Engineering

Electrical Engineering fields

Okayama University *Year* 1999

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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-profiled package equipped with four terminal plates. The main circuit consists of a single-phase full-bridge inverter using the four new modules. The modules' layout is characterized by the two modules forming a half-bridge which are placed back-to-back with each other. 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.

I. Introduction

In recent years, low-temperature plasma has been applied to surface treatment processes for metallic parts, semiconductor material processes, and so on. A high-frequency strong magnetic field has the functions 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 a switching operation. A linear amplifier using BJTs or vacuum tubes is currently used in a high-frequency power supply 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 MOSFETs and SI devices has made it possible to implement high-frequency inverters for induction heating and discharge treating applications. 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 MOSFETs. The stray inductance interferes with turn-on of a free-wheeling 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 forming 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 "Mega Pack," is fabricated in a low-profile package of 8-mm height and possesses four plate-shaped terminals which are led out of its side edges to reduce its internal inductance. 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 mod-

0-7803-4489-8/98/$10.00

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		$R_{DS(ON)}$	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

ules and the proposed device layout.

II. SYSTEM CONFIGURATION

Fig. 1 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 free-wheeling 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 inductances existing in the diodes and connections. Although a diode rectifier with a smoothing capacitor is used as a dc voltage supply, the dc link voltage would be varied to adjust the output power of the inverter in the following experiments.

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. A quartz tube filled with argon gas is inserted into L_L. A high-frequency magnetic field produced by the resonant current establishes and sustains low-temperature plasma in the quartz tube.

III. LOW-PROFILED MOSFET MODULE

Fig. 2 depicts the outline of the new MOSFET module developed for high-frequency applications. The first priority in the design of the new module is to reduce the inductance existing within the module. The module is assembled in a low-profiled package of 8-mm height which is about one-fourth the conventional module height of 31-mm. 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.

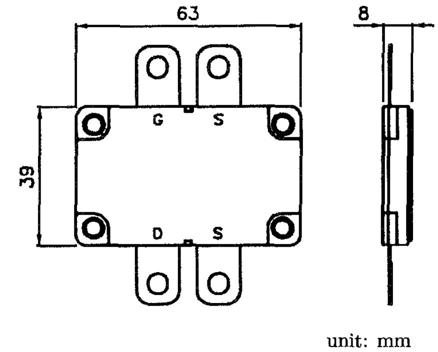

Fig. 2. Outlines of MOSFET module (HF40S60MP).

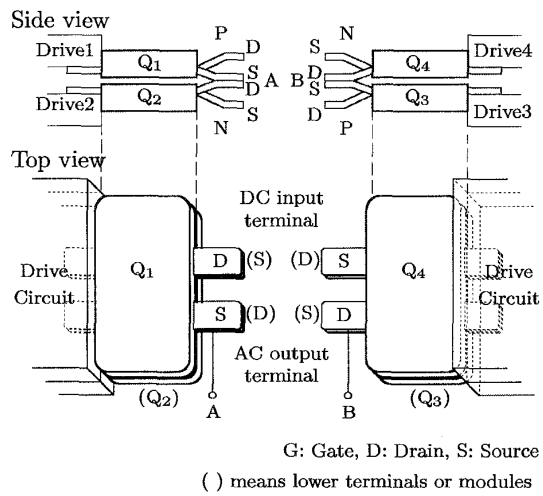

Fig. 3. Layout of switching devices around the main circuit.

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. One of the most interesting characteristics is its gate-to-source and drain-to-source inductances, which are one-tenth the value of those in conventional modules. This results in a great contribution to reducing surge voltage and parasitic resonance at high-frequency operations over 2 MHz.

