RING MAGNET POWER SYSTEM FOR THE ZERO GRADIENT SYNCHROTRON

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Abstract

The power system for the ZGS ring magnet consists of a flywheel motor generator set and four groups of mercury arc rectifiers operating alternately as power rectifiers and power inverters. The system is shown schematically in Fig. 1.

Description

Power for the system is obtained from a 13.2 kV line feeding into the M-G set wound rotor motor and the excitation rectifier transformer. Switching means, not shown in Fig. 1, are included which transfer the excitation system to another power source in case of emergency. Control power for the system is obtained from a 125-volt station battery. In the event of a power system failure, the battery is also used to drive an M-G set lubrication pump. Emergency dc power from a diesel driven generator provides back-up protection for the battery if an extended ac power failure necessitates a complete coast down of the M-G set.

Control of the wound rotor motor is obtained with a liquid rheostat having horizontally moving electrodes. The motor, flywheel and liquid rheostat have been sized so that adjustments of the rheostat are not necessary during a pulse.

The motor and generators are of the enclosed self-ventilated type, each with its own air-to-water heat exchanger and recirculating ventilating system. Each section of the M-G set shaft is centerbored for inspection purposes. For protection against bearing damage due to circulating shaft currents, all bearing pedestals are insulated from ground and an insulated coupling is used between the main shaft and the shaft-driven lubrication pump. The generator winding is made of single-turn coils with the end turns secured by two rows of blocking to provide maximum support consistent with ventilation requirements. The first and last slot wedge of each stator slot is extended beyond the core and bound to the coils to prevent slot wedge migration and abrasion to the coil insulation. The field coils are strap wound with an epoxy insulation system which bonds the turns to the pole body forming an integrated mass.

Generator field excitation is obtained from a 12-tube, 6-phase mercury arc rectifier bank. An automatic voltage regulator acts directly on the grids of the rectifiers. The available ceiling voltage for the fields is 825V; however, present normal operation is with the voltage set at approximately 600V. The dc power from this source is also used for dynamic braking; all breakers are suitably interlocked.

The generators are connected to a common bus through air magnetic power circuit breakers. This arrangement provides independent protection for each generator and the versatility of being able to pulse with one generator if necessary.

The common ac bus supplies power to eight rectifier transformers, four with delta (Δ) and four with wye (Y) connected primaries. The transformers are enclosed in four oil-filled tanks symmetrically located outside the building housing the rectifiers. The secondary windings of each unit are connected 6-phase double-wye. With two double-wye rectifiers displaced 30^{o} from each other and connected in series, a system with harmonics equal to that of a 12-phase rectifier is obtained. Three continuously pumped excitron rectifier tubes with balancing reactors are connected in parallel on each phase. A total of 144 tubes for the system are mounted on eight 18-tube assemblies. Individual vacuum and cooling systems are on each frame. Typical operating temperature is 45^{o}C and the vacuum is 0.1 micron or less as read by a McLeod gage in the vacuum header.

All external power cables for a rectifier assembly are in a common enclosure 85 ft long. The 5kV insulated copper cables are equally distributed to minimize cable impedance. The commutating inductance has been measured to be approximately 130 μH per phase.

"Work performed under the auspices of the U.S. Atomic Energy Commission."

Power for the rectifier phase control circuits is obtained from the generators by means of an auxiliary transformer to make the system self-synchronous. This is a 100 kVA transformer with ten taps.

The system is grounded between two octants through a 50 ohm resistor which limits fault currents to about 40 A. DC over-voltage protection is obtained with adjustable carbon spark gaps and mechanical shorting switches. Gaps are presently set for 3 kV to ground and 6 kV across quadrants. Pertinent data for the system is listed in Table 1.

The power equipment was manufactured by the Allis-Chalmers Mfg. Co. on the basis of specifications prepared by Argonne National Laboratory.

Control of Magnet Current

To cover the operating range from rectification to inversion, the phase control circuit was designed to provide phase delays from $\alpha < 0^{\circ}$ to $\alpha \approx 160^{\circ}$. The circuit consists basically of a ramp voltage which is biased by an adjustable dc voltage to trigger the rectifiers at the desired angle of inversion, α_{INV}. For rectification, a programmed pulsing bias is connected in series with the above voltages to reduce the angle of phase delay to predetermined values.

