Design of the High Frequency Resonant Inverter for Corona Surface Processes

Chul-yong Choi*, Dae-Sik Lee*
*Department of Computer and Communication Engineering Graduate School, Daegu University
Janus1976@lycos.co.kr, dslee@daegu.ac.kr

Abstract – A algorithm for control and performance of a pulse-density-modulated (PDM) series-resonant voltage source inverter developed for corona-dischange precesses is presented. The PDM inverter produces either a square-wave ac-voltage state or a zero-voltage state at its ac terminals to control the average output voltage under constant dc voltage and operating frequency. Moreover it can achieve zero-current-switching (ZCS) and zero-voltage-switching (ZVS) in all the operating condition for a reduction of switching lost. Even though the corona discharge load with a strong nonlinear characteristics, new high frequency resonant inverter is shown the wide range power control from 5% to 100%.

Keywords: Pulse-density-modulated, Zero voltage switching, Zero current switching, Corona surface processe.

1 Introduction

Recently, the researches on increasing the switching time, voltage rating and current rating of power semiconductors such as GTO, power-MOSFET, IGBT, SIT and so on, have been in progress. However, in these researches a big capacity induction heater is used for fusion, surface process, or tube welding, where the speed regulation equipments and the high frequency resonant PWM inverter is widely applying [1] [2].

The corona process is proposed to improve the attraction of the polyethylene film, ink, glue and coating [3] [4]. Generally, to maintain a stable discharge for a corona surface process, a 10 – 20Kv, 10 – 50kHz and 1 – 40kW AC power is needed. And however, AC power supply having a capability to control adherence and flexibility in various kinds of films with different thickness and raw materials and widely controlling discharge from 1 to 100% is required.

AC power supply for corona surface process is composed of bridge rectifier with diode or thyristor, voltage source series resonant inverter and a step-up transformer whose secondary voltage is increased more than 10kV. Basically, AC power supply except step-up/down transformer has the same power circuit as induction heating system. But corona surface process has a strong nonlinear voltage and current. Because of this nonlinearity, series resonant inverter controlling DC bus voltage and frequency has difficulty in controlling wide discharge power from 1 to 100%.

In this paper, we propose a 20kHz, 6kW voltage source PDM (pulse-density-modulated) series-resonant inverter. Power control is activated by PDM inverter controlling phase in zero voltage state of output terminal synchronized by frequency of series resonant circuit. In addition, a PLL (phase locked loop) circuit makes frequency of PDM inverter with any load ZVS and quasi ZCS. In the experiment a corona discharge with a power supply controllable under range 5-100% is presented.

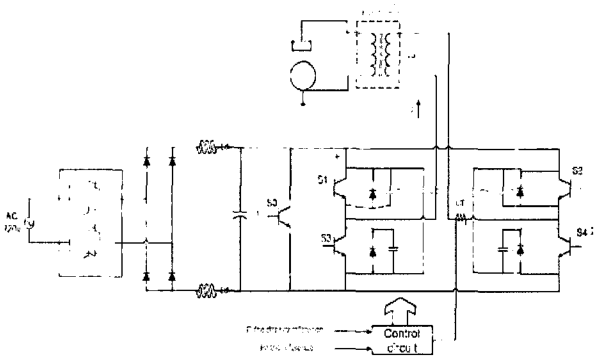

Figure 1. Corona surface processer

2 Corona discharge system

2.1 System structure

In the corona discharge system shown in Figure 1, a single phase H-bridge IGBT inverter is used. The rated voltage and current of IGBT is 600V and 400A respectively. A snub capacitor between the collector and emitter of the IGBT is C_s (0.1uF) and high frequency DC capacitor Cc(1Uf) is connected to DC terminal of IGBT.

