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# Analysis on Frequency Conversion Energy Saving of Fan-Water Coordinated Control in Metro Station Environmental Control Systems

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***Abstract***
*In response to the characteristics of prolonged part-load operation and high energy consumption in metro station environmental control systems (ECS), this study systematically examines the energy-saving mechanisms of frequency conversion regulation in both fan and water systems, while briefly discussing the operational logic of coordinated fan‑water control systems. Through a case study of a typical metro station located in a hot-summer cold-winter climate zone, a comparative analysis is conducted on the energy-saving performance of fan frequency conversion, pump frequency conversion, and fan‑water coordination. The findings reveal that independent frequency conversion retrofits for fan and water systems can achieve daily average energy saving rates exceeding 40%, whereas the coordinated fan‑water control system can attain a maximum energy saving rate of up to 66%. This research provides valuable insights for the energy-saving optimization of metro station ECS*

***Keywords:*** *Metro Station, Fan-Water Coordination, Environmental Control System, Frequency Conversion Technology*

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## I. INTRODUCTION

With the proposal of the carbon peak and carbon neutrality strategy, the total energy consumption of China's rapidly developing rail transit industry has become a key concern. Among this, the energy consumption of ventilation and air conditioning (VAC) systems in underground rail transit stations accounts for about 40% of the total station electricity consumption [1]. Since metro station air conditioning systems are typically designed and selected based on the long-term maximum passenger flow and the most severe operating conditions, the equipment capacity is often much higher than the actual operational demand, creating a phenomenon of "using a large horse to pull a small cart." Furthermore, influenced by factors such as passenger flow and outdoor temperature fluctuations, the system load rate during the cooling season operates below 50% for over 40% of the time, indicating significant energy-saving potential [2].

Currently, Jian Zhiyan et al. [3] proposed a coordinated control scheme for water pump frequency conversion and fan frequency conversion using a metro line's VAC system as a case study. Zhang Hao [4], taking a specific metro station as an engineering example, proposed energy-saving control models including automatic switching of cooling supply modes and global efficiency optimization of cold sources. Wang Xian et al. [5] studied the economy and feasibility of applying frequency conversion energy-saving technology in central air conditioning systems based on a case of frequency conversion energy-saving retrofit in a metro station. However, existing research mostly focuses on frequency conversion regulation of single systems, with comparative studies on the mechanism and energy-saving effects of fan-water coordinated regulation being relatively scarce.

Therefore, based on the energy-saving principles of frequency conversion regulation in fan and water systems, this paper constructs a system framework and coordination mechanism for fan-water coordinated control. Relying on a typical case study, it compares and analyzes the energy savings of three modes: fan frequency conversion, water pump frequency conversion, and fan-water coordination, verifying the energy-saving advantages of the coordinated strategy and providing references for the operation of metro ECS.

## Ⅱ.Frequency Conversion Regulation Methods and Energy-Saving Mechanisms in ECS

### 2.1 Analysis of Fan System Frequency Conversion Regulation

The fan system in a metro station is responsible for environmental control in public areas. Traditional constant air volume (CAV) systems use damper throttling for regulation under part-load conditions. Although this changes the air volume, the reduction in fan shaft power is limited, leading to significant energy waste. Frequency conversion technology changes the fan speed, enabling variable air volume (VAV) operation. The theoretical basis for energy saving is the fan affinity laws, with formulas as follows.

$$\frac{G_s}{G_d}=\frac{n_s}{n_d}=r \tag{1}$$

$$\frac{H_s}{H_d}=r^2 \tag{2}$$

$$\frac{P_s}{P_d}=r^3 \tag{3}$$

$G_s$ is the air volume under operating conditions, $G_d$ is the air volume under design conditions, $H_s$ is the pressure under operating conditions, $H_d$ is the pressure under design conditions, $P_s$ is the shaft power under operating conditions, $P_d$ is the shaft power under design conditions, $n_s$ is the rotational speed under operating conditions, $n_d$ is the rotational speed under design conditions, and r is the relative air volume. From equation (3), it can be seen that the fan shaft power is proportional to the cube of the rotational speed. Common control strategies include constant static pressure, variable static pressure, and total air volume control.

