# Intelligent High-Frequency Pulse Control for Ultra-Low Emission Electrostatic Precipitation

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**Abstract.** With the upgrading of environmental protection standards, traditional electrostatic precipitator technology faces bottlenecks such as high energy consumption and low fine particle capture efficiency due to insufficient high-frequency voltage regulation and limited pulse voltage application. In response to challenges such as unclear application scenarios of high-frequency voltage and pulse voltage, insufficient response of multivariable collaborative control, and weak generalization ability of intelligent algorithms, studies have shown that high-frequency voltage technology combined with resonant soft switching can reduce energy consumption by 90%, reduce smoke emissions by 70%, increase PM2.5 capture efficiency by 20%~35%, and increase corona threshold voltage by 40%~60%. The intelligent control solution reduces comprehensive energy consumption by more than 40%, and the PM2.5 emission concentration is stabilized below 5mg/m³. This study innovatively integrates high-frequency voltage dynamic regulation and pulse voltage transient enhancement technology, combined with AI algorithm optimization, to provide an efficient and energy-saving technical path for ultra-low industrial flue gas emissions. It has both theoretical value and practical engineering significance, and helps the green transformation under the "dual carbon" goal.

**Keywords:** Smoke precipitator, optimize, High frequency pulse power supply.

## 1. Introduction

As market demand grows, industrial dust emissions are huge (about 120 million tons in 2023), and electrostatic precipitators occupy 70% of the industrial dust removal market. In addition, the capacity optimization and green transformation of traditional high-pollution industries (such as steel and electricity) have promoted the demand for high-efficiency dust removal equipment. At the same time, the increasing demand for refined dust removal in emerging industries (such as new energy and electronic manufacturing) has prompted electrostatic precipitators to develop in the direction of high efficiency and intelligence. However, in the context of upgraded environmental protection standards, traditional industrial frequency power supplies have problems such as high energy consumption and low fine particle capture efficiency. High-frequency, high-voltage DC and pulse power supply technology, with the advantages of dynamic electric field regulation, has become a key direction for breaking through technical bottlenecks.

The high-frequency power supply adopts high-frequency inverter and resonant soft switching technology to convert industrial frequency AC power into ultra-high voltage DC, achieving a 90% reduction in energy consumption and a 70% reduction in smoke emissions. It has the characteristics of intelligent control and compact equipment. Pulse technology superimposes nanosecond high-voltage pulses on the DC base voltage, making the field strength instantly exceed 100kV/m, and the space charge density is increased by a thousand times, which can suppress back corona and increase the PM2.5 capture efficiency by 20%-35%. The two types of technologies complement each other. High-frequency power supplies focus on stability and economy, pulse technology specializes in fine dust control, and intelligent control technology achieves dynamic matching of working conditions through PLC closed-loop regulation and AI optimization to improve adaptability.

There are three major limitations in current research. First, there is a lack of systematic definition of the applicable scenarios of high-frequency and pulse power supplies, and the coordination mechanism is unclear. Second, the control strategy mostly uses single parameter feedback, and the response to multi-variable coupling such as dust concentration and coal quality fluctuations is insufficient. Finally, AI algorithm engineering has problems such as poor model generalization ability, insufficient real-time performance, and lack of long-term verification, which restricts technology upgrades.

This study constructed a comprehensive evaluation system for high-frequency and pulse power supplies, proposed a "base pressure-pulse" dynamic coupling strategy, and developed a deep reinforcement learning multi-objective optimization framework. By integrating multi-source information such as flue gas parameters and equipment status, the power supply mode and parameters can be autonomously decided. The study adopts a method combining theoretical analysis, simulation and industrial experiments. First, the circuit characteristics and dust removal mechanisms of the two types of power supplies are compared to quantify their energy efficiency differences; secondly, a hybrid power supply architecture is designed to integrate the advantages of pulse transient enhancement and DC steady-state maintenance, and an LSTM operating condition prediction model is established; finally, an intelligent management platform is built, an optimization algorithm is embedded, and an empirical study is carried out on a 300MW coal-fired unit. The results show that the new scheme stabilizes the PM2.5 emission concentration below 5mg/m³ and reduces the comprehensive energy consumption by more than 40%, which verifies the effectiveness of the integrated power supply and control scheme and provides technical support for ultra-low emissions of industrial flue gas. This paper compares the application of high-voltage DC power supply and pulse power supply technology in electrostatic precipitators, and various methods for optimizing electrostatic precipitator parameters. As the core means of industrial flue gas purification, electrostatic precipitator technology achieves gas-solid separation through a high-voltage electric field.

