Single-phase Resonant Inverter using SiC Power Modules for a Compact High-Voltage Capacitive Coupled Plasma Power Supply

Vo Nguyen Qui Tu, Hyunchul Choi, Youngwoo Kim, Changhee Lee, Hyoyol Yoo

Department of Research and Development, Dawonsys
227, Gyeonggigwagidae-ro, Siheung-si, Gyeonggi-do, Korea
Email: tuvo@dawonsys.com

Abstract

The paper presents a power supply of atmospheric-pressure plasma reactor based on SiC (Silicon Carbide) MOSFET resonant inverter. Thanks to the capacitive characteristic of capacitive coupling plasma reactor type, the LC series resonant inverter had been applied to take advantages of this topology with the implementation of SiC MOSFET power modules as switching power devices. Designation of gate driver for SiC MOSFET had been introduced by this paper. The 5kVp, 5kW power supply had also been verified by experimental results.

Keywords: power supply, plasma reactor, resonant inverter SiC MOSFET.

1. Introduction `

Recently, capacitive coupling plasmas have been popular for developing large-sized material surface cleaners, photo-resistor ashers and material composition. Hence, AC power supplies need to provide AC power to plasma reactor to ignite plasma state and maintain steady state discharge by heating electrons [1], [2]. Due to the capacitance characteristic of plasma reactor type, the series LC resonant single-phase inverter has been applied as power supply of plasma reactors. Fig. 1 shows the topology of power supply which is comprised of three-phase full-bridge diode rectifier, DC link capacitor, a single-phase inverter, LC network and step-up transformer to provide *5*[kVp] sinusoidal output voltage at frequency of *100*[kHz] for providing to a plasma reactor. Moreover, the advantage of SiC MOSFET in high voltage breakdown, low-on resistance and fast switching speed also permits the increase power rated of inverter with compact and highly rated power module. The gate driver had also been designed for SiC power modules to achieve the high performance in high frequency switching operation.

2. Capacitive coupled plasma reactor modelling

The most typical electrode configuration of barrier discharge is shown in Fig. 2. As can be seen, there are gas gap *g* and dielectric barrier *d* between high-voltage and ground electrode which have gas capacitance C_g and dielectric capacitance C_d, respectively. The AC voltage sources and the input gas have been used to excite plasma in the chamber vacuum. In order to calculate the power consumption of AP-DBD, the capacitance C_d and C_g have been obtained by experimental measurements and the V-Q Lissajous diagram [2]. After plasma ignition, total capacitance of DBD reaches to the capacitance of dielectric C_d value which is the resonant capacitance the *LC* resonant network at the output of inverter.

3. Gate driver design for SiC Power Module

SiC power modules consisting of SiC-MOSFET are commonly used to handle high current and high block voltage. Hence, the design of gate driver for driving the voltage-controlled SiC-MOSFETs needs to be carefully considered [3].

The first requirement of the gate driver is that the gate voltage needs to be *+20*[V] positive bias to optimize the performance of SiC MOSFET which can be seen in the typical output characteristics of the device datasheet. The *-5*[V] negative bias is also designed for fast turning the switching devices.

The driver board utilizes gate driver integrated circuit IXD_614 can provide fast *dV/dt* gate voltage with the *14*[A] of source and sink current which allow the use of low external gate resistor to accomplished fast switching speed. The zero ohm external resistor can be achieved good performance due to the exist of 5Ω internal gate resistance of the SiC MOSFET.

The creep clearance has been significantly increased by the design of the groove in the printed circuit board. Consequently, along with the use of high common-mode transient immunity photo-coupler the compact gate driver can accomplish isolation voltage rating of 3750V. Moreover, the gate drive is located to directly on the SiC MOSFET power module in order to minimize the loop inductance. The gate drive board and the waveform for SiC MOSFET are shown in Fig. 3.

