A 2-MHz 6-kVA voltage-source inverter using low-profile MOSFET modules for low-temperature plasma generators

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A 2-MHz 6-kVA Voltage-Source Inverter Using Low-Profile MOSFET Modules for Low-Temperature Plasma Generators

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***Abstract*—This paper presents a 2-MHz 6-kVA voltage-source inverter for low-temperature plasma generators. A new MOSFET module referred to as a "mega pack" is specially designed and fabricated for high-frequency high-power applications. It has a low-profile package equipped with four terminal plates. The main circuit consists of a single-phase full-bridge inverter using the four new modules. The layout of the modules is characterized by two modules, which are placed back-to-back with each other, forming a half bridge. Both device and circuit designs achieve great reduction of stray inductance in the main circuit. A prototype inverter shows stable operation around frequencies as high as 2 MHz.**

***Index Terms*—Device packaging, high-frequency inverter, low-temperature plasma, power MOSFET, stray inductance.**

I. Introduction

In RECENT years, low-temperature plasma has been applied to surface treatment processes for metallic parts, semiconductor material processes, and so on [1]. A high-frequency strong magnetic field has the function of producing low-temperature plasma from low-pressure gas and of sustaining it. A high-frequency power supply of 2–10 kW is required to generate the magnetic field in a frequency range of 2–13.56 MHz, which is too high for conventional semiconductor devices to perform their switching operation [2]. A linear amplifier using BJT's or vacuum tubes is currently used in high-frequency power supplies for plasma generators at the expense of low efficiency and large size.

In addition, such a high-frequency power supply consisting of linear amplifiers needs an impedance-matching circuit which is connected between its high-frequency output terminal and a series- or parallel-resonant load. The discharging conditions of the low-temperature plasma are strongly affected by gas pressure and flow speed, temperature, and so on. Moreover, the quality factor of the resonant circuit drastically decreases when the low-temperature plasma is established. Before the low-temperature plasma flames up, a large current flows into the series resonant circuit even at a low-output voltage. While the low-temperature plasma is hot, a high voltage is required to keep a stable discharge. The low-temperature plasma generator is generally equipped with a matching circuit intended for automatically achieving its impedance matching.

The emergence of fast switching devices such as power MOSFET's and static induction (SI) devices has made it possible to implement high-frequency inverters for induction heating and discharge treating applications [3]–[12]. However, a voltage-source inverter has difficulty in high-frequency operations over 1 MHz. Stray inductance and output capacitance of the MOSFET forms a series resonant circuit which may cause parasitic resonance. The resonance is accompanied not only by increases in the peak voltage and current, but also by conduction losses and stress for the MOSFET's. The stray inductance interferes with turn on of a freewheeling diode when the opposite MOSFET is turned off. Consequently, an excessive surge voltage may appear in the drain-to-source voltage. It is important to reduce the internal stray inductance existing within each MOSFET module and the line inductance between two modules which form a leg for a voltage-source inverter operated at a frequency of more than 1 MHz.

This paper presents a 2-MHz 6-kVA voltage-source inverter developed for low-temperature plasma generators. The main circuit consists of a single-phase H-bridge inverter using four MOSFET modules which are newly designed for high-frequency applications. This new MOSFET module, referred to as a "mega pack," is fabricated in a low-profile package of an 8-mm height and possesses four plate-shaped terminals which are led out of its side edges to reduce its internal inductance [13]. Each leg of the H-bridge inverter consists of two new MOSFET modules forming a back-to-back layout which enables a significant reduction of the line inductance between the modules. The inverter circuit has the advantages of the low-profiled modules and their back-to-back layout. As a result, the developed inverter has the voltage and current ratings required for a low-temperature plasma generator without any auto-tuning matching circuit. Experimental results obtained from a 2-MHz 6-kVA voltage-source series-resonant inverter integrated into a prototype low-temperature plasma generator verify effectiveness in the new MOSFET modules and the proposed device layout.

