EFFICIENT OZONIZER USING VOLTAGE-SOURCE LOAD RESONANT INVERTER WITH PDM AND PWM CONTROL IMPLEMENTATION

Yoshihiro Konishi
Design Depertment, Kobe Factory,
Fuji Electric Co. Ltd., 651-2271, JAPAN

Shengpei Wang, Shinya Shirakawa and Mutsuo Nakaoka
Depertment of Electrical & Electronics Engineering,
Yamaguchi University, Yamaguchi, 755-8611, JAPAN

ABSTRACT- In this paper, the voltage-fed series compensated inductor type load-resonant high-frequency inverter is originally presented for driving a newly-developed silent discharge ozone generating tube. The effective power regulation scheme of this ozonizer is proposed, which is based on PDM (Pulse Density Modulation) related PWM strategy due to DSP implementation. The effectiveness of this inverter type ozonizer is proved in simulation and experiment.

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. It is however mentioned that a variety of applications of ozone gas are hindered primarily because of its low efficient ozone gas generation. Thus, it is more indispensable to improve actual system efficiency of the silent discharge type ozonizer using load resonant inverter, which is composed of series-compensated inductor, high-voltage transformer, ozone generating tube assemblies and its control system. In order to raise the ozone gas producing performances, a PDM based power regulation scheme is effectively introduced for the ozone generating installations in industry.

According to this control strategy of the inverter type ozonizer, the output power of this inverter can be linearly regulated as compared with the other control strategies. The inverter type ozonizer developed in this paper provides excellent ozone generating characteristics over a wide output power regulated range from 10% to 100%. The simulation analysis of the voltage-source type load resonant inverter operating under a principle of a constant frequency PDM and PWM hybrid control scheme is carried out considering the circuit models of high-frequency high-voltage transformer and silent discharge type high concentration ozone generating tube.

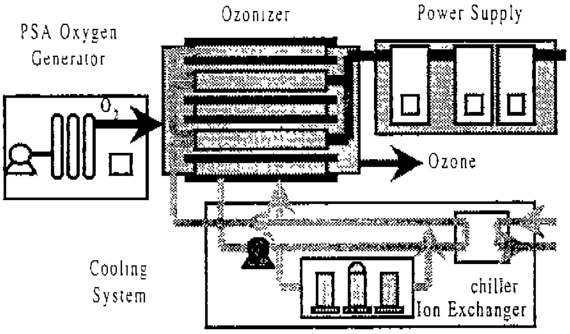


Fig.1 Schematic system diagram of ozonizer

2. SILENT DISCHARGE OZONIZER

In general, it is clearly understood 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 industrial applications. The schematic circuit diagram of ozone generating system using the high-frequency inverter is shown Fig.1. Main blocks of this schematic configuration include PSA (Pressure Swing Adsorption) oxygen generator; silent discharge type ozonizer; power supply system and cooling system.

The internal structure of a novel high-concentration high-efficient ozone generating tube based on silent discharge is illustrated including in Fig.2. It is cylindrical and has a ground electrode on the outside and a high voltage electrode on the inside. Supplying oxygen gas from the left side of the tube and applying a high voltage creates a silent discharge, which converts some of the oxygen into ozone. The ground electrode is made of stainless steel and is lined internally with a glass layer as a dielectric. This glass lined ground electrode has the following features; (a) The ground electrode and the glass are in a close contact, providing high cooling efficiency and superior strength. (b) The glass has only a slight bend, and has a high precision discharge gap length. (c) The ground electrode is sealed with an O-ring and is detachable when a regular inspection is performed. The high voltage electrode is also made of the stainless steel and can be directly cooled by the internal circulation of ion exchange water. The radius of the high voltage electrode can be adjusted by shaving the surface of the AC electrode.

