JPE 2-3-7

# Voltage Source Resonant Inverter for Excimer Gas Discharge Load

Oleg Koudriavtsev* and Mutsuo Nakaoka

The Graduate School of Eng. and Science, Power Electronic Systems and Control Eng Lab.,
Yamaguchi University, Yamaguchi, Japan

## ABSTRACT

Silent gas discharge method has been widely applied for ozone production, ultraviolet light and UV laser generation. Since ozone and ultraviolet applications have tendency to spread widely in industry, the development of efficient and low-cost power supply for such systems is an important task at present. This paper introduces high-frequency inverter type mode power supply designed for ozone generation tube and ultraviolet generation excimer lamp and considerations on the design of the inverter and pulse density modulation control strategy applied in it.

**Keywords:** Silent discharge, Pulse Density Modulation, Zero voltage soft switching commutation, High-frequency inverter.

## 1. Introduction

Rare gas excimers are very unstable molecular complexes of argon, xenon, krypton and other gases with half-life usually less than microsecond, which decay with emitting of UV photons. The most effective way to produce gas excimers as it recognized is the gas discharge in the barrier type silent discharge tube. UV is known to start biological, physical and chemical processes in materials adsorbing UV energy that is widely used in industry. Growing number of such devices and spreading applications fields cause the demands for efficient and small size power supply for gas silent discharge load. This paper describes the operating principles of high-frequency resonant load inverter for such kind of load and its control strategy.

This voltage source resonant load inverter is implemented on IGBTs and operated in ZVS. It has a full-bridge topology and a pulse density modulation control scheme.

## 2. Overall System Description

Usually, gas discharge tube has cylindrical structure of two metal electrodes separated by dielectric material such as quartz glass. When high voltage applied between two electrodes exceeds a certain value, it causes a silent discharge in the discharge gap of the generation tube. High-energy electrons produced in this process excite gas molecules, which decay after a short period of time with UV photon emission. Electrically, this process can be represented by the equivalent electric model shown in Fig. 1[1]. It can be obtained from this model that maximum positive and negative voltage on the gap during silent discharge remains constant defined as discharge sustaining voltage Vz, however, full voltage drop on the dielectric barrier layer is changed.

---

Manuscript received Nov. 14, 2001; revised July 2, 2002.

Corresponding Author: oleg@pe-news1.eee.yamaguchi-u.ac.jp, Tel: +81-836-85-9472, Fax: +81-836-85-9472

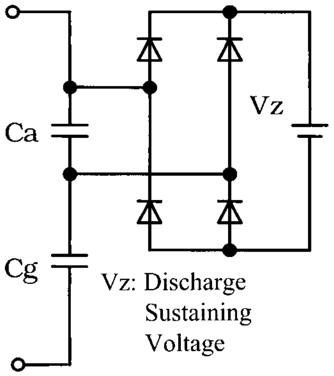


Fig. 1. Equivalent electric model of the silent discharge tube.

In non discharge mode, the discharge gap between two electrodes and capacitance of the dielectric barrier layer substrate are represented as a capacitor circuit composed of capacitor Ca in series with the capacitor Cg. In discharge mode, the discharge sustaining voltage Vz, represented by DC voltage source, is connected to the high voltage DC side of the full bridge diode rectifier circuit. The circuit parameters of the silent discharge type generating tube are affected by the influences of external environment conditions such as working temperature, air pressure, humidity etc. However, they are considered to be almost constant during relatively short time interval.

To provide optimal conditions for energy transferring to the load and total high output power, this load needs inductive compensation. For this purpose, the leakage inductance of the connection transformer can be used, however, sometimes, auxiliary compensating inductor is necessary. Ultraviolet and ozone generation tubes have electric energy utilizing efficiency less than 10-20 percents, therefore usual demand is to obtain the power as high as possible even with low power conversion efficiency. For this reason, series load resonant type inverter topology has been chosen to achieve high power output, even sacrificing overall system efficiency. Furthermore, from other research it was found that series resonant scheme is optimal for the dielectric barrier discharge load, since it has good selectivity allowing to achieve high voltage in the load and prevent high-voltage transformer from the saturation[2][3] . In the experimental setup full-bridge series resonant inverter shown in Fig. is applied as a power supply.

