Intelligent Control System of Vacuum Oil Filter Based on PLC

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Abstract. This paper proposed an intelligent control system of vacuum oil filter based on PLC. The system aims to enhance the automatic control and remote monitoring capabilities of Vacuum Oil Filter. With the S7-200 PLC serving as the control center, it incorporates state-sensing and electronic control components into the critical areas of the vacuum oil purifier. This allows for precise control of the degassing hood's liquid level, detection of insulating oil leaks, and automatic control of the condensation tank. Consequently, the system enables unmanned filtering of insulating oil, demonstrating its practicality.

Keywords: vacuum oil filter; intelligent control system; PLC; insulating oil.

1. Introduction

The quality of insulating oil is a crucial data indicator for the operation of transformers [1]. Only after rigorous filtration, purification, and various testing can the oil be deemed suitable for use [2]. However, during extended operation, the insulating oil gradually oxidizes due to factors such as temperature, electric fields, and metal catalysts, leading to a decrease in its dielectric strength and compromising the insulation of the transformer [3-4]. Consequently, the importance of design, development, and operational control of insulating oil purification equipment have received widespread attention.

The vacuum oil filter is capable of purifying insulating oil by removing solid impurities, moisture, and gases, effectively improving its insulation properties [5]. However, currently, the control of vacuum oil filters heavily relies on manual intervention, resulting in suboptimal operational efficiency and control accuracy. Consequently, there is a need to explore intelligent control methods for vacuum oil filters, aiming to enhance their automation level, precision, and operational efficiency.

Reference [6] presented a neural network-based fault diagnosis technique for vacuum oil filters, improving the diagnostic accuracy of oil leaks in vacuum oil filters. Reference [7] designed a distributed control system for vacuum oil filter through electrically controlled valves and sensors. Reference [8] optimized the filtration and degassing technology of vacuum oil filters. While these literature pieces proposed targeted solutions for the improvement of vacuum oil filters, there is a lack of comprehensive research on the intelligent control from an overall perspective.

In this paper, an intelligent control system based on PLC (Programmable Logic Controller) is proposed, which realizes the liquid level control of the vacuum oil filter's degassing chamber, detection of insulating oil leaks, and automatic control of the condensation tank. The implementation of PLC-based intelligent control not only enhances the vacuum oil filter 's ability to adapt to changing operational conditions but also reduces the operational workload and the potential for human error.

2. Operation Principle of Vacuum Oil Filter

The vacuum oil filter is designed based on the difference in boiling points between moisture and oil, and its functionality is achieved through the coordinated operation of various components such as oil pump, rough filter, heat booster, degassing chamber, condensing canister, fine filter, and vacuum pump [9-10]. The structure of the vacuum oil filter is illustrated in Fig. 1.

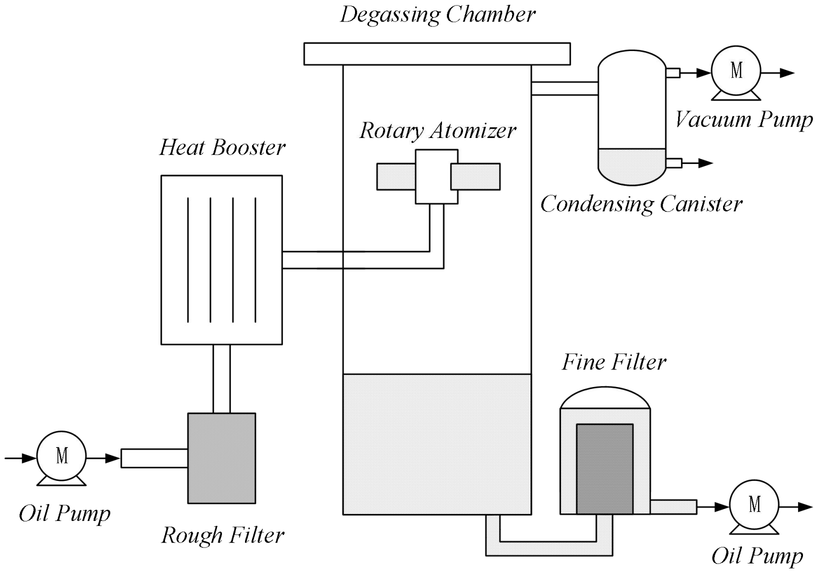

Figure 1. Working process of Vacuum Oil Filter

The working steps of the oil purifier are as follows:

Step 1: Start the vacuum pump to achieve a vacuum environment of -0.08MPa inside the degassing chamber.