This is a newly-developed high-frequency (7kHz) silent discharge type ozone generating tube. With silent discharge type ozone generating tube mentioned above, a parallel quadrilateral lissajous figure of voltage vs. charge Q is shown as Fig.3, which is drawn by oscilloscope. The area of lissajous figure corresponds to discharge energy of one period of AC voltage-source. The discharge power can estimate by multiplying AC voltage frequency for area of lissajous figure. At this lissajous figure, discharge period (A→B, C→D) and non-discharge period (B→C, D→A) illustrates a certain inclination, respectively. The former illustrates a silent electricity capacity Cg of dielectric. The latter shows series synthetic capacity with gap silent electricity capacity Ca and Cg. Again, the value which crosses the voltage axis of lissajous figure expresses 2Vz (discharging sustaining voltage).

The equivalent circuit model of the silent discharge type ozonizer is indicated as Fig.4. A component of the discharge gap between two AC 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.

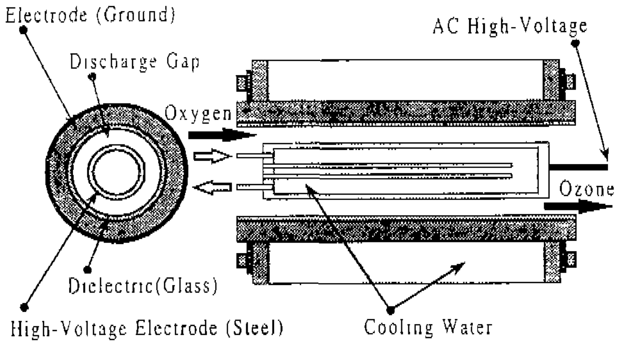


Fig.2 Structure of a novel high-concentration high-efficient ozone generating tube

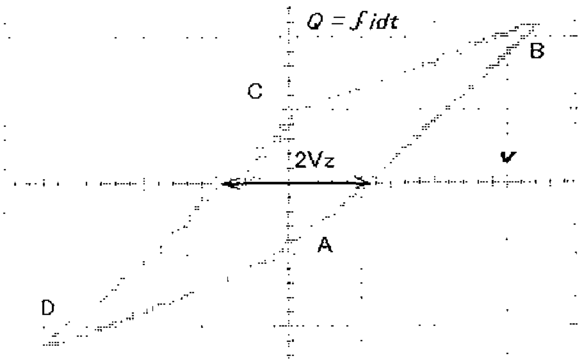
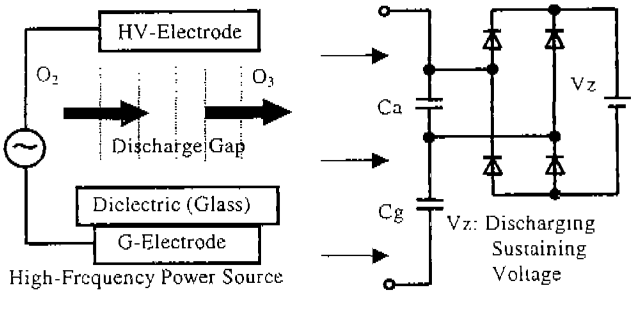


Fig.3 V-Q lissajous figure of silent discharge type ozone generating tube



(a) Ozone Tube Structure (b) Equivalent Circuit Modeling

Fig.4 Equivalent circuit model of silent discharge type ozonizer

3. HIGH-FREQUENCY INVERTER SYSTEM

Fig.5 displays a total configuration of power conversion processing system for an ozonizer which incorporates a voltage source-fed series-compensated inductor type load resonant inverter using IGBT modules. The DC power supply of this inverter consists of three-phase bridge rectifier with a DC smoothing capacitor. This power conversion conditioner consists of a single-phase voltage source-fed type full-bridge load resonant inverter operating 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 secondary side of a high-frequency transformer, which is incorporated with the 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. 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 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. These capacitive load parameters are changed in accordance with some discharge conditions during discharge period. On the other hand, the discharge sustaining voltage Vz between air gaps is equivalently connected in parallel with discharge gap capacitance Ca. The switching frequency of the voltage-fed load resonant inverter using IGBTs is designed for 7 kHz.