Adjusting auxiliary series inductance has some specific, since load parameters are fluctuating during working cycle which can be obtained from the equivalent electric scheme. Turn-off losses of this inverter are decreased by the lossless snubbing capacitors connected in parallel with every transistor switch. The soft-switching condition could be provided over all operating range of the inverter.Where in case of ozone generating system:

Vz=2kV
Ca=6000pF
Cg=9000pF
Ls=0.08 H

Load circuit has resonant behavior that causes necessity to tune the working frequency in practical application to compensate the fluctuations of the load parameters affected by environment condition.

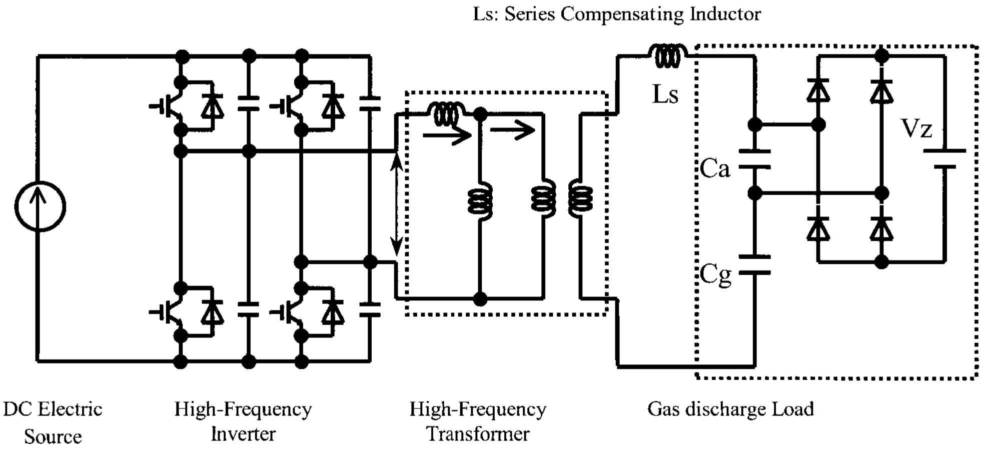


Fig. 2. Electric Scheme of the developed converter.

## 3. Control Strategy

In the resonant inverter, the output power is traditionally regulated by varying the working frequency (Pulse Frequency Modulation) or width of the pulses (Pulse Width Modulation). However, as was found in previous researches, it is impossible to regulate output power in a wide range by PFM or PAM for such nonlinear capacitive load as excimer discharge load is [4]. At the same time, in the experiments it was observed that changing the frequency makes efficiency low, since optimal resonant conditions are affected. On the other hand, in case of the pulse width variation, it becomes a problem to provide stable discharge at low power levels, when very short pulses are applied.

Thus, Pulse Density Modulation (PDM) control strategy has been developed for such applications and has proved its efficiency in experiment. Control procedure of the inverter is based on pulse density adjustment by changing the number of pulses during operation period and keeping the working frequency constant near the resonant. PDM control strategy can be depicted as in Fig. 3. Working time is divided into two operation cycles, which consist of power injection and zero power periods. During power injection period, the working voltage pulses are applied to the generation tube. Zero power period is the time interval, when silent discharge does not occur and load circuit keeps free oscillations.

Output power can be adjusted by changing the number of the working pulses. Since the length of the operation cycle remains constant and only the number of working pulses is adjusted, the pulse density is the only modulated value of the control signal. In other words, the number of pulses per second is changing, so it can be defined as changing of the density of pulses i.e. number of pulses per second.

During one working pulse period circuit passes 6 operation modes shown in Fig. 4. These modes change in the following order. When SW1 and SW4 are open, current in flowing through load as shown in mode1. Then SW1 switches off, and mode 2 begins. When current in load achieves zero, SW2 is switched on and circuit state changes to mode 3.

