottom honeycomb shields permit air flow through the power stage for internal cooling.

The transformer that connects the inverter output to the high-voltage rectifier was specially developed for this application. The high-current, low-voltage terminals are located on one side of the transformer, with the low-current, high-voltage terminals on the opposite side. The transformer is mounted on a solid wall separating two shielded compartments with its high-voltage terminals protruding through the wall, thus providing the output rectifier compartment of the power stage with minimum noise contamination from the inverter's switching circuits.

IV. PULSE POSITION MODULATION AND DEMODULATION

A major design problem in power-feed equipment providing regulated currents at high voltage is the implementation of current sensing in the high-voltage side. Very accurate current sensing is necessary for feedback control of the current as well as for alarm, shutdown, and metering functions. Analog magnetic amplifier technology has been successfully employed in previous high-voltage supplies. However, the need in the SG system for high precision (on the order of 0.01 percent) and the desire for less complex and lower cost apparatus made it necessary to develop a new technique for sensing current at high voltages.

The objectives of the new technique are to:

(*i*) Generate a signal that is an accurate linear function of the current being sensed.
(*ii*) Provide dc isolation in coupling the signal from the circuits referenced to the high-voltage side, where the current is sensed, to the signal-processing circuits referenced to the ground side.
(*iii*) Process the received signal to perform various control, alarm, shutdown and metering functions.
(*iv*) Provide operating power to the sensing circuits located in the high-voltage side, without employing an auxiliary power supply having high-voltage isolation.

The pulse-position-modulation (PPM) method[12] is used for current-sensing and information-coding. The PPM circuits convert a sensed analog signal into pulses whose position in time is varied relative to the occurrence of a trigger pulse. Pulse transformers couple the pulse from the PPM circuits, referenced to the high-voltage side of the power plant's output, to processing circuits referenced to the ground side. The pulse transformers are the only link between the PPM and processing circuits. To minimize EMI susceptibility, a low-impedance, balanced transmission line, terminated at each end with pulse transformers, is used to carry the pulse signals between the PPM circuit and the signal processing circuits.

The PPM method provides excellent signal-to-noise characteristics. Superimposed random noise has little effect on the time position of the pulse carrying the modulated signal. The PPM method is therefore well suited for interbay transmission of signals within various wire cables without appreciable reduction of the signal-to-noise ratio.

4.1 Regulation

The basic PPM circuit is used as the control element in multiple feedback loops controlling the output current and voltage of the power plant.

The principal feedback loop regulates the cable current at 657 mA. Figure 6 includes the current control loop. The switching transistor (Q5)* in the regulator section of each power stage is controlled by the state of a set/reset-type flip-flop in the power-stage-control circuit. Each switching transistor is turned on by a start-pulse signal originating at the 40-kHz clock. The start-pulse signal is applied, through isolation transformers, to the set terminal S of the flip-flop, setting it to a state that supplies a base-drive signal from the Q output to the switching transistor in each power stage.

* Same Q5 as in Fig. 5.

