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TITLE: **Design and Preliminary Test Results of the 40 MW Power Supply at the National High Magnetic Field Laboratory**

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SUBMITTED TO: **Proceedings of Thirteenth International Conference on Magnet Technology**

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Design and Preliminary Test Results of the 40 MW Power Supply at the National High Magnetic Field Laboratory

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Abstract—Four highly stabilized, steady-state, 10 MW power supplies have been installed at the National High Magnetic Field Laboratory in Tallahassee, FL. Each supply consists of a 12.5 kV vacuum circuit breaker, two three-winding, step-down transformers, a 24-pulse rectifier with interphase reactors and freewheeling diodes, and a passive and an active filter. Two different transformer tap settings allow dc supply output voltages of 400 and 500 V. The rated current of a supply is 17 kA and each supply has a one hour overload capability of 20 kA. The power supply output bus system, including a reversing switch at the input and 2 x 16 disconnect switches at the output, connects each supply to 16 different magnet cells. The design of the power supply is described and preliminary test results with a supply feeding a 10 MW resistive load are presented.

Ripple and noise	10 ppm
Precision	10 ppm
Stability, including ripple (over a 12 h period)	100 ppm
Repeatability, including ripple	100 ppm
Regulation with $\pm 10\%$ line voltage, 30% load, and 30°C temperature variation over 24 h period	100 ppm
Accuracy	1000 ppm
Ramp tracking error at 0-500 A/s	100 ppm
Efficiency	>90%
These specifications should also be met with two, three or four supplies running in parallel.	

I. INTRODUCTION

The National High Magnetic Field Laboratory (NHMFL) in Tallahassee, FL, will develop and operate a wide variety of high-field magnet systems in support of institutional and private sector research and development in solid-state physics, biology, chemistry, geology, material science engineering and medicine. Water-cooled, Bitter-type and polyhelix magnets will be energized by four 10 MW, highly stabilized power supplies. Up to four 10 MW magnets can operate simultaneously, or two 20 MW magnets, or one 40 MW magnet. The magnets will be installed in the 16 magnet cells, each being equipped with a water cooling capacity of up to 400 l/s (6400 gpm) of deionized, chilled water (7°C). Research under high magnetic field conditions requires the magnetic field to be as constant as possible. The power supplies were specified to obtain the best performance available today at the given high power level and with as high an availability as expected from industrial supplies.

II. SPECIFICATIONS

Listed below are the most important specifications for the supplies, guaranteed by the supplier.

III. POWER SUPPLY DESIGN

The power supplies were designed with the philosophy to use, as far as possible, industrially proven equipment to obtain the high reliability desired for a user facility. The supplies use a thyristorized preregulator, which is a 24-pulse converter, followed by a passive filter and an active filter in form of a series transistor regulator. Figure 1 shows the schematic of the power supply.

All four power supplies are identical and are fed from one incoming power system. An oil-cooled, 30/40/50 MVA station transformer, which is located in a substation about 400 m away from the laboratory, provides the power to the laboratory. The transformer's primary winding is connected to the 115 kV transmission system. The secondary voltage is 12.5 kV. A $\pm 10\%$ tap changer allows slow voltage adjustments in 5/8% steps. Two sets of underground cables connect the substation to the laboratory. Each cable set is connected to a 12.5 kV feeder vacuum breaker. Each feeder breaker in turn feeds two power supplies and half of the laboratory base load, such as chillers, water pumps and the building load. Two 6.8 MVAR capacitor banks are also connected to each feeder breaker. The capacitor banks are switched in manually, in conjunction with the power supplies,

Fig. 1. 10 MW power supply circuit diagram

to guarantee a power factor of higher than 0.95 for the total laboratory load under all load conditions.

A. Power Circuit Breaker and Transformers

Each 10 MW power supply is protected by a 1200 A vacuum circuit breaker, which is equipped with electronic metering equipment. Real and reactive power, currents, voltages and power factor for each power supply are displayed in the main control room and are available for archiving. Two 5260 kVA, water-cooled transformers step the voltage down to a secondary voltage of 440 V. The primary winding of each transformer is connected as an extended delta winding, with one secondary winding in delta and the other one in wye. The primary winding is outfitted with an 80% voltage tap. The four secondary windings of both transformers form four symmetrical, three phase systems, each with an angle displacement of 15 degrees. A ground shield is placed between the primary and secondary windings. Because of practical limitations in winding turns combinations and manufacturing tolerances, a one percent variation in the no load voltage between the delta and the wye secondary voltage exists.