$\dot{B}$ During Injection

Magnet copper losses are negligible during injection; therefore, the octant voltage can be written:

$$E_{Oct}(t) = n\frac{d\varphi}{dt} = nA\dot{B}(t) \quad \text{, and} \tag{1}$$

$$\dot{B}(t) = \frac{E_{Oct}(t)}{nA} \quad . \tag{2}$$

n = number of turns on octant coil
A = area of octant gap

$\dot{B}$ is proportional to the octant voltage which, in turn, is controlled by the pulsing bias. Two modes of pulsing bias operation and the resulting magnet fields and $\dot{B}$ values are shown in Fig. 2. The range of $\dot{B}$ for successful rf capture of the proton beam is between 18 kG/sec and 26 kG/sec. The magnet field at injection is about 476 G and $\dot{B}$ is generally set to 21 kG/sec. To reach this field with a preset value of $\dot{B}$, the angle of phase delay α, is initially decreased at a rate given by:

$$\alpha(t) = \alpha_o \epsilon^{-t/t_R} \tag{3}$$

t_R = rectification delay

α_o = angle of phase delay at the start of a ZGS pulse.

Figure 2a illustrates a ZGS pulse without flat-top and zero-rest field $\left(\alpha_o = \alpha_{INV}\right)$. The interval of time required for $\int \dot{B}dt$ to reach 476 G is a function of the selected value of rectification delay t_R. $\ddot{B}$ is greater than zero throughout injection in this mode of operation.

There is a rising field gradient dB/dx in the magnet gap due to eddy currents caused by the increasing magnetic field. A rest field, B_r, applied between pulses reduces the time required to reach the injection field. Injection can then occur while the gradient dB/dx is small. Figure 2b illustrates the magnet field and pulsing bias wave for a pulse with rest current and flat top ($\alpha_o = \alpha_r$). A constant value of $\dot{B}$ during and for some time after injection is obtained by holding the angle of phase delay to a fixed value α_{INJ} shortly before $\int \dot{B}dt + B_r = 476$ G. Thereafter, the angle of phase delay is decreased to $\alpha_{Re} < 0^{\circ}$.

Figure 3 illustrates computed values of rectifier currents i^{Y} and i^{Δ}, magnet current i_M and the voltage E across two octants. Included in this figure is an oscillogram of the voltage across two octants and the unfiltered 12-phase rectifier output voltage for the same operating conditions but with less rectification delay.

$\dot{B}$, neglecting ripple, is shown as a function of time for various operating conditions in Fig. 4.

Flat-Top

The rectifier output voltage is decreased to the flat-top level by increasing α. The rate of change depends on both the inversion delay t_{INV} and on the setting of the bias voltage which determines α_{INV}.

$$\alpha(t) = \alpha_{INV}\left(1 - \epsilon^{-t/t_{INV}}\right) \tag{4}$$

This change in α is stopped for the duration of the flat-top when it has reached a value α_F which produces a rectifier output voltage equal to the IR drop in the magnet.

Figure 5 shows computed values of the octant voltage, octant current and rectifier current when the transition is initiated at 10, 800 A with t_{INV} = 25 msec; an oscillogram of a typical flat-top is also included.

To spill the beam, the flat-top can be sloped by using an α_F-value that produces an octant voltage $\gtrless$ than the magnet IR-voltage drop. These slopes are ϵ-functions with a time constant of 1.2 sec.

Inversion

The rate of current decay depends on the rectifier back voltage which is determined by the setting of α_{INV}. For large values of α_{INV}, a reduction in phase delay is required when the magnet current is high in order to have sufficient commutation and deionization time for the rectifiers. A bias voltage proportional to magnet current is used for this purpose. It is obtained by means of a current transductor, matching transformer and rectifier and is inserted in the phase control circuit in series with the ramp and inversion bias voltages.

Rest Field Current

Depending on the desired amount of demagnetization of the magnet iron, rest current may be obtained at the end of inversion by:

a) letting the filter capacitors oscillate with the magnet until their charge is dissipated and then obtaining an exponentially rising rest current by rectifier phase control;

b) using the above oscillations to bring the rest current to its desired value and then holding it by rectifier phase control; or

c) stopping inversion by rectifier phase control when the magnet current has decayed close to its rest current value.

Method (c) is presently the mode of operation used in the ZGS.