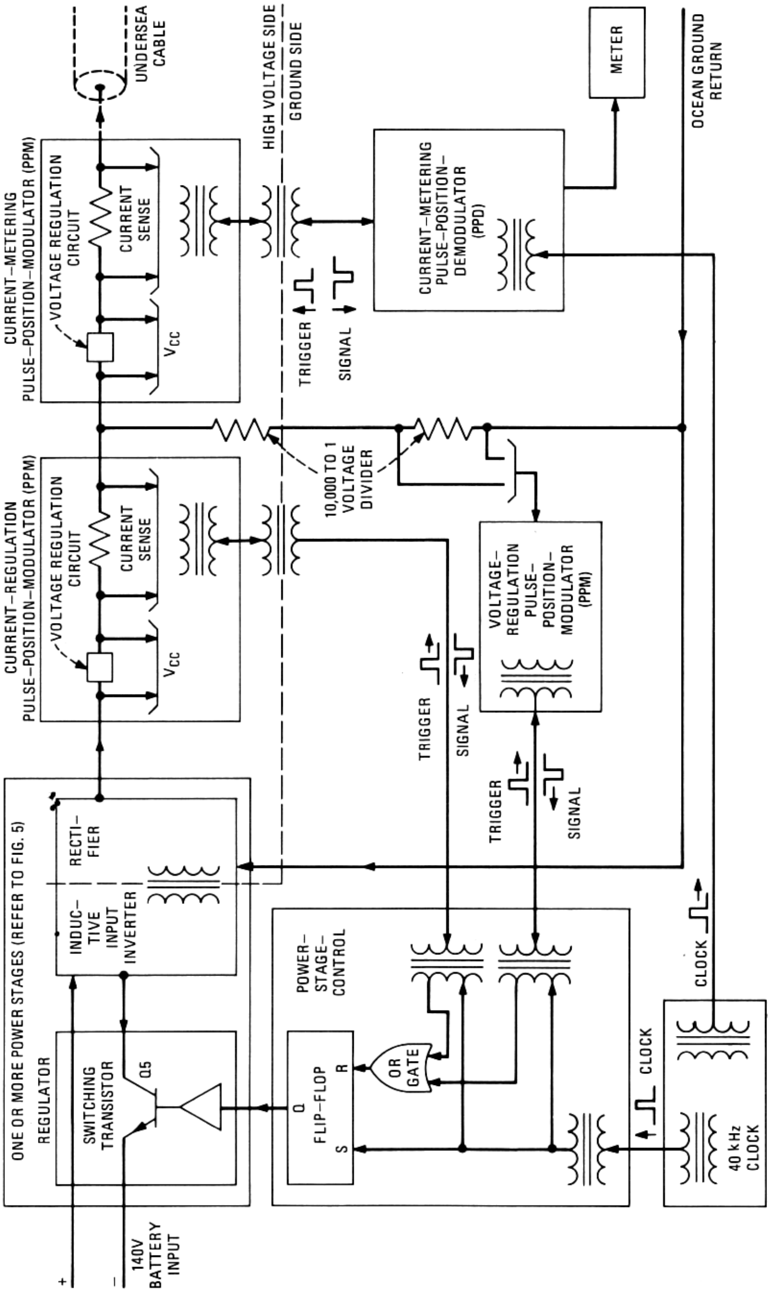

Fig. 6—Simplified circuit showing output-regulation and metering systems using pulse-position modulators.

At the same time, a positive-polarity trigger pulse is also transmitted from the 40-kHz clock to the current-regulation PPM circuit in the high-voltage side. The trigger pulse synchronizes the PPM circuit to the start of the switching-transistor-base-drive pulses. The signal pulse returned from the PPM circuit has a negative polarity. The trigger pulses and signal pulses share a common transmission path. The signal pulse is routed though an OR gate to the reset terminal R of the flip-flop. The flip-flop output is reset by the signal pulse to a state that terminates the base-drive pulse at the output Q. As a consequence, the regulator transistor in each power stage is turned off. The duty cycle (ratio of the time lapse between the trigger and signal pulses to the period of the trigger-pulse train) of the PPM output signal determines the width of the voltage signal to the output of the regulator and, ultimately, the current supplied to the cable.

Power to operate the current-sensing PPM circuits is obtained from the voltage (V_{cc}) developed across the voltage-regulation circuit in the PPM circuits, as shown in Fig. 6. The voltage drop across the voltage-regulation circuit in the PPM circuit is used to furnish 12 V to the PPM circuits. Sixty-mA line current is needed to power the PPM circuits. This permits the PPM circuits to effectively regulate the cable current at any value greater than 60 mA. The voltage-regulation circuit in the PPM circuit bypasses current in excess of 60 mA. The networks required to obtain closed-loop stability are inserted across the error amplifiers (not shown in Fig. 6) located within each PPM.

The current regulation loop has control of the cable current during normal operation. After an initial 5-hour warmup period, the maximum 24-hour current drift is less than ±0.05 percent if the ambient temperature variation stays within ±5°C. This represents a change of ±0.33 mA when the cable current is set to 657 mA.

