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SYSTEM ENGINEERING AND DESIGN OF A PULSED HOMOPOLAR GENERATOR POWER SUPPLY FOR THE TEXAS EXPERIMENTAL TOKAMAK

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Summary

The design of a homopolar generator power supply for the Texas Experimental Tokamak (TEXT) is presented. Four series-connected disk type homopolar machines serve as inertial energy storage and conversion devices to supply 50-70 MW peak power to the toroidal field coil and ohmic heating coil circuits. The system is nominally operated at 150 MJ, 430 V to provide a 0.5 sec flat top, 160 kA TF current pulse and a 0.3 sec, 10 kA OH current pulse every 2.0 min on a continuous basis. The system has a maximum capacity of 200 MJ at a maximum open circuit voltage of 500 V.

The homopolar machine design is described. The vertical shaft generators are excited by water-cooled, copper field coils and have ferromagnetic rotors. The magnetic reluctance torque tends to tilt the rotor between the cast steel pole pieces and hydrostatic journal bearings have been designed to maintain the angular position of the rotor. The rotor is suspended by a Kingsbury type hydrodynamic thrust bearing. The main ac powered oil supply system is backed by a completely redundant dc drive oil supply which is powered by station batteries. Control power is provided by a non-interruptible battery-inverter supply. The generators are driven by SCR controlled, variable speed dc motor drives which are equipped with contactors and resistors for dynamic braking. Internal generators losses are removed by a combination of forced air ventilation and water cooling. The forced air system has provisions for the collection of brush wear debris. The overall generator configuration is designed to require minimum down time for brush maintenance.

The TEXT homopolar generator system was designed under funding support provided by the U.S. Energy Research and Development Administration (ERDA).

Introduction

A conceptual design of a TEXT pulsed power supply consisting of four homopolar generators and auxiliaries, a mechanical making switch, and a variable liquid resistor/interrupter has been described previously.[1,2] The design has been modified as additional engineering trade offs and detail design decisions have been made. The state-of-the system and machine design as a August 1977 is described in the following pages.

The pulsed power supply is designed to meet the following requirements:

1. Toroidal field current	157 kA (3.0 T)
2. Time to peak current	1.3 sec
3. TF current flat top pulse width	0.5 sec
4. Continuous repetition rate	30 pulses/hr
5. OH coil current	10 kA
6. OH current pulse width	0.3 sec
7. Minimum generator bus voltage	225 V
8. Minimum generator brush life	10,000 pulses
9. Maximum pulses per year	40,000

Additional constraints are imposed by the laboratory location, the university utility system, and the operating philosophy of the fusion plasma research facility. These include:

1. 8' x 16' hatch access to basement laboratory
2. 40 ton crane overhead lift capacity
3. Maximum power available - 3.5 MW
4. Peak pulse power demand without levelling - 1.3 MVA
5. Capability to continue experiments during brush maintenance periods
6. Capacity to drive TF coil to 4.0 T

System Design

The homopolar generator load consists of the toroidal field coil circuit and the ohmic heating circuit. The OH coil voltage is controlled by a dc chopper and filter inseries with the homopolar generator bus. The product of OH current and effective OH circuit resistance limits the minimum voltage of the homopolar machine bus to approximately 225 V. The toroidal field coil consists of 16 segments, each having six turns for a total of 96 turns. The coil inductance is 2.0 mH and the dc resistance is 1.2 mΩ. [Accounting for the transmission line, switch, and generator impedances the total TF circuit inductance is approximately 2.1 mH, and the circuit resistance is 1.5 mΩ.] Neglecting mechanical losses, magnetic saturation and current diffusion of the rotor, the homopolar generators model electrically as a 1600 F capacitor (6400 ÷ 4) in series with a small resistance and inductance.

The generator voltage and energy required for a natural RLC discharge are shown in Figure 1 for the nominal and maximum current cases. The minimum capacitance of the system is 1400 F, based on a 1.0% variation in current during the 0.5 sec flat top.

