Dielectric Barrier Discharge for Ultraviolet Light Generation and Its Efficient Driving Inverter Circuit

Kudryavtsev Oleg*, Tarek Ahmed* and Mutsuo Nakaoka*

Abstract - The efficient power MOSFET inverter applied for a simple and low cost power supply is proposed for driving the dielectric barrier discharge (DBD) lamp load. For decades, the DBD phenomenon has been used for ozone gas production in industry. In this research, the ultraviolet and visible light sources utilizing the DBD lamp is considered as the load for solid-state high frequency power supply. It is found that the simple voltage-source single-ended quasi-resonant ZVS inverter with only one active power switch could effectively drive this load with the output power up to 700 W. The pulse density modulation based control scheme for the single-ended quasi-resonant ZVS inverter using a low voltage and high current power MOSFET switching device is proposed to provide a linear power regulation characteristic in the wide range 0-100% of the full power as compared with the conventional control based Royer type parallel resonant inverter type power supplies.

Keywords: Dielectric barrier discharge, E-class high-frequency soft-switching inverter, Pulse density modulation control, ultraviolet light.

1. Introduction

The dielectric barrier discharge is a specific class of high-voltage high-frequency AC electrical discharge in gas with near-atmospheric pressure. The structure of the DBD load is composed of two electrodes separated by one or two solid dielectric layers and gas gap such as shown in Fig.1.

When a high-frequency high AC voltage is applied between the metal electrodes, positive and negative charges are accumulated in the dielectric layers surfaces. With growing these charges, the electric field in the gas discharge gap rises and achieves the gas breakdown level (so-called avalanche level). When the electrostatic field intensity increases above the avalanche level, the energy of free electrons, which are always presented in some amount in the gas, becomes enough to ionize gas molecules at strike. New electrons released in this process are accelerated again and ionized the next molecules. This process has avalanche-like character and occurs near chaotically temporally and spatially in the discharge gap until there are areas with field intensity exceeding the avalanche level. As a result, highly ionized, highly conductive tunnels are formed in gas and the charge is being transferred into these structures between the dielectric layers.

Dielectric barrier discharge is one of the cheapest methods of cold plasma generation. Therefore, its application recently is of high interest. Plasma displays and ultraviolet light devices tend to be the most widely recognized applications of DBD. However, the ozone generation is still probably the most mature technology, which utilizes DBD. A lot of promising results have been obtained in applying of the DBD lamp for the destruction of volatile organic compounds (gaseous wastes treatment), sterilization of materials and dry cleaning of solid surfaces.

The DBD load is commonly driven via a step-up high voltage transformer by full-bridge and half-bridge high-frequency inverters[1-3]. At a low power level, up to several tens watts, the self-oscillating Royer type inverter using a saturable transformer has also become widely used due to its stability and relatively high efficiency. However, over frequencies above tens kilohertz, the efficiency of this type of inverter still do not exceed 80-85 percents. Furthermore, under PWM, PFM and PAM control schemes, the output power levels lower 20-30% of full power can be hardly achieved, since the barrier discharge becomes very unstable, and the efficiency of high-frequency inverter drops significantly[4-5]. With the pulse density modulation control implementation proposed here, it is possible to regulate the effective power in full range over 0-100% with no decreasing of the efficiency[6]-[7].

This paper introduces a Class E soft-switching inverter implemented on a single power MOSFET switch, which has been used for driving the DBD ultraviolet light generating tube. Despite of the proposed circuit is very simple, the high power conversion efficiency of about 95% could be achieved over frequencies up to several kilohertz. The pulse density modulation based output power control

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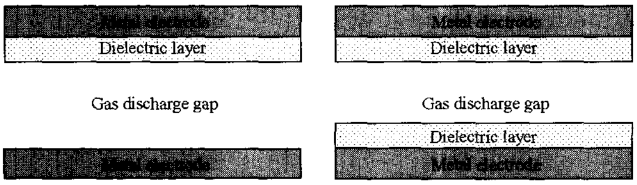
scheme discussed here makes possible to regulate the output power from almost 0 to 100% of the full power. The experimental results are introduced here together with the description of the developed inverter and its control scheme.



(a) Two electrodes separated by one solid dielectric layer (b) Two electrodes separated by two solid dielectric layers

Fig. 1 Principal structure of DBD load.

2. Ultraviolet Light Generation DBD Tube Structure and Equivalent Electric Model

The DBD based ultraviolet light generation tube usually has a structure such as shown in Fig.2. It is composed of two tubes made of UV transparent quartz glass and has stainless steel electrodes. The outer electrode represents stainless steel net, while the inner one is usually a simple stainless tube. The discharge gap is filled with xenon gas. When high frequency high level AC voltage is applied between the electrodes, the ultraviolet light is generated in the discharge gap.

