BALCONES HOMOPOLAR GENERATOR POWER SUPPLY

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Abstract: For the past several years, the Center for Electromechanics at The University of Texas at Austin (CEM-UT) has been involved in the conception, design, fabrication and testing of a large pulsed laboratory power supply. This review of the Balcones Homopolar Generator Power Supply (BHPGPS) project is intended to provide insight into the pros and cons of the design decisions and operating philosophy planned for the system. Capabilities are discussed and power supply parameters, including HPG's, inductors, switches and buswork are documented so that the community can evaluate the system as a power supply for various loads by calculating specific performance.

The power supply consists of the following components and subsystems:

- 6 ea, 10-MJ HPG's each rated at 100 V and 1.5 MA. The machines may be electrically connected in series or parallel and can be sequentially discharged;
- 6 ea, 6.5 μ H room temperature, coaxial, energy storage inductors. Each inductor is rated at 100 kV and 1.25 MA which coincides with a 50% energy transfer (5 MJ ea) from the BHPG's;
- 6 ea, explosively actuated opening switches. Each switch is rated for 1.2 MA and 15 kV stand-off. 50 μ s commutation has been demonstrated into railgun loads;
- Auxiliary systems including a 2400-hp hydraulic motoring system;
- Multiple output buswork rated for 7.2 MA total current;
- Automatic controls, data acquisition and reduction with additional channels available for experimental access. A Vax 11-750 computer is used for data reduction.

All components are operating and the system is presently being used to power two major railgun experiments. To date, three of the machines have been tested at full speed, two at 75% speed, and one has not been run. Operating problems were encountered with bearing seals, hydraulic motors, rotor/shaft runout and switching with the brushes into resistive loads. These issues have been successfully resolved. The inductors have each been electrically stressed to 85 kV and charged to 710 kA. Other than minor difficulties with a brazed joint, the inductors are working very well, demonstrating a 52% charging efficiency. The explosively actuated opening switches are inexpensive, reliable and efficient.

Previous papers [1,2,3] have presented design and fabrication details of these components. The purpose of this paper is to review in retrospect the philosophy of the project and the difficulties encountered and to present experimentally verified characteristics of the overall system. The BHPG's can be used alone to power resistive and inductive loads. When pulse compression and subsequent power amplification are

required, the energy storage inductors and opening switches are easily incorporated. The BHPGPS is intended to be a reliable, easily maintained system for large-scale, high-power laboratory experiments and is available to the community. It's success should do much to establish the feasibility of these machines and components as viable pulsed power supplies for many applications.

Background

The primary goal in creating the BHPGPS was to provide a versatile, high-current, pulsed laboratory power supply of sufficiently high energy to support continuing CEM-UT research efforts into various applications of pulsed power. At the same time, it was felt that the project would serve as a showcase for homopolar generator technology developed at CEM-UT. The requirement for versatility was driven by the wide spectrum of pulsed power applications ranging from precision resistive heating of 50-kg metal billets for forming applications and upset butt welding of metal sections up to 650 cm^2 (100 in.) [4] through a variety of electromagnetic launch [5] and pulsed laser [6] and electron beam experiments [7] to a scale model of a 20-T toroidal magnet for an ohmically heated Tokamak ignition experiment [8].

Homopolar generators model electrically as capacitors, the equivalent capacitance (C_{equiv}) being given by

$$C_{\text{equiv}} = \frac{2E}{V^2}$$

where E is the stored mechanical energy and V the open circuit voltage at the rotor speed corresponding to the stored energy. The relatively large stored energies and low voltages achieved by a typical HPG result in equivalent capacitances on the order of a few thousand Farads. This high capacitance of the HPG coupled with a low source impedance ($< 10 \mu\Omega$; $< 50 \text{ nH}$) results in a pulsed power source well suited to directly driving resistive loads (i.e., resistance heating of billets and upset butt welds) with no more than a closing switch for initiating the discharge.

