FINAL MANUFACTURE AND ASSEMBLY OF A MODULAR 60 MEGAJOULE PULSED HOMOPOLAR POWER SUPPLY

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INTRODUCTION

The Center for Electromechanics at the University of Texas at Austin (CEM-UT) has contracted Parker Kinetics Designs Inc. (PKD) to manufacture and install a modular 60 megajoule pulsed homopolar generator power supply located in the Electromechanics and Energy Building at Balcones Research Center, the University of Texas at Austin. (See Figure 1)

The system consists of six (6) truncated drum-type homopolar generators, each storing 10.0 megajoules rotational kinetic energy at a speed of 6073 RPM (636 rad/sec.). (See Figure 2) Various allowable combinations of series and parallel output connections provide system flexibility. For a full series disharge, the predicted output is 600 VDC and 1.5 million amperes. Each homopolar generator has a minimum effective capacitance of 2000 Farads with a very low internal impedance of 7.1 microohms and 112 nanohenries.

The Balcones Research Center 60 MJ pulsed homopolar power supply also includes a complete set of sophisticated auxiliary equipment designed to support the six homopolar generators. A complex, high-reliability instrumentation and control system is incorporated into the power supply design to safely operate and monitor the performance of the generators. The auxiliary equipment and the instrumentation, control, and data acquisition systems are described in detail in the accompanying paper entitled "Final Design of the Control and Auxiliary Systems for the Balcones 60 Mj Homopolar Pulsed Power Supply", authored by D.J. Hildenbrand, M.A. Pichot, and J.H. Price. This paper primarily deals with the manufacture and assembly of the 10 MJ homopolar generators.

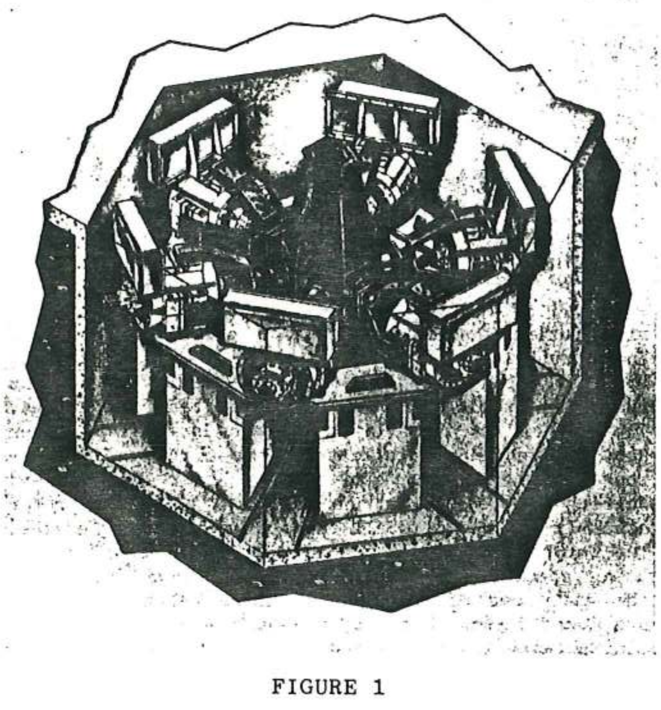

FIGURE 1

FARA-LAB 60, Modular 60 Megajoule Pulsed Homopolar Generator Power Supply

FACILITIES AND SYSTEM DESCRIPTION

The Electromechanics and Energy Building at Balcones Research Center, the University of Texas at Austin, was designed specifically to house the FARA-LAB 60 modular pulsed homopolar generator power supply. It integrates three major equipment packages: 1) six (6) FARA-DRUM 10 truncated drum-type homopolar generators and output buswork; 2) auxiliary power supplies; 3) instrumentation and controls systems.

Each FARA-DRUM 10 homopolar generator is individually mounted 1.37m (54 in) below floor level in a reinforced hexagonal concrete pit, 6.10m (20 ft) wall-to-wall and 3.66m (12 ft) deep. Output current from each generator is conducted to .522-m (21 3/4 in) above floor level through 5.08 cm (2 in) thick by .61-m (24 in) wide, ETP-110 copper parallel plate bus bars. Each set of conductors is bonded and bolted to withstand 62.0 MPa (9000 psi) separation pressure, Separate motoring, brush actuation, bearing supply and scavenge systems are located beneath each generator. These modular systems are connected by an underground tunnel to their main power supplies located in a seperate utilities building. Instrumentation and controls are installed in an adjacent electromagnetic and electrostatic screen room. Specially designed low-impedance ground grid protects personnel and components from ground faults. Individual generator paramenters are given in Table II.