The equivalent electric circuit model of the DBD load is shown in Fig.3.

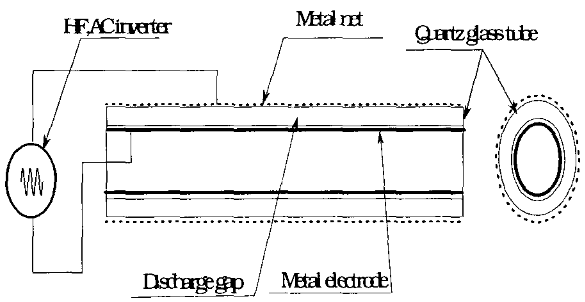


Fig. 2 Structure of the DBD UV generation tube.

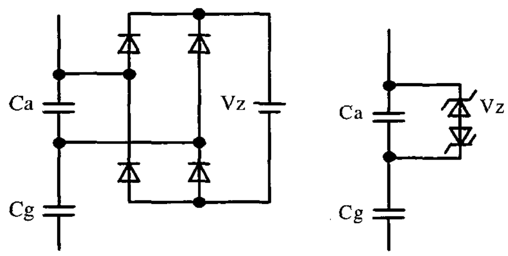


Fig. 3 Electrical circuit models of the DBD load.

The discharge gap is equivalent to capacitance Ca and solid dielectric layer to capacitance Cg. At the voltage below the discharge starting voltage, the DBD is equivalent to two series capacitors Ca-Cg. While, during the discharge, capacitor Ca is bypassed by the DC voltage source Vz. Since the discharge occurs at positive and negative periods of the applied voltage, the DC source is connected through the diode rectifier.

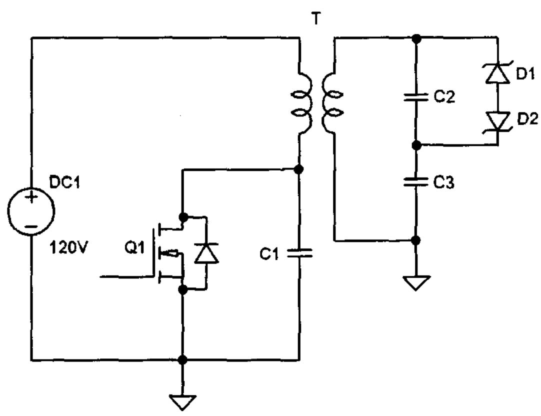
3. High-Frequency Power Conversion Scheme

The class E high-frequency ZVS-PDM inverter using a single power MOSFET shown in Fig.4 is discussed and tested in experiment for driving the DBD ultraviolet light generation tube. The ultraviolet light generation xenon lamp with the nominal output power of 300W is used as a load.

For the high-frequency inverter and the ultraviolet lamp used in experiment, the circuit parameters are below:

C_1=30nF, C_2=105pF, C_3=189pF, T=1:24, D_1 and D_2: 1kV zener diodes, active power MOSFET switch has maximum rated source voltage of 400V and R_{on}=20 m Ohm.

It was observed in experiment, this simple high-frequency inverter can provide up to 600W of the output power without a special heat sink. The convection air-cooled aluminum heat sink is sufficient in this case and a better heat dissipation even with a higher output power levels could be achieved. With the circuit parameters such as illustrated in Fig.4, the complete zero voltage soft-switching conditions are observed when the pulses with frequency 41kHz and duty 50% are applied. The power conversion efficiency in this case is about 95%, which means that is much higher than the conventionally used Royer and other type inverter.



C_1=30nF, C_2=105pF, C_3=189pF, T=1:24, D_1 and D_2: 1kV Zener diodes.

Fig. 4 High-frequency inverter circuit for 300W UV light lamp driving.

4. Power Regulation Scheme

The pulse density modulation (PDM) control strategy is relatively rare method of the output power regulation, which nevertheless appears to be the most suitable for the DBD load. The main idea of the PDM control method is based on the output power regulation by varying of the applied pulses numbers in a constant certain period of the time. The PDM pulse sequence is shown schematically in Fig.5. All the operation time is divided into operation cycles with a constant length. Each operation cycle consists of two operation periods: when pulses are injected to the load and when no operating pulses are generated. The time interval when pulses are applied to the load is called here as a power injection period. The time period when no pulses are generated is called here as non-injection power period. Working pulses have a constant operating frequency, amplitude and width. The output power can be regulated in this method by changing of the number of working pulses in one operation cycle, or, in other words, by varying of the length of the power injection period. Thus, the driving conditions of the load such as operating frequency, amplitude of the applied voltage and dead time remain constant, and the only changing value is the number of applied pulses in constant time interval, that is considered as changing of the pulse density. Output power in the load is formed as an average power during one operating cycle.

