SF System:

Power Conversion

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This article describes the constant current, high voltage power facilities which power the SF Submarine Cable repeaters. The overall power system description includes discussions of the power connections to the cable, and a review of overall design requirements and objectives. The circuit description is covered in a general manner to demonstrate the basic concept. Particular emphasis is given to the description of several significant circuit innovations which include automatic load sharing by two constant current sources, 20 kHz inverter operation with output wave symmetry correction, solid-state alarm detectors, automatic turn-up and turn-down features, electrical noise suppression, redundant shutdown circuits and selective alarm cutoffs.

The physical design includes the extensive use of plug-in modules for ease of maintenance, convection cooling of the entire power supply including the test load, and a key interlock system which prevents access to high voltage components when the power supply is energized. A special high-voltage switch can transfer the cable from one power plant to another without interruption of service.

I. INTRODUCTION

At 7:15 A.M. on 8 August 1968, a technician pushed a button on a power supply in the Jacksonville Beach cable station. Within seconds another technician pushed a button on a power supply in the Magens Bay cable station. One minute later the first units of a new generation of submarine cable power supplies were in service powering the Florida to St. Thomas SF Submarine Cable System.[1]

The direct current needed to power SF Submarine Cable repeaters[2] is carried to the repeaters by the coaxial cable's center conductor. The current originates in shore-based power supplies and is returned from the far cable end through sea (ocean) ground. Since the repeaters are connected in series, the current requirement is the same for all SF

Systems, but the end-to-end cable voltage drop is a function of system length.

The new submarine cable power supplies which went into service on 8 August 1968 are direct current sources designed to accomodate a wide range of voltage loads. These supplies are powered from duplicated −48 volt battery plants. The −48 volt battery-charging rectifiers are powered from commercial power lines. The interposition of batteries between the commercial power lines and the SF Submarine Cable power supply assures continuous power availability in the event of a commercial power failure. In addition, the provision of automatically or manually started engine or turbine driven alternators extends almost indefinitely the time period over which a commercial power failure may be tolerated.

Having provided for a reliable source of continuous input power, the SF Submarine Cable power supply designers have duplicated major power units within the power supply wherever practical and have specified highly reliable components for use where duplication is impractical. In doing this they have drawn heavily on the techniques used by the SB and SD Submarine Cable power supply designers.[3,4] In addition, they have taken advantage of advances in the state of the art and incorporated many innovations which result in new ease of operation and maintenance in a smaller package.

II. DESIGN REQUIREMENTS

The power connections to an SF Submarine Cable System are shown in Fig. 1. Power supplies of opposite polarity are connected at each end to reduce, by half, the maximum voltage stress applied to the repeaters near to the cable ends. On systems short enough to require less than half the end-to-end cable voltage required for a maximum length system, the cable can be powered from one end only, or from both ends. If a short system is powered from both ends, then the power supply at either end has sufficient voltage reserve to power the entire cable. In addition, if a high impedance shunt fault develops in the cable in a short system powered from both ends, the system can be continued in service until repair is made. This is done by adjusting the load sharing between the power supplies until the voltage at the fault is zero.

The electrical design requirements placed on a power supply for one end of an SF Submarine Cable System are shown in Table I. The SF Submarine Cable power supply normally functions as a well-regulated current source. Under appropriate conditions, the supply shifts auto-

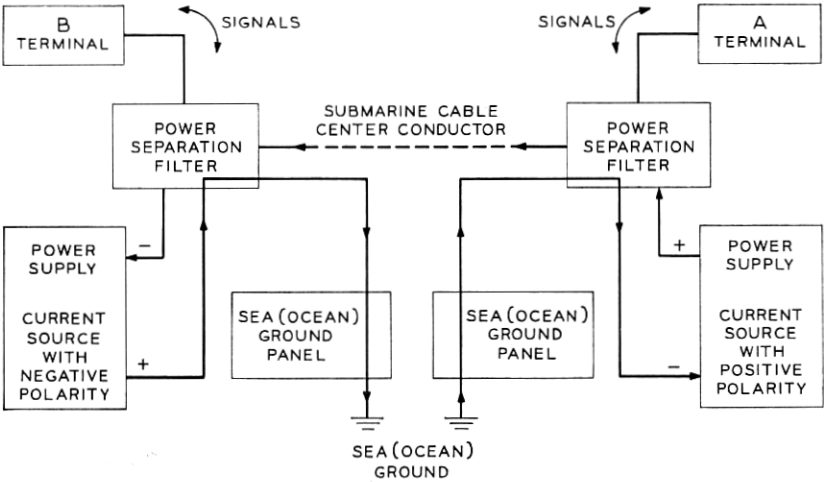

Fig. 1—Power connections to the SF Submarine Cable System.

