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Research on the Input Power Measurement and Control Technology for Ozone Production Process with DBD

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Abstract

The key device of power supply for ozone production process with DBD can cause the distortion of voltage and current and seriously affect the input power measurement and control. This paper presents a power measurement method based on quasi-synchronous algorithms for ozone production process with DBD and designs the power control strategy based on the load frequency tracking phase shift PWM mode. The experimental results show that the accuracy of power measurement can reach 0.3% and the accuracy of power control can reach 5%.

Keywords*: Ozone; DBD; Power Measurement and Control; Quasi-synchronous algorithms; Phase Shift PWM*

1. Introduction

Ozone is widely used in medical, chemical production, wastewater treatment, food processing and other fields [1-3], because it not only has excellent features such as disinfection, sterilization, bleaching, chemical oxidation, etc., but also has the good ecological environment effects [4]. The most common method of ozone generation in industry is the dielectric barrier discharges (DBD). The essence of ozone generation with DBD is a continuous industrial chemical production process. The most critical technology is to inject electric power into the discharge reaction unit. A large number of micro-discharges are generated in the discharge gap. The micro-discharges dissociate oxygen molecules into atom and the ozone molecules are synthesized by the collision of the oxygen atoms and molecules. The measurement and control for input power has important significance for the ozone production and application. This paper analyzes the reason of the harmonic generation and the effects on the power measurement based on discussing the harmonic problems in the ozone production process. And the power measurement method based on quasi-synchronization algorithm is proposed. On the basis of power measurement for ozone production process with DBD, the power control strategy based on the load frequency tracking phase shift PWM mode is designed.

The power measurement and control technology proposed in this paper has practical significance for power measurement of ozone production process with DBD. And it can provide practical guidance and reference for the similar power control issues with harmonics.

2. The Influence of Harmonic on Power Measurement

The power supply is the most critical devices in ozone production process with DBD. And the high-frequency switching power supply is used currently. However, they the high-frequency switching power supply generate a lot of electromagnetic interference and radiation in work. Ozone discharge reactor works in high frequency and high voltage discharge status. So it can generate a lot of electromagnetic interference and radiation.

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These electromagnetic interference and radiation can cause input voltage and current distortion. The voltage and current contains a large number of harmonics. The voltage and current distortion waveform in ozone production process are shown in Figure 1.

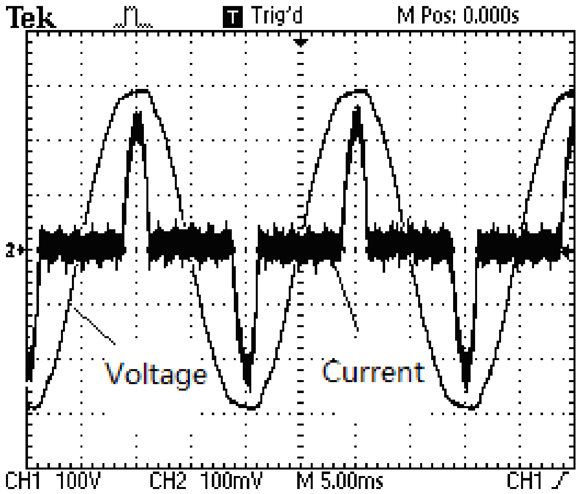


Figure 1. Input Voltage and Current Waveform in Ozone Production Process

As can be seen in Figure1, input voltage and current waveform have a serious distortion. The voltage waveform is not the standard sine wave. In particular, input current contains a large number of glitches. The input voltage and current are implemented FFT transformations respectively and the results are shown in Figures 2 and 3.

