RF Plasma Heating with SIT Inverter Power Source and Its Harmonic Operation

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Abstract

The applications of rf inverter power supply with SIT to laboratory plasma and fusion studies are described together with its harmonic operations to extend the output frequency range higher than a few MHz. The power conversion efficiency, dissipative loss of SIT device and the limit of maximum power are discussed to demonstrate the usefulness and to indicate a hopeful direction to higher-frequency device development with a substantial power capability.

I. Introduction

Over the past few decades, a considerable number of studies have been conducted on high power and high frequency inverter power supply. In recent years, high power semiconductor devices with fast switching speed are rapidly developed [1,2]. Insulated Gate Bipolar Transistors (IGBTs) have expanded the frequency range of inverter power supply with high output power. The appearance of high power and fast switching MOSFETs and Static Induction Transistors (SITs) make it possible to operate the inverter in kW at MHz frequency range [3,4]. Recent sub-micron manufacturing technique may enhance the quality of such power electronics devices.

When compared with conventional linear amplifiers, inverter power supplies have many advantage, such as high conversion efficiency (> 90 %), inexpensiveness, easy maintenance, compactness, and so on. For these reasons, inverter power supplies are expected to be used in high power and high frequency range, taking the place of the linear rf amplifiers with conventional vacuum tubes in many applications. Such advantages give us the utilization of inverter power sources for the laboratory plasma and fusion research.

In this paper, we introduce two examples of application: one is the generation of rf coupled thermal plasma and the other is the ion cyclotron resonance heating of magnetized plasma. In addition a trial to extend the operational frequency with harmonics utilization is discussed.

II. SIT Inverter Power Supply

The rf power supply used for plasma generation and heating is a high frequency inverter, where SIT forms a full bridge inverter. The SIT can be used to generate high powers of rf below around 1.5 MHz. The SIT inverter generates a voltage waveform almost rectangular shape and has a high dc-rf conversion efficiency around 90 %. So far, rf inverter generators are mainly used for inductive heating of conducting metallic materials at frequency around several hundreds kHz since high power semiconductors such as thyristors and IGBTs do not have enough time response to generate the rf power in the MHz range.

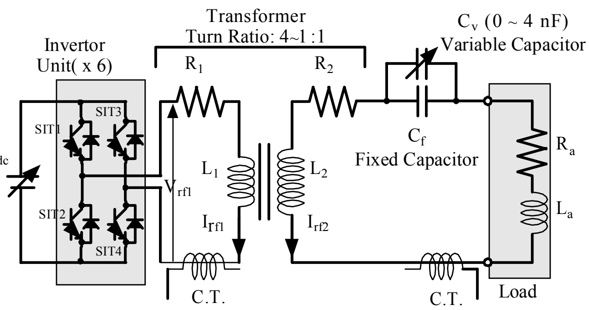

Fig.1 Circuit of SIT inverter rf power supply.

A schematic diagram of the inverter power supply concerned here, which consists of six SIT inverter units, is shown in Fig.1. Each inverter unit has four SIT transistors (Tokin Inc., TM-502D), the specification of which is shown in Table I. A dc voltage is fed to the six inverter unit from a dc-dc converter which has a maximum voltage and current of 400 V and 80 A, respectively. The output rf power is

Table I. Specification of SIT (TM502D)

Drain - Source Voltage	450V
Gate - Source Voltage	50V
Drain Current	30A
Turn-on Time	<50ns
Turn-off Time	<50ns
Dissipative Power	500W
Input Capacitance	<13nF

controlled by changing the dc output voltage of the dc-dc converter. The output from each inverter unit is combined and connected to an impedance transformer. The maximum output power of the present inverter power supply is obtained when the input impedance of the inverter load is about 5 ohms. Present impedance transformer uses toroidal ferrite cores and its turn ratio can be changed from 1:1 to 4:1. The rf specification is shown in Table II. The driving frequency can be changed easily by changing the frequency of the rectangular gate signal for SIT inverter.

