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LARGE DC MAGNET POWER SUPPLIES AT SLAC*

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Summary. *Currently a total of six dc magnet* power supplies, ranging in size from 1.6 MW to 6.0 MW are in operation at the Stanford Linear Accelerator Center (SLAC). Five of these supplies are static converters, using step-down transformers and thyristors, while the sixth one is a two-unit motor-generator set.

Certain design criteria have evolved, dictated by specific needs at SLAC and by operating experience obtained over the three-year period during which this equipment was installed. Primary power distribution is at 12.47 kV. Vacuum switches in place of circuit breakers incorporating special protective equipment to prevent complications have been successfully used to do the frequent switching required by the loads. Provisions have been made to permit reconnection of the output for use with the various loads. All static converters use oil-filled transformers, most of which are of special design. Twelve-pulse rectifier systems using SCR's are employed throughout, and are operated in such a way that in at least one case the inherently poor power factor of phase-controlled converters can be improved.

Introduction

A number of very large magnets, part of the experimental apparatus in use at SLAC, require direct current power supplies larger than 1.0 MW. There are 9 such magnets, 5 bending magnets for the three spectrometers, a 40 in and an 82 in bubble chamber magnet, a 54 in spark chamber magnet, and an 80 in streamer spark chamber magnet. The latter is the largest of these loads, requiring about 5.8 MW of dc power. Additional magnets that will require about 1.2 MW of power are under construction.

To energize these various magnets, a total of six dc power supplies have been built at the Center, ranging in size from 1.6 MW to 5.8 MW. Five of these power supplies are ac to dc converters that use rectifier transformers and silicon controlled rectifiers (SCR's), while the sixth is a two-unit motor generator. All power supplies are operated in the constant current mode, and are electronically regulated using feedback to achieve long-term stability of 0.1% or better.

Over the three-year period during which this equipment was purchased and operated, a considerable amount of experience has been gained. Certain features initially thought to be quite important became less so during actual operation, and some modifications are still in process. Most of the discussion in this paper refers to converters using rectifier transformers and SCR's. When one considers the reduced cost and size of this type of equipment compared to motor-generator sets of similar rating, it is easy to see why most modern converters use static semiconductor devices. The motor-generator set was installed because problems were encountered during startup of the rectifier power supplies, and the motor generators were readily available as used equipment.

Summary Description of the Power Supplies

All six converters use 12 kV ac as their primary source of power. The five rectifier power supplies all employ twelve-pulse systems and use the general circuit arrangement illustrated in Fig. 1. Vacuum switches are

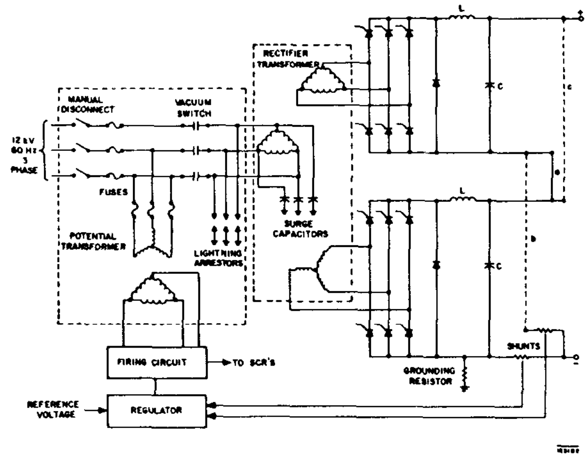

FIG. 1--Elementary schematic diagram of twelve-pulse rectifier power supply.

the main on-off controlling device. Oil immersed convection cooled outdoor transformers are used to step the incoming 12-kV down to the lower voltage required for the rectifier output. The transformers have two secondary windings, one delta-connected and the other wye-connected to produce the necessary phase shift for the 12 pulse or 720 Hz ripple in the output. At least two 6-pulse bridge rectifier assemblies are used in every power supply. The elements of the bridge are silicon controlled rectifiers (SCR's) which are phase-controlled to permit changes in the rectifier dc output voltage. A freewheeling diode and an L-C filter is across the output of each bridge assembly. Shunts are used to measure the current and to provide feedback signals to the regulator. The regulator amplifiers furnish the necessary correction signals to the firing circuits which control the phasing of the SCR's.

In a few of the large power supplies, more than one rectifier transformer is used. Thus, for example, the 5.8 MW power supply consists of four separate dual rectifiers such as shown in Fig. 1, all connected in parallel.

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The four largest power supplies (including the motor-generator set) either have or are about to be modified for a dual output rating. This is accomplished by means of copper links (lines a,b, and c in Fig. 1) which are changed to connect two similar sections in the power supply for either series or parallel operation. Table 1 lists the rating of the power supplies and some of their features. Dual output capability has added considerably to flexibility and interchangeability between the various power supplies and magnet loads.