4. POWER REGULATION CHARACTERISTICS

In order to adjust a production quantity of ozone gas, it is necessary to regulate a discharge power from the voltage-fed inverter type ozonizer. Fig.6 illustrates the relationship between the output power of this inverter and ozone production quantity.

A peak voltage between two AC electrodes must keep sustaining a stable discharge during a discharge, even though an output power of the inverter is reduced. The inverter power regulation principle of PDM control strategy is basically illustrated in Fig.7. The effective power delivered from the ozone generating tube can be continuously controlled by means of high-frequency ac pulse density modulation procedure. This modulation method 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.

In this ozonizer, the 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 depicted in Fig.8. In case of no power injection mode in PDM control scheme, the PWM-related control approach 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.

The proposed PDM inverter can repeat alternate run and stop to adjust the average output power, even when both the operating frequency and the DC voltage are kept constant.

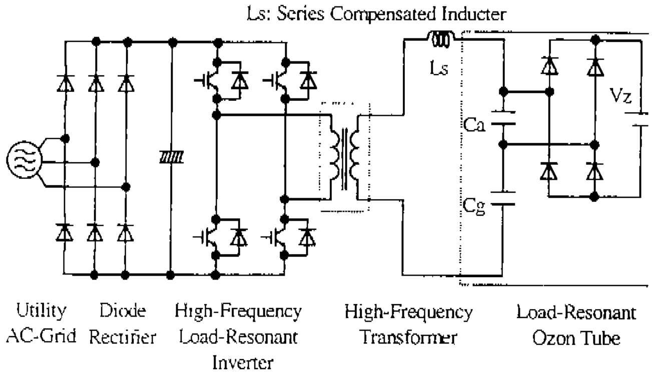


Fig.5 System configuration of load resonant inverter-fed type ozonizer

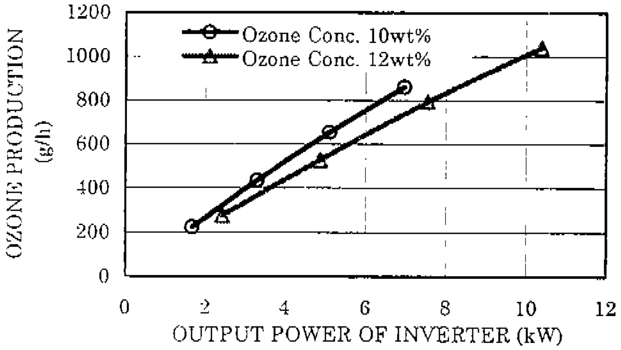


Fig.6 Relationship between inverter output power and ozone production quantity

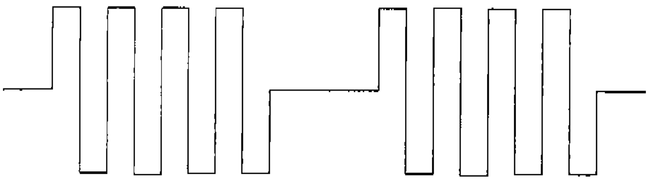


Fig.7 Principle of PDM strategy

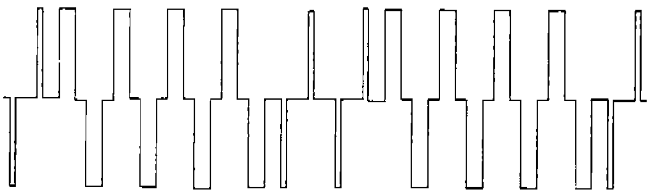
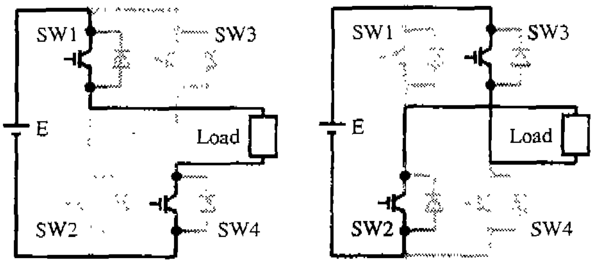
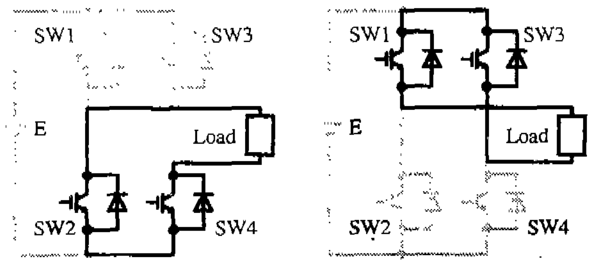


