DEVELOPMENT AND APPLICATION OF AN INVERTER CHARGING SUPPLY TO A PULSE MODULATOR*

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Abstract

A smart modulator is essential to realize a linear-collider with a reasonable performance, such as high reliability, reasonable efficiency, lower construction cost. A capacitor-charging power supply using high frequency inverter technology is suitable for the charging section in the smart modulator. An inverter charging power supply with command charging feature makes the system size small and guarantees higher reliability of switching function. An air-cooled 50-kV, 15-kW inverter charging supply is developed. Design procedure and fabrication detail of the prototype unit are presented. The charging efficiency are analysed and the detail of total power loss 1.1 kW are discussed. The cooling capability is proved a limiting factor of the high power unit.

1 INTRODUCTION

A series resonant inverter is one of best scheme for a current source, capacitor-charging power supply of a pulsed klystron-modulator, especially for a few thousands of modulators for an e+e- linear collider. Its high frequency utilization makes the system size small and the voltage regulation fine. The command-charging feature of the inverter guarantees high reliability of switching function. Typical modulator layout with an inverter power supply is shown in Fig. 1.

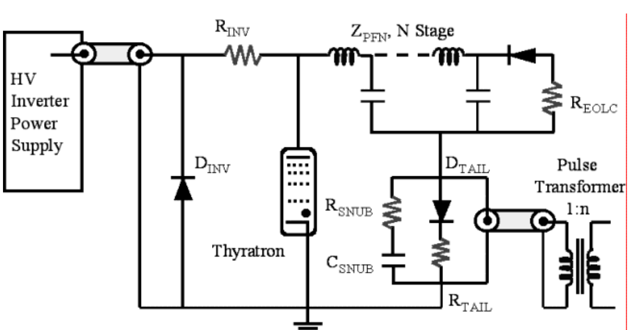

Fig. 1: Modulator layout with an inverter power supply.

The analysis of the system efficiency is essential because thermal design is most critical in this power supply. Better efficiency can be obtained through accurate evaluation of power loss distribution. Design and fabrication detail of an air-cooled 50-kV, 15-kW inverter charging supply are presented in this paper.

2 SYSTEM DESCRIPTION

2.1 Specifications

The inverter power supply is designed to be able to deliver a 15-kW average power with a maximum 50-kV output voltage. Table 1 summarizes the specifications of the power supply. Maximum duty is limited to 80% in order to keep the average power less than 15 kW. The key idea of the work is to develop an air-cooled unit for the simplicity of a system with better efficiency. Rather hard specification of high average power is chosen to examine thermal limitation of the inverter power supply.

Table 1: Specifications of an inverter power supply

Parameter	Value
Peak charging rate (kJ/sec)	18
Maximum output voltage (kV)	50
Average output current (A)	0.6
Maximum duty (%)	80
Average output power (kW)	15
Resonant frequency (kHz)	35
Resonant capacitance (μF)	0.7
Resonant inductance (μH)	30
Resonant impedance (Ω)	6.5
DC bank voltage (V)	650
Efficiency (%)	> 90

2.2 Design

The capacitor-charging power supply utilizes a series resonant "H" bridge topology. [1-3] The current is forced to pass through zero by an LC-resonant circuit in the inverters as shown in Fig. 2. The series resonant inverter has 5-parallel high power IGBT (IXYS IXDR30N120D1, 1200V/30A). The resonant capacitor is consisted of two metalized polypropylene film capacitors (Celem CSM 150, 1.2 uF/ 500V/300A) that are connected in series.

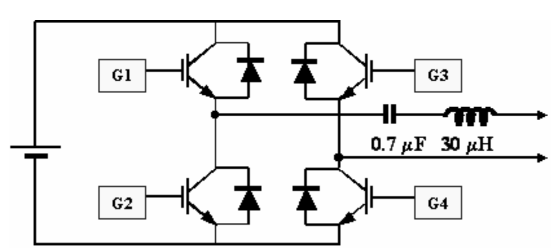

Fig. 2: LC resonant inverter circuit.

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The charging voltage is going linear up to the desired PFN (pulse forming network) level V_{DC} with charging time T_C as shown in Fig. 3. After dwell time T_D, a main switch is triggered to discharge the PFN. The next charging cycle of PFN starts with delay time T_I. This command charging provides safe operation for the thyratron recovery.

