Current-Source Pulse Density Modulated Parallel Resonant Inverter with A Single Resonant Snubber and Its Unique Application

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Abstract- *In this paper, a current-source type parallel inductor compensated load resonant high-frequency soft switching inverter using IGBTs for driving the newly-produced silent discharge type ozone generating tube and excimer lamp for UV generation which incorporate a single switched capacitor resonant snubber between the port in DC busline side is presented, together with its pulse modulated unique output power regulation characteristics.*

Index Terms: *Current-fed high frequency inverter, Soft-switching, Active resonant DC link snubber, PWM and PDM hybrid control, Silent discharge type ozone generating tube. Next generation ozoniger.*

I . INTRODUCTION

In recent years, the ozone gas has been widely utilized for chemical processing of water treatment and exhausted smoke treatment, deodorization and public facilities [1]-[2]. It is also recognized that in semiconductor manufacturing industry field that broad application of ozone gas is hindered primarily because of low efficiency for ozone gas generation. To meet this requirement, much work for improving ozone generation tube and the power supply to drive the ozone generation tube has been directed to raise ozone generation efficiency. However, there are only a few studies on miniaturization in physical size and weight,, high-efficiency, high-performance, control stabilization of power supply system which drives nonlinear silent discharge-based capacitive load [3].

In order to improve the voltage highly concentrated ozone gas production performances, in this paper a new unique power regulation scheme of a single phase current source type parallel inductor compensated load resonance high frequency inverter using a single two-terminal switched capacitor type quasi resonant DC link snubber is developed for driving the silent discharge type ozone generation tube which implements PWM scheme in addition to PDM scheme. The steady-state power regulation characteristics of this active resonant DC link snubber assisted current source type high frequency soft switching load resonant inverter which works under the principle of PDM and PWM hybrid control strategy are illustrated and evaluated as the next generation high-performance ozonizer.

II . NEWLY DEVELOPED SILENT DISCHARGE OZONE GENERATION TUBE

In general, it has been widely considered that the ozone gas can be efficiently produced on the basis of silent discharge phenomena between two electrodes. The silent discharge principle is more widely used for ozone gas generation, CO_2 laser generation, excimer lamp, Plasma Display Panels and electric dust collector in the fields of a variety of industrial and consumer applications [4]. In particular, the main principle of the silent discharge type ozone generation tube driven by the current source type high-frequency inverter using power semiconductor switching devices is schematically illustrated in Fig.1.

The internal structure of a newly developed high-concentration and high efficient ozone generation tube based on silent discharge principle is depicted in Fig.1 (a). This has a cylindrical structure with a stainless steel ground electrode in its outside and a high voltage stainless steel electrode in its inside frame. By supplying oxygen gas toward the inlet of the ozone generation tube across two electrodes with stable silent discharge space this ozone generation tube can continuously convert oxygen into ozone. The ozone generation tube produced here is composed of the discharge gap between two electrodes and the dielectric material substrate of glass spacer as a dielectric barrier inserted into two high voltage AC electrodes. The equivalent electrical circuit model considering discharge and non-discharge operation modes of the silent discharge type ozone generation tube driven and controlled by the current source type high-frequency inverter are illustrated in Fig.1 (b). In a non-discharge period of the ozone generation tube, the electric circuit model of the ozone generation tube represented by the capacitance Ca corresponding to the discharge gap and the capacitance Cg relating to glass dielectric substrate as a dielectric barrier make the capacitive load. On the other hand ,in the discharge period, the average value of the voltage across the discharge gap is approximately kept constant as the discharge property, which is termed as the discharge sustaining voltage Vz represented by the AC voltage source ,the positive voltage +Vz and the negative voltage -Vz. In the electric circuit model of the ozone generation gab tube, the nonlinear capacitive circuit is shown with DC voltage source Vz via full bridge diode rectifier connected in parallel with the discharge gab capacitor with Ca is connected to a series capacitance Cg of glass dielectric barrier. Fig.1(c) shows operating voltage and current waveforms of the ozone generation tube in case of the AC current source provided by the current source type inverter. Observing to the circuit modeling and operating waveforms of ozone generation tube driven by current source type high frequency inverter as shown as Fig.1, the voltage across the discharge gap and the voltage across the glass dielectric barrier are respectively formulated as