## 2. Comparison of high voltage DC power supply and pulse power supply technology in electrostatic precipitator

### 2.1. Introduction to high frequency and high voltage DC power supply

A high-voltage DC power supply is an electric energy conversion device that can convert conventional AC power (50/60Hz) into DC high voltage ranging from thousands to hundreds of thousands of volts. The device has a wide power output capacity (hundreds of watts to hundreds of kilowatts), and its output voltage characteristics are particularly outstanding, up to 100,000 volts, and some special models can even achieve ultra-high DC voltage output of millions of volts. And it is a variable power supply, which has nothing to do with the frequency of the line, and can meet the requirements of the electrostatic precipitator to the greatest extent (that is, high voltage and high power can ensure the best ignition rate of the electrostatic precipitator). High-frequency power supply can realize DC power supply to the greatest extent, increase the amplitude several times, and has high efficiency, so it meets the actual use needs [1].

The three-phase industrial frequency AC power supply is converted into DC power through a three-phase full-bridge rectifier circuit. The rectifier link is controlled by IGBT devices, and the power factor can be stably maintained above 0.98. The IGBT inverter module using a full-bridge topology converts DC power into a 20kHz high-frequency square wave, and significantly reduces switching losses through resonant soft switching technology. The high-frequency energy is converted into voltage through a special nanocrystalline core step-up transformer, and the ultra-high frequency high-voltage pulse output by the secondary side is full-wave rectified by a fast recovery diode silicon stack, and finally outputs a 120kV/200mA DC negative high voltage, providing a stable and precisely controllable high-voltage power supply for the electric field of the electrostatic dust removal system. The entire system achieves closed-loop regulation through a DSP digital controller to ensure that the optimal corona power is maintained under different working conditions. The following is the topology diagram of the industrial frequency boost method. Figure 1 shows the power frequency boost method diagram.

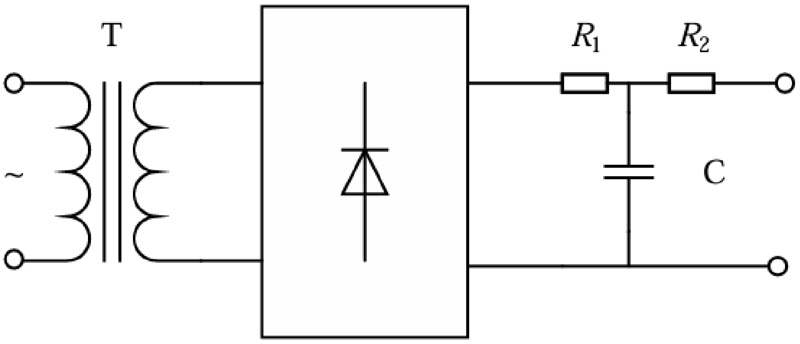

**Figure 1.** Industrial frequency boost method diagram

The three-phase industrial frequency AC power supply is converted into DC power through a three-phase full-bridge rectifier circuit. The rectifier link is controlled by IGBT devices, and the power factor can be stably maintained above 0.98. The IGBT inverter module using a full-bridge topology converts DC power into a 20kHz high-frequency square wave, and significantly reduces switching losses through resonant soft switching technology. The high-frequency energy is converted into voltage through a special nanocrystalline core step-up transformer, and the ultra-high frequency high-voltage pulse output by the secondary side is full-wave rectified by a fast recovery diode silicon stack, and finally outputs a 120kV/200mA DC negative high voltage, providing a stable and precisely controllable high-voltage power supply for the electric field of the electrostatic dust removal system. The entire system achieves closed-loop regulation through a DSP digital controller to ensure that the optimal corona power is maintained under different working conditions. The following is a schematic diagram of the high-frequency switching power supply. Figure 2 shows high frequency switching power supply schematic diagram.

