ADVANCED DEVELOPMENT OF PDM AND PWM HYBRID-BASED VOLTAGE-SOURCE TYPE SERIES INDUCTOR COMPENSATED RESONANT INVERTER FOR OZONIZER

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This paper presents a high-frequency voltage source-fed load-resonant IGBT inverter with a series-compensated resonant inductor and a high-voltage transformer for ozone generating tube drive, which operates under a principle of the PDM(Pulse Density Modulation) and PWM based power control strategy. The high-frequency inverter is composed of a high-voltage transformer series compensated inductor and ozone generating tube which is based on silent discharge principle. The state-of-the art efficient ozonizer incorporating a voltage-fed type high-frequency load resonant inverter with PDM and PWM control scheme is demonstrated, and its operating principle is described for ozone generating tube driving. It is noted that the pulse density modulated series resonant high-frequency inverter using IGBTs makes an ozone generating system simple, thus leading to improve the ozone generation efficiency. Finally, it is proved in feasible experiment and simulation that the series load-resonant inverter type ozonizer developed in this paper provides stable silent discharge characteristics over a wide output power range from 10% to 100%.

Key Words: *Voltage-Source Type Inverter, PDM, PWM, Load Resonant, High-Frequency High-Voltage Transformer, Silent Discharge Type Ozonizer*

1. INTRODUCTION

In recent years, ozone gas has been widely utilized for chemical processing of water and exhausted smoke, deodorization, color removal and disinfection in pipeline systems. Because ozone gas has an strong oxidizing power, which is widely used as well as fluorine. It is however mentioned that a variety of applications of ozone gas is hindered primarily because of its low efficient ozone gas generation. Thus, it is indispensable to improve actual or conventional efficiency of the silent discharge ozonizer using resonant inverter, which is composed of series-compensated inductor, high-voltage transformer, and ozone generating tube assemblies. In order to raise its ozone gas generating characteristics, a pulse density modulation(PDM)-based power control scheme is effectively introduced for the ozone generating appliances.

This paper presents a prototype of high performance ozonizer using the voltage-fed IGBT load-resonant inverter with a series-compensated resonant inductor and high-voltage transformer, which is designed so as to regulate the output power at a constant frequency on the basis of the digitally-controlled pulse density modulation (PDM) and PWM hybrid scheme. According to this control strategy, the output power of this inverter can be linearly regulated as compared with the other control strategies. The ozonizer prototype developed in this paper provides excellent ozone generating characteristics over a wide output power range from 10% to 100%.

The simulation analysis of voltage-fed load resonant inverter operating under a principle of a constant frequency PDM for ozonizer including the circuit models of high-frequency is carried out high-voltage transformer and silent discharge type ozone generating tube. Its output regulation characteristics is illustrated in this paper. The experimental results of load resonant inverter type of power supply using IGBTs for ozonizer are shown and discussed.

2. SILENT DISCHARGE OZONIZER

In general, it is known that the ozone gas can be produced on the basis of silent discharge phenomena, radiative irradiation, electrolytic, optochemical reaction and so forth. Among them, the silent discharge is most widely used in the fields of various industry. The basic principle of ozone gas generation based on silent discharge is illustrated including in Fig.1.

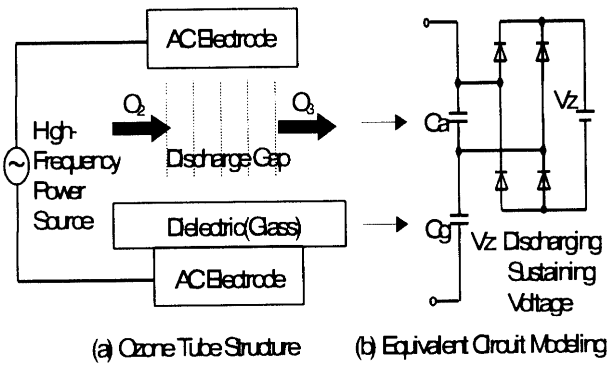

Fig.1 Principle of Silent Discharges Type Ozonizer.

