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Improvement of Charging Resource in Repetitive Pulsed Power by High Power Density Capacitor

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ABSTRACT

Power modulators for compact, repetitive systems are continually faced with new requirements as the corresponding system objectives increase. Changes in pulse rate frequency or number of pulses significantly impact the design of the power conditioning system. In order to meet future power supply requirements, we have developed several high voltage (HV) capacitor charging power supplies (CCPS). This effort focuses on a volume of 6"x6"x14" and a weight of 25 lbs. The primary focus was to increase the effective capacitor charge rate, or power output, for the given size and weight. Although increased power output was the principal objective, efficiency and repeatability were also considered. A number of DC-DC converter topologies were compared to determine the optimal design. In order to push the limits of output power, numerous resonant converter parameters were examined. Comparisons of numerous topologies, HV transformers and rectifiers, and switching frequency ranges are presented. The impacts of the control system and integration requirements are also considered.

Index Terms— pulsed power, Iterative system, High power capacitors.

I. INTRODUCTION

The Directed Energy Technology Office (DETO) at the Naval Surface Warfare Center - Dahlgren Division is engaged in research and development efforts that encompass a broad spectrum of pulsed power technology. In many pulsed power systems of interest, high power density components are essential to enable the systems to fit within defined volumes. A key element of these compact pulsed power systems is the high voltage power supply that typically charges a capacitive storage element. Thus, a significant effort has been devoted to the design of suitable capacitor charging power supplies for these applications. Here, we describe some of this ongoing work and provide some of the important results that have been achieved to date. As pulsed power applications require increased repetition rates, the coffesponding power requirements of the power supplies must also increase. With inductive isolation of the capacitor bank, the pulse repetition frequency (PRF) is primarily limited by the charge rate of the power supplies. DETO has evaluated several CCPS options to determine their applicability for capacitor charging applications with loads varying from 200 nF to more than 4 uF.

While the specific ccps designs focus on charging a Compact Marx Generator (CMG) from a battery pack, the designs have application in a variety of pulsed power systems.

Our CCPS design goals include 50 kV output voltage from a 300-400 Vdc input voltage, peak power (or capacitor charge rate) output above 20 kW, efficiency above 85%, and a pulse to pulse repeatability below 5 %. All of the prototype CCPS were evaluated on a unique CMG test stand to enable an accurate comparison. A versatile control system and a common IGBT module and associated driver circuit allowed evaluation of numerous CCPS topologies in a short period. Some modeling and analytical calculations were attempted, but the majority of the effort focused on design evaluation under realistic configurations.

II. EXPERIMENTAL SETUP

A generalized CCPS consists of the control board, half or full bridge inverter, resonant circuit, HV rectifier and HV feedback as illustrated in Fiqure 1. Control requirements encompass providing gate drive signals, HV feedback monitoring, enable window, and program voltage comparison. An inverter board contains the IGBTs, gate drive circuits and the discrete portion of the resonant circuit. A HV tank houses the transformer, rectifier and voltage divider circuit for HV feedback.

The control system moves most of the functionality from the CCPS to the control software, increasing the control versatility and decreasing the required hardware. The majority of the required control signals involve modification or enabling of the gate drive. The desired output level is set with a program voltage that is compared against voltage divider feedback. The gate drive signals turn the IGBT pairs on for alternate cycles with a short dead time between switching cycles to prevent simultaneous conduction of the switches. An enable window provides a

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secondary level of output voltage limiting by allowing only a fixed operating period for the power supply, which also provides fault limitation. Modifications to the gate drive frequency or duty cycle adjust the CCPS charge rate. For this development effort, only variation in gate drive frequency was investigated. A HV feedback box transmits the signal back to the control software for program voltage comparison via fiber optics. Software additions could permit the controls to vary the switching frequency during the charge cycle to actively modify the charging profile. While the capability to change the frequency designs have application in a variety of pulsed power systems. has been investigated, no effort has been made to incorporate this feature into the control system.

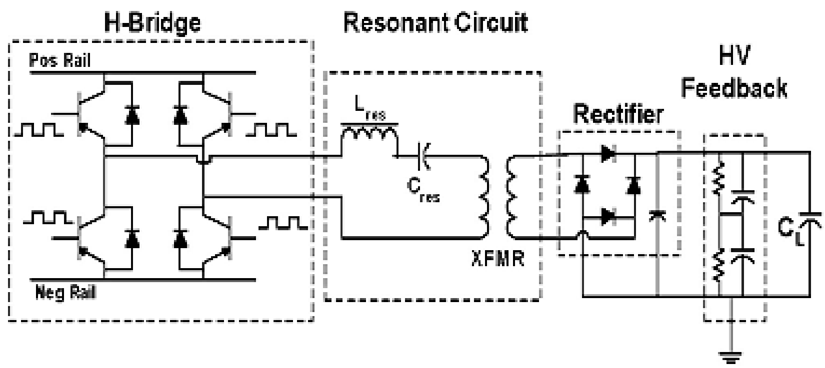

Fig. 1. Block diagram of CCPS.

