STARTUP TESTS AND COMMISSIONING OF A 60 MJ PULSED POWER SUPPLY

Prepared by

J.M. Weldon and J.C. Wright
Parker Kinetic Designs, Inc

D.J. Hildenbrand and M.L. Spann
Center for Electromechanics

Presented at

The 1987 Pulsed Power Conference
Washington, D.C.

June 1987

Publication PN-145

Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
Bldg. 133, EME 1.100
Austin, TX 78758
512/471-4496

STARTUP AND TESTING OF THE DATA ACQUISITION SUBSYSTEM

By: Dennis Hildenbrand CEM-UT

(This paper was included as part of the PKD paper titled "Start-up and testing of the Balcones 60 MJ Power Supply")

The Balcones Power Supply is suited with a virtually stand alone data acquisition sub-system (DASS). In its present configuration it is capable of simultaneously monitoring and recording 128 instrumentation channels. The DASS hardware includes three Aeon, 32 channel simultaneous sampling data loggers, six Lecroy 3521A multichannel rotor speed scaling modules, one 24 channel high speed TRAC 1 data logger, two CAMAC 65 amp crates and two General Purpose Interface Bus (GPIB) crate controllers. The DASS is interfaced to a local micro-VAX work station which in turn interfaces a remote VAX 11/750 main frame computer via an ether-net coaxial cable.

The maximum data file size collected and stored for an experiment requiring all six generators is 1.2 mega bytes. A menu driven interactive progam has been developed to provide for data collection, scaling and transfer to remote tape archival storage. In addition an interactive graphing package has been developed for data retrieval and graphic output to the local control room CRT's or printer/ploter. Post experiment data access for local graphic display has reached an acceptable time frame due to the installation of a fiber optic data link between the local Vax work station (VAX station II) and the CAMAC crates. The data transfer rate has been benched marked at 500 kilobytes per seconds which allows for local graphic display within 180 seconds of data collection.

Start-up, testing and debugging of the DASS has been completed. All analog to digital data loggers, with thier respective data scaling software routines, were verified against calibrated input signals. Each recording channel was judged by its ability to accurately reproduce input signals from DC to thier maximum expected input frequencies ranging from two to 50 KHz. The numeric and graphic output compares favorably with the applied input signals. The measurement error in the recording of the data loggers is +/-1/4096 of reading.

In addition to the data loggers are the rotor speed scaling modules. In contrast to other methods of rotor speed recording the rotor speed scaling modules provide for accurate and convienient format of rpm versus time of the rotor speed transient during discharge. Other methods of speed recording include frequency to voltage conversion which is limited by the slew rate of the converter or direct signal sampling of the rotor speed pulse on digital storage format which is limited by the amount of memory available.

Rotor speed is instrumented via a magnetic probe which generates a square wave output in response to a shaft mounted steel gear tooth. The shaft mounted gear provides 30 pulses per generator revolution (speed pulse). As shown in figure 1 this speed pulse is input to the scaling module where it provides a register pointer advance.

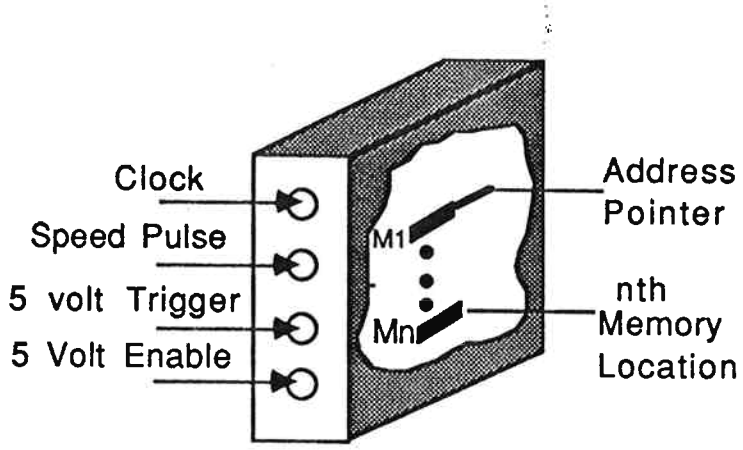

Figure 1
Rotor Speed Scaling Module

The current register pointed to will be loaded with the external clock rate (1 MHz) whereupon a subsequent speed pulse will advance the register pointer. Each register will contain the dwell time of the speed pulse (period). This process continues until the clock overflows the current register which occurs when the rotor is at or near zero speed. Upon data collection each register count is sequentially converted to rpm by the following software algorithm:

$$RPM = 2(\text{clock rate})/(\#\text{counts})$$

Each calculated (scaled) rpm value is associated to a point in time by adding all previous register counts prior to the rpm of interest. The total error in the recording is given by the square of the rpm reading divided by twice the clock rate. Variations in the pitch machining tolerance of the shaft mounted gear tooth are accounted for by performing a continuous rpm average for every three speed pulse periods. The result is a time resolved plot of the rotor rpm.

The rpm scaling module performance was verified by inputing a constant frequency 3 KHz and a frequency sweep from 3 KHz to zero in 10 milliseconds. The results of these tests are shown in figure 2.

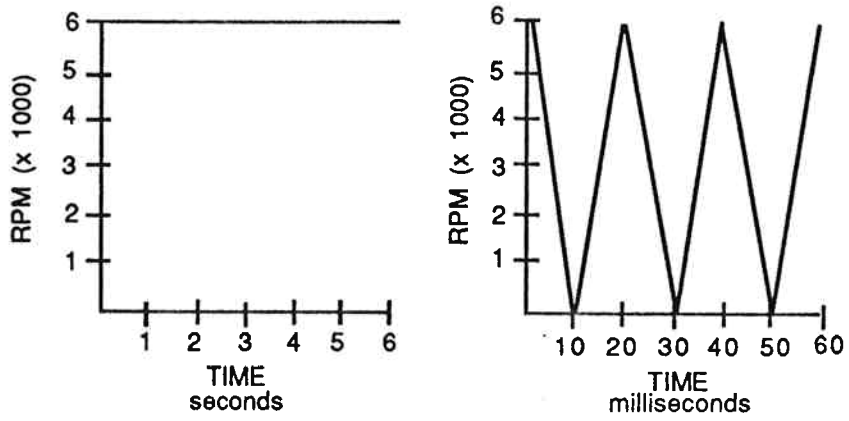

Figure 2
Frequency Response of Rotor Speed Scaling Module

The reliabilty of the data is confirmed through the use of energy balance analysis. As part of the DASS start-up, a computer program was coded to perform this analysis on each experiments' data. The program recalls from memory the parameters of discharge current (I), rotor voltage (V), rotor inertia (J), brush torque(T), rotor resistance (R) and rotor speed (ω). Energy balance equates the electromechanical energy of rotation to that of the electromagnetic conversion energy. The equation shown below expresses the relationship between the two quantities. The sumations are performed from t=0 just prior to the initial discharge current flow.

