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**PRECISION CAPACITOR
CHARGING SWITCHING
POWER SUPPLIES**

Joe Jichetti, Andrew Bushnell, Robert McDowell

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Energy Products
SORRENTO ELECTRONICS
4949 GREENCRAIG LN, SAN DIEGO, CA 92123-1506
858.522.8400

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Joe Jichetti, Andrew Bushnell, Robert McDowell

General Atomics Energy Products

Sorrento Electronics

4949 Greencraig Lane

San Diego, CA 92123

Abstract

Industrial and government applications of pulsed power are driving pulse repetition rates into the kilohertz range and at the same time require precision charge voltage control. Pulsed power systems in these applications must be robust, rugged and compact. We have developed power supplies that, for example, charge capacitors at 2 kHz repetition rate and deliver pulse-to-pulse repeatability of $\pm 2V$ when charging to 2500V. Supplies of this type provide 20KW average power and above. These systems incorporate both external and internal fiber optic data and control links to provide a robust and noise immune power supply system. This paper describes one of these systems and discusses the issues of power supply and pulsed power interaction, power supply design and future trends.

I. INTRODUCTION

A standard, (non-precision), capacitor charging power supply, as shown in figure 1, will charge a load capacitor as shown in Figure 2. The voltage ramp-up on the capacitor is linear due to the constant current output of the power supply. This linear charging profile works well at repetition rates up to 1 kHz where pulse-to-pulse repeatability of $\pm 2\%$ can be achieved. Employing this type of power supply becomes less attractive at higher repetition rates, especially when pulse-to-pulse variation needs to be kept to a minimum.

In standard series resonant topology capacitor charging power supplies, at the end of charge, current is supplied to the capacitor load in discrete pulses. The pulse size is determined by the frequency and impedance of the resonant components and the inverter switching frequency. Reduction of pulse-to-pulse variability via increased switching frequency is limited by the availability of suitable semiconductor switching devices.

In large capacitor bank applications, with charge times of tens of seconds, standard supplies can achieve better than 0.5% pulse-to-pulse repeatability, and modified standard supplies, employing remote sensing, can achieve better than 0.1% pulse-to-pulse repeatability.



Figure 1. Conventional constant current power supplies manufactured by GAEP.

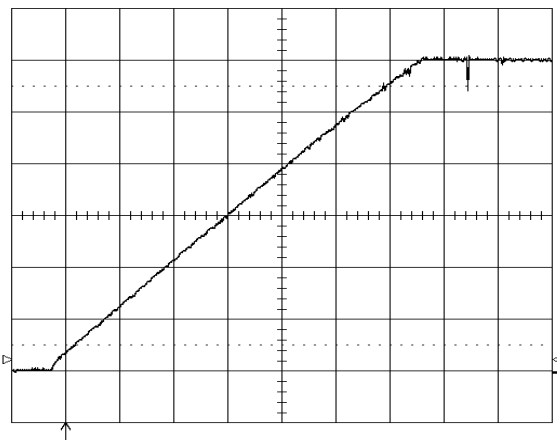


Figure 2. Standard constant current charging profile.

II. A DIFFERENT APPROACH

Recent pulsed power applications have seen a trend toward higher repetition rates and higher power requirements from their high voltage power supply vendors.

If the repetition rate is increased, with the power supply output power remaining the same, then the value of the load capacitor must be decreased. Conversely, if the capacitor remains the same value and the repetition rate is increased, then the power supply output power

must be increased. In both cases the pulse-to-pulse variation, as a percentage of the output voltage, will increase because the ratio of current pulse size to capacitor value increases.

To overcome this challenge, General Atomics Energy Products, (GAEP), has successfully employed a control scheme which permits large inverter peak currents during the beginning, (approximately 90%), of the charge cycle and then logarithmically reduces the size of the peak currents for the remaining 10% of the charge cycle.

This is represented by the waveform shown in Figure 3. This is the output waveform from a negative 3KV power supply charging a 1.13uF load capacitor at a repetition rate of 4kHz. Take note of the large rate of increase in voltage during the beginning stage of the charge cycle. Then note the transition to much smaller increases in voltage at the end of the charge cycle.

Although the peak currents in the inverter decrease logarithmically, you will notice this is not represented in the charging waveform near the end of charge. This is due to capacitance on the secondaries of the high voltage transformer. These capacitors need to be charged, as does the load capacitor. After these internal capacitors become charged, the remainder of the current, (very small), is passed on to the load capacitor in smaller and smaller current buckets. This allows for low pulse-to-pulse repeatability. The gradual decrease in the peak currents in the inverter allows the power supply to provide current to the load capacitor in successively smaller amounts instead of large increments.

