# DEVELOPMENT OF A CAPACITOR-CHARGING POWER SUPPLY FOR A SMART MODULATOR

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*Abstract*

There are many general requirements for colliders, such as high reliability and availability, reasonable power efficiency, lower construction cost, simplicity, and flexible operation. A smart modulator is necessary to realize a linear collider with a reasonable performance. A capacitor-charging power supply using high frequency inverter technology is strongly recommended for the charging section in the smart modulator. A high frequency inverter switching makes the overall system size small. The command-charging feature can guarantee higher reliability of switching function. The protection circuit can be easily included in the system and the good regulation of charging voltage can be achieved by the feedback system. Several modules can be stacked to supply required output power and a failed module is easily replaced. A 50-kV, 42-kW capacitor charging power supply is developed. Design detail and test results of a prototype unit are presented.


## 1 INTRODUCTION

RAM (Reliability + Availability + Maintainability) is the first requirement for large-scale machines. If an inverter power supply is used as a HV generator, it will just meet the RAM demands: (i) The modulator can be divided into two units, the DC HV generator and the PFN section. (ii) The HV generator section is the most complicated part in a modulator. It can be separated from the cabinet and packed into one box. Then, the system becomes very simple. (iii) The HV generator units can be fully tested at the time of manufacture. (iv) Due to low stored energy, the damage to a thyratron and the HV power supply can be minimized even in the case of a load fault. (v) In the case of trouble, the faulty unit will just be replaced. A smart modulator is different from the conventional modulator for the charging power supply, as shown in the Fig. 1. The charging power supply is a constant current source. An inverter power supply is suitable for the current source. The short circuit current is less than a few amperes and is limited by the inverter power supply. The charging profile is linear up to the desired PFN level. As shown in the figure, the PFN charging starts after a long delay, which is controlled by a master trigger-generator. Command charging will certainly provide fault-free operation for the thyratron. This paper describes detailed design procedure of an inverter section, a high voltage transformer, and a heat removal unit. In addition, the operational characteristics of the prototype 50-kV, 42-kW capacitor charging power supply are analysed.

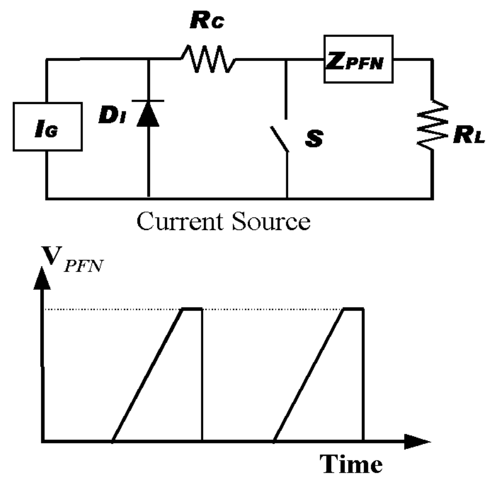


Figure 1: Block diagram of the smart modulator.

## 2 SYSTEM DESCRIPTION

### 2.1 Design

There are four basic modules: input power module, inverter module, high-voltage output module, and control module.

The AC input section includes a common/differential mode EMI filter, an inrush current-limit circuit, a rectifier, and filter capacitors. When the AC power is energized, a high inrush surge during the charging period of the input capacitors is prevented by the inrush current-limiting circuit. The rectifier and the filter provide a stable DC voltage to the inverter section.

The turn-on and the turn-off losses of the switching devices are significantly high in converters with PWM (pulse-width modulation) control. The disadvantages of PWM control can be eliminated or minimized if the switching devices are turned "on" and "off" when the voltage across the devices and/or their current is zero. The voltage and the current are forced to pass through zero by an LC-resonant circuit. The series resonant inverters are based on resonant current oscillation. The capacitor-charging power supply utilizes a series resonant "H" bridge topology. [1-3] The operating frequency is typically in the range of 40 to 60 kHz. This topology is inherently short-circuit proof because of the high source impedance it present to the output circuit.

The series resonant inverter can transfer maximum power P

$$P = f_O E_O$$

$$E_O = 0.5\, C_R\, (2V)^2$$

where $f_O$ is the resonant frequency, $C_R$ is the capacitance of the resonant circuit, and V is the source voltage driving the L-C circuit.

Figure 2 shows the circuit diagram of inverter power supply. The series resonant inverter has 16-parallel high power IGBT (APT 100GF60JRD, 600V/100A). The resonant capacitor has total 44-parallel metalized polypropylene film capacitor (ICEL PPA2203100*J, 0.1 μF/ 630V/7.5A).

