HIGH-PRESSURE RF INDUCTIVE DISCHARGES USING A T-LCL IMMITTANCE CIRCUIT FOR CONSTANT CURRENT OPERATION

M A Razzak[1], Y Suzuki[2], S Takamura[3] and Y Uesugi[4]

[1]Nagoya University, Nagoya 464-8603, Japan, E-mail: razzak@ees.nagoya-u.ac.jp
[2]Nagoya University, Nagoya 464-8603, Japan, E-mail: y-suzuki@ees.nagoya-u.ac.jp
[3]Nagoya University, Nagoya 464-8603, Japan, E-mail: takamura@ees.nagoya-u.ac.jp
[4]Kanazawa University, Kanazawa 920-8667, Japan, E-mail: uesugi@ec.t.kanazawa-u.ac.jp

ABSTRACT
In recent years, the immittance conversion topology has become attractive as a novel power conversion strategy because of its features that a constant voltage source is converted to a constant current source and vice versa. By taking these advantageous features, a T-LCL immittance circuit is employed to generate high-efficiency inductively coupled plasma (ICP) in a gas pressure with up to one atmosphere in Ar. It is observed that the immittance circuit confirms to inject higher power into the plasma thereby enhancing the power efficiency of about 80-90%.

INTRODUCTION
Because of high-efficiency and high-power operation, static induction transistor (SIT)-based inverter power source has become popular in the last decade due to its application to various kinds of induction heating and plasma generations [1-4]. However, at high operating frequencies in the MHz range, rf system shows transient and strongly non-linear characteristics due to the presence of switching devices in the power source, and inherent problems in the SIT inverter power source are observed during high-pressure plasma generation [2].
A typical radio frequency (rf) inductive discharge is usually produced by applying rf power, with conventional series resonance circuit, in a Pyrex glass chamber filled with inert gas such as Ar, He etc. and wound with an induction coil of a few turns. At the initial phase of rf breakdown, an electrostatic discharge (*E* discharge) is generated by the strong electrostatic field (100-200 kV/m) due to the high rf voltage in the induction coil for few milliseconds, and then a rapid mode transition from electrostatic to electromagnetic discharge (*H* discharge) occurs to form the steady state rf induction plasmas [3]. A rapid increase of the coil loading resistance and decrease of the effective coil inductance are observed during these dynamic mode changes of the generated plasmas. The load of the SIT inverter, which is resistive without plasma, becomes inductive in the *E* mode while slightly capacitive in the *H* mode. Therefore, the phase of the rf output voltage to current is changed, and the driving frequency is shifted from its resonance one. The rf coil current is, therefore, dropped abruptly when the load changes from the capacitive to inductive mode due to the impedance rise thereby decreasing the absorbed power and thus the DC-RF conversion efficiency of the SIT inverter at a value of about 30-40% [2]. But, the DC-RF conversion efficiency and thus the power coupling efficiency should be high enough to promote induction plasmas into industrial and commercial fields. In order to overcome these problems, a T-LCL immittance circuit for constant current operation cascading with the SIT inverter power source is employed to generate high-pressure efficient induction thermal plasmas in Ar.

IMMITTANCE CIRCUIT
The immittance converter is a combined word of the impedance-admittance converter. It has an input impedance that is proportional to the load connected across the output terminals. In this converter, the output current is proportional to the input voltage and the input current is proportional to the output voltage. Consequently, it converts a constant voltage source into a constant current source and vice versa.
In the present experiment, we employed a T-LCL type immittance circuit, which is depicted in Fig. 1, to generate efficient induction thermal plasmas. The immittance conversion system combines the SIT-based radio-frequency (0.2-1.7 MHz), high-power (maximum 20 kW in pulse operation) inverter circuit and the immittance conversion elements. The equivalent circuit of the combined electrical system, consisting of SIT inverter, impedance transformer, immittance circuit elements and rf induction coil, is shown in Fig. 2. The value of circuit elements are estimated from the immittance circuit properties along with the overall impedance matching condition.