The transformer coils are epoxy impregnated and the secondary conductors are directly water cooled. The primary conductors are indirectly water cooled. Water-cooled copper pipes conduct the transformer secondary current to the four rectifiers of each supply. The rectifiers are located on the second floor, right above the transformers.

B. Rectifiers

The four 6-pulse rectifiers use a new mechanical layout design, which is very similar to a design used in commercially available, lower power rectifiers for dc motor drive applications. The units use two fused, water cooled, 1800 V, 3000 A, 77 mm thyristors per leg. The two thyristors in parallel result in 100% redundancy for the given application. A common bridge snubber provides transient overvoltage protection. Two 6-pulse bridges are always connected in parallel through an interphase reactor, resulting in a 12-pulse converter. The two 12-pulse bridges are tied together through chokes placed in the four terminal leads of the two converters for a 24-pulse power supply unit. The individual 6-pulse bridges use a microprocessor based, digital control system with a 0.15 degree resolution for the firing angle. A permanent 40 Ω load is connected across each 12-pulse converter output. This load guarantees converter turn-on under inductive loads and discharges the capacitor during current ramp-down operation, thus increasing the control speed. Each 6-pulse bridge has a free-wheeling diode connected across its output to improve the voltage ripple at the low voltage end.

C. Filters

A passive and an active filter connected in series will reduce the voltage ripple, generated by the switching mechanism of the thyristor preregulator, to acceptable values.

The output of the 24-pulse converter is connected to a capacitive filter network, consisting of a 0.12 F capacitor in parallel with a series connection of a 0.56 F capacitor and a 0.027 Ω resistor. The four chokes and the capacitors form a passive filter, which has a resonance frequency of 30 Hz. The passive filter is designed to give a peak-to-peak ripple of 5 V for the 24-pulse converter under full load conditions with a resistive load. The capacitors are arranged in five switchable units so that different resonance frequencies can be selected.

In the initial stage of the active filter design a transformer coupled regulator, which would remove the ac ripple components of the dc supply, was considered. This design has the advantage that a considerably smaller transistor regulator could have been chosen. This scheme, however, cannot regulate slow drifts. It was decided to use the more conventional and proven approach with a pass bank transistor regulator and an industrial type, digitally controlled preregulator. It is expected that this approach will result in a very reliable, instrument quality power supply.

Each transistor regulator, using a classic emitter follower circuit, consists of 302 parallel 400 V, 200 A, disk-type transistors. The 302 passing transistors are driven by three stages of Darlington connected transistors. Each transistor has its own emitter resistor to aid in current sharing. The transistors are water-cooled and fused. Because each additional volt of drop across the circuit is equal to 20 kW of losses, special attention was given to minimize the voltage drops in the system. The transistor bank operates between 5 and 22 V in the controlled region, requesting the preregulator to adjust its output voltage so that the transistor voltage is kept at about 14 V.

The transistor regulator is controlled by a primarily digital controller, which also controls the preregulator. However, several high precision, analog amplifiers are also employed. An 18 bit digital to analog converter is used for the current reference signal and a 20 bit, analog to digital converter to digitize the actual current signal. This signal is obtained from a high precision 20 kA zero-flux current transformer. The controller has an RS-422 serial port that easily connects into the main digital control system (DCS) of the laboratory. Over this port the DCS can send up to 90 commands or queries to the power supply. The controller and the current measuring device are mounted in a separate compartment of the power supply, which is air conditioned and temperature controlled.

A "by-pass" link can be installed to remove the active filter from the circuit. This mode of operation allows a power supply to function only with the passive filter. Taking the active filter out of the circuit results in higher ripple and worse regulation. In this mode of operation the preregulator continues to receive its control inputs, such as current set point or current ramp rate, from the active filter control.

D. Controls

For the active filter to operate in its linear region, the collector to emitter voltage of the transistors must be controlled between the transistor saturation voltage (5 V) and

the clamping voltage (23 V). The clamping voltage is determined by an installed Zener diode. The value was chosen to limit the maximum power dissipation of each transistor to about 1.7 kW at full load current. Therefore, the main control objective is to regulate the transistor voltage to the center of the voltage band. This 14 V value is the reference voltage for the preregulator trying to adjust the converter output voltage to remain 14 V higher than the load voltage. The voltage controller of the preregulator is followed by a fast current control loop in each 6-pulse bridge. The current controllers guarantee equal current sharing between bridges. If the current should be changed in the load, the reference current of the active filter amplifier is changed, resulting in a new transistor driver current. This new driver current moves the transistor voltage away from the desired center voltage, causing the preregulator to make adjustments for bringing the voltage back to the desired value. Figure 2 shows the different control loops of the power supply.

