Power control strategies evaluation of a series resonant inverter for atmosphere plasma applications

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Abstract-A prototype of a high-voltage high-frequency power supply for atmosphere plasma applications such as dielectric barrier discharge and corona-discharge is presented. It is consisted of a rectifier accompanied power factor correction function (PFC) and a resonant inverter. Some technologies, including pulse-amplitude modulation (PAM), pulse-width modulation (PWM), pulse-density modulation (PDM) and pulse-frequency modulation (PFM) have been tested to evaluate the power control performances. Experimental results show that the diversity among these methods and a hybrid control is suggested in accordance with these applications.

Keywords: Plasma, dielectric barrier discharge, phase-shift, PAM, PWM, PDM. PFM.

I Introduction

High-voltage high-frequency pulse power supply has been recognized as one of the feasible solution in the fields of plasma applications, including dielectric barrier discharge (silent-discharge) and corona-discharge [1-7]. The former is the most widely used in industrial large-scale ozone-generation system, and ozone gas can be practically produced on the basis of silent-discharge phenomena. The later is widely used for gas clean system. Atmosphere plasma equipment includes a silent-discharge tube and a resonant inverter with high-voltage high-frequency transformer, a power factor correction (PFC) converter and a cooling system. High-frequency voltage is applied to the tube which is covered with glass to provide a gas discharge conditions in the gap between two electrodes. Gas is supplied from the inlet of the tube to produce ionized gas.

This paper discusses the power control strategies applied to the plasma equipment. The proposed pulse power supply is consisted of a PFC rectifier, a voltage-source full-bridge inverter using the MOSFET power modules. The inverter out is connected to the plasma reactor through a high-voltage high-frequency transformer with a secondary voltage rating of over 10 kV. Thus, the equivalent load of the inverter can be considered a RLC series circuit which means a higher switching frequency than the load resonant value, resulting in a lagging load condition, can have a benefit of ZVS switching. This idea is adopted in this paper. However, as the gas discharge exhibits a nonlinear characteristic, different feedback control schemes should be used to compensate the discharge conditions change.

In this paper, the PFC rectifier control is achieved by UC3854 based controller. The inverter output power control strategies, including PWM, PFM, and PDM control are finished by UC3895 based controller plus a PIC16F877 based microprocessor.

II. System configuration

Fig. 1 shows a schematic configuration of the plasma equipment using a high-frequency inverter with a high-voltage transformer. It mainly consists of a PFC rectifier shown in Fig. 1(a), and a resonant inverter shown in Fig. 1(b). The equivalent circuits of the high-frequency high-voltage transformer and the plasma reactor have also been shown in this figure, where L_r and L_m are corresponding to the leakage inductance and magnetizing inductance of the high-frequency transformer. Since the plasma reactor is connected to the inverter through the high-frequency transformer, the leakage inductance L_r is inserted in series with it. The characteristic of the plasma reactor is greatly dependent on the geometry of the electrode of equipment. Generally, the discharge gap is modeled as a capacitor before plasma operation and as a direct voltage source connected in parallel with a diode rectifier after plasma operation. The buffer dielectric is modeled as a capacitor.

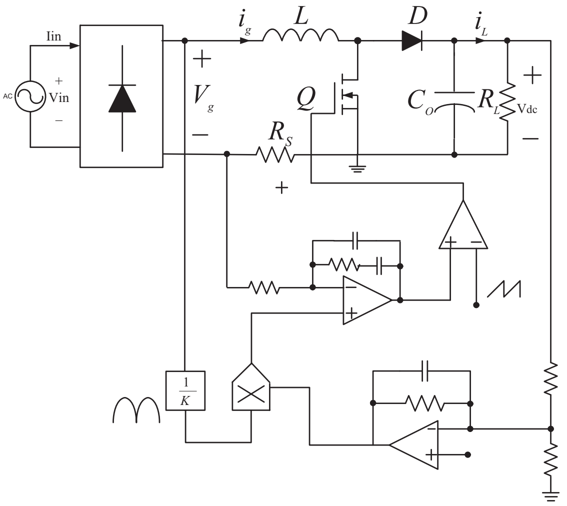


Fig. 1(a) PFC stage control structure.