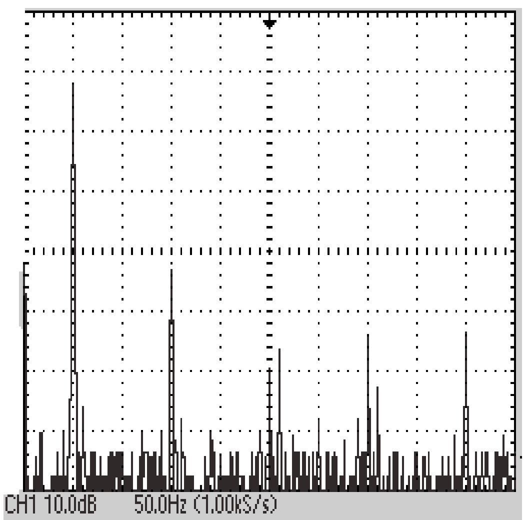


Figure 2. FFT Diagram of Input Voltage

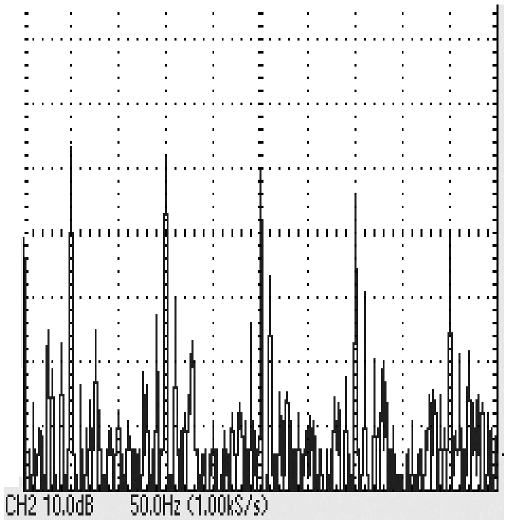


Figure 3. FFT Diagram of Input Current

The harmonic scales after FFT transformations are shown in Table 1.

Table 1. Harmonic Scale of Input Voltage and Current

Harmonic number	second	fourth	sixth	eighth	tenth
Voltage fundamental wave levels （The fundamental wave is 1.）	1.7	0.95	0.65	0.7	0.6
Current fundamental wave levels （The fundamental wave is 1.）	1.47	1.43	1.37	1.26	1.07

As can be seen in Table 1, the harmonics of input voltage and current are mainly concentrated in even harmonics such as second, fourth, sixth and eighth et al. The second harmonic of voltage is as high as 1.7. And even harmonics within tenth of current are higher than 1. The reasons of these harmonics appearance are summarized as the following.

(1) Fast pulse current group in DBD discharge;

(2) Nonlinear elements and storage elements in power supply;

(3) High-power switch tube and high-frequency transformer.

From the analysis above, the input voltage and current are distorted because of the large number of harmonics. The presence of these harmonics can greatly affect the accuracy of input power measurement. Traditional electrical measurement instruments are designed to measure the frequency signals. These instruments are only can be used to measure the signals of near-frequency sine wave and less clutter due to the operating principle and structure. And many harmonics can cause large systematic errors. And the measurement data are even completely unavailable.

3. The Power Measurement Based on Quasi-Synchronous Algorithms

Based on the analysis above, the traditional method of measuring power in ozone production process with DBD can cause the large errors. Therefore, this paper designs a power measurement device. The device can measure the input power of ozone production process accurately based on quasi-synchronization algorithm.

3.1. Quasi-Synchronous Algorithms

Quasi-synchronous sampling algorithm is a technique for data processing by appropriately increasing the sampling points and using the appropriate algorithm based on the synchronous sampling algorithm. For non-sinusoidal voltage and current measurements, the device is not only simple, but also this algorithm can get close to the accuracy of ideal synchronous sampling [5].

Set a stable periodic signal as $f(t)$. Let the period is $2\pi$and the interval [t_0, $t_0+2\pi+\triangle$] ($\triangle$ is synchronization error) is divided into N segments. N+1 sampling data can get by uniform sampling and then calculate in accordance with the following quadrature formula.

$$F^1 = \frac{1}{\sum_{k=t_0}^{N+t_0}\rho_k} \sum_{k=t_0}^{N+t_0}\rho_k f(t_k) \qquad (1)$$

Where, the superscript 1 indicates the first quadrature operation. The ρ_k (k=i,i+1, ⋯i+N) is the weight coefficient determined by the quadrature formula. Then the integration interval with width of n×(2π+Δ) is divided into n×N segments and the n×N+1 sampling data can be obtained. Then the following recursive calculation is executed:

$$F^n = \frac{1}{\sum_{k=t_0}^{N+t_0}\rho_k} \sum_{k=t_0}^{N+t_0}\rho_k F^{n-1} \quad n=2, 3, \ldots \qquad (2)$$

Where, the superscript n is recursive sequence number.