matically to a voltage-limiting mode of operation to prevent excessive output voltages. The power supply is also required to have monitoring circuits which will warn of current or voltage abnormalities and will shut down either or both of its redundant current sources in the event of excessive voltage or current.

III. POWER SUPPLY ELECTRICAL SYSTEM

Figure 2 displays a complete power supply system as it would appear on one end of a cable system. Power continuity is achieved by using reliable, independent current sources which share the voltage load. The redundant current sources are the series connected inverter-rectifier 1 and inverter-rectifier 2. Either will automatically assume the entire voltage load should the other shutdown for any reason. Semiconductor diodes bypass the cable current between the output terminals of the shutdown inverter-rectifier current source.

Nonredundant paths achieve high reliability by use of highest quality, conservatively dc rated components.

Routine maintenance and repairs are facilitated by the inclusion of a second power plant in the system as a standby and by the provision of means of transferring the cable current load from the "in-service" to the standby plant without disrupting service. In Fig. 2, either power plant I or power plant II can be the standby plant. The load

TABLE I—SF SUBMARINE CABLE POWER SYSTEM ELECTRICAL REQUIREMENTS

Normal current	0.136 ampere
Nominal voltage	3500 volts
Maximum voltage (at normal current)	4500 volts
Maximum single frequency tone (appearing at power separation filter transmission terminals)	−120 dBm at 500 kHz −130 dBm at 6000 kHz
Normal accuracy of current control	±0.5 mA, absolute
Load current regulation:	
1000 volts change	±1.0%
one rectifier failure	−0.5%
Output resistance above 4500 volts	2500 ohms
External alarms, power plant output:	
Minor alarm—current	±2%
Minor alarm—voltage	±8%
Major alarm—current	±5%
Major alarm—voltage	±15%
External alarms, each rectifier output:	
Minor alarm—current	−5%
Minor alarm—voltage	200 to 500 volts
Major alarm—current	+5%
Major alarm—voltage	4975 volts
Protective shutdowns:	
Each rectifier	+5% current 4975 volts (electronic) 6500 volts (spark gap)
Plant	6500 volts (spark gap)

transfer provides the means of performing a "hot" transfer of cable load between the power plants, and also provides an adjustable test load to aid in servicing the standby power plant.

3.1 *Power Separation Filter*

The power separation filter is a separate bay in which the transmission signals and the power supply current are jointly applied to the undersea cable. Included in the power separation filter is a means of routing the current from the power supply to either the cable or an auxiliary load. This permits the testing of the power system up to the point of the cable connection before the cable is installed.

3.2 *Power Plant Monitors*

Each power plant contains a variety of circuits and devices which monitor the plant's output. These include meters, recorders, voltage and current alarms, overvoltage current droop circuits, and overvoltage shutdown circuits. These circuits monitor the combined output of the two inverter-rectifier current sources.

3.3 *Inverter Rectifiers*

The inverter-rectifier electrical system is illustrated in Fig. 3. The principle function of the inverter-rectifier is to produce well-regulated current at any voltage up to a maximum of 4500 volts. The conversion of the input battery power into a regulated current with a large voltage compliance is provided by the 20 kHz inverter, the regulator, and the high voltage rectifier. The inherent constant current characteristic of the saturable reactor is enhanced by a closed loop regulation system which reduces output current drift to the low level required of this power supply.