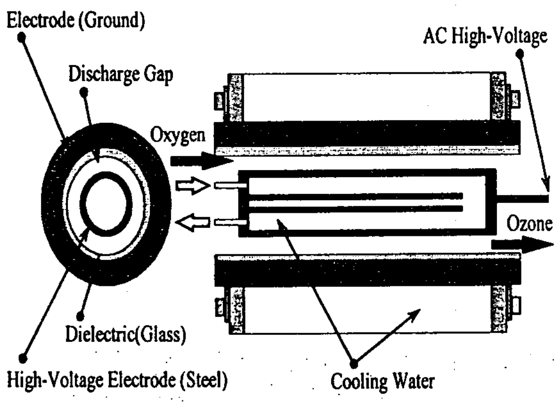
$$v_{Ca}(t)=\begin{cases}\dfrac{I_0}{C_a}t-V_Z & (0\le t\le T_1)\\ V_Z & (T_1\le t\le \dfrac{T}{2})\end{cases}$$

$$v_{Cg}(t)=\frac{I_0}{C_g}t+(-V_p+V_Z)\quad (0\le t\le \frac{T}{2})$$

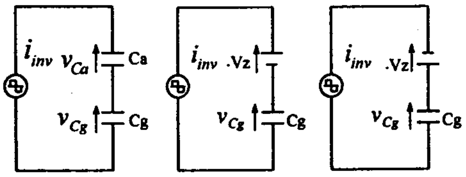
The relationship between the discharge power P_o and the peak voltage V_p across high-voltage AC electrodes is theoretically given in the following equation,

$$P_o=\frac{2}{T}\int_0^T (V_{Ca}(t)+V_{Cg}(t))\cdot I_0 dt=4f\cdot[C_g V_Z V_p-(C_a+C_g)\cdot V_Z^2]\quad (1)$$

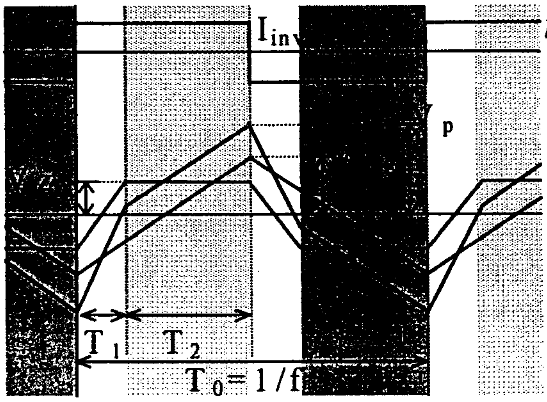
where frequency f of AC voltage , f=7kHz discharge gap electrostatic capacitance C_a= 6000pF,glass dielectric electrostatic capacitance C_g=9000pF, discharging sustaining voltage V_z= 2000V.



(a) Schematic structure of ozone generation tube



(b) Equivalent circuit in case of non-discharging



(c) Operation waveforms in the discharge and non-discharge ozone generation tube

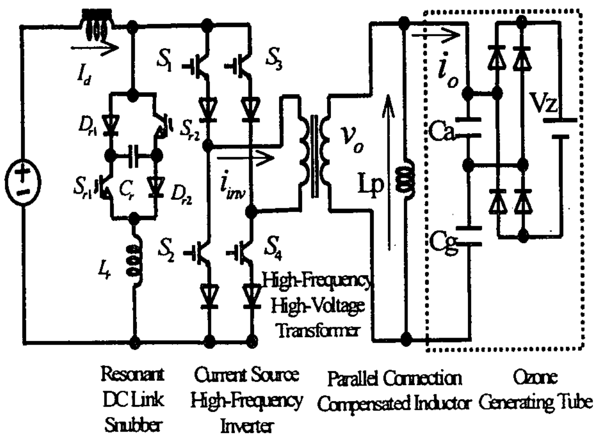
Fig.1. Silent discharge type ozone generation tube driven by current AC source