The voltage-regulation loop is a secondary control loop designed to limit the output voltage to a preset level. Figure 6 illustrates one of the voltage-regulation PPM circuits. The power plant's output voltage is sensed by means of the 10,000-to-1 voltage divider.* A signal pulse is sent from the voltage-regulation PPM circuit through the isolation transformers and the OR gate to the set/reset flip-flop within the power-stage-control circuit. The OR gate, and hence the flip-flow circuit, reacts to the first pulse that arrives at the OR gate during each cycle of operation.

The voltage regulation loop has a combined setability and maximum drift of ±25 V.

* Note the contrast between the direct voltage sensing used in the power plant's output where the circuit common is close to earth potential and the indirect voltage sensing previously described for the converter bay's output where the common of one bay is the high-voltage side of the other.

4.2 Alarms and shutdowns using PPM circuits (not shown in Fig. 6)

The basic PPM circuit is also used in conjunction with pulse-sequence detection and decoder circuits to generate alarm and/or shutdown signals. Alarms of ±1 and ±3 percent are obtained from one PPM circuit sensing the cable current. The PPM circuit receives a trigger pulse from the clock circuit every 25 μs (a 40-kHz rate) and generates a signal pulse in the middle of the time period under normal conditions when the cable current is at its nominal value. The PPM circuit has a negative transfer function. Hence, an increase in the cable current shortens the time delay between the trigger and signal pulses. The signal pulse is sent to four sequence-detection circuits. Each circuit compares the occurrence of the signal pulse to a marker pulse generated by feeding a 2.5-MHz clock frequency* into a decoder circuit that quantizes the period between trigger pulses into 32 discrete time slots, each with a duration of 0.8 μs. Marker pulses are obtained at time slots 4, 12, 20, and 28. The marker pulse occurring at time slot 4 is generated 3.2 μs (4 × 0.8) after the trigger pulse. The marker pulses at time slots 12, 20, and 28 occur at 9.6 μs, 16 μs, and 22.4 μs after the trigger pulse. The PPM circuit has an active range of ±4 percent around the nominal cable current. As a consequence, each time slot is equivalent to 0.25 percent (8 percent ÷ 32) change in the sensed cable current.

No alarms will occur when the cable current is at 657 mA, and the signal pulse appears at time slot 16. When the sensed output current begins to increase, the PPM circuit will send a signal pulse to the sequence-detection circuit earlier than time slot 16. When the signal pulse appears earlier than the marker pulse occupying time slot 12, the sequence-detection circuit will generate a +1 percent current alarm. If the cable current continues to increase until the signal pulse appears before the marker pulse occupying time slot 4, a +3 percent current alarm is generated. Current alarms of −1 and −3 percent are generated when the sensed current decreases enough to cause the signal pulse to appear after the marker pulses occupying time slots 20 and 28, respectively.

Means are provided for in-service checking of the proper functioning of these alarms. Techniques used to check all four alarm circuits in a single operation are described elsewhere.[12]

With slight modifications, a PPM circuit can be used to sense either cable current or cable voltage with an active range suited to detect and send out alarm and/or shutdown signals for any desired percent change in the cable current or voltage.

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* A single 2.5-MHz clock is used to provide, by division, the 40-kHz clock signal that synchronizes all clocks in the power supply.

4.3 Metering using PPM and PPD circuits

Figure 6 also includes a pulse-position-demodulation (PPD) circuit used with a PPM circuit to provide a metering function. The PPD circuit converts the time-delayed pulses from the PPM circuit into an analog signal after the pulse signals pass through the isolation transformers into the ground-side circuits.

A synchronizing trigger pulse is sent from the clock through the PPD to the PPM. The resulting PPM signal is a narrow pulse, linearly controlled in time delay by the amplitude of the sensed cable current. The signal pulses are sent to the PPD where they are used to set and reset a flip-flop circuit within the PPD. The output of the flip-flop is a rectangular-wave signal having a width proportional to the time delay of the signal pulse. This rectangular-wave signal is applied to an averaging filter producing a direct current output. The amplitude of the direct current output signal is a linear function of the time delay of the signal pulse. This direct current output can be used for either digital or analog metering.