E. Bus Distribution and Power Supply Switching System

The output terminals of the power supplies are connected to air operated, air cooled, industrial type, reversing switches. These no load type switches have a steady-state rating of 20 kA and are designed for 1600 V voltage isolation. The 8 terminals of the power supply reversing switches are connected to 64 m long, insulated buses running along the center of the magnet cell building. Each bus consists of four

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Fig. 2. Power supply control diagram - overview

355 mm by 19 mm (14" by 0.75") air-cooled aluminum conductors. Flexible conductor links installed every 12 m allow for thermal expansion and slip joints for movement of the conductors with respect to the mechanical frame support.

Eight bus cross pieces are welded to each longitudinal bus to feed power into the magnet cells. Air operated disconnect switches at the end of the cross buses can isolate the cell from the power supply. The final connection from the disconnect switches to the magnet is made by 3000 mcm (1520 mm²), flexible, water cooled, copper cables.

IV. TESTS

Components that were planned for use in the power supplies and had not been tested previously, were exposed to conditions as near as possible to real load conditions. Potential deficiencies of the design were thus eliminated. A transformer coil, consisting of the primary and two secondary windings, was exposed to the expected full short circuit current in an independent high power testing laboratory. Based on the test results, modifications on the winding end supports were made. A disconnect switch was tested at 240 kA to assure that it can carry a short circuit current as might occur when the input of a magnet shorts. The parallel fuse arrangement for a thyristor was exposed to the expected short circuit currents to guarantee current interruption. All the installed transistors were subjected to a burn-in test for one hour at 25 V and 75 A, exceeding the expected power rating.

Before the power supply components were shipped to Tallahassee, one complete power supply, except for the power transformers, was assembled and tested in the manufacturer's plant. The unit was exposed to a low voltage, full current test. For a 40 h heat run test, current sharing of thyristors and transistors was measured and extensive temperature measurements on all the components were taken. Coarse tuning of the control loops was accomplished. Under the given conditions, the equipment performed to full satisfaction and only minor modifications were necessary before the equipment was shipped to the NHMFL.

It was decided very early that a 10 MW, water cooled resistor was necessary for properly testing the power supplies to ensure that the guaranteed specifications were met. A 10 MW, water cooled resistor was built to allow full power testing of the power supplies up to 20 kA and 500 V. A 4 in.

(101.6 mm), schedule 10, stainless steel pipe (wall thickness, 3 mm) of 52 m length has been mounted on a wall of a magnet cell. Deionized cooling water, at a flow rate of 100 l/s (1585 gpm), passes through the pipe and cools the electrically heated pipe wall. The resistor has 6 current connection taps, which allow several discrete resistance values to be chosen between 22 and 34 m Ω . The different resistance values allow full power testing at both 400 and 500 V output voltages.

All four power supplies have been operated up to rated power in tests with the active filter bypassed. The magnetic and semiconductor components run below the designed temperature rise values, except for cross bracing in a choke. By insulating the bracing to prevent circulatory currents, the temperature could be reduced to acceptable values.

The currents in the four parallel bridges are well balanced. Current sharing of the thyristors at different current levels was measured. While at lower currents (6 kA) the current sharing is not as balanced, at 12 kA the thyristors share currents within a $\pm 10\%$ band. The effect of the 1% no-load voltage difference between the wye and delta connected transformer windings on the voltage ripple before and after the filters has not been determined in detail. It appears that the preregulator meets the expected performance.

Initial tests have now begun with the active filter in the circuit. Low current tests with one power supply show that the active filter controllers and the control system of the preregulator operate together and control a preset current.

ACKNOWLEDGMENT

The authors acknowledge the contributions of many people who have added to the success of this project. In particular, the hard work, diligence, enthusiasm and long hours of the operations crew of the NHMFL during the several months of commissioning of the power supplies are appreciated. The authors acknowledge support by the State of Florida and the National Science Foundation through NSF Cooperative Grant No. DMR 9016241.

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