3RD HARMONIC OPERATION OF SIT INVERTER RF SOURCE FOR ICRF HEATING IN THE DIVERTOR PLASMA SIMULATOR NAGDIS-II

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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 generatd. 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.

I. INTRODUCTION

Recent progress of high power semiconductor technology provides the devices like IGBT, MOSFET and SIT, which can be used for high power (~10kW) and high frequency (>a few 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.

II. EXPERIMENTAL SETUP

A. SIT Inverter power supply

The experiments are carried out using inverter power supply, whose switching devices are SITs (Tokin, TM502D). The upper limit frequency (-3dB band) of this inverter power supply is 1.7MHz, which is determined by the switching time of the SIT devices.

The RF circuit of SIT inverter is shown in Fig.1. As a result of connecting 6 full bridge inverter units in parallel, the maximum output RF power is about 20kW is obtained below f=1.7MHz. An impedance transformer is used to provide a good impedance match between inverter 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.

B. RF Power Calculation

The RF output power P_{RF} is calculated from the voltage V_1 and current I_1 in the primary circuit of the impedance transformer. Namely,

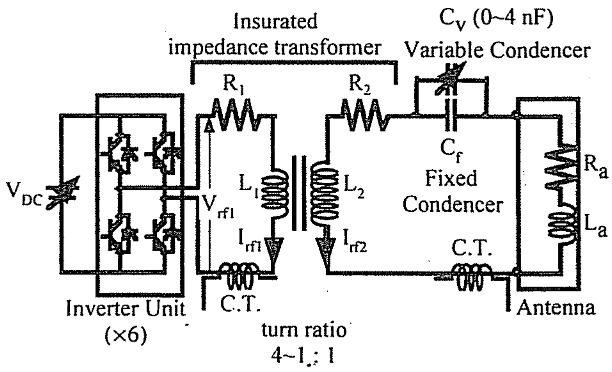

Figure 1. RF Inverter Circuit

$$P_{RF} = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} (I_1 \cdot V_1) dt, \quad (1)$$

where T indicates one period time of RF.

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

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

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

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.

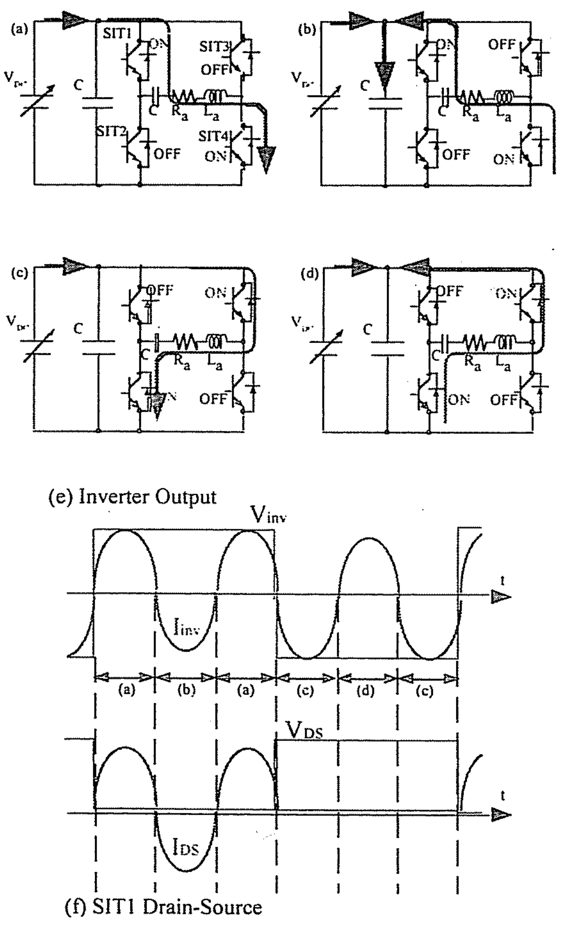

Figure 2. 3rd Harmonic Operation

C. 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 figure2 with a inverter output SIT drain current waveforms.

As you know, current path is shown in Fig.2(a),(c) while fundamental operation is carried out. RF current is run for the load by turning on and off SIT1,4 and SIT2,3 alternately. On the other hand, 3rd harmonic operation is explained as following. While SIT1,4 are turned on, the current is run as (e)$\rightarrow$(f)$\rightarrow$(e) in Fig.2. After SIT1,4 are turned off, SIT2,3 are turned on and the current is run as (g)$\rightarrow$(h)$\rightarrow$(g) in Fig.2. While (f) and (h) period, the current is run in the diode for backward voltage prevention of SITs, and the capacitor C_{COM} in Fig.2 is charged.