Expanded-scale meter PPM and PPD circuits are used with digital meters to provide greater accuracy. The circuits have an active range of 16 mA centered around the nominal 657-mA cable current. The overall measurement accuracy at the 657-mA current is ±0.33 mA (±0.05 percent).

A technique for employing a PPD in the feedback loop of the PPM circuit to linearize its transfer function and render the system insensitive to timing errors is described elsewhere.[12]

4.4 Physical design considerations for PPM circuits

The operation of the PPM circuits with narrow pulses and consequentially broad frequency spectrum in a high-electromagnetic-interference and high-electrostatic-voltage environment required that considerable care be exercised in the physical design of both the PPM circuits and the bays where they are mounted.

The components of the PPM circuits are mounted on three-layer printed-wiring boards and are located, with their associated pulse transformers, in the high-voltage areas of the converter and plant monitor bays. The components of the low-voltage PPD circuits are also mounted on three-layer, printed-wiring boards. Several of these boards comprise a low-voltage plug-in module, located in one of the pull-out equipment slides in a converter or plant monitor bay. Access to PPM circuits located in high-voltage areas is possible only when the circuits are deenergized, while the low-voltage PPD circuits located in the ground-side areas are always available to the operator.

The three-layer boards provide the PPM and PPD circuits with two layers of interconnecting paths and a third layer that is used as a ground plane. The ground plane consists of very wide ground paths to all integrated circuits, thus providing a low-impedance ground that aids in reducing susceptibility to noise pulses.

Figure 7 displays the location of the four PPM circuits (one current-regulation, two alarm and shutdown, and one current-metering) in the high-voltage area of a converter bay. Two PPM circuit boards are mounted on each metal base plate with a perforated metal covering over both boards. This cover and the metal base plate are electrically con-

