SLAC-PUB-329
July 1967

DESIGN, CONSTRUCTION, AND PERFORMANCE OF A 5,800 KW (11,000 amp) POWER SUPPLY FOR A SPARK CHAMBER MAGNET*

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1. Introduction

The 5,800-kW (525 volts at 11,050 amps) power supply (Figs. 1 and 2) discussed in this paper is used to energize a magnet having an 80-inch diameter pole. This magnet is used with a streamer type spark chamber in the experimental area of the 20-GeV 2-mile linear accelerator located at the Stanford Linear Accelerator Center (SLAC), Stanford University, Stanford, California. This solid-state rectifier power supply was manufactured by Ling Electronics (Division of LTV) of Anaheim, California, U.S.A., to satisfy a set of performance specifications.

The rated voltage of this power supply is obtained with four different 24-phase sections that are effectively in series (see Section 5 for details), the voltage control of the power supply is by sequential control of each of these silicon-controlled-rectifier (SCR) sections producing a power supply with 100% range of control and high power factor throughout its control range. See Fig. 3. The sequential phase control of each of the sections ensures that only one section at a time is in a phase retarded control position, thus minimizing voltage transients on the ac power lines during the commutation periods. Figure 3 shows the expected relationship of kW and kVA input to the power supply and three empirical data points.

The current regulation required is ± 0.1 of maximum current; this is easily accomplished with a current loop stabilized with voltage feedback. The triggers for the SCR's are derived in such a manner as to give a high degree of automatic open loop phase control that compensates for a change in line voltage. This compensation is effective over most of the voltage range and leaves the closed loop portions of the regulation system to handle variations in load resistance and random drifts due to the electronics involved. The 12.47 kV, 6,000 kVA, ac used to supply this power supply will be subject to ± 1% fast step changes, and ± 2% slow changes. There may be as much as 7% peak-to-peak harmonic distortion present on this supply line.

This power supply is currently undergoing acceptance testing; therefore, this report must be considered preliminary. The data given in Fig. 3 is based upon only three of the rectifier sections in operation and is therefore limited to 8,000 amps into the load. The empirical data points in Fig. 3 are out of the specification limits because the bias adjustments for the sequential voltage control have not been properly adjusted. Three of the main rectifier transformers are now being repaired; one, resulting from a loose washer that accidentally dropped into the windings and caused a line to line short across one of the delta secondaries; two, resulting from a primary insulation failure on one of the two units.

This power supply was originally designed for water cooling. We tried to substitute oil cooling during one part of the testing program to minimize the problems of drying water out of the dry type high voltage transformer in case of a hose breakage, but the cooling factors were not sufficient and we had to return to water cooling.

(Presented at 2nd Int'l. Conf. on Magnet Technology, Oxford, July 11-14, 1967)

*Work supported by U.S. Atomic Energy Commission

2. Physical Construction

This power supply was built upon a trailer to allow it to be moved within the 12-acre experimental area of SLAC. This mobility is not now considered as important, since we are constructing a water cooled dc bus that will allow this power supply to be connected to various possible loads on a short notice.

The power supply is constructed in 6 separable cabinets and weighs about 93,000 pounds including the trailer. There are four identical rectifier cabinets each containing a main transformer, SCR's and LC filters, one cabinet containing a 12.47 kV manual disconnect (NOT fused), and one control cabinet containing the regulation amplifiers, the SCR trigger generators, the dc terminations and the various control relays. The spaces between cabinets are covered with flexible rubber sheet bonded to the cabinet to allow flexing of the trailer during transportation. Movable platforms with weatherproof tops are arranged on both sides of the trailer to allow easy working on the unit.

Some of the electrical interconnections of the various sections of the rectifier circuits are made with copper pipe (current density 17,000 amps per square inch). Circulating water is used to cool these pipes. This type of construction does away with the heavy busses normally involved with a power supply of this rated current.

The main transformers were specified to be of a dry type insulation to make the transformer as small as reasonable and to not have large volumes of oil present. The main rectifier transformers are constructed with a primary and a secondary foil shield or screen; water cooled copper tubes are also wound near the secondary shields to conduct out some of the transformer losses to keep the sheet wound secondaries cool by conduction. Rate-of-rise indicators and maximum thermal sensors are installed in the roof of the main cabinets; they will trigger off a carbon dioxide flooding system and alert the fire patrol. A combustion products smoke detector also has been installed to call the fire patrol. Both of these systems will shut down the power supply. The smoke detector is valuable because a blown filter capacitor may not disturb the system enough to turn off the power supply on overloads; the smoke from the destroyed capacitor will turn off the system. There is an air to water heat exchanger located within the cabinets to keep the air temperature within the power supply at a reasonable value. This power supply was designed so as not to use outside air for cooling to minimize the possibility of condensation of moisture-laden, foggy air upon cold surfaces within the power supply. Electrical heaters are attached under the cabinets to prevent water condensation during long periods of nonoperation in the winter.