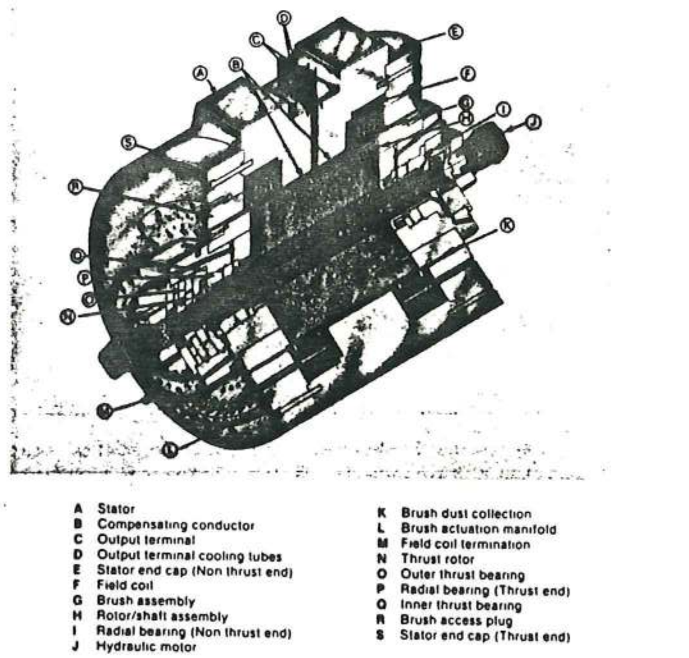

FIGURE 2

FARA-DRUM 10, 10 Megajoule Truncated Drum Homopolar Generator

Table I

FARA-DRUM 10 Homopolar Generator Parameters

Parameter	Value	Units
Peak Current	1,500	kA
Open Circuit Voltage	100	V
Effective Capacitance	2,000	F
Internal Resistance (less output bus)	6.0	μΩ
Internal Inductance	112	nH
Maximum Rotor Speed	6,073	RPM
Rotor Angular Velocity	636	rad/sec
Rotor Inertia	49.44	kg-m^2
Rotor Diameter	.57	m
Rotor Length	.59	m
Rotor Mass	1,217	kg
Stator Diameter	1.07	m
Stator Length with End Caps	1.24	m
Stator Mass with End Caps	6820	kg
Total Generator Length	1.95	m
Length Including Bus	2.0	m
Impedance (including bus)	10 175	μΩ nH
Magnetic Flux Density in Air Gap	1.85	T
Total Generator Weight (less bus bars)	7945	kg

Table II

FARA-LAB 60 Systems Parameters

Parameter	Parallel	Series	Units
Maximum Stored Energy	60	60·	MJ
Maximum Peak Current	9.0	1.5	MA
Maximum Open Circuit Voltage	100	600	V
Effective Resistance	1.7	60.1	μΩ
Effective Inductance	29.2	1,050	μH

MANUFACTURING PROCESSES AND ASSEMBLY PROCEDURES

Parker Kinetic Designs has contracted its sister corporation OIME, Inc., in Odessa, Texas to manufacture various generator components and establish specific assembly procedures.

Stator/Compensating Turn

The stator is cast, using low carbon(0.25%) ASTM-A27 Grade U60-30 class material, in two identical halves. Each half is milled and bored, then joined temporarily for turning to complete the rough machining sequence. After stress relieving, the stator halves are turned to finish diameters and slots are machined to accomodate the output terminals of the compensating turns. The stators halves at this stage are 1.22 m (48 in) wide by .61 m (24 in) high by .613 m (24 1/8 in) long, weight approximately 2050 kg (4500 lbs), and are ready to be bonded to the compensating turn assemblies.