### 2.2 Analysis of Water System Frequency Conversion Regulation

The chilled water system is responsible for transporting cooling capacity, with its energy consumption core lying in the chilled water pumps. Traditional primary-pump constant flow systems rely on regulating valve openings to change flow under part-load conditions, essentially consuming the excess pump head, while the pump operating frequency remains unchanged, resulting in persistently high energy consumption. A primary-pump variable frequency variable flow system is an effective solution. Pumps also follow the affinity laws, with formulas as follows.

$$\frac{Q_s}{Q_d}=\frac{n_s}{n_d}=r \tag{4}$$

$$\frac{H_s}{H_d}=r^2 \tag{5}$$

$$\frac{N_s}{N_d}=r^3 \tag{6}$$

$Q_s$ is the water flow rate under operating conditions, $Q_d$ is the water flow rate under design conditions, $H_s$ is the head und
$N_s$ is the shaft power under operating conditions,
$N_d$ is the shaft power under design conditions, $n_s$ is the rotational speed under operating conditions, $n_d$ is the rotational speed under design conditions, and r is the relative water flow rate.

By reducing the pump speed to adapt to decreased flow demand, significant energy savings can be achieved. In engineering, the temperature difference control method or the pressure difference control method is primarily used. Temperature difference control uses the supply-return water temperature difference as a signal to adjust the pump speed, ensuring cooling capacity is supplied on demand, but it suffers from temperature measurement lag. Pressure difference control uses the pressure difference in the most unfavorable circuit as a signal, offering a more direct response, making it suitable for systems with significant changes in pipeline network resistance.

### 2.3 Analysis of Fan-Water Coordinated Control System

When the terminal load of the system changes, the frequency of the chilled water pumps is adjusted based on the load impact, matching the cooling supply from the chiller to the demand of the air conditioning terminals. This achieves coordination from the cooling supply of the water system to the regulation of the fan system terminals. The control strategy of the fan-water coordinated system runs through the optimized control of all links in the VAC system. A schematic diagram of the fan system and water system in a metro station is shown in Figure 1.

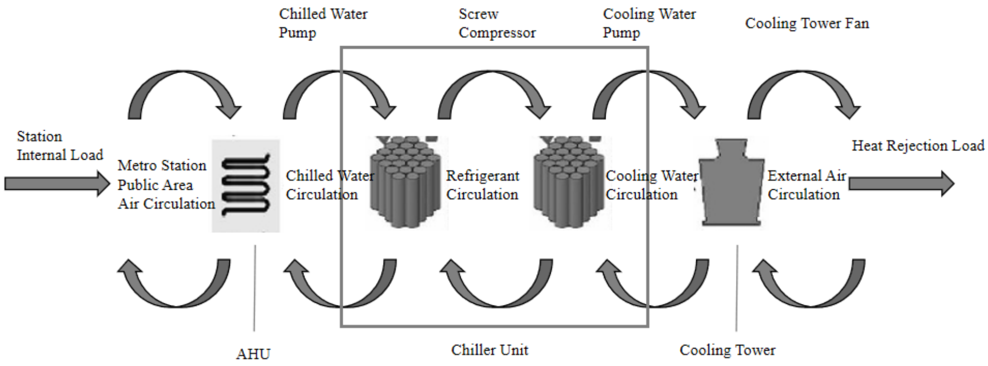


**Figure 1:Schematic diagram of fan system and water system in a metro station**

The fan-water coordinated control strategy is a global optimization method based on the coupling relationship within the system. Its core lies in dynamically coordinating the operating states of the fan and water systems through a central monitoring platform. The system first adjusts the speed of the supply and return fans via frequency converters based on real-time temperature and humidity parameters in the station's public area to change the supply air volume and meet instantaneous load demand. According to the changes in supply air temperature and the principle of on-demand cooling distribution, it dynamically adjusts the water valve openings of each air handling unit to achieve hydraulic balance. Based on the changes in total cooling demand reflected by the collective action of the valves, combined with the performance characteristics of the chiller, the system optimally adjusts the frequency of the chilled water pumps, achieving precise matching between cooling supply and terminal demand. Consequently, the overall system energy efficiency is maximized while ensuring environmental comfort. The control principle is shown in Figure 2.

