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CUSTOM DESIGN OF COMPONENTS AND POWER SUPPLIES FOR PULSED POWER SYSTEMS

**J. B. Ennis, B. M. Song, A. H. Bushnell, R. A. Cooper,
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GENERAL ATOMICS
Energy Products
SORRENTO ELECTRONICS
4949 GREENCRAIG LN, SAN DIEGO, CA 92123-1506
858.522.8400
www.ga-esi.com

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General Atomics Energy Products
Sorrento Electronics, Inc.
4949 Greencraig Lane, San Diego, CA 92123
Email: joel.ennis@sorrento.com, www.gaep.com

Abstract:

This paper presents an overview of custom design requirements for components and power supplies used in pulsed power systems as well as some interesting examples. Various custom design criteria for energy storage capacitors, energy-absorbing resistors, high current fuses, and capacitor charging power supplies are described. In addition, specially designed components are characterized through both simulation and experimental measurements for pulse power system applications.

Index Terms: **Pulsed power system, energy storage capacitor, capacitor charging power supply (CCS).**

I. INTRODUCTION

Pulsed power systems cover a wide range of applications from medical cardiac defibrillators hanging on the office wall to nuclear weapons effects simulators in the national laboratories [1]. They often include custom-designed components such as energy storage capacitors, energy-absorbing resistors, high current fuses, and capacitor charging power supplies. The application-specific nature of the duty cycle, power and energy levels in such systems tend to drive the use of custom-engineered products.

Pulse discharge capacitors, designed for rapid delivery of stored energy and charge, usually are packaged in standard formats, but often require new combinations of dielectric and electrode materials and manufacturing techniques to achieve optimum performance in new applications [2-4]. In some cases, entirely new packaging designs are required to expand the performance envelope. In other cases, capacitor technology advancements allow for reduced size, weight, and cost in new designs.

Energy-absorbing resistors used to safely discharge large capacitor banks, and special fuses designed to carry nominal peak currents in the tens of kiloamperes, are generally customized for specific ratings without requiring new packaging or materials. In some special cases, however, new materials may be needed in order to reduce inductance or increase power density in these components as well.

High voltage power supplies used for capacitor or capacitor bank charging are often customized or modified for the specific application, due the wide range of loads and duty cycles encountered in the industry. In extreme cases, non-standard topologies must be employed to meet specific requirements for voltage, power, regulation, or other factors [6-8].

This paper will provide an overview of custom design requirements for components and power supplies used in pulsed power systems and some interesting examples.

II. CUSTOM DESIGN OF CAPACITORS FOR PULSED POWER APPLICATIONS

Most capacitors used in pulsed power applications are oil-filled, film and/or paper dielectric. Mica paper capacitors are used in military, space, and high temperature applications. Ceramic capacitors are often used in applications where the energy stored is small, such as triggering circuits. Electrolytic capacitors are used in lower voltage applications, such as the implanted cardiac defibrillator. In the following sections, the custom design of film capacitors for pulsed power applications is discussed in more detail.

A. Duty Cycle

The design of a custom capacitor begins with an understanding of the duty cycle. In many pulse power applications, the duty cycle is very low and is referred to as “single-shot”. Examples include medical defibrillators and large experimental physics machines at the national laboratories, where the capacitor may be charged and discharged about once a day. In these instances, the capacitor can be designed using higher loss, more polar dielectric materials, since self-heating can be ignored. In fact, cellulose paper dielectric is still widely used in such applications, and the very lossy ferroelectric polymer polyvinylidene fluoride (PVDF) has been used for portable medical defibrillator applications. The use of these higher permittivity materials allows the designer to make the capacitor smaller, lighter, and, in the case of paper dielectric, low cost.

Moderate duty cycles, often found in industrial and medical processes, require some attention to self-heating limitations, but somewhat lossy dielectric materials such as paper and polyethylene terephthalate (PET) polyester can be used. Often mixed dielectrics of paper and PET or paper and polypropylene are applied. Such laminations of different materials offer a number of advantages during manufacturing and also tend to be more robust than pure dielectrics under severe transient conditions in operation.

