J Electr Eng Technol.2018; 13(1): 345-351
http://doi.org/10.5370/JEET.2018.13.1.345

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Analysis and Design of Resonant Inverter for Reactive Gas Generator Considering Characteristics of Plasma Load

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Abstract – This paper analyzes a resonant inverter to generate plasma. The resonant inverter consists of a full bridge converter, resonant network and reactor to generate a magnetic field for plasma generation. A plasma load has very distinct characteristics compared to conventional loads. The characteristics of plasma load are analyzed through experimental results. This paper presents the study on the resonant network, which was performed in order to determine how to achieve a constant current gain. Another important contribution of this study is the analysis of drop-out phenomenon observed in plasma loads which is responsible for unpredictable shutdown of the plasma generator that requires stable operation. In addition, the design process for the resonant network of a plasma generator is proposed. The validity of this study is verified through simulations and experimental results.

Keywords: Reactive gas generator, High frequency DC-AC inverter, Phase shift full bridge converter

1. Introduction

Reactive gas generators have been used in a wide range of industrial areas. As the semiconductor market continues to grow, demand for reactive gas generator, which are used to clean process chambers and wafers, is also increasing [1]. A plasma generator provides ionized species for deposition, stripping, and surface preparation during the manufacturing process. Predictable and repeatable characteristics are important for the quality of the product. If the ionization fraction increases, the gas becomes more conductive, implying that the current increases, and the power dissipated in the gas increases, causing the gas temperature to rise, which drives the ionization level up in a positive feedback loop. This feedback loop is not only unstable, but also has a small time-constant, which presents a bandwidth challenge for feedback control [1-6].

In the early days of reactive gas generator development, the reactive gas generators were operated at 2.45 GHz using a microwave source. However, the flow-rate of gas was not sufficient, and the systems required a complicated installation process. In order to overcome these disadvantages, newer plasma generators employ magnetic coupling with the plasma to induce an electric field in the gas, use a series resonant network to facilitate frequencies of 200 kHz - 2 MHz with low switching losses, and use the magnetizing inductance of the generator and its parallel plasma load as the inductive element for the resonant circuits. Most of these systems operate in a pulse-width modulation (PWM) mode and use low frequency adjustments to protect power switching elements. Consequently, the reactive gas generators typically operate in the 400-kHz region to optimize the relationship between core losses of ferrite and density of electric field. The reactive gas generators have recently evolved into integrated systems that use DC-AC inverters, a resonant network and a reactor. Fig. 1 presents the basic reactive gas generator structure [3-5]. The plasma load of the reactive gas generator is an AC load with wide impedance ranges and broadband stability dynamics. The DC-AC inverter and the resonant network of the reactive gas generator are similar to the primary side of conventional switch mode power supplies. However, the inverter in the reactive gas generator is difficult to control due to the dynamics of the plasma load. The impedance levels of the plasma load change rapidly from very high impedance in the pre-ignition state to very low impedance in the post-ignition state. Furthermore, the rapid reduction of impedance causes a temperature increase, thus, increasing the instability of the plasma load. Therefore, a detailed analysis of the plasma load is important for designing and controlling the reactive gas generators.

In this study, the electrical characteristics of plasma loads based on experimental results is analyzed. The operation of the reactive gas generator can be divided into

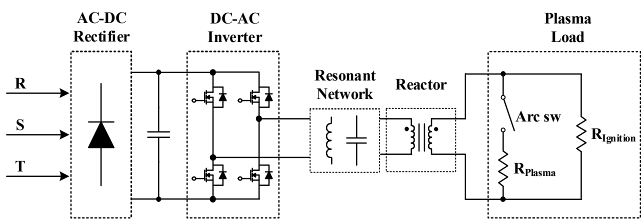

Fig. 1. Basic structure of the reactive gas generator

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Received: September 18, 2017; Accepted: October 20, 2017

the pre-ignition and the post-ignition states. The impedance decreases rapidly during the transient between the pre-ignition and the post-ignition states. Conversely, the impedance increases rapidly when the target gas is injected. Therefore, a resonant network and a control method that considers characteristics of the plasma load is analytically derived. The validity of this study is verified through simulations and experimental results.