The evaluation system is composed of a computer, control box, fiber optic interface, CCPS, and load capacitance. The control box connects to the gate drive boards on the CCPS via fiber optic cables, allowing a variety of connection geometries. A unique CCPS test stand provides the capacitive load for this evaluation. A 200 nF capacitor bank, a triggering circuit, and a high power resistive load allow for rep-rate assessment of the CCPS. While the CCPS described were not evaluated in rep-rate operation, the optimal design will be examined at rep-rate in future testing. Integrated diagnostics provide valuable information regarding charge rate and CCPS operation. Verification of the charging outside of the CCPS HV feedback is provided by a 100 kV HV probe. The test setup also provides for monitoring of the input power, gate drive signals, and switching voltage and current.

Two 20 kW AC-DC supplies or a battery pack provide the DC prime power for testing purposes. The AC-DC supplies are individually capable of 0-600 V, 0-33 A output, but the 33 A limit reduces the actual power available to 11.5 kW per supply at 350 V. These supplies have a 10 ms response time to a load change, severely impacting the voltage stability provided to the CCPS and affecting its performance. While the battery packs also exhibited some amount of voltage droop, this difference must be considered in the overall system design.

III. CCPS DEVELOPMENT PROCESS

Numerous application specific HPD CCPS are currently under development in our lab, although none meet all of the system requirements [1,2]. This development process began as a set of proof of principle experiments to determine the maximum peak charge rate obtainable for the 200 nF capacitive load. A progression of four CCPS were developed and evaluated, as described in Table 1. The initial design incorporated Power Ex IGBTs (PN CM200DU-NFH) and an existing control system with a new HV tank based upon a referenced design methodology [3,4,5,6]. The HV tank design process involved the transformer core selection, turns ratio calculation and discrete resonant circuit component selection for a peak charge rate requirement of 20 kJIs. The design was bounded by both the 70 kHz soft-switching limitation of the IGBT and by the volume limitations of the HV tank assembly. All of the prototypes examined were tested in an insulating container. The first prototype design consisted of a 115:1 five pie HV transformer, with a full bridge rectifier on each pie. A small U-U ferrite core with a ferrite window area to core area product (WaAc) of 28.5 cm4 was used for this device, shown in Figure 2. The series resonant circuit was composed of a 0.22 uF capacitance and a 38 uH inductance, leading to a resonant frequency of 45 kHz. For a switching frequency of 50 kHz with 325 Vdc input voltage, a peak charge rate of 8 kJ/s was obtained.

