The preliminary design of the battery power supply (BPS) was reported to the 6th IEEE Pulsed Power Conference [1]. In 1987, the final design was completed, assembled, and sequentially verified during approximately 1750 operational verification tests. These experiments consisted of single-string verifications at 1000 amperes to a system discharge of 21,500,000 amperes. Final system design is very similar to the preliminary design previously presented. System fabrication is complete and at the present time consists of 858, 16-battery series strings resulting in 13,728 operational batteries. The final switching design has evolved into several levels of redundancy at varying current levels. These include 36 pneumatic, 100,000 ampere switches that control 24, 16-battery strings in parallel. These switches are used for the primary make and break of system current to charge the inductor. There are also 18 pneumatic crowbar switches at the 24-string level that are used to short the inductor from the BPS prior to system opening. At the string level there are 2000 ampere DC conductors that are used as a secondary current break and to pre-set the BPS in the appropriate parallel/series configuration prior to a discharge sequence. Explosively driven opening and closing switches are also employed at the interface junction to any hypervelocity launcher test article. These switches allow the inductor to charge prior to hypervelocity firings, are then opened for the event, and then explosively closed again to allow the inductively stored energy remaining to be dissipated in the busswork and pneumatic crowbar circuits. Detailed descriptions and operations of these switching sequences are discussed further in the switching section along with descriptions and operational data of the final hardware tested. Control system philosophy, capability, and operation during the commissioning tests are also discussed in detail. A BPS system artist’s conception drawing is shown as the facility has been built, in Figure 1.

**ABSTRACT**

The BPS is a modular design that requires a wide range of operational flexibility due to the multiple point load conditions. The basic building block for the current output is the battery string, consisting of two trays of eight batteries, each connected either in parallel (120V) or series (240V). Each string is individually controlled via the engagement of string select contactors. These contactors have also successfully demonstrated the capability of interrupting the full string current, in the event of the primary switch failure. Twenty-four strings are routed to a pneumatic actuated butt-contact switch performing the make/break function. Defined as a "GANG," the total DC current can be as much as 100,000 amps. An arc tolerant contact of copper-Tungsten Elkonite was used in the design as a replaceable low cost insert since the opening arcs result in substantial ablation. Most of the inserts had a dozen cycles of between 40-85 thousand amps each and were still usable at the completion of the baselining/commissioning program. Six "GANGS" are merged into a discrete buss run to the load and is called a "MODULE." Six "MODULES" are installed with their respective busses configured in a field compensated manner, commoned just before the "load" located in the adjacent test-bay building. This results in 858 output current strings for a total available of 13,728 batteries.

Since the batteries are a near constant voltage source, the resultant current is determined by the net effective resistance in the circuit. Peak power is obtained only at a very narrow operating regime.

Although the peak power output for single batteries is approximately 1800 amps, short duration pulses (2-3 seconds) at current levels of 2200 amps per battery have been demonstrated without adverse impact.

At low total system output, the relatively few strings on line would result in excessive current per battery. This abstract is overcome by a stainless steel "limiting resistor" attached to each string and a contact to "bypass" the resistor when desired. The 5-second pulse design requirement has been demonstrated with a worst case of temperature rise of 70 degrees Celsius in these resistors; well below any thermal limitations.

The control system was designed with the capability to independently control 12 Modules of Strings. Implemented under this contract was a system control for 858 strings (6 modules). The approach selected was to use a distributed control system, which involves multiple Prolog System 2 controllers at each of the battery Modules and a master Prolog System 2 controller located in the HPG Facility screen room. A "simplified" block diagram for the incorporated concept is shown in Figure 2. Module controllers are used to...
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perform such tasks as "charging" and "diagnostics" independently of other controllers. Configuration of strings for a "discharge" sequence are also performed by the Module controllers. During a "discharge" sequence, the Module controllers are tied together and required to perform in concert with the Master controller.