Table II Specification of SIT inverter power supply

Power Device	SIT (Tokin TM-502D)
Output Power CW	14 kW
Pulse < 1 s	20 kW
Frequency	0.5 - 1.5 MHz
DC Voltage	400 V
DC Current	80 A
Output Control	DC-DC Converter
Phase Control	0 - π by 5° step

III. Application to RF Plasma Torch

Application of rf inductively coupled plasma has increased enormously over the last few decades because of its interesting characteristics, various structural properties and wide range of industrial applications [5]. This type of plasmas are now being used in many fields such as, in material processing, in analytical chemistry as a source of atomic excitation, in spray coating of metals and ceramics, in chemical vapor deposition of diamond films, in particle spherodization and in waste materials destruction. But promoting industrial applications, the

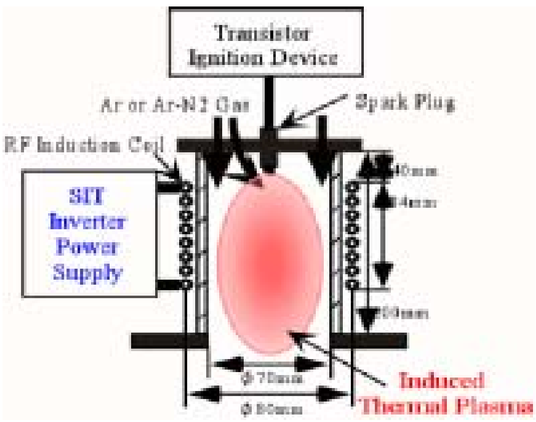

Fig.2 Block diagram of rf plasma torch

power efficiency for plasma generation should be high [6]. In addition a reliable ignition and stable steady state discharge should be obtained.

SIT inverter circuit is used for rf power supply. An automobile spark plug connected to a pulse transformer with a switching FET in the primary circuit is used to induce spark discharge for initiating the main discharge. This technique is so useful that the threshold rf current to have an ignition may be substantially reduced. Several turns rf coil is set around a Pyrex glass tube with 70 mm in diameter and 200 mm in length, as shown in Fig.2.

Fig.3 Pictures of argon plasma at t=60-90 ms. The rf frequency is 0.9MHz and absorbed power is about 3 kW.

Working gas (Ar) is introduced both vertically and spirally into the torch vessel with a flow rate of around 20 lit/min. The gas pressure is controlled in a range of 5-100 kPa. The level of rf power is controlled with a 100 ms square wave pulse. The pulse width is limited by a cooling capability of Pyrex glass tube. A typical video image of plasma torch is shown in Fig.3.

Typical waveforms of voltage and current are shown in Fig.4. We can derive the output power by using

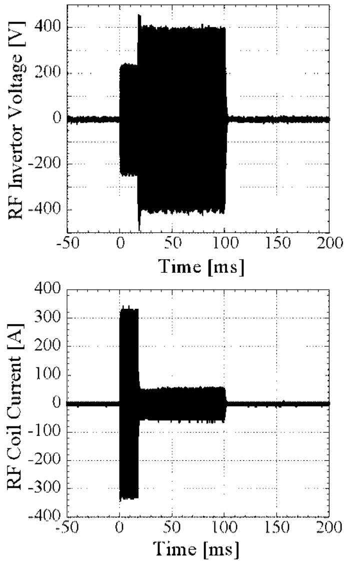

Fig.4 Typical voltage and current waveforms across coupling coil

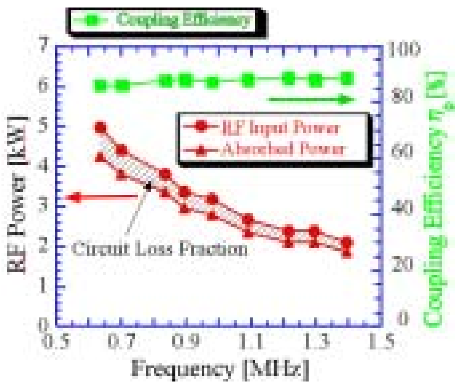

Fig.5 Generated and absorbed rf power, and coupling efficiency as a function of rf frequency. Ar gas pressure is 40 kPa.

primary voltage and current of impedance transformer as follows:

$$P_{rf} = \frac{1}{T}\int_0^T v_{rf} i_{rf}\, dt. \quad (1)$$

The loading resistance looked from the primary circuit is given by

$$R = P_{rf}/\sqrt{<i_{rf}^2>}. \quad (2)$$

The resistance with and without plasma are R_p and R_0, respectively. Then the difference $R_{pl} = R_p - R_0$ is defined as plasma loading resistance. The coupling efficiency is given by the ratio of plasma absorbed power P_{pl} to the output power.

