Technical Analysis and Extended Application of Variable Frequency Power Supply

Ying Chen, Jucai Huang,Hong Xie, Gang Lu, Yu Lin

Fujian Longking Co., Ltd., Longyan City，Fujian ,China

Corresponding author: *13950880939@139.com*

Abstract: This paper introduces the principle and circuit topology of a new-type variable frequency power supply. The variable frequency power supply changes the output impedance of the transformer through amplitude modulation and frequency modulation control to suppress the back corona phenomenon, which provides a new technical means for back corona control of ESP. The output ripple coefficient of the variable frequency power supply is small and the spark is turned off in real time, which can effectively avoid the continuous flashover of the superimposed pulse power supply. Meanwhile, it has a high reliability structure for an ideal basic DC high-voltage unit of pulse power supply. Additionally, the variable frequency power supply can also be used as the supporting power supply of ozone generator for low-temperature flue gas denitration. The power consumption of the ozone generator is less than 7.5kw/kgO_3 at high ozone concentration, and the index is better than the Chinese industry standard.

Key words：Variable frequency power supply（VFPS），Pulse power supply，Ozone generator，ESP，Denitration

1 Introduction

Electrostatic precipitator (ESP) is the leading technical equipment for low-cost and high-efficiency treatment of industrial dust[1,2].As the auxiliary equipment of the electrostatic precipitator, the performance of the high-voltage power supply directly affects the dust removal efficiency of the electrostatic precipitator.Existing cases show that under the same operating conditions, the transformation of high-voltage power supply can improve the dust removal efficiency[3]. For example, the transformation of single-phase power supply to three-phase power supply, the mass collection efficiency can be increased from about 80-85% to 90-95% for the inlet field of the ESP[4-6].Therefore, the research on improving efficiency and saving energy of high-voltage power supply has great social and economic benefits.

The variable frequency power supply has the significant advantages of low output ripple coefficient, high power factor and power efficiency. In the engineering application of transforming single-phase power frequency power supply, it can make use of the old transformer and power cable. It has attracted the attention of dust removal industry at home and abroad and invested in research and development, which promotes the development of this technology. Compared with single-phase and three-phase power supply, the frequency of the voltage output from the variable frequency power supply control cabinet to the primary side of the transformer is variable. By developing the frequency conversion control strategy, the working frequency and modulation degree of the power supply can be automatically adjusted according to the working conditions of the electric field, The output impedance tracks the dynamic change of the electric field operating condition in real time to achieve the best dynamic matching with the electric field impedance of ESP. It make the electric field of ESP obtain the highest corona power and the best power supply effect. Compared with the existing high-voltage power supply for ESP, it can realize a more novel intelligent power supply application.

Variable frequency power supply can be applied to flue gas treatment in the industries of coal-fired power, smelting, cement and paper-making[7]. Widely promoting the application of variable frequency power supply instead of single-phase commercial frequency power supply and three-phase power supply is undoubtedly a technical innovation in the field of high-voltage power supply for ESP, which can improve the dust removal efficiency of ESP[8], realize energy conservation and emission reduction. The variable frequency power supply can also be applied to the ozone generator in the low-temperature ozone denitration industry[9], which will have broad application prospects.

2 Working Principle of Variable Frequency Power Supply

2.1 **Working Principle of** *VTR01* **Variable Frequency Power Supply**

The main circuit principle of VTR01 variable frequency power supply is shown in Figure 1. Its input voltage is three-phase AC 380V, which is rectified by rectifier circuit V1 and filtered by filter circuit LC to obtain stable DC voltage. The DC voltage is inverted into AC voltage of 50 ~ 500Hz by H-bridge converter composed of IGBT[10]. Subsequently, the AC voltage is input into rectifier transformer T1 for step-up rectification and which output negative DC high voltage to supply the electric field of ESP. The rectifier transformer T1 can adopt either a intermediate-frequency transformer or the original power-frequency transformer.