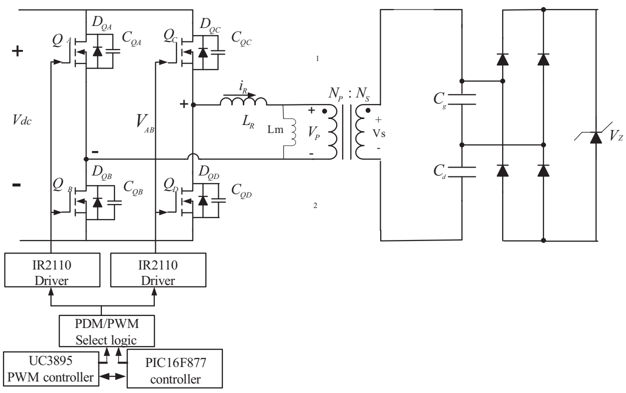
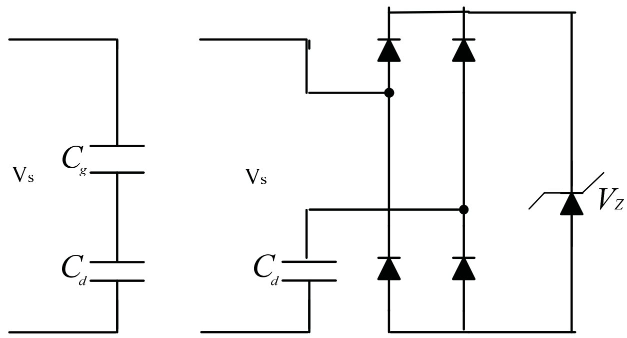


Fig. 1(b) Inverter stage control structure.

Fig. 2 indicates the status of each section, where C_e, C_g presented in the status before plasma operation, and only C_e exists while plasma is generating. V_Z denotes the discharge sustaining voltage. To estimate these parameters is essential for providing a stable power supply operation. However, these parameters can vary with the change of the gas discharge state of the plasma reactor such as gas composition, inflow gas and the geometry of the electrode [5]. It is difficult to measure directly, but can be estimated on the basis of the Lissajours figure[7]. Another way to extract the related parameters of the plasma reactor can been taken from [5], which also pointed out the plasma reactor exhibits two distinct features before and after plasma operation. Thus, one can see that the inverter resonant frequency during plasma operation should be lower than before plasma operation and the power supply needs to be design in accordance with these changes.



(a) (b)

Fig. 2 Reactor model in different operation status, (a) before plasma, (b) plasma operation.

III. Control system design

A. PFC stage

The PFC stage uses the UC3854 based average-mode controller to accomplish fixed frequency current control with stability and low distortion. Unlike peak current-mode, average current control accurately maintains sinusoidal line current without slope compensation and with minimal response to noise transients. Fig. 1(a) shows the control structure.