STARTUP TESTS AND COMMISSIONING OF A 60 MJ PULSED POWER SUPPLY

J.M. Weldon, J.C. Wright
Parker Kinetic Designs, Inc.
Box 27350
Austin, Texas 78755

D.J. Hildenbrand, M.L. Spann
Center for Electromechanics
University of Texas at Austin
10100 Burnet Road
Austin, Texas 78758

Abstract

Parker Kinetic Design, Inc. (PKD) has built and installed a 60 MJ pulsed power supply for the University of Texas' Center for Electromechanics (CEM-UT). This supply consists of six 10 MJ truncated-drum type homopolar generators (HPG's), an instrumentation and control system, and the auxiliary systems that support the HPG's. This paper discusses the startup testing and commissioning of the HPG's in this system, the test and calibration of the instrumentation, and the tuning of the control and auxiliary systems.

Introduction

The HPG's in the 60 MJ power supply can be run singly, in series, parallel, or in various series-parallel arrangements. This feature provides system versatility in providing power to a wide range of electrical loads. With the six HPG's connected in series, system peak current is rated at 1.5 MA and open circuit voltage at 600 V. With the HPG's arranged in a parallel circuit, the peak current rating is 9 MA and open circuit voltage at 100 V.

The control system consists of software-based programmable controllers to provide auxiliary system sequencing and related functions. It has a hard-wired critical fault controller which provides stand-alone control of all critical HPG functions. The critical fault controller employs CMOS electronics which supervise and control system response to all life and machine safety faults, control interlocks, and implementation of emergency control measures.

When the HPG's are in a parallel configuration, it is crucial that rotor speeds be matched in order to prevent circulating currents among the generators. This speed control is accomplished by an electrohydraulic speed control system (EHC) which monitors each HPG's actual speed and adjusts the hydraulic motoring system to keep the speed within a required tolerance. Field tests were carried out to prove the suitability and function of the design control logic as well as the speed matching capabilities of the motoring and EHC.

A computer automated data acquisition subsystem (DASS) is employed to collect data during operation of the 60 MJ system. The DASS stores performance data on a CEM computer so that it may be called up and analyzed at a later date.

The auxiliary systems for the 60 MJ power supply consist of mechanical and electrical subsystems that support the HPG's. These consists of a hydrostatic bearing oil supply, hydraulic motoring oil supply, field-coil power supply, field coil and compensating cooling system, HPG brush cooling system, and a brush actuation system.

HPG Pre-Discharge Testing and Results

Breakaway Torque

Tests were carried out to determine the mechanical resistance to rotation caused by the seals on the rotor shaft. After pressurizing the hydrostatic bearings, the torque required to turn the rotor was measured at both with no field excitation and with full field excitation. (see table I)

Table 1 BREAKAWAY TORQUE

	NO FIELD (lb-ft)	FULL FIELD (lb-ft)
HPG 1	.7	1.3
HPG 2	.7	1.4
HPG 3	.8	0.9
HPG 4	.7	1.0
HPG 5	.9	1.7
HPG 6	.8	2.0

Natural Frequency Response

To insure proper hydrostatic bearing performance and to verify the calculated design stiffness parameters of the HPG's, the radial and axial natural frequency of the generators was measured. Measurements were taken by exciting the HPG's rotor at its first harmonic frequency by impacting it in either the radial or axial direction and then recording its natural vibration using the outputs of the Bentley Nevada Proximity probes used during operation to monitor rotor motion. The results of the natural frequency response test versus calculated critical frequency are shown in Table II.

Table II
BALCONES 10 MJ
HPG NATURAL FREQUENCY

	CALCULATED (RPM)	MEASURED (RPM)	MAXIMUM OPERATIONAL (RPM)
AXIAL	7,124	8,000	6,050
RADIAL	11,566	14,400	6,050

Open-Circuit Voltage Tests

Tests were conducted to characterize the electrical performance of the machines. The initial tests measured the open-circuit voltage characteristics of the HPG's. Using the instrument brushes of the generator, the open-circuit voltage of each generator was measured at 1800 rpm and various field current levels. These tests were conducted at 1800 RPM rather than at the full rated generator speed of 6050 RPM due to the danger of operating a non discharge proven generator at high speeds in case of a possible emergency discharge. The results of these tests are shown in Figure 1.

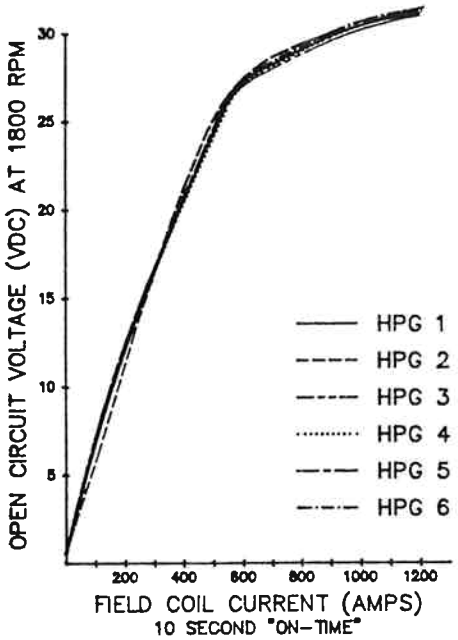

Fig. 1 OPEN CIRCUIT VOLTAGE

Using the curve derived from these data, it is possible to predict the open-circuit voltage of each generator at various rotor speeds and various field current levels. Open-circuit voltage at speeds other than 1800 rpm can be calculated using the following formula.

V(N,If)=V(1800, If) x (N/1800)

where:V(n,If)= open-circuit voltage at rotor speed, n, and field current, If.

V(1800, If)= open-circuit voltage at 1800 rpm and selected field current.

from the graph.

N=selected rotor speed

Figure 2 shows the relationship between open-circuit voltage, the period of time the field coil is excited and the generator voltage is allowed to build before the voltage is measured, and the level of field current excitation. This figure shows that it take approximately 10 seconds for the field in the generator to penetrate the rotor, stator, and conductors and reach a near steady state value. Field building times in excess of 10 seconds show little gain, while a field building time of 5 seconds shows as much as a 15% decrease in the OCV at field coil current near the magnetic saturation point of the rotor and stator.