II. Low-Temperature Plasma Generator

Fig. 1 shows the operation principle of a low-temperature plasma generator consisting of a high-frequency power supply and a series resonant circuit. A quartz tube inserted in the

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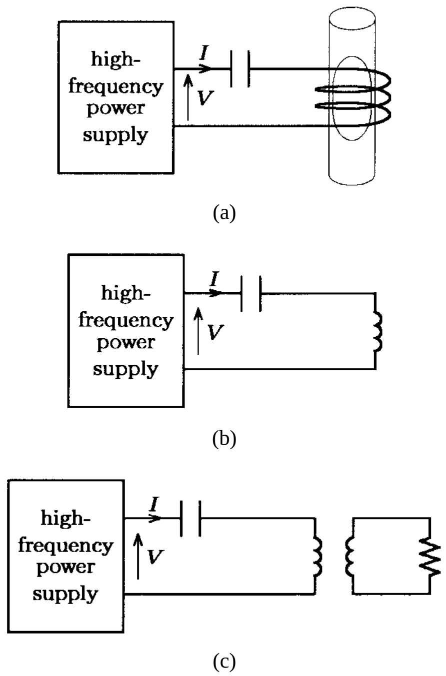

Fig. 1. Principle of plasma generator: (a) configuration of the generator, (b) an equivalent circuit before plasma flames up, and (c) an equivalent circuit during discharge.

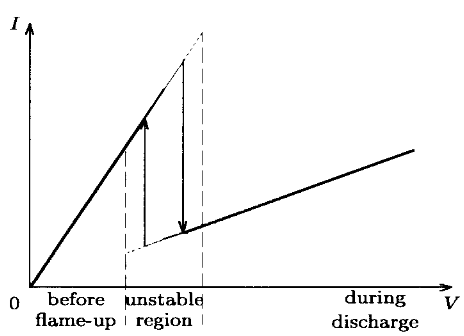

Fig. 2. Nonlinear relationship between voltage and current of a series-resonant plasma generator.

resonant reactor is filled with argon gas. At first, a high-voltage electric field across the resonant reactor excites the gas, and then weak plasma starts to flame up. A high-frequency magnetic field produced by the resonant current produces an eddy current in the plasma, which establishes and sustains plasma discharge in the quartz tube.

Fig. 1(b) shows the equivalent circuit before the low-temperature plasma flames up. No power consumption occurs in the plasma, so that the quality factor of the resonant circuit is 100 or higher. During the plasma discharge, the low-temperature plasma resembles a resistor connected to the secondary side of the transformer, as shown in Fig. 1(c). The quality factor of the resonant circuit is reduced to 20–40.

The relationship between the supply voltage and current is shown in Fig. 2. Before the plasma flames up, a low-voltage and large-current rating is required for the high-frequency power supply, while a high-voltage and medium-current rating is needed to sustain the generated plasma during the discharge. This means that flaming up is accompanied by a drastic change in the equivalent impedance of the plasma generator

TABLE I
RATINGS AND ELECTRICAL CHARACTERISTICS OF MOSFET MODULE "MEGA PACK" (HF40S60MP: ORIGIN ELECTRIC)

Parameter		Symbol	Maximum	Unit
Drain-Source Voltage		V_{DS}	600	V
Gate-Source Voltage		V_{GS}	±30	V
Drain Current	DC	I_D	40	A
	Pulse	I_{DP}	160	A
On-State Resistance		$R_{DS(\mathrm{ON})}$	0.15	Ω
Parameter		**Symbol**	**Typical**	**Unit**
Input Capacitance		C_{iss}	5810	pF
Output Capacitance		C_{oss}	1010	pF
Input Inductance		L_{GS}	4	nH
Output Inductance		L_{DS}	3	nH

seen from the high-frequency power supply. An automatically adjusted impedance-matching circuit, which consists of high-frequency reactors and variable capacitors, is indispensable for a linear-mode amplifier employed as a high-frequency power supply because the efficiency significantly decreases under incorrect impedance matching. The matching circuit, however, has problems in its size, weight, and cost. The theoretical efficiency of a class-B linear amplifier is about 78.5% in a completely matched load [14], while practical efficiency is less than 50% even when a matching circuit is connected. Such a linear amplifier requires a bulky heat sink for dissipating the large loss.