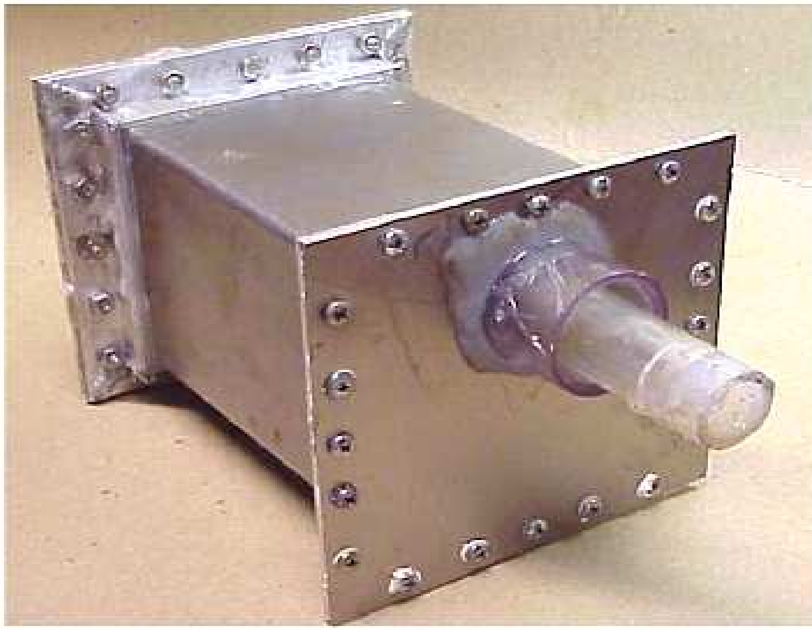

Fig.2.Prototype 5x5x7 CCPS HV tank

The second prototype design was constructed with a larger ferrite core from Magnetics, Inc. (PNOP49925UC). This HV transformer had a turns ratio of 160:1 on the new core with a WaAc of 168 cm^4. Four pies were used for this secondary, again with a full bridge per pie. The resonant frequency was increased to 58 kHz, maintaining the series resonant topology. This design produced a peak charge rate of 30 kJ/s at 39 kV output voltage from 350 Vdc with a switching frequency of 50kHz. This CCPS exhibited an efficiency of 68 %, with a peak input current draw of 175 A.

TABLE I
DEVELOPMENTAL POWER SUPPLY COMPARISON

V	WaAc	TurnsRatio	Pies	Rectifier	fres	PeakPout
1	28.5 cm^4	115:1	5	full-bridge	45 kHz	8 kJ/s
2	168 cm^4	160:1	4	full-bridge	58 kHz	30 kJ/s
3	168 cm^4	270:1	4	full-bridge	60 kHz	50 kJ/s
4	168 cm^4	35:1	5	volt. mult.	57kHz	N/A

IV. **RESULTS**

The two latest versions of the high-voltage circuit will be described in detail. Both versions were tested in a full bridge, series resonant CCPS configuration. The high voltage portion of the CCPS is mounted in an oil-filled tank and consists of the transformer, the rectifier/multiplier circuit, and a HV feedback circuit. The first version is based on a 270:1 transformer that is wound on a standard core (Magnetics Inc. PN OP49925UC), using ten primary turns and about 2700 secondary turns, equally distributed among four pie-shaped windings. The primary and secondary inductances are about 500 uH and 32 H, respectively. The stray primary inductance (with secondary shorted) is about 5 uH, creating a resonant frequency of 60 khz. The rectifier is fabricated from 5kv ,1A, 70 nsec diodes made by Voltage Multiplier Inc. (VMI PN 1N6517). Each leg of the rectifier consists of 28 individual diodes, resulting in a peak inverse voltage of 140 kV. This version does not use a multiplier circuit.

Fig. 3. Prototype CCPS HV tank including the 270:1 transformer, HV diode rectifier and HV feedback circuit.

In operation, the 270:1- transformer CCPS achieved a maximum charge rate of 50 kJ/sec when charging a 200 nF load to 40 kV. This result was achieved at a switching frequency of 60 kHz. However, the overall efficiency under these conditions was only about 36%. The efficiency improved to about 60% at a switching frequency of 50 kHz, but the charge rate decreased to about 14 kJ/sec. For low duty applications, it may be desirable to sacrifice efficiency for the much higher charge rate. Efficiencies near 7500 have been obtained at different output voltages and switching frequencies.

As depicted in Figure 5, the simulated and measured results for the 270:1 HV transformer design track closely at two different switching frequencies. In general, the modeling approach appears to accurately predict the CCPS performance. Figure 6 illustrates the input power requirements of this CCPS design. For 30 kV output voltages at 55 kHz switching frequency, a peak input power of more than 60 kW is required for the 27 kJ/s capacitor charge rate. This peak power draw corresponds to an input voltage droop from 350-310 Vdc and an almost constant input current draw of more than 200 A.

With only 40 °O efficiency at significant input power levels for this design, future CCPS will require increased efficiency objectives.

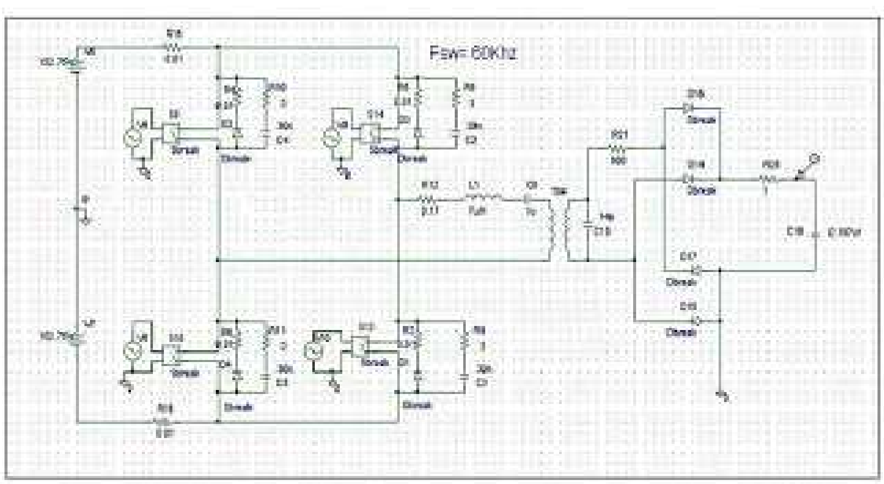

Fig. 4. Detailed circuit schematic of series resonant CCPS with 270:1 HV transformer.