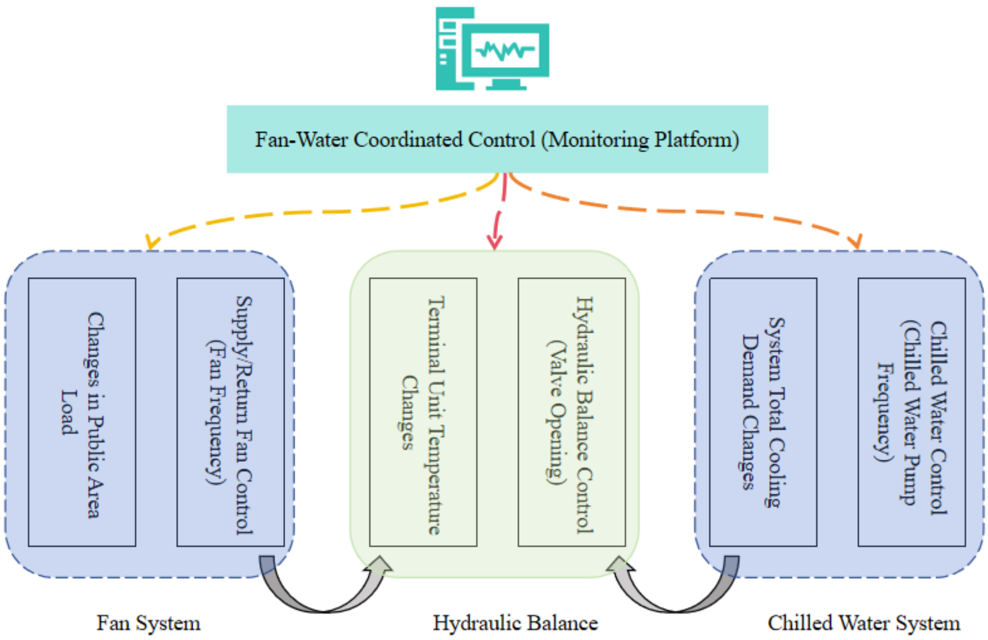


**Figure 2:Schematic diagram of fan-water coordinated control principle in a station**

## Ⅲ. Theoretical and Case Study Analysis of ECS Energy Saving in Metro Stations

### 3.1 Research Object and Parameter Selection

A typical two-level underground island station in a hot-summer and cold-winter zone was selected as the research object to analyze the energy saving of frequency conversion. The hourly cooling load data for a typical summer weekday, shown in Table 1, clearly reflects the load fluctuation characteristics during morning and evening peaks. The main equipment parameters of the supporting VAC system are listed in Table 2.

**Table 1: Hourly cooling load of a metro station in a hot-summer and cold-winter zone.**

| Time | 6:00 | 8:00 | 10:00 | 12:00 | 14:00 | 16:00 | 18:00 | 20:00 | 22:00 |
|---|---|---|---|---|---|---|---|---|---|
| Load (kW) | 358.8 | 689.9 | 586.4 | 614.0 | 620.9 | 627.8 | 676.1 | 586.4 | 517.4 |

**Table 2: Selected equipment parameters.**

| Main Equipment | Main Technical Parameters | Quantity |
|---|---|---|
| Supply Fan | Air Flow: 62628 $m^3/h$; Cooling Capacity: 357.1 kW; Input Power: 37 kW | 2 |
| Return Fan | Air Flow: 48228 $m^3/h$; Input Power: 22 kW | 2 |
| Chilled Water Pump | Flow Rate: 110 $m^3/h$; Head: 28 $mH_2O$; Input Power: 17.5 kW | 2 |