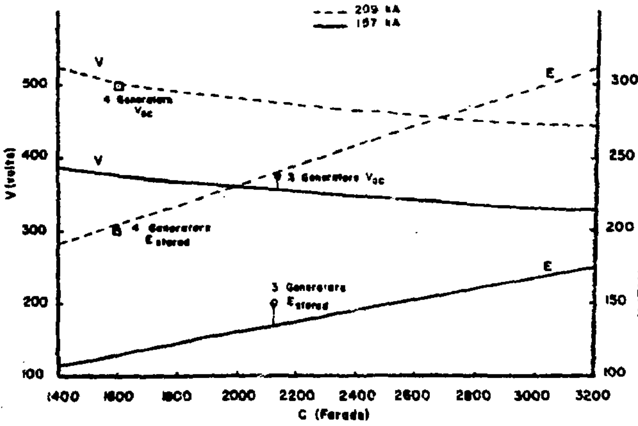

Figure 1. TEXT Power Supply Energy and Voltage Requirements

Note that the proposed generator system is sufficient to approach the 4.0 T case. Also, if one generator is down for routine brush maintenance, the system is still

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more than ample to provide 3.0 T. Normally, however, a natural RLC discharge is not used. Instead the generators are run to a higher speed and voltage than is required for the natural circuit. A variable resistance liquid resistor/switch is inserted into the circuit to control the current waveshape and to later interrupt the generator current. The proposed system schematic diagram is shown in Figure 2. The waveshaping resistor scheme is desirable for several reasons:

1. The time required to reach maximum current is reduced
2. Less i^2R heat is ultimately deposited in the coil
3. Generator brush wear and internal heating are reduced
4. DC drive motor power is reduced for the same duty cycle.

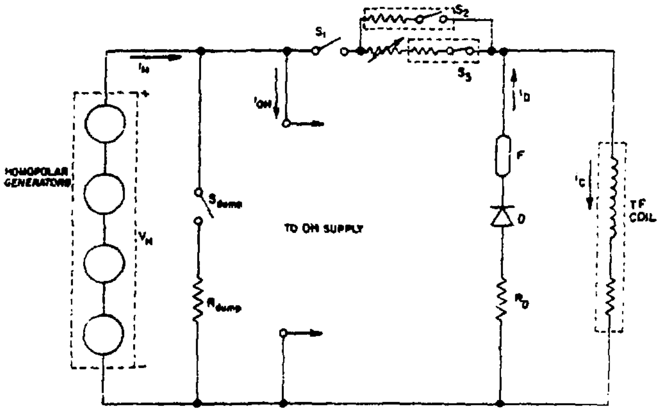

Figure 2. TEXT Homopolar Generator Circuit Diagram

Sample wave forms are shown in Figure 3, and discharge parameters for three basic cases are given in Table 1. The energy balance given in Table 1 is at the time the generator brushes are lifted from the rubbing surface after the discharge current has been interrupted. The nominal operating case represents a compromise between coil i^2R heating and generator brush wear.

A block diagram of the homopolar generator system is shown in Figure 4. The system is sequentially interlocked and designed to shut down safely in the event of laboratory power failure or main bearing oil supply failure. The station battery bank is sized to allow a 1.0 hr coast down from maximum operating speed with full bearing supply pressure and flow. However, to reduce the probability of a high speed rub, the generators are supplied with two braking systems. The dc drive motor supplies are furnished with auxiliary contactors and resistors to serve as a load to absorb the inertial energy stored in the rotors in 5.0 min. In addition a dump resistor and switch are connected to the generator bus to stop the machines in 30 sec in the event of a severe fault elsewhere in the laboratory. Main oil supplies and auxiliaries are cooled with cooling tower water, but emergency oil supplies and auxiliaries are cooled with building water. The major generator subsystems and auxiliaries are described in the following sections.