Furthermore, if inductive loads such as high field magnets or energy storage inductors are appropriately designed (i.e., few turns and large L/R values to allow for the relatively long charging time (100 ms) afforded by the low HPG voltage), they can be resonantly charged by the HPG capacitors at acceptable efficiencies (50-80%). [9]

Low HPG voltage typically limits short circuit current rise times to around 20 ms. Thus, fast pulse loads such as railguns and laser flashlamps require an additional stage of pulse compression beyond the electromechanical conversion of the HPG. This is most easily achieved by resonantly charging an energy storage inductor as described, and then opening a series switch in the HPG-inductor circuit to commutate the inductor current into the load. The inductor will support the voltage required for the fast commutation, providing the opening switch can hold off the voltage. This, of course, leads to a requirement for fast-acting opening switches.

As originally conceived in 1977, the large HPG power supply was to have consisted of a single, large, disk-type HPG storing 50 MJ (see fig. 1). This machine, originally designed to power the toroidal field coils of the Texas Experimental Tokamak (TEXT) [1], was to have been modified with additional brush gear (the TEXT application required only 200 kA) to provide a 125-V, 3-MA HPG power supply. Such a machine would have been ideal for powering slow-pulsed, resistive loads but increasing interest in fast-pulsed loads in the late 1970's [10,11,12] led to investigations of more versatile HPG configurations capable of achieving lower effective capacitances.

Figure 1. 50 MJ text HPG

The design and subsequent development of the compact HPG at CEM-UT in the early 1980's led to an investigation of modular HPG power supplies consisting of a number of smaller HPG's that could be connected in various series and/or parallel configurations as required by specific loads.[13] Although the original modular HPG power supply concept of 12 compact HPG's was not the one finally chosen for construction (see fig. 2) many features of that design were included in the BHPGPS.

As shown in Figure 3, the configuration finally selected for the BHPGPS is a set of six 100 V, 1.5 MA, 10-MJ truncated drum HPG-arranged radially in a 20-ft hexagonal pit in the CEM-UT laboratory.[2] The truncated drum design was selected for its moderate capacitance (2000 F), symmetrical brushgear which minimized the number of different parts to be manufactured, and its ease of water cooling.

The HPG output terminals are arranged as six sets of parallel plate bus bars (60 cm x 5 cm conductors) in a hexagon at the center of the BHPG pit. The rotor and output conductors of each HPG are electrically insulated from the shaft, bearings and stator so that the six outputs may be connected in any series or parallel combination desired. This is the key to the BHPG versatility; the power supply output characteristics may be varied from 600 V @ 1.5 MA (all in series, 333 F equivalent capacitance) to 100 V @ 9 MA all in parallel, 12,000 F. Of course the output can be further varied by adjusting the HPG excitation (voltage) and rotor speed (energy) and the output of individual generators can be accessed as well.

The choice of an inductor design for the BHPGPS required a number of factors to be taken into account.

Figure 3. 60 MJ homopolar generator

Previous work at CEM-UT had shown the advantage of the coaxial inductor configuration in eliminating external magnetic fields with minimal weight penalty.[9] The same configuration allows the fraction of the magnetic flux trapped inside the conductors themselves during a fast pulse (i.e., less than the diffusion time of the flux through the inductor) to be minimized while maintaining a robust, monolithic construction. While earlier CEM-UT coaxial inductor designs utilized multiple turns, cryogenic cooling, aluminum conductors, and vacuum/pressure impregnated insulation to minimize inductor volume and mass, the inductor design chosen for the BHPGPS optimized a different set of parameters. Since a long L/R time was desired without the expense and delay associated with cryogenic cooling, more massive copper conductors were chosen to provide the desired low resistance at ambient temperature. Since the inductors were to be insulated for operation up to 100 kV in anticipation of ultra high velocity railgun experiments and other fast pulse requirements, a two turn bolted construction was selected to allow ready access to all electrical insulation in the inductors for ease of repair or upgrade.

The varied applications anticipated for the BHPGPS impose a wide range of requirements upon the opening switches in terms of charge transfer, peak current, and hold off voltage as a function of time. Since the CEM-UT pulsed power philosophy favors compensated pulsed alternators for repetitively pulsed systems, a simple, fast, reliable, single-shot opening switch was selected as a development goal for the BHPGPS. The resulting switch is of a flat plate geometry and requires only a small quantity of primer cord (2.8 g) to operate. These switches have successfully interrupted 750 kA against a recovery voltage of 7500 V in less than 50 μ s with greater than 90% efficiency.[14] They scale credibly to 1.25 MA and 15-20 kV in the same geometry.

