A Capacitor-Charging Power Supply Using a Series-Resonant Three-Level Inverter Topology

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Abstract

In this paper we present a Capacitor Charging Power Supply (CCPS) using a series-resonant three-level inverter topology to improve voltage regulation and use semiconductor switches having low blocking voltage capability such as MOSFETs. This inverter can be operated with two modes, Full Power Mode (FPM) and Half Power Mode (HPM). In FPM inverter supplies the high frequency step up transformer with full DC-link voltage and in HPM with half DC-link voltage. HPM switching method will be adopted when CCPS output voltage reaches the preset target value and operates in refresh mode - charge is maintained on the capacitor. In this topology each semiconductor devices blocks a half of the DC-link voltage[2]. A 15kW, 30kV CCPS has been built and will be tested for an electric precipitator application. The CCPS operates from an input voltage of 500VDC and has a variable output voltage between 10 to 30kV and 1kHz repetition rate at 44nF capacitive load [3]. A resonant frequency of 67.9kHz was selected and a voltage regulation of 0.83% has been achieved through the use of half power mode without using the forced cut off the switch current [1]. The theory of operation, circuit topology and test results are given.

I. INTRODUCTION

Electrical precipitator system requires short but intense bursts of energy which may be derived by rapidly discharging a capacitor. This process requires that the capacitor be charged by a capacitor charging power supply prior to each repetition of energy release to the load. Fig. 1 shows a typical charge cycle for a CCPS. The charge cycle consists of two different regions. At the beginning of the cycle, the capacitor is initially discharge and the CCPS operates in the charging mode until the target voltage is reached. Upon reaching the target voltage, the CCPS shifts to the refresh mode where charge is maintained on the capacitor by minute packets of energy that compensate for losses due to parasitic resistances and capacitor leakage. The charge mode is a high-power mode where the CCPS operates at full capacity in order to charge the capacitor as quickly as possible. The refresh mode, however, is a low-power mode where the CCPS waits for the capacitor to be discharged. Conventional CCPS, using the series resonant technology has zero current switching characteristics, so during the refresh mode the CCPS should be operated two methods. One is a single charging method. It maintains the resonant switching but at the small capacitance load has bad regulation. The other is a hard switching, but it has turn-off switching losses. The three-level inverter produces two types of output voltages(V_{DC}, $V_{DC}/2$), so it has advantages of control of the charging profile and maintaining of the regulation capability at the small capacitance load without losing zero current switching. And when using the same switch – same blocking voltage ratings, it can increase twice the DC-link voltage to the conventional full-bridge inverter, which reduces the current ratings of all components, such as resonant capacitor, litz wire, solid-switch. A high power CCPS using a series resonant three-level inverter technology has been developed aiming to apply to several kilo pps class applications. In the CCPS, a high switching frequency IGBT inverter of 32kHz and a high-efficiency, high-voltage transformer were adopted to achieve high efficiency and high voltage. This paper describes the design and the experimental results of the CCPS for applying to an all-solid-state electric precipitator for generating a pulse streamer corona.

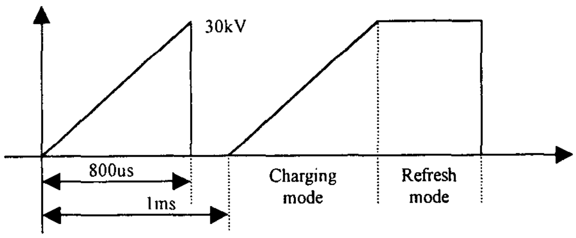

Figure 1. Output voltage of CCPS.

II. DESIGN

A. Requirements

The capacitor charging power supply requirements are summarized in Table 1.

Table 1. Power supply specification.

Items	Spec.
Output voltage	30kV
Load Capacitance	44nF
Repetition rate	1kpps
Charge time	Less than 800us
Efficiency	More than 80%

B. Circuit

Fig. 2 shows a simplified diagram of the CCPS. The CCPS consisted of a high frequency IGBT three-level inverter, a resonant capacitor, a high-voltage transformer and a high voltage rectifier. The high-voltage transformer and the full-bridge rectifier were installed in an oil tank. The resonant capacitor was connected to the primary of the high-voltage transformer and its capacitance was 1uF. A resonant inductance of 5.5uH comprised of leakage inductance of the high-voltage transformer and stray inductance of wiring conductors.

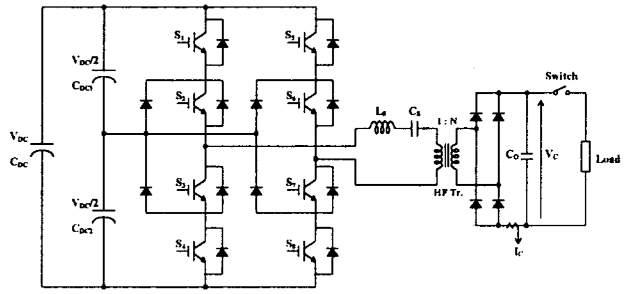

Figure 2. Simplified block diagram of the CCPS.