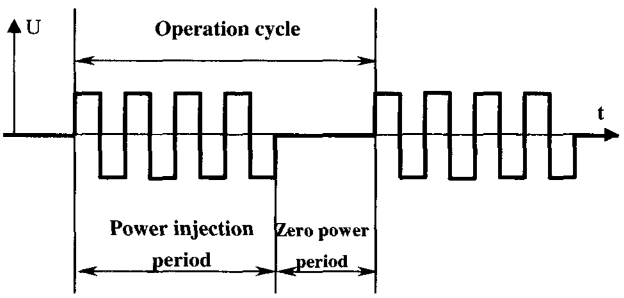


Fig. 5 Principle of PDM control

5. Performances of The Developed Inverter and Its Control Scheme

Developed a high-frequency inverter scheme provides a stable discharge at any output power level and linear regulation of the output power with a high accuracy. The operating waveforms for different power levels are depicted in Fig.6, Fig.7 and Fig.8.

As can be seen from Fig.8, the peak voltage value on the load (Ch4 max value) greatly exceeds the discharge starting voltage, which is about 3kV. Therefore, stable discharge can be observed even when one pulse is applied to the load.

At the same time, the soft-switching commutation conditions are achieved at any power level. Thus in Fig.9, the example for 20% output power is shown and in Fig.10 the same waveforms are enlarged.

As can be seen from the Fig.9, the power MOSFET switch is turned on and off (gate signal is represented by the waveform number one) at moments when the applied voltage on the drain is zero. The drain voltage is shown by the waveform number two. As a result, high efficiency can be expected at any output power level. At the same time

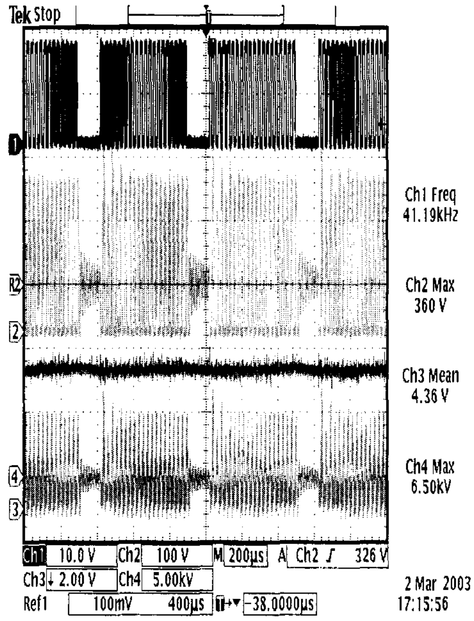


Fig. 6 Operation waveforms for 80% output power level.

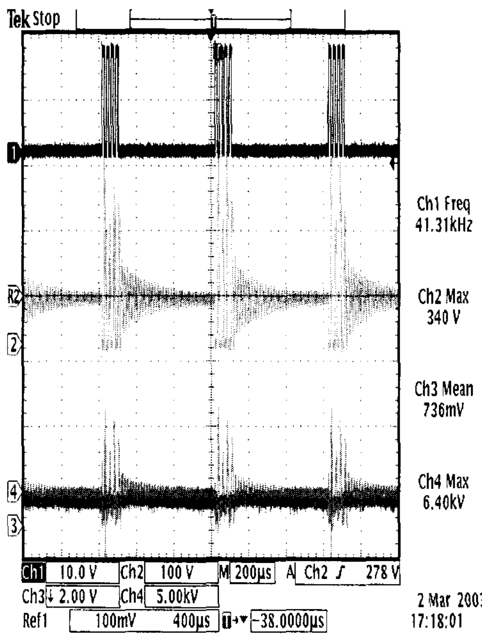


Fig. 7 Operating waveforms for 20% output power level.