2. Electrical Characteristics of Plasma Load

2.1 Negative impedance

The impedance of a plasma load increases as the gas is injected. In order to determine the other characteristics of plasma loads, experiments are performed under conditions of constant gas injection, constant temperature and constant current gain in the resonant network. As shown in Fig. 2, the frequency is not related to the impedance of a plasma load. However, the impedance decreases when the primary current of the reactor increases, as shown in Fig. 3. As a result, the plasma load presents unique characteristics compared to those of a conventional SMPS. For a conventional load, when the output voltage increases, the output current also increases. However, for a plasma load, when the output voltage increases, the output current decreases. This phenomenon occurs due to the characteristics of the plasma load, which include a negative impedance.

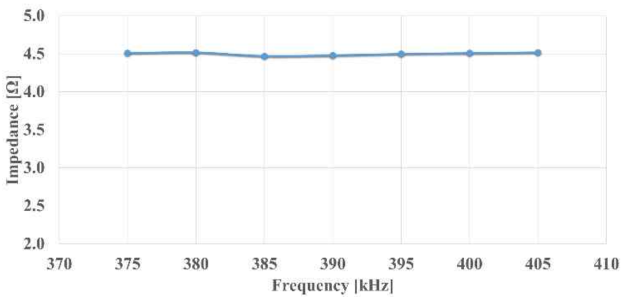


Fig. 2. Impedance of plasma load when the operating frequency varies

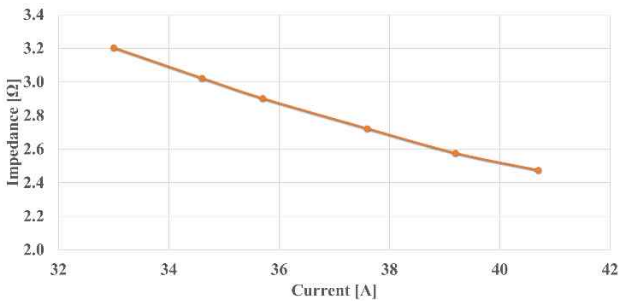


Fig. 3. Impedance of plasma load when the primary current of the reactor varies

2.2 Plasma drop-out

As mentioned in the previous section, stability is one the most important attributes for the reactive gas generators, because the plasma must be sustained while the reactive gas generator operates. There are several reasons for which the drop-out phenomenon occurs. First, the pressure of the gas in the chamber must be maintained at an appropriate level. If the pressure becomes too high, electrons collide too frequently, meaning the electrons are not sufficiently accelerated and the plasma cannot be maintained. However, if the pressure is too low, plasma cannot be maintained due to the low possibility of electrons colliding. Secondly, the induced voltage must be at an appropriate level in proportion to the pressure. As mentioned above, plasma cannot be maintained under the high gas pressures. In order to enable higher gas pressures, a sufficiently high voltage must be supplied to accelerate the electrons.

However, the plasma may not be maintained even when the proper voltage and the gas pressure are supplied. This phenomenon is caused by the negative impedance of the plasma load. In general SMPSs, the output voltage is controlled by varying the frequency at a constant load. If current increases when the output impedance is constant, then the voltage increases and a constant Q-factor is maintained. However, for the plasma load, the output voltage decreases due to the negative impedance that is created when the output current increases. Therefore, when the controller is used to lower the output current, the controller operates at a level lower than the intended current due to the chain reaction, which causes the plasma dropout phenomenon. As shown in Fig. 4, a typical load has a constant Q-factor even if the frequency is shifted to control the output current. However, for a plasma load, the drop-out phenomenon occurs because the current decreases in a cascade due to the negative impedance characteristic of the load.