In full power mode, switch S1, S2, S7 and S8 is turned on. The resonance tank input voltage is inverter DC-link voltage, V_{DC}. Fig. 3 shows it.

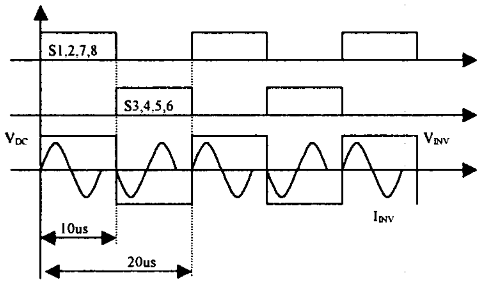

Figure 3. Waveforms of gating signal and resonance tank input voltage and current.

In half power mode, switch S2, S7 and S8 is turned on. The resonance tank input voltage is half of the inverter DC-link voltage, $V_{DC}/2$. Fig. 4 shows it. Therefore, we can control the charging speed voluntarily, using the full power mode and half power mode.

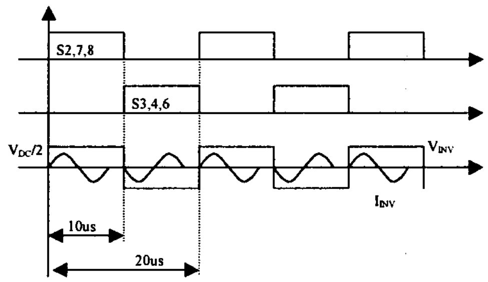

Figure 4. Waveforms of gating signal and resonance tank input voltage and current.

C. IGBT Inverter

Each arm of the IGBT three-level inverter was composed of six IGBTs (IXSH25N1200AU1, 1200V, 50A) connected in parallel. They have parallel diodes integrated in the same package of the IGBT to carry reverse current. All IGBTs were mounted on forced air-cooled heat sinks. The IGBT inverter switching frequency is below half of the resonant frequency f_0 so that zero current switching was realized in order to minimize switching losses at turn-off. The switching frequency was 32kHz. Fig. 5 shows the three-level inverter.

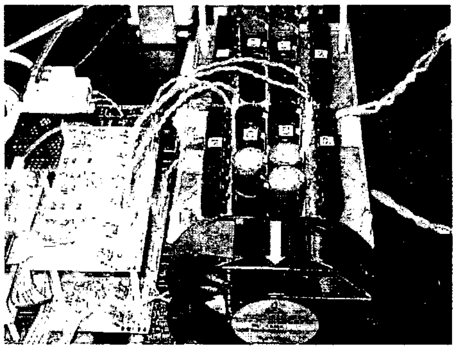

Figure 5. View of the three-level inverter.

D. High Voltage Transformer

High frequency operation requires the high-voltage transformer that has low leakage inductance and high efficiency. Moreover, the high-voltage transformer must have high withstanding voltage. To fulfill these requirements, a simple structure for the high-voltage transformer was adopted in the CCPS. The structure of the transformer and the circuit diagram of output stage are shown in Fig. 6 and Fig. 7, respectively.

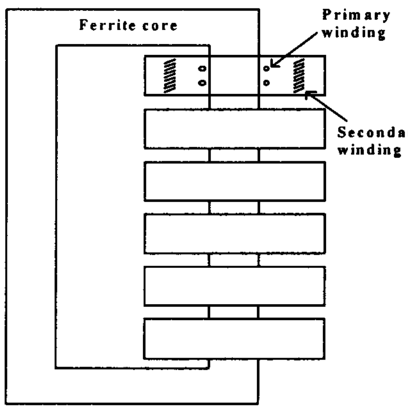

Figure 6. Structure of the transformer.

The transformer comprised six units. Each unit had a secondary winding located over primary windings. To reduce the leakage inductance of the high-voltage transformer, we design the high-voltage transformer under the following aspects. First, the average one-turn lengths of the primary and secondary windings should be short. Second, the height of the primary and the secondary winding could be high. Third, the distance between two layers of the secondary windings should be short. Fourth, all the things above mentioned have minimum or maximum values within the voltage withstand rating. All primary windings of each unit were connected in series. Each secondary winding was connected to full-bridge rectifiers. The primary and secondary windings were made of twisted litz wires: The turn ratio of the transformer was 1:65.

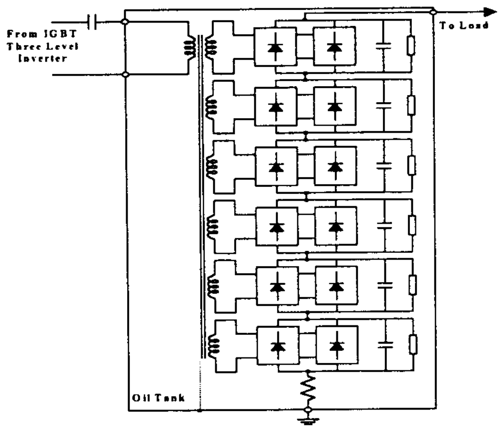

Figure 7. Circuit diagram of output stage.