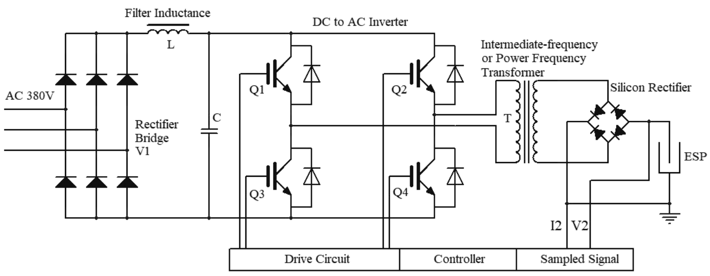

Fig.1. Principle block diagram of major loop of variable frequency power supply

Fig.2. Control cabinet and transformer of variable frequency power supply

Variable frequency power supply adopts synchronous single-phase third-order SPWM inverter[11]. The modulation wave is a sine wave and the carrier wave is a triangular wave. The starting point of the sinusoidal modulation wave takes the positive peak of the triangular wave, and the modulation output waveform is an odd function waveform which is symmetric at the origin. Carrier ratio N is selected as an even value between 6 and 20. The carrier frequency ranges from 300Hz to 10 kHz. The Fourier transform expression[12] of the third-order SPWM wave is shown in the following formula:

$$u = ME\sin\omega t + \frac{2E}{\pi}\sum_{m=1,2,\ldots}^{\infty}\;\sum_{n=\pm1,\pm3,\ldots}^{\pm\infty}\cos(m\pi)\frac{J_n(mM\pi)}{m}\sin[(mN+n)\omega t]$$

where

u is the SPWM output voltage,

ω is the modulation wave angle frequency,

E is the amplitude of the output rectangular square wave ,

M is the modulation degree,

N is the carrier ratio,

m is the multiples of the carrier triangular wave,

n is the harmonic multiple of the modulated wave,

J_n is the Bessel function.

The formula contains only sinusoidal terms and no constant components and cosine terms. This shows that the fundamental wave of the third-order SPWM output wave is a sinusoidal wave. The wave has an adjustable amplitude and an adjustable frequency. Using the third-order SPWM inverter can reduce the harmonics and improve the power supply efficiency[13].

Variable frequency power supply can realize frequency modulation and amplitude modulation through SPWM control strategy[14,15]. Schematic drawings of adjusting operating frequency and modulation degree are respectively shown in Figures 3 and 4 .

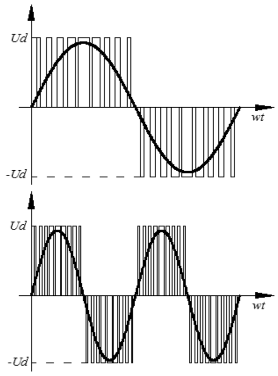

Fig.3. Schematic diagram of adjusting operating frequency of variable frequency power supply

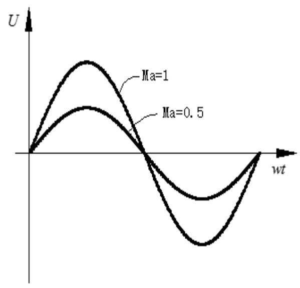

Fig.4. schematic of equivalent voltage waveform when the modulation degree is 1 and 0.5 respectively

2.2 Intelligent Control Strategy of Variable Frequency Power Supply

For the conventional high voltage power supply, the primary side of the transformer adopts a fixed input frequency, and the short circuit impedance voltage drop of the transformer is a fixed value. When high voltage is supplyed to ESP, the impedance of ESP changes in real time. Conventional high voltage power supply can not realize the real-time matching of the transformer’s impedance and the ESP’s impedance. The output of the transformer is prone to "high voltage, low current" or "low voltage, high current" which resulting in low dust removal efficiency of the ESP. When the ESP flashovers, the existing conventional power supply is cut off for tens or even hundreds of milliseconds to turn off the spark. Moreover, the existing conventional power supply mainly relies on intermittent supplying to inhibit the back corona phenomenon which is easy to appear when the

ESP works[16]. The amplitude and frequency modulation control and the real-time spark cut-off characteristics of variable frequency power supply can make up for the deficiencies of the conventional power supply.

According to the calculation formula of the transformer impedance voltage:

$$U_Z = 2\pi f L I$$

Where

f is the input frequency on the primary side of the transformer,

L is the leakage inductance of the transformer,

I is the actual operating current on the primary side of the transformer.

The impedance voltage of the transformer is directly proportional to the input frequency f and the actual operating current I. Changing the impedance of the transformer by changing f can change the current and voltage on the secondary side of the transformer.

Increasing f can increase the impedance of the transformer to adjust the output power of the transformer secondary side which can inhibit the flashover and realize the uninterrupted power supply of the electric field when the electric field of ESP flashovers. At the same time, it can reduce the impact of the flashover current on the high voltage power supply and on the collecting plate and the emitting wire of the ESP. When the back corona phenomenon occurs in the electric field of the ESP, in addition to intermittent power supply mode, increasing the impedance of the transformer by increasing f and reducing M can suppress the back corona phenomenon. It can also improve the dust removal efficiency and save electric energy.

