Development of the Control System and Communication Network for Intelligent SF6 High Voltage Circuit-Breaker

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Abstract

This paper analyses the cause of the major faults of the SF6 high voltage circuit breaker, and then introduces a solution using an embedded control system. The control system consists of the controller for every breaker and a supervisor control system in the control center. Then a double-annular fiber field-bus communication network for the control system is introduced, of which the data link layer is implemented by the CAN controller. According to the operation state of every node and the fiber, the fiber communication module of every node can be configured to several different transmission modes. Due to the influence of temperature, the empirical formula of Beattie-Bridgman is used to calculate the pressure of SF6.

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1. Introduction

High voltage circuit breaker (HVCB) is a crucial equipment to control and protect the electric power systems. With its control function, HVCB can disable or enable the power supply of some electric lines or devices. The circuit breaker mainly consists of two parts: the operating mechanism and the arc-extinguishing mechanism. The operating mechanism is the device that controls the breaker to perform opening and closing operation. The working performance and quality of it play an extremely important role in the working performance and reliability of the breaker. Nowadays, there are four types of operating
 mechanism in application to control the breaker. The spring mechanism, pneumatic mechanism and hydraulic mechanism are the conventional ones that are generally used in various circuit breakers [1]. Another new type of operating mechanism is the electromagnetic mechanism which is designed to meet even the most severe requirement and is fully electronic power controller [2]. But now, for the application on electric systems of 500KV or above, the hydraulic mechanism is still the most widely used mode interior and abroad. For the arc-extinguishing mechanism, it cooperates with the hydraulic mechanism to guarantee circuit breaker operating correctly. There are also several types of arc-extinguishing mechanism, but for HVCB of level 500KV or above, SF6 arc-extinguishing is widely used [3].

This article aimed at the LW12-550 SF6 high voltage circuit breaker, which is widely used in the Hunyuan substation of Shanxi Province. This type of circuit breaker is the one using the hydraulic mechanism and SF6 arc-extinguishing. But since 11 such circuit breakers started their service in 2003, several kinds of failures happened frequently, such as the false alarm of high voltage, reclosing lockout and so on. According to the statistics, most major and minor failures can be traced to the hydraulic operating mechanism and the SF6 gas density problem. In order to overcome the shortcomings of LW12-550, the fault analysis of circuit breaker and a control system for it will be shown in section 2. And then a fiber communication network connecting all of the breakers and the control center in a substation is introduced in section 3. Section 4 shows the system software of which the calculation of SF6 pressure uses the algorithm of Beattie-Bridgman. In the end, the experiment and the conclusion will be shown.

2. The fault analysis and the solution of the control system for HVCB

2.1. The fault analysis

The major issues of the hydraulic mechanism are the false alarm of high voltage, reclosing lockout which may be caused by the fault of hydraulic pressure control system. Nowadays, most of the control of the hydraulic mechanism is implemented by micro switch. As for the breaker of LW12-550, it’s also controlled by micro switch. After long time observation, it’s known that as time goes on, the motion path of the micro switch may be changed and leading to the false control of the hydraulic mechanism. So it’s important to improve the control of the hydraulic mechanism. When the fault of circuit breaker happens, the traditional solution is to adjust the motion path of micro switch according the oil pressure gauge of hydraulic mechanism. However, the measure device of oil pressure and the pressure control system of hydraulic mechanism are two separate devices. According to the above analysis, a new pressure control system using oil pressure sensor is designed for both control and pressure gauge displaying.

For the arc-extinguishing mechanism, the problem of SF6 leaking out is the big hidden trouble. Traditionally, most of the high voltage circuit breakers use the mechanical density relay to monitor the state of SF6. But the mechanical density delay can’t monitor the pressure value and its change of SF6, just sending signals when out of some range. As the technique of electricity progress, high voltage substations need to monitor and control the substation device’s operation in the central control room. According to the requirement of monitoring the SF6 gas, we improve the monitor of SF6 gas density through the electrical sensors just like that of oil. It’s known that the temperature has some influence to the pressure of gas, so we also need to measure the temperature of the gas.

2.2. The Control System for HVCB

According to the above analysis, a control system is designed to monitor and control the pressure of oil of hydraulic mechanism, and also monitor the density of SF6 of arc-extinguishing mechanism. In this part, the system controller for a single high voltage circuit breaker will be introduced. The controller consists of
several modules including ARM control module, sensor module, IO module, power module and fiber communication module, as depicted in Fig. 2. The sensor module includes oil transducer for hydraulic pressure, and SF6 transducer for both pressure and temperature of gas in the tank of circuit breaker. Then both of transducers send the information digitally to the ARM control module. The ARM-based processor AT91RM9200 is chosen as the master MCU for the Controller. The PC104 bus is used to connect IO module and fiber communication module. After getting the pressure value of oil and SF6, ARM control module will generate the outputs of control command together with the system state and alarm signal which are transmitted to the electric circuit of HVCB via the terminal block. Simultaneously, the communication module updates the information of control command, system state and alarm signal to the industrial PC located in central control room. Then the information displays on the screen of industrial PC through the configuration software to be monitored by humans.