Fig.8 Principle of PDM and PWM hybrid strategy

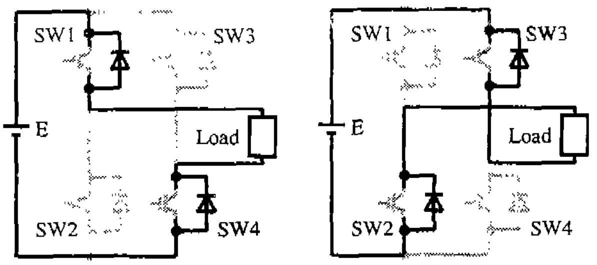
Fig.9 illustrates the operating modes of voltage-fed series load resonant inverter using IGBTs for ozonizer when the output power is regulated by PDM. Conventional frequency controlled inverters have only two switching modes such as modes (a) and (c), while the PDM&PWM control inverter additionally has mode (b), in which the output voltage of the inverter is zero.



(a) Power delivering mode



(b) Free-resonance mode



(c) Power regenerating mode

Fig.9 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.10. In addition, the relationship between the pulse width and the discharging sustaining voltage Vz is in Fig.11.

The peak voltage of ozone generating tube can't be kept a certain value when PDM serial pulse number is lower. So it is required to find out the optimum minimum pulse number. Fig.12 (a) shows the characteristic of peak voltage across the ozone tube for varying serial pulse number. When PDM serial pulse number is more than two, the peak voltage is about 10kV. The power of the ozone tube for varying serial pulse number is shown in Fig.12 (b). As this figure shown, if serial pulse number is 4 or more, power of the ozone tube reaches required value 300W (10% of rated power). Thus, PDM serial pulse number is estimated as 4 and the simulation result is indicated in Fig.12 (c).

5. PERFORMANCE EVALUATIONS

Fig.13 demonstrates an experimental set-up of ozone generation system. This system is made up of three major sections; DSP-based control board, voltage-fed high-frequency load resonant inverter type power supply, and ozone generating equipment. Fig.14 gives the appearance of experimental ozone generating system.
The observed voltage and current operating waveforms of this inverter which are obtained under a new PDM&PWM hybrid regulation scheme are shown in Fig.15 in case of 15% Pulse Density Modulation rate. The experimental voltage and current waveforms of ozone generating tube are illustrated in Fig.16. 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.