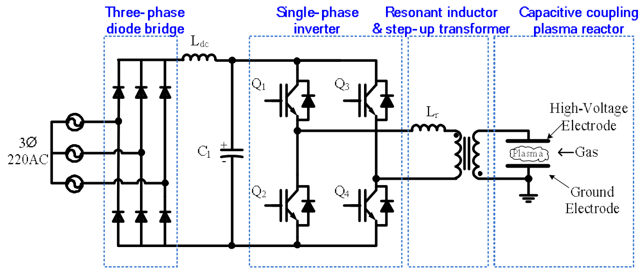

Fig. 1. The configuration of plasma power supply

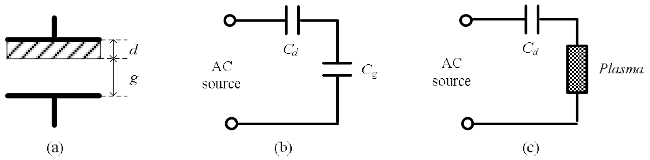

Fig. 2. (a) Typical electrode configuration of barrier discharge ; (b) capacitances before plasma ignition; (c) capacitances after plasma ignition

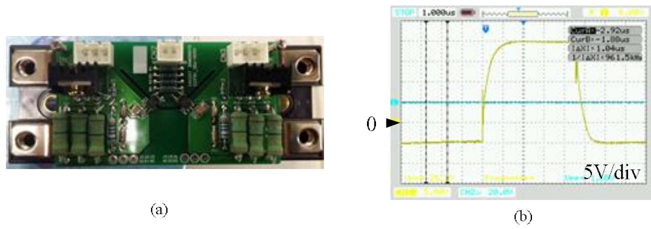

Fig. 3. Gate drive for SiC power module and gate voltage waveform

3. LC Resonant network

Due to the capacitive coupling characteristic of plasma reactor, an inductor and a step-up transformer have been applied to the

TABLE 1
CCP PLASMA POWER SUPPLY PARAMETERS

Parameter	Value
Output power	5 [kW]
Output voltage	5 [kVp]
Operating frequency	100~150[kHz]
Resonant inductance	13.5[uH]
Capacitance of dielectric barrier	3.6[nF]
Transformer turn ratio	5:50

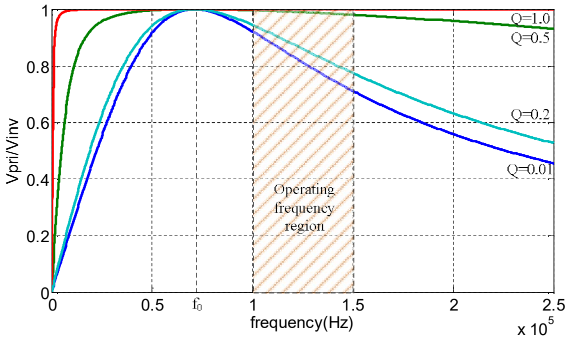

Fig. 4. Voltage gain characteristic in the different cases of load.

output of single-phase inverter to form a LC resonant network. Hence the advantages of LC resonant inverter can be taken by operated at high frequency [4], [5]. The resonant capacitance is equalized by the dielectric capacitor C_d of reactor to the primary-side of step-up transformer. Meanwhile, the resonant inductance is the summation of transformer leakage inductance and additional reactor. Based on the load capacitance, the resonant inductor had been selected to *12*[uH] by matching tests regarding to *74*[kHz] of resonant frequency. The relation of inverter output voltage and the primary voltage of step-up transformer can be described by the following transfer function.

$$H(\omega) = \frac{1}{1 + jQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)}$$

where $\omega_0 = 1/\sqrt{LC}$ is the resonant frequency of resonator, $Q = \omega_0 L/C$ is the quality factor of resonator. Fig. 4 shows the voltage gain characteristic of series resonant network at the different load conditions. As can be seen the maximum voltage gain is at resonant frequency. The operation frequency of power supply is in the region of *100*[kHz] to *150*[kHz].