It can be seen from the empirical formula of Deutsch formula[17] that the driving speed is directly proportional to the square of field intensity, and the field intensity is directly proportional to the voltage applied in electric field. Therefore, the higher the operating voltage of the electric field, the higher the dust removal efficiency of the ESP. Increasing the operation frequency can make the corona voltage waveform smooth, and the average voltage is increased to improve the dust removal efficiency.

2.3 VI Curves at Different Frequencies

Figure 5 shows the VI curves of the variable frequency power supply with the original power frequency transformer applied to the fourth electric field of ESP of sintering machine head under the same working condition, modulation degree and different working frequencies. Comparing these curves, then we can find that the VI curves of 100Hz, 150Hz and 200Hz basically coincide when the voltage is 57kV and the current is 375mA. After the further increase of the current, the current is only increased by about 100mA at 200Hz when the voltage increases to 61kV. It is significantly different from 100Hz.This provides a new commissioning idea for HV power supply. Increasing the operating frequency is conducive to increasing the operating voltage and reducing the secondary current. Due to its strong ability to suppress the back corona phenomenon, it is suitable for the dust working condition with high specific resistance. It is conducive to the application of energy conservation and emission reduction.

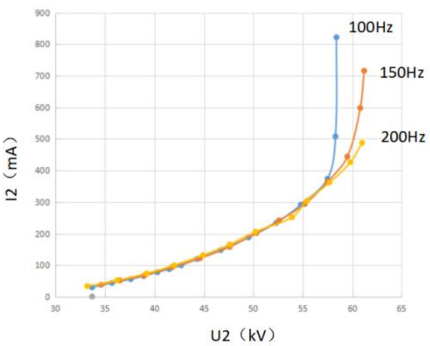

Fig.5. Comparison of VI curves at the operating frequencies of 100Hz, 150Hz and 200Hz

2.4 Application of Copper Smelting ESP

Comparison of the Operating Parameters between Variable Frequency Power Supply, High Frequency Power Supply and Commercial Frequency Power Supply

Different types of power supply were tested in East Zone 2 and West Zone 2 during the selection of electric dust removal power supply for flash furnace in copper smelting workshop of Guixi Smelter of Jiangxi Copper Group Co., Ltd.

Table 1 Comparison of operation parameters of different power supplies

	variable frequency power supply		high frequency power supply		commercial frequency power supply	
secondary data	voltage（KV）	current（mA）	voltage（KV）	current（mA）	voltage（KV）	current（mA）
East Zone 2	73.2	47	71.9	46	60	12
West Zone 2	63.9	63	67.5	34	62	14

From the table 1, we can see that the difference of the secondary voltage between the variable frequency power supply and the high frequency power supply is small under the same electric field condition of the flash furnace, The secondary current of variable frequency power supply is higher than that of the high frequency power supply. Both power supplies can well adapt to the flue gas condition of the flash furnace. Their secondary voltage and secondary current are significantly better than that of the commercial frequency power supply.

Analysing and Comparing the Composition of Waste Acid Primary Liquid in Sulfuric Acid System

In December 2019, 8 sets of variable frequency power supplies with specification of 0.4a/100kv were used for ESP of flash furnace. The operating voltage and current of the power supply of the first to fourth electric fields changed in steps after the repair and maintenance of the body of ESP. The maximum operating voltage of the first electric field is 102kv and the current is 18 ~ 40mA. The maximum operating voltage of the second electric field is 70kv and the current is 30 ~ 50mA. The maximum operating voltage of the third electric field is 65kv and the current is 60 ~ 80mA. The maximum operating voltage of the fourth electric field is 60kV and the current is 120 ~ 300mA.

The dust collection efficiency is significantly improved and then providing a better working condition for the later acid making process. The concentration of various elements (except Cl), acidity and amount of acid sludge in the waste acid primary liquid of sulfuric acid system 1 were decreased to varying degrees. The data sheet analysis before and after remodelling is shown in Table 2:

Table 2 Comparison of the data before and after the variable frequency power supply is put into operation

Time	Acid mud yield t/month	Waste acid quantity m^3/month	The waste acid primary liquid（mg/L）							
			Cu	As	Cd	Bi	Fe	F	Cl	H_2SO_4
Average value from January to October 2019	30.25	25835	77	2838	100	291	44	996	1736	82160
Average value from December 2019 to February 2020	19.37	19455	31	1724	36	150	20	708	1786	47306
percentage reduction	35.9	24.6	59.7	39.2	64	48.4	54.5	28.9	-2.8	42.4