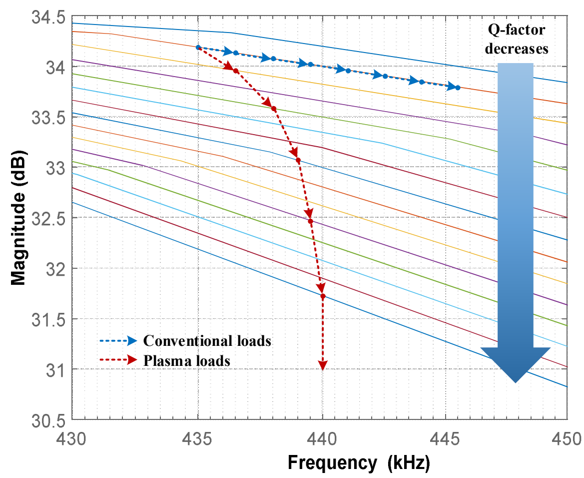


Fig. 4. Comparison of current gain between conventional and plasma loads

3. Design and Control of Resonant Inverter for Reactive Gas Generator System

Considering the characteristics of a plasma load, power circuit topologies must be selected carefully to account for the following:

a. During ignition, output current should be limited by a topological characteristic for output impedance variation between an open circuit and short circuit.
b. After ignition, the frequency ranges used for the load variation should be narrow.
c. Zero-voltage switching is implemented for the entire output power range in order to reduce the switching loss.
d. Constant current output characteristics are required to maintain a stable plasma. This is accomplished by instantaneously supplying a sufficient voltage to a compensate for sudden changes in gas pressure.

A resonant network that satisfies the conditions above is a parallel-loaded resonant converter (PRC). Fig. 5 presents the circuit diagram of the resonant inverter for the reactive gas generator. The inverter consists of a full bridge converter, a resonant network, and a reactor. The reactor of the reactive gas generator has a leakage inductance and is naturally in the form of LCL.

3.1 Resonant network

A square-wave input-voltage source is replaced by its fundamental sinusoidal equivalent. It is assumed that the power transfer from input to output occurs only through the fundamental component and all harmonics are neglected. The turn ratio of the reactor is assumed to be at unity. The RMS-value of the fundamental component of the input square-wave voltage is calculated as follows

$$V_{in,rms} = \frac{2\sqrt{2}}{\pi} V_d \tag{1}$$

The resonant frequency (ω_o) and normalized switching frequency (ω_n) are defined as

$$\omega_o = \frac{1}{\sqrt{L_r C_r}} \quad \text{and} \quad \omega_n = \frac{\omega}{\omega_o} \tag{2}$$

The characteristic impedance (Z_n) and Q-factor of the resonant network are

$$Z_n = \sqrt{\frac{L_r}{C_r}} \quad \text{and} \quad Q = \frac{\omega_o L}{R_O} = \frac{Z_n}{R_O} \tag{3}$$

The ratio of inductors (γ) is defined as

$$\gamma = \frac{L_{lkg}}{L_r} \tag{4}$$

The current gain (H) is defined as

$$H = \frac{I_{Plasma}}{\left(\frac{V_d}{Z_n}\right)} = \frac{1}{\frac{1}{Q}\left(1-\omega_n^2\right) + j\frac{\pi^2}{8}\left[\left(1+\gamma\right)\omega_n - \gamma\omega_n^3\right]} \tag{5}$$

In order to satisfy conditions a and b mentioned above, the inverter should operate at a switching frequency of ω_o, which is the LC resonant frequency, so that a constant current can be maintained regardless of the Q-factor. At $\omega_n = 1$, the plasma current is defined as:

$$I_{plasma}\,|_{\omega_n=1} = \frac{2\sqrt{2}}{\pi}\frac{V_d}{Z_n} \tag{6}$$

The phase difference between the inverter voltage and the current of the LCL resonant converter is calculated as follows:

$$\varphi_{\omega_n=1} = \tan^{-1}\left(\frac{\pi^2}{8} Q\left(\gamma - 1\right)\right) \tag{7}$$

When $\gamma < 1$, the converter operates in a lagging power factor mode so that the zero-voltage switching can be performed. Although $\gamma = 1$ yields a zero-phase angle that would result in the lowest conduction loss, in practice, the