The peak charging power P_O is given by E_O / T_C and the average charging power P_{AV} is given by E_O / T_P, where E_O is the PFN energy $C_O V_{DC}^2 / 2$ and T_P is the charging-discharging period.

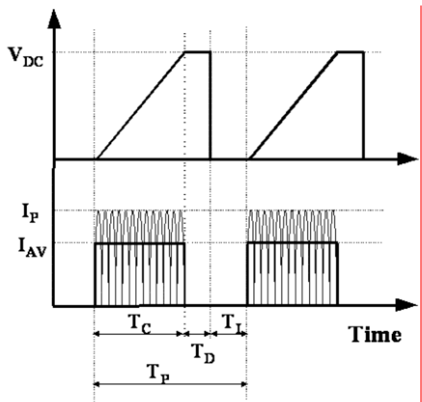

Fig. 3: Charging voltage and current waveform of PFN.

The average current I_{AV}, the peak current I_P, and the resonant energy E_R are given by

$$I_{AV} = \frac{2}{\pi} I_P, \quad I_P = \frac{V_{DC}}{Z}, \quad E_R = \frac{1}{2} C_R (2V_{DC})^2$$

where V_{DC} is the source voltage driving the L-C circuit, Z is the resonant impedance, C_R is the capacitance of the resonant circuit. Then, the series resonant inverter can transfer maximum power P_O

$$P_O = \frac{1}{2} V_{DC} I_{AV} = \frac{1}{\pi} \frac{V_{DC}^2}{Z} = f_R E_R$$

where f_R is the resonant frequency. Therefore, a basic design parameter is C_R that is to be decided for the peak output power P_O with given parameters V_{DC} and f_R. If the switching frequency f_{SW} is smaller than the f_R, it is given by V_{DC} and f_{SW}.

There are a high-frequency transformer, multiple full-wave bridges, and voltage and current monitoring circuits in a high-voltage tank. The high-voltage transformer has seven secondary windings, of which rectifiers are connected in series. Figure 4 shows the high voltage transformer assembly. The transformer has two ferrite cores (TDK PE22 UU120x160x21). Primary winding has 24 turns with Litz wire and each secondary winding has 300 turns. A full-bridge rectifier for each secondary section is made using fast recovery diodes (VMI Z50FG).

Transformer leakage inductance L_L should be less than the value of 30 uH given in the table 1. It is estimated to be 21 uH by

$$L_L = 4\pi N_P^2 U_M (\Delta_G + \frac{\Sigma \delta_i}{3}) \frac{1}{L_M} [\mathrm{nH}]$$

where N_P is primary turns (24 turns), U_M is mean circumference of windings (20 cm), Δ_G is gap length between windings (1 cm), δ_i is thickness of windings (1 cm), and L_M is winding length (9 cm). The magnetizing inductance is about 3.8 mH and the maximum flux is less than 3300 Gauss.

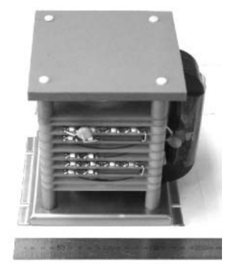

Fig. 4: The high voltage transformer assembly.

2.3 Power Loss

The detail distribution of the power loss is given in Table 2. Total power loss of the inverter power supply is estimated to be 1.1 kW in order to deliver 15 kW. The loss distribution of components depends on the parameters such as step-up ratio of the high voltage transformer, primary turn number, etc. In order to obtain high efficiency, these parameters are adjusted and iterated. The losses are rather evenly distributed around components. The optimised charging efficiency of the inverter power supply is 93%.

Table 2: Power loss of the inverter power supply

Device	Loss (W)
DC bank	70
Inverter switches	133
Resonant capacitors	46
Snubber	217
Fan and control power	120
Transformer windings	247
Transformer core	122
Rectifier diodes	124

2.4 Cooling System

The total power loss of the inverter section is about 350 W and the one of the high voltage transformer tank is about 500 W as shown in Table 2. The heat should be efficiently removed to keep the component temperature under safe level. The heat sink for IGBT stack and snubber is cooled by forced air as shown in Fig. 5. The Al heat sink has 30 channels with cross-section of 116 mm x 4 mm and a length of 300 mm. The cooling fan is directly attached to the heat sink. The sidewalls of the high voltage tank are made by Al heat sink as shown in Fig. 6 and a cooling fan is attached to the tank. The tank dimension is 250 x 210 x 210 mm and the internal volume is 11 *l*.