$$\eta_p = \frac{P_{pl}}{P_{rf}} = \frac{R_{pl}<i_{rf}^2>}{R_p<i_{rf}^2>} = \frac{R_p - R_0}{R_p}. \quad (3)$$

Figure 5 shows the coupling efficiency η_p as a function of driving frequency, as well as the rf input and absorbed power. We finally obtained the total efficiency of 75-80 %, taking dc-rf conversion efficiency of around 90 % into account [7].

IV. Application to Ion Cyclotron Resonance Heating

Generation of high heat flux plasma by high power rf heating has been studied in the divertor plasma simulator NAGDIS-II for fundamental research of fusion plasmas [8] in which the ion cyclotron resonance heating has been employed. Waves are excited at upstream by phased-loop antenna array (see Fig.6) at a frequency range between 0.5 and 1.5 MHz [9]. The antenna is made from copper tubes with a 3/8 inch in diameter. Two pairs of antenna current strap are set in the vacuum vessel along the static magnetic field to generate B_r and E_θ. Two sets of inverter power supply using SIT are employed to excite the ion cyclotron slow wave in a magnetic beach configuration. Each power supply drives its own antenna with the

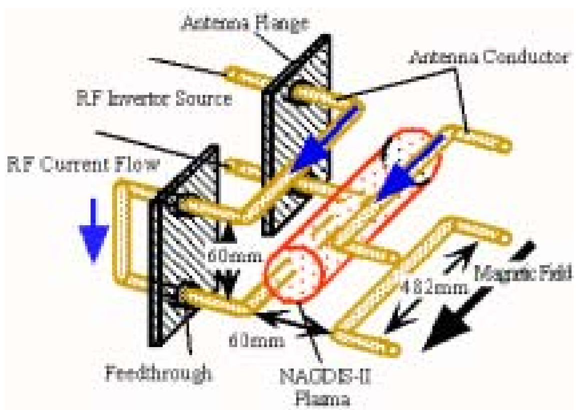

Fig.6 Antenna geometry for ICRH.

maximum power of 20 kW. The electron density is doubled by injecting the power of 16.4 kW, and the

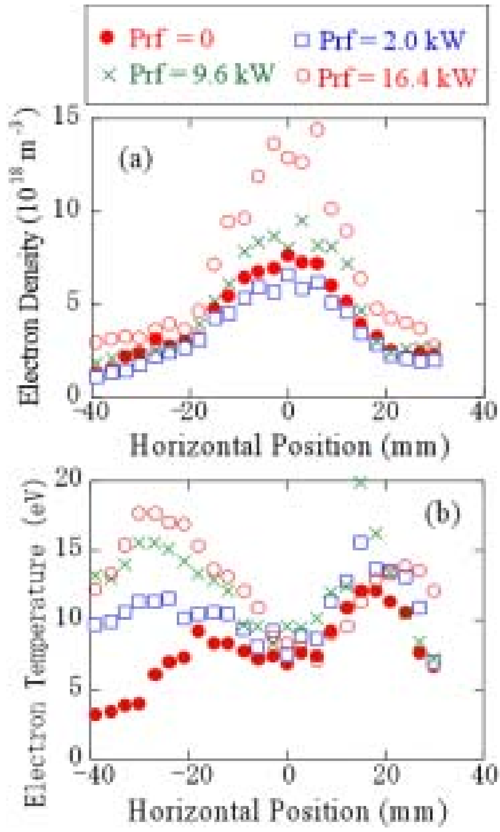

Fig.7 Electron density (a) and temperature (b) profiles for several rf injected power.