B. Inverter stage

The inverter stage is a single-phase full-bridge structure with UC3895 plus PIC16F877 based controller. A step-up high frequency transformer is connected to the output terminal to obtain a high voltage for the plasma reactor operation. The inverter has four stages, determined by the power switching elements of the two legs. The stages in which two diagonally opposite power switches are conducting are called active [8]. On the contrary, the stages in which two switches on the same site of power switches are conducting are called passive. The switching of the leg can moves the inverter from active stage to passive stage is called the leading leg. The other leg which switches only from passive stage to active is called the trailing leg. For phase shift control and with the lossless snubbing capacitor, the ZVS can be achieved in the leading leg for all the load conditions, but can be achieved in the trailing leg only in the case that the inverter operates with a lagging load current. For a RLC series, it means the inverter switching frequency should be higher than the load resonant frequency. The discharging loads exhibit a strong nonlinear relationship between their voltage and current. When the electrodes voltage is lower than the gas breakdown voltage, it is almost no current and no discharging occurs, however, when the electrode voltage is more than the gas breakdown level, then a large amount of discharging current flows, which resulting in the C_g to be short out, and the resonant frequency slightly decreases. Thus, it is difficult to get an equivalent linear mode. For simplicity, a RLC series resonant circuit is used to being treated after combining the step-up transformer. In this paper, some feasible control strategies include PAM, PWM, PFM, and PDM will be investigated and compared. Fig. 1(b) shows the control structure in this stage.

C. Power control strategies

The load characteristic is dependent on the operation status shown in Fig. 2. When the instantaneous electrode voltage is lower than the gas breakdown voltage, the load resonant frequency is almost constant and no discharge occurs. As the instantaneous electrode voltage is larger than a certain value, gas discharge beginning, then C_g to be short out, resulting in a decrease of the load resonant frequency. Thus the inverter output power depends greatly on the electrode peak voltage. This feature should influence the performances of the adopted power control methods.

The PAM controls the inverter input voltage by controlling the PFC stage output voltage to achieve the adjusting inverter output power. Considering the power elements stress and wide voltage range, it is preferred buck-boost scheme to boost scheme as the PFC stage. However, as the instantaneous electrode voltage should be large than the gas breakdown level so as to form a sustain discharge procedure, thus the inverter input voltage can not be lower than a certain level, so it leads to a result that discharge power is difficult to less that half of the full range. Moreover, a low voltage operation may be accompanied a partial or local discharge due to inequality of the gas between the electrode and dielectric. Another disadvantage is that the inverter output power factor decreases as the output increases in the PAM scheme, if the operation frequency is constant.

The PWM controls the pulse width of the inverter output voltage to achieve the adjusting output power. By shifting the phase difference of the control phase with respect to the standard phase, the output power can be varied from full power to low power, therefore it is feasible to regulate the inverter output power. It is also known that the lossless snubbing capacitors can enable the inverter to perform ZVS function when it operates with a lagging load current. For discontinuous load current or leading load current, the ZVS function can not be achieved in the trailing leg, resulting in an increasing switching loss. Similarly to the PAM scheme, the inverter output power factor also decreases as the pulse width increases in the PWM control when the switching frequency is constant. A small pulse width tends to a discontinuous load current or leading load current, which is adverse to the switching loss, thus it is disapproved for a low pulse width control.

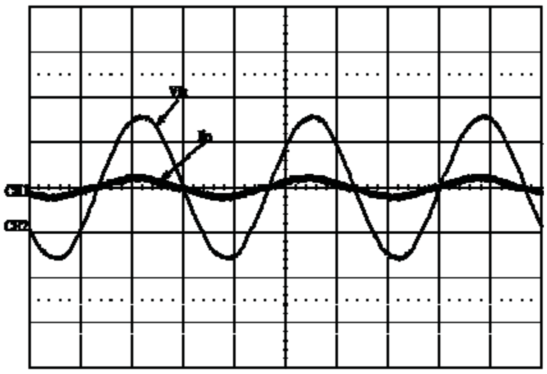
The PFM controls the frequency of the inverter output voltage to achieve the adjusting output power. To realize zero voltage switching, the inverter output frequency should be large than the load resonant frequency. Thus, one can see that the inverter power fact should decline in low power range. Furthermore, the inverter output power will have a steep increase when the frequency is approaching the load resonant frequency. This will increase the difficulty to control the inverter output power stably. As the same as the PAM and PWM situations, it is difficult for the PFM applied to the voltage-source series-resonant inverter to adjust the discharge power to less than half of the full power[3], as the electrodes voltage would be lower than the gas discharge breakdown voltage.