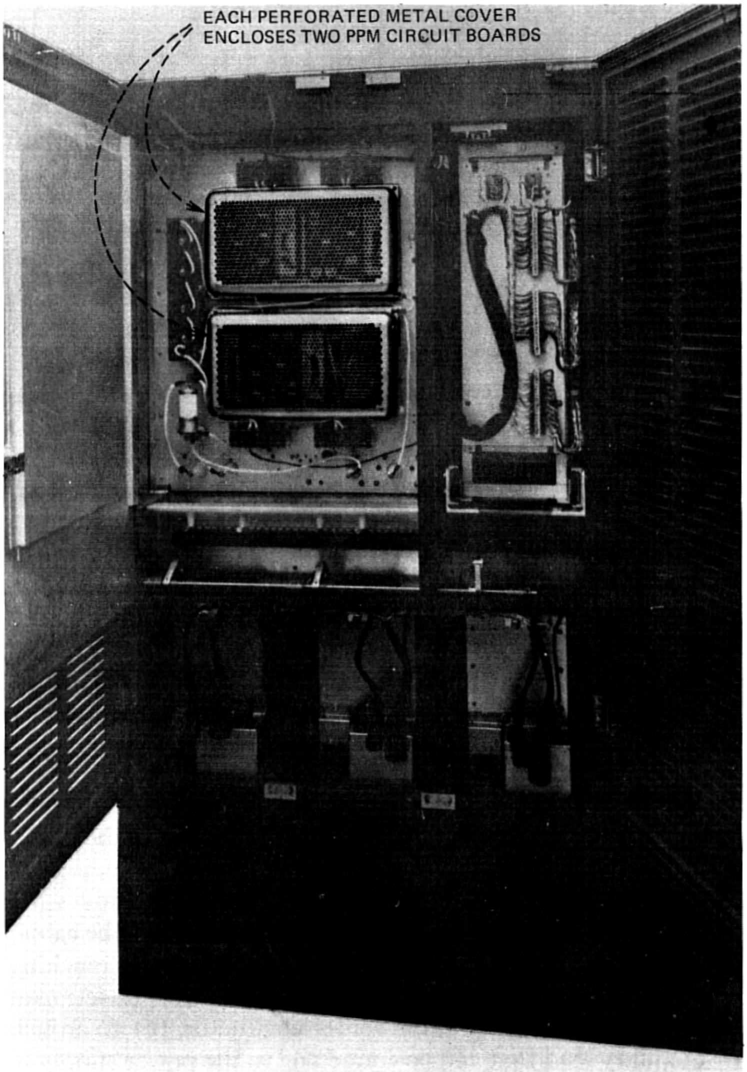

Fig. 7—Pulse-position-modulators shown in the high-voltage area of a converter bay.

nected to the high-voltage circuit to form an equipotential electrostatic field that surrounds the integrated circuits in the modulators. This arrangement prevents any damage to the integrated circuits by eliminating the possibility of large voltage gradients in the surrounding field. The cover and base plate also reduce electrostatic coupling of EMI into the PPM circuits.

The current-regulation PPM in a converter bay is equipped with coarse and fine cable-current-adjust potentiometers, that are electrically at high voltage. These potentiometers are adjusted from the front of the converter bay by means of long, nonconducting shafts.

V. SHORE STATION POWER SEPARATION FILTER

The shore station Power Separation Filter (PSF) bay is so named because it is the bay in which the wideband signal transmission path and the high-voltage dc power path, which share the undersea cable's center conductor, are separated for connection to their respective terminal equipment. Viewed in simplified form, the PSF circuit is a three-port filter, with an all-pass port for connection to the undersea cable, a high-pass port for connection to the wideband line transmission equipment (WLE),[13] and a low-pass port for connection to the power supply.

There are two fundamental but diametrically opposite design requirements for the PSF circuit: (*i*) to pass the wideband signal with some minimum acceptable values of return loss and insertion loss, which requires that components be small and circuit paths short; and (*ii*) to keep high-voltage partial discharge activity ("corona") below some appropriate threshold that requires that components be large and circuit paths widely spaced and long, in order to minimize destructive charge transfer in dielectrics and to satisfy transmission impulse noise objectives. For the SG system, with an upper frequency of 30 MHz and a maximum operating voltage of 7500 Vdc, the resulting dilemma was formidable and required extensive changes in the electrical and mechanical configurations compared to shore station PSFs of earlier undersea cable systems.

In addition to separating the power and signal paths, the PSF bay performs a number of important additional functions in the operation, maintenance, and safety of the cable system. Specifically, it provides: (*i*) proper electrical and mechanical termination of the undersea cable, (*ii*) a 75:50-ohm impedance match between the WLE and the cable, (*iii*) extensive shielding and filtering to prevent EMI from reaching the wideband signal path, (*iv*) facility for quick metallic connection of test equipment to the undersea cable center conductor, (*v*) an adjustable, 5-kW, auxiliary load that can be connected to the power supply in lieu of the undersea cable system, (*vi*) extensive high-voltage protection for equipment and personnel, and (*vii*) in conjunction with the power supply, a key-interlocked safety system that synchronizes their mode of operation and controls access to hazardous voltage compartments.

A simplified diagram of the PSF circuit is shown in Fig. 8. The broken lines represent copper compartments, which serve the dual purpose of EMI shielding and high-voltage protection. The end of the undersea cable connects to the cable compartment, and the wideband signal path is separated from the high-voltage power path by C1 and L. The signal path proceeds from C1 through the transmission compartment to the WLE port. From L, the high-voltage power path goes through the wall of the inner compartment to switch S, through filter network N, to the power supply port. Switch S is a large, key-interlocked, rotary power switch that controls the mode of operation of the PSF and access to its high-voltage compartments. Auxiliary contacts (not shown) operate vacuum relay K.