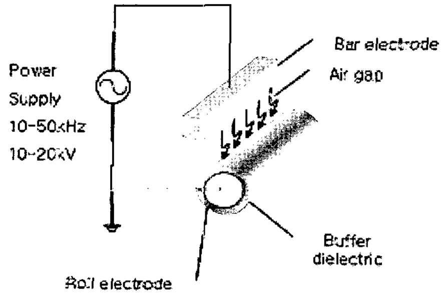

Figure 2. Electrode structure

A 1:10 ratio transformer is connected to AC terminal of inverter to generate 10-20kV for corona discharger. The equivalent circuit is considered as LCR series resonant circuit including the nonlinear loss of capacitance in electrodes and leakage of inductance in transformer. The snubbing capacitor enables the voltage-source inverter to perform ZVS when the inverter operates as a lagging load current. This means that the inverter's operating frequency should be higher than the load resonant frequency. In addition, quasi zero-current switching is also achieved because a PDM inverter operates at a certain frequency in any power control condition. Thus, ZVS and quasi ZCS are significant results from removal of switching losses

2.2 Electrode structure

The electrode structure of corona discharge processor is shown in Figure 2. The roll electrode that connects to ground has an inner-space of 3mm with bar electrode. When 10-50kHz and 10-20kV are supplied to bar electrode, discharge will be happened between bar electrode and roll electrode. While discharging, corona processor passes a film through the gap between bar and roll electrode to enhance the adherence of ink. When voltage of electrode is higher than that of discharge threshold, a lot of current will flow into corona discharger and vice versa, current flow and discharge will be happened.

The equivalent circuit for electrode and transformer is shown in Figure 3. Equivalent capacitor CA, variable resistance Ra are gap impedance between terminals. Leakage inductance of step-up transformer is equivalent to LT. And capacitance of buffer terminal is CD. Since Ra is a variable resistance changed by supplying voltage from the terminal, corona discharge has strong nonlinear characteristic between voltage and current. When the input voltage is smaller than the discharge voltage, Ra has an infinite range and no discharge happens. Contrary, when the input voltage is bigger, Ra will be reduced and Ca will be short. A resonant current can be carried out.

The DC voltage control and frequency control are widely used in series-resonant inverter to adjust the output power of corona system. However, it is difficult for this kind of inverter to control the discharge power if it is smaller than half of full rating for the terminal voltage. Because terminal voltage should be higher than the discharge voltage.

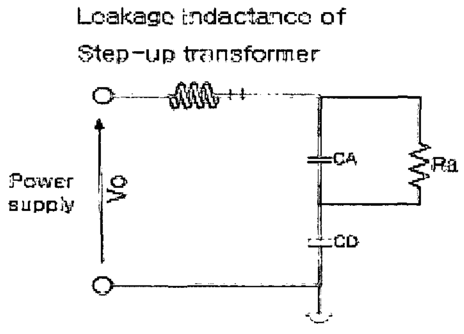

Figure 3. equivalent circuit of electrode

2.3 PDM control

The switching mode of PDM inverter is shown in Figure 4. Typical voltage source of series resonant inerter performs mode I and mode II by turns to shape square wave shown in Figure 4. In addition to mode I and II, PDM inverter will have the shape of mode III to generate zero voltage in output terminal. In this mode III, IGBT gate of S3 and S4 are both turned on. Although one of the IGBT's and diode are on the reverse direction, the other is turned on therefore, the current io is on the free wheeling state as shown in Figure 4 (C). Figure 5 shows the typical power control of PDM. This inverter periodically repeats "run and stop" for adjusting average output voltage and resonant current of series resonant load simultaneously. The pulse ratio is 3/4 shown in Figure 5. PDM inverter creates square wave AC voltage as much as voltage E in 3 resonant cycles by mode I and II. But one cycle of mode III will be performed for zero voltage statues. When there are 4 resonant cycles, output voltage of PDM inverter shows periodic wave and its average output voltage has 3/4 of maximum output voltage.

3 Control circuit

PDM inverter control blockdiagram shown in Figure 6. This is divided into PLL (phase locked loop) circuit which is used to trace the resonant frequency and a PDM control and PDM circuit for controlling cycle of zero-voltage swiching.