A high-frequency AC exciting voltage generated by the power supply using voltage-fed high-frequency load resonant inverter with a high-voltage transformer is applied to ozone generation tube with two electrodes. This is basically composed of the discharge gap and the dielectric material of glass inserted partially between two electrodes, which are shown in Fig.1(a). The equivalent circuit model of the silent discharge type ozonizer is indicated as Fig.1(b). A component of the discharge gap between two electrodes includes a capacitance Ca in series with the capacitance Cg of the glass material substrate when the silent discharge in this ozone generating tube does not occurred. On the other hand, the discharge voltage source Vz named as discharging sustaining voltage is equivalently connected in parallel with the discharge gap capacitance Ca as soon as the silent discharge generates between two electrodes. In addition to this, the part of glass dielectric substrate is illustrated as a capacitor Cg in series with Ca.

3. HIGH-FREQUENCY INVERTER SYSTEM

Fig.2 shows a total configuration of power conversion processing system for an ozonizer which is used voltage source-fed type series compensated inductor load resonant inverter using IGBT modules. The DC power supply of this inverter consists of three-phase bridge rectifier with a DC smoothing capacitor. Three-phase diode rectifier is effectively replaced by the active three-phase power factor correction converter using IGBTs which operates at a sinewave current shaping and unity power factor schemes. This power conversion processor consists of a single-phase voltage source-fed type full-bridge inverter at a high frequency switching. The high-frequency output circuit of this load-resonant inverter is connected to a series-compensated resonant inductor in the primary side of a high-frequency transformer with ozone generating tube.

In order to achieve the effective discharge on the air gap portion between two AC electrodes of ozonizer, it is necessary to apply a high frequency and high voltage AC to two electrodes.

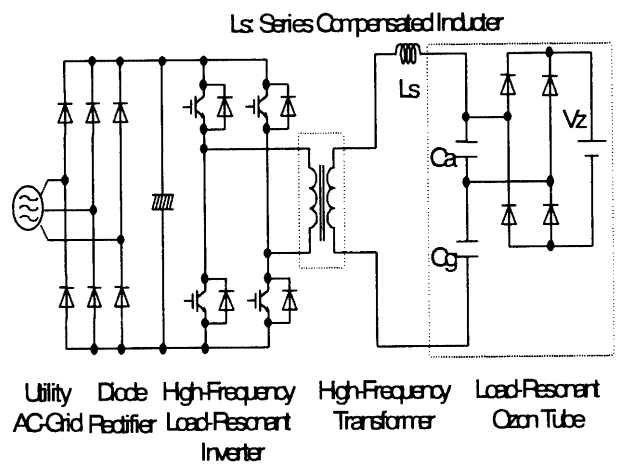

Fig.2 System configuration of load resonant inverter-fed type ozonizer

The ozone generating tube is illustrated with a capacitive load with the voltage source Vz (discharge sustaining voltage) in spite of discharging or non-discharging in the air gap and series compensated inductor, so this type of high-frequency inverter with a voltage matching high-voltage transformer is practically introduced for ozonizer. This capacitive quantity load circuit with the capacitance Ca of the gap in series with the capacitance Cg of the glass dielectric substrate as the ozone generating tube is compensated by a series inductance Ls including the leakage inductance of high-frequency high-voltage transformer. Practically strictly speaking, the capacitive load parameter is changed in accordance with some discharge conditions during discharge period, the discharge sustaining voltage Vz between air gaps is equivalently connected in parallel with discharge gap capacitance Ca. The switching frequency of voltage-fed load resonant inverter using IGBTs is designed for 7 kHz. The optimum value of the series-compensated inductor Ls is estimated so as to realize a series tuned resonant condition by using the computer-aided simulation technique.

4. POWER REGULATION CHARACTERISTICS

In order to adjust a production quantity of ozone gas, it is dispensable to regulate a discharge power in the inverter type ozonizer. Fig.3 illustrates the relationship between the output power of this inverter and ozone production quantity.