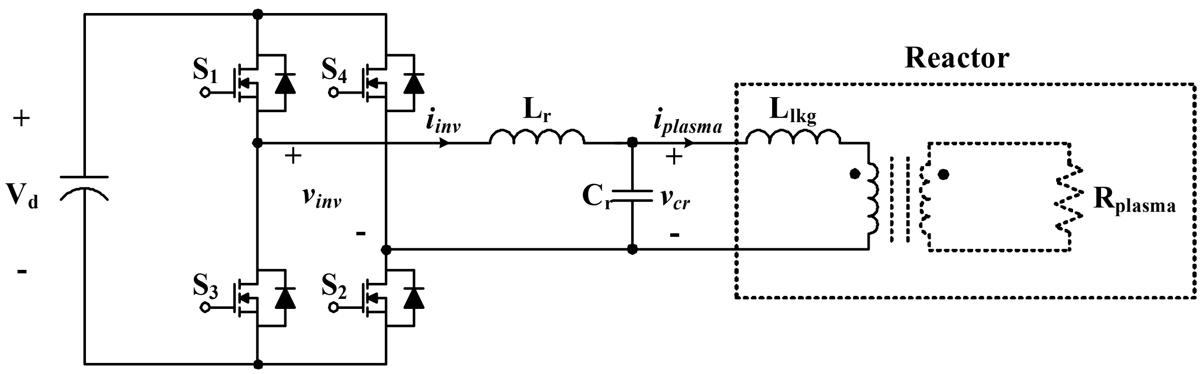


Fig. 5. Circuit diagram of resonant inverter for reactive gas generator

required phase lag can be realized by keeping γ slightly below unity [7, 8]. Therefore, the ZVS can be performed if $\gamma \leq 1$ and the converter operates at the frequency $\omega_n = 1$.

In order to achieve the maximum plasma current, the parameters for the resonant network are as follows:

$$L_r = \frac{2\sqrt{2}}{\pi} \frac{V_d}{\omega_o I_{plasma,max}} \tag{8}$$

$$C_r = \frac{\pi}{2\sqrt{2}} \cdot \frac{I_{plasma,max}}{\omega_o V_d} \tag{9}$$

3.2 Controller for a reactive gas generator

The output plasma current of the reactive gas generator must be adjustable. There are several ways to control output current, including pulse frequency modulation (PFM) and phase shift control. However, as shown in Fig. 6, current gain is relatively flat around $\omega_n = 1$. This means that variations in the switching frequency cannot provide wide a conversion range and output current regulation for large input voltage variations.

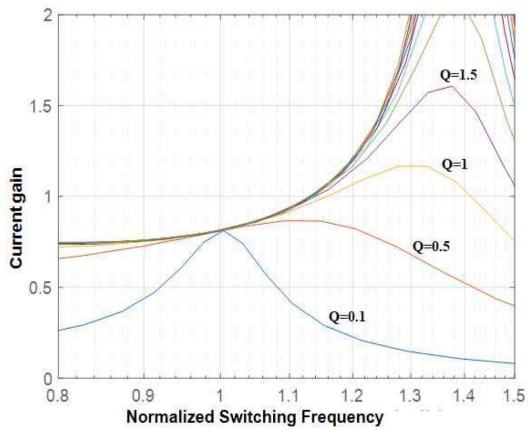


Fig. 6. Current gain (H) for $\gamma = 1$

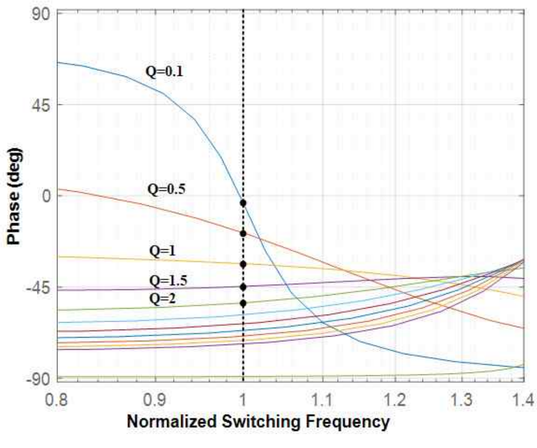


Fig. 7. Phase difference between inverter voltage and current for $\gamma = 0.465$