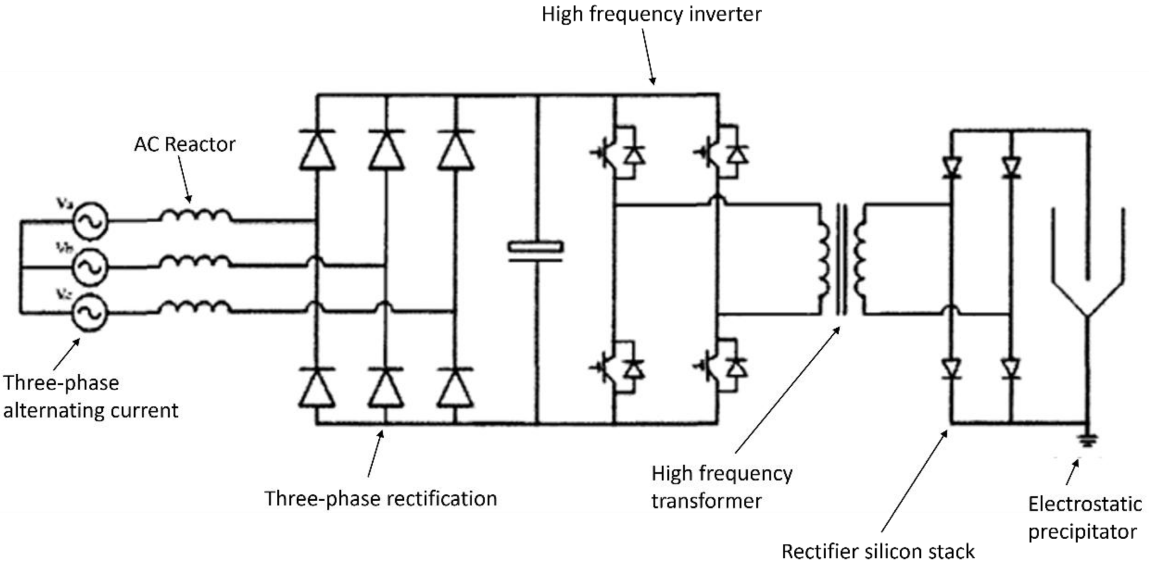

**Figure 2.** High frequency switching power supply schematic diagram

## 2.2. Analysis of the characteristics of high frequency and high voltage DC power supply

The inverter bridge circuit can convert the DC voltage into an alternating square wave with adjustable frequency, which is convenient for microprocessor control. The inverter bridge can be controlled by PWM, PS-PWM, PDM and other control methods alone or in combination. Since the system runs at a high frequency, the dynamic response speed is fast, and the ripple size of the output voltage can be strictly controlled to increase the output electric field strength. In addition, combined with flexible control methods, the high-frequency power supply for electrostatic precipitator can generate a specific high-voltage output waveform according to different working conditions of real-time operation [2].

In addition, the high-frequency, high-voltage DC power supply uses fully controlled power devices with a switching time of several hundred nanoseconds, which greatly improves the response rate of the system. It can respond quickly to flashover discharge, short circuit and other conditions, cut off the power supply, and prevent further arcing discharge from damaging the power supply [2].

The waveform is a high-frequency wave. When an arc short circuit occurs in the electric field and the power supply needs to be stopped for a short time, since IGBT is a fully controlled component, the power supply can be stopped in time, the short circuit duration is short, and the dust removal efficiency is improved [3]. In view of the advantages of high-frequency DC switching power supply with stable output voltage and small ripple, it can play a good dust removal effect in the electrostatic dust removal process and greatly improve the efficiency of electrostatic dust removal. With the above excellent performance, the power supply system that uses high-frequency switching power supply to power electrostatic dust removal equipment has now developed into a popular research and development direction in the field of dust removal at home and abroad. Compared with the industrial frequency power supply, the high-frequency power supply has the following advantages in addition to the high initial investment cost: under the same operating conditions, the smoke emission can be reduced by up to 70%, while maintaining the original dust removal efficiency. The energy saving rate can reach 90%; its intelligent control system integrates multiple operating modes and can adapt to various complex working conditions. The whole machine adopts a compact integrated structure design, and the highly integrated characteristics greatly simplify the installation process and reduce the demand for auxiliary equipment by more than 50%. As for smoke with high resistivity, the power supply technology can be intermittent, which is very similar to pulse power supply. Since the pulse width and pulse frequency can be changed according to the actual situation, the duty cycle can also be adjusted, so back corona will not occur and the dust removal effect can be optimized [4].The three-phase balanced power supply system not only effectively eliminates grid pollution and phase loss, but also achieves zero interference with the grid, meets green power standards, and perfectly balances industrial application needs and sustainable development concepts.