Step 2: Activate the inlet oil pump, allowing the insulating oil to pass through the rough filter to remove large particle impurities and some moisture. The insulating oil is then heated and enters the degassing chamber.

Step 3: Inside the degassing chamber, the insulating oil is dispersed into a semi-mist state by the rotary atomizer. The moisture rapidly vaporizes into water vapor, and dissolved gases escape.

Step 4: The water vapor condenses into liquid water in the condensing canister and is discharged. The vacuum pump evacuates the gases outside the equipment.

Step 5: The dehydrated and degassed insulating oil passes through the fine filter to remove small particle impurities before being discharged outside the equipment through the discharge oil pump.

These steps ensure that the insulating oil is effectively filtered, removing solid impurities, moisture, and gases, thus enhancing its insulation properties.

3. Design of Intelligent Control System Scheme

3.1 Requirements of Intelligent Control System

By leveraging the operational features and procedures of the vacuum oil filter, it is crucial to enhance the system's automation and intelligence by incorporating sensing elements and electrical controls at critical junctions. This integration of advanced technologies, including sensors, data analytics, and intelligent control systems, is imperative for optimizing the filter's performance. These include precise control of the degassing chamber's liquid level, sensitive detection and alerting for insulating oil leaks, and automatic control of the condensing tank. Additionally, a data transmission module must be added to facilitate real-time monitoring and remote control of the equipment's operational status.

3.2 Design of Intelligent Control System

Considering the practical control needs, the control system of the vacuum oil filter needs to have the following functions:

3.2.1 Precise liquid level control of the degassing chamber

The sensor devices transmit liquid level signals to the PLC, enabling precise adjustment of the level through fuzzy PID control [11], thus avoiding the inappropriate liquid level that can impact the efficiency of degassing [12-13].

3.2.2 Detection of insulating oil leaks

Sensors continuously monitor operational parameters and assess the presence of faults and leakage risks through the PLC. In the event of any abnormal conditions, an audible and visual alarm is activated on-site, and an alarm signal is simultaneously transmitted to mobile devices [14]. Automatically, emergency measures are initiated to close valves.

3.2.3 Automatic control of the condensation tank

The system is designed to facilitate the drainage of liquids from the condensing tank without compromising the vacuum environment within the degassing chamber. This ensures that the liquid does not enter the vacuum pump, thereby preventing pump damage.

4. Selection of System Hardware

For the anticipated control functions, an intelligent control system requires the following hardware components:

(1) PLC controller: Replaces traditional relay control, enhancing data analysis capabilities.

(2) Liquid level transmitter: Continuously monitors real-time liquid level data.

(3) Flow sensor: Provides data for liquid level deviation detection.

(4) Solenoid valve: Closes immediately upon detection of insulation oil leakage, preventing the accident from escalating; ensures vacuum isolation between the degassing chamber and the condensing canister.

4.1 Selection of PLC

The SIEMENS S7-200 PLC was selected due to its PROFINET interface and compatibility with various communication protocols. Additionally, considering the variety of input signals, the inclusion of an AC input module (EM DR32) and two DC input modules (EM AE08, EM AM03) is crucial. The address allocation is outlined in Tab. 1.