E. Full-Bridge Rectifier

Each full-bridge rectifier connected to the transformer was composed of ultrafast recovery diodes(VMI 1N6519 rated at 10kV, 0.5A recovery time of 70ns) connected in parallel. Output of each full-bridge rectifier was connected in series. To equalize voltage distribution, a voltage divider consisting of a resistor and a capacitor was connected in parallel to the outputs of each full-bridge rectifier. Fig. 8 shows the HV transformer.

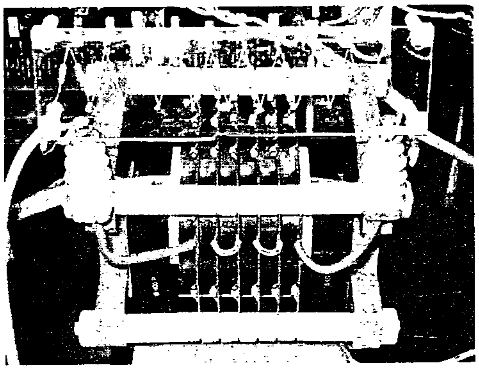

Figure. 8. View of the HV transformer.

III. EXPERIMENTAL RESULTS

The performance test of the CCPS was carried out. Fig. 9 shows the test circuit. A load capacitor C_L of 44nF were charged to 30kV by the CCPS and discharged through a gap switch. Fig. 10 and fig. 11 shows the output voltage and current waveforms.

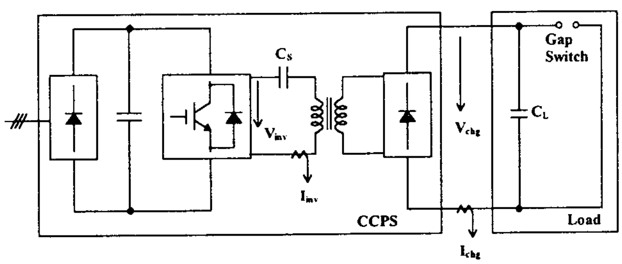

Figure 9. Test circuit.

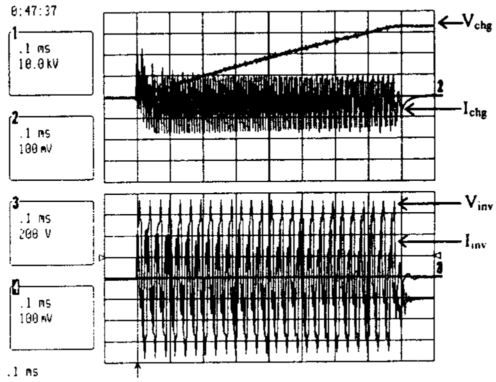

Figure 10. Experimental waveforms of the CCPS(I_{chg}: 5A/div., I_{inv}: 100A/div, time: 1ms/div).

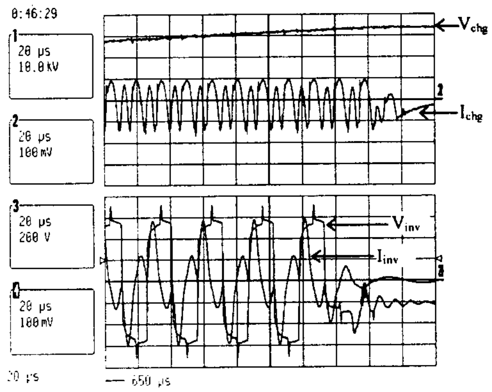

Figure 11. Experimental waveforms of the CCPS(I_{chg}: 5A/div., I_{inv}: 100A/div, time: 20us/div).

IV. CONCLUSIONS

High power CCPS using the 32kHz series resonant IGBT three-level inverter topology has developed. Three-level inverter topology keeps the blocking voltage of each switching device be a half of the DC-link voltage, so this topology can make it possible to increase the blocking voltage ratings of the switch. For medium and high power CCPS systems where minimum volume, high efficiency and regulation are critical design criteria, high frequency constant current charging may be the most practical capacitor charging technique. The use of series-resonant three-level inverter topology, careful design of the transformer to reduce leakage inductance, and appropriate use of damping networks were some of the keys on CCPS design.

V. REFERENCES

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[2] I. H. Song, D. S. Hyun, "A novel three-level ZVS PWM inverter topology for high-voltage DC/DC conversion systems with balanced voltages sharing and wider load range," Proc. of the 31st IAS Annual Meeting, 1996, vol. 2, pp. 973-979.