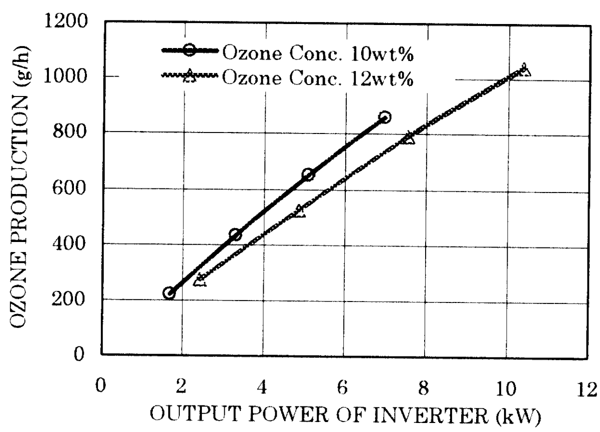

Fig.3 Relationship between inverter output power and ozone production quantity

A peak voltage across two AC electrodes must keep sustaining a stable discharge during a discharge, even though an output power of the inverter is lowered. The inverter power regulation principle of PDM control strategy is basically illustrated in Fig.4. The effective power delivered from the ozone generating tube can be continuously controlled by means of high-frequency ac pulse density modulation. This modulation procedure is based upon a time ratio control of high-frequency ac voltage pulse group which is generated by the voltage-fed load resonant inverter, which operates at a constant frequency of 7kHz in experiment.

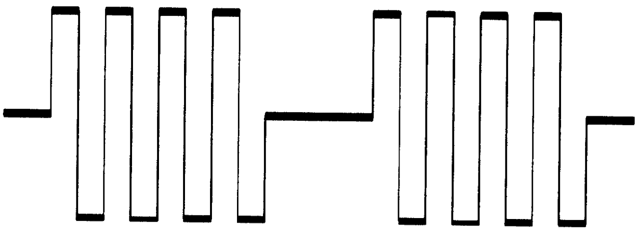

Fig.4 Principle of PDM strategy

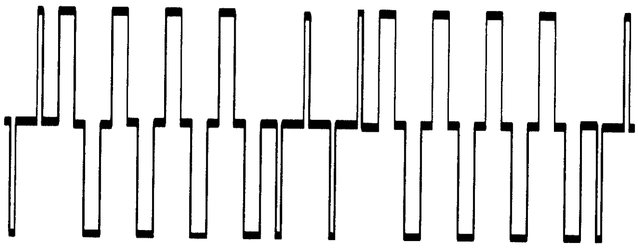

Fig.5 Principle of PDM&PWM hybrid strategy

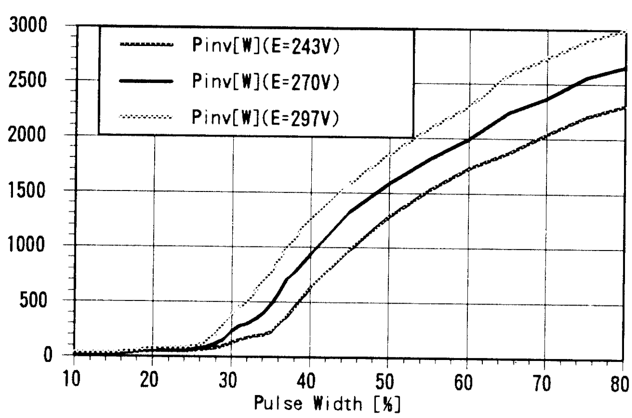

Fig.6 Relationship between output power and pulse width

In this ozonizer, PDM and PWM hybrid-based power control method is effectively introduced for ozone generating tube load. The principle of PDM and PWM hybrid-based power control strategy for this inverter is shown in Fig.5. In case of no power injection mode in PDM control scheme, the additional PWM control is more effective to increase the rising time of the injected current flowing through two electrodes when the power of ozone generating tube is to be delivered from the inverter.