### 3.2 Energy Saving Analysis of ECS Frequency Conversion Regulation

Based on the fan and pump affinity laws, the power consumption of the supply fans and return fans under the hourly loads of the typical day was calculated. The calculation results show that frequency conversion regulation for fans and pumps has significant energy-saving effects. The daily comprehensive energy saving rate for the supply fans was 41.6%. For the return fans, it was 43.4%. The daily comprehensive energy saving rate for the chilled water pumps was 41.1%. Through the calculation and analysis of the typical day data, it was found that under the global optimization of fan-water coordination, the system's energy-saving effect is further improved, as detailed in Figure 3. The highest energy saving rate occurred during the low-load period at 6:00, reaching up to 66%. Meanwhile, the coordinated control, through system-level optimization, effectively avoids the potential energy mismatch issues that may occur during independent frequency conversion operation of the fan and water systems. This enables the fans, pumps, and cold source to work synergistically in a high-efficiency and coordinated state, thereby maximizing the overall system Coefficient of Performance (COP). Both the energy-saving effect and operational stability are significantly better than the simple combination of independent frequency conversion operation of the fan and water systems.

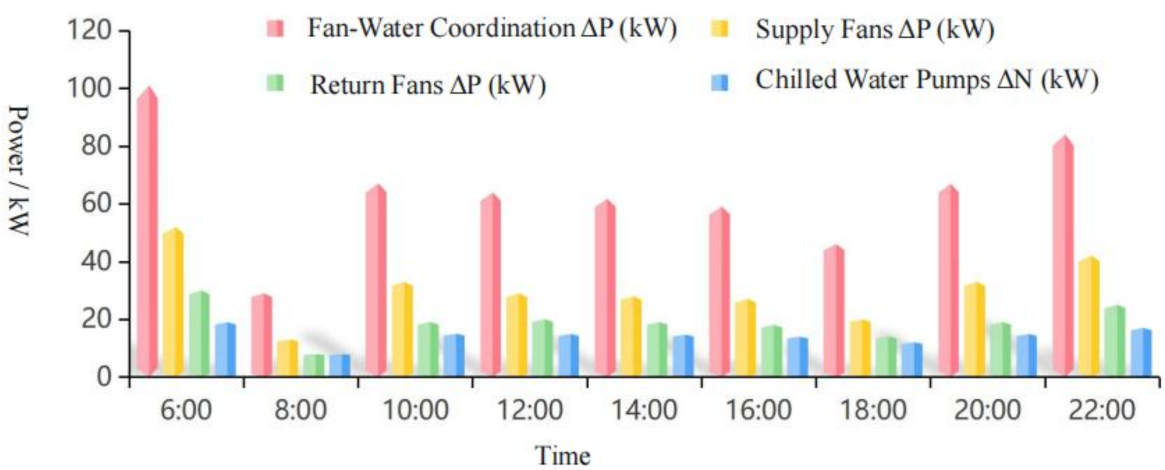


**Figure 3. Analysis chart of frequency conversion energy saving for the ECS**

## Ⅳ.CONCLUSION

Through theoretical derivation and case calculation, this paper conducted an in-depth study on the energy savings of applying frequency conversion technology and fan-water coordinated strategies in metro station ECS, drawing the following conclusions:Frequency conversion in a single system is energy-saving. Based on the affinity laws of fluid machinery, the independent frequency conversion of both the fan system and the water system can achieve a daily comprehensive energy saving rate exceeding 40%.Fan-water coordinated control can achieve overall system energy savings. The fan-water coordinated system effectively solves the dynamic matching challenge of coupled fan-water systems. It increases the maximum energy saving rate to 66% and significantly enhances the stability and reliability of system operation.

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