The power factor capacitors, 12 kV fuses, and vacuum switches are located along the center line of the assembled power supply and are available for servicing. Some of the construction details can be seen in Fig. 4, where one of the power supply cabinets has been removed. There are 84 temperature sensors (Klixon switches) located on critical cooling paths within the power supply to protect against the loss of flow in parallel cooling paths such as the cooling tubes of the transformers and in the SCR heat sinks.

3. The Control System

The Control System of this power supply consists of several individual interlock chains terminating in relay coils, whose contacts are used in a summary chain to provide the ON/OFF control functions and safety interlocking. Those functions that must turn off the power supply on "Emergency off" do so through the summary chain as well as with contacts from the individual chains; two methods of turn-off are available:

> Emergency-turn-off opens the main 12.47-kV circuit breaker and allows the magnet current to decay on its own time constant of about 7 seconds. Several of the power supply protection and personnel protection circuits are considered emergency conditions and turn off the power supply in this mode.
>
> Programmed-off, when energized, takes 5 minutes to automatically run the magnet current down with a motor-driven potentiometer and opens the main

circuit breaker when the current actually reaches a value near zero. This is the normal method used for on/off control of this power supply. The power supply and magnet thermal interlocks are connected to this function. The emergency off-circuit is energized if the programmed-off fails to function after 5 minutes.

Three normally closed high-voltage vacuum switches, K23, K24, and K25, (see Fig. 5) are used to energize the main transformers T3, T4, and T5. They are energized to open at turn-on time and are allowed to close sequentially after the main transformer T2 is energized from the substation 12.47 kV air circuit breaker. The vacuum switches are normally-closed to ensure that they do not open under a fault condition that depends upon the interrupting capacity of the substation 12.47 kV air circuit breaker. The vacuum switches are normally-closed to ensure that they do not open under a fault condition that depends upon the interrupting capacity of the substation air circuit breaker to clear. (The vacuum switches are rated to clear 2,000 amps asymmetrical where 40,000 amps are available from the power system.) The interlock sequence will turn off the power supply if the sequential control of the vacuum relays does not complete within 45 seconds. Once the vacuum switches are closed they remain closed until it is desired to again turn on the power supply after it has been turned off.

The metal components of the spark chamber located in the gap of the magnet are subject to large mechanical forces due to eddy currents resulting from any rapid changing of the magnet current; therefore, a motor-driven potentiometer is used to control the level of the current to be regulated eliminating the chance that an operator will change the current faster than about 2,000 amps per minute.

4. <u>AC Power System</u>

A 12.47-kV circuit breaker located in the Research Area substation is used as the primary on/off control for this power supply. Auxiliary control voltages are 480 volts 3-phase and 120 volts single-phase.

The source impedance of the 12.47 kV ac feeding this power supply may be either 0.2 + j 1.5 ohms or 0.04 + j 0.4 ohm, depending upon the connections to the utility district. Triplexed cables in underground ducts are used to connect the power supply to the air circuit breaker located in the substation 500 feet from the power supply. A fused manual disconnect located near the power supply trailer is used to limit fault current and provide a safety disconnect point. The four main power supply transformers are energized sequentially with vacuum switches in the power supply to minimize line voltage transients. The control circuits force the air circuit breaker to be the "off" control because the vacuum switches are not rated to break the available short circuit current.

The method of sequential control of four series connected power supply sections with 7% reactance transformers should produce minimum transients on the line during the commutation periods.

5. <u>DC Power System</u>

There are four 6-phase rectifier groups connected in parallel to supply the rated output current (Fig. 5). These groups are identical except for the 12.47-kV primary winding connections of delta, Wye, and two zig-zag windings to produce a dc output with 24-pulse ripple. Each of the rectifier groups is made up of 4 different silicon-controlled-rectifier (SCR) voltage sections (210, 133, 99, and 83 volts) connected in series. The identical voltage sections of each group are controlled simultaneously, starting with the 210-volt sections; as the voltage of each of these sections nears its maximum, the next lower voltage section begins to pick up the load. Freewheeling diodes connected across each section carry the load current until the phase angle of firing signals for the section are advanced enough to produce a positive output. The power supply is protected from dc overcurrent with a meter-relay fed from a source that is the average voltage from all 8 shunts R8 to R15. There are 8 other relays on R8 to R15 that specifically protect each parallel group from overloads due to some regulation circuit mal-function.