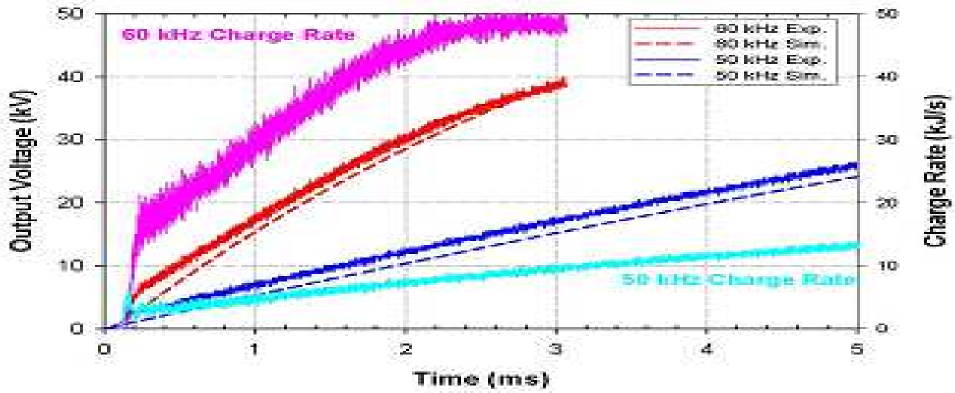

Fig. 5. Comparison of modeled and experimental data. Charge rate and output voltage for f,w of 50 & 60 kHz.

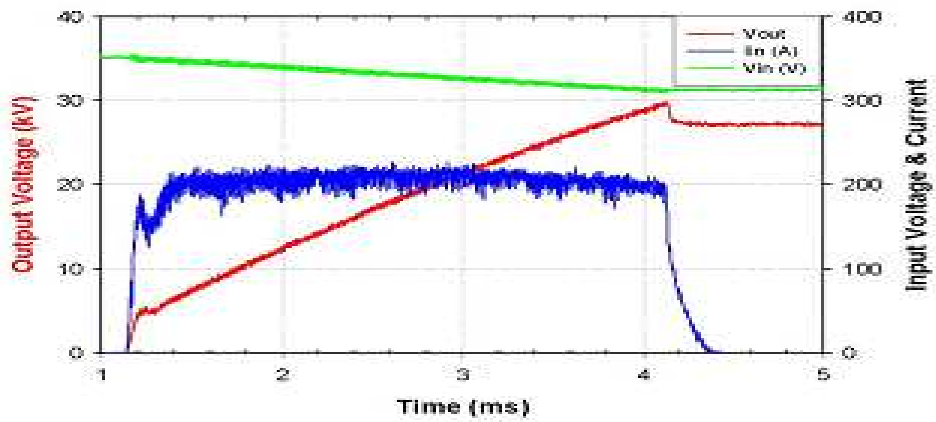

Fig.6. output voltage v. input power at 55 KHZ switching freguency.

One of the numerous CCPS topologies was utilized to examine the impact of the resonant circuit topology. The 270:1 transformer with a voltage multiplier circuit was configured both as a series and parallel resonant circuit with a half-bridge driver. While this configuration may not be the optimal design, the experiment results displayed in Figure 7 indicate the ability to achieve higher charge rates for a given resonant circuit with the series configuration.