IV. BACK-TO-BACK LAYOUT FOR LOW-PROFILE MOSFET MODULE

Fig. 3 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

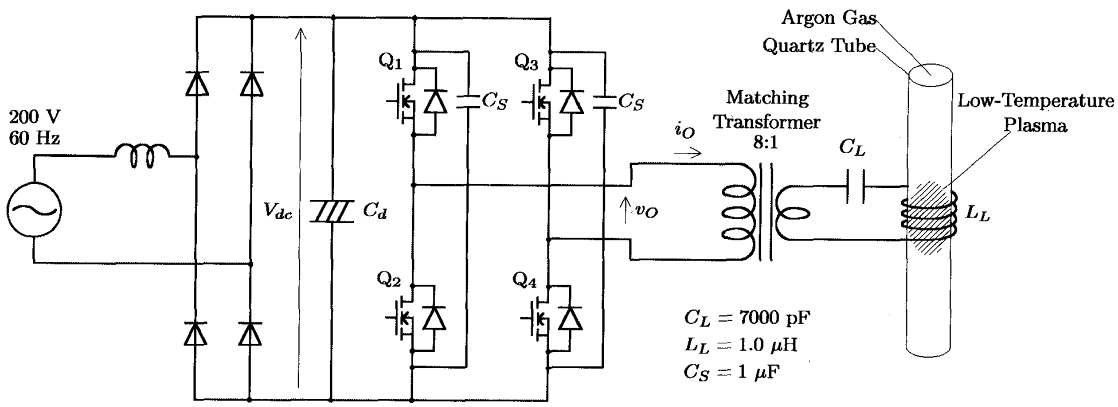

Fig. 1. System configuration.

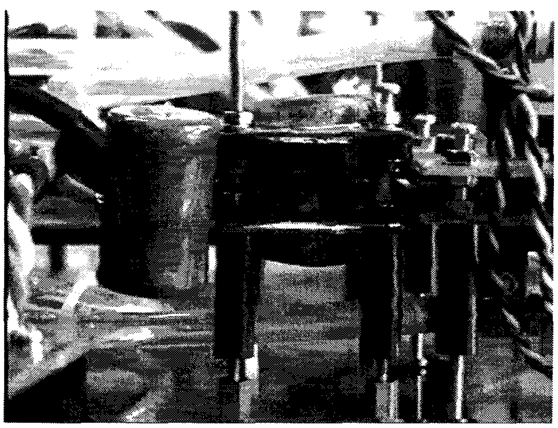

Fig. 4. Half-bridge unit.

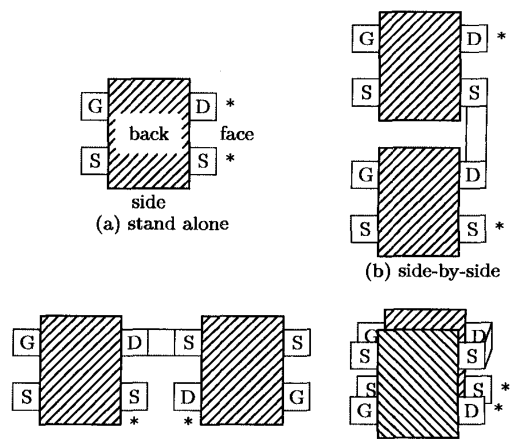

Fig. 5. Device layout comparison.

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. 4 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. It may be difficult to apply the back-to-back layout to a conventional module because it has three terminals on its top. 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.

To evaluate the effect of the back-to-back layout, inductances in two other device layouts were measured and compared with each other. Fig. 5 shows device layouts used for the comparison. In a side-by-side layout shown in Fig. 5 (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

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

drain terminal is far from the lower source terminal, which is connected to the dc capacitor. The face-to-face layout shown in Fig. 5 (c) can also be constructed on a plane. The connections of the power terminals are close, but the gate terminals are located on opposite sides. The back-to-back layout shown in Fig. 5 (d) has short connections of 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, simulating 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 (a) is 6.1 nH, which is a little bit larger than that in Table I because the measured value includes the lead inductance of the MOSFET. The face-to-face layout (c) shows a smaller stray inductance than the side-by-side layout (b) because of the shorter connection of the power terminals. The back-to-back device layout (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 tell us that taking advantage of the back-to-back device layout is the best solution to reduce power circuit inductances.