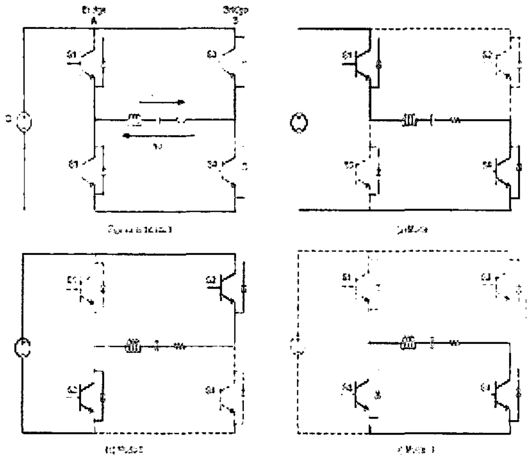

Figure 4. PDM inverter model

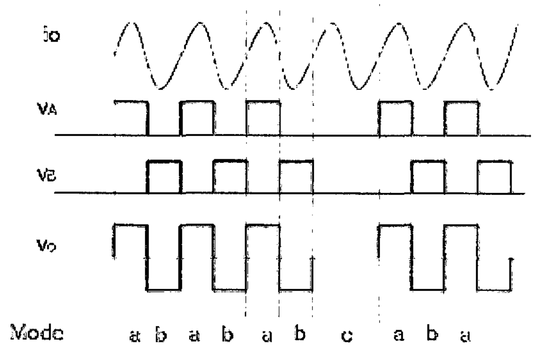

Figure 5. PDM control technical

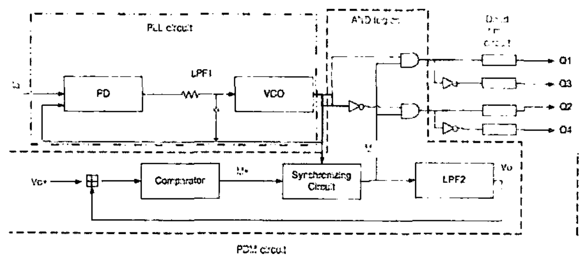

Figure 6. Control block diagram

3.1 PLL circuit

PLL circuit is what the input signal frequency can trace the output. Shown as in Figure 6. a PLL circuit consists of a phase-detector (PD), a low-pass filter (LPD1) and a voltage-controlled oscillator (VCO). PD has a function to create voltage equivalent to the difference of to input phases from feedback of resonant frequency of resonant current and output frequency of VCO. Loop filter LPF1 is used to eliminate the high frequency signal from PD. The VCO generates proportional frequencies of the input and effects PDM circuit as in-phase clock signal.

3.2 PDM control

Figure 6 corresponds to the PDM control circuit based on feedback control and the control signal waveforms are shown Figure 7. The average output voltage reference V0* adjusts the duration of the zero-voltage state. The V0 is obtained from a logic signal corresponding to the actual

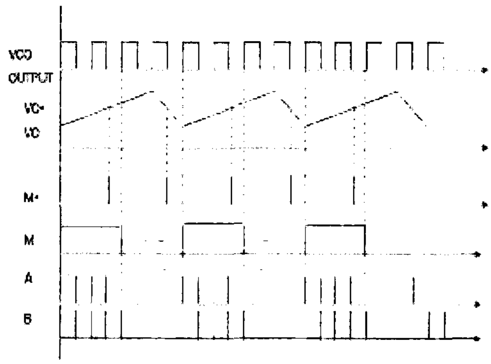

Figure 7. PDM control signal

ac voltage state M via a LPF2. The corona discharge treatment system developed in this paper is intended to operate in a wide range of pulse density from 1/50 to 1. Reference ac voltage input M* from the comparison between V0* and V0 becomes logic signal decides zero voltage status of PDM inverter. A synchronizing circuit consisting of a D-type flip-flop device is employed to avoid the change of the current state during the resonant cycle even when the ac voltage state reference M* changes. The synchronizing circuit checks M* at every rising edges of the VCO output, and holds the logic signal M during the subsequent resonant cycle. A logic AND circuit produces repeatedly mode I and mode Ⅱ during the square-wave ac voltage state of M=1, where it produces mode Ⅲ during the zero-voltage state of M=0. Due to mode III, there is no opposite relationship in output of AND logic.

4 Experiment

Figure 8, 9 and 10 show the wave of output current (i_o) and voltage (v_o) when the DC bus is 200V

Figure 8 shows the wave of maximum power without the zero voltage state. The IGBT acting frequency follows resonant frequency and quasi-ZCS is used as shown figure 8. Wave of 1/2 pulse ratio is shown in Figure 9, where average output voltage of PDM inverter in figure 9 is 1/2 of the maximum output voltage in Figure 8 due to the zero voltage state appears. In addition, the DC input power is 33% of the maximum power that is 1.9kw. The quality factor of corona discharge processor LCR, equivalent circuit, is 10-30 but the quality factor of high-frequency heater system is much smaller as 4.5. So output current converges to zero during zero voltage state even output current is continuous.