High pulse repetition rates, such as those found in particle accelerators, demand careful consideration of self-heating. Only the lowest loss materials are used, usually an all-polypropylene dielectric. Thermal path length is kept to a minimum, and aluminum foil electrodes serve as both electrical and thermal conductors [3]. Very high power densities can be achieved in film capacitors.

B. Lifetime

In pulsed power, capacitor life is usually measured in "shots" or charge/discharge cycles. The electric field in the dielectric, as well as the total voltage across the dielectric, determines the life through various processes of dielectric aging. Longer life capacitors will therefore have thicker dielectrics and be larger in physical volume and weight. The amount of time that the capacitor is dwelled at or near the charge voltage on each charging cycle can limit the number of shots, depending on whether dc or steady state degradation mechanisms, such as ionic conduction, dominate over processes that occur during the transient pulse discharge events.

Other factors also effect lifetime. Temperature is a well-known and key factor in all aging mechanisms, but is usually not a major issue in most pulse power systems. On the other hand, the rate of change of voltage and degree of voltage polarity reversal are especially important in pulse discharge applications, since partial discharges can occur between space charges in the dielectric and the electrodes, gradually eroding away the dielectric material.

C. Speed

The "speed" of the required discharge is an important factor in determining the design of pulse power capacitors. Fast discharge (~microsecond) capacitors must be designed for minimal parasitic series inductance and high peak currents, often hundreds of kiloamps per component [5]. Slower discharge (~millisecond) capacitors may utilize vapor-deposited metallization for electrodes, providing a self-healing capability. Much of the pulse power capacitor research and development taking place today is aimed at developing fast discharge self-healing capacitors in the 10-100 kV voltage range. The self-healing capability enables the capacitors to operate at higher energy density as well as have a graceful failure mode that contributes to system reliability.

Applications for such capacitors include electromagnetic armor and directed energy weapons. Small self-healing capacitors are widely used in commercial industry today, and many of these have high frequency capability. However, these are relatively low voltage, low energy density devices.

D. Voltage

The operating voltage of the capacitor has a significant impact on its design. High voltage capacitors, in the range of 10's of kilovolts to megavolts, are generally constructed using multiple capacitive elements connected in series. The individual element voltage is usually limited to 10 kV or less, due to electric field enhancement at foil electrode edges. The individual elements usually have dielectrics made up of 3-7 layers of material. Lower voltage capacitors may be made compact only if their dielectric is sufficiently thin, so only 1-2 layers of dielectric may be used. For the lowest voltage applications, films of metallized PET as thin as 0.5-0.8 micron are available. Electrolytic capacitors are also used for voltages less than about 1 kV when other conditions are met.

E. Design Examples

Figure 1 illustrates the extensive range of voltage and capacitance represented by the models in our company's computer database. These models include custom packages and mounting, multiple capacitors per unit, special markings, integration with other components, etc.

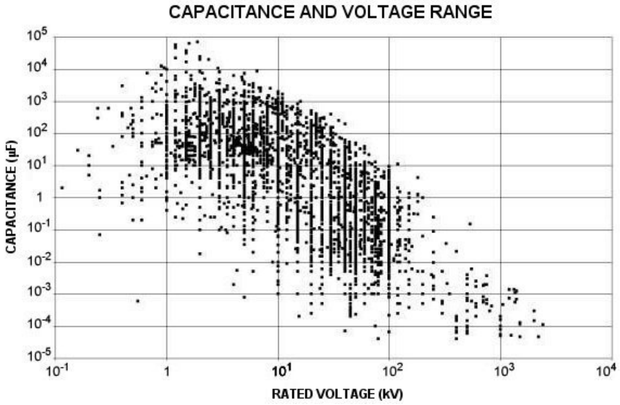

Figure 1. Extensive range of voltage and capacitance of customer capacitors.