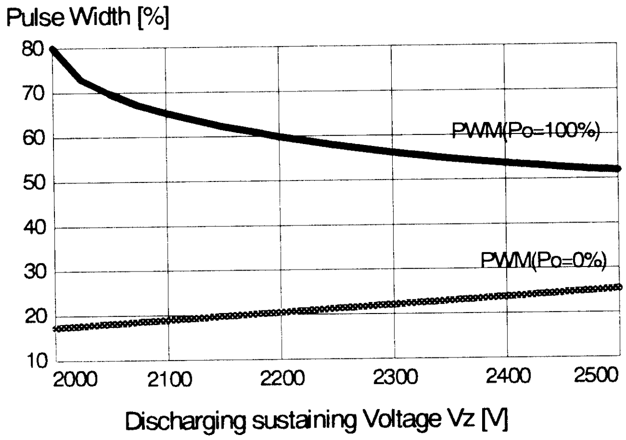

Fig.7 Relationship between pulse width and discharging sustaining voltage Vz

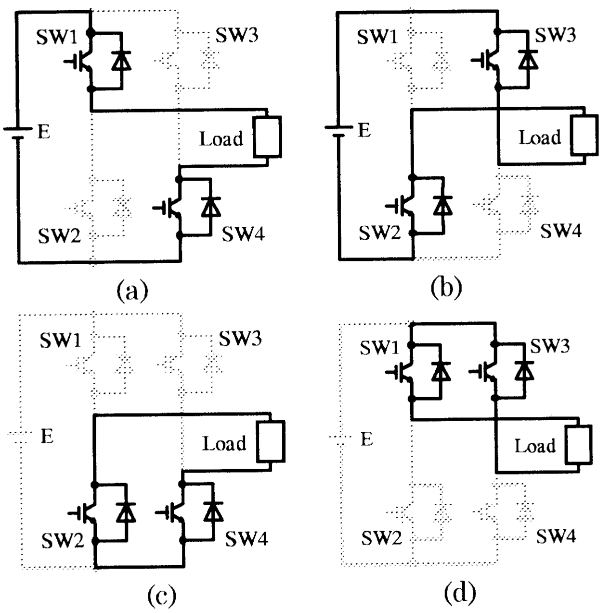

Fig.8 Operating Modes of inverter

In order to regulate the output power of the load resonant inverter, it is necessary to modulate the pulse width in accordance with the input side voltage fluctuations of this inverter as well as the variations of discharging sustaining voltage Vz. The relationship between the output power of inverter and pulse width under condition of the input side steady-state voltage source variations with in±10% is given in Fig.6. In addition, the relationship between the pulse width and the discharging sustaining voltage Vz is in Fig.7.

Fig.8 illustrates the operating modes of voltage-fed series load resonant inverter using IGBTs for ozonizer when the output power is regulated by pulse density modulation.

5. PERFORMANCE EVALUATIONS

Fig.9 shows an experimental set-up of ozone generation system. This system is made up of three major sections, the DSP-based control board, the voltage-fed high-frequency load resonant inverter type power supply, and the ozone generating equipment.