![Fig. 2. The framework of the controller for a single HVCB](image)

3. Fiber Field-Bus Communication Network

As the serious electromagnetic circumstance in the substation, a fiber field-bus communication network will be used for the control system [4]. In the physical layer of the network, fiber instead of twisted-pair cable is used to improve the communication efficiency and the capability of anti-electromagnetic interference.

3.1. The Structure and implementation of the Fiber Field-Bus Communication Network

To improve the reliability of annular topology, the fiber field-bus communication system introduced a double-annular topology structure, shown in the Fig. 3(a). As the delay of the circuit of fiber field-bus network may lead to net jam, a logic control unit (LCU) for the fiber communication network need to be designed to comply with the data link protocol of CAN controller [5]. The LCU is implemented by the CPLD of type XC9572 which also be used to modulate and demodulate signals to translate common digital signals to frequency signals, and to switch the transmission modes of the field devices. The optical module (OPT) is a high-speed single-mode optical transceiver of type SSTR3121-55-113 which is used to
translate frequency signals to optical signals and then takes responsibility of sending and receiving optical signals.

As the optical-fiber just transmits the optical frequency signals which take the scale of frequency to denote explicit electric level and implicit electric level. In this design, 25MHz frequency indicates explicit electric level ‘0’ and 1MHz frequency indicates implicit electric level ‘1’. So, the signal from CAN controller SJA1000 needs to be modulated and demodulated before transmitting. The CPLD is just used to implement the function of that. Fig. 3(b) shows the framework of the physical layer of the fiber communication. When some node is receiving signals, the received optical signals is translated to digital frequency signals by the optical module, and then the digital frequency signals is demodulated by the CPLD. If the frequency of the signal of RX_0/RX_1 received is 25MHz, the register R0/R1 is set to ‘0’; otherwise the register R0/R1 is set to ‘1’. When some node is sending signals, CPLD takes charge of calculating the value of register T0/T1. If the value of register T0/T1 is ‘0’, TX_0/TX_1 transmits the frequency signal of 25MHz to optical module, on the contrary TX_0/TX_1 transmits the frequency signal of 1MHz.

In principle, as the fiber communication is a point-to-point transmitting mode, signals just can be transmitted between every two nodes. If some more nodes need to be connected, the LCU is necessary. The interface of M0/M1 of Fig. 3 is used to implement different transmission modes which enable the LCU to work in different function. Three transmission modes and corresponding LCU functions are shown as follows:

When M0 = 0 and M1 = 0, it’s the first transmission mode: T0 = Rx & R1; T1 = Rx & R0; Tx = Rx & R0 & R1. In this mode, a node can transmit signals in two directions: the signal received from optical module 1 will be sent by optical module 2 and the signal received from optical module 2 will be sent by optical module 1.

When M0 = 1 and M1 = 0, it’s the second transmission mode: T0 = Rx; T1 = 1; Tx = Rx & R0.
When M0 = 0 and M1 = 1, it’s the third transmission mode: T0 = 1; T1 = Rx; Tx = Rx & R1.

In these two modes, a node can receive signals only from one direction which means receive from optical module 1 or from optical module 2. A node can send signals only from one direction too, that send signals to next node from optical module 1 or from optical module 2.

3.2. The Configuration of Fiber Communication for Control System of HVCB

For the control system of SF6 HVCB of type LW12-550 in the substation of Hunyuan, there are 11 high voltage circuit breakers and a control center. So there are 12 nodes including 11 circuit breakers nodes and one control center node. According to the nodes state and the fiber state, different configurations of the fiber field-bus communication network are shown below:
If all of the nodes and the fibers work well, the control center node is set to the second transmission mode or the third transmission mode and all of the circuit breaker nodes set to the first transmission mode, as Fig. 5 (a) shows. The control node just transmit data through A&A’, while all the breaker nodes can transmit data in two different directions. In this way, the information from every breaker node can terminate at the control node to avoid invalid information circulating forever.

If one of node including breaker node and control node break down, its two contiguous node switching to the second or third transmission mode to ensure the communication of the system. As Fig. 5 (b) shows when breaker node 2 fails, breaker node 1 switches to the second mode and breaker node 3 switches to the third mode.

If a section of fiber can’t work anymore, the contiguous nodes of the fiber also switching to the second or third transmission mode from the first mode. As the Fig. 5 (c) shows, when the fiber optic crashes between node 1 and node 2, breaker node 1 switches to the second mode and the breaker node 2 switches to the third mode.

Fig. 5. Configuration of the fiber field-bus communication system

4. Software for pressure data processing and control

In this section, the pressure data processing algorithm and the control strategy will be introduced. In the first part of this section, a pressure processing algorithm will be introduced.