III. NEW SOFT SWITCHING INVERTER

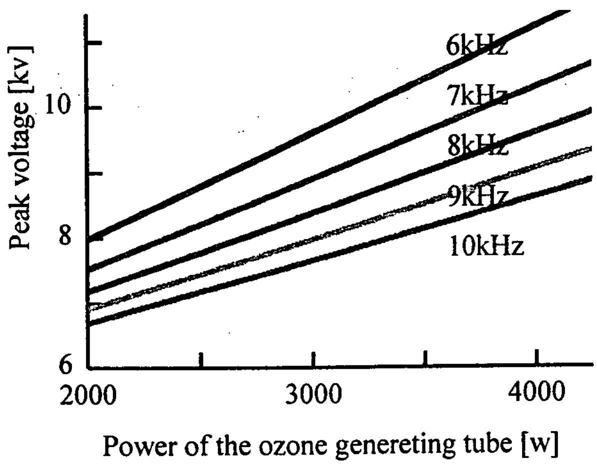
A. Circuit description

Figure.2 shows a schematic configuration of power conversion circuit for a next generation ozonizer driven by a current source type high-frequency parallel load resonant inverter using two terminal switched-capacitor type active quasi resonant DC link snubber, which can operate under a principle of zero current soft-switching side, high frequency step-up transformer, parallel compensation resonance reactor Lp ozone generation tube represented by a nonlinear capacitive load, The high-voltage AC has to be applied for the ozone generation tube Especially, the peak voltage of ozone generation tube is necessary for sustaining a stable silent discharge. Under considering the effect of the magnetizing inductance Lm of the high-voltage transformer, the value of the parallel compensated resonant inductance Lp is designed for an optimum constant value on the basis of the computer-aided simulation, in order to achieve a high total distortion power factor of the current source high frequency inverter with a high-voltage transformer connected to the nonlinear capacitive model of the ozone generation tube with its non-discharge and discharge periods. Observing Fig.2 (b), the relationship between the input power of the ozone generation tube and peak voltage across the ozone generation tube is estimated from equation (1). The operating frequency of current-source type parallel inductor compensated load resonant inverter with a single active resonant DC link snubber proposed is designed for 7 kHz ozone generation tube developed newly by Fuji Electric co Ltd. In this case, the rated power of one ozone generating tube is 3kW. The peak voltage across the ozone generation tube is measured as about 9kV. The parallel compensated resonant inductance Lp is designed for 0.09H.

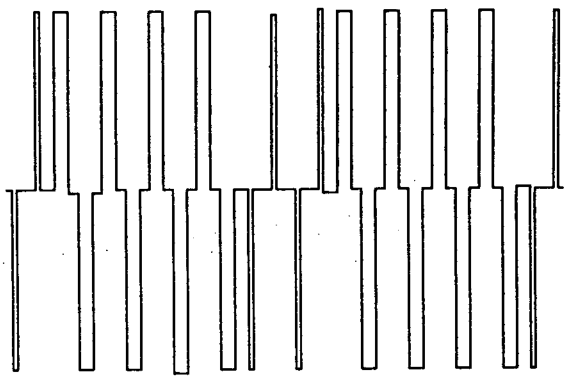
In order to adjust a production quantity of the ozone gas by the ozone generation tube, it is necessary to regulate a discharge power generated by the current-fed type high-frequency zero current soft switching inverter type ozonizer in the next generation. A peak voltage across two high voltage AC electrodes of the ozone generation tube is indispensable for holding sustaining a stable silent discharge, even though an output power of the current source type high-frequency parallel resonance inverter with an active resonant DC link snubber is needed to be adjusted under a lowered pulse modulation conditioning and processing. The silent discharge of the discharge gap indicates the stiff nonlinear characteristics between voltage and current of ozone generation tube. Because of its inherent non-linearity, a conventional current-source type parallel resonant inverter based the PAM due to DC bus voltage control scheme can commutation. This inverter fed ozonizer is composed of the single phase current-source type full bridge high frequency inverter circuit with DC reactor in its input not be used for wide power regulation as well as stable discharge power range.