An enclosed cabinet houses all 12 kV components: the vacuum switch, lightning arresters, fuses, a manually operated safety disconnect, and potential transformers. The only exceptions are the surge capacitors which are in an enclosure around the high voltage bushings of the transformer, to which they must be closely coupled to effectively reduce the rate of rise of transient voltage. The safety disconnect switch has grounding provisions to permit servicing of the equipment. The potential transformers furnish the necessary signals to synchronize the firing circuits with the rectifier voltages.

TABLE 1

POWER SUPPLY DESCRIPTION

Size (Quantity)	Voltage/Current Rating	Type	
1.6 MW (2)	530 V/3,000 A	Rectifier	2 transformer banks, one delta-delta, the other wye-delta
3.4 MW (1)	340 V/10,000 A 680 V/5,000 A	Rectifier	2 similar transformers, delta primary, delta and wye secondaries
5.0 MW (1)	330 V/15,000 A 660 V/7,500 A	Rectifier	1 transformer, delta primary, delta and wye secondaries
5.8 MW (1)	525 V/11,000 A 262 V/22,000 A	Rectifier	4 identical transformers, delta primary, delta and wye secondaries
3.0 MW (1)	300 V/10,000 A 600 V/5,000 A	Motor Generator	2 identical two-unit MG sets

Switchgear for 12 kV Primary Power

For on-off control of the rectifier power supplies, vacuum switch circuit breakers have been very successfully employed at SLAC. The more conventional way of switching and protecting this type of equipment is through the use of air circuit breakers, a scheme which is still used on the 5.8 MW power supply. Unfortunately, the conventional mechanically operated air circuit breakers are not really intended for very frequent operation, such as may be encountered in this application. Their primary function is for system switching and protection against overloads and faults in the power system. Vacuum switches on the other hand can be operated with greater frequency. The vacuum switches which are used are rated 400 A, with a momentary rating of 20,000 A rms, and an interrupting capability of only 4000 A rms. Since approximately 20,000 A fault current is available in some parts of the 12 kV network, the vacuum switch is protected by fuses in the ac line, and blocking circuits which inhibit the overload mechanism from opening the vacuum switch if the fault currents are in excess of the switch's capabilities. Reliance is then placed on the fuses to clear the fault, with the station air circuit breakers serving as further backup. Thus far this scheme has performed very well.

The switchgear also includes protection for the rectifier transformers against ac switching transients caused when transformer exciting current is interrupted. This was considered necessary because of failures in the dry-type transformers which were initially used on some power supplies. A combination of lightning arresters and surge capacitors is used. The lightning arresters are on the load side of the vacuum switch, and serve to clip the voltage transients to 37 kV. The function of the surge capacitors (0.25 μF from each line to ground) is to reduce the rate of voltage rise of a switching transient.

Rectifier Transformers

The rectifier transformers for these power supplies are all liquid filled (askarel oil), convection cooled, and are constructed for outdoor installation. There are no taps on the transformer, since control of the output is accomplished by means of the SCR's throughout the entire operating range. The initial design of some of these power supplies incorporated the use of transformers with dry insulation and water-cooled secondary windings. These transformers were finally abandoned because of failure in the insulation and the cooling system. The present installations use specially designed rectifier transformers in all but the two 1.6 MW power supplies, where utility type distribution transformers are used.

The specifications for most of these power supplies required the use of a 24-pulse rectifier system. Actual experience showed that various sources of unbalance, either in the transformer, the ac lines, or in misalignment of the firing circuits, caused some of the lower harmonics which the ideal 24-pulse system eliminates to reappear. When other difficulties forced replacement of the original transformers, the new design abandoned the 24-pulse system in favor of the simpler 12-pulse configuration. The latter can be accomplished with a simple three-coil delta-wye configuration (Fig. 1), eliminating the need for zig-zag, extended delta, or similar designs.

The transformer specifications called for tests as outlined in ASA C57.18 (Rectifier Transformers). Since a special design was necessary, an impulse test

(Basic Impulse Insulation Level of 110 kV) for the high voltage winding was also required. The impulse test is probably not the ideal test for simulating operating conditions of a rectifier transformer, where transients resulting from rectifier commutation stress the insulation in a manner quite different from ordinary applications. This test more nearly simulates the possible effects of lightning on a power system, but it was adopted for lack of a more suitable standard to insure a minimum insulation level.

A special feature of these transformers is the inclusion of electrostatic shields. Two kinds of shields are used: The primary winding shield which separates the high voltage winding from the others and is electrically tied to the transformer core or frame, and the secondary winding shield, which surrounds both the inner and outer layers of the low voltage rectifier windings and is brought out to an isolated terminal. The purpose of the primary shield is to provide a ground path for noise generated during commutation of currents in the secondary windings; this noise could appear on the ac lines through electrostatic coupling. The purpose of the secondary shield is to reduce common mode noise in the dc output leads, present because of the practice of grounding the magnet winding or power supply output through a limiting resistor. The secondary shield, tied to the dc output, balances the ground capacitance of all rectifier windings.