Generator Design

A cutaway view of an individual generator is shown in Figure 5. The generator is a single pass disk type machine with water-cooled copper excitation

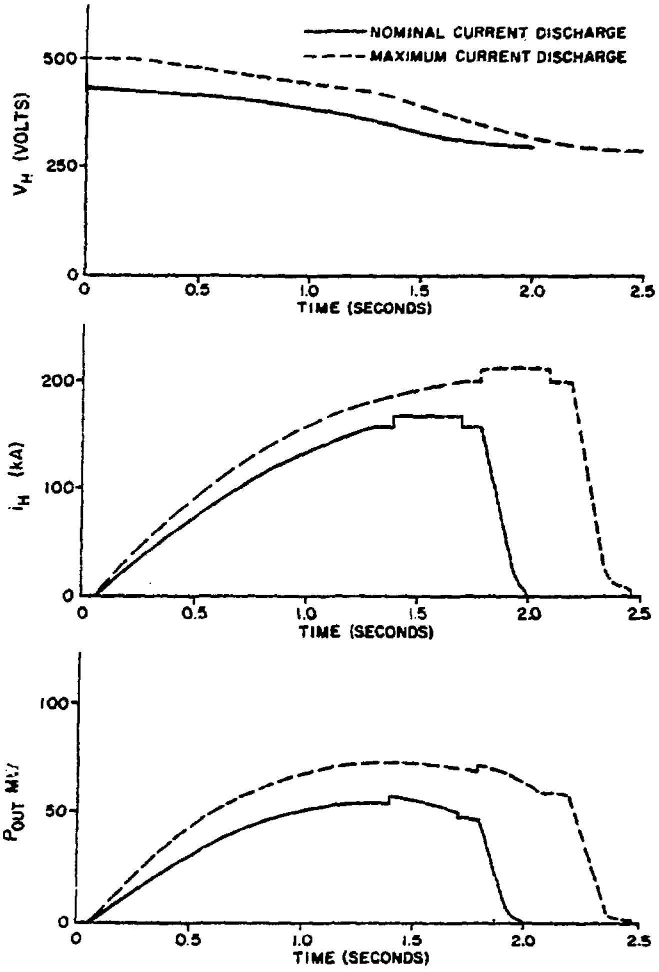

Figure 3. TEXT Homopolar Generator System Discharge Waveforms

Table 1. TEXT Homopolar Generator System Discharge Circuit Parameters & Energy Balance

PARAMETER	3 GENERATORS FROM 2480 RPM	4 GENERATORS FROM 2215 RPM	4 GENERATORS FROM 2560 RPM
DISCHARGE TIME (sec)	2.8	2.1	2.5
PEAK OUTPUT POWER (MW)	42	56	72
MAXIMUM GENERATOR CURRENT (kA)	167	167	210
INITIAL OPEN CIRCUIT VOLTAGE (volts)	363	433	500
RESIDUAL SPEED (rpm)	1540	1540	1510
ROTOR BRUSH WEAR/SHOT (μm)	3.3	1.9	3.1
MAXIMUM MAGNETIC ENERGY IN COIL (MJ)	26	26	42
INITIAL ENERGY STORE (MJ)	141	150	200
ENERGY BALANCE AT BRUSH LIFT (MJ):			
Brush Friction and Contact Drop	2.8	2.6	3.8
Bearings and Windage	0.4	0.3	0.4
Armature I^2R	1.6	1.6	3.1
Total Generator Losses	4.8	4.5	7.3
OH Circuit	1.0	1.0	1.0
Waveshaping Resistor I^2R	2.8	9.7	6.2
Crowbar Diode I^2R	-	-	-
Remaining Magnetic Energy	16.0	16.0	26.1
Coil I^2R	62.3	46.4	89.6
Total Energy Delivered to Loads	82.1	73.1	122.9
Residual Inertial Energy	54.1	72.4	69.8
GENERATOR DISCHARGE EFFICIENCY η*(%)	94	94	94

$*\eta = \dfrac{\text{Energy Delivered to Loads}}{\Delta\ \text{Inertial Energy}}$