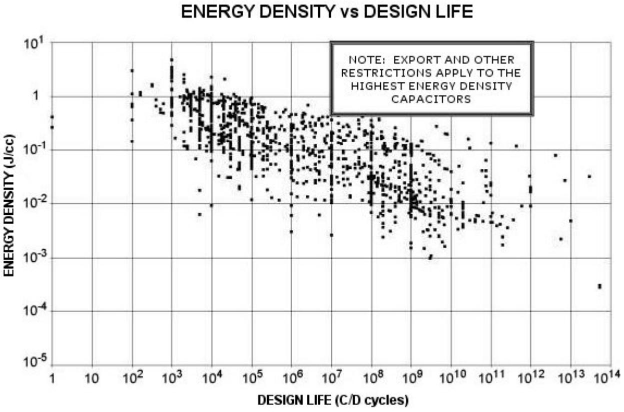

Figure 2. Energy density at rated voltage of the capacitor models.

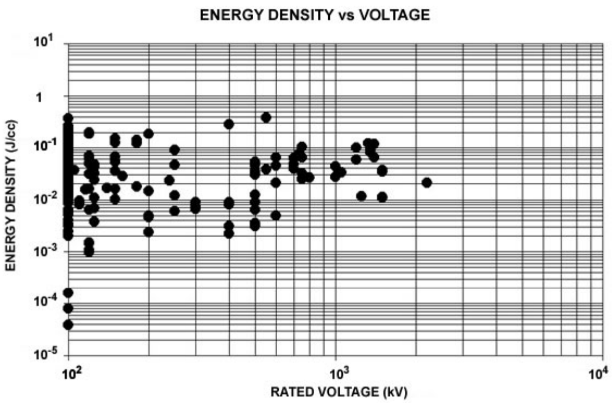

Figure 3. The energy density of 100 kV –2.2 MV rated capacitors.

Figure 2 illustrates the energy density at rated voltage of the models in our database. The highest energy density, high voltage capacitors typically have short lifetimes, are designed for military applications, and are export controlled. The lower the energy density, the longer the lifetime at rated voltage, and the greater the repetition rate capability.

Figure 3 shows the capacitance values ranging from microfarads at one hundred kilovolts to nanofarads at one megavolt have been designed and delivered to numerous customers.

General Atomics Energy Products (GAEP) Type PKR Megavolt Peaking Capacitors as shown in Figure 4 are typically used under oil for pulse shaping or peaking in large pulse power systems. Some of these machines simulate the EMP (Electromagnetic Pulse) or X-ray radiation or magnetohydrodynamic effects of nuclear explosions. The capacitors are manufactured using a large number of mixed-dielectric, foil-electrode windings connected in series, arranged so as to grade the voltage linearly along the axis of the capacitor.

Special attention is made to the materials used and their arrangement so as to avoid internal flashover. The capacitors are housed in plastic cases with axial terminals, and are thoroughly vacuum-dried and impregnated with an insulating liquid. The same unique technology has been used to manufacture corona-free high voltage capacitors rated in the 10’s to 100’s of kilovolts AC, as well as for long life DC filter and pulse discharge capacitors operating in the 100’s of kilovolts. Energy density depends on required lifetime, but is typically in the range 0.01 to 0.1 J/cc.

Figure 5 shows two photographs of custom high voltage capacitor packages; (a) Model 35405, a very low inductance design, rated at 0.005 µF- 50 kV is used in a pulse forming network driving a kicker magnet in an accelerator, and (b) Model 39273 which is rated at 4 x 15.6 µF- 8.0 kV and used in a Cable Fault Locator.