Based on the recursive calculation above, the $\overline{f(x)}$ (average of $f(x)$) can be expressed as following:

$$\overline{f(x)} = \lim_{n\to\infty} F^n \approx A_0 + \sum_{m=1}^{M} \gamma_m^n f_m(x_0 + n \bullet \frac{\Delta}{2}) \qquad (3)$$

Where, M is the highest harmonic number of $f(x)$. The γ_m is the attenuation factor. Δ is the phase deviation of quasi-synchronous. The γ_m determines the accuracy degree of $\overline{f(x)}$. The sufficient condition of formula (3) established is as follows.

$$N > \frac{2\pi + \Delta}{2\pi} \bullet M \qquad (4)$$

Where, N represents the sampling number and M is the highest harmonic number of $f(x)$.

Taking these operations, errors between recurrence results and actual values are very small. This is the principle of quasi-synchronization algorithm.

3.2. The Power Measurement of Ozone Production Process with DBD

The harmonic analysis above shows that the amplitude of harmonics corresponding to more than 50 times has been declined to very low levels and the power can be neglected. Therefore it requires that the device can measure the harmonic number higher than 50. The highest harmonic number what the device can measure is 60 in this paper. The frequency range of power source signal f(x) is about 50Hz±10 %(47.5-52.5Hz). The algorithm error of input power measurement is less than 0.02%.

The sampling frequency is synchronous with 50Hz which is the center frequency of power source. That is we can sample100 times in 20ms. It meets the conditions sampling frequency N> 1.2M (M is the maximum harmonic number and N> 72). So the sampling interval is 200μs. There is delay in the sampling process. But each sampling operation is same. So each sample is considered as equal interval. There are:

$$\Delta_{\max} = \frac{1/50 - 1/52.5}{1/52.5} \bullet 2\pi = 0.05 \times 2\pi \qquad (5)$$

Taking $|\gamma_m|$=0.05, then sampling and recursive calculation in two and three cycles, there are $|\gamma_m|^2$=0.25% and $|\gamma_m|^3$=0.0125% respectively. The measurement system is designed to retain a certain error margin for meeting the computing error. So the sampled period m is taking as 3. That means the iterative processing starts after 3 sampling cycles. So the total number of sampling points is:

$$W = m \times N + 1 = 3 \times 100 + 1 = 301 \qquad (6)$$

Where, W is the total number of sampling points, m is the sampling period, N is the number of sampling points per period.

Based on the compound trapezoid formula, the quasi-synchronous algorithm is used in this paper. The iterative formula of quasi-synchronous algorithm can be developed gradually in advance for the convenience of calculation, then the final weighted value of each sampling point can be obtained and it is convenient for realization algorithm. The algorithm in this paper uses cubic iterations and the sampling points of each cycle are 100. So the iterative formula is as follows:

$$F^3 = \frac{1}{\sum_{i=0}^{100}\rho_i}\sum_{i=0}^{100}\rho_i\left\{\frac{1}{\sum_{i=0}^{100}\rho_i}\sum_{i=0}^{100}\rho_i\left[\frac{1}{\sum_{i=0}^{100}\rho_i}\sum_{i=0}^{100}\rho_i f(x_i)\right]\right\} = \sum_{i=0}^{300}\eta_i f(x_i) \qquad (7)$$

By the formula (7), the input power measurement of ozone production process with DBD can be achieved. The power measurement results in this way were compared with the results measured by high precision oscilloscope in this paper. The comparing results are shown in Figure 3. It can be seen from the Figure 4, the measurement error with the quasi-synchronization algorithm is less than 0.3%. This method can realize the real-time accurate power measurement.

