Prototype Test and Manufacture of a Modular 12.5 MJ Capacitive Pulsed Power Supply

H. F. Ding, C. X. Jiang, T. H. Ding, Y. Xu, L. Li, X. Z. Duan, Y. Pan, and F. Herlach

***Abstract*—A new Pulsed High Magnetic Field Facility (PHMFF) is under construction at the Huazhong University of Science and Technology (HUST) in Wuhan, China. In order to provide a wide spectrum range, a modular capacitive pulsed power supply is designed to energize 12.5 MJ at 25 kV and a large variety of coils are designed for magnetic fields in the 50–80 T with pulse duration 15–200 ms, respectively. In order to energize multi-coil systems, the 12.5 MJ power supply is divided into 11 independent 1 MJ modules with a short circuit current of 44.7 kA each and 2 independent 0.75 MJ modules for 61.2 kA each. Each module is provided with its own protection inductor, thyristor switch, crowbar circuit, dump circuit, polarity-changing circuit, charging unit and switchgear. The current pulses can be modified in shape, amplitude and duration by varying the charging voltage, the number of modules and the crowbar resistors. For verifying the design scheme and gaining experience in the construction and operation of pulsed power supply, a 1 MJ prototype that is used to energize pulsed magnets for 50–72 T fields with reversible polarity has been developed. In this paper, after the introduction of the system configuration with different module types and system settings, the design of both the 1 MJ and 0.75 MJ modules is described in detail. Finally, test results of the 1 MJ prototype are presented.**

***Index Terms*—Capacitor bank, high magnetic field, prototype, pulsed power.**

I. Introduction

A NEW Pulsed High Magnetic Field Facility is under construction at the Huazhong University of Science and Technology in Wuhan, China. According to the schedule, it can be partly used in 2010 and will be fully operational by the end of 2012. The goal of the PHMFF is to build pulsed magnets in the parameter range from 50 T, 34 mm, 200 ms to 80 T, 12 mm, 15 ms for maximum field, bore, and pulse duration respectively, as well as a quasi-continuous magnet of 50 T with a flat-top of 100 ms. These high field magnets have pulsed power requirements of a hundred to several thousands MVA, lasting for a few milliseconds to seconds. Such a power demand cannot be met by Wuhan's public utility system but must be provided from a pulsed power supply system. Capacitors are the most powerful of the pulsed power sources; they are very energy efficient and also relatively inexpensive [1]. Therefore, capacitors storing 12.5 MJ at 25 kV were selected as the power source to energize magnets of the PHMFF except for the quasi-continuous magnet, which is energized by a 100 MW 100 MJ flywheel pulse generator.

For scientific research under pulsed high magnetic fields, many different and flexible arrangements are needed. Therefore, a modular design concept for the capacitive power supply is adopted that enables the generation of different pulse shapes with continuously variable energy [2]. The 12.5 MJ power supply is divided into 11 independent 1 MJ modules and 2 independent 0.75 MJ modules. At present, all components including protection inductor, thyristor switch, crowbar circuit, dump circuit, polarity-changing circuit, charging unit and switchgear of the capacitive power supply are ordered. The work to build and integrate this power supply will be completed in the third quarter of 2010. Before we ordered the components of the capacitive power supply, a prototype of the 1 MJ capacitor module was developed and tested for verifying the design scheme and gaining experience in the construction and operation of power supply.

In this paper, the overall system configuration with different module types and possible combinations is reviewed in Section II. Section III describes the design scheme of both the 1 MJ and 0.75 MJ capacitor modules. The test results of the 1 MJ prototype and conclusions are included in Sections IV and V.

II. System Configuration

A number of magnets with different bore sizes, peak fields and pulse durations are under design and construction at PHMFF [3]. The pulsed magnets energized by the capacitor bank can be divided into three groups: short pulse magnets, long pulse magnets and dual stage pulsed magnets. All magnets are designed with the efficient pulsed magnet design package PMDS 2.2 [4], [5]. The magnets are designed for capacitances ranging from 3.2 mF to 32 mF, voltages ranging from 8.8 kV to 23 kV, peak currents ranging from 12.4 kA to 39.6 kA and voltage reversals of the capacitor bank ranging from 6.6% to 16.9% [6]. Based on the power supply requirements of the designed magnets and using the experience of the Dresden High Magnetic Field Laboratory for reference, the main features of the capacitive power supply design are as follows:

- Satisfying the needs of the designed magnets and future magnets, including positive as well as negative field pulses.
- Modular and compact, high flexibility, easy for future expansion, simple operation and maintenance.
- Good electromagnetic compatibility, efficient protection and security measures.
- Parallel operation of modules, local and remote control.