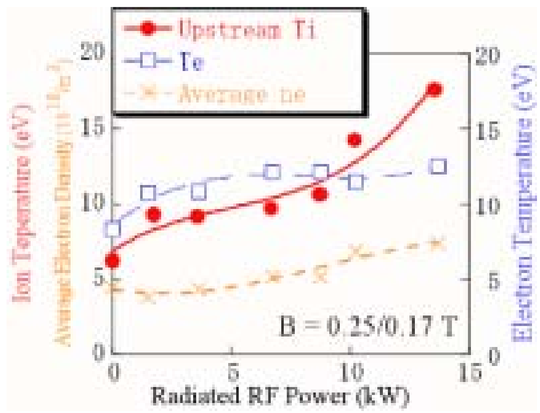

Fig.8 Power dependence of the average electron density , electron temperature at the center and the ion temperature.

peripheral electron temperature increases enormously as shown in Fig.7. The power dependence of plasma parameter including the ion temperature measured by Doppler broadening of singly ionized helium ion spectral line is shown in Fig.8.

By injecting rf power of 14 kW, the average electron temperature increases about 5 eV, and the ion temperature rises about 10 eV at the electron density of 1-2 x 10^{19} m^{-3}. Roughly, 30 % of the injected rf power is converted to the plasma thermal energy which is finally dissipated at the end plate and anode surface or at the wall of vacuum chamber through charge-exchange collisions. A substantial power is consumed at the antenna due to the formation of the so called rf-induced dc sheath [10].

V. Harmonic Operation for Power Source with Higher Frerquency

LCR series resonance frequency for the rf output circuit is designed to be tuned at the 3rd or 5th harmonics to generate rf power with higher frequency than the operating switching frequency of the SIT device [10]. The voltage and current waveforms with the 3rd harmonic operation, and Fourier spectrum of the voltage waveform are shown

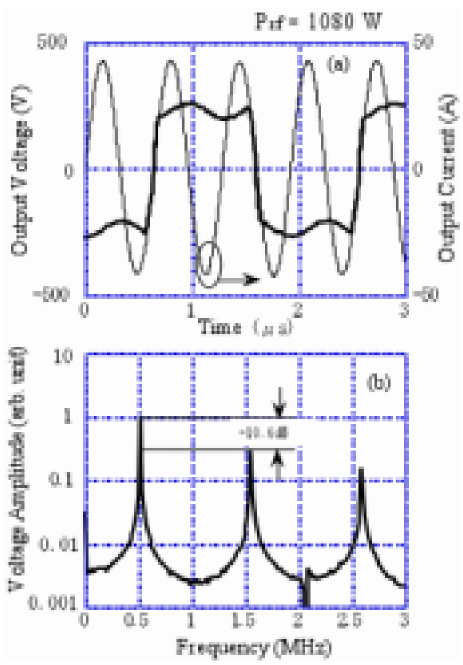

Fig.9 Voltage and current waveforms (a) and Fourier spectrum of the voltage (b) with 3rd harmonic operation. The gate switching frequency is 561 kHz, and output power is 1080 W.

in Fig.9. The odd-order harmonics is found to be useful although the intensity is little bit smaller than ideal one due to a slight deformation from the exact rectangular waveform.

Figure 10 compares the 3rd harmonic operation with fundamental one. The dc voltage for the 3rd harmonic operation is three times as high as that for fundamental one to have the same intensity of rf current through the

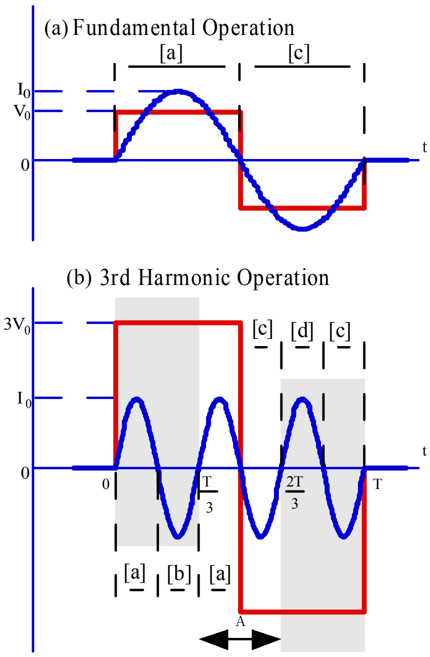

Fig.10 Comparison of (a) fundamental operation with (b) 3rd harmonic one in terms of ideal voltage and current waveforms.