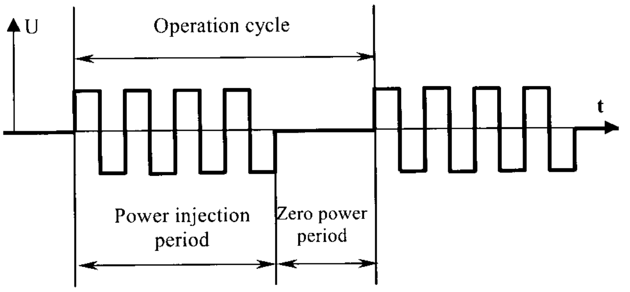


Fig. 3. PDM control pulses sequence.

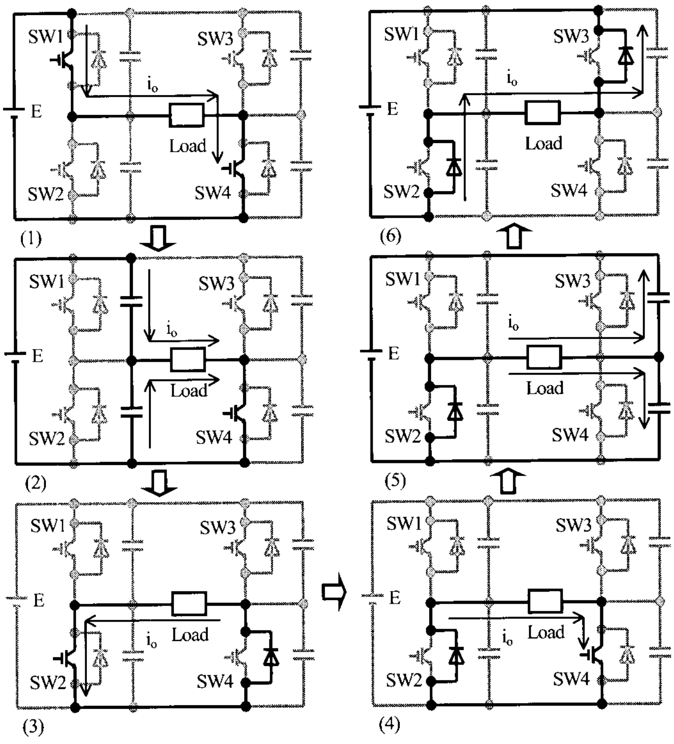


Fig. 4. Operation modes.

Since the load has highly resonant behavior, current changes its direction after a while and mode 4 takes place this time. Then after a time specified by the pulse width, switch SW4 goes off and current starts flowing as it is shown in mode 5. When the voltage across the capacitor parallel to SW3 achieves zero, parallel diode starts conducting that is shown in figure as mode 6. During mode 6, SW2 and SW3 are turned on and next sequence of 6 modes starts. Circuit operation during this time is almost the same, however it starts from SW2 and SW3 conducting states but all the processes are taking place in the same order.

During the free oscillations in zero power periods, the current phase in the load shifts from the phase of the control signal, because the frequency of the oscillations differs from the working frequency. This leads to the instability of the initial conditions of the next power injection period from cycle to cycle, that causes deviations of energy delivered by the first pulse in the next cycle. Thus, discharge at low power levels could become unstable and control characteristic nonlinear.

This problem can be resolved by applying auxiliary short signal pulses during zero power periods. Since the load has resonant behavior, signal with frequency different from resonant, will not cause the discharge, because voltage on the tube in this case will be less than discharge starting level. Therefore, the load will be equal to reactive impedance and energy losses will be low. Electric energy in this case is insufficient to cause silent discharge, but destroys some gas molecules and provides by this way hot standby conditions until next working period. As a result, initial energy consumption during discharge start becomes lower that provides stable discharge even at low power levels. At the same time, pulses applied during zero power period, prevent shifting the phase of the free oscillations in the load from the phase of the control signal during zero power periods. Due to this, the portion of energy delivered to the tube by the first working pulse in the next power injection period is kept constant and, otherwise, power regulating characteristic becomes more linear. This improved control signal sequence is shown in Fig. 5.