The design, development and fabrication of the coaxial inductors and explosive opening switches were supported by funding from the Strategic Defense Initiative Organization, the Defense Advanced Research Projects Agency, and the U.S. Army Armament Research, Development and Engineering Command. Parker Kinetic Designs, Inc. (PKD) was responsible for manufacturing, installation and acceptance testing of the generators. They have invested substantial resources to the project.

Figure 2. Modular compact HPG power supply

Technical Discussion

HPG Parameters

The BHPG's and auxiliaries are designed for a rep-rate of six minutes which allows three minutes for motoring and a three-minute cool-down between discharges. Electrically, the machines can be configured to meet the requirements of a given load by connecting them in various singular, series, parallel or series-/parallel arrangements or by sequentially discharging them. The maximum ratings are shown in Table 1 below:

Table 1. Maximum BHPG Ratings

	Voltage (V)	Current (MA)	Energy (MJ)	Capacitance (F)
Any Single	100	1.5	10	2,000
Six Parallel	100	9.0	60	12,000
Six Series	600	1.5	60	333
2 Series/ 3 Parallel	200	4.5	60	3,000

To be able to connect the machines in series, the armature circuit in each machine must be electrically isolated from ground. Rather than isolating the stator, which must transmit structural and discharge loads, or the shaft, which makes contact with bearings, seals and hydraulic drive, insulating layers of aluminum oxide were placed between the rotor and shaft and between the shaft and a sleeve on which the hydro-static bearings are run. Both the rotor and bearing sleeves are thermally assembled onto the shaft which keeps the aluminum oxide under compressive loading. Each layer of ceramic is 20-mils thick which at 50-V/mil dielectric strength results in redundant 1000 V to ground insulation.

Connecting the machines in parallel into a common load imposes the most stringent requirements on the controls and auxiliaries. Through failure analysis, it was determined that each machine's open-circuit voltage had to be within 1% of the voltage setpoint to prevent excessive energy transfer between machines during a discharge. Since machine voltage is proportional to rotational speed and applied field strength, both parameters have to be tightly controlled. The two field coils in each machine are connected in series to assure that the same current is flowing through each coil. Rotational speed is controlled by a feedback control system which matches rotor speed to within 1 rpm. After reaching speed, the controller compares rotor speed and voltage to the selected values, and then initiates discharge if the values are within 1% of the setpoints.

HPG Instrumentation

Machine voltage is determined through the use of instrument brushes. These brushes are electrically and mechanically independent of the main brush assembly and, therefore, provide an accurate indication of the rotor voltage both prior to and during a discharge. In addition, each machine is equipped with four Hall probes which measure magnetic field strength in the air gap. These probes also provide an indication of the magnitude of reduction in magnetic field during a discharge (armature reaction). Rotor speed is obtained using digital pulse technology. A shaft-mounted toothed wheel and stator-mounted magnetic pick up generate a square wave proportional to rotor speed. This information is digitally stored and scaled to produce an accurate record of rotor speed transients.

Rogowski coil belts, calibrated with a 500 kA current viewing resistor, are used to measure discharge current. Each machine has a Rogowski belt located in the armature circuits' coaxial output and a

Rogowski belt located in the busbar risers measures total current for the six machines. Information from the Rogowski belts is collected and digitally stored in integrated form.

Mechanical instrumentation includes gauges and go/no-go logic on hydraulic and cooling systems. The rotor/shaft position is monitored with Bentley Nevada Series 7200 Proximimeters which are located in the radial and axial bearings. This monitoring system provides information on rotor/axial shaft position, shaft runout and machine vibration.

HPG Control System

The operating philosophy of this system allows for operator inputs to control the power supply energy level and the rate at which this energy is delivered to the load. The data acquisition system provides 1.5 megabytes of post-shot data. This information is archived, hard copied and available to the operator within three minutes after each discharge. In addition to providing hard copy of the experimental data, the data system will provide accurate computation of energy balance between mechanical energy delivered and electrical power consumed in the discharge.