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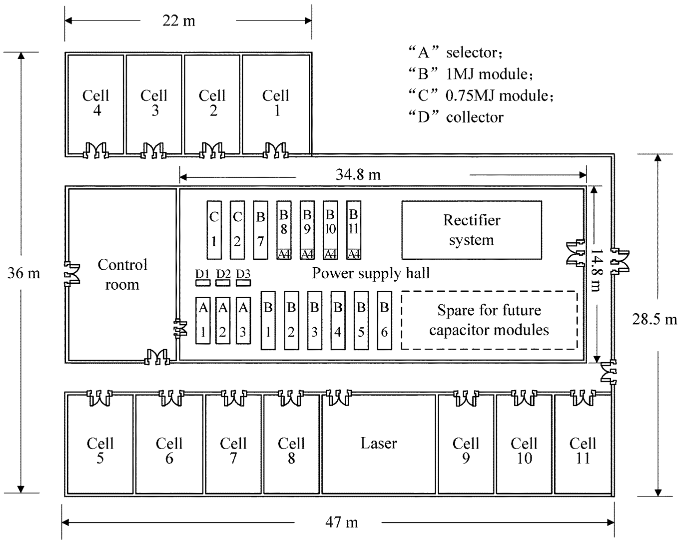

Fig. 1. Overall layout of the power supply hall and the measurement cells.

- Use of standard and proven technology, high reliability, long service life.

Fig. 1 shows the overall layout of the power supply hall and the measurement cells. The capacitor modules and rectifiers for the pulse generator will be installed in the power supply hall. The control center is adjacent to the power supply hall. Among 11 measurement cells surrounding the power supply hall and the control center, cell 1 is for the quasi-continuous magnet, cells 10 and 11 for superconducting magnets to provide static fields higher than 14 T, and the other cells for pulsed magnets.

As shown in Fig. 1, the capacitive power supply consists of 11 modules with a maximum energy content of each 1 MJ (3.2 mF, 25 kV, modules B1 to B11) and 2 modules with each 0.75 MJ (2.4 mF, 25 kV, modules C1 and C2). The total stored energy of the 13 modules is 12.5 MJ. There is a small difference between the layout of the capacitor bank and the initial layout that provided for eleven 1 MJ modules and two 0.5 MJ modules with 12 MJ total stored energy [6]. All modules are equipped with switches in order to connect (disconnect) them to (from) current collectors in the following way: modules B1 to B7 can be connected to collector D1, modules B8 to B11 alternatively to collector D1 or D2 via selector A4, and finally modules C1 and C2 to collector D3. The three collectors are connected to the measurement cells 2 to 9 through the selectors A1 to A3: the collector D1 which can provide a maximum energy of 11 MJ can be switched to the measurement cells 5 to 7; the collectors D2 and D3 with respective maximum energy of 4 MJ and 1.5 MJ can be switched to the measurement cells 2 to 9. In general, the collector D1 can be used to energize the short pulse magnets, the long pulse magnets and the outer coil of the multi-stage magnets, and the collector D3 to energize the short pulse magnets with short rise-time and the inner coils of the multi-stage magnets. The collector D2 is reserved for the middle coil of a three-stage magnet. There are three connectors in cells 5 to 7, two connectors in cells 2 to 4 as well as 8 and 9. Under this modular concept, we are able to energize coaxial multi-coil systems with up to three separate sub-coils.