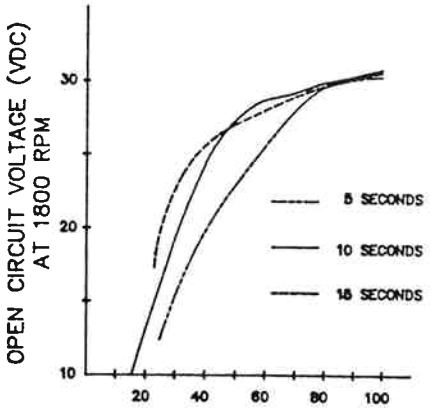

Fig. 2 RATE OF FIELD CHANGE

Electrohydraulic Speed Control System Tests

Startup testing and commissioning of the HPG and auxiliary control systems has been rather conventional, along the same lines as that for a typical industrial facility:

1) Individual field instrument calibration;
2) Individual checkout of each control and data acquisition loop;
3) Verification and modification of initial PLC and critical fault controls logic by actual operation of auxiliary and primary control loops for an individual generator, and;
4) Tuning of individual control loop by classic step response methods.

This was done for each of the six (6) generators and their auxiliary subsystem separately, with special attention above and beyond that normally paid to an industrial facility for:

1) Elimination of instrumentation and data acquisition ground loops which might contribute to data error and/or noisy data and control channels.
2) Precision tuning and elimination of drift and potential control error problems in the generators speed control circuitry by control scheme and circuitry modifications during the testing phase.

Each generator has been individually tested over portions of its speed and load (discharge range), with full load discharge testing and multiple generator speed matching tests currently in progress.

It is of interest to make the design methodology, tuning, and modification of the generator Electro-Hydraulic speed Control (EHC) to achieve the high speed and precession control necessary for this system apparent. When the HPG's are in a parallel configuration, it is crucial that rotor speed be matched in order to prevent circulating currents among the generators.(1) A design goal of 0.25% FS (+/- 18 RPM) over the entire speed range of the controllers (7500 RPM) was desired. This sort of accuracy and repeatability is well beyond the capabilities of normal analog PID control techniques when the necessary speed of response is considered.

A hybrid digital/analog control scheme was therefore applied to achieve both the high speed of response and actual setpoint precision. Digital speed sampling and a high speed, proportional-only, digital integrator (up-down counter) is used to compare actual speed to setpoint and output the next demanded pump stroke position to the high speed closed loop pump servo controller. This primary control scheme was

initially augmented only by an analog, instantaneous proportional gain stage and acceptable control results were obtained at higher speeds, but significant overshoot resulted at lower speeds (see Figure 3). This was primarily due to the natural (~20 sec.) time constant of the system with its long hydraulic line lengths of approximately 200 ft. between the pumps and drive motors. This overshoot problem for the lower speeds was corrected with the addition of analog derivative trim, resulting in the smooth and precisely repeatable control desired (see figure 4). Note the absence of overshoot on the speed trace and the absence of pressure undershoot and overshoot at speed match found on figure 3. Speed matching and discharge tests of multiple machines currently in progress also demonstrate that design goals for speed control have been achieved. (see figure 5).

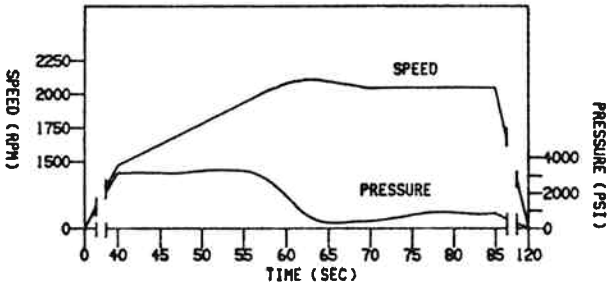

Fig. 3 ROTOR SPEED AND MOTORING PRESSURE (UNTUNED)

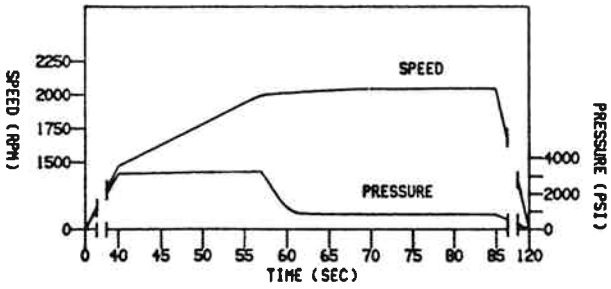

Fig. 4 ROTOR SPEED AND MOTORING PRESSURE (TUNED)

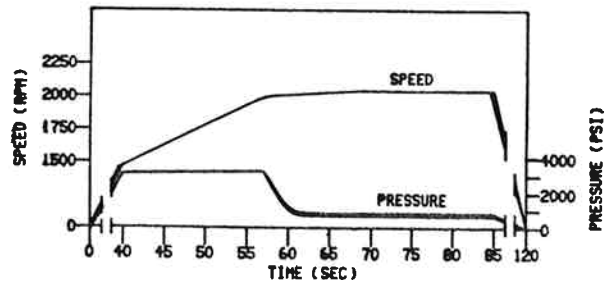

Fig. 5 DUAL GENERATOR SPEED MATCHING

Data Acquisition Subsystem

The Homopolar Generator is equipped with a stand alone data acquisition sub-system (DASS). In its present configuration it is capable of simultaneously monitoring and recording 128 instrumentation channels. The DASS hardware includes three Aeon 32 channel simultaneous sampling data loggers, six Lecroy 3521A multichannel rotor speed scaling modules, one 24 channel high speed TRAC 1 data logger, two CAMAC 65 amp crates and two General Purpose Interface Bus (GPIB) crate controllers. The DASS is interfaced to a local micro-VAX work station which in turn interfaces a remote VAX 11/750 mini computer via an ethernet coaxial cable.

The maximum data file size collected and stored for an experiment requiring all six generators is 1.2 mega bytes. A menu driven interactive program has been developed to provide for data collection, scaling and transfer to remote tape archival storage. In retrieval and graphic output to the local control room CRT's or printer/plotter. Post experiment data access for local graphic display has reached an acceptable time frame due to the installation of a fiber optic data link between the local Vax work station (VAX station II) and the CAMAC crates. The data transfer rate has been bench marked at 500 kilobytes per seconds which allows for local graphic display within 180 seconds of data collection.

