Fundamental and Third Harmonic Operation of SIT Inverter and its Application to RF Thermal Plasma Generation

Y. Uesugi*, T. Imai, K. Kawada** and S. Takamura****
Center for Integrated Research in Science and Engineering*
Graduate School of Engineering**
Nagoya University,
Furo-cho Chikusa-ku Nagoya, Aichi, 464-8643, Japan
Phone:+81-52-789-3144
E-Mail:uesugi@nuee.nagoya-u.ac.jp

Abstract

The purpose of this paper is to study the 3rd harmonic operation of a voltage source inverter power supply. A Static Induction Transistor (SIT) inverter power supply is used in this experiment. This power supply can generate 14kW in steady state operation and its upper limit frequency of the gate driver is 1.7MHz. The advantage of the 3rd harmonic operation is that the RF power at higher frequency range beyond the switching limit can be generated. It should be also noted that the driver circuit needs no special modification for this operation. The conversion efficiency and maximum output power are investigated as a function of output frequency. The conversion efficiency with harmonic operation is a little lower than the conversion efficiency with fundamental operation. At the frequency of<3MHz, the conversion efficiency is higher than that of conventional linear amplifiers when using this SIT inverter power supply.

Key words: Static Induction Transistor, Harmonic operation, RF Inverter, Thermal plasma production

1 Introduction

Recent progress of high power semiconductor technology provides the devices like IGBT, MOSFET[1] and SIT[2, 3], which can be used for high power (~10kW) and high frequency (~2 MHz) inverter power supply.

High frequency inverter power supplies have many advantages in comparison with conventional linear amplifiers. For example, high conversion efficiency (>80%), inexpensive, compact, low output impedance, and so on. For advantages mentioned above, inverter power supplies are expected to be used below several MHz range, taking the place of the linear RF amplifiers in the induction heating of the metallic materials and other applications.

The frequency band of the inverter power supply is determined by the switching characteristics of the switching devices. In addition to this, there are some technical problems. One of the serious problems is the heat load in the driver circuit, which is due to the gate capacitance of the switching transistor.

In this paper, we investigated the 3rd harmonic operation of inverter power supply to overcome these problems.

2 Experimental Setup

2.1 SIT Inverter power supply

The experiments are carried out using inverter power supply, whose switching devices are SITs (Tokin, TM502D)[2]. The upper limit frequency (-3dB band) of this inverter power supply is about 1.8MHz, which is determined by the switching time of the SIT devices.

The specification and RF circuit of SIT inverter are shown in Table 1 and Fig.1, respectively. As a result of connecting 6 full bridge inverter units in parallel, the maximum output RF power is about 20kW is obtained below f=1.8MHz. An impedance transformer is used to provide a good impedance match between inverter

Table 1 Specification of SIT inverter

Output Power (CW)	14 kW
Output Power (1 sec. pulse)	20 kW
Operation Frequency	0.2~1.8 MHz
DC Voltage	400 V
DC Current	80 A
Output Power Modulation	DC Voltage Mod.

and load. The output voltage of the inverter is almost rectangular shape, which contains non-negligible harmonic components. Usually, the harmonic components of the antenna current are attenuated by tuning the LCR series resonance frequency at the fundamental frequency in the secondary circuit of the impedance transformer. Typically, the content of the 3rd harmonic component is ~-32dB or less when the LCR series resonant frequency is tuned at the fundamental frequency. This suppression rate of the higher harmonic components is as good as that of conventional linear amplifiers.

2.2 RF Power Calculation

The RF output power P_{RF} is calculated from the instantaneous voltage V_{rf1} and current I_{rf1} in the primary circuit of the impedance transformer as,

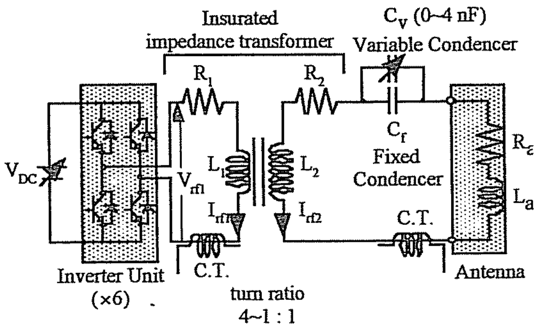

Fig. 1 SIT RF inverter circuit

$$P_{RF} = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} (I_{rf1} \cdot V_{rf1_1})dt, \qquad (1)$$

where T indicates one period time of RF waves.

