# Research on Intelligent Condensation Recognition and Environmental State Diagnosis Method of High-Voltage Switchgear Based on STM32

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**Abstract: As the core power transmission and distribution equipment in the power system, the condensation problem of high-voltage switchgear has long threatened the insulation performance and operational safety of the equipment, and has become a key hidden danger that restricts its reliable operation. This paper focuses on the condensation formation mechanism and detection difficulties, and proposes a set of condensation intelligent identification and environmental state diagnosis system design scheme based on STM32 embedded platform. The system integrates multi-parameter sensors such as temperature and humidity, surface temperature, etc., and intelligently recognizes and evaluates the risk of environmental state through dew point calculation and fuzzy logic algorithm. The system design scheme has good real-time, scalability and engineering adaptability, and provides theoretical reference and system conception for realizing intelligent monitoring and preventive operation and maintenance of high-voltage switchgear.**

**Keywords: High-Voltage Switchgear; Condensation Identification; STM32; Fuzzy Logic; Environmental State Diagnosis**

## 1. Introduction

In the power system, the high-voltage switchgear is an important equipment to realize the distribution, control and protection of electric energy, and the safety and stability of its operation is directly related to the reliable operation of the power grid. With the continuous improvement of the automation level of the power system, the functions assumed by the switchgear in the transmission and transformation links are becoming more and more complex. However, under the complex climatic conditions of humidity, high temperature, and large temperature difference between day and night, condensation is very easy to occur inside the switchgear cabinet, which seriously threatens the insulating performance and operational reliability of the equipment, and has become one of the main hidden dangers triggering the failure of the switchgear cabinet.

Condensation is a phenomenon caused by the condensation of water vapor into liquid water when the air temperature inside the cabinet is reduced below the dew point. Water droplets adhering to the insulation surface may cause partial discharge, breakdown, short circuit and other serious consequences. Especially during the gradual spread of condensation from the bottom to the top of the cabinet, key components such as current transformers are often the first to be affected, significantly increasing the risk of failure. Therefore, how to realize the accurate identification and effective prevention and control of condensation state of switchgear has become an important research topic in the field of intelligent operation and maintenance of power equipment.

Currently, condensation monitoring and prevention mainly rely on temperature and humidity sensors, dew point sensors and other means to realize the identification and control of potential condensation risk through the real-time collection of environmental parameters. Hwa et al. designed a miniature condensation sensor based on the refractive index change of the optical waveguide, which can identify the generation of a water film on the surface with high precision and improve the accuracy of condensation judgment. [1] Meanwhile, with the development of computer vision technology, non-contact image detection has also begun to be applied to condensation/frost identification. Zhu et al. (2014) developed an image brightness and texture change recognition method, which has a recognition accuracy of more than 90% in glass substrate condensation experiments,[2] providing a new way of thinking for non-invasive detection.

In the analysis of the causes of condensation in switchgear cabinets, the research mostly focuses on the relationship between equipment structure, airflow arrangement and environmental coupling. Jiang Tao et al. pointed out through the investigation of ring network cabinet accidents that the poor sealing between the cable trench and the cable room is an important causative factor for the generation of condensation. [3] Ying et al. further proposed to improve the internal microenvironment by rectifying air channels and moisture-absorbing materials from the perspective of switchgear internal structure optimization. [4] Sun and others use temperature and humidity sensors instead of traditional condensation sensors to improve the sensitivity and adaptability of monitoring. [5]

In terms of prevention and control means, the traditional physical methods such as heating dehumidification, rotor dehumidification and condensation dehumidification are still commonly used in the current engineering. Among them, the heating dehumidification method is widely used because of its simple structure and convenient control, which reduces the relative humidity by raising the temperature inside the cabinet. Li and Zhou proposed to introduce temperature and humidity controllers in the heating system to realize automatic start and stop and avoid the heating lag problem. [6,7] Liao used finite element simulation to determine the optimal arrangement area of the heater so as to improve the dehumidification efficiency. Yang analyzed the difference in energy consumption of the heater in three operating states based on the Magrath formula, and pointed out that the dew point control strategy can maximize energy saving under the premise of guaranteeing the effect. [8]

Although the traditional methods alleviate the condensation problem to a certain extent, there are still shortcomings such as delayed response, high energy consumption, and system independence, which make it difficult to adapt to the needs of intelligent operation and maintenance of modern power grids. Most of the existing research focuses on the control optimization of a single physical parameter or independent equipment, and lacks multi-dimensional data fusion, environmental trend analysis and intelligent decision-making capabilities. Therefore, building a high-voltage switchgear condensation monitoring and diagnosis system that integrates sensing perception, edge computing and intelligent judgment has become a key direction of current research.