III. SYSTEM CONFIGURATION

Fig. 3 shows the system configuration of a 2-MHz 6-kVA voltage-source inverter for a low-temperature plasma generator. The main circuit is a single-phase H-bridge inverter using the four MOSFET modules. The ratings and electrical characteristics of the module are summarized in Table I. Since the body diode of the MOSFET is used as a freewheeling diode, no additional diode is connected to the MOSFET. This results not only in downsizing the power circuit of the inverter, but also in reducing the inductances existing in the diodes and connections. The inverter output terminals are connected to a series-resonant circuit through a step-down transformer having a turns ratio of 8:1. The series-resonant circuit consists of a water-cooled seven-turns coil L_L and a high-frequency mica capacitor C_L.

The combination of a slide regulator and a diode rectifier with a smoothing capacitor is used to adjust the dc-link voltage in the following experiments. It may be difficult to vary the output power by means of a frequency or duty control method because it is too critical to make fine adjustments of the displacement factor and the blanking time in an operating frequency as high as 2 MHz. A back converter will be employed to adjust the dc-link voltage in a practical setup.

IV. LOW-PROFILE MOSFET MODULE

Fig. 4 depicts the outline of the new MOSFET module developed for high-frequency applications [13]. The first priority in the design of the new module is to reduce the inductance

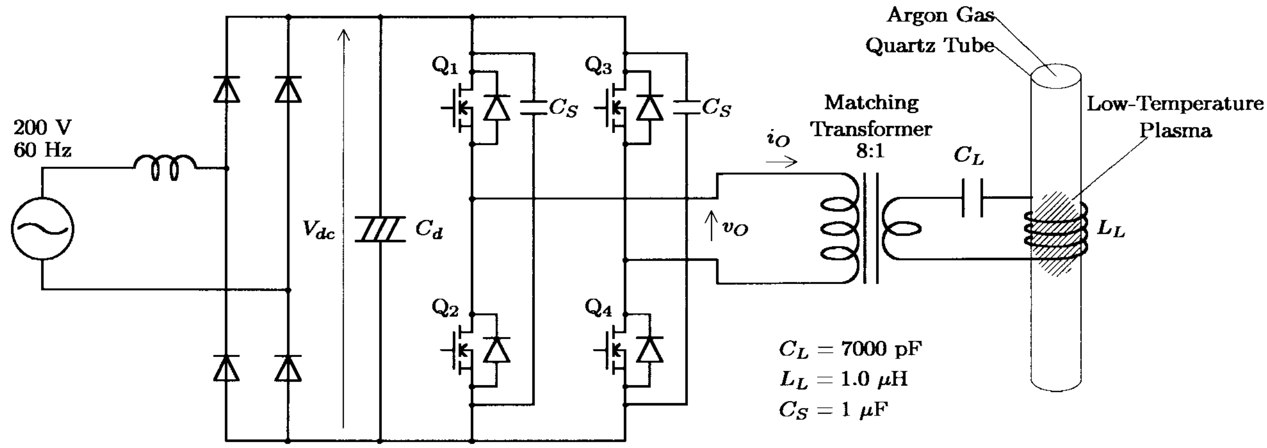

Fig. 3. System configuration.

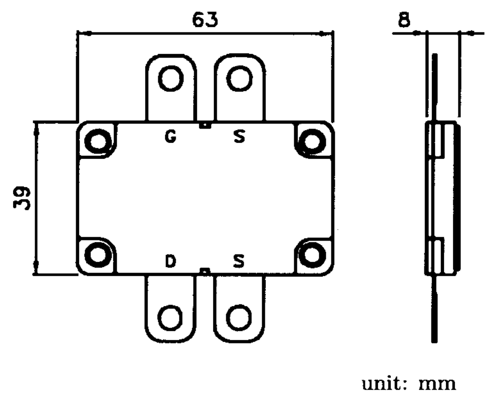

Fig. 4. Dimensions of MOSFET module (HF40S60MP).