V. Gate Drive Circuit

Fig. 6 shows the drive circuit for each MOSFET. The drive circuit consists of a half-bridge inverter using two low-voltage power MOSFETs. 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 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 the main MOSFET on, 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 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 so it is not required to insert any additional resistor. This results in a fast charge or discharge of the input capacitance of the MOSFET.

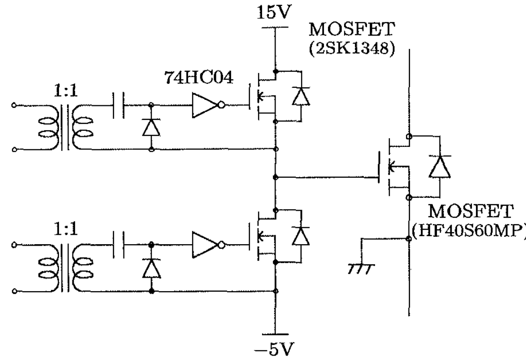

Fig. 6. Drive circuit.

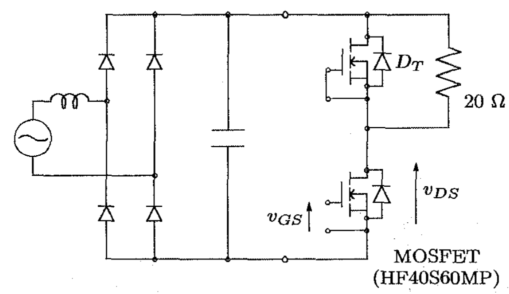

Fig. 7. Test circuit for a single half-bridge unit.

VI. Experimental Results

Fig. 8 shows experimental waveforms of gate-to-source and drain-to-source voltages, obtained from a chopper test circuit shown in Fig. 7. A single half-bridge circuit is used, and the gate and source terminals of the upper module are shorted out. Thus, the MOSFET cannot be turned on but the internal anti-paralleled 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

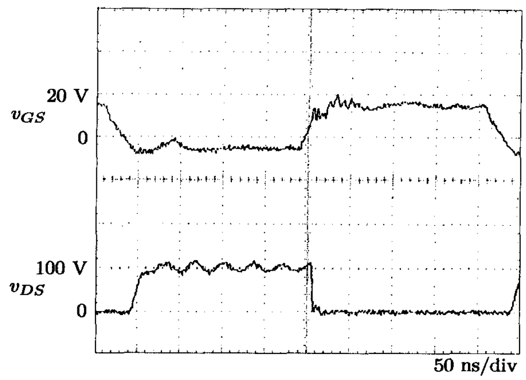

Fig. 8. Experimental waveforms in the chopper test.

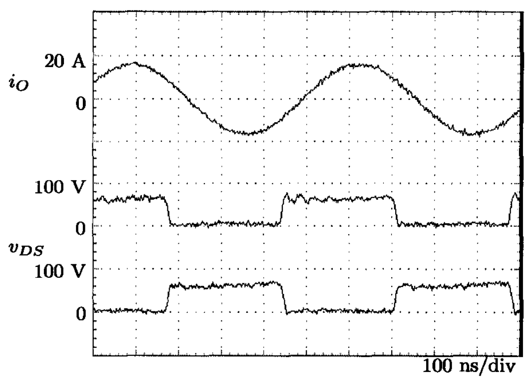

Fig. 9. Experimental waveforms without the stainless-rod load.

v_{DS} during turn off because stray inductance around the module is reduced. The fall time of v_{DS} is about 10 ns and the rise time is 20 ns. The rise time equals a time constant determined by the load resistor and output capacitance of the MOSFET:

$$T = RC_{oss} = 20^{\Omega} \cdot 1010^{\text{pF}} = 20^{\text{ns}}.$$

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

Figs. 9 and 10 are experimental waveforms of the inverter output current i_O and the drain-to-source voltage v_{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 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.

