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An Approach to a Broad Range of Power Control in Voltage-Source Series-Resonant Inverters for Corona Discharge Treatment – Pulse-Density-Modulation –

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Abstract— This paper implements a wide range of power control with pulse-density-modulation (PDM) in a voltage-source series-resonant inverter which realizes a corona discharge for surface treatment of film. The use of the pulse-density-modulated inverter, or the PDM inverter, enables the employment of a three-phase diode bridge rectifier as a utility interface. The PDM inverter produces either a square-wave ac voltage state or a zero voltage state at its ac terminals to control the discharge power of a corona surface treater. Moreover, it can achieve zero-current-switching (ZCS) and zero-voltage-switching (ZVS) in all the operating conditions, thus leading to a significant reduction of switching losses and electromagnetic noises. A 30 kHz, 6 kW surface treatment system consisting of a voltage-source PDM inverter, a step-up transformer and a corona discharge treater shows the establishment of a stable corona discharge in an extremely wide range of power control from 0.5 % to 100 %, and therefore succeeds in performing both strong and weak surface treatment processes for film.

I. INTRODUCTION

In recent years, significant progress has been made in switching speed and voltage/current rating of semiconductor power devices such as IGBT's and power MOSFET's. This has made a great contribution to the proliferation of PWM inverters for adjustable speed drives and high-frequency high-power resonant inverters for induction heating applications such as melting and surface quenching [1]-[6].

The purpose of corona discharge treatment is to render the affinity of polyethylene film to ink, glue and coating [7][8]. In general, corona discharge treaters require specially designed ac power supplies of 10-20 kV, 20-50 kHz and 1-40 kW to maintain a stable corona discharge in air at atmospheric pressure. Moreover, the capability of adjusting the affinity and adaptability to various kinds of film differing in thickness and/or material requires an ac power supply capable of controlling the discharge power in a wide range of 1 % to 100 %.

An ac power supply for a corona discharge treater comprises a diode or thyristor bridge rectifier, a voltage-source series-resonant inverter and a step-up transformer with a secondary voltage rating of over 20 kV. The ac power supply basically has the same power circuit topology as that for induction heating except for the use of either a step-up transformer or a step-down transformer. However, the corona discharge treater exhibits a strong nonlinear characteristic of voltage and current. Due to this non-linearity, a

conventional voltage-source series-resonant inverter based on either dc bus voltage control or frequency control [9][10] has difficulty in controlling the discharge power in a wide range of 1 % to 100 %.

This paper introduces pulse-density-modulation (PDM) to a 30 kHz, 6 kW voltage-source series-resonant inverter for corona discharge treatment. A broad range of power control is obtained by the PDM inverter which controls the duration of a zero voltage state at its output terminals in synchronization with the resonant frequency of the series-resonant circuit. Although the "pulse-density-modulation" in this paper is somewhat similar in operating principle to the "discontinuous mode control" in [11], a significant difference in output voltage and current waveforms exists between the two. A sophisticated control circuit based on phase-locked loop (PLL) makes the PDM inverter achieve zero-current-switching and zero-voltage-switching in all the load conditions. The oscillating frequency of the PLL circuit always follows the resonant frequency; nevertheless, the actual average switching frequency of the IGBT's varies in a range of 600 Hz to 30 kHz. An experimental system of 30 kHz and 6 kW verifies the establishment of a stable corona discharge in an extremely wide range of power control from 0.5 % to 100 %.

II. CORONA DISCHARGE TREATMENT SYSTEM

A. System Configuration

Fig. 1 shows the power circuit configuration of a corona discharge treatment system developed in this paper. The 30 kHz, 6 kW inverter consists of a single-phase voltage-source H-bridge inverter using two IGBT modules. Each two-in-one IGBT module is rated at 600 V and 50 A. A lossless snubbing capacitor $C_S = 0.03 \mu\text{F}$ is connected between the collector and emitter of each IGBT, and a high-frequency dc capacitor $C_C = 1 \mu\text{F}$ is connected between the dc terminals of each IGBT module, thus leading to a significant reduction of switching losses. A step-up transformer with ferrite core, the turn ratio of which is 1 : 20, is installed on the ac terminals of the inverter in order to obtain a high voltage of 10-20 kV for corona discharge treatment. This paper addresses a wide range of power control in the voltage-source series-resonant inverter based on PDM. The authors, therefore, exclude a detailed description of such a high voltage high frequency step-up transformer from this

Fig. 1. Corona discharge treatment System.

Fig. 2. Structure of electrodes.

paper, although the design of the transformer becomes as much an electric challenge as the implementation of the PDM inverter is a power electronic challenge.