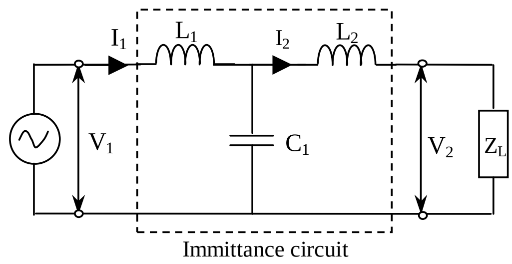


Fig. 1 T-LCL immittance circuit for constant current operation

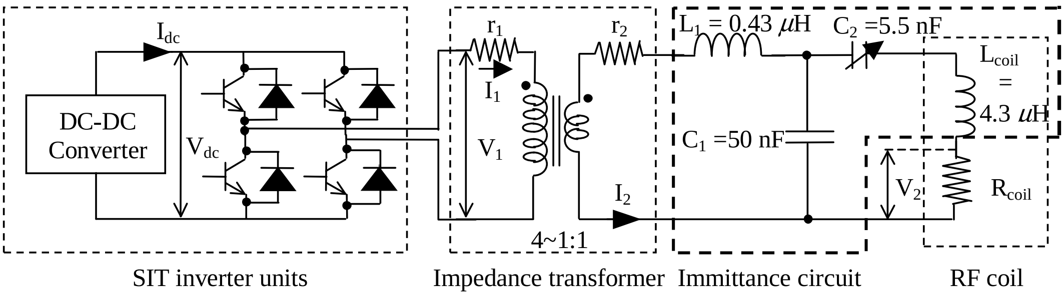


Fig.2 Equivalent circuit of the combined system (SIT inverter units, impedance transformer, immittance circuit and rf induction coil) for efficient rf inductive discharges)

From Fig.1, the basic voltage-current relation can be written as

$$V_1 = \left(j\omega L_1 + \frac{1}{j\omega C_1} \right) I_1 - \frac{1}{j\omega C_1} I_2 \tag{1}$$

$$V_2 = \frac{1}{j\omega C_1} I_1 - \left(j\omega L_2 + \frac{1}{j\omega C_1} \right) I_2 \tag{2}$$

$$V_2 = Z_L I_2 \tag{3}$$

Using the resonance condition, $\omega = \sqrt{1/L_1 C_1}$, from eqs. (1) and (2) the characteristics of the immittance circuit can be represented by the following F-matrix:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} 0 & jZ_0 \\ j\dfrac{1}{Z_0} & 0 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{4}$$

where $Z_0 = \sqrt{L_1 / C_1}$ is the characteristic impedance. To design an ideal immittance circuit applying to induction thermal plasma generation, we employ the impedance matching with overall resonance condition of the *RLC* circuit. By choosing the value of C_1 as 50 *n*F, we found the values of L_1, L_2 and C_2 as 0.43 μH, 4.3 μH and 5.5 *n*F, respectively. The overall resonance frequency is found to be about 1.185 MHz.

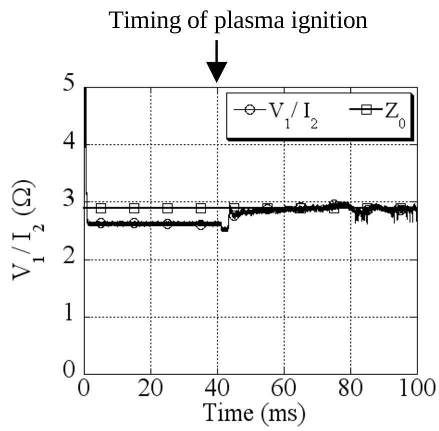
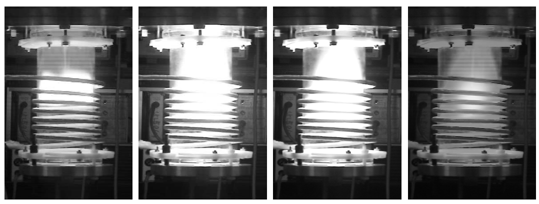


Fig.3 Evaluation of immittance circuit (Comparison of V_1/I_2 with Z_0)

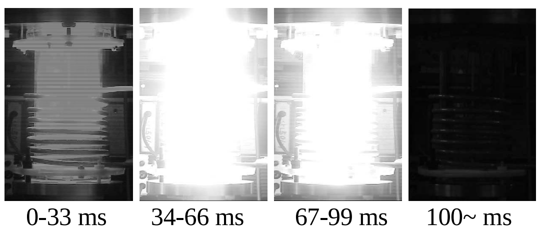
Now it is customary to evaluate the properties of the immittance circuit applying to induction thermal plasma generation. From eq. (4) it is noticed that the ratio V_1 / I_2 should be a constant value, which is equal to the characteristic impedance, Z_0 as

$$\frac{V_1}{I_2} = jZ_0 . \tag{5}$$

Figure 3 shows the comparison of Z_0 calculated by circuit elements with that of the experimental results calculated from V_1 and I_2. The estimated results agree well with that of the experimental one after the plasma ignition, which justify eq. (5). However, the estimated value has a slight deviation before the plasma ignition since the internal resistances of the primary inductor and the coil are not included in the circuit calculation. The influences of internal resistances of the primary inductor and secondary rf coil will be discussed in another full paper.