(a) System configuration of current source load resonant inverter with a single soft-switching quasi-resonant snubber.



(b) Peak voltage vs output power characteristics.



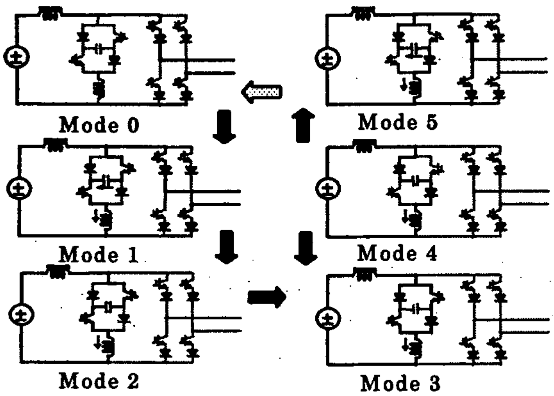
(c) PDM&PWM hybrid control strategy

Fig.2 Current-source high-frequency inverter for ozonizer

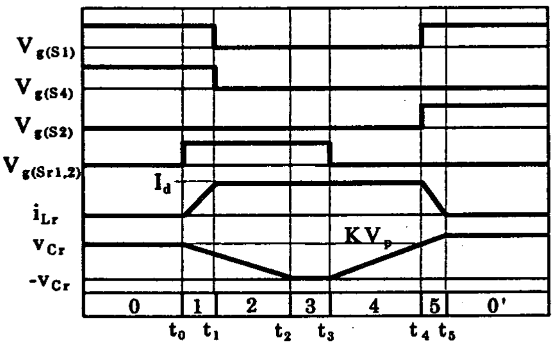
B. Control Implementation

A PDM and PWM hybrid-based power regulation method proposed newly is effectively introduced for the 7kH ozone generation tube load which is implemented into the current source parallel resonant inverter. The advanced new conceptual of PDM and PWM hybrid-based power regulation strategy [5]-[7] for current-source high-frequency load resonant soft switching inverter with a single active resonant DC link snubber is illustrated in Fig.2(c). The effective power delivered into the ozone generation tube can be continuously regulated by means of high-frequency AC current-based PDM and PWM hybrid control scheme. On the other hand, the PWM strategy is effectively implemented during the discharge condition fluctuation. This PDM control procedure is based upon a time ratio control or duty cycle factor control of high-frequency AC current pulse number modulation, which is produced by the current-source type load resonant inverter employing the magnetizing inductor as one of the parasitic component of high-frequency transformer.

The auxiliary active DC resonant link commutation switched capacitor circuit connected in current-source DC busline is composed of the resonant capacitor C_r, each IGBT (S_{r1} or S_{r2}) in series with each fast recovery diode (D_{r1} or D_{r2}) and resonant inductor Lr. Current commutation of one a single power switch in the bridge leg side of the full bridge inverter circuit to another active switch is to be performed on the basis of zero current soft switching transition PDM and PWM scheme. In this case, the DC bus line current of this inverter has to be commutated from the full bridge inverter power circuit to the auxiliary active resonant snubber circuit. This allows all the active power switches of the full bridge inverter to turn on and off under zero current switching conditions in spite of PWM regulation in addition to some load parameter disturbances.



(a) Equivalent circuits for operating modes



(b) Timing pulse segucuces of gate voltage and operating waveforms of resonant DC link snubber

Fig.3 Principle of resonant DC link snubber

C. Operating principle of soft commutation

Figure.3 illustrates the soft commutation operating principle based on the equivalent circuits and the steady-state voltage and current operating waveforms of the resonant inductor current i_{Lr} and resonant capacitor voltage V_{cr} in current source type switched capacitor type quasi-resonant DC Link snubber circuit. The steady state circuit operation of this current-fed parallel resonant soft switching inverter incorporating the current source type switched capacitor resonant DC link snubber is illustrated as follows.