The dominant requirement on the design of the signal path is a return loss of ≥20 dB over the entire SG band. This requires that impedance discontinuities be kept to a minimum. These occur primarily in the cable compartment, where high voltage considerations require large clearances, resulting in significant structural variations from the desired signal path impedance. The 20-dB return loss requirement is equivalent to a voltage reflection coefficient $|\rho| \leq 0.1$, since return loss = $20 \log |1/\rho|$. For a cable of characteristic impedance Z_0, terminated in an impedance Z_T,

$$\rho = \frac{Z_T - Z_0}{Z_T + Z_0}.$$

Let the PSF be represented by its equivalent series impedance $Z_S = R_S + jX_S$, and let each signal port be terminated in its characteristic impedance, Z_0 (both ports referred to the same impedance level). Then the reflection coefficient at either port is:

$$\rho = \frac{(Z_S + Z_0) - Z_0}{(Z_S + Z_0) + Z_0} = \frac{Z_S}{Z_S + 2Z_0}.$$

The series resistance is small, and at the higher frequencies lead inductance dominates, so that

$$\rho = \frac{jX_S}{2Z_0 + jX_S},$$

whence for

$$|\rho| \leq 0.1, X_S \leq \sqrt{4/99}\, Z_0 \simeq 0.2\, Z_0.$$

This result provides a means of estimating the maximum allowable lead length through the cable compartment. At the undersea cable port, $X_S = 0.2 \times 50 = 10\ \Omega$, and at the top frequency of 30 MHz, an allowable