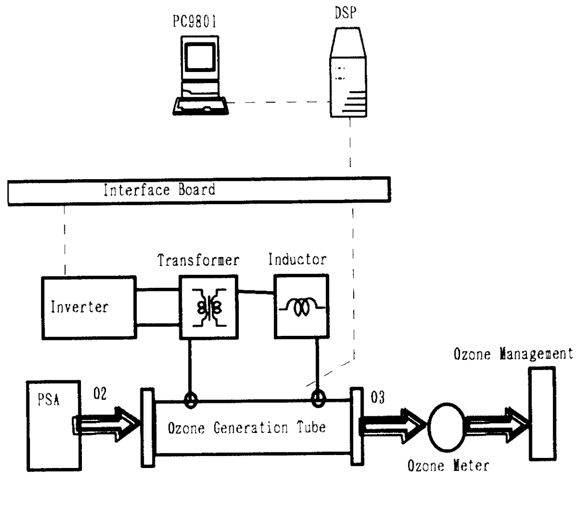

Fig.9 Set-up of ozone generation system

The inverter operating waveforms which are obtained by a new PDM&PWM hybrid regulation scheme are shown in Fig.10 in case of Pulse Density Modulation rate 15%. These measured waveforms are illustrated in Fig.11. The experimental voltage and current waveforms of ozone generating tube are illustrated in Fig.12. The operation in steady-state includes positive polarity-based charging and discharging modes in ozone generating tube as well as negative polarity-based charging and discharging modes in the ozone generating tube.

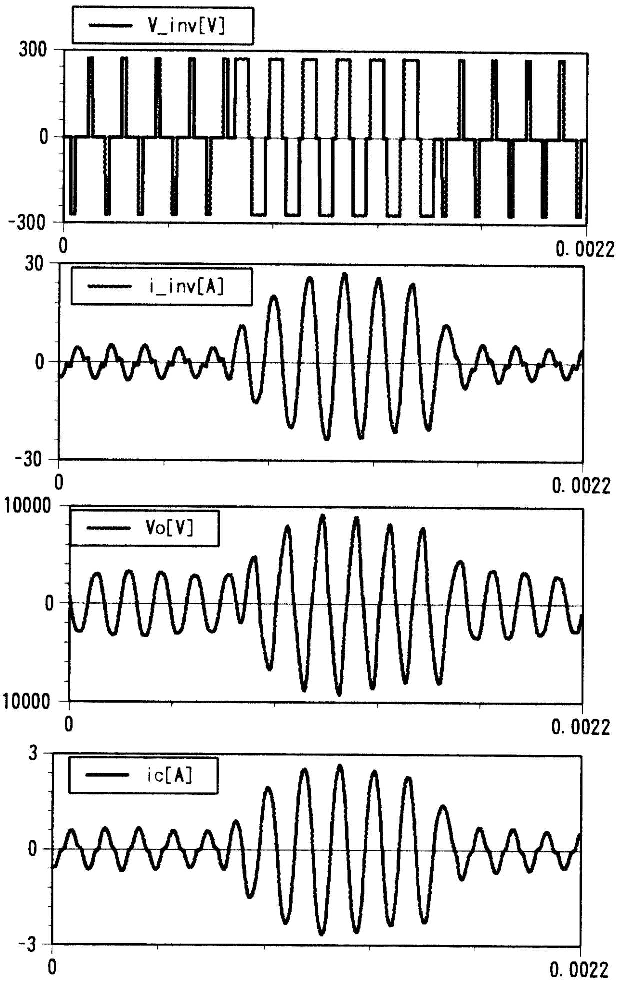

Fig.10 Voltage and current waveforms in PDM&PWM hybrid strategy

The silent discharge in the ozone generating tube does not caused when a voltage across its discharge gap is below a certain voltage value to start a discharge phenomena occurred in this gap. The voltage across the discharge gap in a discharge mode maintains the voltage Vz when this gap voltage exceeds a specified voltage to start a silent discharge. The silent discharge type ozone generating tube has a non-linear characteristics. So, the applied voltage across the ozone generating tube has to be a specified peak value (9kV-10kV). In this case, the power is delivered from the high-frequency load-resonant inverter. If the applied high-frequency AC voltage across two AC electrodes is much lower, the discharge phenomena doesn't occur at all and reveals a partial discharge phenomena. To raise over a voltage across two electrodes, the electrical insulation is distracted on an edge of an ozone generating tube and an arc discharge generates around two AC electrodes.Fig.13 shows lissajous figure of the ozone generating tube for discharging period, non-discharging period and incomplete discharging period when the output power of the inverter is regulated under PDM&PWM hybrid controlled scheme. The internal area of lissajous figure illustrated as *v-q* characteristics of ozone generating tube is proportional to an output power.