Start-up, testing and debugging of the DASS has been completed. All analog to digital data loggers, with their respective data scaling software routines, were verified against calibrated input signals. Each recording channel was judged by its ability to accurately reproduce input signals from DC to the maximum expected input frequencies ranging from two to 50 KHz. The numeric and graphic output compares favorably with the applied input signals. The measurement error in the recording of the data loggers is +/-/4096 of reading.

In addition to the data loggers are the rotor speed scaling modules. In contrast to other methods of rotor speed recording the rotor speed scaling modules provide for accurate and convenient format of rpm versus time of the rotor speed transient during discharge. Other methods of speed recording include frequency to voltage conversion which is limited by the slew rate of the converter or direct signal sampling of the rotor speed pulse on digital storage format which is limited by the amount of memory available.

Rotor speed is instrumented via a magnetic probe which generates a square wave output in response to a shaft mounted steel gear tooth. The shaft mounted gear provides 30 pulses per generator revolution (speed pulse). This speed pulse is input to the scaling module where it provides a register pointer advance. The current register pointed to will be loaded with the external clock rate (1 MHz) whereupon a subsequent speed pulse will advance the register pointer. Each register will contain the dwell time of the speed pulse (period). This process continues until the clock overflows the current register which occurs when the rotor is at or near zero speed. Upon data collection each register count is sequentially converted to rpm by the following software algorithm:

$$RPM = 2(\text{clock rate})/(\#\text{counts})$$

Each calculated (scaled) rpm value is associated to a point in time by adding all previous register counts prior to the rpm of interest. The total error in the recording is given by the square of the rpm reading divided by twice the clock rate. Variations in the pitch machining tolerance of the shaft mounted gear tooth are accounted for by performing a continuous rpm average for every three speed pulse periods. The result is a time resolved plot of the rotor rpm.

The rpm scaling module performance was verified by inputting a constant frequency 3 KHz and a frequency sweep from 3 KHz to zero in 10 milliseconds.

The reliability of the data is confirmed through the use of energy balance analysis. The program recalls from memory the parameters of discharge current (I), rotor voltage (V), rotor inertia (J), brush torque (T), rotor resistance (R) and rotor speed (ω). Energy balance equates the electromechanical energy of rotation to that of the electromagnetic conversion energy. The equation shown below expresses the relationship between the two quantities. The summations are performed from t=0 just prior to the initial discharge current flow.

$$\frac{J\omega^2}{2} = \Sigma V I \Delta t + T\Sigma\omega\Delta t + R\Sigma I^2 \Delta t$$

Discharge Tests and Results

Each HPG was discharged in to test loads from a variety of speeds, ranging from 600 rpm up to 6000 rpm. These tests were conducted to verify the electrical and mechanical performance of the HPG's. The initial test load was a stainless steel resistor. The second test load was a coaxial, 2-turn copper inductor. Figures 6 and 7 present data from these tests which are ongoing. After completing this test regime, the HPG's will be tested in multiple-generator discharges. These tests will verify the capability of the system to discharge multiple generators simultaneously into a common load with both series and parallel circuit arrangements. The characteristics of the various loads are shown in Table III.

Table III
DISCHARGE CIRCUIT PARAMETERS

LOAD	CIRCUIT L (μH)	CIRCUIT R ($\mu\Omega$)
SS RESISTOR	1.043	68.7
2 TURN COPPER INDUCTOR	6.932	128.2

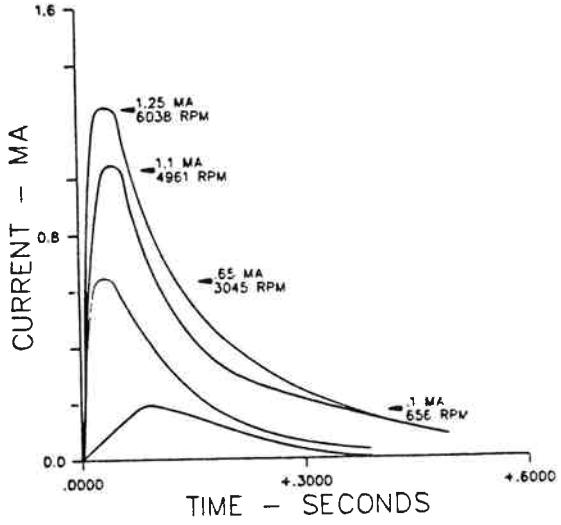

Figure 6 Current vs. Time for HPG 5 (stainless steel load)

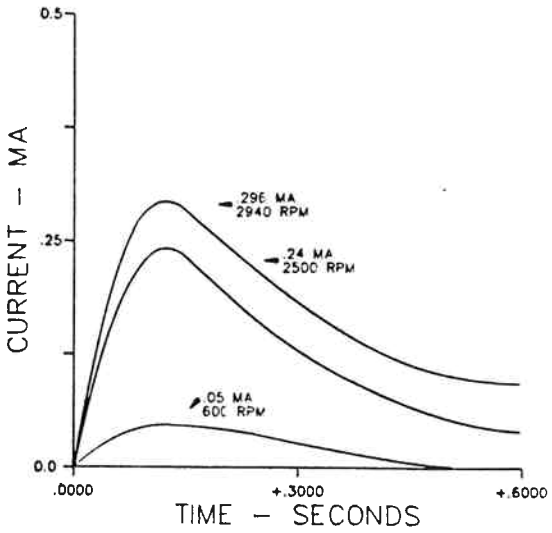

Figure 7 Current vs. Time for HPG 3 (two-turn inductor load)

Conclusions

The results of the tests that have been completed verify the performance of the HPG's, the control and data acquisition system, and the auxiliary systems. The open-circuit voltage and the HPG output current agree with the predicted values. Tests of the field coil power supplies demonstrated a capacity 30% greater than the HPG's will require at maximum performance. Testing to characterize the performance of the system with multiple-generator discharges is ongoing.

(1) D.J. Hildenbrand, M.A. Pichot, and J.H. Price, "Final Design of the Control and Auxiliary Systems for the Balcones 60-MJ Homopolar Pulsed Power Supply", Proc. Electromagnetic Launch Technology Symposium, 3rd, Austin, Texas., April 21-24, 1986

(2) W.L. Noble and J.M. Weldon, "Final Manufacture and Assembly of a Modular 60 Megajoule Pulsed Homopolar Power Supply", Proc. Electromagnetic Launch Technology Symposium, 3rd, Austin, Texas., April 21-24, 1986.