The PDM controls the output power by controlling the number of inverter output voltage pulses, in other words, it is to repeat “run and stop”, in accordance with the desired output power. The inverter repeats the gas discharge procedure which consists of power-on period and zero-power period, while the inverter frequency is constant. For example, if a working cycle represents a time interval of 40 working pulses, thus by varying the number of these working pulses from 10 to 40 will have a regulated output power from 25% to 100%. [1] has shown this method can work well over a range of pulse densities from 3/30 to 1. The PDM scheme can have lower switching loss than other schemes as it achieves quasi-ZCS and ZVS functions [3]. However, if a shorten rising time when the next discharge period starts is desired, it was found useful to apply pulses with reduced width to the plasma reactor during zero-power periods, which is used to prevent deionization of gas [4]. Thus, the control signal will consist of full-width pulses during the discharge period and reduced-width pulses during the zero-power period. In PDM scheme, the inverter output power should be controlled as the environment temperature fluctuations can cause the change of the discharge voltage. Two strategies can be applied in this situation: one is PDM plus an additional PWM based feedback control algorithm [4]; the other is PDM plus PFM based control algorithm [1]. This paper utilizes a UC3895 plus PIC16F877 based hybrid control to realize this control scheme. The PIC16F877 microprocessor determines the control algorithm, and a corresponding control signal is given to the UC 3895 controller and the PDM/PWM select logic circuit. The desired synchronized signal is provided by the UC3895 controller.

IV Experimental results

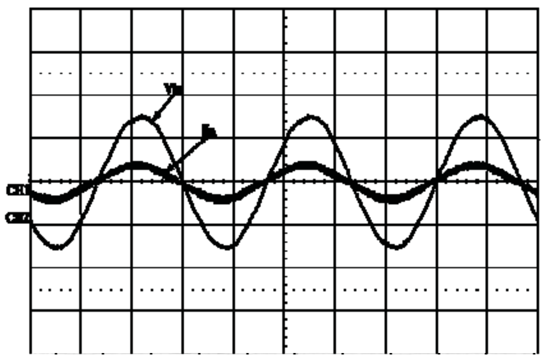
The topology presented in Fig. 1 has been implemented to evaluate these power control strategies. A prototype of 1 kW has been settled in the experimental test. The DC bus voltages are regulated at 400 V.

Figure 3 shows the experimental results for the PFC stage. Fig. 3(a) shows the source voltage and current for a load case of 500W; Fig. 3(b) shows the source voltage and current for a load case of 1000W. It shows the source current has in-phase with the source voltage.



CH1-20A CH2-200V M-5ms/div

Fig. 3(a) The source voltage and current for a load case of 500W



CH1-20A CH2-200V M-5ms/div

Fig. 3(b) The source voltage and current for a load case of 1000W

Figure 4 shows the experimental waveforms of PWM based control scheme. Fig. 4(a) shows a case of 50% pulse width duration. Fig. 4(b) shows another case of 75% pulse width duration. It shows the inverter output power increases as the pulse width increases, and the power factor decreases as the output power increases. The input power related to Fig. 4(a) and Fig. 4(b) is 470W and 630W. The switching frequency used here is 40 kHz. For a switching frequency of 35 kHz, the above two cases of power output are related to 700W and 950W.