Programmer

The ZGS programmer controls initial start-up of the system, pulse period, pulsing bias, generator excitation and re-energizing of the ring magnet after an emergency invert or fault trip.

Performance

The series of curves in Fig. 6 summarizes the performance of the system from generator excitation through magnet current. These curves are characteristic of operation with the voltage regulator regulating for constant voltage at the generator terminals and 3.8 second repetition period.

Except for generator frequency and power factor, conditions at the end of the rectification period are referred to as 100%. The actual values for this point are shown. The generator voltage and current are plots of the peak value of the generated wave throughout the pulse. The line-to-line voltage of 8.46 kV rms remains essentially constant throughout the rectification period. During flat-top and inversion, the generated voltage wave becomes quite distorted. Since the regulator error signal is the difference between a dc reference voltage and a rectified and filtered signal taken from the generator terminals, the distortion of the generated wave is reflected in the voltage regulator as a decrease in terminal voltage. The regulator then attempts to correct the system by applying ceiling voltage to the generator fields. This data is representative of the majority of ZGS pulsing during the past 1-1/2 years. Variations at times have included lower peak currents, higher repetition rates, and flat-top periods extended to 500 msec.

Figure 7 is a summary of the occurrence of rectifier arc faults between February 1, 1964 and February 1, 1965. Each vertical line represents the total number of a particular fault during the preceding 20, 000 pulses. Horizontal lines are drawn to show that simultaneous faults occurred in more than one rectifier tube. The height of the horizontal line indicates the number of tubes involved. During the last six months, several conditions were changed which most likely account for the increase in the occurrence of these faults. The increase can be partially attributed to extending the flat-top period and increasing the repetition rate. Also contributing was the failure of capacitors in the spike filters connected across the rectifier tubes. The rate of the occurrence of arc faults during the period shown averages one fault per day of operation.

Problems

Corrosion on the external water side of the rectifier water-to-water heat exchangers necessitated a revision in water treatment and the addition of controls to periodically flush the system during down periods.

A problem associated with the cooling water connections to the rectifier frames resulted in unbalanced leakage currents to ground. The cathodes of all tubes are connected to ground through a column of cooling water. Typical resistance of this path has been 10 kΩ; however, this value changes with the quality of the cooling water. Referring to Fig. 1, it can be seen that this leakage path does not exist on the octants connected to interphase transformers. These unsymmetrical leakage currents were eliminated by adding cooling water resistors between ground and the four points where octants connect to interphase transformers. Typical leakage resistance of an octant to ground is 100 kΩ, which is equivalent to 200 kΩ at each end. Variations of ±80% are not uncommon, the lowest values developing during extended shutdown of the magnet cooling water flow.

Slip ring peripheral speeds, in excess of 11,000 feet per minute, in addition to the pulsing type load make the selection of a suitable grade of brush very critical. A number of brushes were tried before a suitable type was found for the generator slip rings. Wide variations in humidity, normal during the fall and winter months, also affected brush performance adversely. An automatically controlled steam system which regulates the ambient humidity in each machine enclosure has corrected this problem. Plans have been made to machine spiral grooves in the motor slip ring surface to reduce the tendency towards unequal brush loading. This selective loading has resulted in occasional rapid deterioration of motor brush shunts.

The addition of an emergency invert circuit to the rectifier control has greatly reduced mechanical stress due to unnecessary operation of protective devices, such as the circuit breakers and shorting switches. This circuit puts the rectifiers into inversion on overcurrents, M-G set underspeed and cooling problems and prevents further pulsing. This, in addition to preventative maintenance programs, has eliminated equipment problem areas.