3.4 *Load Sharing Between Inverter-Rectifiers*

The requirement of low drift of output current results from the independent regulation of the two series-connected inverter-rectifiers and the large value of slope resistance connected across each inverter-rectifier's output. The slope resistance is selected at approximately the lowest value consistent with the "one rectifier failure" regulation requirement listed in Table I. The difference in output current drift

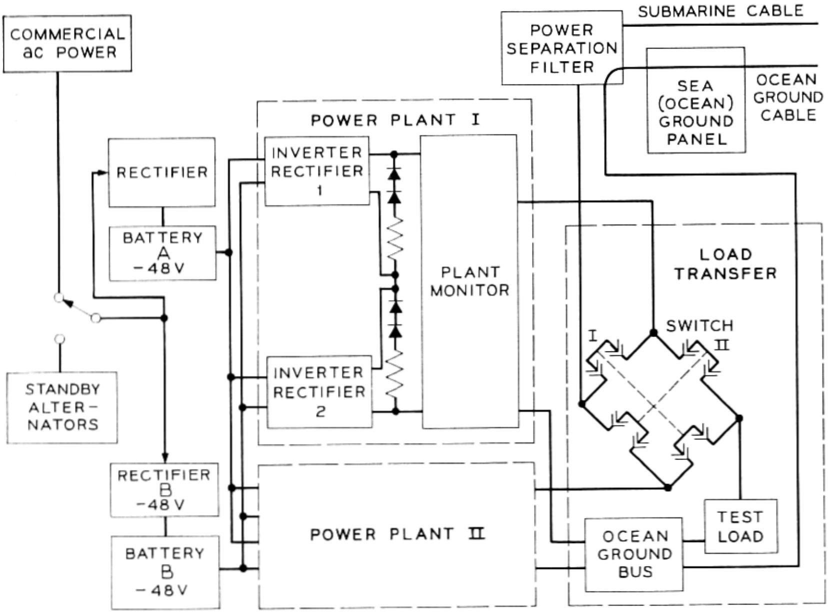

Fig. 2—SF Submarine Cable power system.