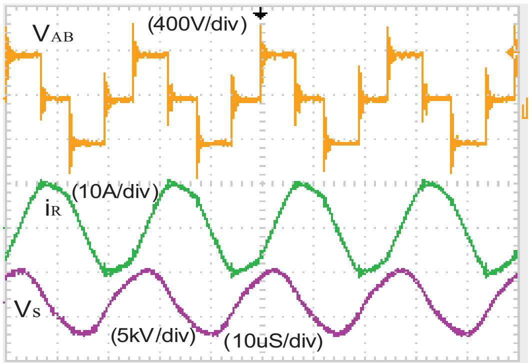


Fig. 4(a) The experimental waveforms of 50% PWM control

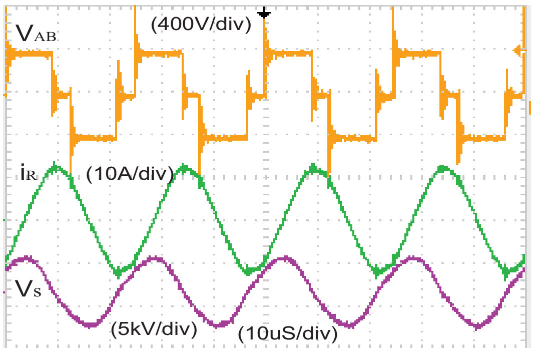


Fig. 4(b) The experimental waveforms of 75% PWM control

Figure 5 shows the experimental waveforms of PFM based control scheme. Fig. 5(a) shows a case of switching frequency of 50 kHz. Fig. 5(b) shows a case of switching frequency of 40 kHz. It shows the inverter output power increases as the switching frequency increases, and the power factor decreases as the output power increases. The input power related to Fig. 5(a) and Fig. 5(b) is 270W and 720W.

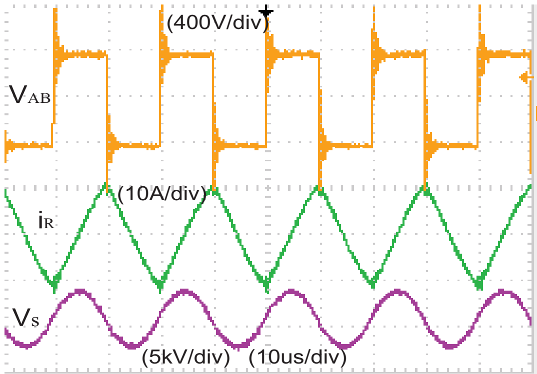


Fig. 5(a) PFM control for 50 kHz switching frequency.

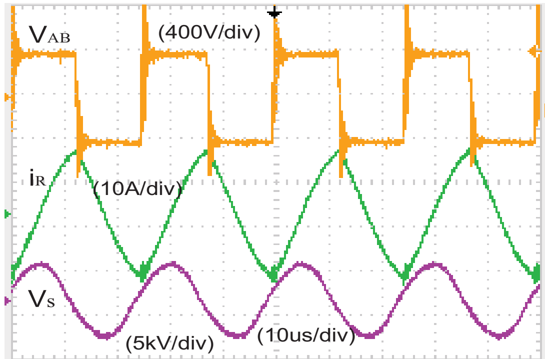


Fig. 5(b) PFM control for 40 kHz switching frequency.

Figure 6 shows the experimental waveforms of PDM based control scheme. Fig. 6(a) shows a case of during operation at a pulse density of 25% (10/40). The input power is about 230W. Fig. 6(b) shows a case of during operation at a pulse density of 50% (20/40). The input power is about 420W. The switching frequency in this case is about 40 kHz. It shows the inverter output power increases as the pulse density increases.

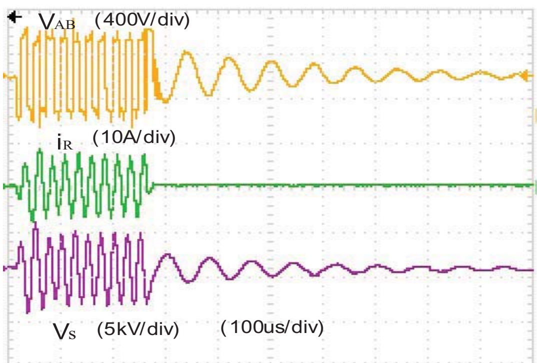


Fig. 6(a) PDM control for a case of during operation at a pulse density of 25% (10/40).