TABLE I. PLC I/O ADDRESS ALLOCATION

Module	Input	Add.	Output	Add.
s7-200	Photoelectric Sensor	DIa.0	No Current Signal	DQa.0
	Oscillator	DIa.1	Over Pressure Signal	DQa.1
	High Condenser Oil Level	DIa.2	Oil Level Ultra-Low Signal	DQa.2
	Emergency Stop Switches	DIa.3	Oil Level Ultra-High Signal	DQa.3
	Power Start & Reset	DIa.4	High Condenser Oil Level	DQa.4
	Inflatable Valve Switch	DIa.5	Inlet Oil Pump Signal	DQa.5
	Vacuum Pump Switch	DIa.6	Outlet Oil Pump Signal	DQa.6
	Booster Pump Switch	DIa.7	Alarm Signal	DQa.7
	Inlet Oil Pump	DIb.0	Inflator Valve	DQb.0

	Switch			
	Outlet Oil Pump Switch	DIb.1	Inlet Valve	DQb.1
	Low Oil Drain Switch	DIb.2	Inlet Oil Leak Alarm	DQb.2
	Leak Detection Switch	DIb.7	Outlet Oil Leak Alarm	DQb.3
	Control Mode Selection	DIc.0-.1	/	
Em Dr32	Six Sets of Heater Switches	DIa.0-.5	Pumps, Heating Signals	DQa.0-.7
Em Ae08	Inlet Oil Pressure Sensor	0+	/	
	Outlet Oil Pressure Sensor	1+		
	Oil Temperature Sensor	2+		
	Discharge Oil Temperature Sensor	3+		
	Inlet Oil Flow Sensor	4+		
	Outlet Oil Flow Sensor	5+		
	Vacuum Sensor I	6+		
	Vacuum Sensor II	7+		
Em Am03	Liquid Level Control Signal	0+	Frequency Output Signal	Qm
	Heating Temperature Sensor	1+	/	

4.2 Selection of Liquid Level Transmitter

The liquid level transmitter utilizes a float ball linkage structure for measuring liquid level in degassing chamber. The deformation leads to variations in the resistance value in the circuit, converting the liquid level signal into an electrical signal ranging from 4-20mA. This signal is then transmitted to the PLC, enabling real-time monitoring of the liquid level inside the degassing chamber.

The YEk-800 liquid level transmitter is used within this control system, requiring a 24V DC power supply for its operation.

4.3 Selection of Turbine Flowmeter

The turbine flowmeter is a typical velocity meter that utilizes the kinetic energy generated when a liquid flows over turbine blades to measure flow rate. The signals are shaped into rectangular pulse waves by a signal amplifier and further converted into analog signals via D/A conversion for transmission to the PLC.

The LWGB-50 flowmeter is selected for this system. This flowmeter requires a DC 24V power supply and is capable of outputting a 4-20mA current signal.

4.4 Selection of Solenoid Valve

Three solenoid valves need to be installed within this control system. The solenoid valve F1 on the oil outlet flange of the oil-filling equipment requires a normally open design. Upon receiving an electrical signal indicating a leakage accident, it automatically closes to prevent a significant leakage of insulating oil. Considering the diameter of the oil pipeline, a DFD-50 pilot-operated solenoid valve is selected.

The solenoid valve F2 between the degassing chamber and the condensing tank is used to isolate the vacuum between the two components, and a normally open solenoid valve DFD-80 is a preferable choice. The solenoid valve F3 at the outlet of the condensing tank is used to automatically discharge the liquid inside, and a normally closed solenoid valve DFD-15 is suitable.

5. Design of System Software

The software for the control system is developed specifically to meet the operational requirements of vacuum oil filter.

5.1 Precise control of the degassing chamber's liquid level

The liquid level transmitter continuously monitors the level inside the degassing chamber in real-time. The vacuum oil filter sequentially activates the vacuum pump and pressure booster pump. Once the desired vacuum level is achieved, the inlet oil pump is activated. Once the liquid level reaches a set point, the outlet oil pump turned on, and the fuzzy PID algorithm begins its continuous monitoring and control of the insulating oil level within the degassing chamber.

If the deviation exceeds 10%, the PLC automatically computes the optimal flow rate for the inlet oil pump and transmits adjustment signals to the frequency converter. This adjustment aims to modify the inlet oil pump's flow rate, thereby restoring the liquid level to the set point, as shown in Fig. 2.