The conversion efficiency η and switching loss rate η_{sw} of the inverter is given by

$$\eta = \frac{P_{RF}}{V_{DC} I_{DC}}, \qquad (2)$$

$$\eta_{sw} = \frac{\left(\frac{1}{T}\right)\int_{-\frac{T}{2}}^{\frac{T}{2}} V_{DS} I_{DS}\, dt}{V_{DC} I_{DC}}, \qquad (3)$$

where V_{DC} and I_{DC} is the voltage and current of the DC power supply, V_{DS} is the voltage between drain and source of SIT, I_{DS} is the drain current.

2.3 3rd harmonic Operation of SIT Inverter

The RF current, whose frequency is higher than the possible switching frequency of the SIT device, is generated by tuning the LCR series resonance at 3rd of 5th harmonic frequencies.

Assuming that the output voltage is exactly rectangular shape, the fundamental component of the output voltage is three times larger than that of the 3rd harmonic component. Consequently, the 3rd harmonic operation requires a DC input voltage three times larger than that of fundamental operation to keep the same output current. The current path of the SIT inverter in 3rd harmonic operation is shown in figure 2 with SIT drain current waveforms. The current path is shown in Figs. 2 (a) and (c) while the fundamental operation is carried out. RF current flows the load by turning SIT1, 4 and SIT2, 3 on and off alternately. In the third harmonic operation, while SIT1, 4 are turned on, the RF

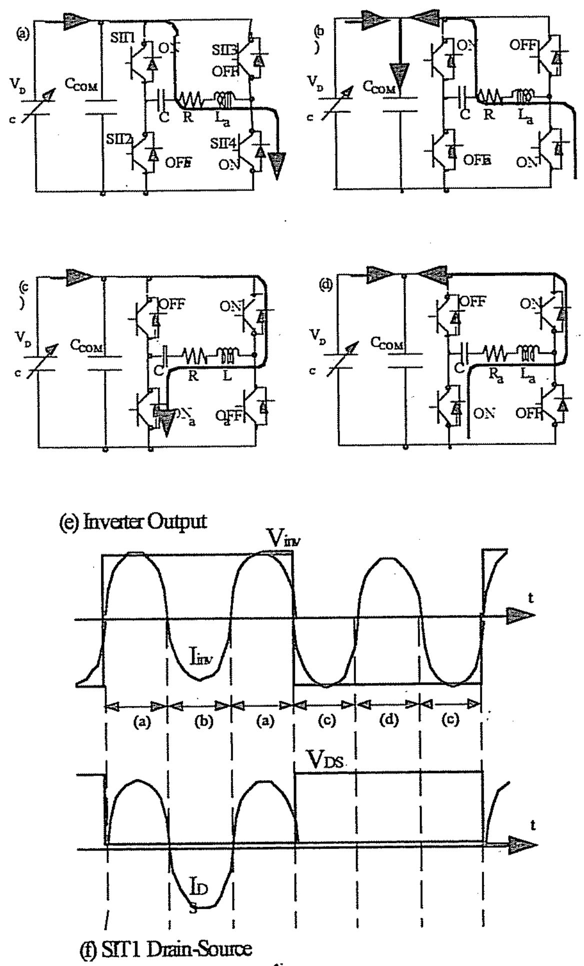

Fig. 2 Voltage and current flow in the 3rd harmonic operation.

current flows as shown in Figs. 2(e), (f) and (e). After SIT1, 4 are turned off, SIT2,3 are turned on and the RF current flows as in Figs. 2(g), (h) and (g). While (f) and (h) periods, the current flows the flywheel diode for backward voltage prevention of SITs, and the capacitor C_{COM} in Fig. 2 is charged.