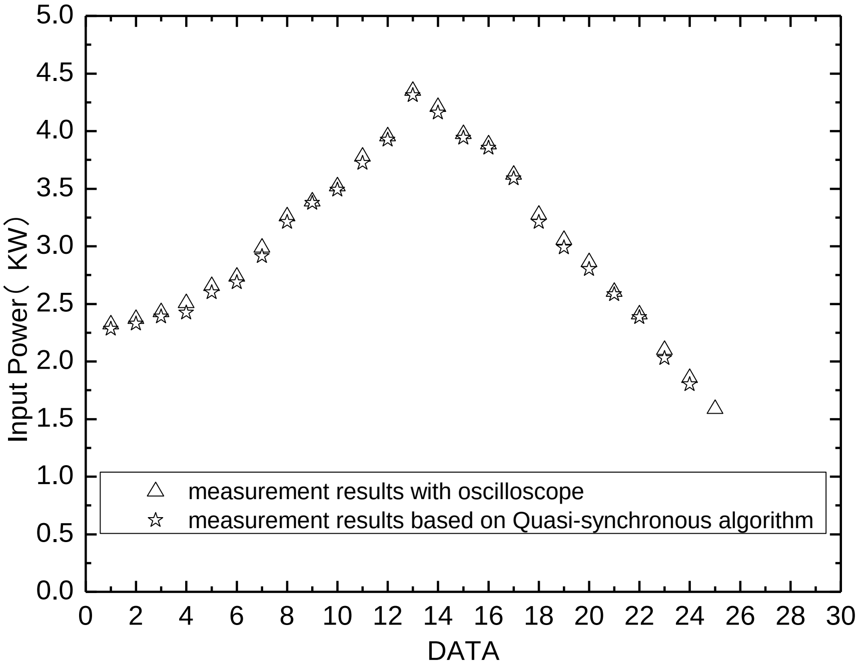


Figure 4. The Result of Measuring Input Power with Quasi-Synchronous Algorithm

4. The Power Control Strategy Based on the Load Frequency Tracking Phase Shift PWM Mode

The power control for DBD ozone production process is actually to control the power supply. At present, high-frequency switch power supply is commonly used in ozone production and the structure diagram of the power supply is shown in Figure 5.

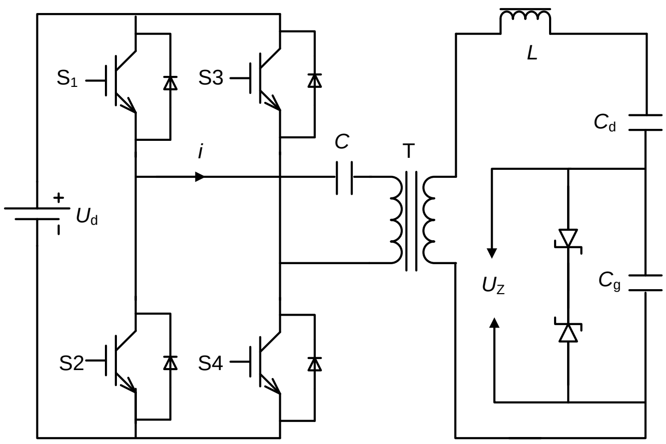


Figure 5. The Structure of High Frequency Switch Power

In Figure 5, T is the ideal transformer. L is the leakage inductance of the transformer. C_d is the dielectric capacitor. C_g is the gap capacitance. U_Z is the breakdown voltage. C is blocking capacitor. S1 ~ S4 are IGBT modules with anti-parallel diode. The main circuit of the power supply consists mainly of the rectifier unit and inverter unit in Figure 5. The power control in system is reflected in the control for rectifier and inverter circuits. Therefore, the power control can be roughly divided into two categories: DC control and AC control.

Through analysis and comparison for several methods about power control [6-9], this paper proposes power closed-loop control strategy based on load frequency tracking phase shift PWM in ozone production process. The control principle diagram is shown in Figure 6.