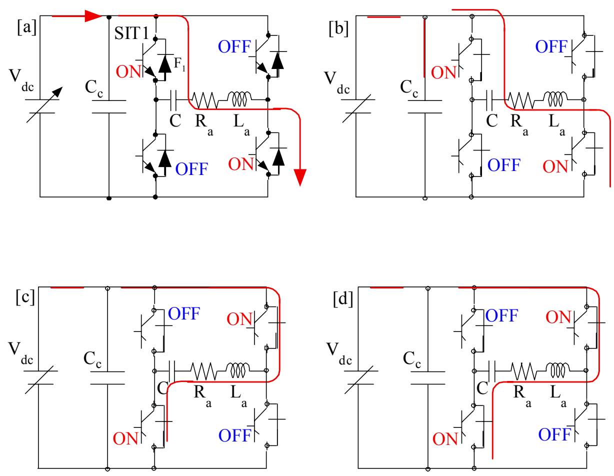

Fig.11 The rf current paths for various phases corresponding to Fig.10 in fundamental and 3rd harmonic operation.

load since a square wave contains the 3rd harmonic component whose amplitude is one-third of the fundamental mode. As is shown in Fig.11, the net dc current from the dc source for 3rd harmonic mode is three times as small as that for fundamental operation. Therefore, the dc input impedance of SIT inverter for the 3rd harmonic operation is nine times higher than that of

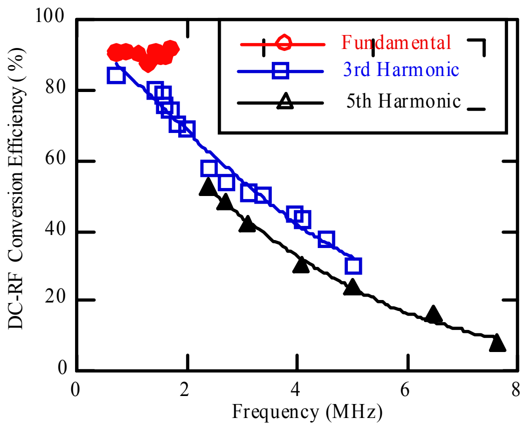

Fig.12 The dc-rf conversion efficiencies for fundamental and harmonic modes.

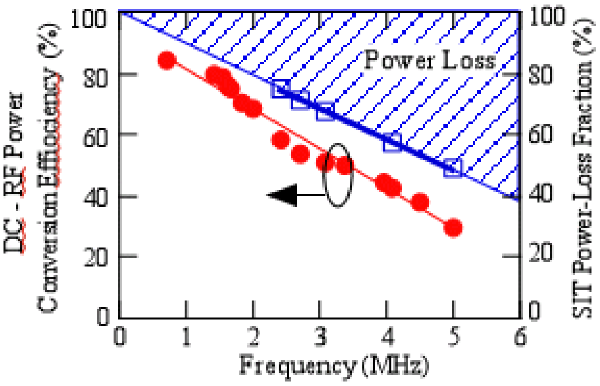

Fig.13 Comparison of the loss on SIT devices with conversion efficiency for 3rd harmonic mode.

fundamental operation.The rf current paths for various phases indicated in Fig.10 are shown in Fig.11 for the fundamental as well as the 3rd harmonic operations. Figure 12 shows dc-rf power conversion efficiency in the fundamental, the 3rd and 5th harmonic operations as a function of the output frequency. The conversion efficiency of the 3rd harmonic mode is about 5-10 % less than that of the fundamental operation at the -same output frequency. The efficiency of the fundamental mode below f = 1.7 MHz is as high as 90 %. The difference in efficiency between the 3rd and the 5th modes at the same output frequency is about 10 %. As discussed below, the difference and the reduction of the efficiency are explained by the increase in the SIT losses. The 50 % efficiency of the 3rd and 5th harmonics corresponds to the output frequencies of around 3.5 and 2.5 MHz, respectively.