2.4 Application to RF Thermal Plasma Production

In the present experiment a SIT inverter power supply with output power of 20 kW and operating frequency range of 0.2-1.8 MHz is employed for thermal plasma generation. The use of the RF inverter is expected to bring the efficient and flexible operation of the RF induction plasma torch. The initial start-up of the induction plasma is also another important issue. So far, hybrid plasma torch and tandem RF plasma torch has been developed[4, 5]. Here, an automobile ignition spark plug with high voltage transistor circuit is employed to initiate the RF induction plasmas in a controlled manner. Schematic diagram of SIT RF plasma torch is shown in Fig. 3. The Argon gas is injected into a Pyrex glass discharge tube with an inner diameter of 70mm straightly and swirly. The spark plug is installed at the center of the top flange as shown in Fig.3. The use of spark discharges makes the start-up of RF thermal plasma significantly reproducible and stable.

3 Experimental Results

3.1 Efficiency of SIT Inverter

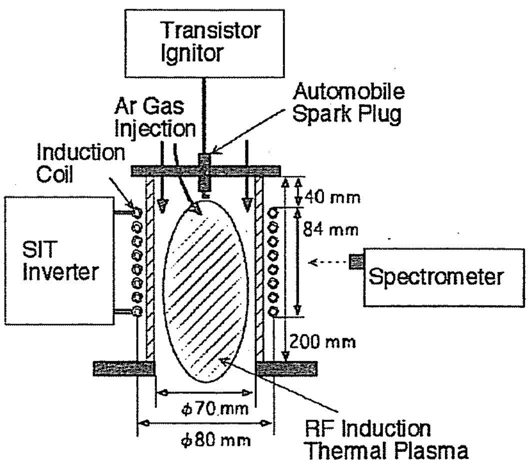

Fig. 3 SIT inverter plasma torch

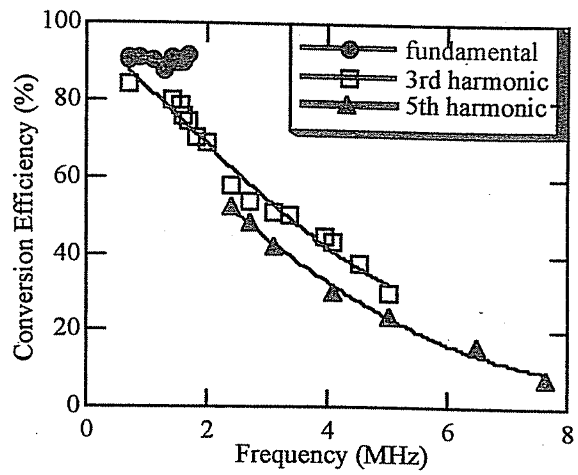

Fig. 4 Conversion efficiency of SIT inverter at fundamental, 3rd and 5th harmonic operation.

Fig.4 shows the DC-RF conversion efficiency in the fundamental, 3rd harmonic and 5th harmonic operations as a function of the output frequency. The conversion efficiency of the 3rd harmonic operation is about 5-10% lower than that of the fundamental operation, and decreases quickly with the output frequency. The efficiency of the fundamental operation below