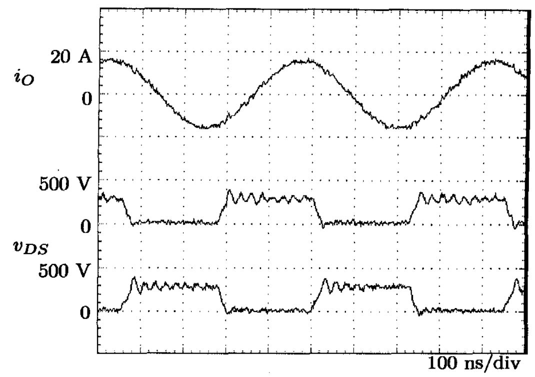

Fig. 10. Experimental waveforms with the stainless-rod load.

Fig. 9 shows waveforms produced when the stainless-rod load 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_{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. 10 shows waveforms under aload condition with the stainless 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_{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. 11 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 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. This experimental result tells us that the developed inverter is applicable to a low-temperature plasma generator without any auto-tuning matching circuit.

Figs. 12 and 13 are photographs of low-temperature plasma generated by the prototype system. Fig. 12 was taken before plasma flame-up. The argon gas was excited by the high-frequency electro-magnetic field. Fig. 13 was taken during discharge.

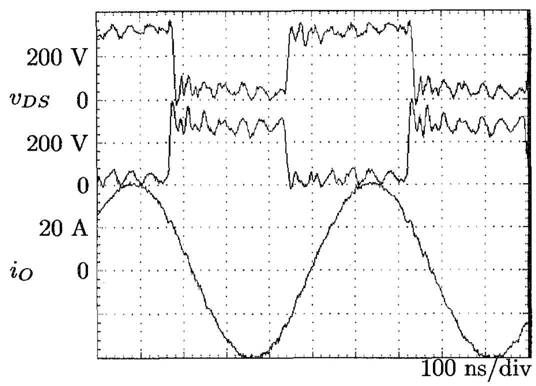

Fig. 11. Experimental waveforms in case of full-load condition

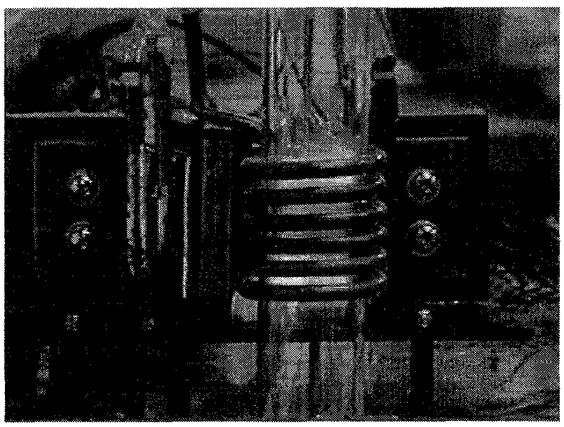

Fig. 12. Low-temperature plasma before flaming up.

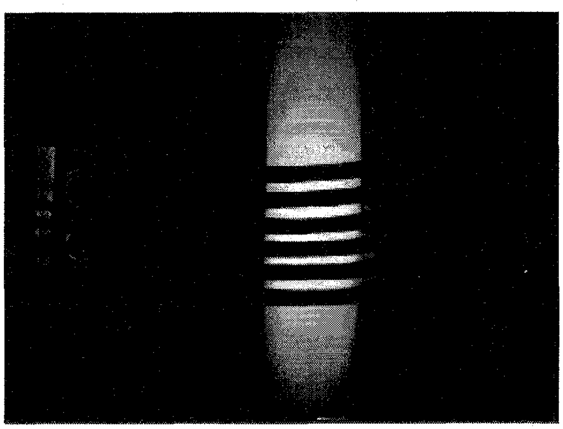

Fig. 13. Low-temperature plasma during discharge.

VII. Conclusions

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.

Acknowledgment

The authors would like to thank Kuniro Hirao, former graduate student in the department of Electrical Engineering at Okayama University, for his support in these experiments.

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