TABLE 1

SYSTEM DATA

Equipment Ratings	
Motor	15,500 hp, 893 rpm, 13 kV, 3/60, 70°C rise
Liquid Rheostat	1750 kW, 2100 V, 3300 A
Flywheel	93 tons, 4 ft long x 10 ft diameter
Generator Output	38 MVA (81.8 MVA peak), 11 kV, 3/60, 60°C rise
Generator Field	825 V, 850 A rms, 60°C rise
M-G Set Assembly	92 ft x 15 ft, 1.1×10^6 lbs, 7 bearings
M-G Set Rotating Mass	273 tons, 3.33×10^6 lbs ft^2
Exciter Transformer	2270 kVA, 13 kV, 3/60, 90°C rise
Power Circuit Breakers	15 kV, 500 MVA
Rectifier Transformers	16.6 MVA, primary 9.6 kV L-L, 3/49.8
Excitron Rating	1750 V, 300 A (average)
Operational Data	
Design Ratings	
Applied Voltage	10,700 V
Current Rise	0-10,950 A in 1 sec
Current Flat-Top	10,950 A for 0.2 sec
Current Decay to Zero	from 10,950 A in approximately 1 sec
Stored Energy	41.4×10^6 joules, peak
Dissipation in Magnet	27.7×10^6 joules/pulse
Peak Power Input	117×10^6 W
Repetition Rate	15 pulses/minute
Typical Operation	
Applied Voltage	10,700 V no load, 9300 V full load
Current Rise	0-10,060 A in 1 sec
Current Flat-Top	10,060 A for 0.2 sec
Current Decay to Zero	from 10,060 A in approximately 1.1 sec

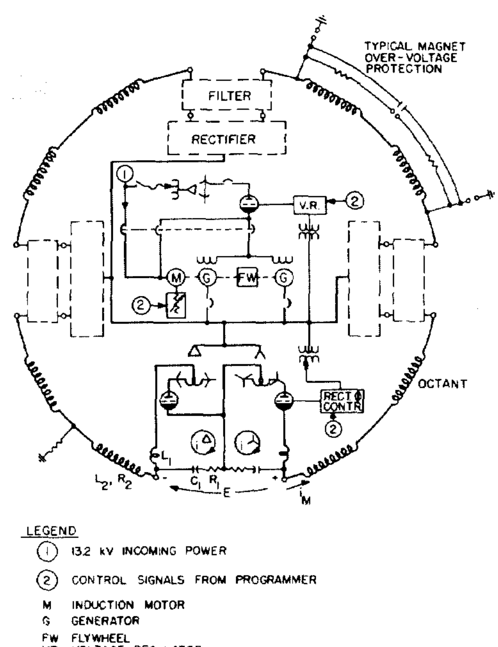

Fig. 1. System Schematic.

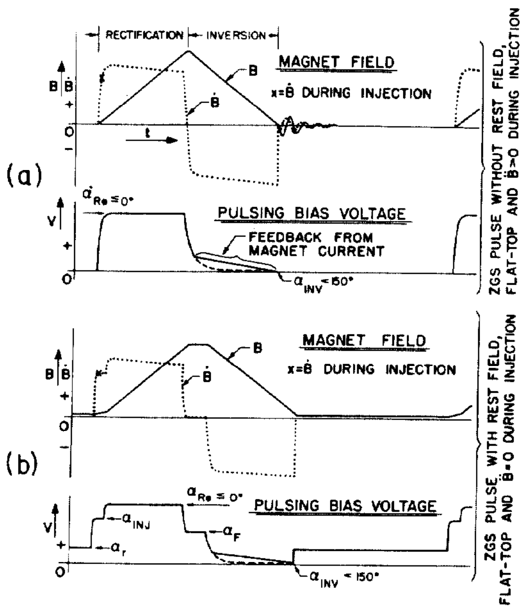

Fig. 2. Magnet Field and Pulsing Bias Voltage.

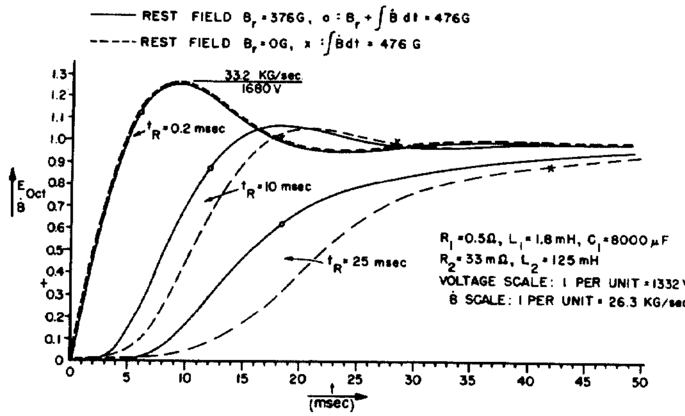

Fig. 4. Ḃ at Injection.