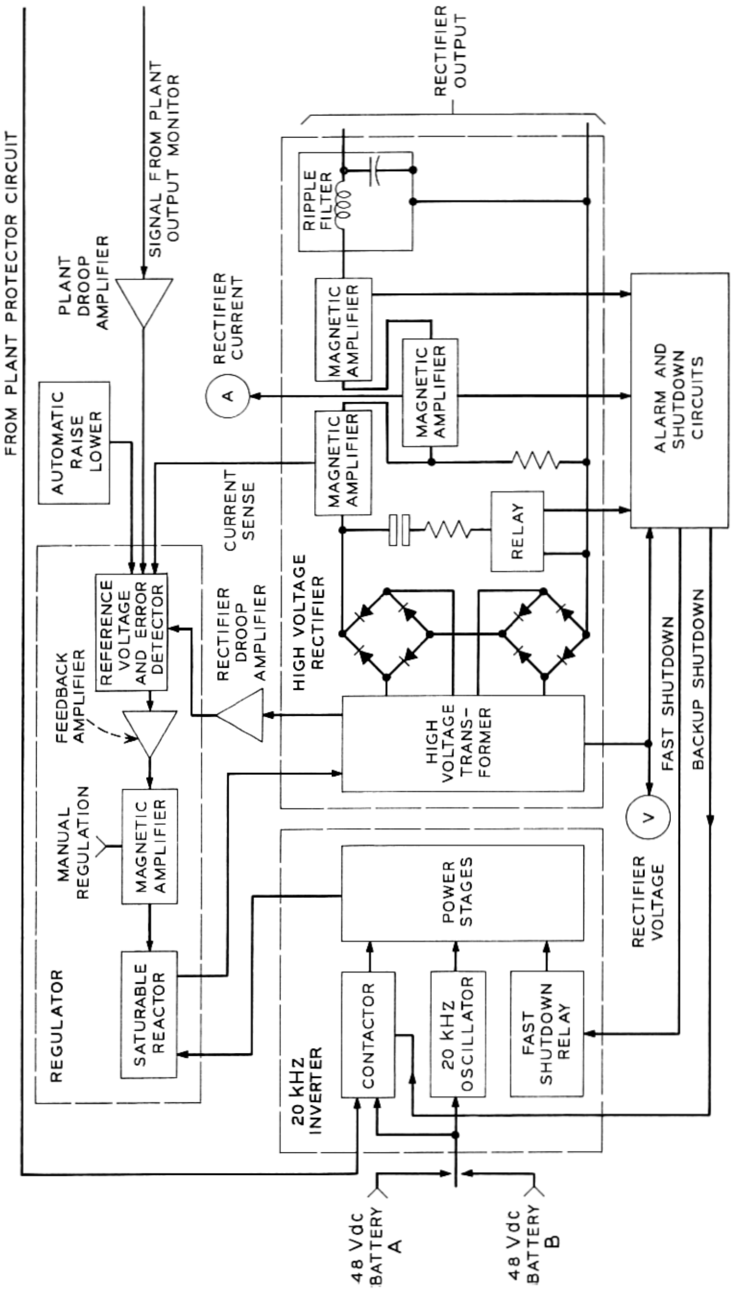

Fig. 3—SF Submarine Cable power supply inverter—rectifier system.

between the two inverter rectifiers must be less than 0.0215 percent if the drift in load sharing between inverter-rectifiers is to be less than fifty volts. (In the SD power supply, the equivalent figures were 0.025 percent current drift for a 75 volt load sharing drift—see pp. 1347–1348 of Ref. 4.) Both SD and SF have proven stable with respect to voltage sharing between rectifiers.

Normally the inverter-rectifiers are manually adjusted to equally share the load voltage. Equal load voltage sharing is essential neither to normal cable power nor to the automatic assumption of the full load voltage by one inverter-rectifier if the other should fail. Equal load sharing does, however, minimize the output voltage and current excursions which occur when one inverter-rectifier is shut down.

3.5 *Load Sharing Between Cable Ends*

Load sharing between power supplies on each end of a long cable is possible only because of the low output drift and the inclusion of a finite fixed slope which is introduced into each power supply by the slope resistances connected across their outputs. A lower slope resistance is used across the plant output because the "1000 volts change" regulation requirement listed on Table I is less severe than the "one rectifier failure" requirement. The lower slope resistance facilitates load sharing between power supplies. Load sharing between power supplies on a long system is essential since neither can power the complete system. Equal load sharing between power supplies on a short system powered from both ends is desirable from a monitoring point of view but not essential to system operation.

IV. POWER SUPPLY PHYSICAL SYSTEM

An SF Submarine Cable power supply is composed of either:

(*i*) Two power plant bays and a load transfer bay as shown schematically in Fig. 2; or

(*ii*) One power plant bay and a load transfer bay.

Figure 4 is a photograph of the two bays in the "one-power-plant" system. These bays are presently installed in the Jacksonville Beach cable station. A similar power supply with opposite polarity is installed on the other end of the system in the Magens Bay cable station.

A power plant bay is equipped with one plant monitor and two inverter-rectifier pullout units which house low voltage circuits. These are displayed in Fig. 5. Their associated high voltage components are mounted in the rear portion of the bay. The high voltage section is

Fig. 4—Single power plant SF Submarine Cable power supply.