The compensating turns conduct discharge current from the current collection brush rings to the output busbars. Each compensating turn is machined from a 250 kg (550 lb) spool shaped EPT-110 copper rolled ring forging. The compensating turns are rough turned to their approximate finish dimensions an then circuitous grooves are milled in the bore and on the end faces of the spool forgings. These grooves are designed to accept .635 cm (.250 in) square by .356 cm (.140 in) inside diameter copper tubing which is silver soldered into the grooves. This tubing is used for circulating coolant through the compensating turns and is designed so that it has no breaks or splices within the generator itself. After completion of the tubing soldering procedure, the two compensating turns are each bonded to a .32 cm (.12 in) thick G-10 insulator using FM-123, an American Cyanimid high strength film adhesive. This bonded compensating turn assembly is then bonded into the two stator halves using the same high strength adhesive system. The cure cycle for the stator to compensating turn bond is 250 degrees F for nine hours. Throughout the bonding and curing process care is taken to insure proper insulation integrity between the two compensating turns and the stator. After cure the stator/compensating turn assembly is machined to finish length and diameters and is then ready for final machine assembly.

Rotor/Shaft

The rotor on the FARA-DRUM 10 homopolar generator is made from an aircraft quality E4340 alloy steel forging heat treated to 320 minimum Brinell hardness. This treatment provides a yield strength of approximately 690 MPa (100,000 psi). The forging is rough machined to size and then the bore is flame sprayed with Al_2O_3 ceramic. This ceramic layer is sealed using a silicone base sealer and then cured at 250 degrees F. The ceramic lined bore is then ground to finish dimensions and resealed. Finish ceramic insulation thickness is .432mm (.017 in.).

To minimize stray magnetic fields in the bearing and seal areas of the generator, a 316 stainless steel forging was chosen as the shaft material. This forging was rough machined to size and then ceramic sprayed, sealed, and ground in a procedure similar to the one used on the rotor. The rotor and shaft were then put together using a shrink-fit technique. The minimum diametrical interference of this fit is .330mm (.013 in) which corresponds to a loosening speed of 8757 rpm. Hardened steel centers were shrunk-fit into each end of the shaft to help control center distorsion during the final precision grinding procedure. The shrunk-fit assembly is then finished, machined, sprayed, sealed and ground to accept the various required ceramic insulated seal and bearing sleeves. The use of the dual layer ceramic insulation system provides redundant protection from circulating currents in the bearings and seals. After the seal and bearing sleeves are shrunk-fit into place the rotor assembly is ground to all final diameters and lengths. The rotor is then balanced to within 144g-cm (2 oz-in) using specially provided balancing screws located on the end faces of the rotor. These balancing screws are located such that they can be removed through special accessholes in the end plate of the stator. This provision allows the rotor to be balanced on its own bearings within the stator if the need arises. (See Figure 3)

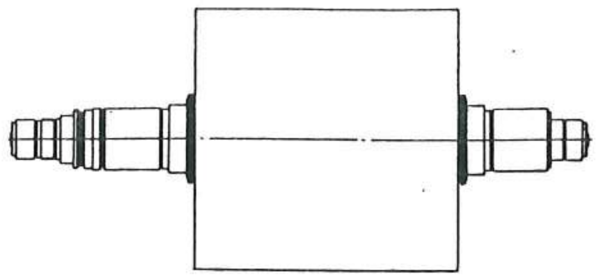

FIGURE 3

FARA-DRUM 10 Rotor Shaft Assembly

End Plate/Bearing Housings/Bearings

The stator end plates are manufactured out of carbon steel forgings approximately 1.07m (42 in) in diameter by .20m (8 in) thick. The end plates include close tolerance, taper-fit access ports and plugs to allow removal of the generator brush ring assemblies without disassembly of the generators. The end plates also provide air feed ports for the main and instrument brush actuation, as well as cooling air and brush debris collection exhaust ports. Carbon steel bearing housing shrunk fit into the end plates to form the stator end cap assembly. These bearing housings provide all required internal porting for bearing pressure, bearing scavange, and seal nitrogen pressure. After assembly the end caps are ground to the final dimensions required to accept the radial bearings.