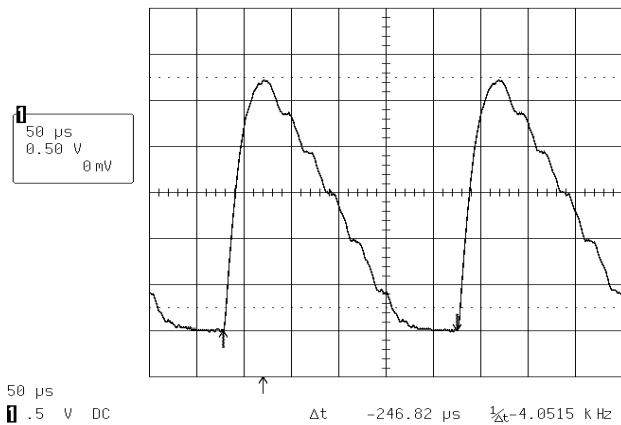


Figure 3. 4kHz Repetition rate.

This allows the power supply to approach the final voltage without overshoot.

A. Additional Output Power Requirements

Due to the time used up by the “plateau” near the end of charge, as seen in Figure 3, the initial section of the charging profile needs to provide a faster dv/dt to compensate for the slow charge at the end of the charging profile. Thus a higher peak power output is required.

There may be other reasons for additional output power. As is common in some applications in the pulsed power industry, such as in photolithography laser applications, there needs to be a substantial dead time after the discharge of the capacitor to allow time for the calculation of energy from the previous discharge pulse, (the amount of light energy directed at a semiconductor wafer). To achieve consistency from wafer to wafer, the energy is measured and the power supply voltage levels are adjusted on a pulse-to-pulse basis if needed.

In the waveform shown in Figure 3, there is a full 50us of dead time, (10us before the capacitor is discharged and 40us after the discharge), where the power supply output is inhibited. Add this 50us to approximately 50us from the plateau near the end of charge and the “effective” charging time drops from 250us down to 150us. Although the average power in this example is 20KW, the charge rate required during the initial portion of the charging cycle must now be increased to 33KJ/S.

B. Pulse-to-Pulse Repeatability

Even though there is an average power output of 20KW, a capacitor charging rate of 33KJ/S, a repetition rate of 4kHz and internal inverter peak currents of greater than 300A, the pulse-to-pulse repeatability for the power supply in this example is less than +/- 1%.

Figure 4 shows an expanded waveform at the end of the charging cycle. This waveform shows a peak-to-peak pulse-to-pulse repeatability measurement of 56V. Based on an output voltage of 3KV, this calculates to +/- .93% pulse-to-pulse repeatability. (Note: The original customer specification for pulse-to-pulse repeatability was +/- 2%, or a peak-to-peak span of 120V).

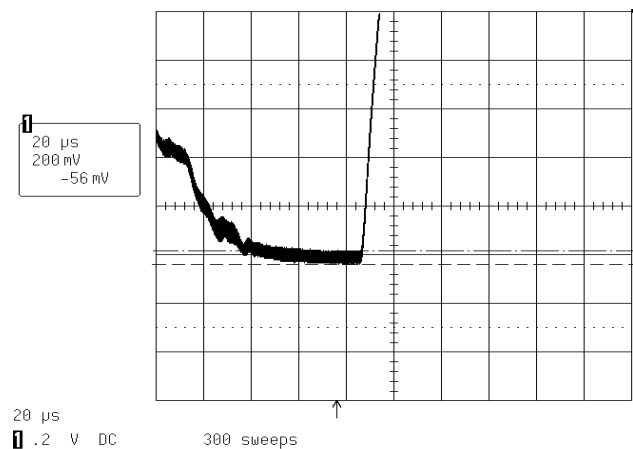


Figure 4. Pulse-to-pulse repeatability.

C. Noise Immunity

High voltage capacitor charging power supplies in pulsed power applications generally find themselves in noisy environments. The noise levels generated inside a modulator, pulser or laser cabinet can easily be transmitted into the control circuitry of the power supply

unless precautions are taken. Noise entering the power supply can cause many problems including improper output voltage level, premature shutdown of the power supply or unwanted triggering of the inverter drive signal. All of these effects can have a negative impact on the pulse-to-pulse repeatability of the power supply. These effects become exaggerated as the repetition rate and power levels increase or the size of the load capacitor decreases.

In the example being discussed, the decision was made to use both external and internal fiber optic data and control signal links. Because noise can enter on either an input or an output signal, fiber optic links were employed on both.