4. Simulation and Experimental Results

The power supply for the capacitive coupled plasma reactor had been verified by simulation and experimental results. The CCP power supply parameters are shown by table 1. SiC MOSFET Power Modules *180*[A], *1200*[V] had been used as switching devices of single-phase resonant inverter. Fig. 5 shows the experimental setup of *5*[kW] CCP power supply. The plasma reactor load for experiment test is equalized by a *3*[kΩ] resistor parallel connected with a *3.6*[nF] capacitor. The results of CCP power supply output voltage, inverter output voltage and inverter output current are shown in Fig. 6. The output voltage had been accomplished as a sinusoidal waveform of 5kVp which is power source of capacitive coupled plasma reactor. As can be seen, the inverter current is lagging the inverter voltage because of the larger of inverter switching frequency to the resonant frequency.

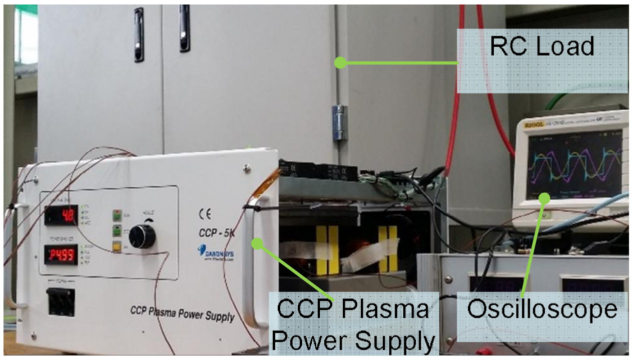

Fig. 5. Experimental setup of CCP Plasma Power Supply

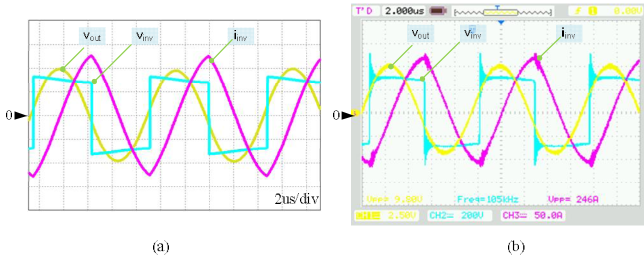

Fig. 6. (a)Simulation results,(b) experimental result of CCP plasma power supply. v_{out}: output voltage (*2.5*[kV]/div) v_{inv}: inverter output voltage (*200*[V]/div) and i_{inv} :inverter output current (*50*[A]/div)

5. Conclusion

The paper had presented a power supply for capacitive coupled plasma reactor using a resonant inverter based on SiC devices. The specific design of gate driver for high power SiC MOSFET module had been described. The smaller size of power supply has been achieved by the resonant inverter based on the compact SiC power modules and high frequency operation which allows the optimization of the resonant inductor and step-up transformer. The sinusoidal output voltage waveform, AC power source of plasma reactor, had been generated and verified by the experimental result.

References

[1] G.-H. Kim, S.-Y. Jeong and H.-C. Kwon, “Capacitance Between an Atmospheric Discharge Plasma and the Dielectric Electrode in the Parallel Cell Reactor,” in Journal of the Korean Physical Society, Sep. 2006, vol. 49, pp. 1307~1311.

[2] N. Y Babaeva, J. K. Lee, and J. W. Shon, “Capacitively coupled plasma source operating in Xe/Ar mixtures,” in Journal of Physics D: Appl. Phys 2005, vol. 38, pp. 287–299.

[3] Rohm Co., Ltd, “SiC Power Devices and Modules” Application note, Jun. 2013 Rev.001.

[4] H.-S. Choi, “Design Consideration of Half-Bridge LLC Resonant Converter,” in Journal of Power Electronics, Jan. 2007, vol. 7, pp. 13~20.

[5] H.-M. Han, M,-Y. Kim, K.-D. Seo and J.,-S. Kim, “A Study On High Power Factor Sine Pulse Type Power Supply For Atmospheric Pressure Plasma Cleaning System with 3-Phase PFC Boost Converter ,” The Transaction of the Korean Institute of Power Electronics , Feb. 2009, pp. 72~81.