One of the legs of the dc output is connected to ground through a 100-ohm soft ground circuit. The current through this resistor is monitored and the power supply is turned off if it exceeds some value that is adjustable from 0.1 amp to 0.5 amp.

The Schmitt trigger circuit used to generate the variable phase control triggers is shown in Fig. 6 with the typical phase relationships. The line voltage supplying the signal for this comparison circuit is well-filtered to remove all line harmonics that would cause instabilities in the resultant triggers. Two sine waves, 90^{o} apart, are diodecoupled; the used portions of the resultant signal, see Fig. 6, are so phased and adjusted that variations in line voltage automatically adjusts the timing of the firing signals to nearly compensate for the line change. The use of the near negative peak values of the sine wave produces an overall transfer function that is nearly linear for control voltage versus output voltage. A special control relay prevents firing signals from being generated for a short time after all 12 kV vacuum switches have closed and immediately on turn off before the main-12 kV circuit breaker has opened; this is required to prevent spurious triggers. The number and current ratings of the SCR's were chosen to allow full current operation with one unit disconnected in each rectifier leg. The Peak Reverse Voltage (PRV) ratings of the SCR's used are at least 2-1/2 times the normal circuit voltages. The primary of this power supply is fed from the 12.47-kV ac system and is, therefore, subject to 40% overvoltage transients due to lightning surges in the power network.

The 45 Hz cutoff frequency filter used in the output of this power supply was chosen because of regulation loop closure considerations. Empirical data on the magnet has shown that about 1% peak to peak voltage ripple at 60 Hz is the maximum that can be tolerated from a vibration of components due to eddy currents. The ac impedance of the magnet is about 20 ohms at 60 Hz and 150 ohms at 1440 Hz. The calculated inductance of the magnet at low frequency is about 0.7 Henries.

The normal 24 pulse voltage ripple is less than 0.6%, we had called for a maximum ripple current of 0.1% peak to peak into the magnet, (we have measured about 0.02%).

6. Regulation System

The regulation system, Fig. 7, treats each of the 4 main parallel groups as separate current-regulated power supplies with cross connections to force current balancing. Each group uses identical current monitoring shunts so that the transfer function between the reference voltage and current should be nearly identical. The smoothness in the progression from one voltage level to the next is controlled by the bias adjustments with the variable resistor shown in Fig. 6.

The main characteristics of the various operational amplifiers in the regulation loop are summarized in Fig. 8.

The dc stability of the system depends upon the gain stability and drifts of A8 to A15, the 100-MV shunts, and upon the temperature regulated reference voltage.

7. Radio Frequency Interference

The specifications call for meeting the requirements of F.C.C. regarding radio frequency interference. The power supply was constructed with only the minimum provisions for the reduction of radiated or conducted RF noise. RF by-passes were installed on all exiting control wires; the HV plate transformers and auxiliary transformers were doubly shielded, and suppression networks were added on the main transformers. Measurements are yet to be made of the radiated and conducted RF noise.

8. Provisions for testing and Monitoring

Voltage dividers and trigger monitoring circuits have been provided to allow circuit surveillance during power supply operation. Provisions were made to allow operation of all of the SCR triggers from an auxiliary power line without the main high voltage being turned on. This was done to allow trouble-shooting any trigger circuit problems without danger to equipment located in the magnet.

A transducer that measures the total output current is used to monitor the current to the magnet and gives a power isolated 1-volt signal that can be transmitted to the experimenter.

Acknowledgements

The cooperation of many individuals was necessary to bring about the successful culmination of a project of this type. The authors wish to thank the management of Ling Electronics for graciously supplying all of the required data regarding the design and construction of this power supply, and the many persons who have been instrumental in the procurement of this power supply and have offered constructive assistance in the preparation of this report.

