Voltage Source Resonant Inverter for Excimer Gas Discharge Load

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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 a task of great impotency. This paper introduces high-frequency inverter type mode power supply designed for ozone generation tube and ultraviolet generation excimer lamp and considerations on this inverter and pulse density modulation control strategy applied in it.

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

I . INTRODUCTION

Rare gas excimers are very unstable molecular complexes of argon, xenon, krypton and the 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 operating in ZVS. It has full-bridge topology and pulse density modulation control scheme.

II .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 on Fig.1. It can be obtained from this model that 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.

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, respectively. 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. In reality, 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.

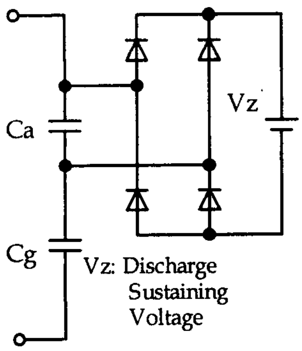

Fig.1 Equivalent electric model of the silent discharge tube

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. Taking into the consideration that ultraviolet and ozone generation tubes themselves have electric energy utilizing efficiency less than 10-20 percents, the usual demand is to obtain the power as high as possible even with low power conversion efficiency. Therefore, the series load resonant type inverter topology has been chosen to achieve high power output, even sacrificing overall system efficiency. In the experimental setup full-bridge resonant inverter shown on Fig.2 is applied for 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.

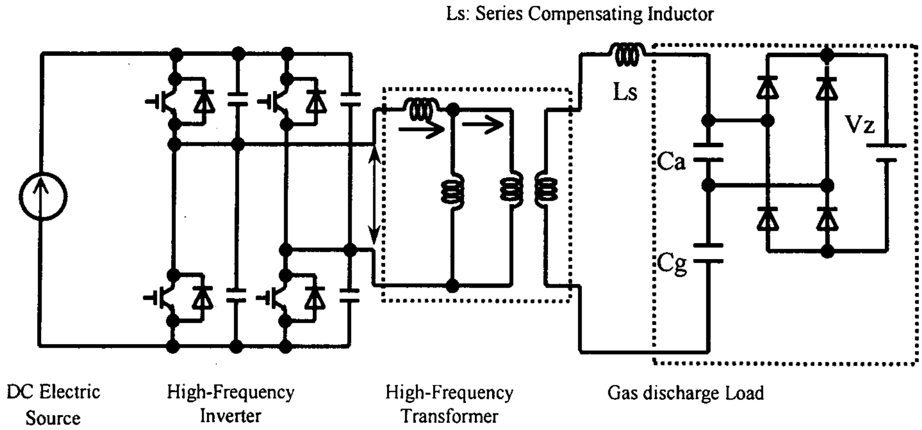

Fig.2 Electric scheme of the developed converter

Where in case of ozone generating system:
Vz=2kV
Ca=6000pF
Cg=9000pF
Ls=0.08 H

Load circuit has strong 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.

Ⅲ.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, in experiment 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.

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.

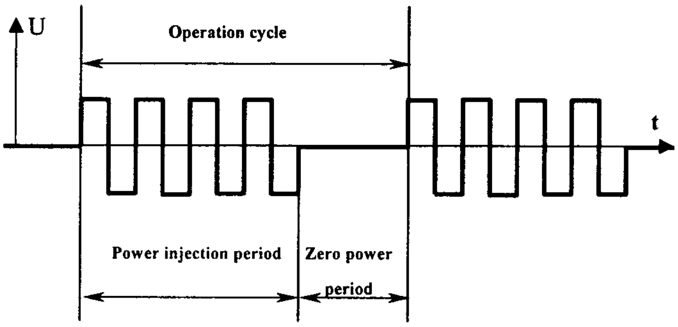

Fig.3 PDM control pulses sequence

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 mode2 begins. When current in load achieves zero, SW2 is switched on and circuit state changes to mode3. Since the load has highly resonant behavior, current changes its direction after a while and mode4 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 mode5. When the voltage across the capacitor parallel to SW3 achieves zero, parallel diode starts conducting that is shown in figure as mode6. 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.

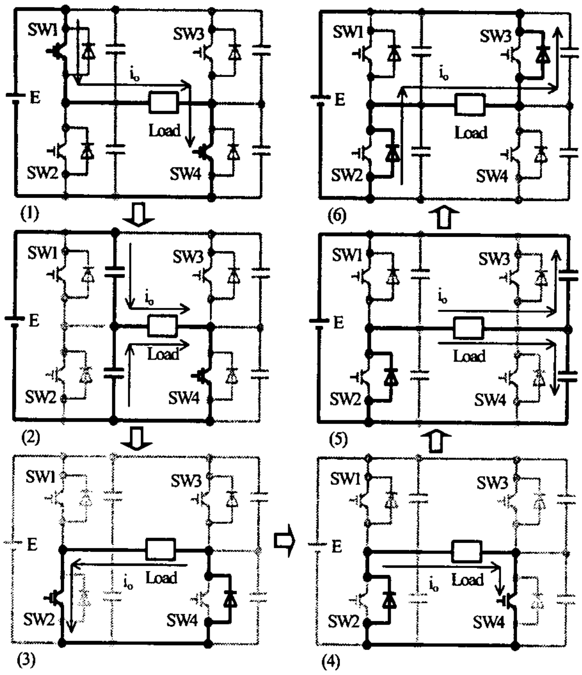

Fig.4 Operation modes and principle of PDM control

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 become more linear. This improved control signal sequence is shown in Fig.5.