(a) Using series resonance circuit



(b) Using immittance circuit

Fig.4 CCD camera pictures of rf inductive discharges at a gas pressure of 20 kPa. The rf power is about 1.75 kW in the case of series resonance circuit while about 10 kW in the case of immittance circuit.

PLASMA GENERATION

The immittance circuit, described in the above section, cascading with the SIT inverter rf power source (20 kW, 0.2~1.7 MHz) is employed to generate induction thermal plasmas with a driving frequency of 1.2 MHz. The plasmas are sustained in a Pyrex glass chamber with an inner diameter of 70 mm and a length of 200 mm. An induction coil consisting of a 7-turn copper tube of ¼ inches outer diameter is used for the discharge to be occurred. Ar gas with a neutral pressure of 10-50 kPa and a flow rate of 20 l/min is injected both axially and swirly into the discharge chamber. Spark discharge technique [4] is applied to initiate the discharge. A typical automobile spark plug with a high voltage transformer circuit is employed for this purpose. To observe the visible emission of the rf discharge, CCD camera pictures are taken setting the camera perpendicular to the discharge axis.

A series of typical CCD camera pictures of rf inductive discharges at a gas pressure of 20 kPa are presented in Fig. 4. Fig. 4(a) represents the discharges generated by conventional series resonance circuit while 4(b) represents the discharges generated by using immittance circuit. It is noticed that the visible emission intensity is much higher in the case of immittance circuit due to higher absorbed power than that of the series resonance circuit. Due to high rf power, the plasma temperature and density may become high, which are not measured so far and will be reported in another paper in near future.

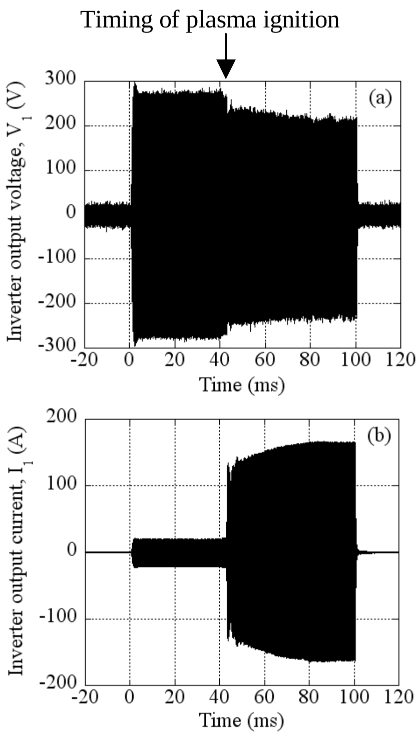


Fig.5 RF output voltage (a) and current (b) of the SIT inverter power source with immittance circuit

The rf output voltage and current waveform of SIT inverter power source during plasma generation using immittance circuit is shown in Fig. 5 (a) and (b), respectively. It is seen from Fig. 5(a) that the rf output voltage of the SIT inverter power source drops slightly after the plasma generation. The rf output current [Fig. 5(b)], on the other hand, increases abruptly at the time of plasma generation, which confirms higher rf power injected into the plasma.

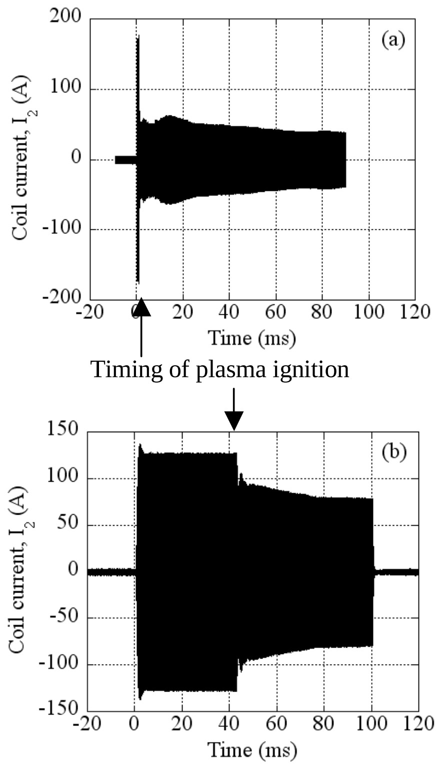


Fig.6 RF coil current waveform during plasma generation with series resonance circuit (a) and with immittance circuit (b)