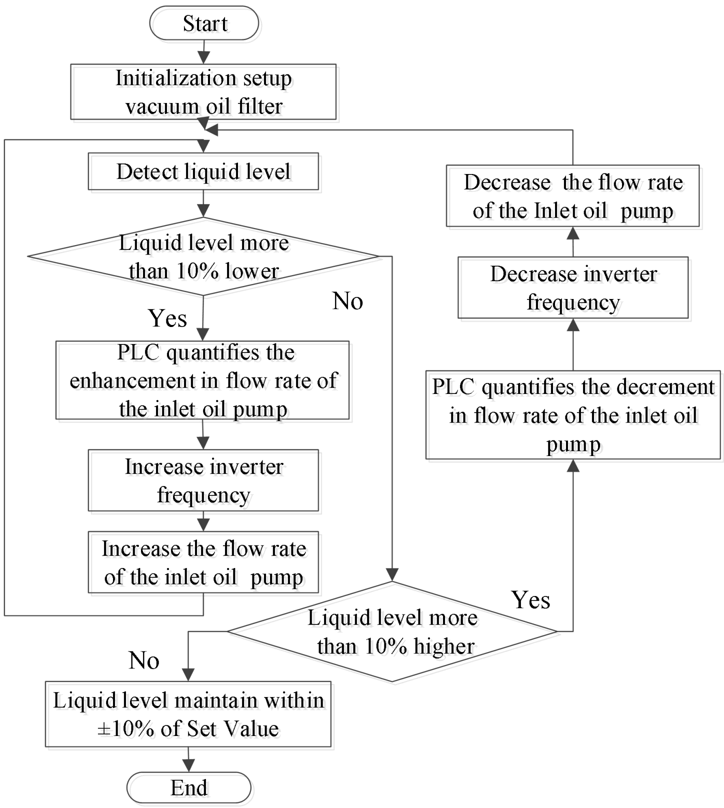

Figure 2. Flowchart of Liquid Level Control

5.2 Detection of insulating oil leak

The control system continuously monitors the flow rates of the supply pipeline L1i and discharge pipeline L1o of the vacuum oil filter, as well as the inlet flow rate L2i and outlet flow rate L2o of the oil-filling equipment. These flow signals are transmitted to the PLC via a wireless signal transmitter.

The PLC automatically calculates the difference between the pipeline flow rates and the equipment-side flow rates. The PLC identifies an oil leakage incident when the deviation exceeds a certain threshold. In response, the PLC automatically sends commands to shut down the vacuum oil filter and the solenoid valve F1, as shown in Fig.3.