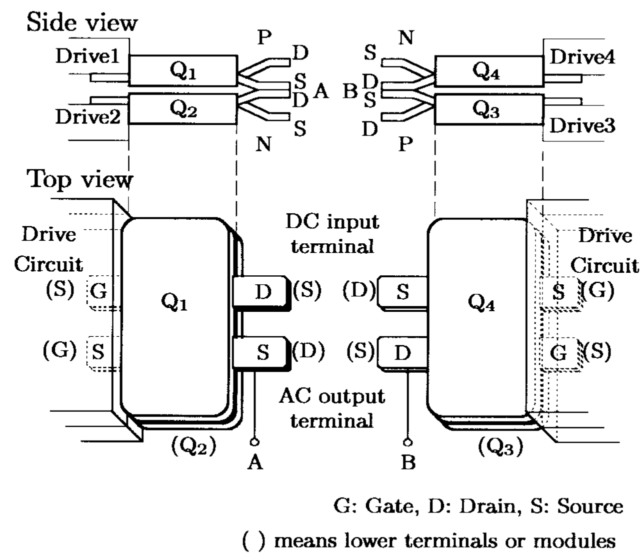

Fig. 5. Layout of switching devices around the main circuit.

existing within the module. The module is assembled in a low-profile package of an 8-mm height which is about one fourth the height of a conventional 31-mm module. The terminals, shaped into thin plates, are led from both side edges of the module. This results in a great reduction of the inductance caused by interconnections. Moreover, a "control" source terminal separated from a "power" source terminal has the ability to avoid interference between a gating signal and a main current.

The ratings and electrical characteristics are also summarized in Table I. Attention should be paid to its gate-to-source and drain-to-source inductances, which are one-tenth those of conventional modules. The magnetic energy stored in the inductances is dissipated in the switching devices as a result of producing surge voltage and parasitic resonance. In the high-frequency operations over 2 MHz, minimizing the inductances is most effective in improving the inverter efficiency and in reducing the voltage and current stress for the switching devices.

V. Back-to-Back Layout for Low-Profile MOSFET Module

Fig. 5 shows the layout of the MOSFET modules around the main circuit of the voltage-source inverter. The MOSFET modules Q_1 and Q_2 forming one half-bridge inverter are placed back-to-back, with their heat sinks located outside. The source terminal in Q_1 and the drain terminal in Q_2 are directly connected and so form one ac output terminal of the H-bridge inverter. In the other half-bridge inverter, the source terminal in Q_3 and the drain terminal in Q_4 are also connected, and so form the other ac output terminal. The drain terminals in Q_1 and Q_3 and the source terminals in Q_2 and Q_4 are connected to the dc smoothing capacitor of the diode rectifier. A high-frequency film capacitor of 1 μF is installed in the vicinity of each half-bridge inverter to absorb current ripples produced by high-frequency switching.

Fig. 6 is a photograph of the half-bridge inverter used in the following experiments. The modules placed in the back-to-back layout are sandwiched in water-cooled heat sinks. The high-frequency film capacitor and two drive circuits are connected to the MOSFET modules as closely as possible. Applying the back-to-back layout to conventional modules may be difficult because it has three terminals on its top. In the case of the new MOSFET modules, the back-to-back layout is realized by a low-profile package and four plate-shaped terminals. This layout greatly contributes to reducing stray inductance around the main circuit.