In recent years, embedded systems have been widely used in intelligent power equipment due to their advantages of low power consumption, high real-time, easy integration, etc. STM32, as a mainstream high-performance microcontroller platform [9], has rich peripheral interfaces and strong data processing capabilities, and is able to carry multi-channel sensor signal acquisition, judgment and feedback control logic, which provides a solid foundation for the construction of a highly efficient and intelligent condensation recognition system. Solid foundation for the construction of efficient and intelligent condensation identification system. Combined with dew point algorithm, fuzzy control or machine learning technology, it can further improve the system's prediction capability of condensation trend and realize the transformation from “dehumidification after the fact” to “intervention before the fact”.

In summary, the condensation problem of high-voltage switchgear is still a key factor restricting the long-term stable operation of equipment. Although the traditional method is technically mature, there are problems such as lagging detection, low energy efficiency and insufficient intelligence, which are difficult to meet the development needs of the future smart grid. Therefore, the research of condensation intelligent identification and environmental state diagnosis method of high-voltage switchgear based on STM32 platform [10] not only has important theoretical significance, but also has significant engineering application value. This paper will focus on the research of multi-parameter sensing, intelligent identification model and control system integration, and put forward a set of system solutions with real-time monitoring, trend judgment and linkage response capabilities, in order to enhance the safety of switchgear operation to provide effective support.

## 2. Research Basis

### 2.1 Condensation Phenomenon and Condensation Identification in High-voltage Switchgear

Condensation is one of the most common and destructive physical phenomena in the operating environment of high-voltage switchgear, and its fundamental cause lies in the phase change process of water vapor from gas to liquid. When the operating environment of the equipment humidity, poor ventilation or significant temperature difference between day and night, the water vapor in the air is very easy to condense on the surface of the equipment to form water droplets or water film. These water droplets once attached to the electrical insulation parts, such as contacts, bus bar, insulated pillars, etc., it is very likely to lead to partial discharge, insulation breakdown or short-circuit tripping, and in serious cases may even lead to equipment burnt and power grid accidents.

The formation of condensation and temperature, humidity and the close relationship between the key to its occurrence in the determination of air dew point temperature. Dew point temperature (Dew Point) is a specific humidity conditions, the air in the water vapor began to condense into liquid water at the lowest temperature. When the surface temperature of the equipment falls below the dew point, condensation will occur. Therefore, the first task in determining condensation is to accurately obtain the current dew point temperature of the air and compare the actual temperature difference on the equipment surface in real time.

The dew point temperature is usually calculated using the Magnus formula, which uses air temperature and relative humidity to derive the dew point value:

$$T_d = \frac{b \cdot \alpha(T,RH)}{a-\alpha(T,RH)}, \alpha(T,RH) = \frac{aT}{b+T} + \ln(RH) \quad (1)$$

Where T is the current ambient temperature (℃), RH is the relative humidity (%), and a and b are empirical constants related to air temperature, often taking the values a=17.62 and b=243.12℃. The above dew point temperature is compared with the actual surface temperature of the device, and if the latter is lower than the dew point temperature, there is a risk of condensation. This principle is one of the theoretical foundations of the current intelligent identification system. Compared with the traditional monitoring methods based on manual inspection or simple threshold sensing, the dew point-based condensation discrimination method provides theoretical support for the subsequent realization of intelligent identification.

### 2.2 Principle of Intelligent Identification Technology and Embedded Realization Basis

Under the background of increasingly intelligent condensation prevention and control technology, how to accurately extract the key information of "condensation or not" from multi-dimensional environmental data has become the core of the system's identification capability. The intelligent recognition technology adopted in this study is essentially a method based on sensor data fusion and rule-based reasoning, and its key steps include environmental parameter acquisition, data processing and logical judgment.