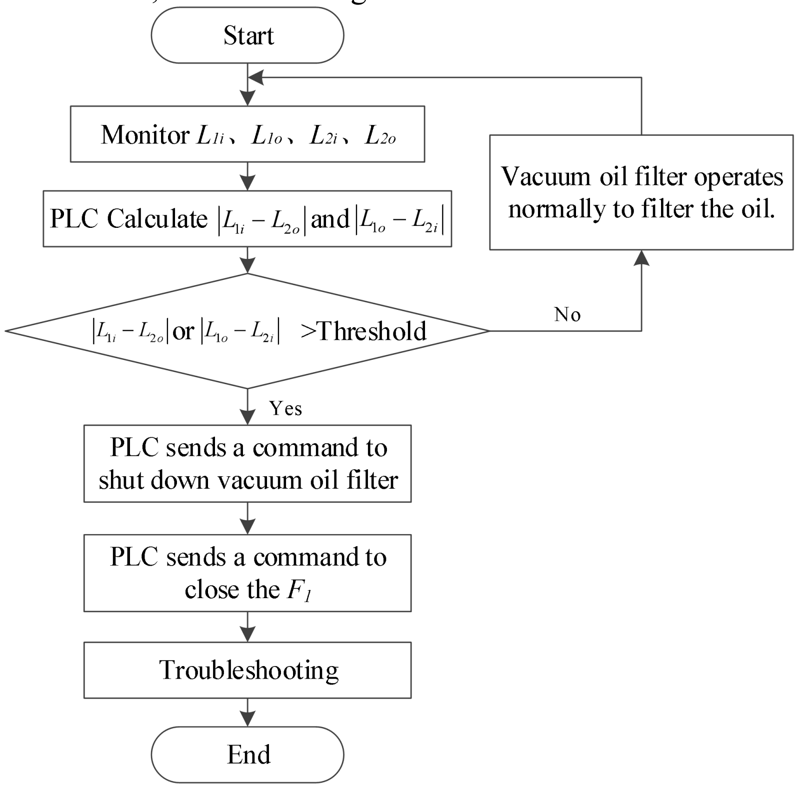

Figure 3. Flowchart of Preventing Leakage

Simultaneously, this system uploads real-time status signals such as temperature and pressure detected by sensors, as well as video files captured by video monitors, to a server through a 4G network. Mobile device terminals can log in to their accounts at any time to check all the information.

When a critical failure occurs in the vacuum oil filter, the system not only shuts down the unit but also promptly notifies mobile devices via text message. If the issue remains unresolved after a certain period, the notification method switches to phone calls until the fault is being handled, at which time the alerts stop.

5.3 Automatic control of the condensation tank

Liquid level sensor continuously monitors the liquid level inside the condensation tank and transmits the data to the PLC. When the liquid level reaches a predetermined height, the PLC initiates a sequence of commands: initially closing valve F2, and subsequently opening valve F3, to discharge the liquid from the tank.

With confirmation from the liquid level sensor that the liquid has been fully drained, the PLC proceeds to close valve F3 and subsequently open valve F2. During this process, the degassing chamber maintains a vacuum state, enabling rapid resumption of oil filtration. The automatic control flowchart for the condensing tank is shown in Fig.3.

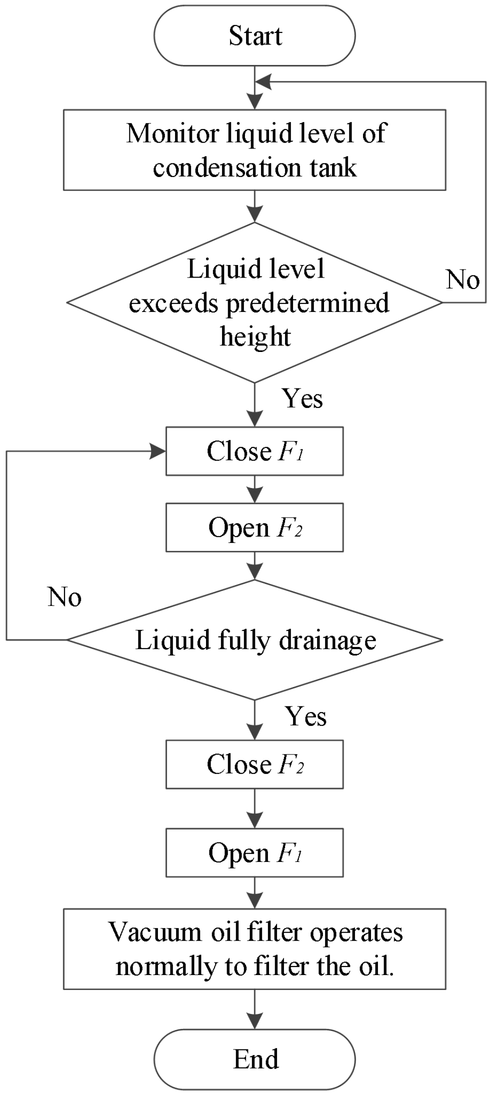

Figure 4. Flowchart of Condensing Tank Automatic Control

6. Conclusion

This paper presents a design of an intelligent control system for a vacuum oil filter, utilizing a Siemens S7-200 PLC as the core component to replace traditional relay control. Additionally, key components such as liquid level transmitters, turbine flow meters, and solenoid valves have been integrated into the existing vacuum oil filter. These upgrades enable the liquid level control of the vacuum oil filter's degassing chamber, detection of insulating oil leaks, and automatic control of the condensation tank.