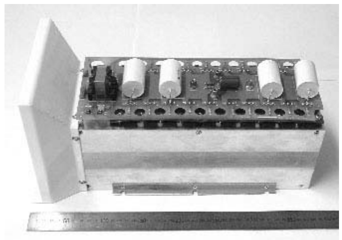

Fig. 5: Al heat sink for IGBT stack and snubber.

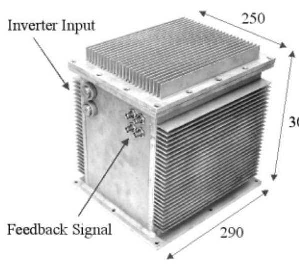

Fig. 6: High voltage tank.

3 RESULTS

The inverter charging power supply is linearly charging up to 36 kV on a 216 nF capacitor within 10.8 ms as shown in Fig. 7. The bottom waveform is charging voltage V_O and the middle one is output charging current I_O, and the top waveform is resonant current I_R of the inverter capacitor. The average output current is 0.73 A. The peak-charging rate is 13.2 kJ/sec that will give 18.2 kJ/sec at 50 kV charging level with nominal DC bank voltage.

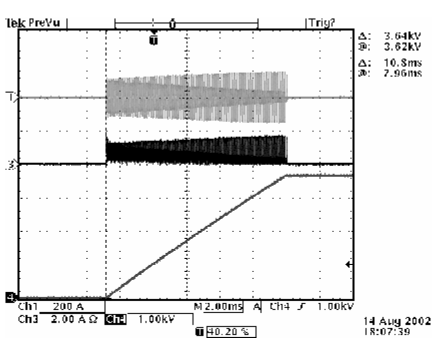

Fig. 7: Charging waveforms with a 216 nF load.

Figure 8 is the expanded view of Fig. 7, which shows the resonant current waveform in detail close to top charging level. The resonant frequency is 35 kHz and the peak resonant current is 152 A.

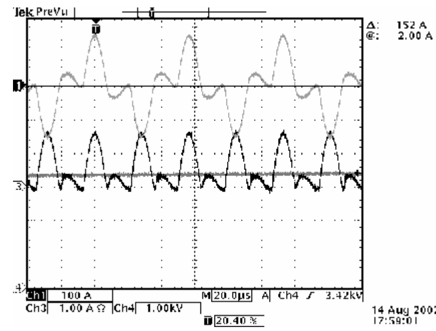

Fig. 8: Expanded view of figure 7 (horizontal: 20 us/div).

The cooling capacity of heat sink is examined using calorimetric measurement. The heat load up to 500 W is controlled by an electrical heater. Figure 9 shows that maximum oil temperature rise is 40℃ with pressure rise of about 1 kgf/cm^2 at air temperature of 35℃.

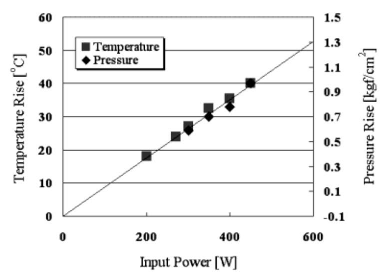

Fig. 9: Cooling performance of the high voltage tank.

4 SUMMARY

The air-cooled, series-resonant inverter power supply is developed for the capacitor charging application. The peak-charging rate is evaluated to be 18.2 kJ/sec at 50 kV charging level. The resonant frequency is 35 kHz with 0.7-uF capacitor and total series inductance 30 uH. Total power loss of 1.1 kW is evenly distributed by parameter optimisation. The cooling capability of heat sink for the high voltage tank is confirmed to be 500 W. The average power is 15 kW with 80% duty factor and system efficiency is about 93%.

5 REFERENCES

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[2] A. C. Lippincott, R. M. Nelms, "A Capacitor-Charging Power Supply Using a Series-Resonant Topology, Constant On-Time/Variable Frequency Control, and Zero-Current Switching," IEEE Transactions on Industrial Electronics, Vol. 38, No. 6, pp. 438-447, December 1991.

[3] E. E. Bowles et al., "A High Power Density, High Voltage Power Supply for a Pulsed Radar System," Conference Record of the 1994 Twenty-First International Power Modulator Symposium, pp. 170-173, 1994.