First, in the data perception stage, the system collects the temperature and relative humidity parameters of the ambient air in real time through the temperature and humidity sensors, and at the same time is equipped with surface temperature sensors (e.g., thermocouples or DS18B20 digital thermometers) to obtain the actual temperature of the key parts of the switchgear cabinet. In order to ensure the acquisition accuracy and response speed, it is necessary to use low-delay, strong anti-interference ability of industrial-grade sensor devices, and to realize multi-channel parallel acquisition.

Then, the system pre-processes and calculates the above multi-source sensing data through STM32 embedded controller, which features high performance, low power consumption and rich peripheral interfaces to flexibly access multiple types of sensors, and at the same time realizes fast dew-point calculations and logic judgment with the help of floating-point operation unit (FPU). The main program running inside STM32 will call the Magnus formula for real-time dew point calculation, and the judgment conditions are as follows:

$$\text{If } T_{\text{surface}} < T_d \Rightarrow \text{Condensation Risk} = \text{High} \quad (2)$$

On this basis, multiple judgment levels (e.g., safe, critical, hazardous) can be further set, and differential rate of change analysis (e.g., early warning if the rate of temperature drop exceeds the threshold) is introduced to enhance the sensitivity and foresight of the system.

Compared with traditional PLCs or industrial controllers, STM32 has lower power consumption and higher deployment flexibility, making it ideal for switchgear environments with limited field space and sensitive power consumption. Meanwhile, STM32 supports a variety of communication interfaces (e.g., UART, SPI, I2C), which facilitates subsequent interfacing with remote monitoring systems and realizes the integrated architecture of edge computing + remote diagnosis.

The intelligent recognition system is not limited to static judgment; it can also identify condensation trend changes (e.g., temperature-humidity crossover feature points) by performing time series analysis with embedded algorithms.

### 2.3 Theoretical Basis and System Support for Environmental Condition Diagnosis

In the operating environment of high-voltage switchgear, the generation of condensation is often affected by a variety of environmental parameters, such as temperature, humidity, air pressure and temperature difference between equipment surfaces, etc., and there is a certain degree of ambiguity and nonlinear relationship between these factors. The traditional judgment method based on a fixed threshold is difficult to fully reflect the complex environmental state, and thus cannot realize the accurate prediction of condensation trend. For this reason, the fuzzy logic algorithm, as an intelligent method applicable to uncertainty and multi-factor reasoning, has significant advantages in environmental state diagnosis.

Fuzzy logic does not rely on precise mathematical models, but through the construction of fuzzy sets and “if-then” rules, environmental parameters are fuzzified to achieve the transition from perception to determination. For example, the temperature and humidity input variables can be divided into linguistic variables such as “high”, ‘medium’, “low”, etc., and the condensation risk level of the current environment can be calculated by fuzzy inference rules. This method is especially suitable for dealing with the actual situation of frequent parameter fluctuations and incomplete information in natural environments.

In terms of system implementation, STM32 series microcontrollers provide a good hardware platform for the localized operation of the fuzzy inference algorithm. With its efficient processing capability and rich peripheral interfaces, the system can realize the real-time acquisition and fusion calculation of multiple sensor data, complete the environmental state judgment on the edge side without relying on external servers, reduce the response latency, and improve the independence and stability of intelligent recognition.

In summary, the environmental state diagnosis mechanism with fuzzy logic algorithm as the core provides important theoretical support for the design of the subsequent system modules, and also lays the foundation for the realization of intelligent and highly reliable condensation recognition system.

## 3. System Design Framework and Theoretical Model

To realize the intelligent recognition of condensation state and effective diagnosis of environmental operation condition of high-voltage switchgear, this paper designs a system architecture based on STM32 embedded platform. The system is based on sensor network, combined with edge computing and fuzzy logic reasoning to realize real-time sensing and dynamic judgment of condensation risk. This chapter will focus on the overall architecture of the system, the core theoretical model and module functions to carry out specific elaboration, and clarify the logical structure and synergistic relationship of each link of the system.