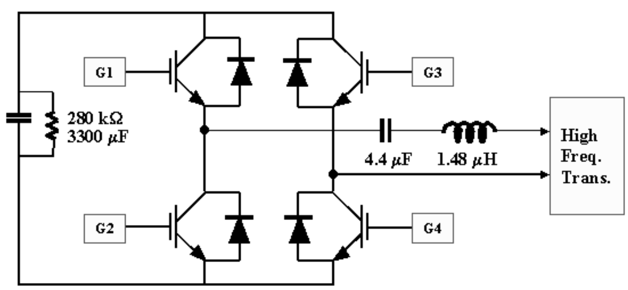


Figure 2: Circuit diagram of inverter power supply.

The high-voltage tank includes a high-frequency transformer, multiple full-wave bridges, and voltage and current monitoring circuits. The high-voltage transformer has multiple secondary windings to reduce the parasitic resonance caused by the secondary inductance and self-capacitance. All rectifiers are connected in series to sum the rectified voltage levels to obtain the final output voltage. Figure 3 shows the high voltage transformer assembly. The transformer has two ferrite cores (TDK PE22 UU120x160x21). Primary winding has 6 turns with Litz wire and secondary has 12 sections with total 1260 turns. Each section has full-bridge rectifier using fast recovery diodes (VMI Z50FG).

Transformer leakage inductance, $L_L$ is 1.34 μH that is given by

$$L_L = 4\,\pi\, N_p^2\, U_m\, (\Delta g + \Sigma\, \delta i / 3) / L_m \;\; [\text{nH}]$$

Where $N_p$ is primary turns, $U_m$ is mean circumference of windings (204.5 mm), Δg is gap length between windings (9.85 mm), δi is thickness of windings (7.9 mm), $L_m$ is winding length (86.5 mm).

The inverter operates in the fully resonant mode during the charging time; then, the PFN voltage is maintained at the same level by the refresh mode. During the refresh mode, the switching frequency is much lower than it is during the charging mode and depends on the leakage rate of the networks. In the high regulation mode, PWM is activated to avoid overshooting the target voltage.

When designing an inverter with given source-voltage and power-output requirements, the ratio of L and C is fixed. If a certain resonant frequency is desired, then both L and C are uniquely determined.

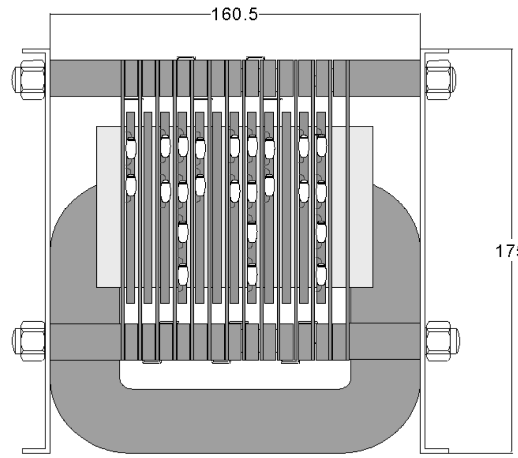


Figure 3: High voltage transformer assembly.

## 2.2 Specifications

The prototype power supply can deliver a 42-kW average power with a maximum 68-kV output voltage. Table 1 summarizes the specifications of the power supply. The high peak charging rare of 57.8 kJ/s is suitable for fast capacitor charging. Maximum duty is 80% to keep the average power level up to 42 kW.

Table 1: Specifications of the inverter power supply

| Parameter | Value |
|---|---|
| Peak charging rate (kJ/sec) | 57.8 |
| Maximum output voltage (kV) | 68 |
| Average output current (A) | 1.7 |
| Maximum duty (%) | 80 |
| Average output power (kW) | 42 |
| Resonant frequency (kHz) | 62.5 |
| Resonant capacitance (μF) | 4.4 |
| Resonant inductance (μH) | 1.48 |
| Resonant impedance (Ω) | 0.58 |
| DC bank voltage (V) | 324 |
| Peak switching current (A) | 1120 |
| Efficiency (%) | 90 |

## 2.3 Power Loss

Total power loss of the inverter power supply is estimated to 3.9 kW in order to deliver 41.6 kW. The inverting switches and rectifying diodes are major responsible devices for this loss. The charging efficiency of the inverter power supply is 91.5%.