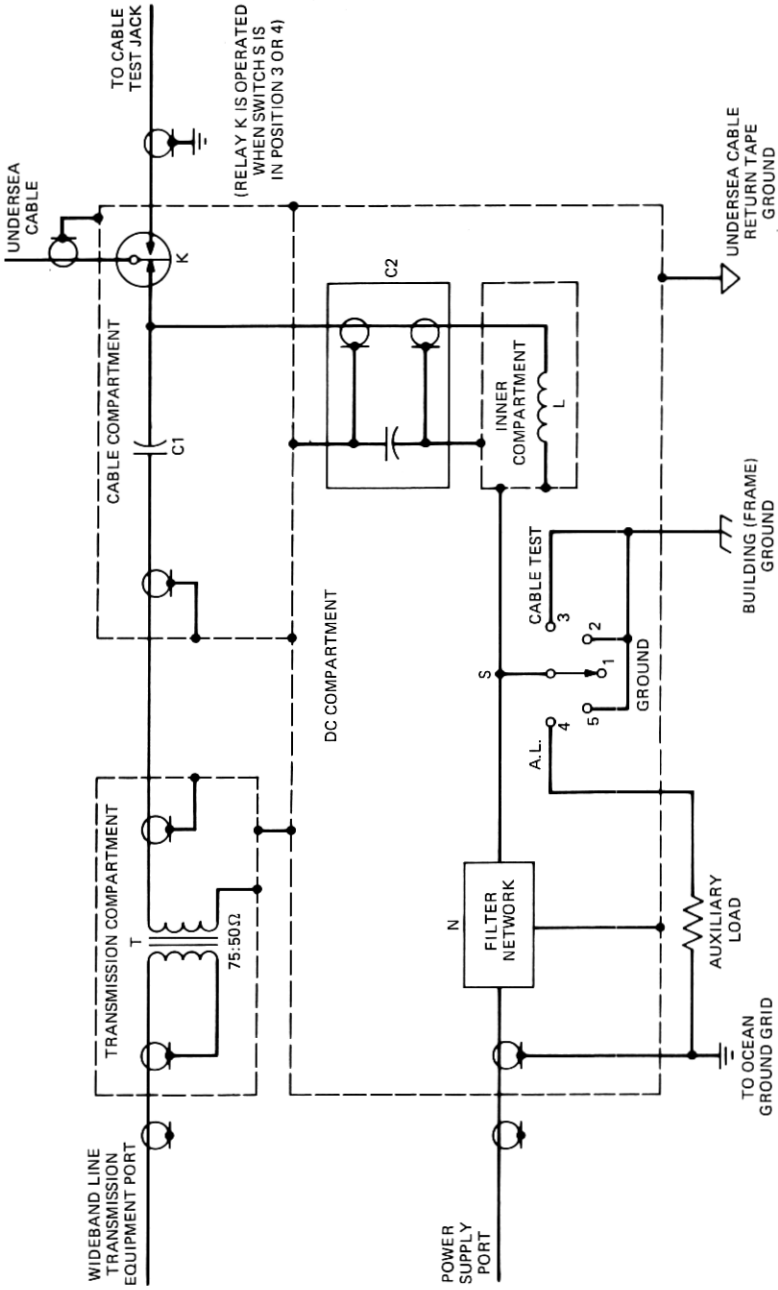

Fig. 8—Simplified circuit of the shore-station power-separation filter.

equivalent series inductance of 53 nH is obtained. Assuming, for illustration, a distributed lead inductance of 3.94 nH/cm (10 nH/inch), the maximum lead length is 13.5 cm (5.31 in.).

To attain the 53-nH requirement, the equivalent series inductance can be reduced by (*i*) shortening the path length, (*ii*) reducing the distributed inductance per inch, or (*iii*) adding shunt compensating capacitance. The path length was minimized by using a small high-voltage vacuum relay (K) to perform the required transmission path switching and by using the small capacitor (type 732A) designed for the SG repeater as the high-voltage blocking capacitor, C1. The distributed inductance of the remaining path was reduced by creating the separate cable compartment for the high-voltage portion of the signal path. The radial dimension of this compartment was made as small as possible (about 5-cm clearance from path to ground plane) consistent with the high-voltage, partial-discharge, activity requirements, thereby reducing the distributed inductance. Shunt compensating capacitance was not added, as this would have required the introduction of additional components into the high-voltage circuits in the cable compartment, increasing the possible sources of impulse noise and reducing reliability.

The actual, achieved path length of open leads through the cable compartment was approximately 20.3 cm (8 in.). The actual achieved return loss was greater than 30 dB over most of the 0.5- to 30-MHz band. Minimum values were 25.3 dB on a laboratory-built exact prototype, and 25.7 dB on the Green Hill PSF.

The principal requirements affecting the design of the high-voltage path are those concerned with high-voltage, partial-discharge activity, which must be kept below some appropriate level to satisfy signal-path impulse-noise objectives and to minimize destructive charge transfer in dielectrics. (The term "partial discharge activity" is preferred over "corona," since it more precisely describes the phenomenon taking place, viz., intermittent partial discharges of the dielectric. Strictly speaking, corona is a continuous discharge accompanied by a glow.) An excellent analysis of high-voltage partial discharge considerations in an SG-type cable system is given by Franke.[14]

Impulse-noise objectives established for SG terminals for the 48-kHz group data bands allow one "pop" (partial discharge pulse) per 15 minutes exceeding a threshold of −10 dBm0. This is equivalent[14] to a peak instantaneous voltage threshold of 100 mV from a 48-kHz bandpass filter placed anywhere in the SG signal band. Since there are a number of possible sources of impulse noise in a terminal other than the PSF, the actual pop rate allocated to the PSF should be significantly less than one each 15 minutes.

Attempting to establish limits to minimize the destructive effects is more difficult. Destructive charge transfer limits for dielectrics are nebulous and difficult to specify. Franke suggests a maximum value of 10 pC, based on levels permitted in previous undersea cable systems, with a rate corresponding to that of the data transmission interference requirement. For a maximum pulse duration of 50 ns in a 50-ohm system, he calculates a peak voltage threshold of 5 mV.

If the impulse noise and destructive charge transfer requirements are now combined, the resultant partial discharge activity requirement is a threshold of 5 mV, with a rate limitation of under 1 pop per hour.