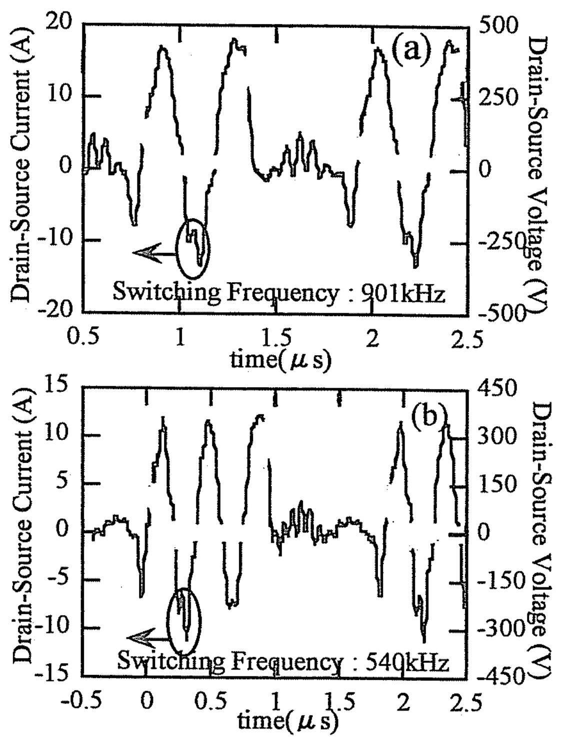

Fig. 5 Waveforms of the drain-source voltage and drain current in the fundamental and 3rd harmonic operation.

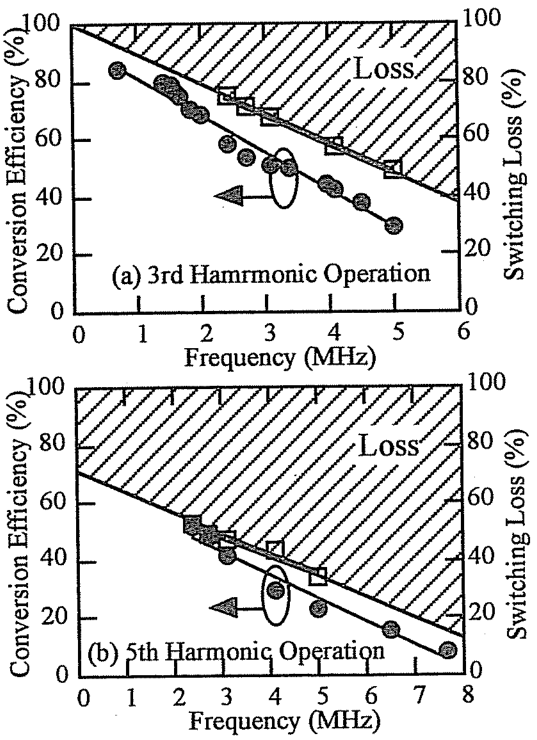

Fig. 6 Comparison of the switching loss with DC-RF conversion efficiency.

f=1.7MHz is as high as 90%. The difference of the efficiency between 3rd and 5th harmonic operation at the same output frequency is about 10%. The 50% efficiency of 3rd and 5th harmonic operations corresponds to frequencies about 3.5MHz and 2.5MHz, respectively.

Fig.5 (a), (b) shows the drain-source current and voltage with 3rd and 5th harmonic operation respectively on SIT1 in Fig.2. From these figures, we can calculate the loss on SITs by (3). In addition to this, we can find that the loss power at current inversion without gate switching can be ignored. This drain loss of SIT is compared with the conversion efficiency of SIT inverter in Fig.6. The total drain loss is obtained by multiplying the drain loss of a single SIT by 24 since the present SIT inverter power supply has 24 SITs. The observed drain loss of SIT increases proportionally with output frequency. From these figures, it can be seen that the drain loss of SIT including the switching loss is a dominant loss mechanism in 3rd and 5th harmonic operations. These results show that higher frequency output from the RF inverter can be obtained by 3rd harmonic operation without any additional losses except for the switching losses

The available output power in the 3rd and 5th harmonic operations is shown in Fig. 7. By tuning the optimum impedance match between SIT inverter and load the available power should be increased. The output power of several kW from present SIT inverter can be obtained up to f=4 MHz. In near future a detail comparison of the RF conversion efficiency and drain loss between fundamental and 3rd harmonic operations will be done and the operational limit of high frequency drive in the present SIT RF inverter will be clarified.