The ability to ABORT any test sequence has also been incorporated to ensure a safe BPS system. During a "charging" or "discharging" operation, both voltage and current are continuously monitored in a multiplexed fashion from each string resulting in a simultaneous abort in an orderly sequence. The capability to "close" and "open" contacts and pneumatic switches at selected times has also been incorporated.

**BPS COMMISSIONING PROGRAM**

After the finalization of the BPS design, anenergetic commissioning test program was undertaken in parallel with the assembly of the six modules. This program was used to formulate assembly procedures, verify and finalize control system operation, verify system electrical integrity, and demonstrate the critical electrical and mechanical design parameters of the overall system. Although the above stated components/parameters of the system were under direct scrutiny during the commissioning program, they represent only a fraction of the overall system knowledge obtained.

**SCHEDULED SYNOPSIS**

During the seven months commissioning program, several types of experiments were conducted. Of these, the first to be completed on any assembled module involved control system diagnostic programs that measure the open circuit voltages of each string individually, in the series and parallel mode, and is then printed for the operator to review the status of the batteries. The next step involved discharging the battery strings one at a time at approximately 1000 amps through a diagnostic load for 0.1 to 1.0 seconds to again verify the operational status of each string to include the resistor bypass and string select controllers. After successful completion of these two diagnostic routines, system current discharges through one turn of the inductor began at the multiple string level, proceeded to the multiple gang level, and culminated in the multiple module level. Demonstrated current levels range from 1000 amps, in the diagnostic load experiments, to 2,150,000 amps conducted for three seconds in a full system discharge on 27 September 1988.

The following chart shows the commissioning experiments completed from 3 March to 27 September 1988. The experimental acronyms, dates, and demonstrated current levels are listed in numerical acronym order. These experiments are not necessarily in Julian order due to the assembly of modules in parallel with this experimental effort and the reverification of certain experiments.

**Figure 2. Simplified Control Diagram**

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The integration into a system really begins with the multiple "GANG" tests. Significant variances in the actuation times of the large pneumatic switches demanded an individual control program. Disparities of hundreds of milliseconds are compensated for by pre-discharge firing of the "GANG" switches, storing the delays in a matrix and compensating for these delays in the control system trigger signals during the actual shot. The real limit to simultaneous switch operation is the shot-to-shot repeatability of the pneumatic chain of events.

The mechanical jitter limit for any give "GANG" switch/crowbar is approximately a ± 10 ms window. System wide this results in about a 40 ms jitter from first to last switch. This difference is sufficient to excite transients particularly in the opening procedure when the storage inductor is charged and the source impedance changes. When the high current "by-pass" mode is used, these transients result in a notable current surge in the later "GANGS" to open, exacerbating arc ablation of those switches.

**MULTIPLE MODULE EXPERIMENTS**

When multiple modules are discharged increasing system output current to significant levels (1.0 to 2.0 Megaamperes), the prevalent electromagnetic fields and their associated forces are of concern. Additionally, the high current "by-pass" mode could only be attempted if three or more modules were on line to prevent a battery over current situation. An example of such a three module "by-pass" test is shown in Figure 3 where the simulation predicts a current profile up to 1.46 MA and Figure 4 showing the test data current profile up to 1.487 MA. Other tests demonstrated still more significant milestones including:

- (a) 130 MW of power produced for five seconds.
- (b) 2.15 MA through the single turn inductor.

**SYSTEM STATUS/FUTURE PLANS**

Presently an EMG switch/gun system as well as long conduction time explosives switches are being integrated into the BPS facility test bay. The intent is to perform EMG demonstration testing using the single turn inductor coil, while a new building is constructed to house the 4-turn storage inductor. This new building will contain the massive fields and forces associated with the 2.5 MA, 200 MJ capable storage inductor. In order to reach this power level with the increased resistance of a bus run, the BPS will be increased from its original six modules to ten containing a total of 22,880 batteries. The fact that the system performance obtained thus far exceeds initial design levels, allows the reduction from the originally anticipated 12 modules required to 10 modules for this application.

**REFERENCES**