The creation of a separate cable compartment not only aided in the solution of signal-transmission design problems, but also provided an effective way to isolate the high-voltage and signal paths, and thereby attenuate any noise which might otherwise be introduced via the high-voltage path. High voltage is fed from the dc compartment into the cable compartment via a novel skin-effect, low-pass filter* consisting of L, C2, and the inner compartment. C2 is a feed-through, ground-separating capacitor (type 729A) constructed like a coaxial cable. The feed-through lead is the center conductor, and the outer conductor is composed of two high-voltage, insulated, concentrically wrapped foils, each of which is connected to a ground cap at opposite ends of the cylindrical structure. At dc, the two ground ends of C2 are isolated, but at higher frequencies, they are effectively connected, and C2 is equivalent to a short piece of coaxial cable. One ground of C2 is connected to the cable compartment, while the other ground is connected to the inner compartment. The high-voltage path from the power supply is connected to the outside surface of the inner compartment. Hence, the inner compartment floats at the cable supply voltage, while for ac signals it is effectively an extension of the cable compartment (undersea-cable-return-tape ground).

The inside surface of the inner compartment is connected to L, which bridges the high voltage onto the signal path via the center conductor of C2. The high-voltage path consequently passes through the wall of the inner compartment, and any noise following this path is attenuated by the skin effect of the 0.0794-cm (0.0313-in.) wall. Using the classical formula for current penetration, it can be shown that, for thickness, t (cm), and frequency, f (Hz), at 20°C,

$$\text{Attenuation} = 20 \log_{10} e^{-0.151 t \sqrt{f}},$$

which, for $f = 0.5$ MHz, gives 73.6 dB.

Filter network N provides attenuation for the 20-kHz converter frequency and its harmonics and protects against tones which might be radiated or conducted around the power supply output filters. Together,

* The skin-effect filter concept is from G. H. Deshaies of Bell Laboratories, North Andover, Massachusetts, and was used in the PSFs of the L5 land transmission coaxial system.

N and the skin-effect filter provide a minimum loss of 80 dB from 20 kHz to beyond 60 MHz, as measured from the power supply port to the signal path.

High-voltage performance of the prototype and TAT-6 PSFs was evaluated using a wideband partial discharge detector developed by Franke and Czekaj.[15] With the detector connected to the 50-ohm signal path, the prototype had no pops exceeding 1 mV in 86 hours at +10 kV, and no pops exceeding 2 mV in 56 hours at −10 kV. The Green Hill PSF had no pops exceeding 1.4 mV in 8 hours at +10 kV, and the St. Hilaire PSF had no pops exceeding 1.4 mV in 15 hours at −10 kV. Since normal PSF operating voltages are less than 7.5 kV, these results provide a high degree of confidence that PSF high-voltage performance will not only meet but exceed design objectives.

VI. SUMMARY

The TAT-6, shore-station, power-feed equipment has been described. A modified version has been developed and installed and is in service on Cable Ship *Long Lines*. The shipboard power-feed equipment can power any long-haul, undersea cable in service at the time of the shipboard installation of the power-feed equipment.

VII. ACKNOWLEDGMENTS

The multiple-team concept that produced the SB, SD, and SF power-feed equipment was continued in the SG development. Significant contributions have been made by many individuals; directly by those participating as members of the development teams and indirectly by others. It is impractical to acknowledge all of the team members directly involved.

B. H. Hamilton, as leader of the power-supply-circuit-development team, is primarily responsible for both the system concept and specific techniques used in the power conversion, control, monitoring, protection, and switching circuits. From among the several members of this team, E. T. Calkin, W. J. Schatz, and R. E. Schroeder were selected as contributors to this article.

S. Mottel provided leadership for the power-supply-equipment-development team that is represented among the writers by I. Golioto. The physical design team was responsible for all aspects of the physical design of the power supply's bays, including the development and implementation of physical design techniques related to EMI suppression, maintainability, component selection, and installation methods, and the generation of manufacturing information.

W. G. Ramsey supervised the activities of D. S. Shull and R. E. Curlee, who were responsible for all aspects of the development of the terminal PSF equipment for both cable installation use and permanent system

operation. Mr. Shull did the general planning and circuit development, and Mr. Curlee did the physical design.

Close cooperation among all three teams contributed to the successful development of the power-feed equipment.

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