An equivalent load of the inverter can be considered an LCR series-resonant circuit comprising a leakage inductor of the transformer and a nonlinear lossy capacitor existing between the electrodes of the corona discharge treater. The PDM inverter enables use of a three-phase diode bridge rectifier as an ac/dc power converter.

B. Structure of electrodes

Fig. 2 shows the structure of electrodes in a corona discharge treater for film web. Film passes through an air-gap of around 3 mm between a bar electrode and a grounded roll electrode. The grounded roll electrode is coated with a buffer dielectric to avoid a sudden transition from corona discharge to arc discharge. When an ac voltage of 20-50 kHz and 10-20 kV is applied to the bar electrode, breakdown occurs in the air-gap. During breakdown, corona discharge provides the film passing through the air-gap with the affinity to ink. The capability of adjusting the affinity and adaptability to various kinds of film differing in thick-

ness and/or material requires an ac power supply capable of controlling the discharge power in a wide range of 1 % to 100 %.

However, corona discharge exhibits a strong nonlinear voltage and current characteristic: Almost no discharge current flows while the voltage applied to the bar electrode is less than the breakdown voltage, whereas a large amount of discharge current starts to flow as soon as the electrode voltage is more than the breakdown voltage. This indicates that dc bus voltage control and frequency control, which have been practically applied to conventional voltage-source series-resonant inverters for the purpose of adjusting their output power, would not be able to achieve such a wide range of power control. Notably, a partial or local corona discharge between the bar and roll electrodes would appear during low-power operation, due to a significant drop of the electrode voltage which results from lowering the discharge power.

III. PRINCIPLE OF PULSE-DENSITY-MODULATION

Fig. 3 shows the switching modes of the voltage-source series-resonant PDM inverter. For the sake of simplicity, the combination of the step-up transformer and the corona discharge treater is represented by an LCR series-resonant circuit. A conventional voltage-source series-resonant inverter takes alternate mode I and mode II in Fig. 3 (a) and (b) to produce a square-wave ac voltage state. In addition to modes I and II, the PDM inverter introduces mode III to produce a zero voltage state at its output terminals. During mode III, a gate turn-on signal is provided to both lower leg IGBT's, Q_2 and Q_4 , in half bridge inverters A and B. As a result, both one IGBT and a diode connected in anti-parallel to the other IGBT remain turned on, thus forming a bi-directional free-wheeling circuit for the output current i_O , as shown in Fig. 3 (c).

Fig. 4 illustrates the principle of the PDM-based power control. The PDM inverter frequently repeats "run and stop" in accordance with a control sequence to adjust its

Fig. 3. Switching modes in PDM inverter.

Fig. 4. Principle of PDM control.

average output voltage, synchronized with the resonant frequency of the series-resonant load. Fig. 4 corresponds to the case of a pulse density of 3/4. Taking alternate mode I and mode II every half resonant cycle, the PDM inverter creates the square-wave ac voltage with the amplitude of E for three resonant cycles. For the subsequent resonant cycle, however, the PDM inverter takes mode III during which $v_O = 0$, and therefore produces the zero voltage state. When attention is paid to the four resonant cycles, the output voltage of the PDM inverter is a periodic waveform. Hence, the average output voltage is 3/4 of the maximum output voltage with unity pulse density. Note that no dc component is included in the waveform of the output voltage v_O ; otherwise flux saturation would occur in the step-up transformer with ferrite core.

A PLL-based PDM control circuit discussed in the following section makes the PDM inverter achieve zero-current-switching and zero-voltage-switching, with the help of a $0.03 \mu\text{F}$ capacitor connected across each IGBT.

IV. CONTROL CIRCUIT

Fig. 5 shows a block diagram of the control circuit developed for the PDM inverter. The control circuit is divided

into the following two parts:

- a PLL circuit for phase control between v_O and i_O .
- a PDM circuit for duration control of the zero voltage state.

The PLL circuit consists of a phase detector (PD), a low-pass filter (LPF1) and a voltage-controlled oscillator (VCO), along with an analog switch (AS) and a peak current detector (PCD). Because it is impossible to precisely detect a very small amount of current, a conventional PLL circuit does not work properly during weak surface treatment which needs to lower the discharge power into 1-10 % of the full power. The combination of the AS and the PCD plays an important role in solving the problem. The output signal from the PCD opens and closes the AS which is installed on the input side of the LPF1. When the peak value of the output current is larger than a preset level, the AS remains closed, thus resulting in a conventional PLL circuit. On the other hand, when the peak value is smaller than the preset level, the AS remains opened. In this case, a $0.068 \mu\text{F}$ capacitor in the LPF1 enables the VCO to continue oscillating at the same frequency as the operating frequency of the VCO just before opening the AS. The $0.068 \mu\text{F}$ capacitor, along with the opened analog switch, acts like a memory device storing the resonant frequency of the series-resonant load.