The programming fiber links, (for clock, sync and data), were used to feed digital signals to a D/A converter on the control board. Power supply Inhibit and HV Enable fiber optic links round out the remainder of the input signals. Interlock, Load Fault, (for both short circuit and over voltage), Over Temperature and End-of-Charge were the fiber optic output links.

There was a perceived risk in using fiber optic bulkhead feedthrough connectors on the rear panel of the power supply due to possible misalignment of the fiber optic fibers. Instead, a fiber optic repeater board was mounted to the rear panel of the power supply as an interface between the customer's cables and the control board. Connections between the repeater board and the control board were also made with fiber optic cables. This was to reduce, or eliminate, noise being generated inside the power supply from entering the control signals. This completed the noise immunity interface between the customer's links and the power supply's control circuitry.

D. Remote Sensing

One of the more important factors in achieving low rates of pulse-to-pulse repeatability is to sense the voltage at the load capacitor and provide this remotely sensed signal to the power supply as the feedback signal to the control circuitry.

In many pulsed power applications, the discharge of the capacitor creates a voltage reversal. This reversal can damage the diodes in the output section of the power supply if the magnitude of the reversal is high enough to cause excessive current flow in the diodes. To protect the power supply, an inductor is often placed between the power supply and the load capacitor. Although this inductor protects the power supply from a reversal, it also prevents the power supply's internal voltage sense circuitry from receiving a signal that can be used effectively to regulate the output voltage properly.

Figures 5 and 6 show the waveforms at the output of the power supply, (before the inductor), and at the load capacitor, respectively. If the power supply were to rely on internal voltage sensing, the control circuitry would be reacting to voltage excursions on the near side of the inductor, (see Figure 5), that would not represent the voltage on the capacitor (see Figure 6). These incorrect readings would prevent the power supply from effectively

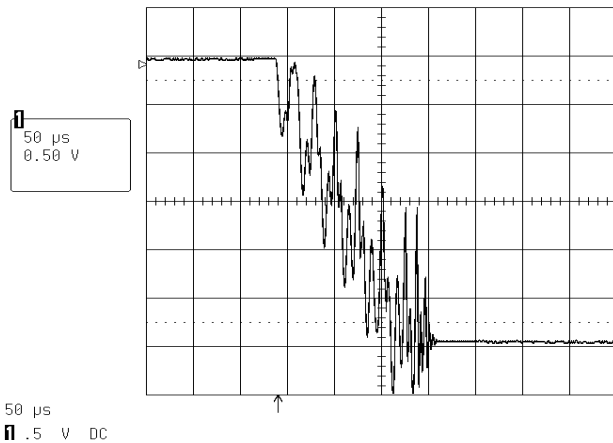


Figure 5. Voltage at power supply output.

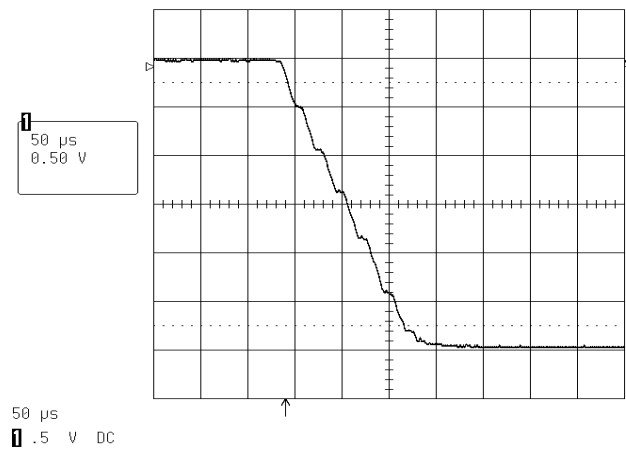


Figure 6. Voltage at capacitor.



Figure 7. North Star High Voltage Probe.

regulating the output voltage on the capacitor. The solution was remote sensing using a commercially available probe from North Star Research Corporation, Model PVM-10 and is shown in Figure 7.

E. Additional Features

The power supply discussed in this paper is pictured in Figure 8. In addition to the low pulse-to-pulse repeatability and fiber optic controls already discussed, the power supply is water-cooled and has full front panel controls, indicators and voltage and current metering.

Water-cooling was required in order to provide high power density and high reliability for continuous duty operation in an industrial environment.



Figure 8. 4kHz repetition-rate power supply.

III. CONCLUSION

If the past ten years are an indication of future trends, then the future will hold opportunities for manufacturers with the ability to provide pulsed power systems operating at both higher power and higher rep-rate frequencies. Challenges will be for the power supply manufacturers to work at these higher frequencies without sacrificing pulse-to-pulse repeatability, capacitor manufacturers to produce a robust product able to withstand these harsher operating conditions and the system integrators to be able to design pulsers that can reliably operate in this new environment.