3 Basic Power Supply of Pulse Power Supply

3.1 Introduction of Variable Frequency Power Supply which Pulse Power Supply is Superimposed on

The circuit topology of variable frequency power supply which pulse power supply is superimposed on is shown in Figure 6. The variable frequency power supply has the control characteristics of both frequency modulation and amplitude modulation, which makes its output voltage ripple coefficient small. As a basic power supply of pulse power supply, its performance is better than that of high frequency power supply. High frequency power supply has similar ripple coefficient only when the output parameters are close to the rated current and rated voltage.

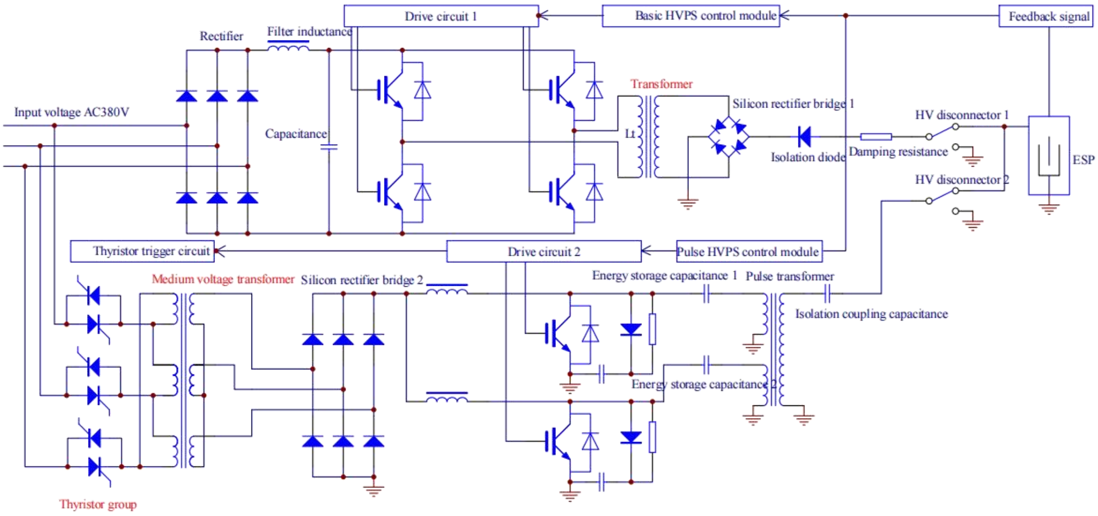

Fig.6. Circuit topology of variable frequency power supply which pulse power supply is superimposed on

The variable frequency power supply adopts a full bridge inverter composed of IGBT, which adopts hard switch working mode. Then it can turn off the spark in real time. Its ARC extinguishing time is shorter than that of commercial frequency power supply (10ms), three-phase power supply (20ms) and high-frequency power supply (50uS). It can avoid the continuous flashover of pulse power supply and effectively reduce the rise of energy storage capacitor level caused by flashover feedback energy. The flashover control characteristics meet the operation requirements of pulse power supply. The variable frequency power supply adopts the structure of separation of transformer and control cabinet, and its stability is better than that of outdoor power supply. It is an ideal basic power supply of pulse power supply at this stage.

3.2 Application Introduction of Sanbao Iron and Steel Plant in Fujian, China

Variable frequency power supply and pulse power supply are applied to ESP of 320m^2 sintering machine head in Fujian Sanbao Iron and Steel Plant, China. The ESP adopts the structure of double row, double chamber and four electric field. The flue gas volume is 2 × 960000m^3/h when the operating temperature is 130 ℃. The Specific Collection Area (SCA) is 93.06m^2/m^3/s. Under the condition of rated inventory, the operating parameters of power supply are shown in Table 3.