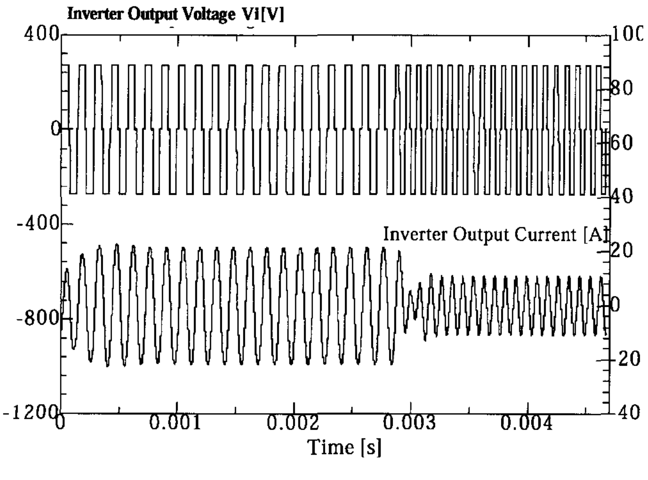
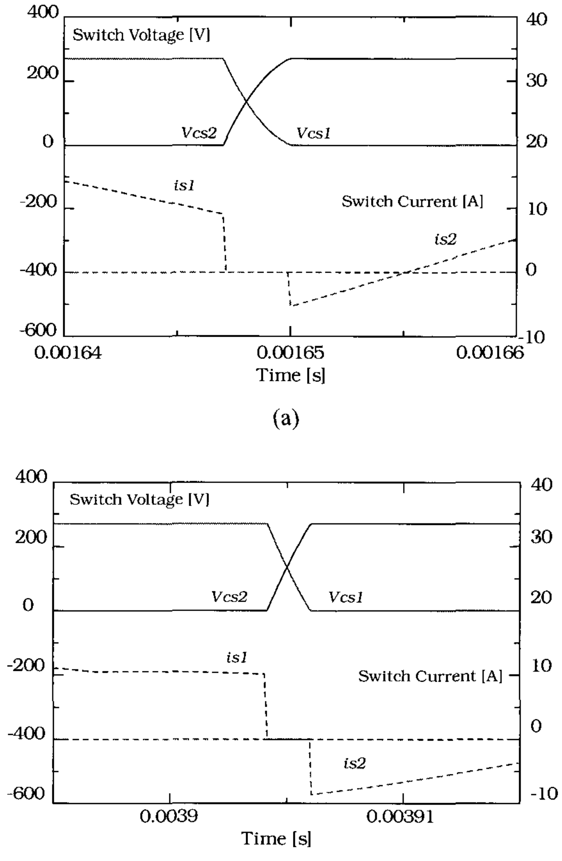


Fig. 5. PDM strategy with auxiliary pulses.

Additional short pulses are added to the basic PDM signal (see Fig. 3) during zero power periods. Since the frequency of these pulses is much higher then the frequency of the working pulses, discharge does not take place in the load and inverter output current is very low, that is seen in Fig. 5 for the time after 0.003 seconds. Because of these auxiliary pulses, load is operated in forced oscillation mode that stabilizes the discharge start when new power injection period starts.

## 4. System Operating Performances

Fig. 6(a), (b) illustrate the simulation waveforms of the voltage and current for turn-off switching transients in power injection and zero power periods, respectively.



(a)

(b)

Fig. 6. (a) Operating waveforms at turn-off transient during power injection period, (b) Operating waveforms at turn-off transient during zero power period.

Where, $V_{CS1}$ is voltage across the active power switch SW1, $V_{CS2}$ is the voltage across the active power switch SW2, $i_{S1}$ is current through the active power switch SW1, $i_{S2}$ is current through the switch SW2.

As it can be observed, zero voltage soft-switching operation mode is achieved both for power injection and zero power periods. Since the working frequency is constant, this soft commutation conditions can be realized at any output power level only by lossless snubbing capacitance, however, proper adjusting of the capacitance value, working frequency and dead time is needed.

Power regulation characteristic of the inverter has been taken and its simplified curve is shown in Fig. 7. Due to PDM scheme with auxiliary pulses during zero power periods, the output power can be regulated linearly by the adjusting the density of the applied pulses. Furthermore, the output power can be regulated in a wide range with keeping the output voltage stable, sufficient to certainly provide the discharge in the load (shown as the Peak Voltage curve in Fig. 7). As mentioned in the other researches such wide regulation range cannot be achieved by other control strategy[4].