(3) W.F.Weldon, et. al., "The Design of a Pulsed Homopolar Generator Power Supply for a High Current Laboratory", Proc. IEEE Pulse Power Conf., 4th, Albuquerque, NM., June 6-8. 1983.

STARTUP AND TESTING OF THE DATA ACQUISITION SUBSYSTEM

By: Dennis Hildenbrand CEM-UT

(This paper was included as part of the PKD paper titled "Start-up and testing of the Balcones 60 MJ Power Supply")

The Balcones Power Supply is suited with a virtually stand alone data acquisition sub-system (DASS). In its present configuration it is capable of simultaneously monitoring and recording 128 instrumentation channels. The DASS hardware includes three Aeon, 32 channel simultaneous sampling data loggers, six Lecroy 3521A multichannel rotor speed scaling modules, one 24 channel high speed TRAC 1 data logger, two CAMAC 65 amp crates and two General Purpose Interface Bus (GPIB) crate controllers. The DASS is interfaced to a local micro-VAX work station which in turn interfaces a remote VAX 11/750 main frame computer via an ether-net coaxial cable.

The maximum data file size collected and stored for an experiment requiring all six generators is 1.2 mega bytes. A menu driven interactive progam has been developed to provide for data collection, scaling and transfer to remote tape archival storage. In addition an interactive graphing package has been developed for data retrieval and graphic output to the local control room CRT's or printer/ploter. Post experiment data access for local graphic display has reached an acceptable time frame due to the installation of a fiber optic data link between the local Vax work station (VAX station II) and the CAMAC crates. The data transfer rate has been benched marked at 500 kilobytes per seconds which allows for local graphic display within 180 seconds of data collection.

Start-up, testing and debugging of the DASS has been completed. All analog to digital data loggers, with thier respective data scaling software routines, were verified against calibrated input signals. Each recording channel was judged by its ability to accurately reproduce input signals from DC to thier maximum expected input frequencies ranging from two to 50 KHz. The numeric and graphic output compares favorably with the applied input signals. The measurement error in the recording of the data loggers is +/-1/4096 of reading.

In addition to the data loggers are the rotor speed scaling modules. In contrast to other methods of rotor speed recording the rotor speed scaling modules provide for accurate and convienient format of rpm versus time of the rotor speed transient during discharge. Other methods of speed recording include frequency to voltage conversion which is limited by the slew rate of the converter or direct signal sampling of the rotor speed pulse on digital storage format which is limited by the amount of memory available.

Rotor speed is instrumented via a magnetic probe which generates a square wave output in response to a shaft mounted steel gear tooth. The shaft mounted gear provides 30 pulses per generator revolution (speed pulse). As shown in figure 1 this speed pulse is input to the scaling module where it provides a register pointer advance.

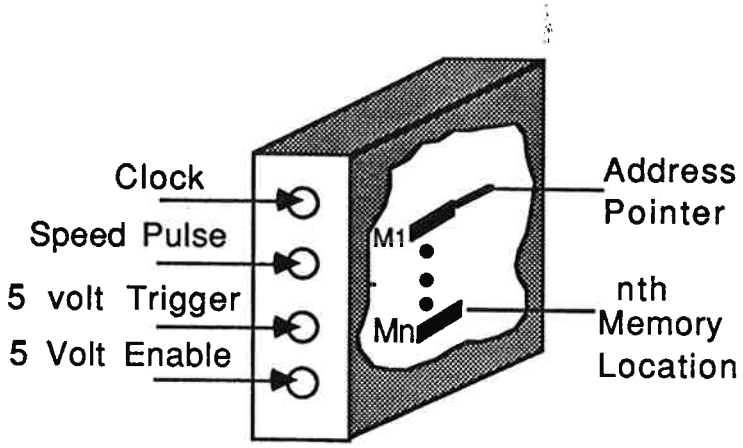

Figure 1
Rotor Speed Scaling Module

The current register pointed to will be loaded with the external clock rate (1 MHz) whereupon a subsequent speed pulse will advance the register pointer. Each register will contain the dwell time of the speed pulse (period). This process continues until the clock overflows the current register which occurs when the rotor is at or near zero speed. Upon data collection each register count is sequentially converted to rpm by the following software algorithm:

$$RPM = 2(\text{clock rate})/(\#\text{counts})$$

Each calculated (scaled) rpm value is associated to a point in time by adding all previous register counts prior to the rpm of interest. The total error in the recording is given by the square of the rpm reading divided by twice the clock rate. Variations in the pitch machining tolerance of the shaft mounted gear tooth are accounted for by performing a continuous rpm average for every three speed pulse periods. The result is a time resolved plot of the rotor rpm.

The rpm scaling module performance was verified by inputing a constant frequency 3 KHz and a frequency sweep from 3 KHz to zero in 10 milliseconds. The results of these tests are shown in figure 2.

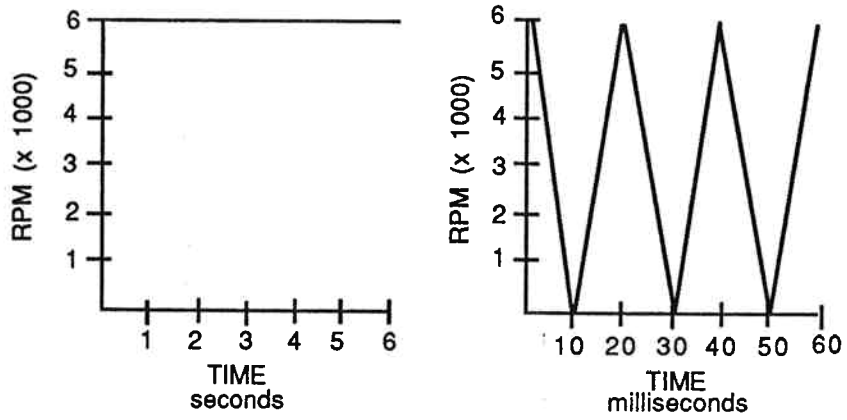

Figure 2
Frequency Response of Rotor Speed Scaling Module

The reliabilty of the data is confirmed through the use of energy balance analysis. As part of the DASS start-up, a computer program was coded to perform this analysis on each experiments' data. The program recalls from memory the parameters of discharge current (I), rotor voltage (V), rotor inertia (J), brush torque(T), rotor resistance (R) and rotor speed (ω). Energy balance equates the electromechanical energy of rotation to that of the electromagnetic conversion energy. The equation shown below expresses the relationship between the two quantities. The sumations are performed from t=0 just prior to the initial discharge current flow.