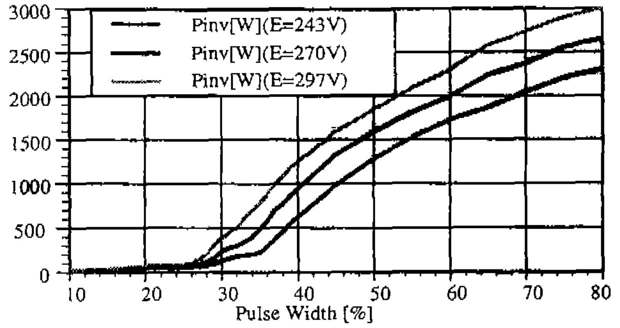


Fig.10 Relationship between output power and pulse width

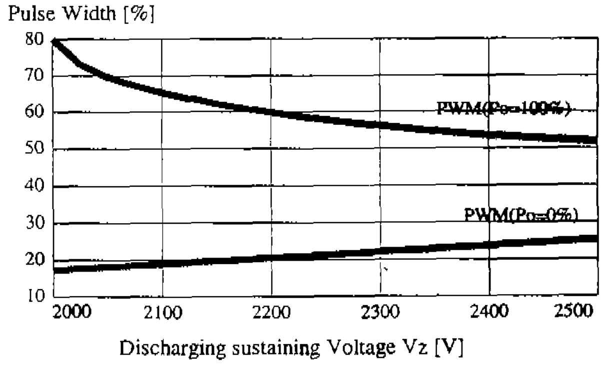
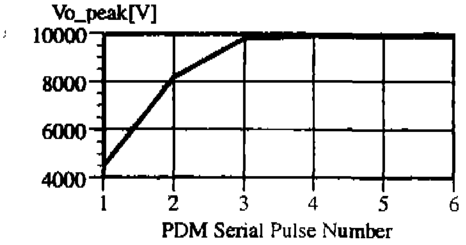
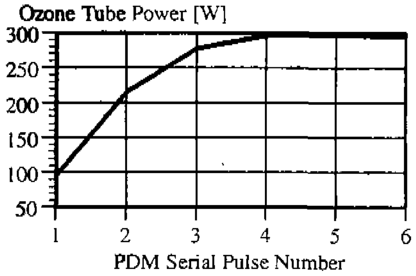


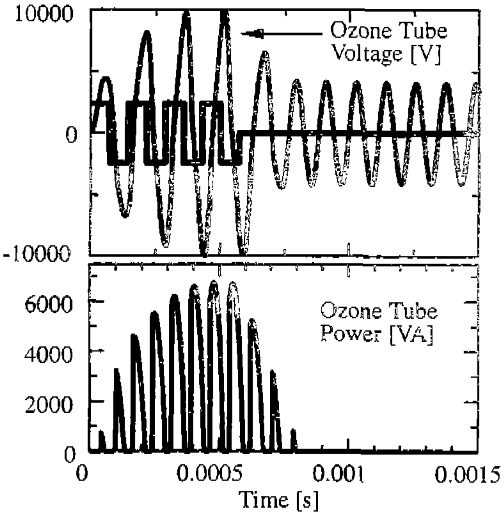
Fig.11 Relationship between pulse width and discharging sustaining voltage Vz



(a) Peak value of voltage across ozone tube



(b) Power of ozone tube



(c) Waveforms of ozone tube in case of four serial numbers

Fig.12 PDM minimum serial pulse numbers evaluation

The silent discharge in the ozone generating tube does not cause when a voltage across its discharge gap is below a certain voltage value to start a discharge phenomenon within 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. In practice, the discharge sustaining voltage Vz has a non-linear characteristic. Thus, 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 a voltage between two electrodes, the electrical insulation is distracted on an edge of an ozone generating tube and an arc discharge generates around two AC electrodes.