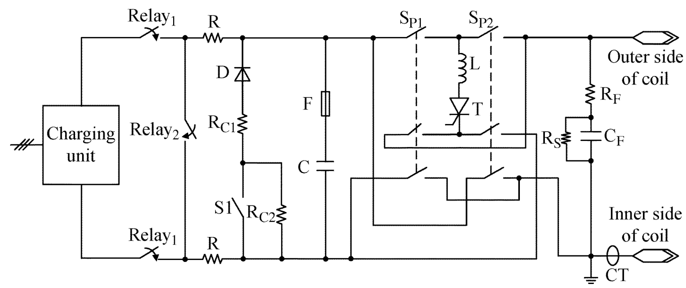

Fig. 2. Circuit diagram of a 1 MJ capacitor module.

TABLE I
SPECIFICATIONS OF THE CAPACITOR MODULES

	1 MJ	**0.75 MJ**
Capacitance	3.2 mF	2.4 mF
Maximum Charge Voltage	25 kV	25 kV
Maximum Output Current	44.7 kA	61.2 kA
Protection Inductor	1 mH	400 μH
Charge Time to 25 kV	54 s	40 s
Crowbar Resistor	0.2 Ω, 0.4 Ω	0.08 Ω, 0.16 Ω

The cable for energy connection and distribution is coaxial to minimize the inductance. The inner and outer conductors have equal cross sections and consist of woven wires to prevent being entangled into one side due to the electromagnetic force. Two types of coaxial cables with equal inner and outer conductor cross sections of 70 mm^2 and 240 mm^2 will be used in the laboratory. The collectors are designed to withstand extreme forces generated by electromagnetic fields of the discharge current. The collector 1 may suffer a peak current up to 490 kA under the short circuit condition; the peak currents of collector 2 and collector 3 are 179 kA and 122 kA, respectively. The selectors are composed of motor-operated disconnecting switches. The entire modular 12.5 MJ capacitive power supply is controlled via an integrated automation system based on optical fiber communication between power supply hall and control room.

III. Capacitor Module Design

The 1 MJ and 0.75 MJ capacitor modules have a similar circuit diagram as shown in Fig. 2. It consists of the capacitor (C), the protection inductor (L), the main discharge switch (T), the crowbar circuit (D, $\mathrm{R_{C1}}$, $\mathrm{R_{C2}}$ and S1), the discharging circuit (R and $\mathrm{Relay_2}$), the polarity-changing switches ($\mathrm{S_{P1}}$ and $\mathrm{S_{P2}}$), the filter circuit ($\mathrm{R_F}$, $\mathrm{C_F}$ and $\mathrm{R_S}$), the charging unit and the switchgear [6], [7]. The specifications of the two different modules are given in Table I.

In our design, eleven 1 MJ modules or two 0.75 MJ modules can operate in parallel. Before a module is selected to operate, all switches except for $\mathrm{Relay_2}$ of this module are set to the 'open' position. When the capacitor module is designated, the following steps will be carried out: 1) Set $\mathrm{Relay_2}$ to the 'open' position; 2) According to the magnetic field polarity requirement of the experiment, close switch $\mathrm{S_{P1}}$ or $\mathrm{S_{P2}}$; 3) Set the resistor value of the crowbar circuit via switch S1; 4) Close $\mathrm{Relay_1}$, start the charging unit to charge the capacitors; 5) After charging the capacitor module, switch off the charging unit by $\mathrm{Relay_1}$; 6) Fire the main discharge switch.

A brief overview over the characteristics of some critical components and subsystems of the 1 MJ and 0.75 MJ modules is given below.

A. Capacitors

The 1 MJ capacitor module consists of 20 (15 for the 0.75 MJ module) high energy density capacitors with metallized electrodes. The main specifications of each capacitor are:

- 160 μF/25 kV/50 kJ
- High energy density $(> 0.5\ \mathrm{MJ/m^3})$
- Dielectric loss angle tangent no more than 0.0003
- The dielectric between the two electrodes of the capacitor should endure 29 kV DC voltage for 1 minute
- The insulation between the capacitor's electrode and shell should endure 35 kV DC voltage for 1 minute
- After 20,000 charge/discharge cycles with 25 kV charge voltage, 10 kA discharge current and 30% rated voltage reversal, the loss of capacitance should be less than 5% and the loss angle tangent no more than 0.002.