STARTUP TESTS AND COMMISSIONING OF A 60 MJ PULSED POWER SUPPLY

J.M. Weldon, J.C. Wright
Parker Kinetic Designs, Inc.
Box 27350
Austin, Texas 78755

D.J. Hildenbrand, M.L. Spann
Center for Electromechanics
University of Texas at Austin
10100 Burnet Road
Austin, Texas 78758

Abstract

Parker Kinetic Design, Inc. (PKD) has built and installed a 60 MJ pulsed power supply for the University of Texas' Center for Electromechanics (CEM-UT). This supply consists of six 10 MJ truncated-drum type homopolar generators (HPG's), an instrumentation and control system, and the auxiliary systems that support the HPG's. This paper discusses the startup testing and commissioning of the HPG's in this system, the test and calibration of the instrumentation, and the tuning of the control and auxiliary systems.

Introduction

The HPG's in the 60 MJ power supply can be run singly, in series, parallel, or in various series-parallel arrangements. This feature provides system versatility in providing power to a wide range of electrical loads. With the six HPG's connected in series, system peak current is rated at 1.5 MA and open circuit voltage at 600 V. With the HPG's arranged in a parallel circuit, the peak current rating is 9 MA and open circuit voltage at 100 V.

The control system consists of software-based programmable controllers to provide auxiliary system sequencing and related functions. It has a hard-wired critical fault controller which provides stand-alone control of all critical HPG functions. The critical fault controller employs CMOS electronics which supervise and control system response to all life and machine safety faults, control interlocks, and implementation of emergency control measures.

When the HPG's are in a parallel configuration, it is crucial that rotor speeds be matched in order to prevent circulating currents among the generators. This speed control is accomplished by an electrohydraulic speed control system (EHC) which monitors each HPG's actual speed and adjusts the hydraulic motoring system to keep the speed within a required tolerance. Field tests were carried out to prove the suitability and function of the design control logic as well as the speed matching capabilities of the motoring and EHC.

A computer automated data acquisition subsystem (DASS) is employed to collect data during operation of the 60 MJ system. The DASS stores performance data on a CEM computer so that it may be called up and analyzed at a later date.

The auxiliary systems for the 60 MJ power supply consist of mechanical and electrical subsystems that support the HPG's. These consists of a hydrostatic bearing oil supply, hydraulic motoring oil supply, field-coil power supply, field coil and compensating cooling system, HPG brush cooling system, and a brush actuation system.

HPG Pre-Discharge Testing and Results

Breakaway Torque

Tests were carried out to determine the mechanical resistance to rotation caused by the seals on the rotor shaft. After pressurizing the hydrostatic bearings, the torque required to turn the rotor was measured at both with no field excitation and with full field excitation. (see table I)

Table 1 BREAKAWAY TORQUE

	NO FIELD (lb-ft)	FULL FIELD (lb-ft)
HPG 1	.7	1.3
HPG 2	.7	1.4
HPG 3	.8	0.9
HPG 4	.7	1.0
HPG 5	.9	1.7
HPG 6	.8	2.0

Natural Frequency Response

To insure proper hydrostatic bearing performance and to verify the calculated design stiffness parameters of the HPG's, the radial and axial natural frequency of the generators was measured. Measurements were taken by exciting the HPG's rotor at its first harmonic frequency by impacting it in either the radial or axial direction and then recording its natural vibration using the outputs of the Bentley Nevada Proximity probes used during operation to monitor rotor motion. The results of the natural frequency response test versus calculated critical frequency are shown in Table II.

Table II
BALCONES 10 MJ
HPG NATURAL FREQUENCY

	CALCULATED (RPM)	MEASURED (RPM)	MAXIMUM OPERATIONAL (RPM)
AXIAL	7,124	8,000	6,050
RADIAL	11,566	14,400	6,050

Open-Circuit Voltage Tests

Tests were conducted to characterize the electrical performance of the machines. The initial tests measured the open-circuit voltage characteristics of the HPG's. Using the instrument brushes of the generator, the open-circuit voltage of each generator was measured at 1800 rpm and various field current levels. These tests were conducted at 1800 RPM rather than at the full rated generator speed of 6050 RPM due to the danger of operating a non discharge proven generator at high speeds in case of a possible emergency discharge. The results of these tests are shown in Figure 1.

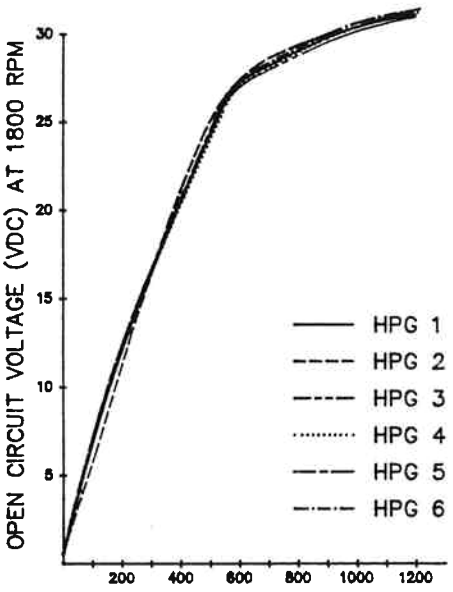

Fig. 1 OPEN CIRCUIT VOLTAGE

Using the curve derived from these data, it is possible to predict the open-circuit voltage of each generator at various rotor speeds and various field current levels. Open-circuit voltage at speeds other than 1800 rpm can be calculated using the following formula.

V(N,If)=V(1800, If) x (N/1800)

where:V(n,If)= open-circuit voltage at rotor speed, n, and field current, If.

V(1800, If)= open-circuit voltage at 1800 rpm and selected field current.

from the graph.

N=selected rotor speed

Figure 2 shows the relationship between open-circuit voltage, the period of time the field coil is excited and the generator voltage is allowed to build before the voltage is measured, and the level of field current excitation. This figure shows that it take approximately 10 seconds for the field in the generator to penetrate the rotor, stator, and conductors and reach a near steady state value. Field building times in excess of 10 seconds show little gain, while a field building time of 5 seconds shows as much as a 15% decrease in the OCV at field coil current near the magnetic saturation point of the rotor and stator.