III. EXPERIMENTAL RESULT

Fig.3 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 f=1.7MHz is as high as 90%. The difference of the efficiency between 3rd and 5th harmonic operation at the same

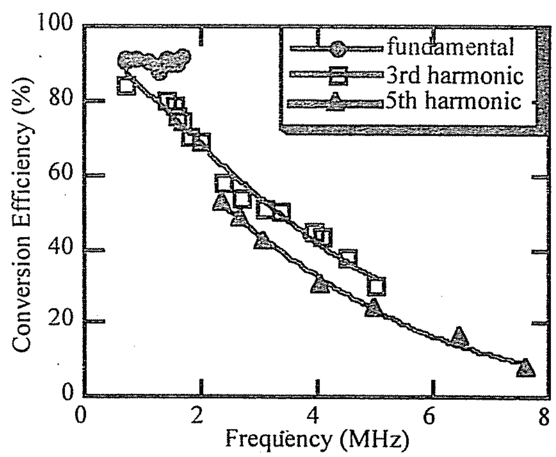

Figure 3. Conversion Efficiency

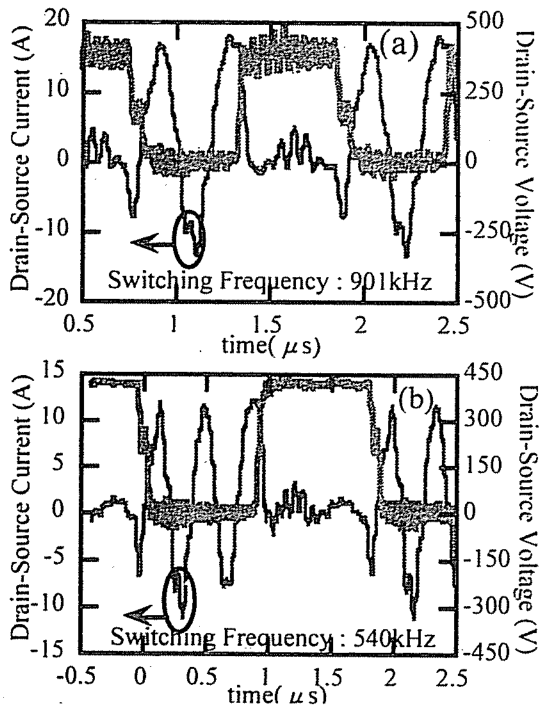

Figure 4. Waveform of the Voltage between the Drain and Source and of the Drain Current

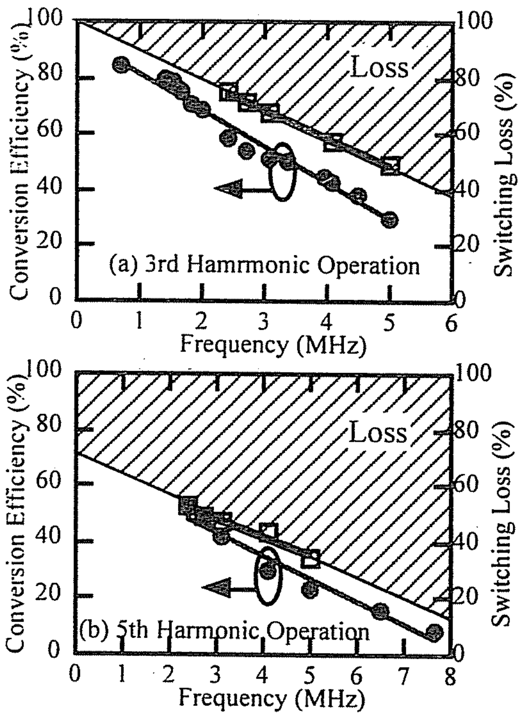

Figure 5. Comparison of the Switching Loss with Conversion Efficiency

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.4(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 eq.(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.5. 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 proportinally with output frequency. From these figures, it can be seen that the drain loss of SIT including the swiching loss is a dominat 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. 6. By tuning the optimum impedance match between SIT inverter and load the avilable 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.

IV. SUMMARY

The 3rd and 5th harmon ic 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

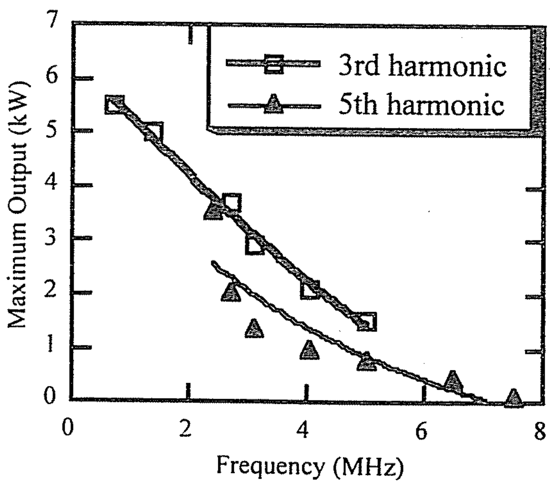

Figure 6. Maximum Output Power with Harmonic Operation

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.

ACKNOWLEGEMENTS

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