To operate the power supply the operator need only provide input selection of the desired generators, speed, field current level and expected open circuit voltage. Table 2 below shows the allowable operating ranges of these parameters. The generator open circuit voltage characteristics are shown in the graph of Figure 4 below. Note magnetic field saturation at field currents above 900 Adc. The generator voltages were measured at 1800 rpm at 10 s of field on time. Voltages for a given field level at speeds other than 1800 may be obtained by scaling the voltage values from this graph by the ratio of the desired speed to 1800.

Table 2. BHPG Operator Input Ranges

Rotor Speed (rpm)	0 to 6050
Field Current (A)	0 to 900
Open Circuit Voltage (V)	0 to 100

BHPG INSTRUMENT BRUSH VOLTAGE AT 1800 RPM 10 SEC. FIELD ON TIME

Figure 4. Open circuit voltage at 1800 rpm

In response to these inputs, the appropriate number of generators and their auxiliary support systems are warmed up and brought to a ready status. At this point the "Motor-to-Speed" command is initiated, whereupon a fully automatic sequence is initiated which matches rotor speeds to within 5 rpm, energizes the field coils when the rotors match the setpoint speed, compares BHPG voltage to the selected value and energizes the main brushes if the voltage is within 1% of setpoint. After each discharge, a 3 minute cool-down is initiated to bring the generators and their auxiliary equipment to a ready-to-motor status.

The control and instrumentation system is enclosed in an EMI/RFI screen room. The screen room serves to protect the relatively low voltage control and data signals from interference due to the BHPG current pulse and the inherent background electrical interference present in a pulse power laboratory. The instrumentation shielding and screen room are continuously monitored for ground loops by means of a ground fault detection system. This system will sound an audible alarm if any point in the control, data system, experiment or screen room is connected to building ground. When an experiment is under way, the monitor is bypassed and a single point star ground is established. The method of star grounding has served to minimize noise injection in to instrumentation signal leads and maintain signal integrity.

The control system consists of nine microprocessor based Programmable Logic Controllers (PLC) and a CMOS based Critical Fault Controller (CFC). The CFC acts as supervisor of all life and machine safety faults. The "System Control" PLC allows for spare user inputs and outputs to accommodate future expansion and interface to the users experiment. This interface is either 120 Vac, 24 Vdc or 1-A dry relay contact.

The control system permits the generators to be operated in a variety of modes. To accommodate pulse shaping, the field current may be stepped through three values and periods of duration. The rotor flux time constant has been measured to be 1.5 s while the generator field current time constant is 0.5 s. Field stepping is accomplished through the use of "Field Stepping Timers" and "Percentage Field Setpoint" thumb-wheels. In addition to field stepping the voltage matching requirement mentioned above may be bypassed to allow for discharging multiple machines at different voltages. The control system will permit microsecond sequencing of switches or simultaneous switching of multiple switches.

Operating Experience

To date, operating experience with the BHPGPS has involved discharges into various types of resistive/inductive loads. Figures 5 through 8 illustrate discharge data associated with resistive, non-linear inductive, inductive and inductive switched into a 45-mm round bore railgun discharges, respectively.

Initial testing of the BHPGPS required that each generator produce the maximum current rating of 1.5 MA. A 56- μ R, 225-nH load resistor was designed to meet this requirement and to provide an overdamped RLC circuit to prevent the HPG from experiencing reverse rotation (ringing). In these tests, the low inductance of the circuit resulted in a fast current rise time which can be approximated by dividing the initial HPG voltage by the total circuit inductance. The armature brushes are used as the closing switch for the circuit. Discharge is initiated when one brush in each of the two brush sets is in contact with the rotor. To prevent over-current conditions, the rest of the brushes must come into contact before the

Figure 5. Typical discharge, $56 \mu\Omega$, 225 nH stainless steel load resistor

Figure 6. 4.3 MJ discharge into a non-linear inductor

current rises to a value exceeding the current rating of however many brushes are in contact at any point in time. For the current profile shown in Figure 5, a sufficient number of brushes were not in contact and several brush straps were bent.