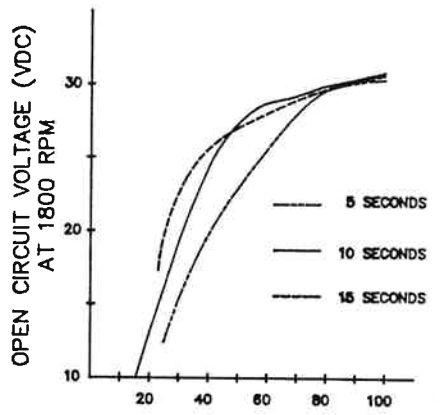

Fig. 2 RATE OF FIELD CHANGE

Electrohydraulic Speed Control System Tests

Startup testing and commissioning of the HPG and auxiliary control systems has been rather conventional, along the same lines as that for a typical industrial facility:

1) Individual field instrument calibration;
2) Individual checkout of each control and data acquisition loop;
3) Verification and modification of initial PLC and critical fault controls logic by actual operation of auxiliary and primary control loops for an individual generator, and;
4) Tuning of individual control loop by classic step response methods.

This was done for each of the six (6) generators and their auxiliary subsystem separately, with special attention above and beyond that normally paid to an industrial facility for:

1) Elimination of instrumentation and data acquisition ground loops which might contribute to data error and/or noisy data and control channels.
2) Precision tuning and elimination of drift and potential control error problems in the generators speed control circuitry by control scheme and circuitry modifications during the testing phase.

Each generator has been individually tested over portions of its speed and load (discharge range), with full load discharge testing and multiple generator speed matching tests currently in progress.

It is of interest to make the design methodology, tuning, and modification of the generator Electro-Hydraulic speed Control (EHC) to achieve the high speed and precession control necessary for this system apparent. When the HPG's are in a parallel configuration, it is crucial that rotor speed be matched in order to prevent circulating currents among the generators.(1) A design goal of 0.25% FS (+/- 18 RPM) over the entire speed range of the controllers (7500 RPM) was desired. This sort of accuracy and repeatability is well beyond the capabilities of normal analog PID control techniques when the necessary speed of response is considered.

A hybrid digital/analog control scheme was therefore applied to achieve both the high speed of response and actual setpoint precision. Digital speed sampling and a high speed, proportional-only, digital integrator (up-down counter) is used to compare actual speed to setpoint and output the next demanded pump stroke position to the high speed closed loop pump servo controller. This primary control scheme was

initially augmented only by an analog, instantaneous proportional gain stage and acceptable control results were obtained at higher speeds, but significant overshoot resulted at lower speeds (see Figure 3). This was primarily due to the natural (~20 sec.) time constant of the system with its long hydraulic line lengths of approximately 200 ft. between the pumps and drive motors. This overshoot problem for the lower speeds was corrected with the addition of analog derivative trim, resulting in the smooth and precisely repeatable control desired (see figure 4). Note the absence of overshoot on the speed trace and the absence of pressure undershoot and overshoot at speed match found on figure 3. Speed matching and discharge tests of multiple machines currently in progress also demonstrate that design goals for speed control have been achieved. (see figure 5).

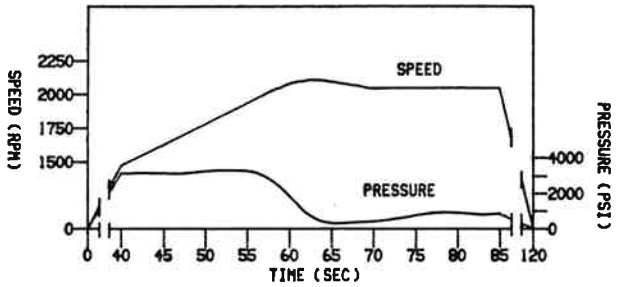

Fig. 3 ROTOR SPEED AND MOTORING PRESSURE (UNTUNED)

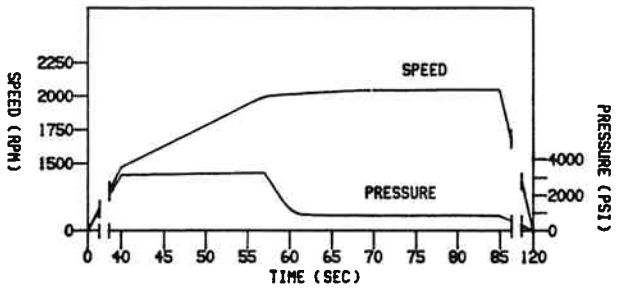

Fig. 4 ROTOR SPEED AND MOTORING PRESSURE (TUNED)

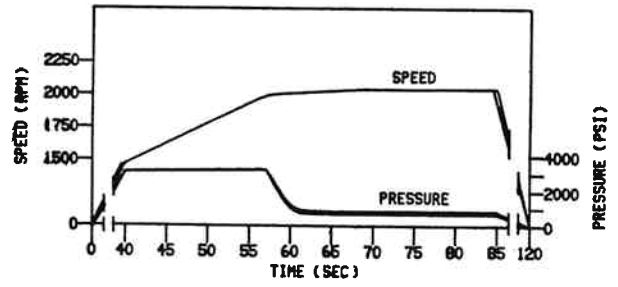

Fig. 5 DUAL GENERATOR SPEED MATCHING

Data Acquisition Subsystem

The Homopolar Generator is equipped with a stand alone data acquisition sub-system (DASS). In its present configuration it is capable of simultaneously monitoring and recording 128 instrumentation channels. The DASS hardware includes three Aeon 32 channel simultaneous sampling data loggers, six Lecroy 3521A multichannel rotor speed scaling modules, one 24 channel high speed TRAC 1 data logger, two CAMAC 65 amp crates and two General Purpose Interface Bus (GPIB) crate controllers. The DASS is interfaced to a local micro-VAX work station which in turn interfaces a remote VAX 11/750 mini computer via an ethernet coaxial cable.

The maximum data file size collected and stored for an experiment requiring all six generators is 1.2 mega bytes. A menu driven interactive program has been developed to provide for data collection, scaling and transfer to remote tape archival storage. In retrieval and graphic output to the local control room CRT's or printer/plotter. Post experiment data access for local graphic display has reached an acceptable time frame due to the installation of a fiber optic data link between the local Vax work station (VAX station II) and the CAMAC crates. The data transfer rate has been bench marked at 500 kilobytes per seconds which allows for local graphic display within 180 seconds of data collection.