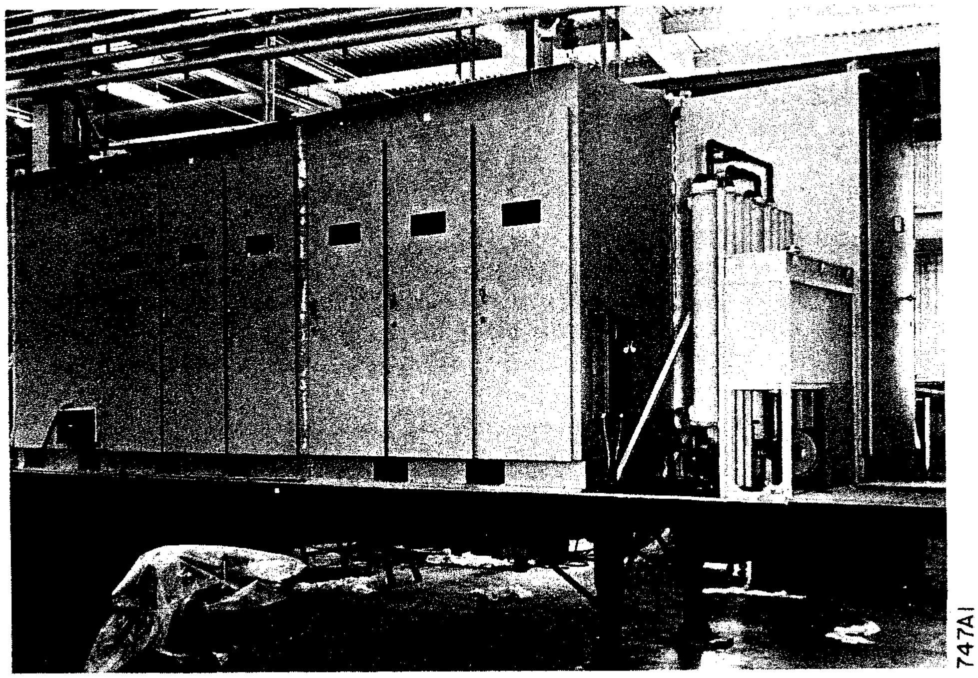

FIG. 1 -- 5800 kW POWER SUPPLY 525 VOLTS, 11,050 AMPERES

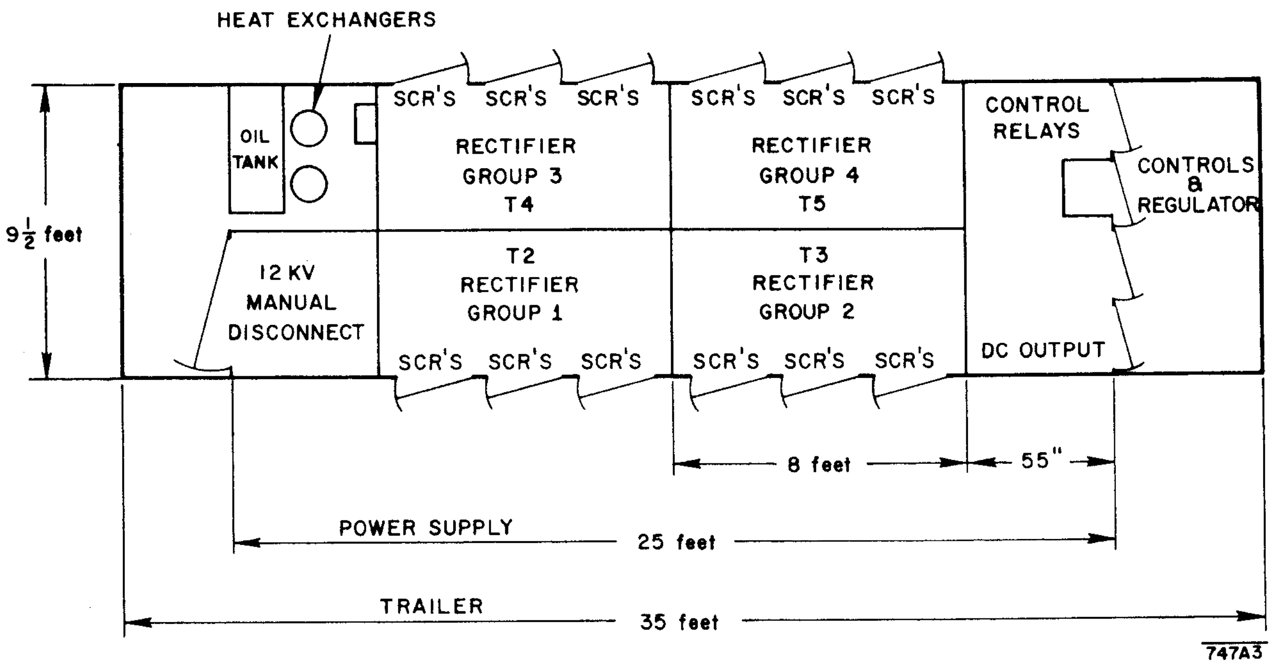

FIG. 2 -- 5,800 KW POWER SUPPLY TRAILER LAYOUT

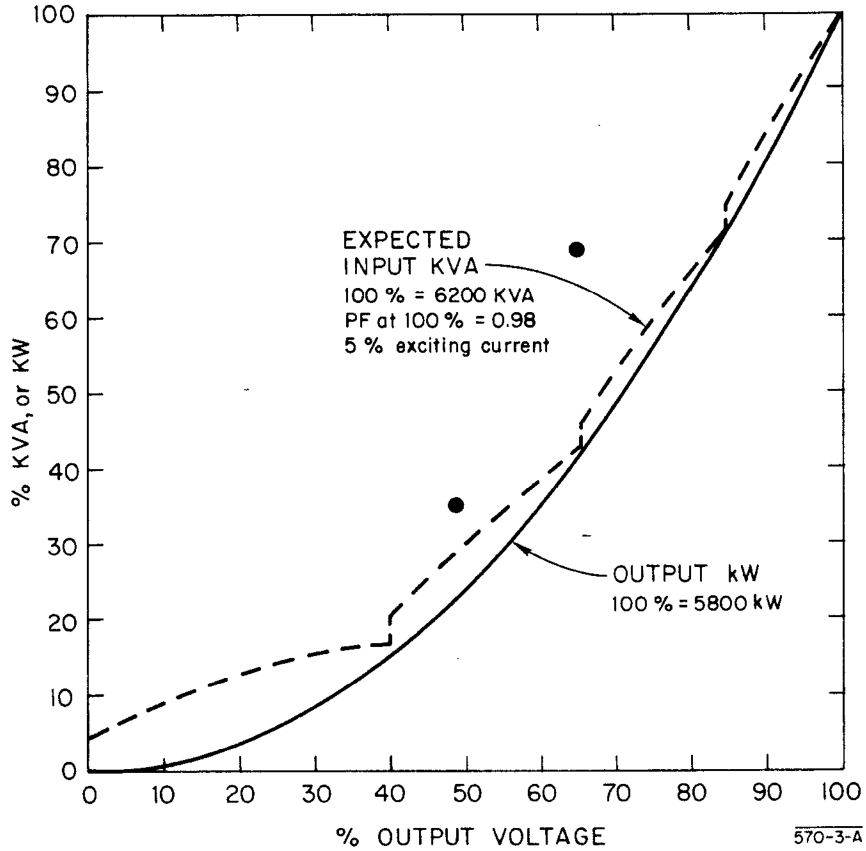