3.2 RF Induction Thermal Plasma Generation

In cases of with and without spark discharges, the argon gas pressure dependence of the threshold RF cur-

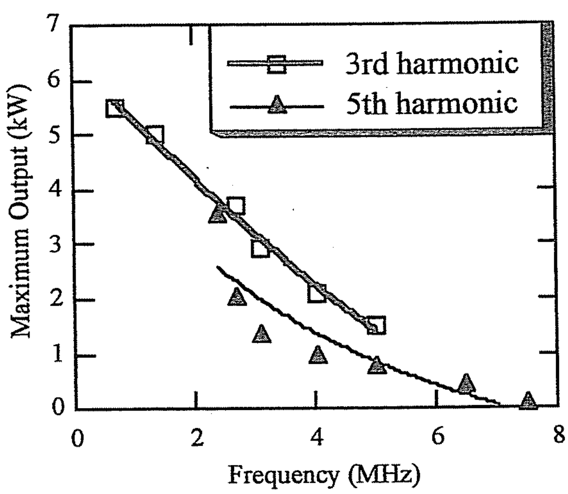

Fig. 7 Maximum output power in the 3rd and 5th harmonic operation.

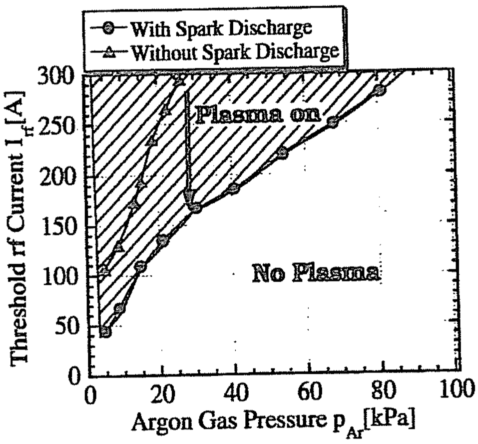

Fig. 8 Threshold rf current required for start-up as a function of Ar gas pressure with and without spark discharges. The driving frequency is 1 MHz

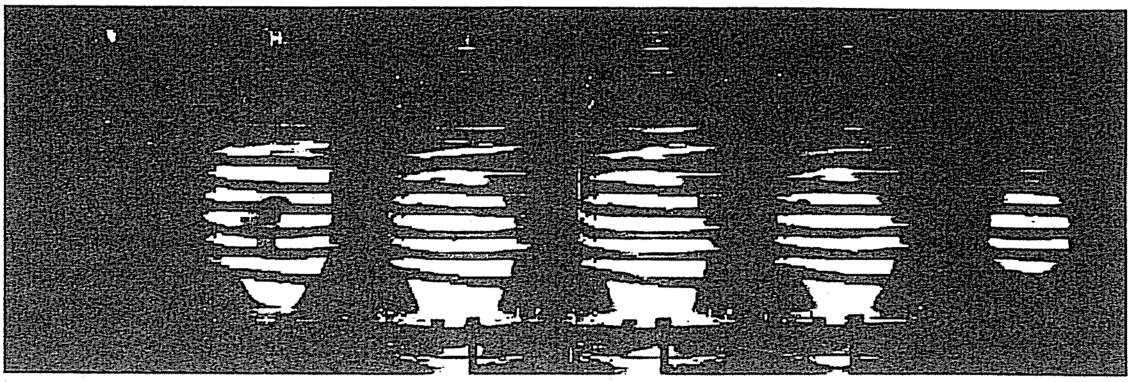

Fig. 9 Pictures of argon thermal plasmas at every 33 ms at a pressure of 20 kPa. The RF power is amplitude-modulated with a triangular waveform with a peak power of about 3 kW.

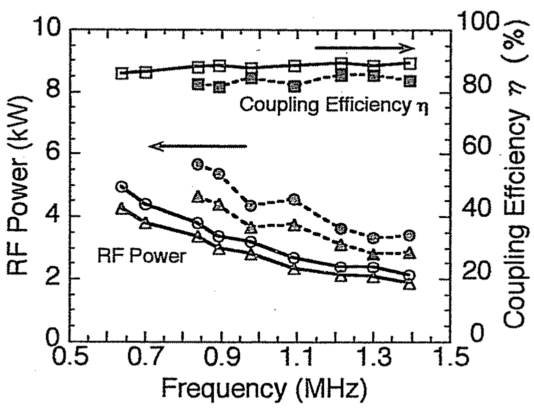

Fig. 10 Threshold rf power and coupling efficiency as a function of the rf frequency, taking the Ar pressure as a parameter. Open and closed symbols show the results at 20 kPa and 40 kPa, respectively. ○, ● : RF output power , △ , ▲ :absorbed RF power.