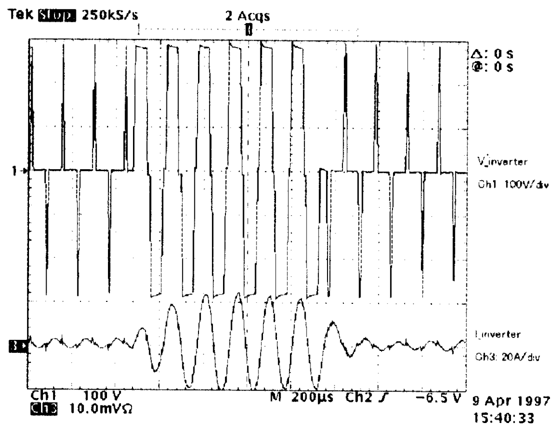

Fig.11 Experimental output voltage and current waveforms of the inverter

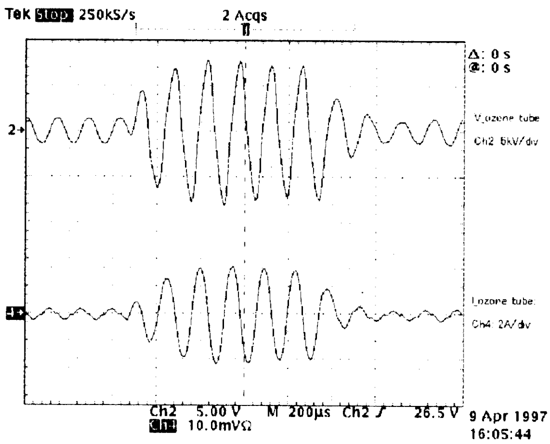

Fig.12 Experimental voltage and current waveforms of ozone tube

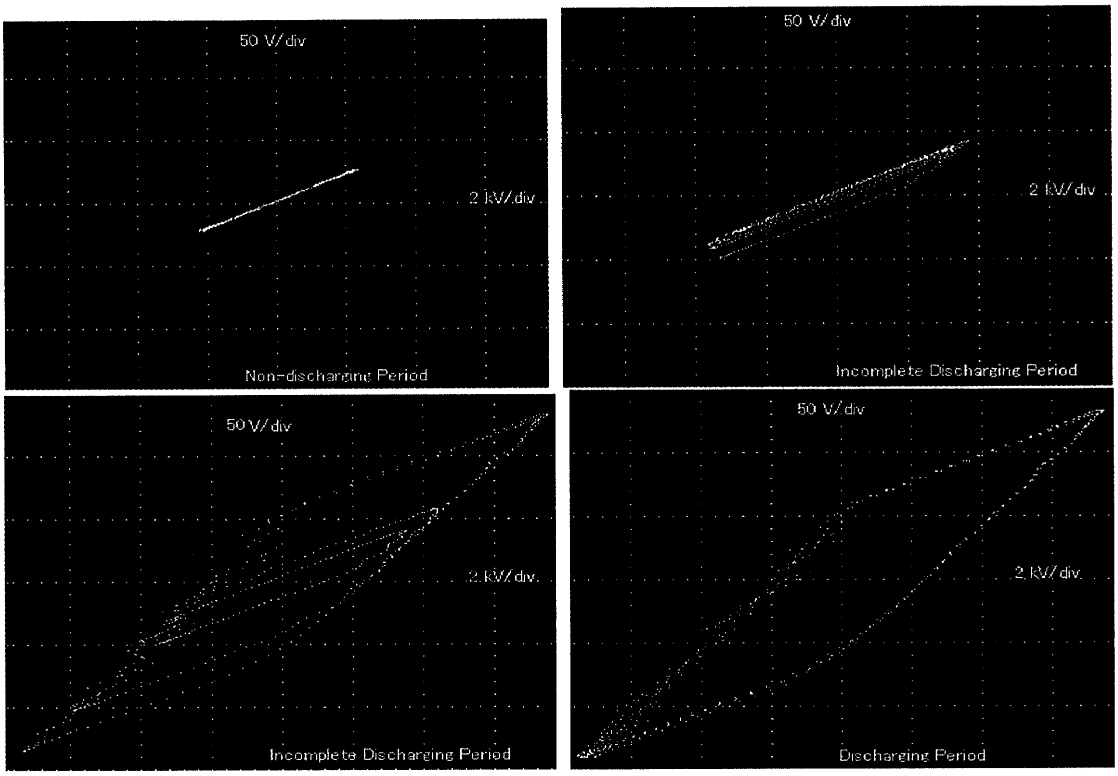

Fig.13 Lissajous figure

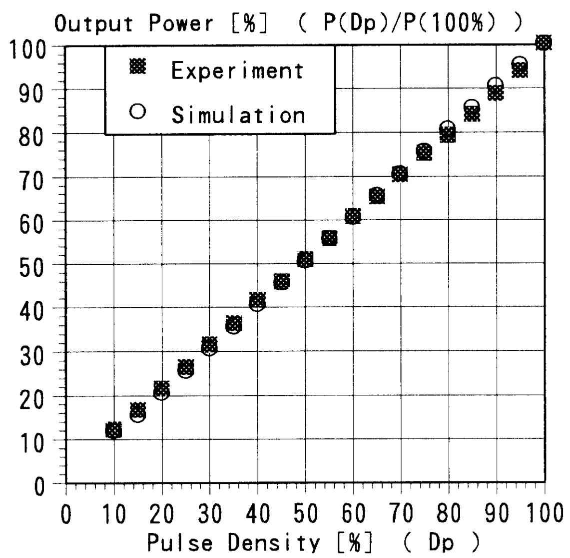

Fig.14 Steady-state characteristics in case of PDM and PWM hybrid control scheme

Fig.14 indicates a relationship between pulse density modulation rate and output power of this inverter. The PDM and PWM hybrid control scheme under a constant output frequency of the load resonant inverter is more effective in order to maintain a stable discharge when the output power delivered to the ozone generating tube is lowered. The output power on the basis of this PDM and PWM hybrid scheme is regulated linearly over wide ranges within duty ratio 10 % to 100 %.

6. CONCLUSIONS

A novel prototype of DSP-based PDM and PWM hybrid mode series inductor compensated load-resonant inverter using IGBT modules has been developed for high-performance silent discharge type ozonizer. The operating principle of this inverter working under PDM and PWM hybrid control strategy has been described as the ozone generating tube drive and evaluated for high-performance ozonizer, along with the power regulation performances of