FIG. 3 -- 5800 kW POWER SUPPLY KVA AND kW INPUT vs OUTPUT VOLTAGE. (THE EMPIRICAL DATA POINTS (o) ARE PROBABLY HIGH BECAUSE OF IMPROPERLY ADJUSTED BIAS LEVELS).

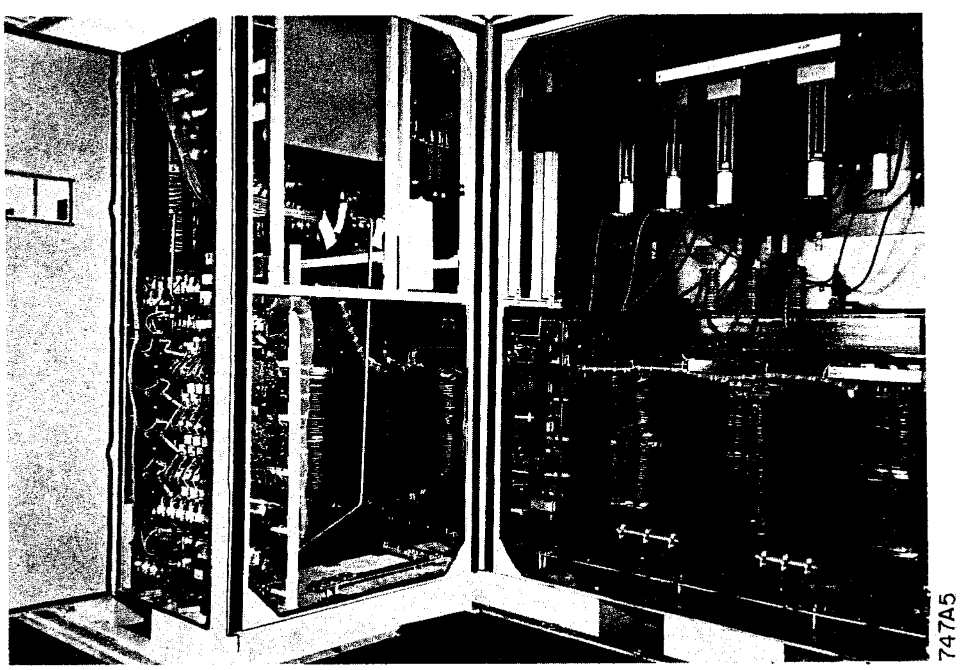

FIG. 4 -- 5800 kW POWER SUPPLY RECTIFIER CABINET 2 REMOVED.