The main brush actuators are designed to operate at 100 psig. Brush actuation time (the time required for the brush actuators to reach 90% of full pressure) has been measured to be 25 ms $\pm$ 5 ms. This short period ensures that all brushes are in contact with the rotor. Since the brushes are used to make the discharge circuit, particular attention must be paid to the current rise time. Current rise times below the design limit of 8 MA/s will prevent damage to the brush assemblies. (Note: operation at 11 MA/s has shown no adverse effects.) Consequently, switching with the brushes dictates a practical choice of load resistance and inductance. If rise times in excess of

Figure 7. 10 MJ discharge into a $100 \mu\Omega$ load resistor and a $6.5 \mu\text{H}$ inductor

Figure 8. 6.7 MJ, simultaneous discharge of HPG's 5 and 6 into a 45-mm railgun

8 MA/s are required, a separate closing switch should be incorporated.

To increase the circuit inductance a laminated steel core, non-linear inductor was designed and installed in the circuit. The effect of this modification was to slow the initial current rise while imposing no limitation upon the magnitude of the peak current. Figure 6 below is a 4.3-MJ discharge into the non-linear inductor.

The non-linear inductor was replaced by the 6.5- μ H, 9.8- μ Ω inductor. Figure 7 illustrates the discharge results of a full energy discharge into a 100- μ Ω generator test load resistor and 6.5 H inductor.

Current experimental loads are of the railgun type. To date, both staged and simultaneous discharges have been successfully completed. Figure 8 shows data from a 6.7-MJ, 1.4-MA simultaneous, explosively switched discharge into a 45-mm railgun of HPG's 5 & 6. The figure shows the pre-discharge, inductor charging, opening switch and railgun crowbar events. The 1.2-MA inductor/opening switch charging circuit has been determined to have a total circuit inductance of 9.85 μ H and 32.8 μ Ω . These circuit parameters govern the time-to-peak inductor charging current of 160 ms.

Acceptance testing of the BHPG's revealed several problems with the machines and auxiliaries. These problems were amplified by the fact that there are six machines and, therefore, six repairs per problem were required. A major decision early in the project concerned whether to build one machine and test it before building the remaining five machines or to build six machines in parallel. From a technical standpoint, the first option was the most attractive. From a time and funding standpoint, the second option, which was selected, appeared to be the most attractive. It took 14 months to fabricate the machines and 18 months to resolve problems and bring them on line. In retrospect, it may have been better to build one and then five, although there would have certainly been another whole set of difficulties. Regardless, the problems have been resolved, the machines are operational; and, cost and schedule for future systems will be predictable.

During initial mechanical tests of the machine, a bearing oil seal seized. The seal which was being used was a Bal Seal (TM) similar to ones used in the past at CEM and which, to the best of our ability, was properly installed. The seal is nominally kept from rotating in its housing by a spring. This did not work; the seal spun in the housing which caused the housing to heat up, grow, and make contact with a rotating labyrinth seal. It is plausible that the seal spun in its housing because of high friction at the seal/runner slip surface. The runner had a 32-rms finish and was made of stainless steel, a poor choice of material for a slip surface. To repair the seal, a Bal Seal with a lip that can be mechanically clamped was installed. The runner was ground to a 20-rms finish and chrome plated. No further problems have been encountered. It took two months to remove, repair the seals and reinstall each of the six machines.

Unusual axial motion of the rotor and shaft was observed with the Bentley-Nevada Series 7200 proximeters during high speed tests. An axial shaft proximeter is located on the opposite end of the shaft from the thrust bearing to observe axial dynamic motion and axial shrinkage of the shaft as the rotor comes to speed and the interference pressure between the rotor and shaft is relieved. Above 5000 rpm, the rotor would move a few thousandths of an inch axially when the magnetic field was excited. It was also noted that the shaft was shrinking axially only 70% of the predicted value. After considerable discussion, reduced interference between the shaft and rotor was identified as the problem. The rotor and shaft were thermally assembled at the designed interference of 0.012 inches. After thermal assembly, the shaft was sprayed with ceramic to provide redundant, bearing-to-ground electrical insulation. Because the shaft is stainless steel and has a higher coefficient of thermal expansion than the steel rotor, the thermal input from the ceramic spraying operation caused the shaft

to grow faster than the rotor which subsequently relieved the interference pressure from the design of 30,000 psi down to 18,000 psi. At full speed, the rotor would have been dangerously close to coming loose as 15,000 psi is relieved due to centrifugal loading. To correct the problem, all ceramic spraying of the shaft had to be completed before thermal assembly with the rotor. It took six months to analyze and correct this problem.