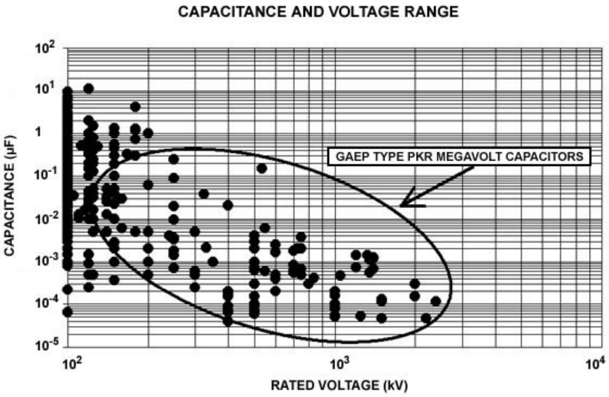

Figure 4. Capacitance and voltage ranges of very high voltage capacitors.

(a)Model 35405 capacitor 0.005 µF - 50 kV
for a Pulse Forming Network (PFN)

(b) Model 39273 contains 4 each 15.6 µF- 8.0 kV capacitors

Figure 5. Photographs of recent examples of custom high voltage capacitor packages.

III. DESIGN OF RESISTORS AND FUSES

This section describes energy-absorbing resistors and fuses widely used for safely discharge large capacitor banks, and special high current fuses. They are generally customized for specific ratings without requiring new packaging or materials.

A. Resistors

High energy-absorbing resistors consist of a metallic resistive element housed in a robust frame constructed of metal end terminals separated by insulating angle bracket side frames. Standard resistors come in several basic cross sections, with lengths from 6 to 48 inches. The frame is designed to provide support for the resistor element and dimensional stability to the entire assembly. For high current and low resistance (below 50 ohms) applications, the element is a continuous, wide, flat strip of metal that is covered with a special insulation tape and then folded, accordion style. For lower currents and high (above 50 ohms) resistance values, the element is a continuous, narrow metal ribbon, spiral wound around a flat insulator tape, which is also subsequently folded accordion style.

GAEP resistor elements are continuous metal winding with no welds or joints to cause electrical or mechanical failures. The open case, folded element design effectively dissipates heat and allows for the use of forced air or oil cooling under severe conditions. When cooled by air or liquid flow, these resistors can be used for average power dissipation which is beyond the capability of other conventional resistors. The materials used in the resistors have been carefully selected for their mechanical, electrical and thermal stability. The design of these resistors makes them suitable for many applications where other types of resistors fail to perform.

Customization of a resistor design involves selection of element alloy (for resistivity), element cross-section, element length and number of folds (to control turn-to-turn voltage gradient), and finished dimensions. In some cases, multiple resistors in parallel and/or series may be required.

Future development of this resistor design for lower inductance and more compact size will require higher resistivity metal alloys and high-temperature insulating tape materials and framework.

B. Fuses

Custom fuses are available for pulse power applications that generally have current ratings beyond the capability of standard commercial fuses. These fuses have metallic wire elements, fan-folded between insulating plates, and the entire assembly is filled with an insulating material that helps to quench the arc. GAEP standard fuse cartridges are 2 3/8 and 4 1/2 inch in diameter by 12 inches long (nominal) with threaded stud connectors on each end. The cases are fabricated from a composite material. Custom fuses rated at up to 150 kV have been supplied in 36-inch long tubes. Typical values of self-inductance for a 12-inch long fuse cartridge range from 150 to 250 nH.

Customization of a fuse design involves determining the length of the fuse cartridge based on the maximum voltage standoff required, and the diameter and number of wire elements in parallel to carry the maximum “normal” action (Amps^2-second or Joules/ohm). The number of parallel elements usually determines the diameter of the cartridge. In many cases, the normal action is high enough to require multiple fuses in parallel.

Future development of this fuse design to reduce size and inductance will require higher rated temperature insulators and internal framework (possibly inorganic), cartridges designed for greater flashover voltage per unit length, and possibly an improved filler material. A blown-fuse indicator would be a desirable modification to the design.