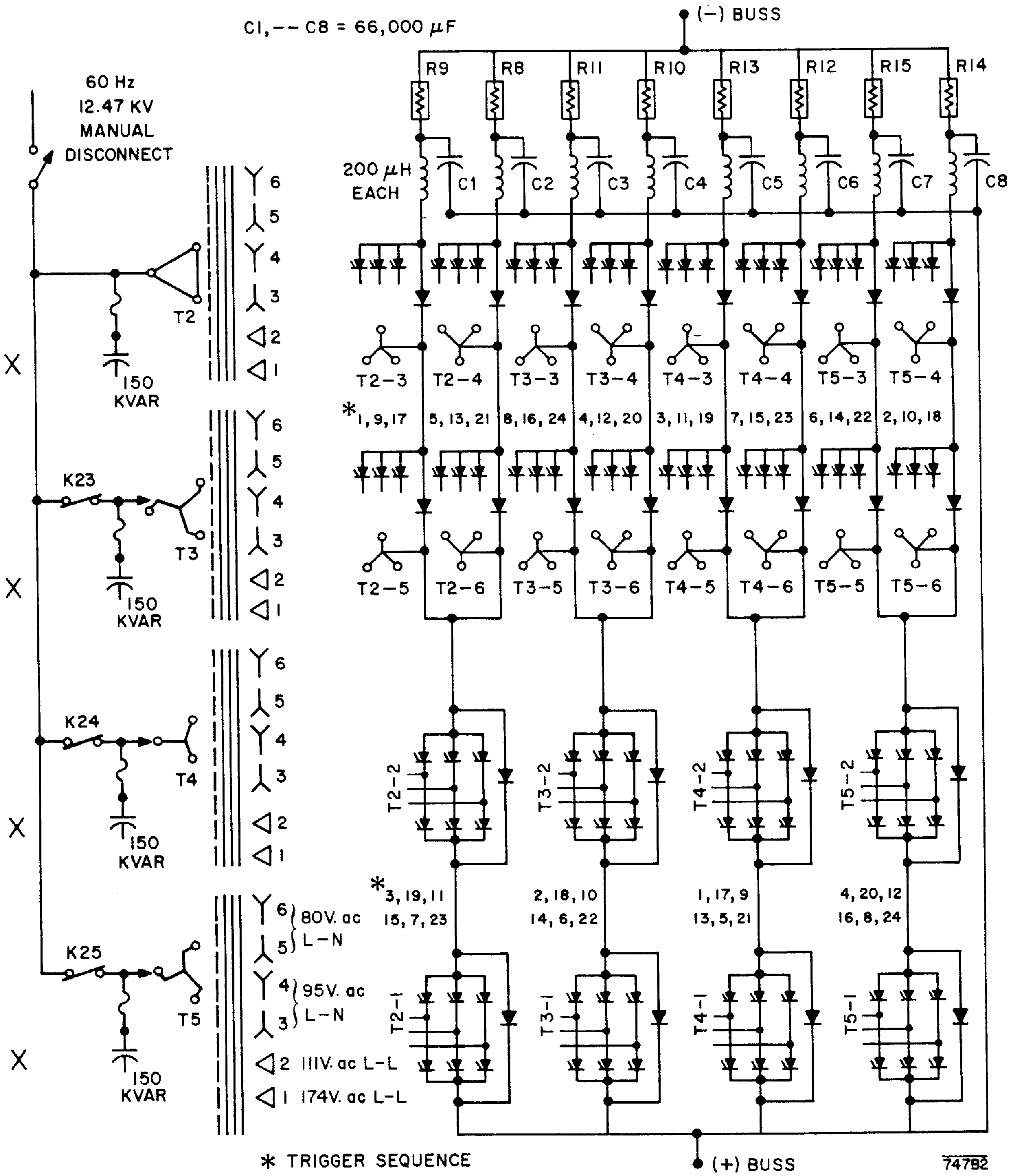

FIG. 5 -- 5800 kW POWER SUPPLY RECTIFIER POWER CIRCUITS

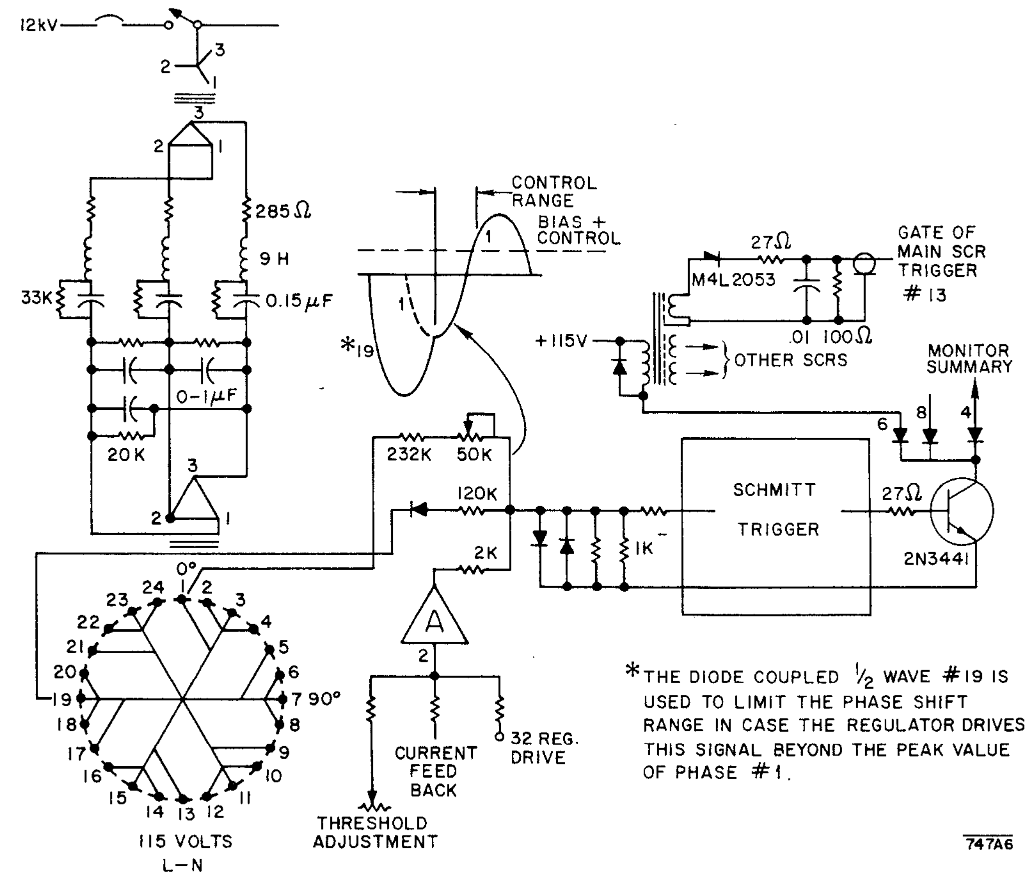