Start-up, testing and debugging of the DASS has been completed. All analog to digital data loggers, with their respective data scaling software routines, were verified against calibrated input signals. Each recording channel was judged by its ability to accurately reproduce input signals from DC to the maximum expected input frequencies ranging from two to 50 KHz. The numeric and graphic output compares favorably with the applied input signals. The measurement error in the recording of the data loggers is +/-/4096 of reading.

In addition to the data loggers are the rotor speed scaling modules. In contrast to other methods of rotor speed recording the rotor speed scaling modules provide for accurate and convenient format of rpm versus time of the rotor speed transient during discharge. Other methods of speed recording include frequency to voltage conversion which is limited by the slew rate of the converter or direct signal sampling of the rotor speed pulse on digital storage format which is limited by the amount of memory available.

Rotor speed is instrumented via a magnetic probe which generates a square wave output in response to a shaft mounted steel gear tooth. The shaft mounted gear provides 30 pulses per generator revolution (speed pulse). This speed pulse is input to the scaling module where it provides a register pointer advance. The current register pointed to will be loaded with the external clock rate (1 MHz) whereupon a subsequent speed pulse will advance the register pointer. Each register will contain the dwell time of the speed pulse (period). This process continues until the clock overflows the current register which occurs when the rotor is at or near zero speed. Upon data collection each register count is sequentially converted to rpm by the following software algorithm:

$$RPM = 2(\text{clock rate})/(\#\text{counts})$$

Each calculated (scaled) rpm value is associated to a point in time by adding all previous register counts prior to the rpm of interest. The total error in the recording is given by the square of the rpm reading divided by twice the clock rate. Variations in the pitch machining tolerance of the shaft mounted gear tooth are accounted for by performing a continuous rpm average for every three speed pulse periods. The result is a time resolved plot of the rotor rpm.

The rpm scaling module performance was verified by inputting a constant frequency 3 KHz and a frequency sweep from 3 KHz to zero in 10 milliseconds.

The reliability of the data is confirmed through the use of energy balance analysis. The program recalls from memory the parameters of discharge current (I), rotor voltage (V), rotor inertia (J), brush torque (T), rotor resistance (R) and rotor speed (ω). Energy balance equates the electromechanical energy of rotation to that of the electromagnetic conversion energy. The equation shown below expresses the relationship between the two quantities. The summations are performed from t=0 just prior to the initial discharge current flow.

$$\frac{J\omega^2}{2} = \Sigma V I \Delta t + T\Sigma\omega\Delta t + R\Sigma I^2 \Delta t$$

Discharge Tests and Results

Each HPG was discharged in to test loads from a variety of speeds, ranging from 600 rpm up to 6000 rpm. These tests were conducted to verify the electrical and mechanical performance of the HPG's. The initial test load was a stainless steel resistor. The second test load was a coaxial, 2-turn copper inductor. Figures 6 and 7 present data from these tests which are ongoing. After completing this test regime, the HPG's will be tested in multiple-generator discharges. These tests will verify the capability of the system to discharge multiple generators simultaneously into a common load with both series and parallel circuit arrangements. The characteristics of the various loads are shown in Table III.

Table III
DISCHARGE CIRCUIT PARAMETERS

LOAD	CIRCUIT L (μH)	CIRCUIT R ($\mu\Omega$)
SS RESISTOR	1.043	68.7
2 TURN COPPER INDUCTOR	6.932	128.2

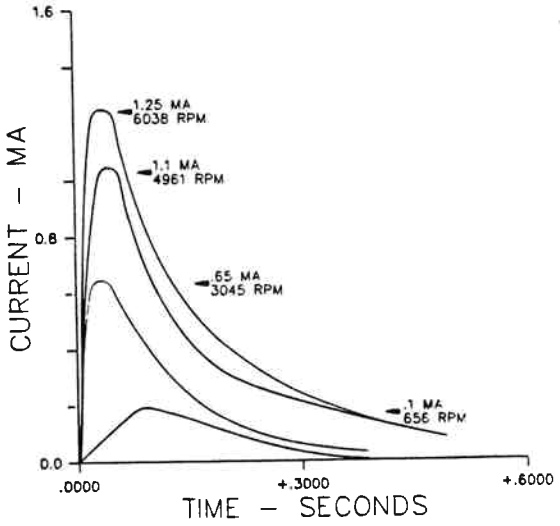

Figure 6 Current vs. Time for HPG 5 (stainless steel load)

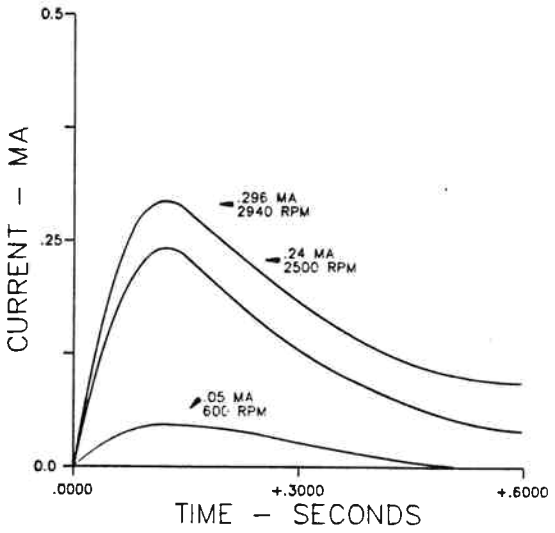

Figure 7 Current vs. Time for HPG 3 (two-turn inductor load)

Conclusions

The results of the tests that have been completed verify the performance of the HPG's, the control and data acquisition system, and the auxiliary systems. The open-circuit voltage and the HPG output current agree with the predicted values. Tests of the field coil power supplies demonstrated a capacity 30% greater than the HPG's will require at maximum performance. Testing to characterize the performance of the system with multiple-generator discharges is ongoing.

(1) D.J. Hildenbrand, M.A. Pichot, and J.H. Price, "Final Design of the Control and Auxiliary Systems for the Balcones 60-MJ Homopolar Pulsed Power Supply", Proc. Electromagnetic Launch Technology Symposium, 3rd, Austin, Texas., April 21-24, 1986

(2) W.L. Noble and J.M. Weldon, "Final Manufacture and Assembly of a Modular 60 Megajoule Pulsed Homopolar Power Supply", Proc. Electromagnetic Launch Technology Symposium, 3rd, Austin, Texas., April 21-24, 1986.

(3) W.F.Weldon, et. al., "The Design of a Pulsed Homopolar Generator Power Supply for a High Current Laboratory", Proc. IEEE Pulse Power Conf., 4th, Albuquerque, NM., June 6-8. 1983.