The implementation of this intelligent control system not only enhances the safety of system operation and reduces the workload on-site personnel, but also enables unattended oil filtration, demonstrating strong practicality and promotion potential. It can be applied not only during the maintenance of oil-filled equipment like transformers but also in other scenarios that require oil filtration, such as insulation oil manufacturing facilities.

References

[1] G. C. Huang, “Research on High-efficiency Transformer Oil Vacuum Filter,” Chemical Engineering & Equipment, vol. 9, 2018, pp. 200-201, doi:10.19566/j.cnki.cn35-1285/tq.2018.09.081.

[2] J. M. Song, J. B. Mao and W. H. Ma, “Research on Oil Filtration and Injection Process Fault Diagnosis for Ultrahigh Voltage Transformers Based on Deep Neural Networks,” Power System and Clean Energy, vol. 39, 2023, pp. 95-103.

[3] G. Y. Bai, C. Zhang, T. J. Li, “Improved Integrated Design on Automatic Insulating Oil Treatment device of UHV Converter Station,” Electronic Design Engineering, vol. 31, 2023, pp. 21-24, doi:10.14022/j.issn.1674-6236.2023.11.005.

[4] F.Jing, “Discussion on The Improvement of Vacuum Oil Filter Technology,” Telecom Power Technology, vol. 35, 2018, pp. 58-59, doi:10.19399/j.cnki.tpt.2018.09.021.

[5] W. Y. Li and Y. B. Xu, “Development of Transformer Oil Sampling Bags,” Plant Maintenance Engineering, vol. 16, 2023, pp. 30-31, doi:10.16621/j.cnki.issn1001-0599.2023.08D.14.

[6] J. M. Wang, D. X. Yu, H. M. Wang, Z. B. Du, L. R. Liu and D. S. Liu, “Influence of natural ester insulating oil on main and longitudinal insulation strength of 110kV power transformer,” Insulating Materials, vol. 56, 2023, pp. 62-69, doi:10.16790/j.cnki.1009-9239.im.2023.01.010.

[7] X. C. Hu, S. H. Xue and L. Q. Sun, “Effect of Antioxidant Types in Transformer Oil on Thermal Ageing Performance of Insulating Paper,” Insulating Materials, vol. 56, 2023, pp. 47-52.

[8] Y. Fan, Z. J. Zhou, Z. R. Wu, Y. H. Wu, J. B. Chen, S. W. Cai and C. J. Zhou, “Oxidation Resistance Study of Several Vegetable Insulating Oil,” Insulating Materials, vol. 46, 2013, pp. 45-48, doi:10.16790/j.cnki. 1009-9239.im.2013.02.013.

[9] H. L. Ma and H. R. Ye, “Research and Design of Variable-Frequency Automatic Vacuum Oil Filter,” East China Electric Power, vol. 42, 2014, pp. 802-805.

[10] H. L. Ma, “Study on the High Efficiency Transformer Oil Vacuum Purifier,” Hydraulics Pneumatics & Seals, vol. 30, 2010, pp. 55-59.

[11] Y. F. Wu and R. C. Wen, “Design of Vacuum Oil Filter Control System Based on PLC,” Machine Tool & Hydraulics, vol. 39, 2011, pp. 96-98.

[12] D. W. Yi and J. J. Chen, “Liquid Level Control in Storage Cylinder of Beer Filling Machine Based on Fuzzy Fractional PID,” Packaging Engineering, vol. 40, 2019, pp. 161-165, doi:10.19554/j.cnki. 1001-3563.2019.11.024.

[13] Y. F. Sun, “Design and Optimization of Intelligent Monitoring System for Industrial Boiler,” Industrial Heating, vol.51, 2022, pp. 41-44.

[14] C. X. Cai, K. Yi and Y. Q. Liao, “Research Progress on Leak Detection and Location Technology for Long-distance Oil Pipeline,” Science Technology and Engineering, vol.23, 2023, pp. 10177-10189.