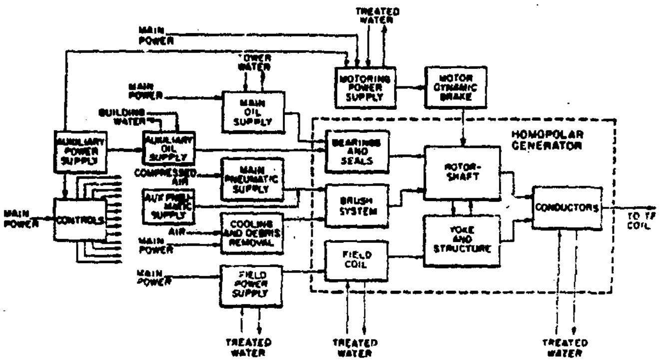

Figure 4. Block Diagram TEXT Homopolar Generator System

coils and a ferromagnetic rotor. The field coils are split to allow radial access to the rotor brushes through an arrangement of six hinged doors. The armature current conductors are also water-cooled, and the rotor tip, shaft slip rings, and brush rigging are cooled by forced air ventilation. The brushes are constructed of sintered copper graphite material and are pneumatically actuated. The rotor is suspended from a Kingsbury type thrust bearing and the radial support is maintained at all speeds by hydrostatic journal bearings.

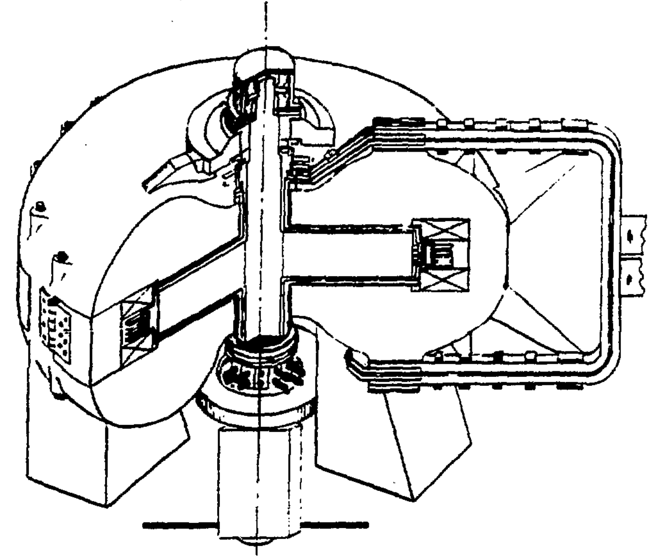

Figure 5. Cutaway View of TEXT Homopolar Generator

Yoke

Each generator yoke is constructed of a lower carbon content cast alloy steel to obtain favorable magnetic permeability. The casting is poured in two 18,000 kg, 2.7 m diameter halves, which are shaped for a 1.5 T average flux density. The casting is poured so that the pole faces are the highest quality zone of the casting. Access to rotor brushes is through six hinged 900 kg doors which are 28x43x89 cm. The doors are equipped with jackscrews for opening and are slightly tapered to minimze the air gap in series with the main magnetic circuit. The design replaces the circular port concept which was originally proposed.[2] The door design results in a lower reluctance path and simplifies the routing of cooling air ducts. Each yoke half is equipped with manually operated jack screws which support and/or fix the position of the rotor during shipping and assembly.

Field Coil

The excitation coil is constructed in two pieces, each constructed of three water-cooled pancake coils. The pancake coils are wound of extruded 1.6 cm square Cu (OFHC #102) with a 1.0 cm circular coolant passage. The die is commercially available so that a special tooling charge is not required. Each conductor is insulated by a half lap wrap of 0.2 x 2.5 cm fiberglass tape which is vacuum impregnated with epoxy. The coil insulation thickness is determined by mechanical and thermal requirements rather than the turn-to-turn voltage. The number of turns and cooling passages are determined by the maximum coolant head loss. The design is a compromise between power supply costs and coil insulation and winding costs. The coil set of one generator is described by:

Total turns	132
Total cooling passages	6
Coolant flow per passage (ℓ/min)	11.3
Maximum pressure drop (Mpa)	0.5
Total pumping power (W)	450
Inlet coolant temperature (°C)	35
Maximum temperature rise (°C)	20
Hot spot temperature (°C)	70
Coolant passage length (m)	130
Coil O.D. (m)	2.1
Coil I.D. (m)	1.7
Half coil width (cm)	12
Nominal current (A)	750
Nominal power (kW)	48.4
Maximum current (A)	850
Maximum power (kW)	62.4

Rotor and Shaft Assembly

The rotor is manufactured from a solid 4340 steel forging which has been stress relieved and heat treated to provide a minimum tensile strength of 1975 Mpa, yield strength of 1858 Mpa, and a fatigue strength of 686 Mpa (100 Ksi). The rotor is shrunk fit onto a 304 stainless steel shaft with an interference sufficient to insure a 42 Mpa interface pressure at the maximum operating speed and greater than 0 at 130% maximum speed. Rotor and shaft parameters are:

Rotor O.D. (m)	1.63
Rotor thickness (m)	0.25
Shaft diameter (m)	0.33
Shaft length (m)	2.03
Finished assembly mass (kg)	4,980
Maximum stress (Mpa)	523
Dynamic unbalance per plane (m-nt)	0.23

Other 4340 steel sleeves are shrunk fit on the shaft as brush sliprings and as bearing journals. The shaft is also designed with provisions for mounting the thrust bearing runner, split ring seal runner and slinger ring assembly, and an insulating coupling to the dc drive motor. The top end of the shaft is drilled and topped as provision for a lifting eye for the assembly.

The critical assembly dimensions and tolerances are rotor diameter concentricity and waviness, rotor-to-shaft perpendicularity, and the bearing journal clearance, concentricity, taper, and surface finish. The waviness is specified as $n^2 e \leq 1.6$ mm, where n is the number of waves along the periphery and e is the wave amplitude. Concentricity is specified at 0.13 mm TIR. These tolerances primarily affect brush dynamics. The rotor/shaft perpendicularity tolerance is critical because it influences the magnitude of the tilting moment, and is specified within 0.13 mm. Bearing journal concentricity and clearance are held with 12.7 μm.

Bearings

Each generator is equipped with two hydrostatic journal bearings, a hydrodynamic thrust bearing and associated oil supply pumps, reservoirs, and heat exchangers. The bearing stiffness is sized to maintain system critical speeds at least 30% above the maximum operating speed. The bearing(s) are supported by a 15 cm thick steel ring which is mounted on three structual pads attached to each yoke half.

In a ferromagnetic rotor homopolar machine, the magnetic thrust and tilt forces become significant when the generator is built within practical mechanical tolerances. An analysis of these forces is presented in a companion paper.[3] Nominal thrust bearing loads are:

Rotor/shaft weight (nt)	4.9×10^4
Magnetic force (nt)	$\pm 2.7 \times 10^4$ (0.5 mm misalignment)
Impulse force (nt)	$\pm 1.4 \times 10^3$ (210 kA ±5% discharge)

Nominal radial loads are:

Magnetic tilt force (nt)	2.3×10^4 (6.3×10^{-4} radian angular misalignment)
Dynamic unbalance (nt)	1.0×10^3

A 27 cm double-sided, self-equalizing type JVJ Kingsbury bearing has been selected. The bearing has a load capacity of 9.6×10^4 nt at 2560 r/min with a combined stiffness of 8.14×10^8 nt/m. Oil flow is 45 ℓ/min at 0.1 Mpa, and the maximum viscous drag is 39.8 nt-m at maximum speed. The bottom side of the bearing is equipped with hydrostatic lift pads for daily starting and stopping the generator.

The radial bearing journals are reduced to 0.20 m in diameter to minimize rotational losses while maintaining load capacity and stiffness. Each journal diametral clearance at temperature is 0.02 cm. Hydrostatic pressure is 6.9 Mpa at a flow rate of 45.4 ℓ/min depending on shaft temperature (clearance). The minimum load capacity is 9.8×10^4 nt per bearing at a stiffness of 1.5×10^9 nt/m. The maximum drag torque is 84 nt-m per bearing at 2560 r/min.