The total drain loss power shown in Fig.13 is obtained by the following equation

$$P_{SIT} = \frac{1}{T}\int_{-T/2}^{T/2} v_{DS} \cdot i_{DS}\, dt. \quad (4)$$

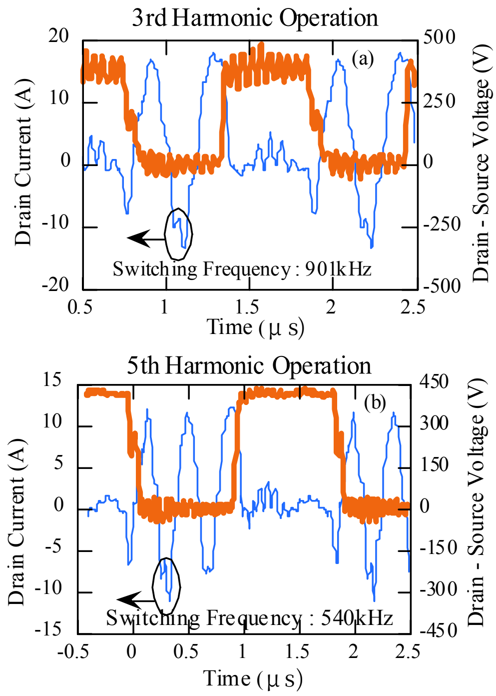

Fig.14 Drain-source voltage and drain current for (a) 3rd and (b) 5th harmonic modes.

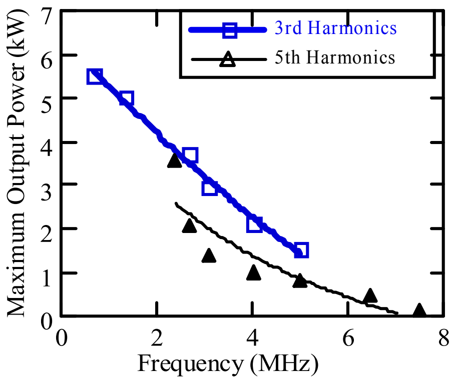

Fig.15 Maximum output power for higher harmonic operation.

The drain - source voltage and drain current are shown in Fig.14. The loss power increases proportionally with the output frequency, similar to the conversion efficiency. The difference between the conversion efficiency estimated by power loss and the observed one may come from a deviation of voltage waveform from ideally rectangular wave and a loss at the flywheel diodes.

The available maximum output power in the 3rd and 5th harmonic operations is limited by the rated voltage, current and power loss on SIT. The output power of several kW from the present SIT inverter can be obtained up to 4 MHz as shown in Fig.15. Two factors limiting the present available power may be solved as follows: The first one is the dc voltage limit since the input impedance of the inverter in 3rd harmonic operation is nine times as high as that in fundamental one. This is solved by changing the turn ratio of impedance transformer. The second is the source - drain voltage perturbation as is shown in Fig.14, which increases with lowering the input impedance. Such parasitic perturbation may be suppressed by an appropriate circuit design.

VI. Summary

(1) SIT inverter power supply

The high frequency inverter with a full bridge of SIT was employed for some plasma and fusion applications. The switching frequency is below 1.5 MHz with the dc-rf conversion efficiency of around 90 %.

(2) Application to plasma torch

An rf inductively coupled Ar thermal plasma is successfully generated at atomospheric pressure by using SIT inverter in the frequency range of 0.5 - 1.5 MHz. The plasma generation efficiency is as high as 75 - 80 % due to a high dc-rf conversion of SIT inverter.

(3) Application to ion cyclotron resonance heating of plasma

The SIT inverter power supply was applied to ion cyclotron resonance heating of high density plasma in a linear device with the frequency of around 0.8 MHz and the maximum power of 14 kW. The high heat flux plasma is generated with the plasma density of 1.5×10^{19} m^{-3}, the ion temperature of more than 15 eV, and the electron temperature of more than 10 eV.

(4) Harmonic operation for high operational frequency

The 3rd and 5th harmonic operations of SIT rf inverter have been carried out for the inverter to work at more than 5 MHz. The increase in loss of SIT device reduces the conversion efficiency with increase in frequency. The maximum output power is limited by the voltage endurance between drain and source. The 3rd harmonic operation gives around 3 kW with the frequency of around 3 MHz and the efficiency of as high as 50 %. Such a 3rd harmonic operation broadens the available frequency range and is expected to be widely applied to other inverter power supplies with various switching devices including MOSFET, IGBT, MCT and so on.

Finally, we should note a hopeful direction to the device development towards high frequency with a substantially high power capability.

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