IV. DESIGN OF CAPACITOR CHARGING POWER SUPPLY

With advanced switching technologies, highly efficient soft-switching resonant topologies are widely used for various capacitor charging power supply (CCS) applications [7-8]; lasers, flashlamps, x-ray generators, impulse generators and many other applications. The CCS provides a charging current for a load capacitor, which may be the total capacitance in the pulse discharge circuit, or may be only a portion of a large bank of capacitors. The specification of the charging supply depends primarily on the voltage, capacitance, charging time, repetition rate or duty cycle, and available input power sources. In many instances, however, other considerations, such as pulse-to-pulse repeatability, accuracy, fault conditions, and so on, may influence the design of the supply.

In this section, the design of the CCS is discussed with regard to application parameters. The following provides a design guideline to how to specify a capacitor charging power supply. However, the choice of a main circuit topology is not included in this paper.

A. Power ratings

Power ratings start with a power supply for a specified load. In the case of a large bank of capacitors, the number of capacitors to be charged by a single supply may be first determined by the size of a bank module, which can store amount of energy to be used for the pulse power system. After determining the capacitance to be charged, the charging power is determined from the time rate of change of energy on the load capacitor during charging within the desired charge time. The peak power, expressed in Joules per second (J/s), is defined as the maximum power required to charge the capacitance, and will occur at maximum voltage in a constant current supply. The average power rating is also important, and is one-half the peak rating in a constant current supply.

Figure 6 illustrates a typical charging profile for a constant current power supply. The profile depicts the charge voltage as a function of time. The peak power P_{pk} occurs at maximum charging voltage V_O at end of charging time t_c. After t_c, the power supply has dwell time t_d, during which it may need to supply a small amount of charge to maintain the capacitor voltage, after which the capacitor is discharged. As shown, T is the time period per cycle, and t_D is the dead time during which the power supply output is inhibited.

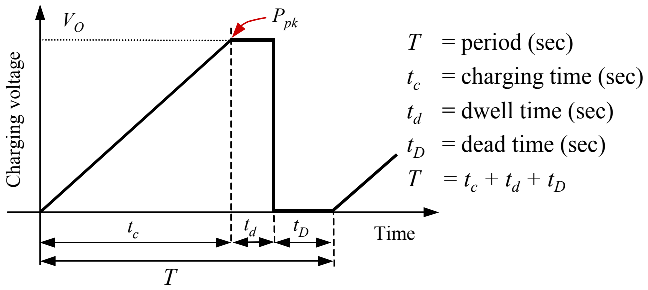

Figure 6. Typical capacitor charging profile.

Consider the case where the capacitor is charged to the maximum rated voltage. The charge time t_c can be calculated using the value of the load capacitor and its rated voltage. The charging time determines the average power rating:

$$P_{av} = \frac{\frac{1}{2} \cdot C_O \cdot V_O^2}{t_c} \qquad [\mathrm{s}] \qquad (1)$$

where, C_O is the capacitance of the load capacitor, and V_O is the maximum charge voltage. The peak power rating of the power supply P_{pk} is calculated based on the charging time of the load as:

$$P_{pk} = I_O \cdot V_O = 2 \cdot P_{av} = \frac{C_O \cdot V_O^2}{t_c} \ [\mathrm{W}] \qquad (2)$$

where, I_O is the output current at the maximum charge voltage.

B. Maximum repetition rate

The maximum repetition rate capability of a power supply depends on the energy to be stored in the capacitive load and the average power rating of the supply, according to

$$\text{Repetition rate} = \frac{2 \cdot P_{av}}{C_O \cdot V_O^2} \ [\mathrm{Hz}] \qquad (3)$$

As capacitance is reduced, however, other factors, such as pulse-to-pulse repeatability, may impose another limitation on maximum repetition rate. Recently, repetition rates of 2-8 kHz have been achieved with excellent repeatability in custom power supplies built by GAEP.