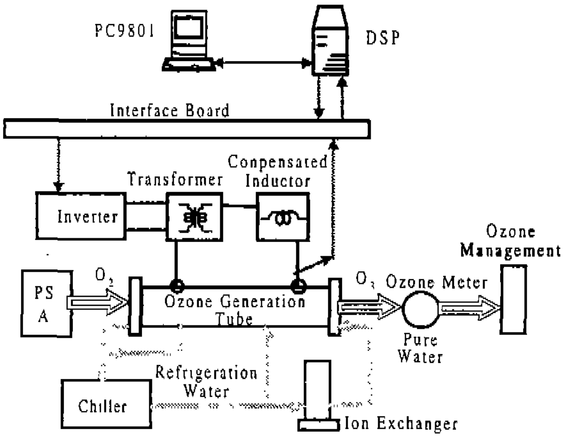


Fig.13 Experimental ozone generation system configuration

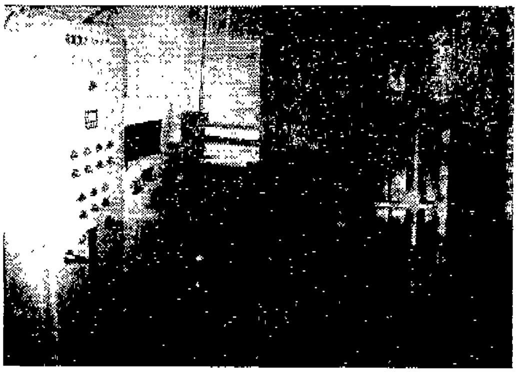


Fig.14 Appearance of inverter type ozonizer

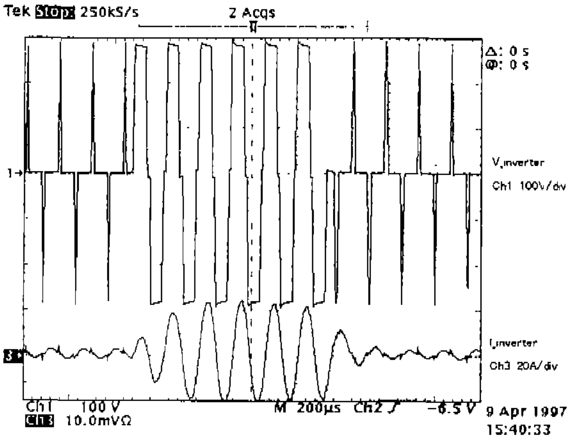


Fig.15 Experimental output voltage and current waveforms of the inverter

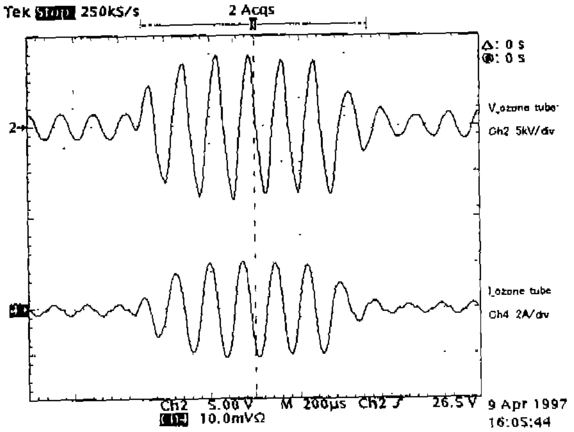


Fig.16 Experimental voltage and current waveforms of ozone tube

Fig.17 indicates a relationship between pulse density modulation rate and output power of this inverter. The PDM and PWM hybrid control scheme 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 and the power regulation performances of the ozonizer have been evaluated for high-performance ozonizer. The circuit model of ozone generating tube was displayed and the inverter analysis was carried out and the performances of this inverter-fed ozonizer have been evaluated 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 proved from an experimental point of view.

In this future, a PDM and PWM mode voltage-fed high-frequency load resonant inverter using the 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 ozonizer using a current-fed type load resonant inverter with PDM and PWM strategy has to be practically evaluated as compared with the ozonizer using voltage-fed type load resonant inverter with PDM and PWM hybrid control strategy.

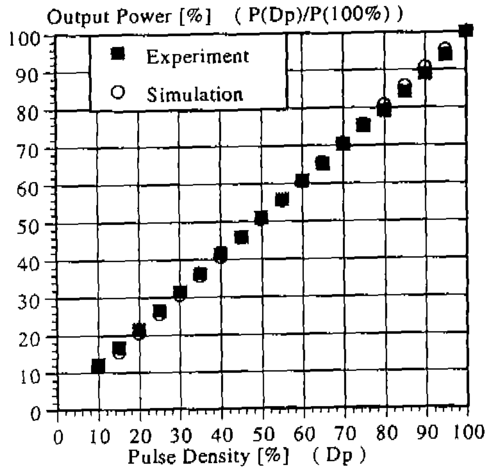


Fig.17 Steady-state characteristics in case of PDM and PWM hybrid control scheme

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