Table 2: Power loss of the inverter power supply

| Device | Loss (%) |
|---|---|
| DC bank | 12.8 |
| Inverter switches | 33.6 |
| Resonant capacitors | 0.9 |
| Transformer windings | 15.5 |
| Transformer core | 0.4 |
| Rectifier diodes | 36.8 |

### *2.4 Cooling System*

The cooling system has to remove 4 kW heat from the insulation oil generated by inverter and rectifier devices. The compact air-cooled heat exchanger, Lytron's ViscoFlo™ 5321G10AN is adopted. It has multiple extended-surface channels inside each tube to increase cooling capacity. The overall dimension is 461 mm [W] x 212 mm [D] x 78 mm [H]. The maximum cooling capacity of this unit is 133 W/℃ with oil flow rate of 12 l/min. So oil temperature can be kept below 60℃ with 4 kW heat loading. Forced airflow rate of 300 cfm is provided by two fans directly mounted on the heat exchanger. The air temperature is assumed to be 30℃.

## 3 RESULTS

The prototype inverter power supply is linearly charging up to 50 kV on a 208 nF capacitor within 6.47 ms as shown in Fig. 4. The average output current is 1.61 A with DC bank voltage of 308 V. The peak-charging rate is 38.6 kJ/sec that will give 55.4 kJ/sec at 68 kV charging level with nominal DC bank voltage.

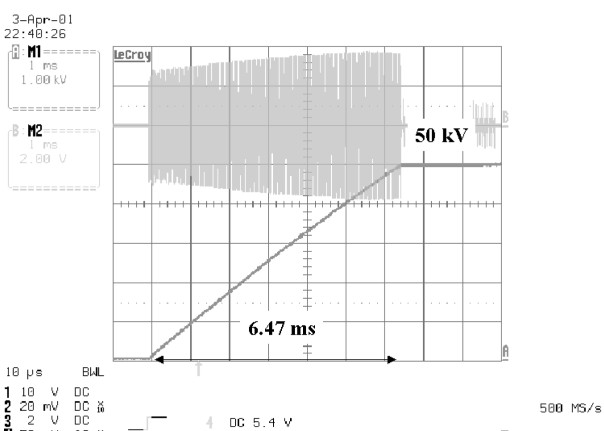


Figure 4: Charging waveform on a 208 nF capacitor.

Figure 5 is expanded view of the figure 4, which shows the resonant current waveform in detail at the initial charging. The resonant frequency is 62.5 kHz and the peak resonant current is 528 A. It means that total series inductance is approximately 1.5 µH including the leakage inductance 1.3 µH of the transformer.

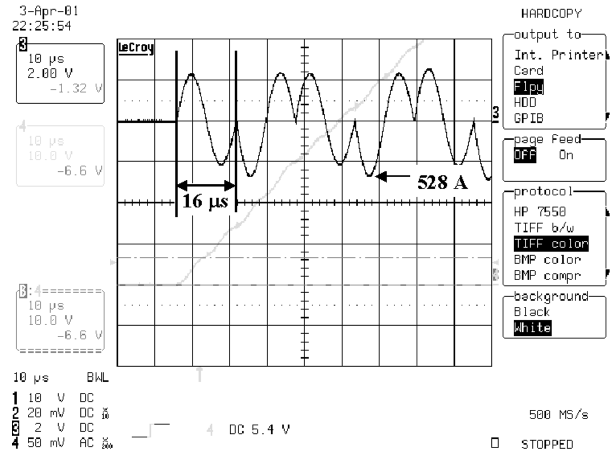


Figure 5: Resonant circuit current waveforms.

The cooling capacity of heat exchanger is examined using calorimetric measurement. The heat load 4 kW is controlled by an electrical heater. Maximum oil temperature is 63℃ with oil flow rate of 13 l/min and air temperature of 35℃, which gives 3.92 kW heat removal by this heat exchanger. The calorimetric power measured by oil temperature difference of 11°C is 3.95 kW.

## 4 SUMMARY

The series resonant inverter power supply is developed for the capacitor charging application. The peak-charging rate is tested up to 38.6 kJ/sec at 50 kV that will give 55.4 kJ/sec at 68 kV charging level. The resonant frequency is 62.5 kHz with 4.4 µF capacitor and total series inductance 1.5 µH. Total power loss of 3.9 kW is mainly due to active semiconductor devices such as resonant switches and rectifier diodes. The cooling capability of compact oil cooler is confirmed to be 4 kW. Maximum average power is 42 kW with 80% duty factor. System efficiency is over 90%.

## REFERENCES

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