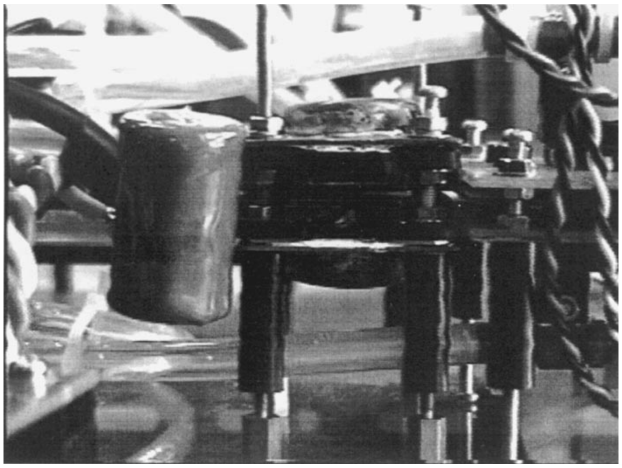

Fig. 6. Half-bridge unit.

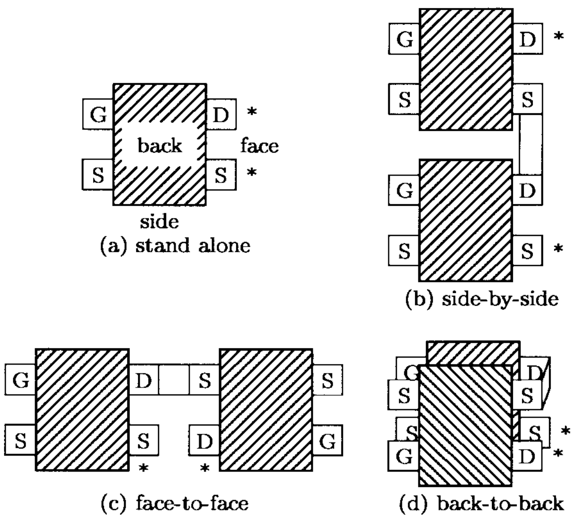

Fig. 7. Device layout comparison.

To evaluate the effect of the back-to-back layout, inductances in two other device layouts were measured and compared with each other. Fig. 7 shows device layouts used for comparison. In a side-by-side layout shown in Fig. 7(b), two MOSFET modules are placed on a plane side by side. The gate terminals of the two modules are located in the left side, so that it is easy to connect the gate drive circuit with the modules. However, the upper drain terminal is far from the lower source terminal, which is connected to the dc capacitor. The face-to-face layout shown in Fig. 7(c) can also be constructed on a plane. Although the connections of the power terminals are close, the gate terminals are located on opposite sides. The back-to-back layout shown in Fig. 7(d) has short connections between the power terminals, and the gate terminals are located on the same side. However, two separate heat sinks are required, and the construction is not so easy as the side-by-side and face-to-face layouts.

The results of the inductance measurements are shown in Table II. A device model made of a copper plate was used for the measurement in order to simulate the outline and internal structure of the MOSFET module. An LCR meter (HP4263A: Hewlett Packard) was used to measure the inductances between the terminals marked with "∗." The inductance of the device stand-alone model in Table II(a) is 6.1 nH, which is slightly larger than that in Table I because the measured value includes the lead inductance of the MOSFET. The face-to-face layout in Table II(c) shows a smaller stray inductance than the side-by-side layout in Table II(b) because of the shorter connection between the power terminals. The back-to-back device layout in Table II(d) shows the smallest inductance, which is less than twice the inductance of the stand-alone module. The inductances of the two modules are coupled together in the back-to-back layout because the modules are closely stacked. Therefore, the total inductance of the back-to-back layout is smaller than twice that of the stand-alone module. These results show that the back-to-back device layout is one of the most effective solution to stray inductance problems.