Table 3 The operating parameters of Sanbao Iron and Steel Plant

T/R	Uc/Vdc	IL/Aac	U2/kVdc	I2/mAdc	U2p/kVdc
A1HV1	509	51	72.1	508	/
A1HV2	506	88	62.3	838	/
A1HV3	507	79	60.9	910	/
A1HV4（PULSE）	508	86	60.7	953	74.2
A2HV1	515	52	71.2	486	/

A2HV2	519	81	61.3	834	/
A2HV3	525	108	70.7	906	/
A2HV4（PULSE）	512	87	60.8	913	74.6
B1HV1	514	75	67.8	703	/
B1HV2	517	87	60.4	841	/
B1HV3	520	90	56.9	915	/
B1HV4（PULSE）	513	61	50.4	973	66.8
B2HV1	512	74	65.3	703	/
B2HV2	525	70	61.2	838	/
B2HV3	498	89	58.9	907	/
B2HV4（PULSE）	513	89	55.6	980	70.7

According to the running parameters of the table 3, the average value of the variable frequency power supply's secondary voltage in the first to the third electric fields can reach more than 56kV under the working condition of ESP at sintering machine head part. The fourth electric fields adopt variable frequency power supply that is supeFrimposed pulse power supply on, and the secondary peak voltage is increased by about 15kV. It can efficiently capture fine dust and high specific resistance dust in the electric field, so that the discharge value at the outlet of the dust collector is stable below 20mg/Nm^3.

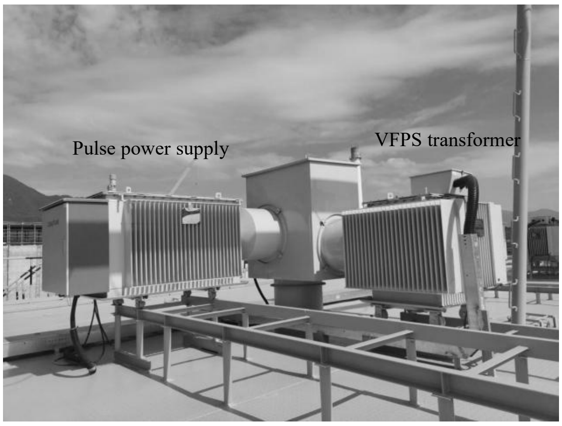

Fig.7. Site picture of Sanbao Iron and Steel Plant

4 Application of Variable Frequency Power Supply to Ozone Generator in Flue Gas Denitration

4.1 Introduction to Electrical Characteristics of Ozone Generator

In recent years, as a new NOx control technology, ozone oxidation denitration has the advantages of high efficiency, small floor area and low reaction temperature. It has been widely concerned and applied in the waste gas treatment industry, especially in the field of industrial boilers, iron and steel plants[18-20]. It has gradually become the research hotspots of flue gas denitration technology. Its core technology is ozone power supply technology and ozone generator technology.

The equivalent circuit of variable frequency power supply applied to ozone generator is shown in figure 8. Ozone generator is equivalent to a lossy capacitor composed of discharge electrode, dielectric material and discharge gap. It can be equivalent to a circuit composed of dielectric equivalent capacitance C_d, air gap equivalent capacitance C_g and discharge sustaining voltage V_z. The electrical characteristics of the load of ozone generator are analyzed as follows:

According to Manley power formula[21]:

$$P = 4C_d S U_s f[U_0 - (\frac{C_d + C_g}{C_d})U_s]$$

Where

U_s is the discharge sustaining voltage,

U_o is the peak value of the applied voltage,

f is the frequent of the power supply,

S is the electro-discharge area(cm^2),

C_d is the Electrostatic capacity per unit area of dielectric(F/cm^2),

C_g is the Electrostatic capacity per unit area of air gap(F/cm^2).

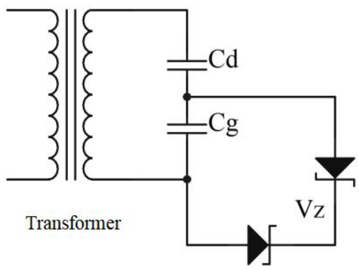

Fig.8. The equivalent circuit of variable frequency power supply applied to ozone generator

It can be seen from the above formula that the discharge power P is directly proportional to the frequent of the power supply f and the starting voltage of air gap discharge. Under the action of high voltage, cold plasma discharge occurs in the discharge gap of ozone generator and ozone is generated. The actual operation waveform of ozone power supply is shown in Figure 9. The operating parameters are as follows: f is 800Hz, the RMS value of the secondary voltage is 8000V, the peak value of the secondary voltage is 11000V, the RMS value of the secondary current is 4.8A, and the peak value of the secondary current is about 9A.