The value of the transformer shields was well demonstrated in the two 1.6 MW power supplies, which use ordinary distribution transformers that have no shields. The 1 V current shunt signal was superimposed on common mode noise of up to 300 V peak to peak; this noise had to be reduced with large bypass capacitors that caused undesirable side effects on the ground fault detection circuits. By way of contrast, the power supplies which use shielded transformers have only a few volts of common mode noise superimposed on the shunt signal.

The winding arrangement of the transformer coils is as shown in Fig. 2. The primary winding is split in

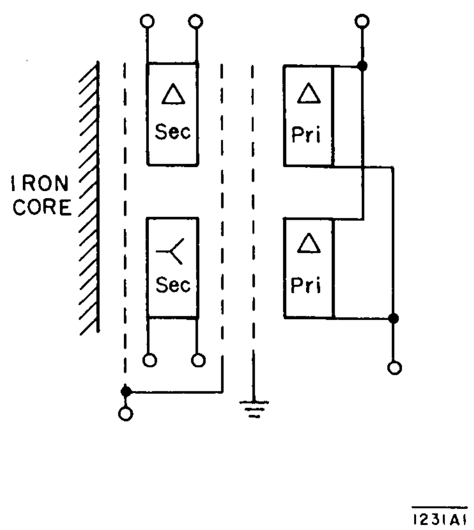

FIG. 2--Transformer winding arrangement.

equal sections which are parallel connected. Coupling between the two secondary windings is reduced with this arrangement, a desirable feature. Delta to wye secondary turns ratios of 7:4 or 12:5 were adequate, since electronic control of the output of the SCR bridges connected to these windings allows individual control for equalizing the currents. The current inrush for the first half cycle after being energized is not more than six times the normal full load current, thus causing a dip in the ac system of less than 3.5% during inrush. The flux density in the iron is less than 13.5 kG, and the transformer impedance is between 6 and 8% (measured for both secondaries short circuited). The conducted RFI noise level is well below 50 μV at 1 MHz.

Rectifier and Filter

The rectifier section is made up of three-phase bridges connected to each of the transformer secondary windings. The largest SCR's available on the market at the time this equipment was built (470 A rms) were used to make up the individual legs of the bridge. Sufficient SCR's are used in parallel in every leg to allow uninterrupted operation with one SCR disconnected. Since the units are not matched, equalizing reactors are used between parallel SCR's. A safety factor of at least 2.0 in the voltage rating of these units was specified. The SCR's are individually fused. The purpose of these fuses is not to protect the individual elements from overloads, but rather to quickly isolate a faulty SCR and prevent damage to the remaining healthy units. Recommended R-C transient suppression networks across SCR's are used throughout.

Free-wheeling diodes are connected across the output of all bridge assemblies. Thus the power supply cannot be operated in the inverter mode. The advantage derived from the use of free-wheeling diodes are a reduction in the ripple in the dc output voltage and a slightly improved power factor at output voltage levels below 50% of maximum.

All SCR's are mounted on water-cooled heatsinks. In addition to a flow switch which protects the equipment in case water flow is interrupted, thermostats on the heatsinks are also used wherever multiple parallel water paths are necessary.

A filter in the dc output, consisting of a series inductor and a shunt capacitor bank is used on all magnet power supplies and is connected in the output of each bridge rectifier (Fig. 1). The filters are designed to have a cutoff frequency $1/\sqrt{LC}$ of somewhere between 20 to 40 Hz, and a characteristic impedance $\sqrt{L/C}$ approximating that of the dc resistance of the magnet loads. For these power supplies this has resulted in filter chokes L with an inductance of up to about 100 μH, a size for which an air-core annular wound inductor using a water-cooled conductor yields a very practical solution. The capacitor bank C becomes quite large, about a half farad in a few cases. The individual electrolytic capacitors which make up the bank are protected with thin fuse wires which serve to isolate a faulted capacitor. The ripple current in the capacitor bank is monitored with a current transformer. A thermal overload in the secondary winding of this current transformer serves to shut down the power supply when the ripple in the output has reached excessive levels, either because of misalignment of the firing circuits or because a hunting condition exists in the electronic regulator.