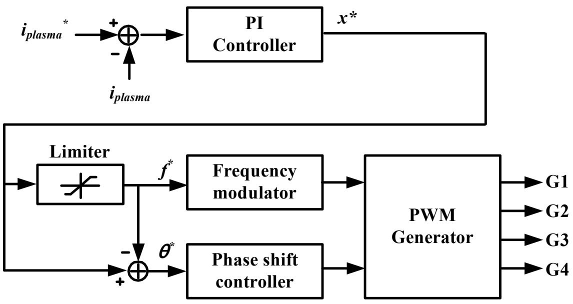


Fig. 8. Proposed control diagram

Additionally, the aforementioned drop-out characteristics of the plasma load are more likely to appear in the region where the change in the current gain is large, depending on the Q-factor. Therefore, in order to change the magnitude of the output current, the magnitude of the output current should be controlled using the phase shift control method rather than the frequency modulation. By using the phase shift control method, the dropout phenomenon can be avoided. However, as shown in Fig. 7, the larger the load (the smaller the Q-factor), the smaller the phase difference between the inverter voltage and the current.

Therefore, it is difficult for the converter to operate in the ZVS region. In order to overcome this problem, a control method combining the frequency modulation method and the phase shift method is proposed. As shown in Fig. 8, the controller consists of a frequency modulator and a phase shift controller. When the output of the PI controller (x^*) increases, the controller operates from the frequency modulator. At this time, the phase shift controller operates with a minimum phase difference. This is because the input of the phase shift controller ( ) is zero. However, as the output of the PI controller increases and approaches the maximum frequency of the limiter, the input of the frequency modulator stops increasing and the input of the phase shift controller starts increasing. By applying the proposed controller, current control in the ZVS region can be secured not only in the light load region but also in the heavy load region where the phase difference between voltage and current is narrow.

4. Simulations and Experimental Results

A 5-kW reactive gas generator system was designed and tested to verify the validity of this study. The design parameters are listed in Table 1. The resonant frequency (ω_o) is set to 300-kHz.

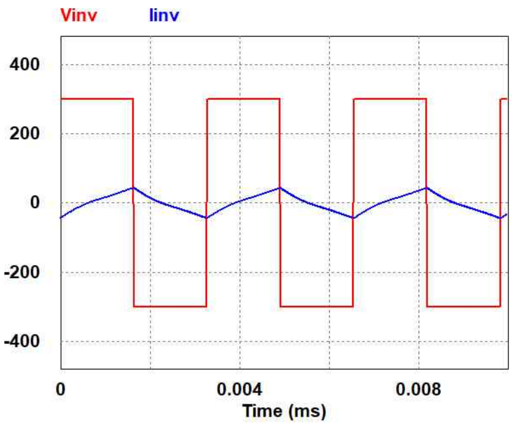
4.1 Simulation results

The simulations are performed in states of low gas pressure (low R_o) and maximum gas pressure (large R_o). Fig. 9(a) presents the inverter voltage and current when the gas pressure is low. Fig. 9(b) presents the plasma current.

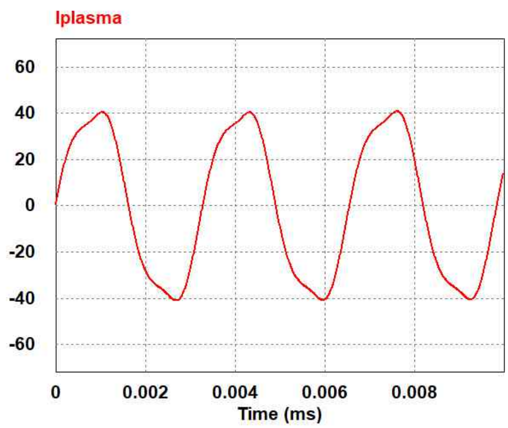
As shown in Table 1, the maximum plasma current of 30 A is used as the output. Fig. 10 presents the simulated waveforms with maximum gas pressure. It represents the state where the phase shift is minimized to follow the current reference of 30 A. Fig. 11 presents the simulated waveforms when the current reference is lowered to 20 A with the maximum gas pressure. It is difficult to output 20 A only frequency variation. A small current can be controlled to be output only at a fixed frequency of 300-kHz. However, since a large phase shift is required in this case, ZVS is difficult to be performed and a large switching loss can occur. Therefore, phase shift control is also performed.