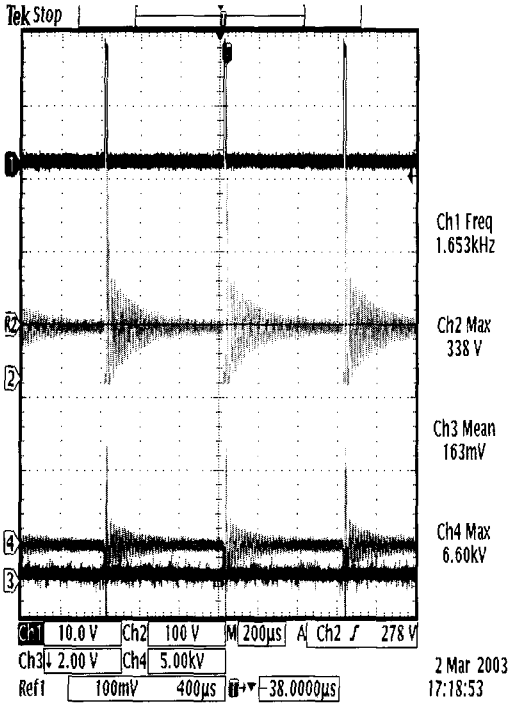


Fig. 8 Operation waveforms for 4% output power level.

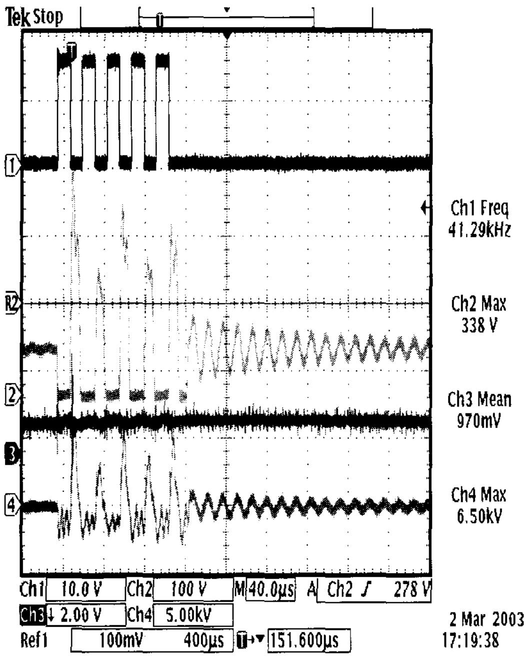


Fig. 9 Operating waveforms for 20% output power

the first turn on transient of the power MOSFET switch in the cycle is under the hard-switching conditions, because the constant voltage equal to the DC power supply is applied to the switch in the beginning of the power injection period. However, it is found in experiment that no significant power loss can be observed due to this.

The measured actual efficiency of the high frequency inverter becomes in range of 90-95% on frequencies from several tens to 200-300 kilohertz.

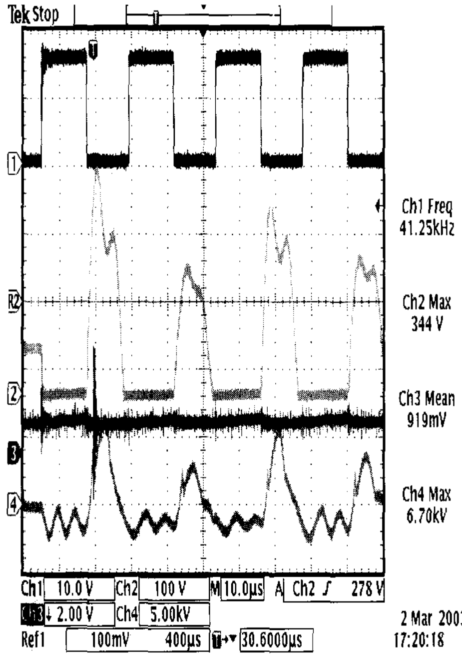


Fig. 10 Transients in the power injection period.

6. Conclusions

In this paper, the class E zero voltage soft-switching high-frequency inverter with the pulse density modulation control strategy applied to the dielectric barrier discharge lamp load has been introduced for UV generation tube. This inverter is based on a very simple circuit configuration with only one power MOSFET switch, however it provides a high operating efficiency more than 95% that is significantly higher than in conventional inverter schemes. As well, the output power regulation principle used in this inverter has such superior performances as stable discharge and high efficiency at any output power level starting from 0% and high accuracy of power regulation. The developed high-frequency generator scheme has been built up and tested for driving of 300W dielectric barrier discharge based ultraviolet light generation lamp and its effectiveness was confirmed from a practical point of view.

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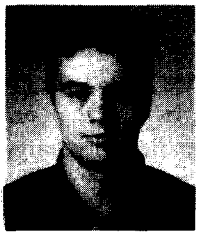

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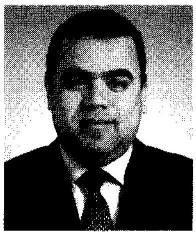

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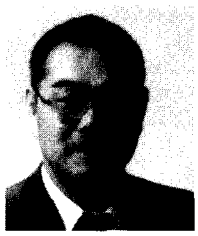

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