FIG. 6 -- SCHMITT TRIGGER AND PHASE NETWORK

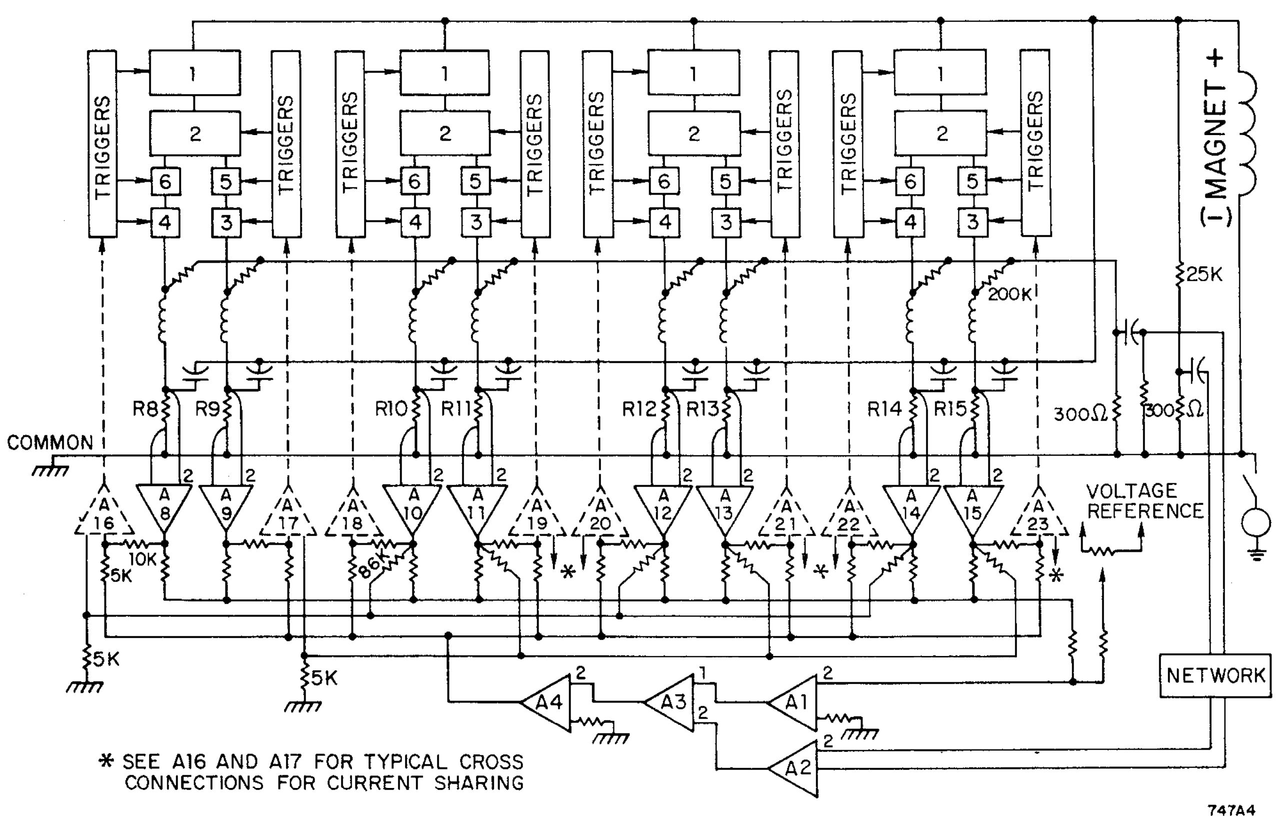

Fig. 7 – 5,800 kW P.S. BLOCK DIAGRAM REGULATION LOOPS