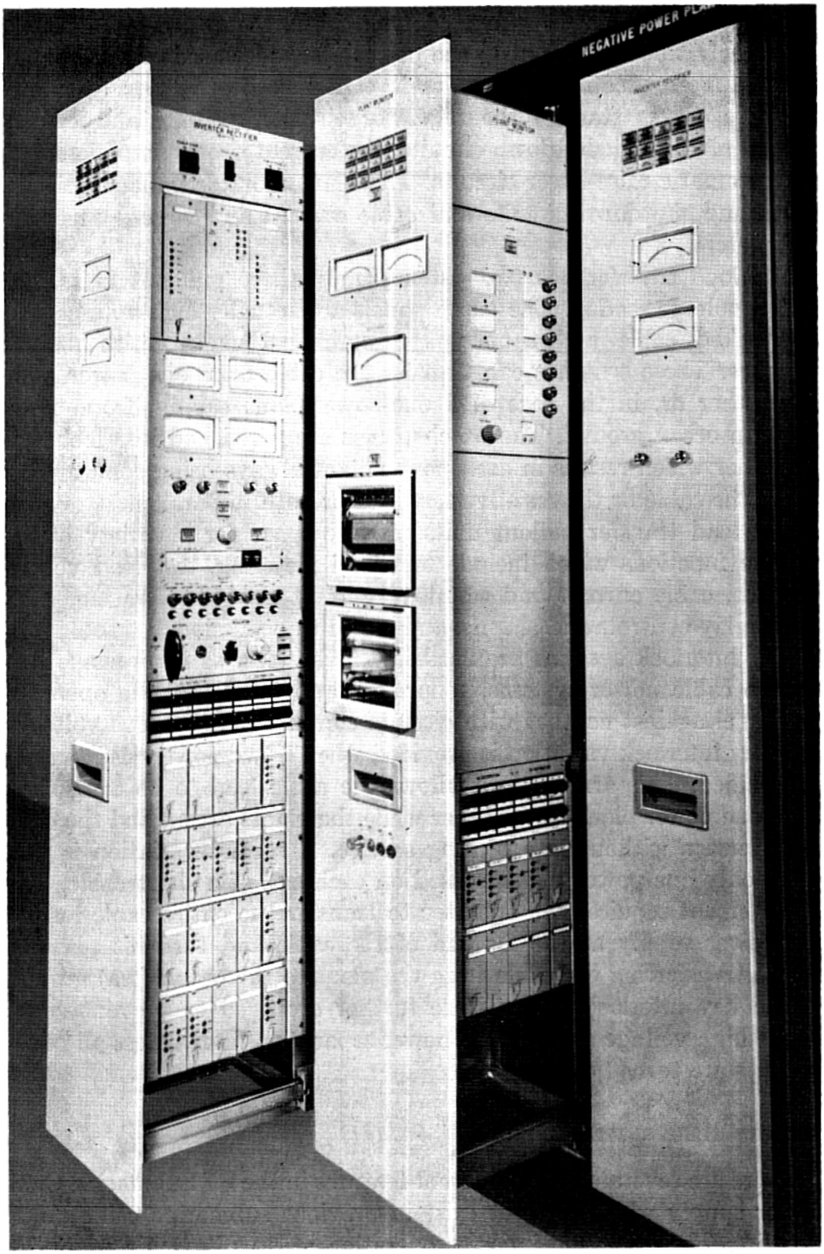

Fig. 5—SF Submarine Cable power plant pull-out units.

interlocked with power plant controls in a manner which permits access only when the input to the power plant is turned off.

The inverter-rectifier pullout unit contains the inverter (oscillator and two power stages), the regulator circuits, voltage and current meters, alarm and shutdown circuits, the current droop amplifiers, and the automatic raise-lower circuits. The plant monitor pullout unit has alarm and shutdown circuits and cable current and voltage recorders and meters.

The load transfer has two patch panels, three pull out units, and a high voltage section. The patch panels are actually high-voltage key-interlocked cable and connector assemblies that serve as manual switches. These switches can transfer the cable from one power plant to another or, in the case of a one-power-plant supply, from power plant to ocean ground. The patch panels are wired and interlocked in a manner which results in each power plant always being connected to either the cable or the resistive test load or both in parallel.

The load transfer pullout units provide space for a variety of low voltage functions which include test load metering, test load voltage controls, cable current and test load current meter calibrating, cable short relay controls and alarms, and alarm transmission.

Key interlock systems are used in this system, as in previous submarine cable power systems, to provide protection for the operating personnel against contact with circuits containing hazardous voltages. One key interlock variation is provided when a two-power-plant supply is specified. This arrangement allows the cable load to be transferred from one power plant to the other while the plants are on and the cable is in service without interrupting service. A second variation is used when only one power plant is used on each end of a short cable. This arrangement requires the operator to transfer the entire cable load to the power supply at the far end of the cable and turn his plant off before transferring the cable from the plant to the ocean (sea) ground.

The key interlock systems are further arranged to prevent access to the high voltage areas in the power separation filter unless all power supplies are turned off.