4.1. Pressure data processing algorithm

According to the oil pressure, the ARM control module outputs the control command for hydraulic pressure control, and also outputs some state information to indicate the state of mechanism operation. By comparison to the pressure value at 20°C which is used as a reference standard in the industrial project, the control module can judge whether current pressure is abnormal and then generate the corresponding outputs. Because the temperature in the hydraulic mechanism is relatively steady as the influence of heater, it is not necessary to calculate the pressure of oil at 20°C. But for SF6, the temperature has a serious influence for the pressure of SF6 gas and the pressure values must be converted to the pressure under 20°C for analysis and control [6]. In this paper we calculate the pressure at 20°C utilizing the empirical formula of Beattie-Bridgman which has been proven as the most reliable formula available at the time and today in its gaseous and liquid phase by the 1992 experiment of Thuries [7]. Then the ARM control module will judge whether to output the alarm of the fault of SF6 pressure. The empirical formula of Beattie-Bridgman is shown below:

\[ p = 56.2 \gamma T (1+B) - \gamma^2 A \]  

(1)
Where $p$ is the absolute pressure (Pa); $\gamma$ is the gas density (kg/m$^3$); $T$ is the thermodynamic temperature (K); $A = 74.9(1-0.727 \times 10^{-3} \gamma)$, $B = 2.51 \times 10^{-3} \gamma (1-0.846 \times 10^{-3} \gamma)$.

According the equation (1) and the value of $A$ and $B$, with the value of $p$ and $T$ confirmed, the density of $\gamma$ will be calculated through a cubic equation of it. The algorithm of Newton Iteration is used to calculate the value of $\gamma$, which will ensure the minimum truncation error. After getting the value of $\gamma$, with $T = 20 + 273$, equation (1) will be used again to calculate the pressure of $p$ at 20$^\circ$C.

4.2. The control strategy

After getting the pressure of oil and SF6, the controller judge the output according the pressure and the setting value shown blow in the Table 1. Then the IO module generates switching value which controls the joint relay. If the pressure of oil is lower than the action value, corresponding relay will work to activate the motor working until the pressure of oil achieve the release value. Other commands of closing lockout, opening lockout, reclosing lockout and alarm of high pressure of oil will also be outputted through IO module when the oil pressure lower than the action value. If the pressure of SF6 is lower than 0.45Pa, the first level alarm will be activated until the pressure reaching the release value. If the pressure of SF6 is lower than 0.40Pa, the second alarm will be also triggered.

Table 1. The setting value of pressure for oil and SF6 (20$^\circ$C)

| Item | Setting Value (Pa) | Remarks |
|------|------------------|---------|
|      | Action Value     | Release Value |         |
| Oil  | 32 ± 0.7         | 34 ± 0.7  | Oil Control               |
|      | 27.5 ± 0.7       | 28.2 ± 0.7| Closing Lockout           |
|      | 26 ± 0.7         | 26.7 ± 0.7| Opening Lockout           |
|      | 30.5 ± 0.7       | 31.2 ± 0.7| Reclosing Lockout         |
|      | 37 ± 0.7         | 36.3 ± 0.7| Alarm of High Pressure of Oil |
| SF6  | 0.45$^\circ_{-0.02}$ | ≤ 0.48$^\circ_{-0.02}$ | First Level Alarm |
|      | 0.40$^\circ_{-0.02}$ | ≤ 0.43$^\circ_{-0.02}$ | Second Level Alarm |

5. Experiment and Conclusion

The control system of SF6 high voltage circuit breaker has been applied in a circuit breaker of type of LW12-550 in the substation of Hunyuan. Fig. 6 shows the picture of the configuration software supervising the pressure and the system state.

The pressure of oil and SF6 displayed on the pressure gauge and screen of industrial PC are almost equal which shows the problem of the measure device of oil pressure and the pressure control system of hydraulic mechanism in two different devices is well resolved. Through changing the value of pressure of oil and SF6 factitiously to test the action of the controller, comparing with the result of the micro switch, the control result and precision are much better. According comparing the pressure value of gauge displayed with that of configuration software displayed, it’s proved that the communication network works well. Cutting off a part of fiber or letting a node breaking-down factitiously and then switching the contiguous nodes to the second and third transmission mode, the pressure displayed on the screen are right which proved the fiber communication network still works well. The device of optical attenuation is
used to simulate the long distance fiber communication, which proved that the communication rate is 500kbps when the communication distance is 10km. The experiment result proves that the design of the control system works well as we expected.

This paper proposes a solution of embedded control system for HVCB to replace the mechanical control method, which improving control precision for the breaker. The double-annular fiber field-bus communication network introduced improves the capability of EMI and the transmission distance, which is very suitable for the control system for the high voltage circuit breakers. Using the empirical formula of Beattie-Bridgman to calculate the pressure of SF6 at 20°C can ensure the precision of gas pressure. After the experiment proved, the control system works well in the circuit breaker of type of LW12-550, and the control system is also applicable to other types of SF6 high voltage circuit breakers.

Though the fiber communication network solves the communication problem of serious EMI, the compatible with the power electrical standard has not been solved. Nowadays standard of Communication Networks and Systems in Substations IEC61850 is progressing quickly and has more and more application in substations. So, the future work is to solve the compatible with the IEC61850 for the fiber field-bus communication network.

Fig. 6. The Picture of oil monitor and SF6 monitor

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