### 3.1 Overall System Architecture Design

The system consists of three layers: sensor acquisition layer, embedded computing layer and diagnostic decision-making layer. The sensor acquisition layer is responsible for multi-point monitoring of temperature, humidity, dew point and electrical environment. Multiple MEMS sensors are deployed in this layer, combining the timing scheduling mechanism and multi-channel analog-to-digital conversion (ADC) technology to achieve synchronous acquisition of data from multiple sources. The sensor signals are input to the STM32 main control chip through analog or digital interfaces and are refreshed in real time. The embedded computing layer constitutes the core processing unit of the system. The STM32 microcontroller filters, fuses and pre-processes the raw data before entering the intelligent recognition module. This module integrates a condensation risk model based on environmental weight adjustment and a fuzzy logic diagnostic engine. Through programmed modeling, this layer can complete the key judgment of “whether condensation occurs” and output the corresponding status level. Based on the calculation results of the previous layer, the diagnostic decision-making layer classifies the condensation trend into risk levels and realizes a comprehensive time-window-oriented assessment by combining the operating history of the equipment. After the risk level triggers the strategy rule, the system automatically links the control module, such as heating, dehumidification or alarm output.

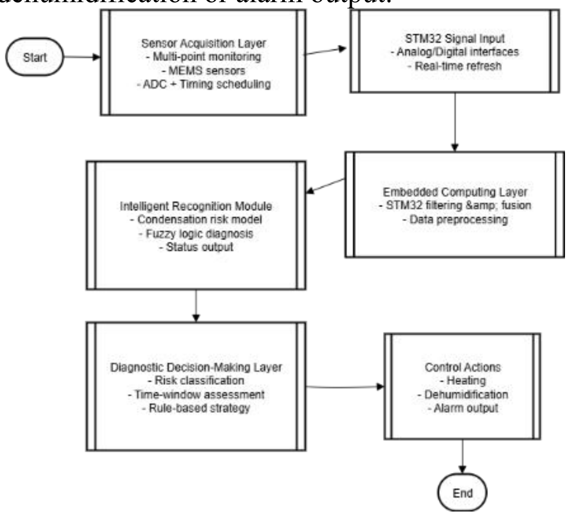


**Figure 1. System Architecture Diagram**

In the system architecture diagram shown in Figure 1, the functional divisions, data transmission paths and logical sequences between the layers are demonstrated. The diagram helps to understand the interaction mechanism between the modules and the overall operation flow of the system.

The architecture design takes into full consideration the real-time and independent requirements of field deployment, especially suitable for intelligent identification application scenarios in remote or communication-restricted environments. Each level of the system is stably connected through standard communication protocols (such as I²C, SPI, UART), and interfaces are reserved for subsequent function expansion.

### 3.2 Intelligent Identification and Fuzzy Diagnosis Model Construction

The design goal of the intelligent identification module is to determine whether there is a risk of condensation in real time based on limited sensor data. To this end, this paper constructs a dynamic weight model of environmental parameters to estimate the risk probability with key environmental factors such as temperature, humidity and dew point difference as input variables. The model takes temperature (T), humidity (RH), dew point temperature difference (Td-Tcab), and historical condensation records as inputs, and calculates the value of condensation risk R in the current environment through a weighting function:

$$R = w_1 \cdot f(T) + w_2 \cdot g(RH) + w_3 \cdot h(\Delta T_d) + w_4 \cdot H(t) \quad (3)$$

where Wi denotes the dynamic weights of each parameter and H(t) denotes the influence weight term of the historical state (e.g., condensation has occurred several times in a certain time period). The model provides quantitative support for subsequent fuzzy logic judgment. The model comprehensively considers the weight adjustment strategy for the influence of parameters on condensation under different working conditions, which can improve the accuracy and adaptability of judgment.

On this basis, the fuzzy logic inference mechanism is introduced into the environmental state diagnosis. The system fuzzy-processes continuous variables, constructs linguistic variables such as “high temperature”, “medium humidity” and “small dew point difference”, and sets the inference in the form of “if-then”. -Then" form of inference rule base.

For example:

1. If the temperature difference is “negative large” and the humidity is ‘high’, then the risk is “very high”;
2. If the temperature difference is “positive small” and the humidity is ‘medium’, the risk is “low”.

The fuzzy logic module outputs the results through the three-step process of fuzzification, inference and defuzzification, and runs in the form of discrete rules in the STM32 controller, taking into account the computational efficiency and model interpretability.

### 3.3 State Evaluation and Strategy Linkage Mechanism

After completing the determination of the state of the environment, the system will respond hierarchically according to the recognition results. Specifically, the output of fuzzy inference will be converted into three state levels of “normal”, ‘warning’ and “high risk”, corresponding to different response strategies.