The part enclosed with a broken line in Fig. 5 corresponds to the PDM control circuit based on feedback control. The average output voltage reference $\bar{V}_O^*$ adjusts the duration of the zero voltage state. The actual average output voltage $\bar{V}_O$ is obtained from a logic signal corresponding to the actual zero voltage state M via a low-pass filter (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. The inverter output voltage v_O has various low frequency components caused by the PDM control. The most dominant frequency is 600 Hz ($=30/50$ kHz) under the conditions of a resonant frequency of 30 kHz and a pulse density of 1/50. Therefore, the cut-off frequency of the LPF2 is designed to be 160 Hz. Comparison of $\bar{V}_O^*$ with $\bar{V}_O$ by means of an analog comparator generates a logic signal of the zero voltage state reference M^* , choosing which output the PDM inverter produces, either the square-wave ac voltage state or the zero voltage state for the subsequent resonant cycle. A synchronizing circuit produces and holds the logic signal M in synchronization with a logic signal from the VCO. A logic "AND" circuit produces alternate mode I and mode II during the square-wave ac voltage state of $M = 1$, whereas it produces mode III during the zero voltage state of $M = 0$. Note that mode II always follows mode I because the logic signal M does not change for at least one resonant cycle. Hence, no dc component is included in the output voltage v_O . However, each gate signal includes a dc component, and therefore a photo-coupler taking the place of a pulse transformer achieves electric isolation of a gate signal in the control circuit from the corresponding gate drive circuit. Although the sophisticated PDM control circuit cannot continuously adjust the pulse density in theory, it is considered to have

Fig. 5. Block diagram of control circuit.

Fig. 6. Experimental waveforms in case of full-power operation.

Fig. 8. Experimental waveforms in case of minimum output power by using PDM control (pulse density 1/50).

Fig. 7. Experimental waveforms in case of FDM control (pulse density 1/2).

Fig. 9. Voltage and current waveforms of electrodes in case of dc voltage control.

the capability of performing continuous power control in practice because it forms feedback control based on the detected average output voltage.

V. EXPERIMENTAL RESULTS

Figs. 6 to 8 show experimental waveforms of the inverter output current and voltage, i_O and v_O , under the condition of a constant dc bus voltage of $v_d = 250$ V.

Fig. 6 corresponds to the case of maximum power operation at unity pulse density by producing no zero voltage state. The dc input power of the inverter is 5.6 kW. Fig. 7 shows experimental waveforms during operation at a

pulse density of 1/2. The PDM inverter creates alternating square-wave ac voltage states and zero voltage states, and therefore the average output voltage is half the maximum output voltage shown in Fig. 6. The dc input power is 1.9 kW, which is only 33 % of the maximum power of 5.6 kW. The quality factor of the LCR series-resonant circuit equivalent to the corona discharge treater including the step-up transformer is 4.5, which is much smaller than the quality factor of 20-30 in high frequency induction heating systems. Therefore, the amplitude of the output current decays to 60 % in the duration of the zero voltage state although i_O

Fig. 10. Voltage and current waveforms of electrodes in case of PDM control.

Fig. 11. Relationships between dc input power and maximum voltage of v_2 .

is continuous.

Fig. 8 shows experimental waveforms in the case of minimum power operation at a pulse density of 1/50. The PDM inverter produces the square-wave ac voltage state once every fifty resonant cycles, and it continues to produce the zero voltage state for the other forty nine resonant cycles. The dc input power is 28 W, which is only 0.5 % of 5.6 kW. Note that the inverter output current i_O decays and reaches a value of zero in the duration of the zero voltage state, resulting in significant difficulty to detect it. Opening the analog switch AS in Fig. 5 prevents the capacitor in the LPF1 from discharging, and thus results in continuous oscillation of the VCO at the same frequency as the operating frequency of the VCO just before opening the AS. As a result, the output frequency of the inverter in the duration of the subsequent square-wave ac voltage state coincides with the resonant frequency of the corona discharge load.

Figs. 9 and 10 show measured waveforms of the bar electrode voltage, v_2 , and the discharge current, i_2 , under the conditions of a dc bus voltage of 200 V¹ and a dc input power of 1.9 kW. The bar electrode voltage and the discharge current are identical to the secondary voltage and current of the step-transformer, respectively. Fig. 9 shows the measured waveforms under the dc bus voltage of 140 V at unity pulse density. The amplitudes of v_2 and i_2

¹Because of the use of a 20 kV probe in this measurement, the dc bus voltage is reduced from 250 V to 200 V for safety.

Fig. 12. Relationships between dc input power and average switching frequency f_{sw} .

are constant due to the dc bus voltage control, and the maximum voltage of v_2 is 13 kV. Fig. 10 corresponds to the case of the PDM control at a pulse density of 2/3. Although the amplitudes of v_2 and i_2 fluctuate, the maximum voltage of v_2 is 16 kV.