■ Mode0-Initial mode($t<t_0$)

The input current of this inverter is now flowing through the main active power switches S_1 and S_4. It is assumed that the resonant capacitor C_r has to be initially charged to $-KV_p$, where K is a little positive value greater than unity and V_p is the maximum peak value of parallel resonant voltage.

■ Mode1-Current transfer mode($t_0<t<t_1$)

When the auxiliary active power switches; S_{r1} and S_{r2} are turned on under a condition of the zero current soft-commutation. The input current I_d in DC current side is commutated from the parallel resonant inverter to the resonant DC link snubber circuit as the switched capacitor. After the current flowing through the main active power switches; S_1 and S_4 is zero, S_1 and S_4 are both turned off at the same time under a condition of zero current soft-switching commutation.

■ Mode2-Resonant capacitor discharging mode ($t_1<t<t_2$)

In this mode, the input current source I_d is now flowing through the current-source type with two terminal active resonant DC link snubber. This current continues to flow through $S_{r1}$and C_r throngh S_{r2} until C_r, is fully discharged.

■ Mode3-Freewheeling mode($t_2<t<t_3$)

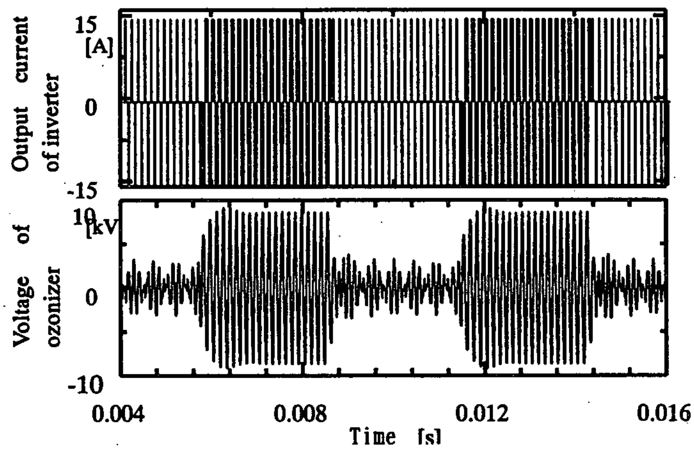
The inductor current flows through (S_{r1}, D_{r1}) in parallel with (S_{r2}, D_{r2}.)During this mode, the voltage across resonant capacitor C_r keeps zero.

■Mode4-Resonant capacitor charging mode ($t_3<t<t_4$)

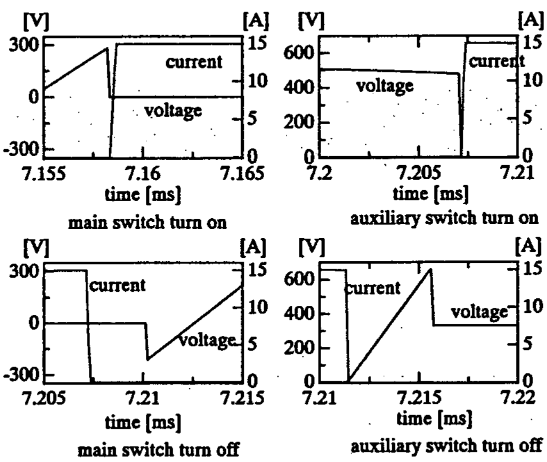
The auxiliary active power switches; S_{r1} and S_{r2} are all turned off under a ZVS condition. The current flows through D_{r1}, C_r and D_{r2}. As a result, C_r begins to charge.