When the status is “Normal”, the system maintains the monitoring status without additional operation; when it is in “Early Warning” status, the system uploads the relevant information to the main control platform in real time through RS485 serial port or 4G wireless module, which is convenient for remote monitoring and early warning management; Once judged as “high risk”, the system will automatically start the heater or dehumidification equipment for on-site intervention, effectively reducing the possibility of condensation and ensuring equipment safety.

The linkage mechanism realizes the closed-loop control from environment sensing, intelligent recognition to response execution, which not only meets the real-time monitoring of the operation status and data feedback needs, but also improves the system's ability to adapt to and protect against environmental changes.

## 4. Key Challenges and Optimization Measures in System Application

After the design of the high-voltage switchgear condensation intelligent identification and environmental state diagnosis system based on the STM32 platform is completed, the actual application is still faced with various technical challenges. They mainly include embedded platform resource limitations, industrial environment complexity, and system operation energy consumption. This chapter will focus on these core challenges, combined with specific optimization measures for analysis, aiming to ensure the stable operation of the system and the value of engineering applications.

### 4.1 Embedded Platform Resource Limitations and Industrial Environment Adaptability

STM32 microcontroller has become the preferred hardware platform for intelligent identification systems due to its small size, low power consumption and good real-time response performance. However, its computational power and storage resources are limited, especially when performing fuzzy logic reasoning and multi-parameter fusion, the resource bottleneck is prominent. For this reason, the system adopts fixed-point computing instead of floating-point computing, which significantly reduces the CPU load and memory occupation and improves the algorithm operation efficiency. Meanwhile, by streamlining the fuzzy rule base and optimizing the data processing flow, the recognition process is simple and accurate. In addition, the sensor data acquisition adopts the interrupt and cache mechanism to reduce the acquisition delay and improve the real-time response capability.

The industrial site environment is complex and variable, with high humidity, dust, and strong electromagnetic interference, which puts strict requirements on the anti-interference ability of the system. Hardware selection of industrial-grade sensors and components to improve the temperature, humidity and vibration resistance. The circuit design strengthens filtering and shielding to ensure signal stability. At the software level, self-test and fault-tolerance mechanisms are introduced for sensor status, and redundancy design is realized for key modules to ensure long-term stable operation of the system and prevent single-point failures from affecting the overall performance.

### 4.2 Intelligent Energy Consumption Control and Communication Interface Design

Considering the limitations of internal space and heat dissipation in the switchgear cabinet, the energy consumption of heating and dehumidifying equipment is large for long-time operation, and the system design focuses on intelligent energy consumption management. Based on the results of fuzzy logic reasoning, dynamically adjust the heater start and stop and power output to avoid ineffective heating and realize risk grading control. High-risk phase full-power operation, low-power maintenance during the warning phase, and shut down the equipment in normal state, effectively saving energy and prolonging the life of the equipment. At the same time, the data collection frequency is rationally arranged to balance real-time and power consumption.

In terms of communication, the system is equipped with various interfaces (UART, RS485, 4G wireless) to ensure stable data upload and remote monitoring. The modularized design reserves interfaces for future expansion of more sensors and functions to enhance the compatibility and flexibility of the system and meet the diverse needs of different application scenarios.

In summary, through the optimization of algorithms, industrial-grade hardware design, intelligent energy consumption control and diversified communication solutions, the challenges brought by the STM32 platform and industrial environment are effectively dealt with, which provides a solid guarantee for the practical application of the high-voltage switchgear condensation intelligent identification and environmental state diagnosis system.

## 5. Conclusion

In this paper, a set of intelligent identification and environmental state diagnosis system based on STM32 embedded platform is designed for the widespread condensation hidden problem in high-voltage switchgear. By constructing a judgment model with temperature and humidity, dew point temperature difference and other key parameters as inputs, and introducing a fuzzy logic algorithm to classify the environmental risk level, the real-time identification of condensation risk and the design of dynamic response strategy are realized. During the system design process, the complexity of the field environment and the resource limitations of the embedded platform are fully considered, and a number of feasible engineering improvement measures are proposed from hardware selection, algorithm optimization to energy consumption control and anti-interference design. Although no experimental verification is carried out in this paper, the proposed theoretical model and system framework are of good engineering guidance significance, which can provide an important reference for the practical development and deployment of subsequent related systems.

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