Each capacitor has a safety fuse to protect it against abnormal current flowing in the event of capacitor faults. A voltage indicator with a high voltage resistor is connected in parallel to each capacitor [2]. The indicators will not only display a signal by an LED at the control panel of the module if the capacitors are charged, but also provide a safety discharge channel with about 30 minute time constant.

In case of malfunction the capacitors of the 1 MJ (or 0.75 MJ) capacitor module can be discharged with two resistors of 100 Ω via a normally closed high voltage relay in about 3 s.

B. Protection Inductor

The protection inductor is used to limit the maximum discharge current (short circuit current) and the rate of current change through the main discharge switch and crowbar diode in case of a load failure. With a view to the power supply requirements of the designed magnets and future magnets, as well as the cost, the short circuit current is limited to 44.7 kA for the 1 MJ capacitor module (61.2 kA for the 0.75 MJ module) under 25 kV charging voltage. The corresponding inductance values of the 1 MJ and 0.75 MJ capacitor modules are 1 mH and 400 μH, respectively. The values of the limited short circuit currents and the specifications of the protection inductors are different from those of our initial design scheme.

In order to reduce the influence of the stray field of the protection inductor to the environment, the inductor is designed as a toroidal system consisting of 12 Bitter type coils evenly distributed over the perimeter of a circle.

C. Discharge Switch

The main discharge switch should survive a discharge of the fully charged module at 25 kV into a short circuit with the protection inductor. The peak current and maximum load integral $\mathrm{i^2t}$ of the switch under the short circuit condition are 44.7 kA and 8×10^6 $\mathrm{A^2s}$ respectively for the 1 MJ capacitor module and the corresponding values for the 0.75 MJ capacitor module are 61.2 kA and 11×10^6 $\mathrm{A^2s}$. The discharge switches of the 1 MJ and 0.75 MJ capacitor modules consist of seven series-connected T1503N80T and T2563NH80T light triggered thyristors (LTTs) respectively [8], [9]. Fig. 3 shows the discharge switch of the 1 MJ capacitor module.

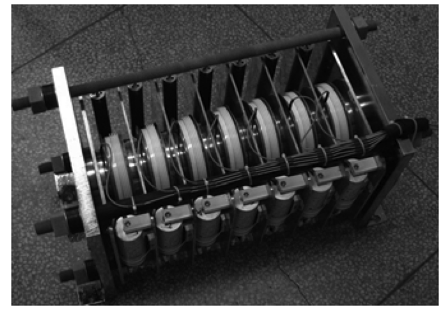

Fig. 3. Discharge switch of the 1 MJ capacitor module.

D. Crowbar Circuit

A crowbar circuit is used to protect the capacitor bank from the high reverse voltage. Moreover, it can modify the magnetic field pulse shape and minimize coil heating. The crowbar circuit consists of crowbar resistors and large-current high-voltage diode stacks. Both the diode stacks of the 1 MJ and 0.75 MJ modules are composed of eight series-connected D3001N68T diodes made by the EUPEC Company [10]. The ZnO linear resistor with high thermal capacity and dinky self-inductance is adopted as the crowbar resistor. The crowbar resistor value can be selected as 0.2 Ω or 0.6 Ω in the 1 MJ capacitor module via a motor-operated 1-pole disconnecting switch, and 0.08 Ω or 0.24 Ω in the 0.75 MJ capacitor module.

E. Charging Unit

The charging unit based on the AC/DC/AC/DC converter circuit utilizing IGBT switches operating at high frequency in a series resonance topology has been developed at HUST. The unit provides a local and remote control interface; the operating state indications can be displayed on the front panel and remote control computer. The typical specifications of the charging unit are: input voltage 400 V AC 3 phase 50 Hz; output voltage 0 to 25 kV; constant charging current 1.8 A; charging power limitation 30 kW; stability of charging voltage ±0.5%; efficiency larger than 85%; power factor larger than 0.85; forced air cooling mode.

The filter circuit in Fig. 2 is used to suppress the overvoltages induced by the stray capacitance and inductance of the wiring of the capacitor module.

IV. Prototype and Test Results

A prototype of the 1 MJ capacitor module has been built and tested in order to validate the design for being applied in the 12.5 MJ system. Fig. 4 gives a view on the 1 MJ prototype with

Fig. 4. View of the 1 MJ capacitor module prototype.