Table 1. Specification of the reactive gas generator

Specification	Value
Rated power (P_{rated})	5 kW
Input voltage (V_d)	300 V_{dc}
Maximum plasma current ($I_{plasma,max}$)	30 A_{rms}
Leakage inductance of reactor (L_{lkg})	1 μH



(a) Inverter voltage and current



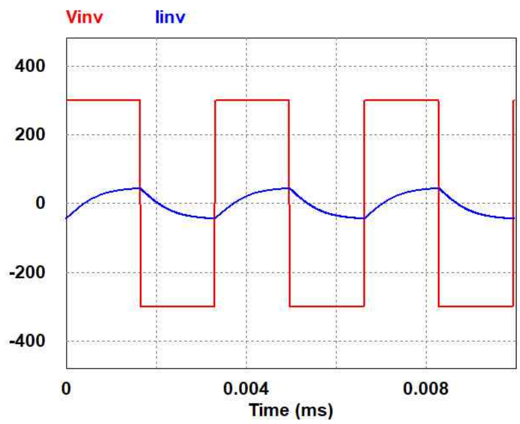
(b) Plasma current

Fig. 9. Simulation waveforms (R_o=2Ω, I_{plasma}^*=30A)

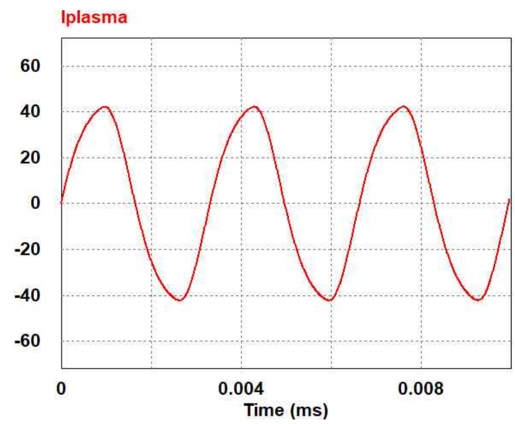
4.2 Experimental results

The 5-kW reactive gas generator was constructed using the proposed control scheme and design method. The specifications are the same as in the previous section. Fig. 12(a) presents the experimental waveforms under heavy load. 5 *l/min* of oxygen is injected, and the output current is controlled to 30 A. At this time, the converter operates at a switching frequency of 300-kHz, and the phase shift is minimized. Fig. 12(b) presents the experimental waveforms when the current reference is lowered using the same oxygen levels as in Fig. 12(a). The converter operates at a switching frequency of 360-kHz and the plasma current is controlled through a phase shift. If the frequency control method is used, a wide frequency variation is required to control the magnitude of the plasma current as shown in Fig. 12(b). On the other hand, if a resonant network is designed to be controllable with narrow frequency fluctuations, a plasma dropout phenomenon will occur.

By using the proposed control method, it is possible not only to limit the frequency fluctuation to a minimum but also to avoid the dropout phenomenon caused by the fluctuation of the current.

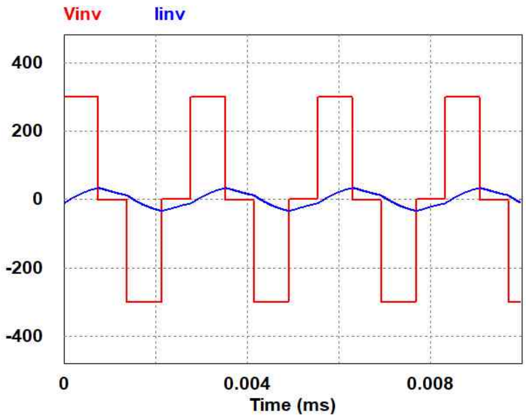


(a) Inverter voltage and current

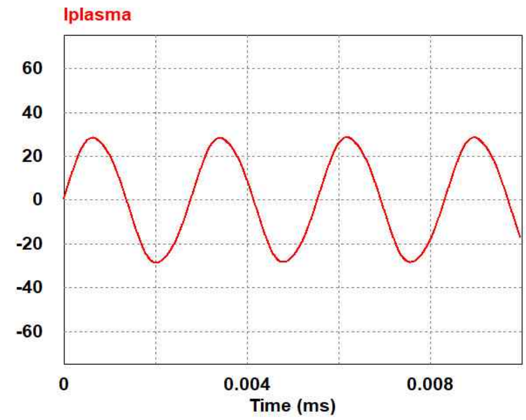


(b) Plasma current

Fig. 10. Simulation waveforms (R_o=6Ω, I_{plasma}^*=30A)