### 2.3. Pulse power supply

The structure of an electrostatic precipitator pulse power supply combines high-voltage DC output with coupled high-voltage pulses. Depending on different configurations of the basic DC unit and varying forms of high-voltage pulse generation in the pulse unit, six distinct structural configurations of electrostatic precipitator pulse power supplies can be formed through different combinations [5]. Based on this composite voltage output characteristic, the power supply is typically defined in technical literature as a "DC-based voltage coupled pulse power supply". The system achieves nanosecond-level pulse leading-edge control through high-precision IGBT modules, and employs magnetically isolated drive technology to maintain ±2% voltage accuracy even under 1200V DC bias, making it particularly suitable for industrial electrostatic applications requiring dynamic electric field adjustment. Below is the schematic diagram of the DC superimposed pulse power supply. Figure 3 is a schematic diagram of a DC superimposed pulse power supply.

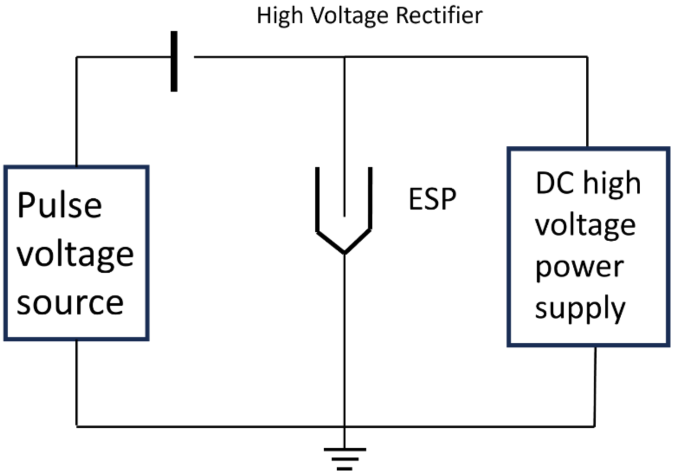

**Figure 3.** DC superimposed pulse power supply diagram

The pulsed power supply utilizes high-voltage narrow pulses to induce a penetrating corona discharge between the plates of the dust removal equipment within a short duration, enabling dust particles to acquire sufficient charges. Additionally, the DC voltage component of the DC-pulse superimposed power supply (hereinafter referred to as the base DC voltage) operates at a lower level compared to traditional DC power supplies, thereby reducing the frequency of back corona phenomena. Consequently, for high-resistivity dust, the DC-pulse superimposed power supply is expected to achieve higher dust removal efficiency while maintaining a lower average output voltage. This configuration decreases the probability of spark flashover, conserves electrical energy, and may ultimately enhance electrical energy utilization efficiency.

### 2.4. Analysis of the Characteristics of Pulsed Power Supplies

In the field of electrostatic dust removal, the improvement coefficient of migration velocity is commonly used to characterize the enhancement of dust removal efficiency achieved by adopting new power supply methods (e.g., pulsed power supply) compared to conventional DC power supply. This improvement factor is defined as the ratio of the migration velocity under the new power supply mode to that under conventional DC power supply. Table 1 gives the relevant parameters of the pulse power supply.

**Table 1.** Pulse power supply parameter table

| Item | Value |
|---|---|
| Input Voltage (VAC) | 3-phase 380 |
| Base Voltage (kV) | 40 ~ 60 |
| Pulse Voltage (kV) | 80 ~ 100 |
| Pulse Peak Current (A) | 300 |
| Pulse Average Power (kW) | 15 |
| Pulse Peak Power (MW) | 20 |
| Maximum Repetition Frequency (Hz) | 200 |
| Pulse Width (μs) | < 100 |

Since the formation of a flashover in the electric field requires a certain amount of time, the pulsed power supply voltage applies rapidly rising pulses (on the microsecond scale) to the electrodes within an extremely short duration. This increases the electric field's breakdown voltage, enhances the migration velocity of dust particles, and thereby improves the dust removal efficiency of the electrostatic precipitator [6]. High-voltage pulsed power supplies demonstrate significant technical advantages in the field of electrostatic precipitation. Their high-voltage, low-duty-cycle characteristics (low average voltage and high peak voltage) effectively enhance the charging efficiency of submicron particles and high-resistivity dust through the synergistic enhancement effect of field-induced charging and diffusion charging. The migration velocity enhancement factor can reach magnitudes on the order of 1.5–3.0.A key feature of high-voltage pulsed power supplies is their high instantaneous voltage amplitude combined with a low average value.