V. NEW ELECTRICAL FEATURES

There are several new or different features in the SF Submarine Cable power supply which did not exist in previous submarine cable power supplies. These include inverter operation at an ultrasonic frequency (20 kHz), an automatic output current raise-lower function on each inverter-rectifier, automatic load sharing between power stages in an inverter-rectifier, output waveform symmetry correction in the inverter's oscillator-buffer circuit, solid-state alarm level detectors and selective remote alarm cutoff.

5.1 *Inverter Frequency and Power Supply Electrical Noise Suppression*

Direct voltage inversion to alternating voltage was introduced to submarine cable power supplies in the SD Submarine Cable power supply as a necessary adjunct to the use of a saturable reactor as a constant current source. A saturable reactor designed to work at 60 Hz would have been impractically large (see p. 1345 of Ref. 4). The state of the development of power semiconductors and broad experience then current in 400 Hz circuits led the SD Submarine Cable power supply designers to select an inverter frequency of 400 Hz even though they believed "higher frequencies would have been more suitable from a size standpoint" (see p. 1346 of Ref. 4).

The availability of improved power semiconductors and a dissatisfaction with the audible noise levels produced by the magnetic component cores of the SD Submarine Cable power supply led to the selection of 20 kHz as a nominal inverter operating frequency for the SF Submarine Cable power supply. The 20 kHz operating frequency and the reduced SF maximum output power requirement (approximately one-quarter of that required for SD) have enabled the SF physical designers to eliminate the separate inverter bay used in the SD Submarine Cable power supply by installing the SF inverter as one section of the inverter-rectifier pullout unit.

Operation of the SF inverter at 20 kHz has eliminated the audible noise problem but increased the electrical interference problem by moving the inverter's fundamental frequency of operation relatively closer to the lowest transmission frequency. Both the SD and SF inverters generate quasi-rectangular current and voltage waves. The 100 kHz lower frequency limit of the SD transmission band is the 250th harmonic of 400 Hz, but the 500 kHz lower frequency limit of the SF transmission band is only the 25th harmonic of 20 kHz. A further problem arises from the fact that the upper limit of the SF transmission is 6 MHz against the SD upper limit of 1.1 MHz. The net effect is to require better filtering and electrical noise suppression in the SF power systems than was necessary in previous submarine cable power systems.

Several new features are included in the SF power system's ripple and electrical noise suppression system. These include:

(*i*) The location of the power separation filter in a separate equipment bay which is installed at a distance from the power supply to reduce electrical noise which may result from direct electromagnetic radiation from the power supply;

(*ii*) The installation of new design, low pass filter networks in the output of each high voltage rectifier, in the power plant output and in the power separation filter;

(*iii*) The extensive use of shielded and coaxial leads throughout the power system; and

(*iv*) The extensive use of capacitors to by-pass longitudinal noise signals in the various input and output leads, other than high voltage leads, connecting to the power supply.

5.2 *Automatic Turn-up and Turn-down Circuits*

A major new operational feature introduced to submarine cable power supplies is the automatic raise-lower circuit installed in each inverter-rectifier. In the SD Submarine Cable systems, power is turned up by manually rotating the rectifier output current adjustment until the desired current level is achieved. On a long system, there are two "in-service" rectifiers on each end, or a total of four current adjustments which must be turned up.

The SF Cable system power may be turned up manually as is the SD Cable system, but SF is normally turned up automatically. In the automatic turn-up procedures, the power supplies on each end are manually preadjusted into their test loads. The adjustments are made with the automatic raise-lower circuits turned off. By doing the tedious and exacting initial adjustment on the test load when there is neither urgency nor danger of system damage, less pressure is placed on the operator. At the moment of the most tension, that is when the cable is being powered for the first time, the operators have nothing to do except push the cable current raise button and watch meter indications.

The automatic raise-lower function is achieved by means of a solid-state voltage ramp circuit which connects into the regulating control loop as illustrated in Fig. 3. The regulating control loop is a direct current amplifier system with negative feedback. The inverter-rectifier's output current is directly proportional to a reference voltage. The automatic raise-lower circuits achieve a smooth, automatic variation in the inverter-rectifier's output current by superimposing a voltage ramp on the reference voltage.