TABLE II
DEVICE LAYOUT AND CIRCUIT INDUCTANCE

device layout		inductance
(a)	stand-alone	6.1 nH
(b)	side-by-side	45 nH
(c)	face-to-face	20 nH
(d)	back-to-back	8.2 nH

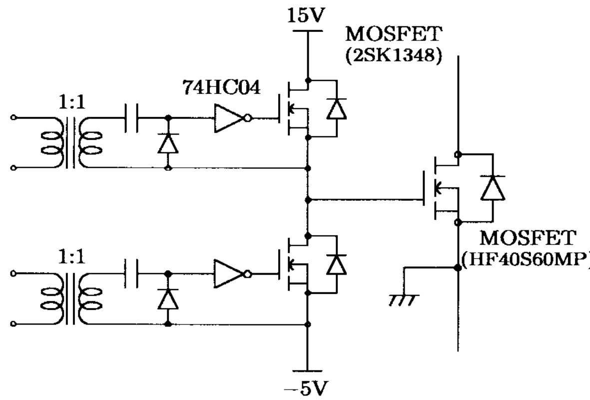

Fig. 8. Drive circuit.

VI. GATE DRIVE CIRCUIT

Fig. 8 shows the drive circuit for each MOSFET. The drive circuit consists of a half-bridge inverter using two low-voltage power MOSFET's. A small transformer is used to isolate the drive circuit from the control circuit. The isolated gate signal is amplified by a TTL device, and then it is provided to the low-voltage MOSFET. Two dc voltages, +15 V and −5 V, are fed to the half-bridge inverter: +15 V for turning on the main MOSFET and −5 V for turning it off.

In general, a damping resistor is inserted between the drive circuit and the gate terminal of each MOSFET to damp resonance caused by the line inductance and the input capacitance. In the developed system, the drive circuit output terminals are directly connected to the gate and source terminals of

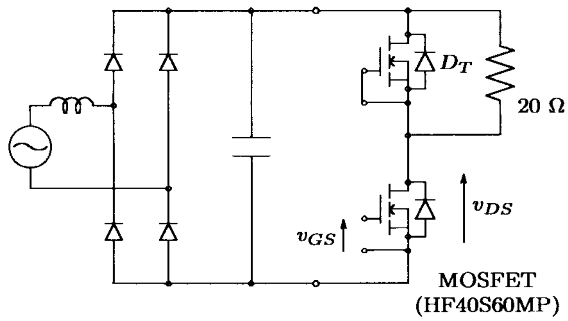

Fig. 9. Test circuit for a single half-bridge unit.

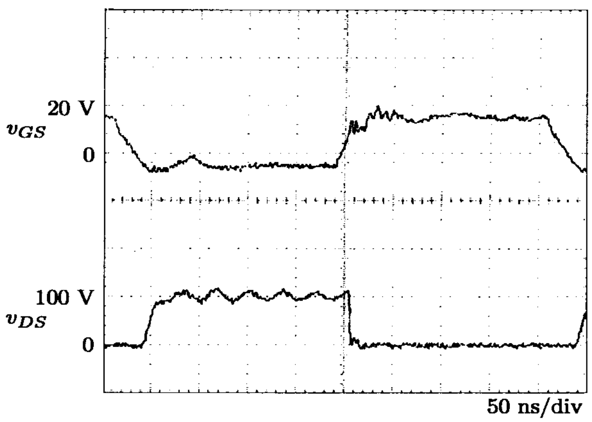

Fig. 10. Experimental waveforms in the chopper test.

the main MOSFET without connecting any damping resistor. The drive circuit is located close to the main MOSFET to reduce the line inductance, and the inductance across the gate and source terminals is small enough. Thus, such resonance can be damped by the on-state resistance of the low-voltage MOSFET alone, and it is not required to insert any additional resistor. This results in a fast charge or discharge of the input capacitance of the MOSFET.

VII. Experimental Results

Fig. 10 shows experimental waveforms of gate-to-source and drain-to-source voltages, obtained from a chopper test circuit shown in Fig. 9. A single half-bridge circuit is used, and the gate and source terminals of the upper module are shorted out. Thus, the internal antiparalleled diode D_T acts as a freewheeling diode. Here, the dc-link voltage is 100 V, the frequency of the gate signal is set to 1 MHz, and a 20-Ω resistor is connected as a load. No surge voltage appears in $v_{\rm DS}$ during turn off because stray inductance around the module is reduced. The fall time of $v_{\rm DS}$ is about 10 ns and the rise time is 20 ns. The rise time equals a time constant determined by the load resistance and output capacitance of the MOSFET

$$T = RC_{\rm oss} = 20^{\Omega} \times 1010^{\rm pF} = 20^{\rm ns}.$$

Accordingly, the MOSFET module provides turn-off switching as fast as 20 ns or less.