Figure 6(a) and (b) shows the rf coil current waveforms during plasma generation with series resonance circuit and immittance circuit, respectively. Fig. 6(a) shows that, with the conventional series resonance circuit, the coil current drops abruptly at the time of plasma generation since the overall plasma loading impedance changes during this period. In the case of using the immittance conversion circuit [Fig. 6(b)], on the other hand, the rf coil current drops, due to the non-linear characteristics of the inductive plasma [2], but not as much as in the case of series resonance circuit. This high rf coil current confirms higher rf power injecting into the plasma. However, in an ideal case, this rf coil current should not be decreased. But in the present experiment, since the rf power is controlled from the DC side of the SIT inverter, it is very difficult to maintain the rf coil current very strictly. Also, the internal resistance of the primary inductor and the secondary rf coil should have some effect, which deviate the ideal situation of the immittance circuit as mentioned in the previous section. Another point has to be noticed that the threshold current, which corresponds to the maximum rf coil current needed for the plasma ignition, is much lower in the case of immittance circuit (125 A) than that of the series resonance circuit (175). For this reason, the initial ignition time is much higher in the case of immittance circuit than that of the conventional RLC series resonance circuit as shown in Fig. 6. Comparing Fig. 6(a) and (b), it is seen that the ignition starts just 2-3 ms after switching ON the SIT inverter power source in the case of series resonance circuit. On the other hand, ignition starts after 40 ms in the case of immittance circuit. This is one of the disadvantages of the immittance conversion circuit over the series resonance circuit.

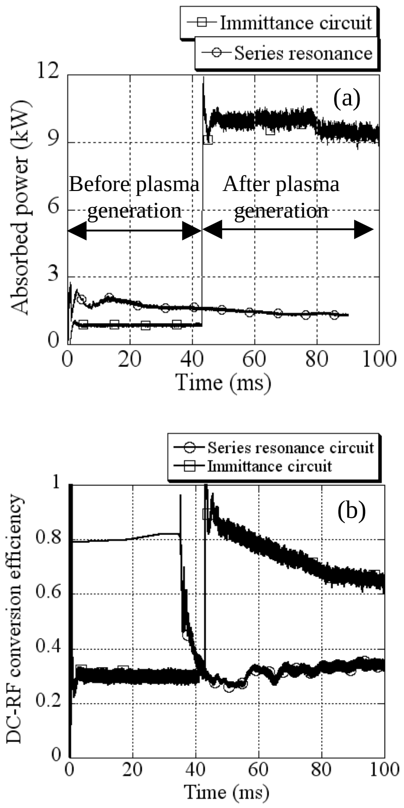


Fig.7 Comparison of absorbed rf power (a) and DC-RF power conversion efficiency (b) using immittance circuit with that of the series resonance circuit during plasma generation

Figure 7(a) shows the comparison of rf power absorbed by the plasma in the case of using immittance circuit with that of the conventional series resonance circuit. In the case of immittance circuit, the value of absorbed rf power, calculated from the rf power supply side, is about 10 kW after the plasma ignition, while about 1.5-2 kW with series resonance circuit under the present condition of power source. The absorbed rf power is about 5 times larger in the case of immittance circuit than that of the series resonance circuit after the plasma ignition. The immittance circuit, therefore, confirms injecting higher rf power into the plasma thereby increasing the DC-RF conversion efficiency [4] at about double than that of using the conventional series resonance circuit, which is shown in Fig. 7(b).

CONCLUSIONS

A T-LCL type immittance circuit for constant current operation is designed in order to generate high-pressure radio-frequency induction thermal plasma efficiently. Although it is difficult to design an ideal immittance circuit applying to plasma generation due to the non-linear characteristics of the inductive plasma, the results reported in this article shows comprehensive improvements over the conventional series resonance circuit. The experimental results shows that the immittance circuit confirms injecting higher rf power into the plasma, and enhances the DC-RF power conversion efficiency of the SIT inverter power source as much as double than that of the series resonance circuit.

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