All intermediate and high pressure oil supply lines are run in guarded pipe. A non-flammable lubricant with properties similar to ASTM 215 oil is recommended. The bearing oil supply system is completely redundant with the emergency pumps driven by dc motors powered by station batteries. An in-line accumulator is included in the supply line to maintain bearing pressure during the changeover from primary to auxiliary pumps in an emergency.

Bearing support structures are provided with jackscrews and wedges which are used to align the bearings. Pocket pressures in four pockets per journal bearing are used as feedback signals during the alignment process, which is performed in a series of steps with increasing levels of field current.

Seals

A total of five seals are required for each generator. One set of three 0.2 m split carbon rings, tandem, circumferential seals are provided to restrict oil and oil vapor to the bearing sump areas and to keep bearing oil free of brush debris. Seal housings are electrically insulated from other parts to prevent pitting caused by circulating shaft currents. Rotational drag of each oil seal is approximately 1.31 nt-m. The tandem seal design life is greater than 10,000 hrs at full speed.

A second set of two seals is provided to restrict the flow of air and wear debris into the generator cavity. A partial vacuum is maintained at the rotor/shaft interface area. Windage losses caused by flow through are reduced. The 0.33 m diameter seals have a drag torque of 2.3 nt-m and a design life of at least 5,000 hrs at full speed. A non-rubbing labyrinth type screw seal is an alternative for this service.

Armature Conductors

The generator armature circuit consists of the shaft busbars, shaft brush ring, shunts and brushes, shaft, rotor, rotor brushes, shunts and brush ring, disk return conductors, cylinder return conductors, and rotor busbars. The circuit impedance also includes the non-linear resistance of the sliding brush contacts. Current diffusion is only important in the steel rotor. The magnetic field of the radial discharge current also tends to drive the edges of the rotor into saturation. However, at current levels 200 kA and less, this problem is not significant.

The estimated internal impedance of each generator is 20 μΩ and the air gap and non-ferromagnetic inductance is 25.2 nH. The estimate of the variable rotor inductance is 1.0 μH, based on an unsaturated rotor carrying current in a 2.5 cm skin depth. Relative circuit resistance is given below.

Rotor brushes, shunts, and contact drop	18%
Shaft brushes, shunts, and contact drop	16%
Shaft	14%
Rotor	7%
Return conductors	5%
Busbar	40%
Total:	100%

Conductors internal to the generator are braced for a 2.0 MA per side fault and external busbar is braced for a 1.0 MA per side fault. The generator support structure is designed to take the torque of a 4.0 MA short circuit.

Internal conductors are made of 6061-T6 aluminum and external busbars are made of 6101-T6 aluminum. Brush shunts are made of copper. Aluminum-copper joints are specially prepared with joint compound to reduce contact resistance. Depending on the effectiveness of the compound, copper or silver plating of the brush ring surface may be required. All other internal joints are welded.

Brushes

Rotor and shaft brushes are constructed of a sintered copper graphite material, Morganite CM1S. The brushes are silver soldered to the copper brush shunts. Rotor brushes are supported by the cantilevered brush shunt (solid 0.3 x 2.5 cm copper). Since the anticipated brush wear is about 2.5 cm over the 10,000-20,000 pulse life of the brush and shunt, the mechanism is designed to allow the 2.5 cm travel over the life by indexing a ratchet and pawl. The brush shunt displacement is limited to 0.3 cm per shot to prevent cyclic fatigue failure. The brush is loaded by a 0.1-0.14 Mpa spring force and is air retracted between shots to minimize friction and wear. The air cylinder is double acting so that down pressure is used to index the brush mechanism as wear occurs. Shaft brush shunts are a four layer laminate constructed of 0.8 mm copper strap.