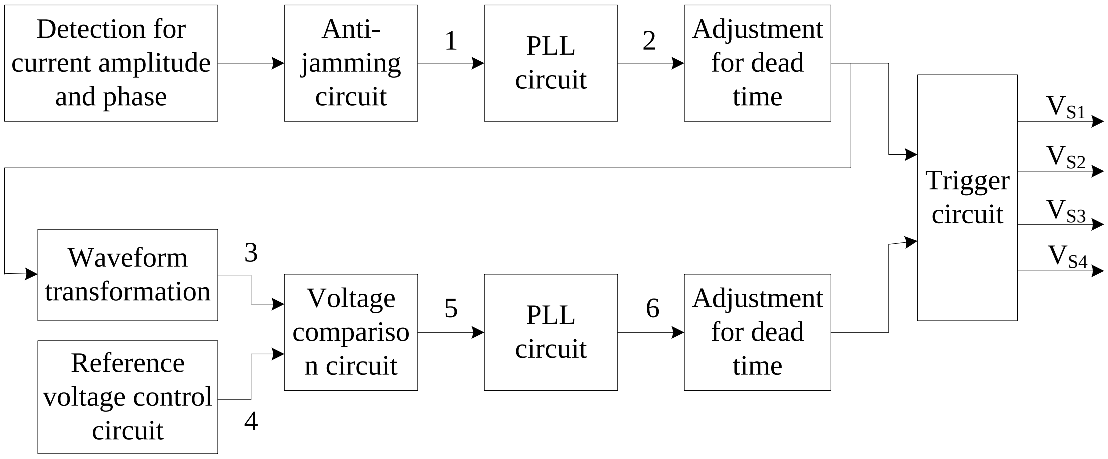
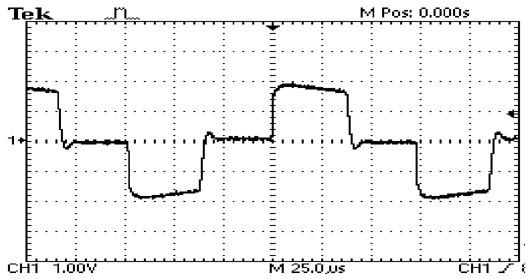


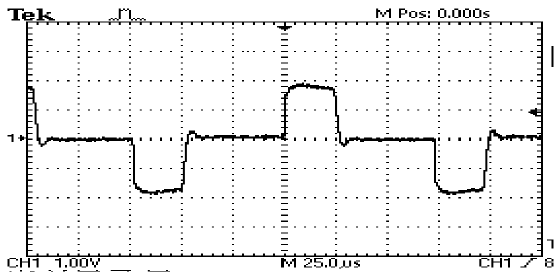
Figure 6. The Principle of Frequency Tracking Phase Shift PWM Control

In Figure 6, the output current of inverter circuit is sampled by the current amplitude and phase detection circuit. Then the signal filters out glitches via anti-jamming circuit and the signal 1 can be obtained through zero amplitude comparator circuit. The signal 2 is obtained when the signal 1 goes through the phase-locked loop circuit. And it is always the same in frequency and phase with signal 1. The signal 2 goes through the trigger signal generating circuit and the trigger signals of S1 and S2 with the dead time are obtained. Meanwhile the signal 2 turns into the triangle wave of signal 3 via waveform conversion circuit. Signal 5 is obtained via voltage comparison circuit between triangular wave signal 3 and the given signal 4 outputted by reference voltage control circuit. Then the signal 5 converts into square wave signal 6 with 50% duty after PLL circuit. The signal 6 goes through the trigger signal generating circuit and the trigger signals of S3 and S4 with the dead time are obtained. It is known that the phase shift size of trigger signal can be adjusted by changing voltage magnitude of signal 4 and the power control is achieved.

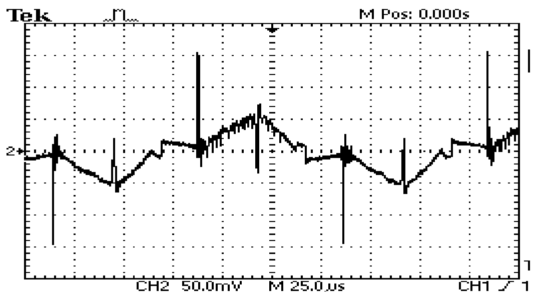
The control strategy in this paper uses the PLL circuit to achieve the frequency automatic tracking. Then the square wave--triangle wave comparator is used to achieve phase shift PWM control. Frequency automatic tracking technology is used as phase-locked loop. It is fast response, stable and reliable. And it can realize the adjustment of phase shift by controlling the reference voltage. The adjustment range is 0°-180°. The control strategy is simple, convenient and high reliability. The output of inverter circuit controlled by frequency tracking phase shift PWM is shown in Figure 7.