C. Output current

In the CCS, a constant output current is supplied to charge the load capacitor. The value of the current can be calculated from the average power and output voltage as:

$$I_O = \frac{2 \cdot P_{av}}{V_O} \qquad [\mathrm{A}] \qquad (4)$$

Since the output voltage is zero at the beginning stage of charging the capacitor, the derived power from the power supply is also zero. Approaching complete charge of the capacitor to full voltage, the instantaneous power is at its peak. Thus, when using constant current charging for repetitive pulses without dwell time, the peak power is twice the average power.

D. Other specifications

After defining the primary parameters mentioned above, the next step is to define the required voltage regulation, efficiency, power factor, external safety interlock, remote control, protections [6], connections, size, weight, etc. These parameters are generally determined by the load requirements and available input power source.

E. Example

A power supply was designed with 10 kJ/s-50kV for capacitor charging. Table 1 shows the design parameters of the power supply. Based on the design specifications, the performance of the CCS has been evaluated with experimental waveforms.

Table 1. Design parameters of a 10 kJ/s - 50kV CCS power supply

Parameters	Specifications
Input voltage	208 VAC, 3ϕ
Peak power	20 kW
Input efficiency	> 90% @full power
Output voltage	0 – 50 kV
Output current	0.4 A
Average output power	10 kJ/s
Charging capacitor	42.3 nF

Figure 7 shows the measured output voltage and inverter current waveforms of the power supply for 10kJ/s capacitor charging. During charging, the capacitor of 42.3 nF was charged and discharged at the repetition rate of approximately 180Hz and its peak output voltage was 50kV. At the end the charged current increased from 300A to 400A.

Figure 8 shows the resonant current and control signal waveforms of the power supply at the constant charging period. During constant charging, the resonant-tank frequency is fixed at 50kHz, and the peak resonant current is 400A, and the output current is inherently regulated.

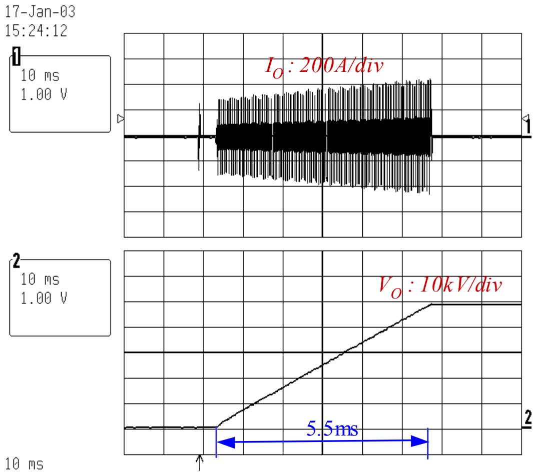

Figure 7. Capacitor charging current and voltage waveforms.

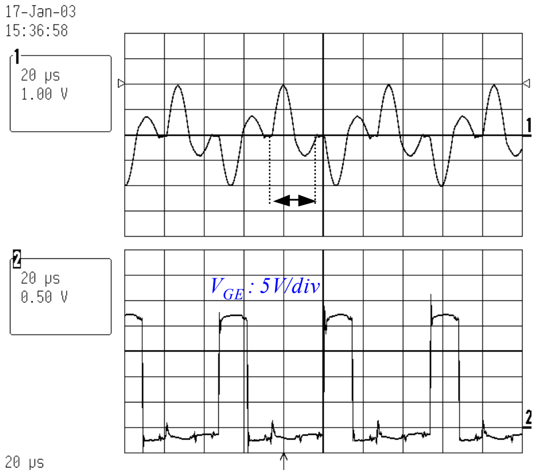

Figure 8. Resonant current and control signal waveforms of the power supply during charging.

V. CONCLUSION

This paper has described the custom design of energy storage capacitors, energy absorbing resistors, high current fuses, and capacitor charging power supplies for pulsed power applications. These components are specially designed and manufactured by GAEP based upon a well-established technology base and methodology for designing to custom requirements. Past designs have been characterized through various simulation tests as well as experimental results for the actual pulse power system applications.

On-going expansion of the technology base and improvement of the design methodologies used are continuously being driven by leading-edge applications.

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