The rotor/shaft assembly is supported at each end of the generator by six-pocket, orifice-compensated, hydrostatic radial bearings. Each radial bearing is machined from aluminum-bronze alloy D forgings. The bearings are installed in their respective end caps and machined to their final diameters. Final diameters and roundness on the bearings are held within .055mm (.0002 in) and bearing-to-bearing concentricity is held within .025mm (.001 in). After machining, the bearings are removed and individual flow restriction inserts are installed in supply ports to each pocket. Test ports are provided to monitor individual pocket pressures.

Axial restraint of the rotor is provided by six-pocket, orifice compensated hydrosatic thrust bearings. Each bearing is manufactured from heat treated E4340 alloy steel. The bearings are machined, then surface ground to within .0025mm (.001 in) flatness and parallelism. Individual flow restriction inserts are installed in supply ports to each pocket. Test ports are provided to monitor individual pocket pressures.

Brush Ring Assembly

The brush rings on the FARA-DRUM 10 homopolar generator are designed to collect current from each end of the drum-type rotor as well as act as high speed making switches. The brush system consists of brush straps and pneumatic actuators. The brush mounting rings are segmented, current-collection rings machined from an ETP-110 copper forging. Each segment is approximately 120 degree arc length and is designed so it can be removed through the end-plate brush access port. The brushes are made of Morganite CM1S brush material silver soldered to three .813mm (.032 in) thick brush straps. The inner two of these straps are made of AL-15 dispersion strengthened copper. This special material maintains its high strength and is not annealed by the silver soldering process and is used to provide the brush retraction spring back force. The current compensating brush straps are arranged so that the current collected by every brush is caused to double back on itself thereby causing a repulsive force between the compensating straps and the brush strap. This repulsive force helps prevent the brush from lifting off the rotor surface during discharge. The pneumatic actuators are a Viton elastomer bellows molded around an aluminum-bronze core. The actuators are housed in an aluminum-bronze shroud which confines the side motion of the bellows during pressurization. Each brush bellows actuates one brush assembly, which consists of 7 individual brushes. (See Figure 4)

The brush rings are assembled using an appropriate electrical joint compound to help insure minimum resistance. After final assembly the brushes are machined to a precise radius which closely matches the slip ring radius of the rotor. Each brush ring assembly has 42 rows of seven brushes each, for a total of 294 main brushes. Each brush is 19.0mm (.750 in) by 12.7mm (.500 in) thereby yielding a maximum discharge current density of 2,109 A/cm^2 (13,605 A/in^2) or a current per brush of 5,102 amps. Each brush ring also includes three electrically isolated, independently actuated instrument brushes used for monitoring machine voltage. The brushes are cooled by air jets directed onto the slip ring surface between the rows of brushes.