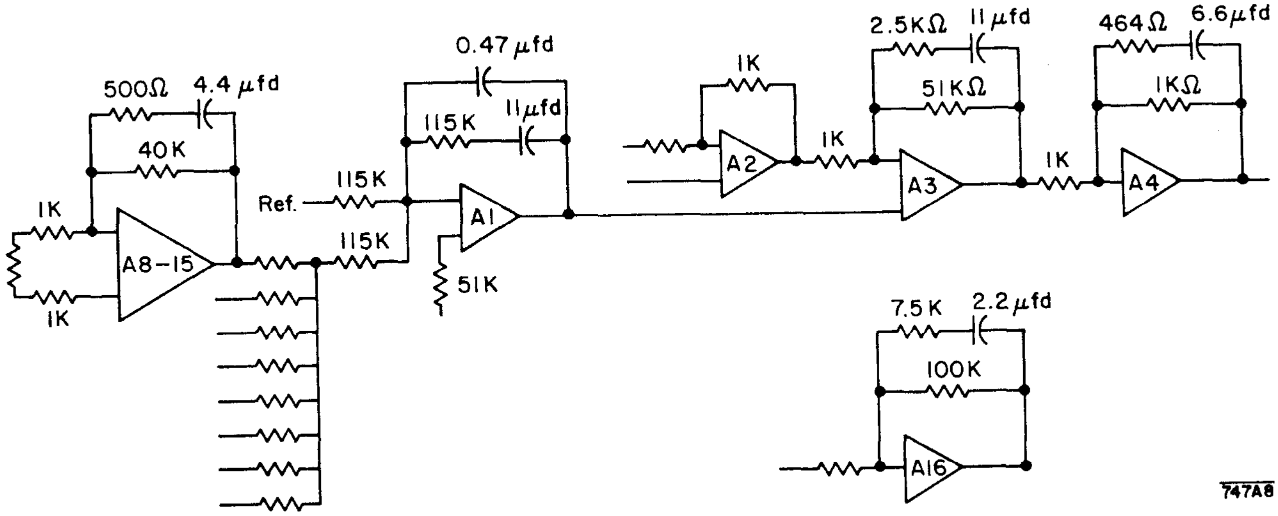

FIG. 8 -- 5,800 kW POWER SUPPLY OPERATIONAL AMPLIFIER FEEDBACK CIRCUITS