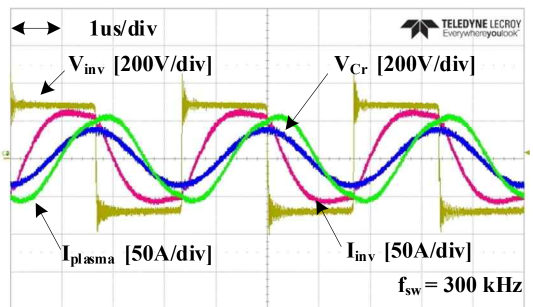


(a) Inverter voltage and current

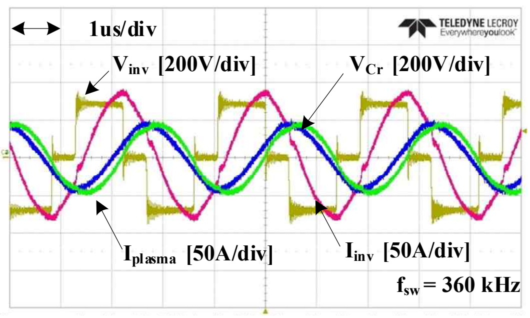


(b) Plasma current

Fig. 11. Simulation waveforms (R_o=6Ω, I_{plasma}^*= 20A)



(a) I_{plasma}^* = 30A, O_2 = 5 L/min



(b) I_{plasma}* = 24A, O_2 = 5 L/min

Fig. 12. Experimental waveforms

5. Conclusion

In this paper, the characteristics of plasma loads were analyzed using experimental results. Reactive gas generators should be designed with considerations for the characteristics of plasma loads, in particular, the negative impedance, which causes the drop-out phenomenon. A design procedure for a resonant network was also presented. Moreover, control scheme that combines the PFM with the phase shift method is proposed. The validity of this analysis and the proposed control scheme was verified through simulations and experimental results. The design procedure for the resonant network and the proposed control scheme with consideration for the characteristics of plasma loads can be applied to optimize reactive gas generator systems.

Acknowledgements

This work was supported by “Human Resources Program in Energy Technology” of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (*No. 20164030200980*)

References

[1] S. S. Kim, D. K. Choi, “The development of RF generator for remote plasma cleaning source,” *The 30th International Conference on Plasma Science*, 2003. ICOPS 2003.

[2] J. H. Lee, D. K. Choi, S. S. Kim, B. K. Lee, C. Y. Won “RF Power Conversional System for Environment-friendly Ferrite Core Inductively Coupled Plasma Generator,” *Journal of the Korean Institute of Illuminating and Electrical Installation Engineers*, vol. 20, no. 8, pp. 6-14, Sep. 2006.

[3] Ken Tran, Alan Millner, “A new power supply to ignite and sustain plasma in a reactive gas generator,” *2008 Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition*, pp. 1885-1892, 2008.

[4] S. Raoux, J. G. Langan, “Remote NF_3 Chamber Clean Virtually Eliminates PFC Emission from CVD Chamber and Improves System Productivity,” *semiconductor fabtech-9th edition*, pp. 107-113.

[5] Y. K. Lee, D. S. Lee, K. H. Bai, C. W. Chung, H.Y. Chang, “On inductively coupled plasma for next-generation processing,” *Surface and Coatings Technology*, pp. 167-170, 2003.

[6] D. K. Choi, applied for a U.S. patent (Appl. No.10-2002-63298).

[7] M. Borage, S. Tiwari, S. Kotaiah, “Analysis and design of an LCL-T resonant converter as a constant-

current power supply," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 6, pp 1547-1554, 2005.
[8] G. S. N. Raju, S. Doradla, "An LCL resonant converter with PWM control-analysis, simulation, and implementation," *IEEE Transactions on Power Electronics*, vol. 10, no. 2, pp. 164-174, 1995.

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