This ensures that the energy released instantaneously does not disrupt the existing spark stability within a short timeframe, while substantially improving the charging rate of difficult-to-charge particles such as high-resistivity dust. By ingeniously avoiding conditions that trigger spark flashover, these systems achieve breakthroughs in dust removal efficiency, meeting or even exceeding stringent requirements.

Furthermore, leveraging the low-frequency spark characteristics of pulsed power supplies, advanced control technologies and algorithms—such as artificial intelligence and big data analytics—can be integrated to realize novel advancements in dust removal power systems [7].

### 2.5. Efficiency Analysis of Different Power Supply Methods

The cyclone pulse electrostatic precipitator demonstrates 0.1-1 percentage points higher dust removal efficiency compared to conventional cyclone electrostatic precipitators, with outlet dust concentration reduced by 3-30 mg/Nm³, effectively lowering emission levels. This pulse-enhanced system significantly improves the collection efficiency of fine particulates, particularly showing a marked advantage in capturing dust particles smaller than 2μm (micrometers) when compared to standard cyclone electrostatic precipitators. For instance, at an inlet gas velocity of 6.97 m/s, the grade efficiency under pulse power supply demonstrates a 22.6% improvement over DC power supply operation [8].

The power supply mode significantly impacts the dust removal efficiency of electrocyclone dust collectors. Pulse power supply demonstrates a 0.1%-1% improvement in dust removal efficiency compared to DC power supply, with outlet dust concentration reduced by 7%-27%. This pulsed operation significantly enhances the collection efficiency of fine particulate matter, particularly demonstrating a notable 20%+ advantage in capturing sub-micron particles below 1μm compared to DC operation [9].

High-frequency high-voltage DC power supplies and pulsed power supply technologies each exhibit distinct advantages in electrostatic precipitation, with differing applicable scenarios. High-frequency DC power supplies utilize high-frequency inversion and resonant soft-switching technology, significantly reducing switching losses while delivering stable output with minimal ripple. Under normal operating conditions, they achieve 90% lower energy consumption and 70% reduced particulate emissions. Additionally, they feature intelligent regulation, compact design, and grid-friendly operation, making them ideal for long-term, stable dust removal requirements.

In contrast, pulsed power supply technology superimposes high-voltage narrow pulses onto a DC base voltage, instantaneously increasing electric field strength and space charge density. This effectively enhances the charging efficiency of submicron and high-resistivity dust particles, boosting migration velocity by 1.5–3 times and PM2.5 capture efficiency by 20%–35%. Simultaneously, it reduces the probability of back corona and flashover, further lowering energy consumption by 30%–50%. Its transient high-voltage characteristics are particularly suited for complex operating conditions and fine particulate control.

Overall, high-frequency DC power supplies excel in stability and cost-effectiveness, while pulsed power supplies demonstrate greater innovative potential in dust removal efficiency and adaptability. The two technologies can be complementarily deployed based on specific dust properties and emission standards, jointly driving the advancement of electrostatic precipitation toward higher efficiency, energy conservation, and precision.

## 3. Optimizing Operational Parameters of Electrostatic Precipitators Using AI, Machine Learning, and Other Artificial Intelligence Methods

Typically, intelligent control strategies are divided into three parts: first, real-time adjustment of electrostatic precipitator and induced draft fan operation modes based on dust concentration in flue gas, boiler soot blower engagement, coal quality characteristics, and required flue gas treatment volume to reduce power consumption; second, monitoring ash conveying volume and dust concentration to adjust cleaning frequency for lowering ash removal power; finally, adjusting voltage and current according to different power levels to reduce corona power.