Figs. 11 and 12 are experimental waveforms of the inverter output current i_O and the drain-to-source voltage $v_{\rm DS}$ obtained from the 2-MHz 6-kVA voltage-source series-resonant inverter integrated into a prototype low-temperature plasma generator. The inverter output current i_O is measured by using an ac current transformer (Pearson's) which has a detecting delay time as short as 10 ns. During the experiments, a stainless-steel rod is inserted into the resonant coil instead of the quartz tube filled with argon gas because the low-temperature plasma is affected by gas pressure, temperature, and so on.

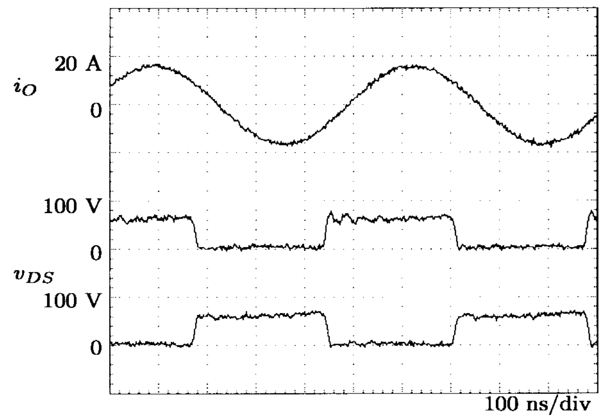

Fig. 11. Experimental waveforms without the stainless-steel rod load.

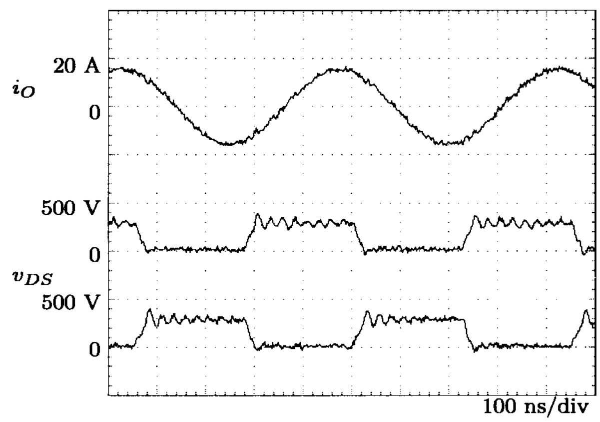

Fig. 12. Experimental waveforms with the stainless-steel rod load.

Fig. 11 shows waveforms produced when the stainless-steel rod is removed from the working coil. The quality factor Q of the resonant circuit is higher than 100 because of no load. Therefore, this condition is similar to that of low-temperature plasma before it flames up. The wave shape of $v_{\rm DS}$ has almost no surge voltage nor parasitic resonance. The inverter achieves 10-ns rise and fall times and a power factor as high as 90%.

Fig. 12 shows waveforms under a load condition with the stainless-steel rod inserted into the working coil. The voltage and current waveforms are similar to those produced during low-temperature plasma flame up because the quality factor Q decreases to 40. Since the dc-link voltage and current are 300 V and 8.5 A, the dc input power of the inverter equals 2.5 kW. The waveform of $v_{\rm DS}$ includes a surge voltage as low as 80 V due to the output capacitance of the MOSFET. The rise and fall times are about 20 ns.