■ Mode5-Current transfer mode($t_4<t<t_5$)

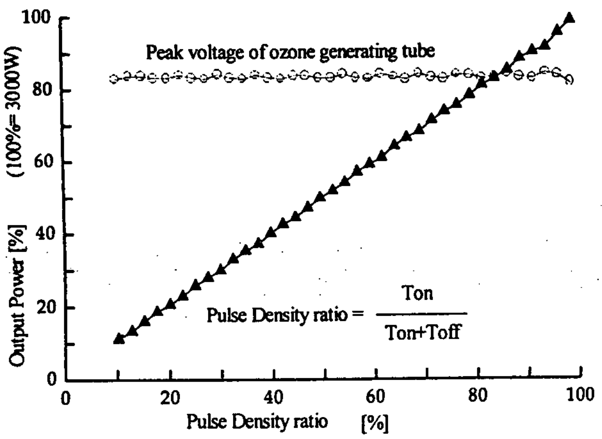
When the voltage across resonant capacitor is charged to KV_p, the main active power switches; S_1 and S_2 are all turned on under a ZCS condition. At the end of this mode, the DC bus current commutates through parallel resonant the inverter.



(a) Voltage and current waveforms



(b) Voltage and current switching wafeworms



(c) Output power regulation characteristics

Fig.4 Characteristic of current-fed ZCS-PDM&PWM inverter

The voltage and current operating waveforms of this parallel resonant inverter, operating under a new Pulse Density Modulation (PDM) and Pulse Width Modulation (PWM) hybrid regulation scheme, are shown in Fig.4 (a). The stable inverter operation in repetitive steady-state condition includes a positive polarity-based charging and discharging modes in ozone generation tube as well as a negative polarity-based charging and discharging modes in the ozone generation tube. The voltage across the discharge gap in a discharge period maintains a certain high voltage Vz when this gap voltage exceeds a specified voltage enough to start a silent discharge. The silent discharge type ozone generation tube driven by a current source type high-frequency parallel resonant soft switching inverter has non-linear characteristics.

Accordingly, the high-voltage AC across the ozone generation tube has to be kept a specified peak value (9kV-10kV). In this case, its output power is delivered from the current source type high-frequency parallel load-resonant soft switching inverter. If the high-frequency AC voltage across two high voltage AC electrodes is to be much lower, the discharge phenomena doesn't occur at all and comes to a partial discharge phenomena. In case of a vated voltage across two high voltage AC electrodes, the electrical insulation is destructed on an edge of an ozone generation tube and a harmful discharge is possible to generate around two high voltage AC electrodes.

Figure.4 (b) shows the magnified operating voltage and current switching waveforms in the case of the turn on and off soft-commutation of the main active power switch of the bridge arm of inverter. It is proven that the switching mode transition is basically performed under a condition of no switching losses. In addition, this figure illustrates the turning on and turning off voltage and current waveforms of the auxiliary active power switches in two terminal capacitor type active resonant DC link sunbber. It is understood that all the auxiliary active power switches in two terminal switched capacitor type resonant DC link snubber circuit do not essentially generate the switching power losses of IGBTs because of zero voltage soft switching as well as electromagnetic interference noise.

Figure.4(c) illustrates a power regulation performance between the pulse density modulation rate and the output effective power of this inverter. The PDM and PWM hybrid control scheme under a constant output frequency 7kHz of the current-source load resonant soft switching inverter is more effective in order to maintain a stable discharge even when the output power delivered to the ozone generation tube is to be lowered. The output power of the current source type parallel resonant ZCS inverter with PDM&PWM hybrid control scheme is able to be regulated linearly over wide ranges from PDM duty ratio 10 % to 100 % of the rated power.

Ⅳ. CONCLUSIONS

A novel prototype of current-source type parallel compensated inductor load-resonant high frequency inverter using IGBT modules which operates under a soft commutation based upon a single two-terminal switched capacitor type active resonant DC link snubber circuit has been developed and demonstrated for driving high-performance 7KHZ silent discharge type ozone generation tube, this appliance was implemented so as to operate under a PDM and PWM hybrid control scheme.

In accordance with this PDM and PWM hybrid control strategy of the current-fed parallel resonant ZCS inverter type ozonizer, in the futuer generation the effective output power of this current fed soft switching inverter could be linearly regulated over a wide PDM duty factor range from 10% to 100% of the rated power, the soft-commutation of this current-fed inverter could be completely achieved under the principle of ZCS condition in main power switches of inverter bridge arms and ZVS condition of auxiliary active power switches in resonant DC link snubber.

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