For the developed scheme full output power is equal to 40 working pulses, therefore, the accuracy of the power regulating characteristic is 2,5%, however, by changing the operation cycle length or operating frequency, this accuracy can be adjusted at any level.

Thus, the developed inverter power supply provides linear regulation in a wider output power range then in previous researches. At the same time, comparing to the conventional schemes, low output power levels can be adjusted with providing stable discharge that is impossible when using other control method.

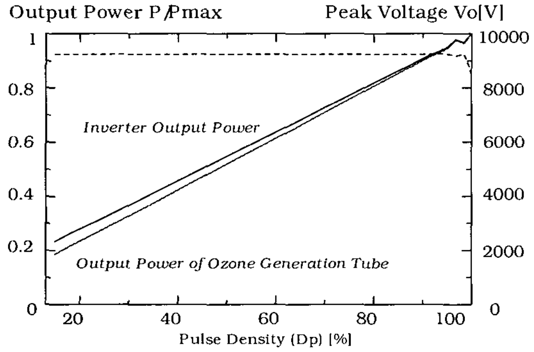


Fig. 7. Power regulation characteristics.

## 5. Conclusions

A power supply for gas silent discharge load has been developed and introduced in this paper. Its high performances were proved by simulation and experiment. Developed topology and control strategy can be applied with slight corrections both for ozone and ultraviolet generation systems. However, in case of ultraviolet generating lamp more attention must be paid to decreasing of the converter losses due to its high working frequency, which is about several hundred kilohertz. On the other hand, the series leakage inductance of the transformer can be used as compensating inductance that makes auxiliary coil unnecessary. Furthermore, higher frequency allows design more compact power supply and make output power control more precise.

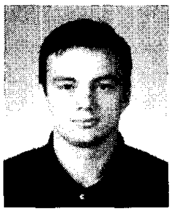
## References

[1] M. Tanaka, "Measurement of silent discharge electric characteristics by Lissajous figure", ED-84-50, pp.17~26, 1984.

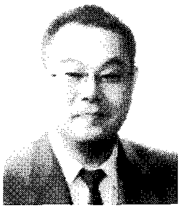
[2] O. Godoy-Cabrera, J.S. Benitez-Read, R. Lopez-Callejas, and J.Pacheco-Sotelo, "A high voltage resonant inverter for dielectric discharge barrier cell plasma applications", Int. J. Electronics, Vol. 87, No. 3, pp. 361~376, 2000.

[3] J. Kunze, N. Frohleke, H. Grotstollen, B. Margaritis, and F. Locken, "Resonant Power Supply For Barrier Discharge UV-Excimer Sources", IEEE Proc. No. 0-7803-0634-1/92 pp. 750~753.

[4] H. Fujita and H. Akagi, "Control and Performance of a Pulse-Density-Modulated Series-Resonant Inverter for Corona Discharge Processes", IEEE Transactions on Industry Applications, Vol. 35, No. 3, pp. 621~627, May/ June 1999.



**Oleg Koudriavtsev** Received the M.S. degree from Kobe University of Mercantile Marine, Japan in 1999. He is currently studying toward the Ph.D. degree at the Dept. of System Engineering, Yamaguchi University, Yamaguchi, Japan. His current research interests include practical development of high-frequency inverter and converters with control schemes.



**Mutsuo Nakaoka** was born in Hiroshima, Japan. He received his doctoral degree in Electrical Engineering from Osaka University, Osaka, Japan in 1981. He joined in the Electrical and Electronics Engineering Department, Kobe University, Kobe, Japan in 1981. Since 1995, he has been a professor in the Electrical and Electronics Engineering Department, the Graduate School of Engineering and Science, Yamaguchi University, Yamaguchi, Japan. His research interests include circuit and control systems of power electronics, especially in soft-switching areas. Dr. Nakaoka is a member of the Institute of Electrical Engineers of Japan, the Institute of Electronics, Information and Communication Engineers of Japan, the Institute of Illumination Engineering of Japan and a senior member of IEEE.