Fig. 13 shows experimental waveforms in the case of a full-load condition. In order to demonstrate a stable operation of the developed inverter, a resistor as a load is connected in series

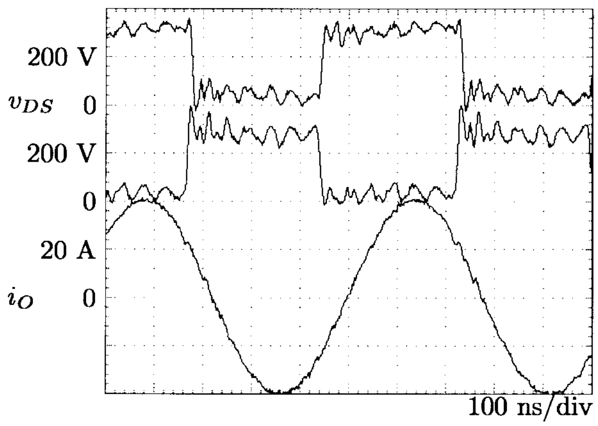

Fig. 13. Experimental waveforms in case of full-load condition.

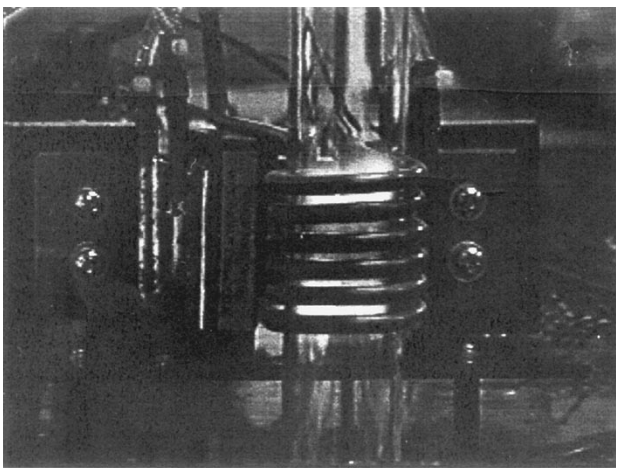

Fig. 14. Low-temperature plasma before flaming up.

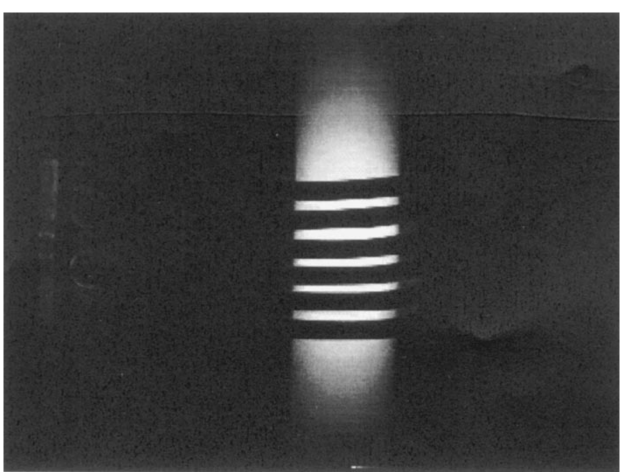

Fig. 15. Low-temperature plasma during discharge.

with the series-resonant circuit. The dc-link voltage is 300 V, the resonant rms current is 28 A, and the output power reaches 4.8 kW. The dc input power is 5.4 kW, so that the inverter efficiency is about 89% which is much higher than that in linear-type power supplies. This experimental result concludes that the developed inverter is applicable to a low-temperature plasma generator without any auto-tuning matching circuit.

Figs. 14 and 15 are photographs of low-temperature plasma generated by the prototype system. Fig. 14 was taken before the plasma flames up. The argon gas was excited by the high-frequency electromagnetic field. Fig. 15 was taken during discharge.

VIII. Conclusion

This paper has dealt with a 2-MHz 6-kVA voltage-source inverter developed for low-temperature plasma generators. It is clarified that the back-to-back device layout using two new low-profile MOSFET modules greatly reduces stray inductance around the main circuit. This leads to damping of parasitic resonance and to suppressing surge in the drain-to-source voltage. Experimental results obtained from a prototype low-temperature plasma generator verify effectiveness in the new MOSFET modules and the proposed device layout.

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