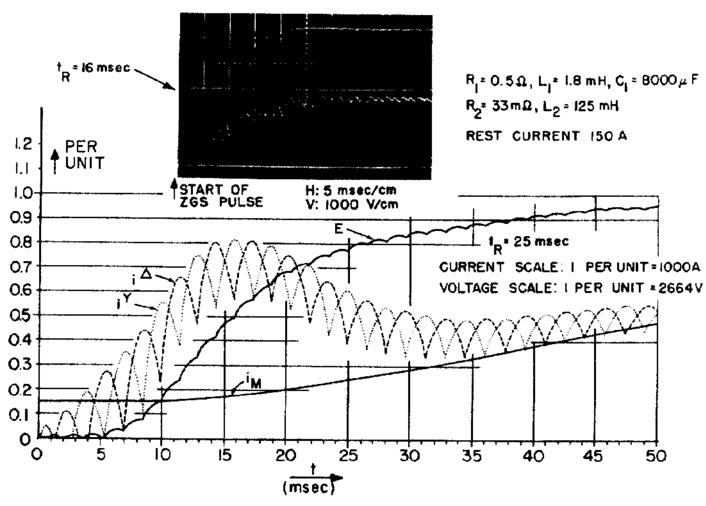

Fig. 3. Start of Rectification.

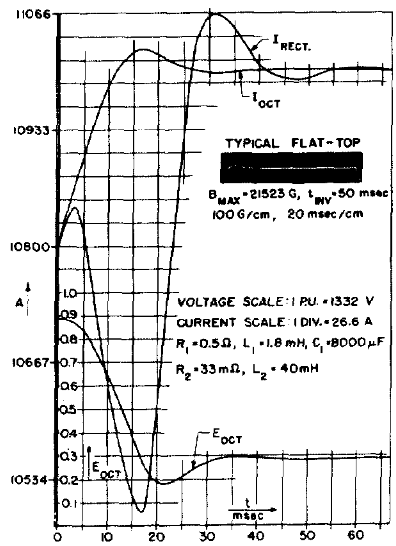

Fig. 5. Typical Transition into Flat-Top.

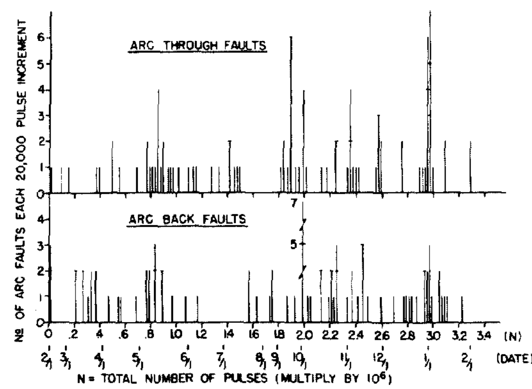

Fig. 7. Summary of Rectifier Faults.

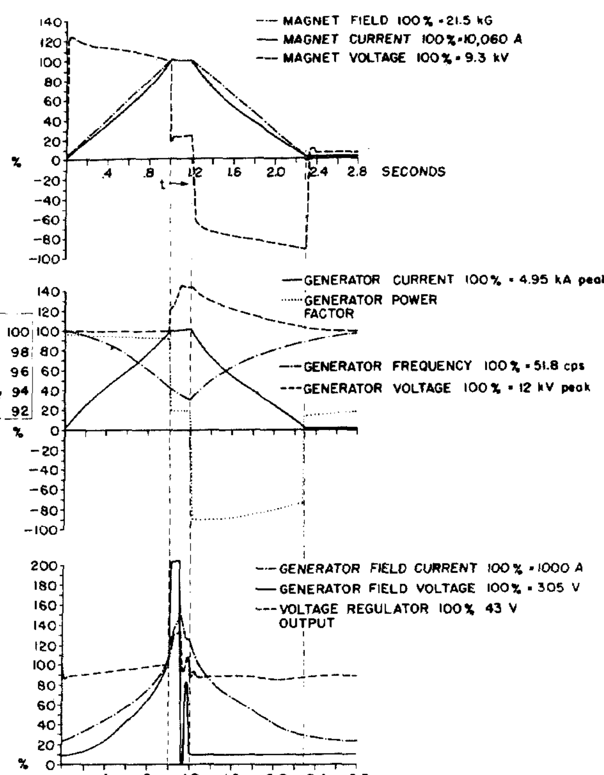

Fig. 6. System Performance.