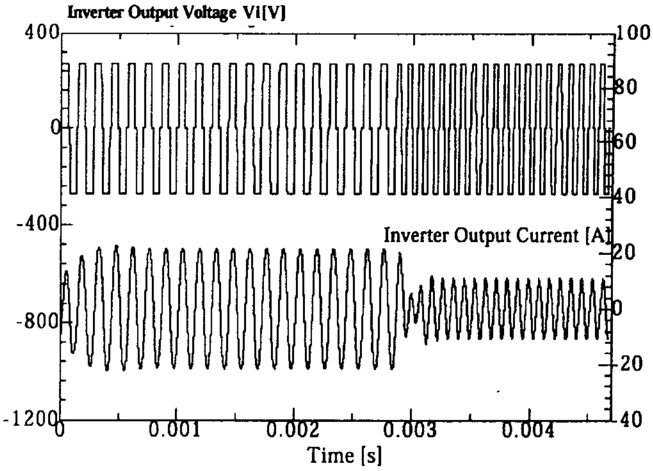

Fig.5 PDM strategy with auxiliary pulses

IV.SYSTEM OPERATING PERFORMANCES

Developed system operates under the soft-switching condition in whole power regulation range as well as linear control characteristics. Fig.6 (a),(b) illustrate the voltage and current waveforms for turn-off switching transients in power injection and zero power periods, respectively. 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 can be achieved both for power injection and zero power periods. Furthermore, due to constant working frequency, this soft commutation conditions are realized at any output power level. Due to the constant frequency and stable discharge condition, the soft-switching is provided with no further means just by lossless snubbing capacitance, that is also one more advantage of this scheme.

Power regulation characteristics of this inverter are shown in Fig.7. Power delivered to the load can be linearly adjusted with 2,5% accuracy in range from 10 to 100% of full power.

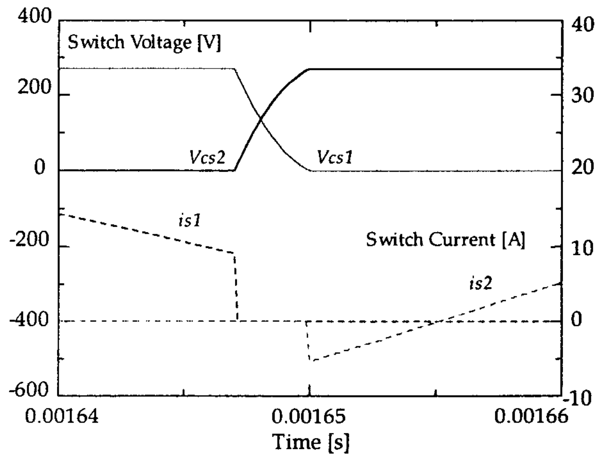

Fig.6 (a) Operating waveforms at turn-off transient during power injection period

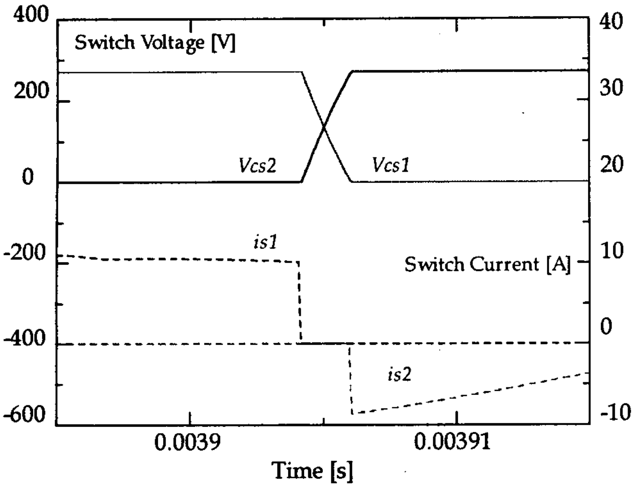

Fig.6 (b) Operating waveforms at turn-off transient during zero power period

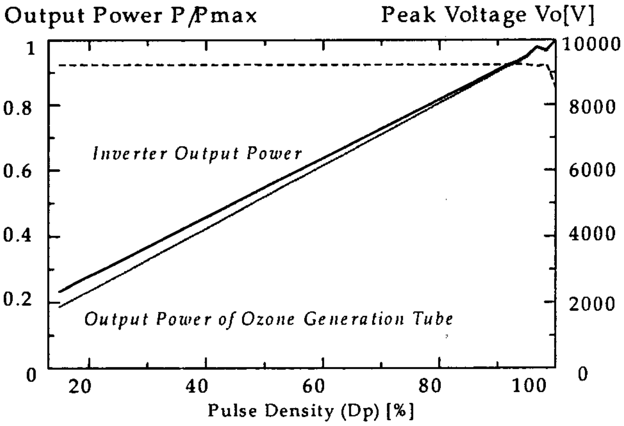

Fig.7 Power regulation characteristics

As additional remark, it should be mentioned that PDM strategy appears to be useful for the other type of applications, such as induction heating and corona discharge coating, due to its simplicity for realization by digital technique and providing soft-switching conditions.

V.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.

Ozone and ultraviolet industrial processing technology was developed not so long time ago, however, due to their superior features for cleaning, ecological safety and relatively easy generation, the application fields are spreading out rapidly. Thus, the demands of high quality power supply that could optimize the gas discharge characteristics and provide simple control for many concrete applications have tendency to increase. Further work should be made in aim to decrease power losses caused by high currents in the load and switching schemes, and losses in the transformer and auxiliary series inductance on the high frequencies. However, principally, the main possibility in increasing of the system efficiency concerns to the improving of the efficiency of the electric energy transformation in the discharge tube. Nevertheless, even at present, the silent discharge is the highly effective method of ozone and ultraviolet generation and it opens perspectives of development not just large-scale industrial applications, but also as very compact units for house purposes and probably even as household appliances.

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