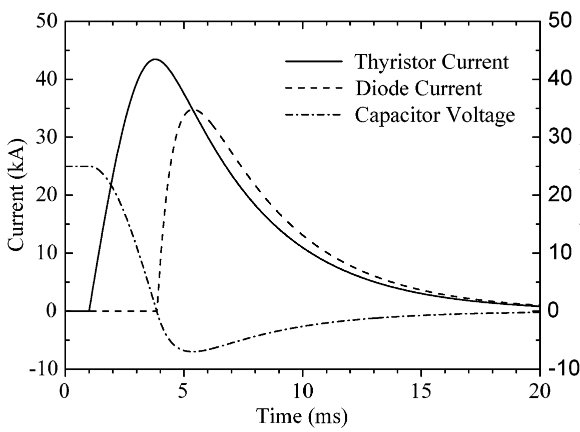

Fig. 5. Short circuit test pulses of the 1 MJ prototype.

dimensions $4.9\ \mathrm{m} \times 1.2\ \mathrm{m} \times 2.6\ \mathrm{m}$ and weight 3.2 tons. A series of tests and experiments were carried out on all components of the prototype and the entire prototype.

Before the capacitors were assembled in the prototype, three different types of tests were performed. The first test was a high voltage test to ensure the insulation behavior with DC voltage of 35 kV and 29 kV applied to the capacitor electrode against the shell and electrode against electrode for one minute. The second test was 25 charge/discharge cycles for each capacitor with 10 kA peak current and 30% voltage reversal. The last test was the lifetime test for one capacitor that was randomly selected from 21 capacitors. By a dummy load, the discharge peak current and voltage reversal were set to 8 kA and 28%, respectively. After 20,000 shots, the capacitance decreased from 162.25 μF to 161.93 μF (less than 0.5%), and the other key parameters did not show any obvious attenuation.

After the high voltage and maximum operating current tests of all components of the prototype, short circuit tests were performed at the output terminals of the prototype with 0.2 Ω crowbar resistor and 25 kV charge voltage. Fig. 5 shows the output current (thyristor current), capacitor voltage and crowbar diode current of the short circuit test with a positive pulse.

Up to now, the 1 MJ prototype has been used to energize several coils to obtain 50–72 T magnetic fields. Fig. 6 shows the field record for a 72 T positive pulse. The pulse shapes of the design and experiment are in excellent agreement.

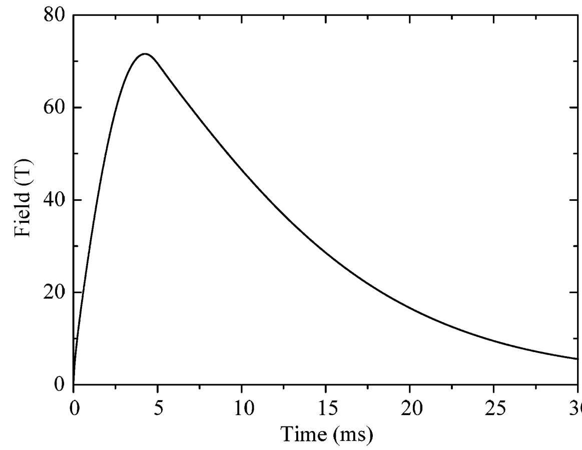

Fig. 6. 72 T field record obtained with the 1 MJ prototype.

V. Conclusion

A modular capacitive pulsed power supply storing 12.5 MJ at 25 kV is under construction at HUST to energize high magnetic field coils in the 50–80 T range with pulse duration from 15 ms to 200 ms. The power supply consists of 11 independent 1 MJ modules with a short circuit current of 44.7 kA each and 2 independent 0.75 MJ modules for 61.2 kA each. Different types of coils can be connected to the power supply in eight measurement cells by an arrangement of collectors and selector switches. A system consisting of two or three coils can be energized with current pulses at different trigger times. As a prototype, a 1 MJ capacitor module with reversible polarity was developed and has been used to energize several coils to get 50–72 T magnetic fields. The test results of the prototype agreed well with those of the design scheme.

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