Fig. 11 shows experimental relationships between the dc input power and the maximum voltage of v_2 . As the dc input power is gradually lowered from 3.6 kW, the electrode voltage sharply decreases in both the dc bus voltage control and the frequency control cases, and then it drops to less than 10 kV at 1 kW, accompanied by a partial corona discharge in the air-gap. On the other hand, the PDM control can keep the maximum voltage of v_2 being 15 kV when the dc input power is lowered from 3.6 kW to 1.5 kW. As the dc input power is lowered from 1.5 kW, the electrode voltage gradually decreases, and then it drops to less than 10 kV at 0.1 kW; nevertheless, a stable corona discharge is maintained equally throughout the air-gap.

Fig. 12 shows experimental relationships between the dc input power and the average switching frequency f_{sw} . Note that the average switching frequency is defined by the actual switching times per second. The average switching frequency in the PDM control is lower than the resonant frequency except for operation at unity pulse density, whereas the average switching frequency in either the dc bus voltage control or the frequency control is always equal to the resonant frequency. Because of the strong nonlinearity of corona discharge, the resonant frequency goes up as the dc input power goes down. The reason is as follows: During strong corona discharge treatment, the air-gap between the electrodes is so gaseous as to be considered a short-circuit state. As a result of the short-circuit state, the total capacitance between the electrodes is nearly equal to the capacitance existing in the buffer dielectric with which the grounded roll electrode is coated. In the contrast, during weak corona discharge treatment, the total capacitance decreases because the capacitance equivalent to the air-gap is connected in series to the buffer capacitance.

When the PDM inverter continuously produces the zero voltage state, no switching occurs in any of the four

Fig. 13. Corona discharge in case of full-power operation (dc input power 3.6 kW).

Fig. 15. Corona discharge in case of PDM control (dc input power 0.1 kW).

Fig. 14. Corona discharge in case of dc voltage control (dc input power 0.1 kW).

Fig. 16. Corona discharge in case of PDM control (dc input power 16 W).

IGBT's. The average switching frequency significantly goes down, thus contributing to a considerable reduction of the switching loss during low-power operation.

Figs. 13 to 16 are photographs focusing on a discharge state around the electrodes during corona discharge treatment in the case of no film passing over the roll electrode. Fig. 13 corresponds to the case of maximum power operation at unity pulse density, where the dc bus voltage is 200 V and the dc input power is 3.6 kW. Figs. 14 and 15 are photographs taken under the same condition as the dc input power of 0.1 kW. Fig. 14 corresponds to the case of dc voltage control, where the dc bus voltage is reduced to 20 V under unity pulse density. Fig. 15 corresponds to the case of PDM control, where the pulse density is reduced to 1/14 under the constant dc bus voltage of 200 V. Because of a significant voltage drop between the electrodes, a local discharge occurs during dc voltage control, as shown in Fig. 14. In the case of PDM control, however, a stable discharge is observed equally throughout the electrodes, as shown in Fig. 15.

Fig. 16 is a photograph taken during minimum power operation, where the pulse density is the lowest value of 1/50 under the constant dc bus voltage of 200 V. Even in such an extremely low-power discharge as the dc input power of 16 W, that is, 0.5 % of 3.6 kW, the PDM inverter succeeds in establishing a stable discharge without producing any partial or local discharge. Since the resonant frequency in the experimental corona discharge load is about 30 kHz, discharge power fluctuates at 600 Hz ($\approx 30/50$ kHz) in the

case of a pulse density of 1/50. In usual corona discharge treatment systems, the sending speed of film is 1-2 m/s, and the width of the bar electrode is around 20 mm. While film passes between the electrodes, the PDM inverter operating at a pulse density of 1/50 produces the square-wave ac voltage state 6-12 times. This suggests that the surface treatment is thorough, without inequalities. In fact, experiments verify that the PDM control has no bad effects on surface treatment of film.

VI. CONCLUSIONS

This paper has proposed a voltage-source series-resonant PDM inverter for corona discharge treatment. The PDM inverter has enabled control of the discharge power in a wide range of 0.5 % to 100 % so as to perform both strong and weak surface treatment processes for film. In addition, the PDM inverter can achieve ZCS (zero-current-switching) and ZVS (zero-voltage-switching) in all operating conditions, thus leading to a significant reduction of switching loss and electromagnetic interference.

The experimental system consisting of a 30 kHz, 6 kW voltage-source PDM inverter, a step-up transformer with a turn ratio of 1 : 20, and an actual corona discharge treater has verified the viability and effectiveness of the PDM inverter for corona discharge treatment.

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