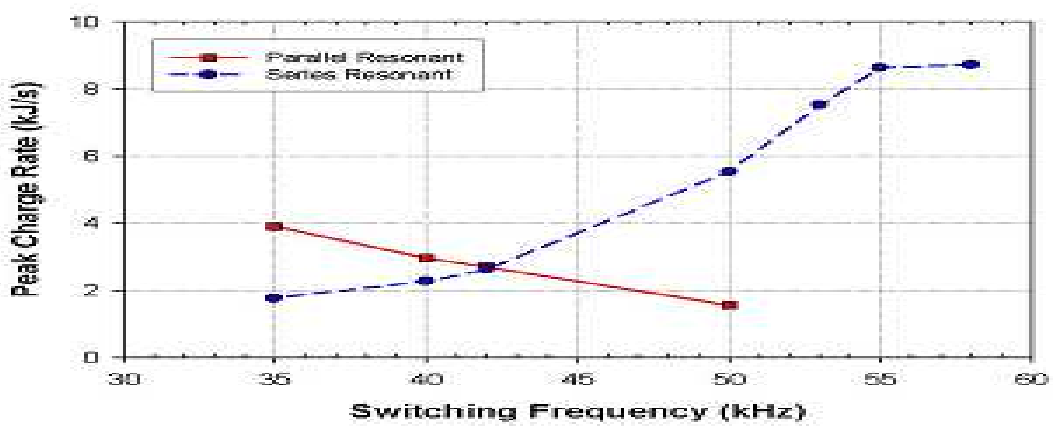

Fig. 7. Charge rate v. switching frequency for series and parallel resonant circuits.

The second version incorporates a 35:1 transformer wound on the same type of core with the same 10-turn primary. However, the secondary consists of five pie-shaped windings of 70 turns each. The smaller diameter pies allow stronger coupling and reduced stray inductance. With this transformer, the primary inductance is about 410 uH, the secondary is about 520 mH, and the stray primary inductance is about 3.2 uH. This version also incorporates a 4x multiplier circuit to provide the desired high-voltage output. As illustrated in Fig. 8, the multiplier consists of a combination of diode stacks, along with high-voltage capacitors. Although this version was originally designed to charge a higher capacity load, there are some intrinsic advantages of this topology that might also be preferable in general. The reduced primary stray inductance results in a lower charging inductance (defined as the series combination of the primary stray with the external inductance between the IGBT bridgeand the transformer). This allows operation at a higher resonance frequency. Additional potential advantages include increased impedance matching and corresponding efficiency, simplified construction, and the possibility for Litz wire secondary.

The 35:1 transformer CCPS has not been tested to the extent of the 270:1, but indications are that the efficiency is much higher (over 80%). With the same 200 nF load, the SPICE model predicts a charge rate of about 22 kJ/sec for this power supply version at an input voltage of 380 V and a switching frequency of 61 kHz. Initial testing with a 4.4 uF load indicates potential value of this design.

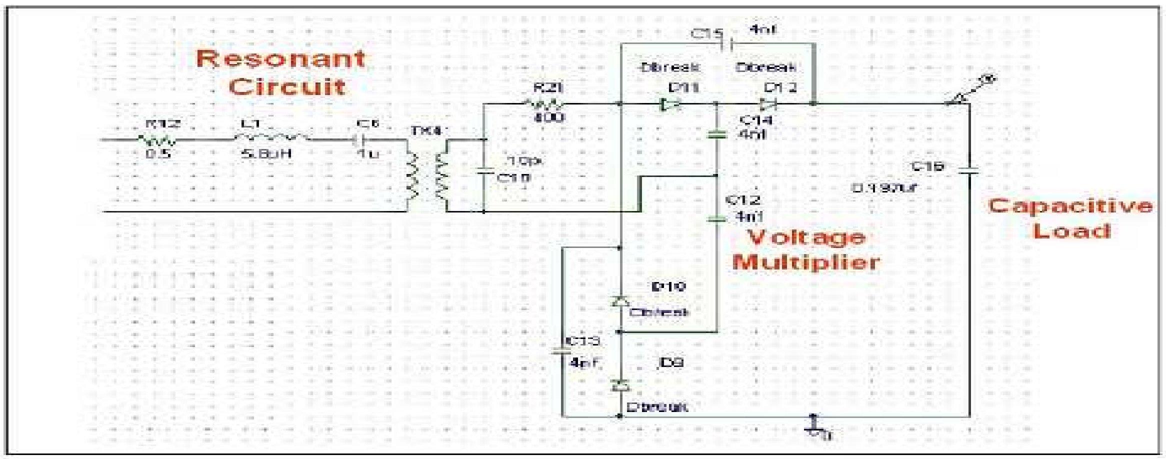

Fig. 8. Detailed circuit schematic of CCPS with 35:1 HV transformer and voltage multiplier.

V. SUMMARY

This development effort has produced four CCPS prototypes. Most of the power supplies examined utilized a series resonant topology with an IGBT full-bridge. The HV transformer and rectifier characteristics were both varied throughout the design process. While the primary focus of charge rate increase was exceeded by more than two times with 50 kJ/s peak obtained, improvements in CCPS efficiency require additional investigation. Verification of the observed performance in rep-rate operation and with increased load capacitance is necessary to ensure thermal issues do not develop. Future development plans include efforts to increase efficiency, testing with various capacitive loads, and packaging of the optimal design. Investigation of various resonant frequencies may also provide increased peak charge rate capabilities.

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