the ozonizer as well as the other ozonizer characteristics. The circuit model of ozone generating tube and the inverter analysis are carried out and the performance of this inverter-fed ozonizer have been replanted through the simulation and experimental results. The effectiveness of the ozonizer using voltage source type load resonant inverter with DSP-based PDM&PWM control scheme has been demonstrated from an experimental point of view.

In this future, a PDM and PWM mode voltage-fed high-frequency load resonant inverter using next generation IGBTs for ozonizer which can operate under a principle of soft-switching transition scheme should be investigated and evaluated. In addition to this, the silent discharge ozonizer using a current-fed type soft-switching load resonant inverter with PWM strategy has to be practically evaluated as compared with the ozonizer using voltage-fed type soft-switching load resonant inverter with PDM and PWM hybrid control strategy.

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オゾナイザ用 PDM&PWM 制御方式電圧形高周波負荷共振インバータの開発

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本論文は、無声放電(SD)式オゾン発生管駆動用電圧形高周波負荷共振インバータを考察の対象とし、そのシステム構成,と回路モデリング、動作原理および PDM&PWM ハイブリッド制御による電力制御特性について述べている。本論文で提案する電圧形共振インバータの PDM&PWM ハイブリッド制御によれば、オゾン発生管への出力電力が 10%～100%の広範囲にわたって電力指令に対し線形制御できオゾナイザ応用における有効性が明らかになっている。