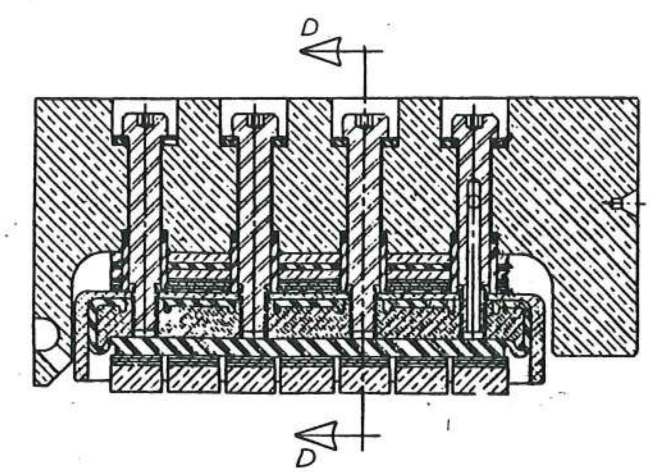

FIGURE 4

FARA-DRUM 10 Brush Ring Assembly

Field Coils

The field coils on the FARA-DRUM 10 homopolar generators are water-cooled, copper coils, vacuum epoxy impregnated into a composite coil. The conductor in the coil is a .864cm (.340 in) square ETP-110 copper tube with a .396cm (.156 in) diameter hole through its center. Each coil has 56 turns of conductor and is rated to operate at 1200 amps. This excitation current produces 67,200 amp-turns of magnetomotive force for each coil. The conductors are double-layer built, wrapped with .13mm (.005 in) thick by 12.7mm (.500 in) wide fiberglass tape, and are then wound onto an aluminum field coil spool. The alumimum surfaces of the spool are insulated from the conductors with additional layers of fiberglass cloth and tape. After the coils are wound an aluminum sleeve is seal welded to the flanges of the field coil spool to provide a vacuum tight impregnation mold. The coils are then vacuum tested and impregnated using a Dow 332 Epoxy Resin system. After curing, the coil and spools are finished machined to their final dimensions. The field coils are located in the stator through the use of a 1/2 degrees tapered cylindrical fit between the bore of the stator and the outside diameter of the coils. The coils are confined axially by the end plates on the stator. The field coils are also used to radially locate the brush rings through the use of a 1/4 degree tapered cylindrical fit between the field coil spool bore and the outside diameter of the brush ring. A 3.18mm (.125 in) G-10 insulating sleeve is used between the field coil and brush ring.

Output Busbars

The output busbar system used on the Balcones homopolar generators is a compensated, flat-plate busbar system specifically designed for the Balcones generator arrangement. Each generator has four pairs of output busbars which form the output bus spider. Each bar pair in the spider assembly consists of two ETP-110 copper bars 2.54cm (1.00 in) thick by .305m (12.00 in) wide backed up by carbon steel plates of the same size. A G-10 isulator is located between the copper bars and their steel backup plates. Grade-8 steel bolts 1.91cm (.750 in) in diameter are located every 10.2cm (4.00 in) on center in both directions to clamp the busbars together.These bolts are sleeved with a 2.54cm (1.00 in) diameter .318cm (.125 in) thick G-10 insulator tube to prevent short circuit currents between busbars. The copper busbars are also epoxy bonded to the central G-10 insulator using the same high-strength film adhesive used to bond the compensating turns into the stator. The epoxy bond is capable of developing an adhesive tensile strength of 27.58 MPa (4000psi) and the bolts and an additional clamping force of 25.93 MPa (3760 psi). This clamping method provides separation resistance between the spider busbars of up to 1.67×10^6 kg/m.

The four spider busbar pairs are connected to the main vertical output busbar system through a pair of horizontal coaxial ETP-110 copper tubes. These tubes are insulated from each other with a 12.7cm (.500 in) thick G-10 sleeve. The cross sectional area of the inner tube is 350 cm^2 (54.2 in^2) and the area of the outer tube is 649 cm^2 (100.5 in^2). The horizontal output coaxial busbars are joined to the busbars and to the main vertical busbars using grade-8 bolts and heavy duty bellville spring wahsers. All bolted joints are cleaned and coated with electrical joint compound before final assembly to minimize the output busbar resistance.

The main vertical output busbars are a pair of 5.08 cm (2.00 in) thick by .610m (24.00 in) wide copper bars. These bars are bolted and bonded in a similar manner as the one described on the spider busbar assemblies. The separation resistance on these busbars is 2.10 X 10^6pounds/fts.

CONCLUSION

The Center for Electromechanics Balcones 60 megajoule Pulsed Power Supply will be the largest, and most advanced, modular, homopolar-generator-based power supply in the world. Its capabilities will establish CEM-UT as the foremost high current research laboratory in the world and will provide a unique tool for exploration in the fields of electromagnetic propulsion, high-current pulsed welding, and many other pulsed power application areas. The sophisticated design and attention to detail which were used in the manufacturing of this system will provide a highly reliable, rugged power supply for many years to come.

ACKNOWLEDGMENTS

Parker Kinetic Designs, Inc. and the Center for Electromechanics wish to acknowledge and thank the many engineers, draftsmen, machinists, and technicians who have diligently worked on the Balcones pulsed homopolar supply since its conception. Far too many people have been involved with this project to single out particular persons for acknowledgement. The finished 60 megajoule homopolar generator pulsed power supply will serve as a tribute to the hard work, craftmanship and dedication of all persons involved.

We wish to express a special vote of thanks to the University of Texas at Austin and to Parker Drilling Company of Oklahoma for their financial and corporate support during the course of this project.

W.L. Noble and J.M. Weldon are affiliated with Parker Kinetic Designs, Inc. J.H. Gully is affiliated with the Center for Electromechanics, The University of Texas at Austin.

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