Full-speed testing, from 4700 rpm up to 6050 rpm, once again produced unusual axial motion of the shaft. To date, one machine has been run to 4300 rpm, one to 4700 rpm and three to 6050 rpm. One machine is being held in reserve. On each of the machines tested, a different axial motion was observed. One machine went to full speed and performed exactly as predicted. On each of the other four machines which were tested, at some speed, the shaft would grow axially somewhere between 0.002 and 0.005 inches. Remember that the shafts are supposed to shrink axially as they are motored to speed. Calculations show that this phenomena is caused by the thermal assembly of high strength Nitronic shafts which were substituted during the previous rebuild. When the rotor and shaft are being thermally assembled, at some point the rotor first contacts the shaft. As the rotor, which is originally hot and has substantially more thermal inertia than the shaft, cools off, it shrinks. If the rotor grips the shaft on each end, as it would since the ends of the rotor will cool off first, subsequent axial shrinkage of the rotor puts the shaft in axial compression which builds strain energy. If the shaft were a low strength material, it would yield rather than store the energy. The mechanical compressive stress is a minimum of 50,000 psi and could be as high as 100,000 psi depending on where and how the rotor grabs the shaft. This results in an axial strain of approximately 0.017 inches. As the rotor is spun to speed, the interference pressure is relieved until the force from the strain energy is sufficient to overcome the retaining force from the remaining interference pressure and friction, and the strain energy is relieved as an axial increase in shaft length. Since the shaft does not grow uniformly, the release of strain energy also results in the shaft bending and subsequent rotor runout.

Two options were considered. One, the rotors could be run to 10% over design speed which would relieve the strain energy. After over speeding, the rotors and shaft would be reground straight and true. This option would put the machines at risk and, if all the strain energy (0.017 in.) were relieved at once, could result in a bearing or rotor failure. The other option was to attempt to thermally relieve the energy by chilling the shaft and heating the rotor to return the components to their original state and then actively control the thermal assembly to force the rotor to contact first in the center. With this technique the interference pressure was lowered to 2500 psi. This resulted in a net axial increase in length of 0.008 in. which was sufficient for safe operation at design speed. This exercise took approximately three months to analyze and resolve.

In addition to the problems encountered with the HPG proper, testing of the hydraulic motoring system proved that the HPG shaft-mounted hydraulic motors (Volvo A4V) were not suitable for sustained operation at the system design operating pressure of 5600 psi. Stress failures of the radial piston assembly have forced the reduction of the operating pressure to 3800 psi which in turn increased the time required to reach full speed from two to three minutes. Subsequent operation of the motors at this pressure has shown no adverse effects.

The above mentioned mechanical setbacks have been reconciled; however, the control system uninterruptable power supply (Excide 2000) has presented ongoing service problems. To date, the UPS has been incapable of carrying control and computer type loads. Repeated failures in the inverter output section have forced CEM-UT to consider replacement of the existing UPS with an alternate source (i.e., diesel generator, motor/generator set or another UPS from a different manufacturer).

Characterization of Power Supply Parameters

Figure 9 is a photograph of the BHPGPS. A piece wise lumped parameter circuit model has been determined for the BHPG proper, 1.2 MA inductor, opening switch, HPG paralleling turret and the interconnecting bus work. Figure 10 below illustrates the simplified circuit model and component values which make up the power supply. The component values have been determined through experimentation and agree favorably with theoretical predictions. Each generator rotor center line is located 54 in. below floor level. The output is brought to floor level via a parallel plate "bus riser" assembly which consists of two 24 x 2 in. copper bus bars. Each HPG and output bus riser models electrically as a capacitance in series with a $13.7 \mu\Omega$

Figure 9. Balcones homopolar generator power supply

Figure 10. BHPG/inductor/opening switch circuit model

resistance and a 432 nH inductance. The addition of a horizontal bus extension, explosive switch and 1.2 MA inductor make up the complete inductor charging circuit.

The charging performance of the BHPG/1.2 MA inductor circuit has been determined. Figure 11 illustrates HPG voltage and peak inductor current as a function of generator rpm for 900 Adc field excitation which corresponds to the minimum HPG effective capacitance of 2000 F. This figure can be used to determine the peak charging current and HPG voltage for a given rpm.