Figure 10 shows wave of the minimum output power with a 1/50 pulse ratio. From the figure 10, it can be seen that there is one cycle of square AC wave following 49 cycles zero voltage state. So the 1% of power is 48W when DC input is 5.6kW.

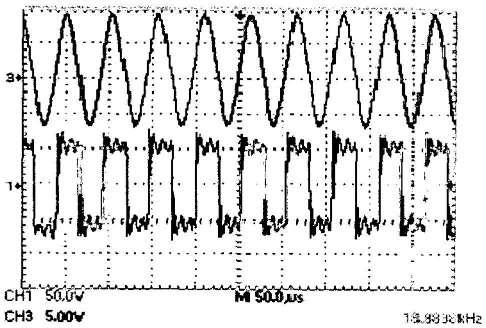

Figure 8 Full power

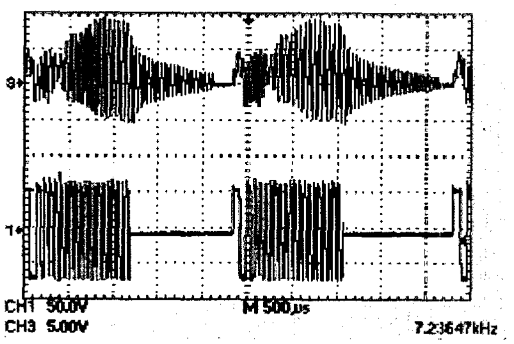

Figure 9 Half power

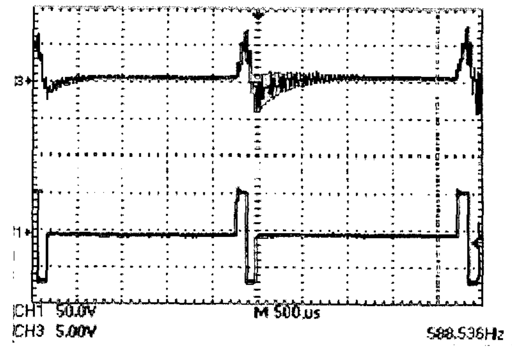

Figure 10 Minimum power

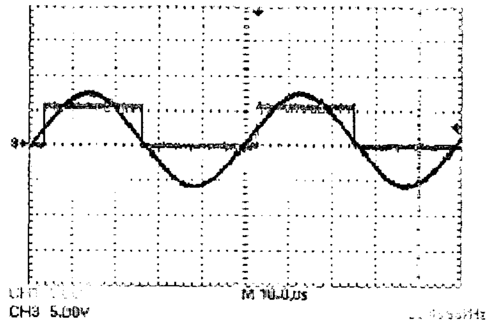

Figure11. Output current and gate signal

Figure 11 shows the gate signal of IGBT and the resonant current with quasi ZCS under maximum power. It can be seen that 1µs dead time is used to avoid circuit short.

5 Result

In this paper a series-resonant PDM inverter for corona dischage system is experimented. This PDM inverter has a wide control range of discharge power of 5-100%, even the current and voltage have intensive nonlinear charac teristics. To reduce switching loss of PDM inverter, ZVS and quasi ZCS technology has been adopted. The applicability of the corona discharge system can be seen in this paper.

References

[1] H. Fujita and H. Akagi. "Pulse-density-modulated power control of a 4kW 450kHz voltage-source inverter for induction melting applications," in IEEE Trans. Industry Appli., vol.IA-32, no.2, pp-.279-286, 1996.

[2] S. Bottari, L. Malesani and P. Tenti, "High frequency 200kHz inverter for induction heating applications," in IEEE/PESC Rec., 1985, pp. 308-316

[3] H. Akagi and A. Nabae, "A voltage-source inverter using IGBT's for a 50kHz 10kV corona surface treater" in IEEE/IAS Annu. Meet., 1989, pp. 1164-1169.

[4] L. A. Rosenthal and D. A. Davis, "Electric characterization of a corona discharge for surface treatment," in IEEE Trans. Industry Appli., vol.I-A-11, no.3, pp. 328-335, 1975