rent of the induction coil required for start-up is shown in Fig.8. The threshold RF current is strongly reduced to be about half of that without spark discharges. The threshold power at 80 kPa corresponds to about 17 kW in the present experiments. Typical pictures of argon thermal plasmas generated with spark discharges are shown in Fig. 9. Growth of the initial streamer-like discharges and Transition to the thermal plasmas can be seen under the induction coil in the figure. Figure 10 shows the driving frequency dependence of the threshold RF power and coupling efficiency at the pressure of 20 kPa and 40kPa respectively. The threshold power decreases with increasing the driving frequency since the induced electric field is proportional to the frequency and coil current. The coupling efficiency is kept almost constant when the driving frequency is changed.

The vacuum coil loading resistance of the induction coil is about 0.2 Ω, and that with plasma increases significantly to be about 2.5 Ω. These value gives the coupling efficiency of 92%. Taking account that the present SIT inverter has the power conversion efficiency of about 90%, the total system efficiency given by the ratio of the absorbed RF power to the DC input power is estimated to be 75~85%.

4 Summary

The 3rd and 5th harmonic operations of SIT RF inverter have been carried out to study the high frequency operation of SIT inverter. We show the conversion efficiency as a function of the current frequency with fundamental and harmonic operation. It is clarified by investigating the voltage and current waveform of SIT that the increase of its switching loss causes the lowering the conversion efficiency. At the same time, the maximum output power with the harmonic operation is also investigated. The voltage endurance between drain and source prevents the generation of the high output power in spite of the fact that the DC power supply has much available power. When the 3rd harmonic operation is carried out at the frequency of ~3MHz, the conversion efficiency is ~50% and the maximum output power is ~3kW. That is comparable with the conventional linear amplifier. Considering the other advantages like compact, inexpensive and so on, that is practical enough.

We have been developing a high efficiency and compact induction thermal plasma torch using a static induction transistor inverter in the frequency range of 0.5~1.5MHz. The ignition of an initial plasmas is assisted by spark discharges using an automobile spark plug. The use of spark discharges makes the ignition of the induction plasma reproducible and stable. The threshold RF current of the induction coil required for start-ups is strongly reduced to be about half of that without spark discharges. The RF voltage and current measurement in the RF inverter circuit shows that more than 80 % of the generated RF power is consumed to sustain argon thermal plasmas at the atmospheric pressure.

Acknowledgments

We would like to thank Dr. N. Ohno for the useful discussions and Mr. T. Fusato (D.K.K. Co., Inc..) for his technical support.

References

[1] T. Sakuta, Y. Tanaka, Y. Hashimoto and M. Katsuki, "A novel system of an inductively coupled thermal plasma with pulse amplitude modulation of electromagnetic field", Trans. IEE Japan, **120-A**(2000)972.

[2] S. Watanabe, Y. Uesugi, S. Ohsawa and S. Takamura, "Application of high performance inverter circuit to plasma generation and heating in fusion devices", Rev. Sci. Instrum., **69**(1998)355.

[3] T. Imai, H. Sawada, N. Hattori, Y. Uesugi and S. Takamura, "Characteristic performance of radio-frequency(RF) plasma heating using inverter RF power supplies", Trans. IEE japan, **120-A**(2000)768.

[4] J. R. Roth, *INDUSTRIAL PLASMA ENGINEERING* Vol. 1, Institute of Physics Publishing Bristrol and Philadelphia, 1995.

[5] T. Uesugi, O. Nakamura, T. Toyonobu and K. Akashi, "A tandem radio-frequency plasma torch", J. Appl. Phys., **64**(1988)3874.