The specific implementation method involves the automatic management and control of the operation of electrostatic precipitator equipment such as high and low voltage systems. Through operating condition characteristic analysis and feedback control, the system automatically selects the duty cycle of intermittent high-voltage power supply and operational parameters, ensuring the equipment consistently operates in an optimal state of minimum power consumption and highest efficiency [10]. Furthermore, we can integrate ambient climate and temperature data to intelligently regulate heating for insulation boxes and ash hoppers: reducing heat input when temperatures are high and increasing it when temperatures drop. Additionally, intelligent material level management can be implemented through precise monitoring and control of ash levels in hoppers, ensuring stable and continuous dust removal operations.

The specific method is as follows:,First, when the material level is too high, increase the conveying frequency of the ash removal equipment to reduce the material level. Then, by analyzing historical data and integrating system conveying volume calculations, the automated system can predict the trend of ash accumulation in the hopper and adjust the conveying frequency of the ash removal equipment promptly. Finally, it issues alerts when necessary to allow operators to take corresponding measures [11]. Furthermore, the dust collector can stabilize the secondary current intensity below 600 mA and employs an external UPS power supply to enhance the secondary voltage level of the electrostatic precipitator. This effectively reduces the mismatch between the secondary current and voltage, thereby suppressing corona suppression phenomena. Such measures will significantly improve the operating environment of the electrostatic precipitator system, leading to notable enhancements in flue gas purification rate and dust removal efficiency [12].

We can integrate a smart energy management system consisting of reactive power analysis, higher-order harmonic compensation analysis, compensation strategies for reactive power and harmonics, and an electrostatic precipitator optimized operation control module (ESP-ATC system). By analyzing historical data, the system automatically adjusts electrostatic field operating parameters through advanced control algorithms, achieving real-time response to load variations and dust concentration fluctuations, ensuring optimal operation of the electrostatic precipitator under diverse working conditions [13].

We can implement a turbidity closed-loop optimization control strategy that stepwise adjusts operating modes and parameters based on turbidity levels, combined with a load optimization control module. This system establishes preset control mode and parameter configuration menus for rectifier transformers across different load ranges, automatically executing corresponding preset settings according to real-time load signals. The control modes and parameter settings allow parameter modifications or operational mode adjustments through menu interfaces under administrator privileges. According to the conclusions in the retrofitted system achieves energy-saving effects exceeding 50%, demonstrating that the electrical control system modification of the electrostatic precipitator (ESP) significantly enhances energy efficiency [14].

The Artificial Bee Colony (ABC) algorithm can be implemented, which simulates the natural division of labor and coordinated operations in biological bee colonies. While individual bees exhibit simple behavioral patterns, the entire swarm efficiently accomplishes complex tasks through optimized scheduling of each member, demonstrating emergent intelligence through decentralized coordination mechanisms [15]. A Programmable Logic Controller (PLC) is an industrial controller centered around a microprocessor, designed for performing digital operations. It utilizes a programmable memory to internally store instructions for executing operations such as logical operations, sequential control, timing, counting, and arithmetic calculations. Through digital or analog inputs and outputs, it controls various types of machinery and production processes [16]. Figure 4 shows the PLC workflow.