5.3 *Load Sharing Between Inverter Power Stages*

Another new feature is automatic load sharing between the two power stages within each SF power plant inverter. (This automatic sharing is not to be confused with the manually controlled load sharing between the virtually independent inverter-rectifiers.) The automatic load sharing is accomplished in a new circuit,[5] the functioning of which depends on multiple gate windings on the power saturable reactor and corresponding multiple cores and primary windings on the high voltage transformer. The essential details of the circuit are shown in Fig. 6. The two gate windings are identical and the transformer's two primary windings are identical and wound on identical cores. A detailed description of the operation of this circuit is found in Ref. 5.

5.4 *Inverter Switching Signal Symmetry*

The inverter is composed of two power stages and an oscillator-buffer stage. The latter provides switching signals to the power stages. It is desirable that the switching signals to the power stages be symmetrical with respect to time, that is, the negative half-cycle which turns a power stage transistor off should be equal in length to the positive half-cycle which turns the same transistor on. The inherent oscillator output waveform was not as symmetrical as desired, due principally

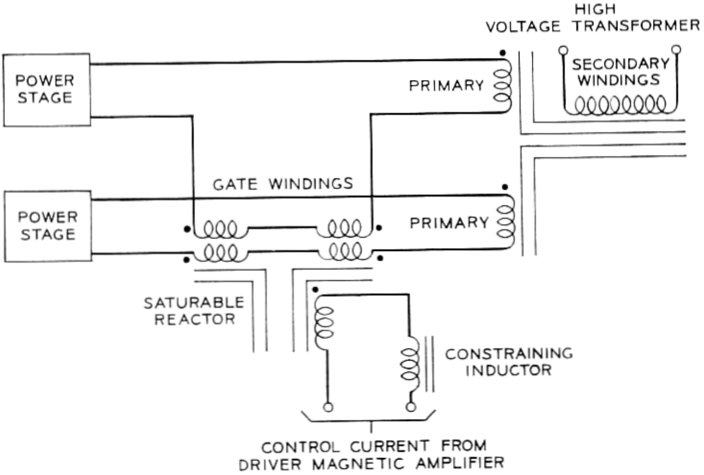

Fig. 6—Power stage forced load sharing circuit.

to differences in switching times between the two oscillator transistors. The symmetry is greatly improved by the circuit shown in Fig. 7.

This figure shows essential elements with the buffer stage, starting networks, and shaping networks omitted. A simplified description of the symmetry correction network circuit operation is as follows:

(*i*) Equal voltages are assumed across C1 and C2.

(*ii*) Assume that Q1 tends to conduct longer than Q2.

(*iii*) When the on-time of Q1 equals the total on-time of Q2, then L1 saturates and a current flows in winding 1–2 of T1 in such a direction as to turn Q1 off, thereby correcting the tendency of Q1 to be on longer than Q2.

An expanded description of the circuit operation is given in Ref. 6.

5.5 *Alarm-Level Detectors*

The current alarm-level detectors are semiconductor circuits which can be adjusted to detect over or under currents to within a few tenths of a percent of the desired alarm level. A single detector circuit can detect both over and under current levels from a single signal current. The semiconductor level detector circuits permit easier adjustment than that provided by the meter type relay used in earlier voltage and current alarms. Furthermore, shutdowns can be tested and circuits calibrated while the power supply is connected to and powering the cable.