The entire rectifier assembly, as well as the filters and the current shunts are installed in an enclosed indoor cabinet with access through locked doors. Since all SCR's, diodes, heavy current busses and high current chokes are water-cooled, little heat is given off and no air cooling of the cabinets has been necessary. Distance between the bridge assembly and the transformer low voltage output terminals is kept as short as practical, but is at least 15 ft in all cases. The need to carry these heavy current carrying conductors from the outdoor transformer through the building walls to the indoor rectifier cabinet makes it difficult to have shorter runs. Since the reactive voltage drop in these lines can be appreciable, and add also to the commutating impedance, it is desirable to keep this lead inductance to a minimum.

Current Regulator Circuits

The electronic current regulator circuits used in all these power supplies were not developed at the Center, but were designed and built by Ling Electronics of Anaheim, California. Semiconductor devices only are used, including integrated circuit operational amplifiers. An oven is used to stabilize the high gain error amplifier.

The regulator consists of a current loop stabilized with voltage feedback. Schmitt trigger circuits produce the pulses which control the SCR firing time. The pulses are generated using a filtered sine wave from the incoming line voltage, so phased that the gain transfer function of the system is linearized. This scheme also results in automatic compensation of the output voltage for line changes at voltages where the free-wheeling diodes are not conducting. Later models of these firing circuits were modified to produce a firing pulse at least 3 milliseconds long instead of only a few microseconds, with the result that double pulsing of the SCR's becomes unnecessary, and potential misfiring at maximum dc output voltage is avoided.

A unique scheme exists in the 5.8 MW power supply for improving the power factor, which inherently is very low for any system that uses phase control over its entire range. The two series connected sections are controlled sequentially, with one section phased completely off until the other is at maximum. Since the power supply consists of four parallel units of the type shown in Fig. 1, two delta connected and two wye connected rectifier sections are used in each step of the sequence, thus preserving 12-pulse ripple at all times.

Current shunts are used to derive the feedback signals in all rectifier supplies, whereas the motor generator set uses transductors. Generally, 100 mV shunts have been used where 0.1% stability was required. A 1.0 V shunt was used in the 1.6 MW supplies where the required stability was 0.01%.

Operation of the Power Supplies

Initial design of a few of these power supplies required installation on a trailer which would then have been moved to various locations in the research yard. This idea was soon abandoned when the transformers for the trailer-mounted power supplies were replaced. All power supplies are now installed inside buildings, with the transformers and switchgear outside. A portable building is used in one such installation, as shown in Figs. 3 and 4. Flexibility rather than mobility is

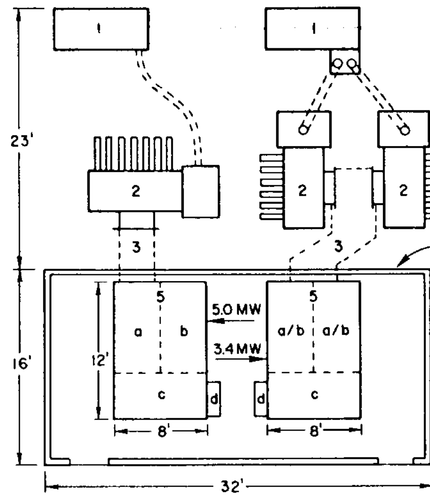

FIG. 3--Plan view of the 3.4 MW and 5.0 MW power supply installation.

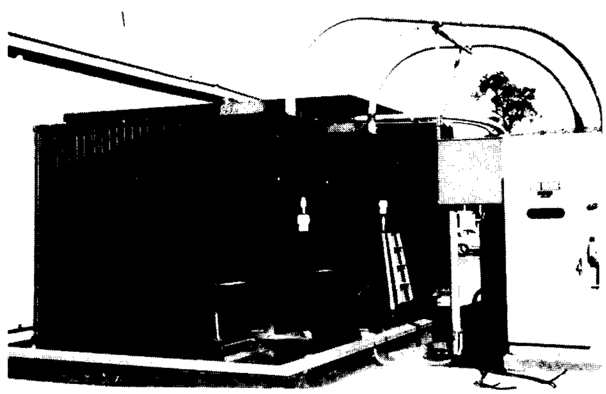

FIG. 4--3.4 MW and 5.0 MW power supply installation. Left to right: shelter, transformers, vacuum switch.

achieved by a 15,000 A water-cooled tie-line, with branches to all large magnet loads and the four large power supplies, allowing interchangeable use of this equipment through a system of links. The two 1.6 MW power supplies can be used with either of three spectrometers, also by changing links. For the four large power supplies reversal of the dc current is done at the magnet, whereas the two smaller power supplies use motor driven reversing switches in the power supplies. Each of the large magnets is provided with its own measuring shunt independent of the power supply to which it is connected. This eliminates the necessity for accurate calibration of the power supply shunts and transductors, subject to changes from aging and geometry.

Conclusion

The criteria for the construction of these large power supplies has evolved rather than being entirely the result of initial design. The approach described here seems satisfactory and will be used, except for refinements, in the design of new 1.5 MW power supplies now under consideration.