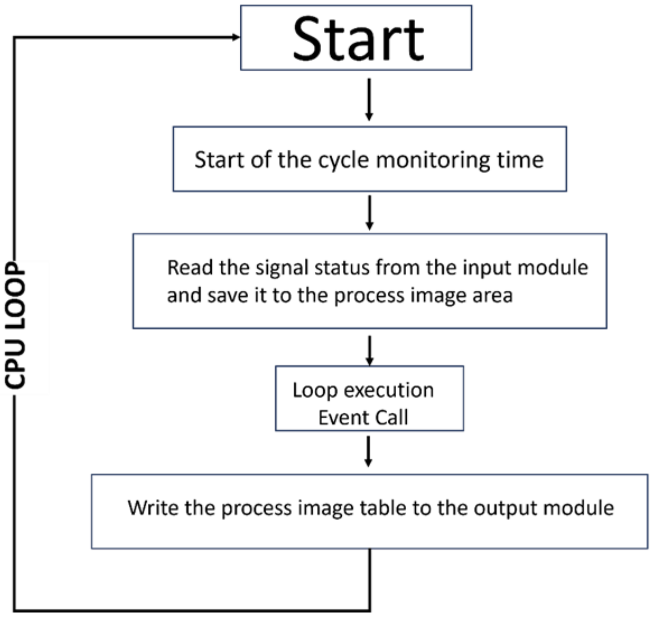

**Figure 4.** PLC workflow diagram

The energy-saving optimization control system calculation process is as follows: First, data acquisition collects real-time unit load and dust concentration, sets the target dust concentration, then calculates the input deviation of the PID controller, followed by computing the secondary current command, and finally adjusts the secondary current command sent to the ESP high-frequency power supply to regulate its output. During ESP operation, operators can exit the energy-saving optimization control system via the host computer interface at any time and switch to manual mode, with this transition being highly flexible. Integrated with PLC, the system significantly reduces staff workload and achieves an average power saving rate of 15.36% within the 500-1000 MW unit load range compared to pre-optimization operation [16].

## 4. Conclusion

This study systematically investigates the synergistic optimization mechanisms and intelligent control strategies of high-frequency high-voltage DC power supplies and pulse power supplies in electrostatic precipitation through theoretical analysis and industrial trials. The core findings reveal significant technological advancements: an intelligent control innovation featuring a dynamically coupled "base voltage-pulse" strategy has been developed alongside a deep reinforcement learning optimization framework. By integrating multi-source operational data, this framework achieves autonomous decision-making for power parameters, resulting in over 40% reduction in comprehensive energy consumption while maintaining PM2.5 emissions consistently below 5mg/m³.

Moreover, the research demonstrates complementary application values: high-frequency power supplies exhibit distinct advantages in operational stability and economic performance, whereas pulse power supplies show enhanced adaptability for fine particulate matter treatment. The coordinated application of both technologies effectively promotes high-efficiency and precision optimization in electrostatic precipitation systems.

Theoretically, the study establishes a comprehensive evaluation system for hybrid power supplies and proposes a dynamic operating condition prediction model (LSTM) integrated with a multi-objective optimization framework, thereby laying a solid theoretical foundation for coordinated power control. Practically, the developed intelligent management platform has been successfully validated on a 300MW coal-fired unit, providing robust technical support for achieving ultra-low industrial emissions and carbon reduction targets.

Nevertheless, current limitations persist, including undefined application boundaries for power supply configurations, inadequate real-time responsiveness to multivariable coupling effects, and unverified generalization capabilities of AI algorithms. Future research directions should focus on extending hybrid power applications to non-coal industrial sectors, developing real-time multivariable control strategies, and enhancing edge computing algorithms to improve engineering practicality.

Notable technical breakthroughs include high-frequency power supplies employing resonant soft-switching technology that reduces energy consumption by 90% and dust emissions by 70%, alongside pulse power supplies utilizing nanosecond-level high-voltage pulses to achieve instantaneous field strengths exceeding 100kV/m. These innovations boost PM2.5 capture efficiency by 20%-35% and elevate anti-corona threshold voltages by 40%-60%.

Through systematic technology integration and intelligent optimization, this study pioneers' new pathways for energy efficiency enhancement and precision management in electrostatic precipitation. Looking ahead, efforts will concentrate on improving technological universality to accelerate industrial green transformation and facilitate the realization of dual-carbon objectives. The proposed "base voltage-pulse" dynamic coupling strategy integrates a deep reinforcement learning optimization framework that synthesizes multi-source operational data, enabling autonomous decision-making for power parameters. This approach achieves over 40% reduction in comprehensive energy consumption while maintaining PM2.5 emissions consistently below 5mg/m$^3$.

Furthermore, high-frequency power supplies demonstrate significant advantages in stability and cost-effectiveness, while pulse power supplies exhibit superior adaptability for fine particulate treatment. Their complementary application enhances both efficiency and precision in electrostatic precipitation technology.

Theoretical advancements include establishing a comprehensive evaluation system for high-frequency and pulse power supplies, along with a dynamic operating condition prediction model (LSTM) and multi-objective optimization framework, which collectively form the theoretical foundation for coordinated power control. Practically, the developed intelligent management platform has been validated on a 300MW coal-fired unit, providing technical support for ultra-low industrial emissions and carbon reduction.

However, current limitations persist, including undefined application scenarios for power supplies, insufficient real-time response to multivariable coupling effects, and unvalidated generalization capabilities of AI algorithms. Future efforts should expand hybrid power applications to non-coal industries, develop real-time multivariable control strategies, and enhance engineering effectiveness through edge computing-optimized algorithms.

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