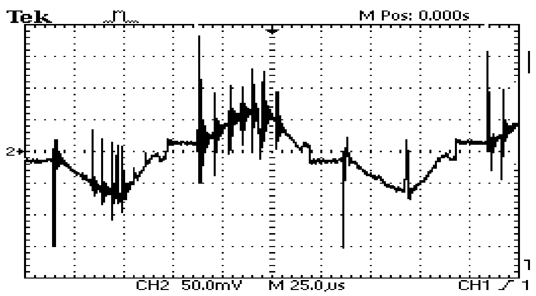
(A)Output Voltage of Inverter Circuit (Little Phase-Shift Angle)



(B) Output Voltage of Inverter Circuit (Big Phase-Shift Angle)



（C）Output Current of Inverter Circuit (Little Phase-Shift Angle)



（D）Output Current of Inverter Circuit (Big Phase-Shift Angle)

Figure 7. The Waveform of Experiment

In Figure 7, when the phase shift size is large the output voltage of the inverter circuit is small. At this moment, the discharge reaction unit does not discharge. With the decrease of the phase shift size, the inverter output voltage increases. When the voltage of two ends of discharge electrode is higher than the gas discharge threshold voltage, the discharge is beginning. The output power control is achieved by adjusting the phase shift size.

In the laboratory, the effect of power control strategy is tested by setting the power target within one hour in this paper. The control results are shown in Figure

8. We can know that the power controlled by our control strategies can fast track the power target value in Figure 8. And the accuracy of power control can reach 5%. It is fully able to meet the needs of ozone production process with DBD.

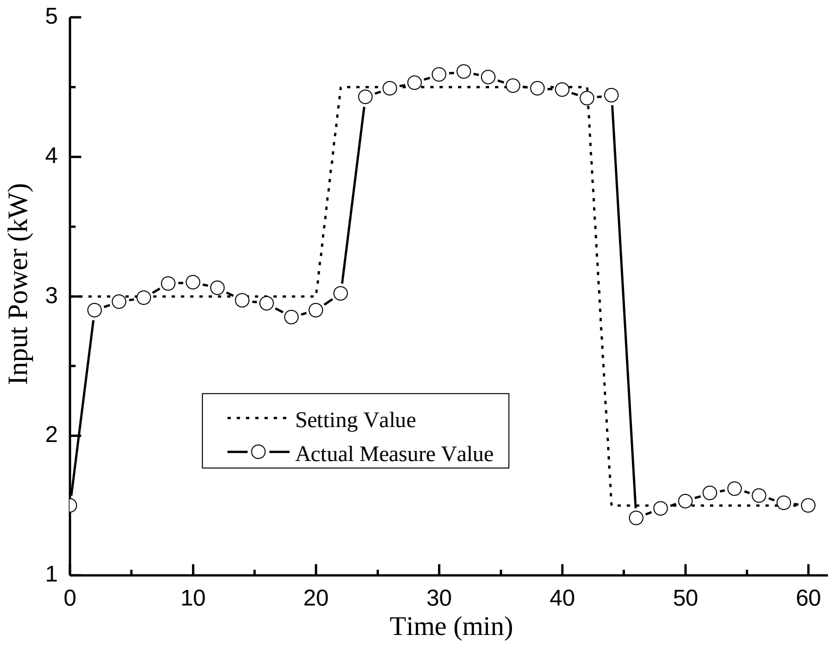


Figure 8. The Result of Input Power Control

5. Conclusions

The input power measurement and control technology for ozone production process with DBD is introduced in this paper. Based on the analysis and research on the input power harmonic problems, this paper proposes a power measurement method based on quasi-synchronization algorithm. The measurement method can measure precisely the input power in the case of input voltage and current distortion. According to the characteristics of power supply, this paper designs the power control strategy based on the load frequency tracking phase shift PWM mode and realizes the closed loop control for power.

The following conclusions are arrived in this paper:

(1) The voltage and current distortion of input power supply exist in ozone production process with DBD and there are a lot of harmonics. The harmonics mainly concentrate in even harmonics within 10 times.

(2) In the case of the input voltage and current distortion, the power measurement method based on quasi-synchronization algorithm can obtain good results in practice. Experimental results show that the measurement error of this method is less than 0.3%.

(3) The power control strategy based on the load frequency tracking phase shift PWM mode can achieve good closed-loop control for power and can response quickly. The accuracy of power control can reach 5% and the control strategy can fully meet the actual demand.

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