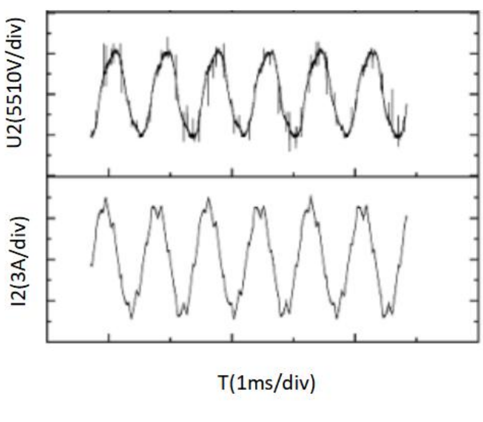

Fig. 9. Waveform of the secondary voltage and the secondary current during operation of ozone power supply

At present, the commercial large-scale ozone generators adopt mainly medium and high frequency power supplies whose IGBT inverter are based on PWM control strategy. The PWM circuit is relatively simple with only one power control stage which can adjust the output voltage and output frequency. The PWM circuit can use uncontrollable rectifier bridge to make the power factor of the system to be independent of the output voltage of the inverter. PWM can adjust frequency and voltage at the same time, which is independent of the component parameters of the intermediate DC link, and the dynamic response speed of the system is fast. However, the inverter outputs square voltage which contains not only sinusoidal fundamental wave, but also rich high-order harmonics, such as 3rd, 5th, 7th, etc. The existence of high-order harmonics (such as single waveform time) can promote the generation of more discharge filaments. However, its adverse impact is more prominent which will have an adverse impact on the power grid and the stability of equipment from the perspective of long-term operation. SPWM control is changing the modulation pulse mode based on PWM. The pulse width is arranged according to the sinusoidal law, so that the output waveform of inverter can be output in the form of sine wave after appropriate filtering. The advantage of SPWM control is that it can suppress or even eliminate harmonics, and control frequency and voltage at the same time. Its output waveform has good quality, stable performance, reliable operation, strong real-time performance and online adjustment. Using SPWM control technology to adjust the output waveform can greatly eliminate parts of harmonics,make the load operate under the alternating voltage similar to sine wave, and improve the power efficiency.

4.2 Test

Test Scheme

The rated power of ozone power supply based on SPWM control strategy is 160kW, the maximum RMS value of output secondary voltage is 10kV, the operating frequency is greater than or equal to 800Hz, the RMS value of operating secondary current is 60A, and the supporting load is an ozone generator with rated ozone output of 20kg / h.

Data of Test

The test uses oxygen as the air source, and the standard odor oxygen flow at the gas outlet is about 140 Nm^3/h. The test data are shown in table 4.

According to the test data, when the standard odor oxygen flow at the gas outlet is about 140 Nm^3/h, power factor of the ozone power supply is greater than or equal to 0.95 and the ozone concentration is $150.2g/Nm^3$, the ozone ouput and power consumptiion of ozone power supply are respectively 21.03 kg/h and 7.45 kWh/kgO_3. Compared with the energy consumption index of 10kWh/kgO_3 in GB/T 37894-2019 "*Technical Requirements for Ozone Generators for Water Treatment*", it saves 25.5% energy.

Fig.10. Variable frequency power supply applied to ozone generator

Table 4 The test data of ozone power supply

test item			technical requirement	test result
Rated technical indexes and performance parameters	Rated ozone concentration is 150g / Nm3 (actual ozone concentration is 150.2g / Nm3)	Supply voltage	3φ380 ±10％ 50Hz	U_{AB}=403V
				U_{AC} = 404V
				U_{BC} = 405V
		Gas temperature	Intake temperature	22.5℃
			Outlet temperature	25.7℃
		Cooling water volume	Internal circulating cooling water	44m^3/h
		Cooling water temperature	Inlet water temperature	22.6℃
			Outlet water temperature	25.3℃
		Inlet pressure of generator chamber	Working pressure≤0.1MPa	0.095MPa
		Ozone output		**21.03kg/h**
		Input power of power supply		156.8kW
		Power consumption of ozone power supply		**7.45kWh/kgO$_3$**
		Power factor		⩾0.95

5 Conclusion

The technology of variable frequency power supply has been mature, and the performance parameters can well meet various dust removal applications. Its excellent adaptability of dust removal working conditions has been fully verified and quickly recognized by the market. In the technical selection of many transformation projects or new projects, variable frequency power supply has become the mainstream technical option. The transformation scheme of variable frequency power supply superimposed with pulse power supply in the rear electric field can fully tap the potential of the existing ESP and realize the ultra-low emission of ESP. At the same time, the transformation period is short, so as to save the transformation cost. The variable frequency power supply can also be used as a supporting power supply for efficient ozone generator with excellent indicators, which is suitable for wide-ranging popularization and application.

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