At the nominal operating speed of 2215 r/min, the rotor surface velocity is 180 m/sec. The brush temperature rise due to friction heating and contact voltage drop is approximately 44°C per shot. Under worse case conditions the rotor brush temperature rise is 61°C per shot. Although the shaft brushes run at a lower velocity, the brushes are packed much tighter circumferentially so that the brush slipring temperature rise is 20% higher. The thermal diffusion time in steel is long compared to the discharge time so that the majority of the heat input to the rotor and shaft is deposited in the outer 0.3 cm. The resulting thermal stress is approximately 69 Mpa.

Cooling System

Each homopolar generator is cooled by a combination of forced air ventilation and water cooling. The forced air system is designed to reject brush related losses and a fraction (≈15%) of the rotor windage loss. The remainder of the windage and the armature i^2R losses are rejected to the water cooled return conductors. Field i^2R losses are removed by water which is circulating through the six pancake coils. Bearing and seal losses are rejected to the bearing oil.

Based on a typical 120 sec cycle the nominal generator average losses are given below:

Seal friction	1.7 kW
Viscous bearing drag	22.8 kW
Bearing pumping loss	10.9 kW
Windage	9.4 kW
Brush friction	3.8 kW
Brush contact drop	1.3 kW
Armature i^2R	3.2 kW
Field i^2R	48.4 kW
Total	101.5 kW

Air is circulated by a positive displacement lobe blower, and is filtered at inlet and outlet. The 5.0 micron outlet filter is used to trap brush wear debris. The relative humidity of the cooling air is controlled to eliminate brush dusting.

The relatively low voltage field and armature conductors are cooled with distilled water provided by the university power station. The distilled water has a resistivity of 50,000 Ω-cm and is actually the condensate from steam turbines. A 760 ℓ fiberglass tank and 400 ℓ/min 0.9 Mpa pump, and watertower heat exchanger are common to all machines.

Motoring System

Each homopolar generator is provided with a 224 kW vertical shaft variable speed dc motor drive which is sized to accelerate the rotors from 1540 r/min to 2215 r/min in 100 sec in a constant power mode. Speed is controlled by field weakening. The system does not require a gear box as the maximum motor speed is 2750 r/min. The armature and shunt field voltages are SCR controlled (500/300 V). The system meets the maximum pulse power limit set by campus utilities. Otherwise, constant power equipment (resistor bank, etc.) would be required. The motor drives are designed to supply 150% rated torque for 1.0 min and can withstand the deceleration torques experienced without harm. The motor-generator shafts are joined by an insulating coupling rated to 2.0 kV.

The dc armature circuits are equipped with contactors and resistor banks to be used for dynamic braking of the rotor. Standard dynamic braking gear is designed to absorb up to ten times the motor interial energy so that a larger resistor bank is used.

Station Battery Bank

The station battery bank is designed to provide power to the auxiliary oil supply system and all four motor drive shunt field coils in the event of a laboratory power failure. The batteries are Exide type EC-19 and have a capacity of 800 A-h at an initial terminal voltage under load of 240 V. The batteries will supply 460 A for 1.0 hr with a minimum final voltage of 216 V. The batteries are capable of supplying 660 A for 6.0 sec when starting the dc motors for the auxiliary oil pumps. The battery banks are equipped with interlocks and alarms to indicate improper voltage, electrolyte level, or loss of ac power.

The non-interruptible power supply consists of a battery bank and charger, inverter, filters, and other necessary equipment. The batteries are Exide type CC-9 and are designed to provide control power for 1.0 hr with a 92% final voltage. The inverter output is nominally 115 V ac, 60 Hz.

Conclusion

A homopolar generator system has been designed to meet the requirements of the Texas Experimental Tokamak toroidal field coils and ohmic heating coils. The system can provide toroidal magnetic fields approaching 4.0 T at a 3.0 to 4.0 min repetition rate, and the nominal 3.0 T field on a 2.0 min repetition rate. The generators are actively cooled and can be operated on a continuous basis, up to 13,000 shots between brush maintenance periods. The generator system was designed for TEXT by the Center for Electromechanics, The University of Texas at Austin, under funding of the U.S. Energy Research and Development Administration.

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