Figure 11. Voltage and current vs rpm - calculated

Removal of the circuit components shown in Figure 10 allows for the power supply to accommodate an alternative load to the 1.2 MA inductor. Figure 12 illustrates the effect of varying the values of R, L and C on time to peak current and peak current. For a given value of total circuit resistance and inductance, the values of C and HPG voltage (V_0) can be varied to achieve the desired circuit response. By fixing a value for "C" then calculating the value for gamma, the corresponding normalized values (i.e., points 1 and 2) given by the "Peak Current" and "Time to Peak" curves will yield the resultant values for peak current (I_{pk}) and time to peak (t_{pk}). [3]

Figure 12. Determining t_{pk} and I_{pk} given R, L, C and V_0

Conversely, Figure 13 can be used to determine the total circuit resistance and inductance given the capacitance, HPG voltage V_0 , I_{pk} and t_{pk} . Equation 1 below can be used to locate normalized value for use with the product curve.

Figure 13. Determining R and L given I_{pk} , t_{pk} , C and V_0

$$N_p = \frac{2 I_{pk} t_{pk}}{\pi V_0 C} \quad (1)$$

The corresponding product curve value (3) yields a value for gamma. Projection from this gamma up to either the "Peak Current" (4) or "Time to Peak" (5) curves will yield normalized values from which the value for L can be determined.

Conclusions

Until several years pass and the project can be reviewed in hindsight, the pros and cons of the many decisions involved with the BHPGPS will not be known. However, some conclusions can be made. For a laboratory system, where reliability, maintainability and flexibility are more important than energy and power density, the decision to use iron core, drum type HPG's, room-temperature, coaxial inductors and explosively actuated opening switches was correct.

Iron core, drum type HPG's have a low effective capacitance (2000 F) and, therefore, efficiently charge inductive loads. They have only two sets of brushes which are identical. Since brushes are the major maintenance item on an HPG and can be accessed without dismantling the machine, ease and cost of maintainability were satisfactorily addressed. Having six machines rather than one or twelve struck a good balance between versatility and cost. The ability to connect the machines in series or parallel and sequentially discharge them is an absolute must for a power supply which is being scheduled to power not only EM gun experiments but also resistive welding and inductive tokamak loads. By putting the machines in a pit with remote auxiliaries connected through a service tunnel and 50 T overhead lift capacity, excellent experimental access was realized. Working on the machines in the pit is difficult, but they can each be removed in less than a day. After commissioning is complete, based on CEM experience, routine maintenance should be minimal.

Although the decision to build six machines was correct from a technical standpoint, the difficulty in implementing the concept was underestimated. Achieving a control system which would allow safe machine operation with the operator having no particular knowledge of internal characteristics of the HPG's, auxiliaries or load required a complex controller and auxiliary package. Installing six machines with all of the valves, hoses and electrical hook-ups, then connecting to the controller and checking performance as well as fail-safe shutdown modes was a major undertaking. In addition, there was the "ignorance is bliss" factor. Because of the value and energy level of the power supply, these are the most heavily instrumented machines CEM-UT has ever built. As each new characteristic was discovered, such as the shaft shrinking as the rotor is spun up, time and money was spent understanding the phenomena. These factors were compounded by the contractual arrangement under which the machines were built. CEM-UT combined technology transfer with new machine development-- CEM-UT was responsible for conceptual design; PKD, Inc. was responsible for detail design, fabrication, installation and commissioning. Some oversights were made and communication was sometimes difficult. However, The University of Texas got the power supply on budget and PKD, Inc. is now well qualified in HPG technology so both groups achieved their objectives.

The only technical decision which we would clearly have changed and will, if possible, would be to install closing switches in the busbar risers as opposed to using the armature brushes as a closing switch. As was discussed in the text of this paper, closing switches will be required to drive resistive loads because of the fast current rise time and relatively slow brush actuation time. More generally, for a lab based system where the major maintenance is the armature brushes, combining switching duty with current transfer places too much demand on the brushes. The decision to use the brushes as a closing switch was based upon our success with the Compact HPG and is viable for a high energy density system.

Once again, the system is operational and available to the community. This paper documents component and power supply characteristics so that evaluations can be made by the community as to the future use of the system for powering specific loads.

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