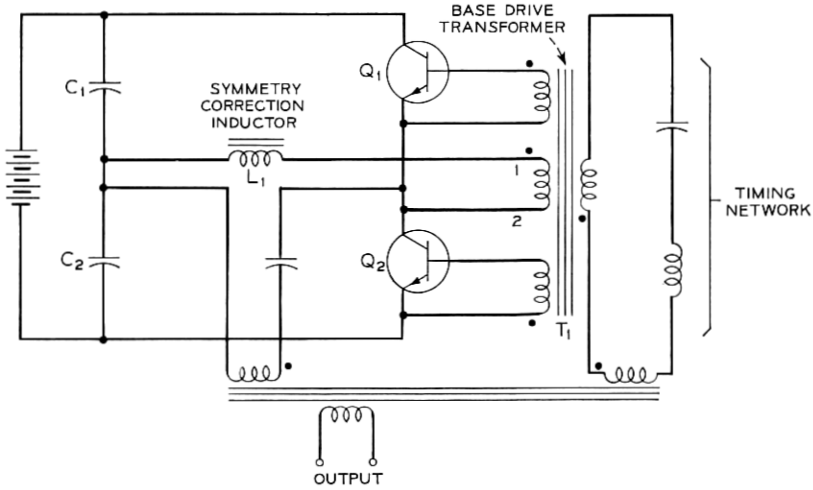

Fig. 7—Simplified SF oscillator circuit with a symmetry correction network.

5.6 *Selective Alarm Cutoff*

Still another new alarm feature is the selective cutoff of remote alarm transmission. There is only one alarm cutoff push button, but operation of this push button will cutoff the remote transmission of those alarms which exist at the instant the alarm cutoff push button is operated. If a new alarm condition appears, it is remotely transmitted and it is necessary to again operate the alarm cutoff push button to silence the remote alarm.

VI. NEW PHYSICAL FEATURES

The SF Submarine Cable power supply is the first submarine cable power supply to make extensive use of plug-in modules. The majority of the components in the power supply other than high voltage items, are mounted on 54 plug-in modules. The number of different types of plug-in modules is minimized by putting only the common features of similar circuits on a plug-in module. Hence, the 54 plug-in modules represent only 17 different types.

Two advantages of this commonality result. First, component density is increased, permitting smaller overall power supply dimensions than would otherwise be possible. Second, the small number of different types permits the storage of at least one spare of each type in the power supply. The presence of these spares facilitates maintenance procedures and repairs.

6.1 *Precision Calibrator and Test Load Location*

The separate equipment bay that housed the test load circuits and the precision current meter calibration circuit (see p. 1360 of Ref. 4) in the SD Submarine Cable power supply, are not needed in the SF Submarine Cable power supply. Both the calibration circuit and the test load circuits are installed in the SF load transfer bay.

The SF precision current meter calibration circuit is similar (except for shunt resistances) to that used in the SD Submarine Cable power supply.

The SF test load maximum power dissipation is approximately one-quarter of that required for the SD test load. Hence, not only is the SF test load located in the load transfer bay, but it is cooled by natural convection rather than by the fan driven air circulation.

6.2 *Natural Convection Cooling*

It has been possible to dispense with cooling fans in the SF Submarine Cable power plant despite the location of the inverter's power stage and oscillator modules in the inverter-rectifier pullout unit. The lower power rating of the SF power supply (relative to the SD power supply) and the physical design of the equipment (to take advantage of natural convection) make this possible. The principal heat producers, the inverter's oscillator and power stage plug in modules, are located at the top of the inverter-rectifier pullout unit. An opening in the front panel, just below the inverter modules, allows air to come in and flow through the inverter modules before exiting through the top of the bay. This arrangement keeps the rest of the equipment at or near room temperature.

VII. SHIPBOARD POWER SUPPLY

The shipboard power supply (see pp. 1364-65 of Ref. 4) formerly designed and used for SD Cable laying and repair operations, now has been modified to provide power for SF Submarine Cable systems. The modification consisted of the installation of magnetic amplifier and meter options.

VIII. SUMMARY

The SF Cable power supply contains may design innovations. Inverter operation at 20 kHz and convection cooling result in silent operation in a smaller plant. These features introduced several challenging problems in the area of electromagnetic noise suppression and magnetic apparatus design.

The sophisticated use of semiconductors in combination with relays permits stability, small size and reliability in the alarm and protection systems. In addition, automatic turn-up and turn-down circuits and modular physical design contribute to new ease of operation and maintenance.

IX. ACKNOWLEDGMENTS

The SF Submarine Cable power supply design is the result of the team effort of over twenty circuit, physical, and apparatus designers. We particularly acknowledge the guiding and co-ordinating roles of the following persons: circuit design—Mr. J. D. Bishop; physical design—Mr. S. Mottel; and magnetic component design—Messrs. T. G. Blanchard and B. E. Stevens.

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