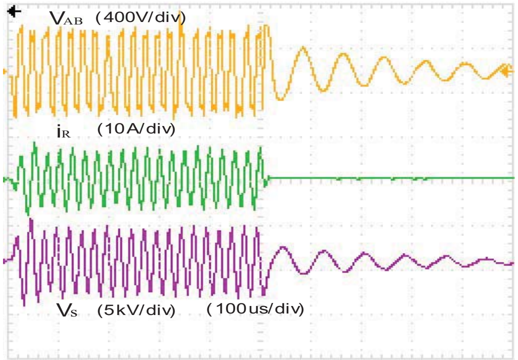


Fig. 6(b) PDM control for a case of during operation at a pulse density of 50% (20/40).

V. Conclusion

In this study, a prototype of a high-voltage high-frequency power supply for atmosphere plasma applications has been presented. Different control strategies have been tested to evaluate the power control effect. As the experimental results, some conclusions can be made as follows:

1. The only PAM control is not encouraged as it needs a complicated front stage to achieve voltage regulation function, and is hardly used to less that half of the full range due to the required gas breakdown voltage level
2. The PWM control can fulfill the full load range conditions. However, a small pulse width tends to a discontinuous load current or leading load current, which is adverse to the switching loss, thus it is disapproved for a low pulse width control.
3. The only PFM control is also not encouraged as it should be large than the load resonant frequency to realize zero voltage switching. Thus, one can see that the inverter power fact should decline in low power range, and it is difficult to adjust the discharge power to less than half of the full power as the electrodes voltage would be lower than the gas discharge breakdown voltage.
4. The PDM can work well over a range of pulse densities from 3/30 to 1, however, the environment temperature fluctuations should disturb the stability of the inverter output power. To compensate this influence, a hybrid control such as PDM plus PFM or PDM plus PWM is suggested.

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VI. References

1. Y. Liu, X. He, “ PDM and PFM hybrid control of a series-resonant inverter for corona surface treatment, “ IEE Proc.-Electr. Power Appl. Vol. 152, no.6, pp. 1445-1450, November 2005.
2. J. Marcos, J. Cardesin, E. L. Corominas, R. Secades, and J. Carcia, “ Low-power high-voltage high-frequency power supply for ozone generation,” IEEE Transactions on Industry Applications, vol. 40, no. 2, pp. 414-421, March/April, 2004.
3. H. Fujita, H. Akagi, “ Control and performance of a pulse-density-modulated series-resonant inverter for corona discharge processes, “IEEE Transactions on Industry Applications, vol. 35, no. 3, pp. 621-627, May/June, 1999.
4. O. Koudriavtsev, S. Wang, Y. Konishi, and M. Nakaoka, “ A novel pulse-density-modulated high-frequency inverter for silent-discharge-type ozonizer, ” IEEE Transactions on industry applications, vol. 38, no. 2, pp. 369-378, March/April, 2002.
5. Y. D. Lee, W. C. Lee, T. K. Lee, “ A study on the reactor parameter of atmosphere plasma power supply, “ IEEE Power Electronics and Applications, 2007 European Conference, pp. 1-8, Sept. 2007..
6. Y. M. Kim, J. Y. Kim, S. P. Mun, H. W. Lee, S. K. Kwon, K. Y. Suh, “ The design of inverter power system for plasma generator,” IEEE Electrical Machines and Systems, pp. 1309-1312, 2005.
7. R. Feng, G. S. P. Castle, S. Jayaram, “ Automated system for power measurement in the silent discharge, “IEEE Transactions on Industry Applications, vol. 34, no. 3, pp. 563-570, May/June, 1998.
8. R. Redl, N. O. Sokal, L. Balogh, “ A novel soft-switching full-bridge DC/Dc converter : analysis, design considerations, and experimental results at 1.5kW, 100kHz., ” IEEE Transactions on Power Electronics, vol. 6, no. 3, pp. 408-418, july, 1991.