An Integrated Sensing Architecture Used for Depth State Perception of High Voltage Circuit Breakers

Yujie Li¹, Ke Zhao⁴, Yong Ma¹, Jian Wang*, Hua Liu², Ming Tang²

¹ State Grid JiangSu Electric Power Research Institute, JiangSu 210029, China
² Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610213, China
*Corresponding author’s e-mail: jianwang16@foxmail.com

Abstract: In order to strengthen the management of circuit breakers and sense its operation status at any time, condition-based maintenance has been carried out in power grids. Depending on the advanced condition monitoring and diagnosis technology, the abnormality of equipment can be judged and the failure of equipment can be predicted effectively. This paper discusses the state parameters need to be monitored for deep state sensing of high voltage circuit breakers. Monitoring parameters mainly include the current of opening/closing coils and energy storage motor coil, primary current and displacement of operating mechanism, respectively. And then, aiming at the complex installation environment of switch cabinet, a small integrated depth sensing node architecture is designed.

1. Introduction

High voltage circuit breaker is one of the most important high voltage switchgears in power system, and an indispensable part of power grid operation. On the one hand, it plays the role of switching operation mode of power grid in normal operation. On the other hand, the switchgear can remove the function of the fault in time when the power grid fails. Its dual functions of control and protection will directly affect the safe operation of power grid [1].

However, there are several kinds of common faults of circuit breaker such as rejection and malfunction, which include rejection of opening and closing, and incorrect opening and closing. In addition, spring operating mechanism will have abnormal energy storage and hydraulic operating mechanism will have abnormal hydraulic pressure faults. In the summary of the operation status of 12~800 kV high voltage circuit breakers in China in 2005 by the State Grid, it is shown that the malfunction caused by rejection is about 46%, the insulation failure is about 13%, the mechanical failure is about 23%, and other faults is about 18%. Operating mechanism and energy storage mechanism accounted for 8-9% of the failures, and mechanical and hydraulic mechanism accounted for about 10% of the failures [2].

With the vigorous construction of smart grid, the traditional "periodic maintenance" cannot meet the development of power system. Besides, traditional condition detection usually monitors specific signals, which makes it difficult to obtain the overall characteristics of high voltage breaker. Therefore, in order to further enhance the monitoring effect of high voltage circuit breaker equipment, more comprehensive, detailed and dynamic online monitoring is required. By building a large-scale distributed sensor network to monitor the multi-source state of high voltage breakers, it can optimize resource allocation, fault behavior prediction and fault identification.
Experts and scholars have done some researches on the state evaluation of high voltage circuit breaker. In [3], a monitoring system has been built to gather mechanical, electrical and environmental parameters of the switching process. Five common failures of permanent magnetic mechanism are simulated in [4]. Backward propagation neural network model is used to predict the circuit breaker's operation time in [5], mechanical failure monitoring in [6] and transient characteristic parameters monitoring in [7]. However, there are few studies on the design and deployment of integrated sensor networks with depth state perception.

In this paper, the monitoring principle of state depth perception of circuit breaker based on intelligent operation and inspection is analyzed. The parameters such as the current of the opening and closing coils, energy storage motor and the displacement of the operating mechanism should be monitored synchronously and continuously. Besides, a miniature integrated sensing architecture including primary current Hall-sensors, concentrator unit and LoRa data transfer unit is proposed.

2. Principle of Condition Monitoring for High Voltage Breaker

Figure 1 shows the typical structure of VS1 vacuum high voltage circuit breaker. The structure of high voltage circuit breaker mainly includes operating mechanism, transmission mechanism, lifting and buffering structure, interrupting element and energy storage mechanism. Firstly, the opening and closing signal of the control mechanism is sent out, then the energy stored in the energy storage structure is acted on the transmission mechanism by the operation mechanism, and finally the contact is closed or disconnected by the action of the interrupting element driven by the transmission mechanism.

![Figure 1. The typical structure of VS1 vacuum high voltage circuit breaker](image)

2.1 Primary Bus Current Monitoring

The electrical wear of contacts depends on the charge released during the arcing process of high voltage circuit breaker. And the charge is related to the breaking current and arcing time. In addition, other factors affecting electrical wear of circuit breaker contacts include contact materials, magnetic field structure, etc. For the same circuit breaker, the arcing time is basically the same, so its electrical wear is mainly reflected in the breaking current and breaking times [9].
Accumulated electrical wear algorithm is used to calculate the electrical wear of circuit breakers. Assuming that the electrical wear caused by each break of circuit breaker under rated short circuit current is $M$ and the corresponding allowable number of breaks is $N$, respectively, it can be considered that the allowable total electrical wear of circuit breaker is $MN$. If the allowable electrical wear of contacts of a new circuit breaker is defined as unit 1, the electrical wear caused by each operation should be $1/N$. The calculation of electrical wear of circuit breaker accords with the following table:

| $(I_c/I_e)$ | 100% | 100 | 75  | 50  | 35  | 25  | 10  | 3   |
|------------|------|-----|-----|-----|-----|-----|-----|-----|
| $Mc$       | $1/N$| $2.2N$| $5N$| $12N$| $20N$| $140N$| $300N$|     |

Where $I_c$ and $I_e$ is the breaking current and rated operating current, respectively. There are some interpolation algorithms such as piecewise linear interpolation (PLI), nearest interpolation (NI), and cubic Hermite polynomial interpolation (CHPI) could be used to interpolate those data items mentioned in Table 1. According to the technical requirements of different circuit breakers, the $N-I_c$ curves of different circuit breakers can be obtained. Therefore, electrical wear $Mc=1/Nc$ which is corresponding to any on and off current $I_c$ can be calculated. Since the number of switching times of circuit breakers is known, the total wear of circuit breakers, $W$, can be calculated as $W = \sum M_c$.

2.2 Closing and Opening Coil Current Monitoring

When the opening and closing coil of high voltage breaker receives the instruction of switch on or off in the control circuit, the auxiliary contacts are connected. The current through the coil generates electromagnetic force to drive the core pin to move. And then, the pin impact mechanism is connected so that the circuit breaker mechanism is released to complete the opening and closing action. In the process of switching on and off, the coil passes through a short current of several amperes at the moment of circuit conduction. After the closing and opening process, the auxiliary contacts are disconnected and the coil is cut off. Figure 2 shows the measured opening and closing coil current waveform. Taking the closing current waveform as an example, the current waveform includes four stages of the operation mechanism [8].

![Closing and Opening Coil Current Monitoring](image)

(a) closing coil current waveform
(b) opening coil current waveform

Figure 2. Two coil current waveforms of breaker operation mechanism

In the first stage, the rising trend of coil current is exponential and the current velocity increases to the peak due to the small back EMF affection. This stage is determined by the coil resistance and the control power supply, which can reflect the working state of the coil. And then, the second stage, the iron core begins to move and coil current begins to drop until the core stops moving. According to this stage curve, it can be judged whether there are tripping, jamming and load change of energy releasing machine in the process of core movement. The third stage, the locks of the transmission mechanism are opened by moving the contacts. The magnitude of current reflects the coil voltage and circuit resistance. Meanwhile, the current curve at this stage can reflect the working condition of the transmission mechanism of the switch body. Finally, the auxiliary contacts cut off the power supply of the coil circuit, and the final coil current drops to 0. At this stage, the current curve can reflect the working condition of the auxiliary contacts.
Therefore, the current signals of the opening and closing coils can be used as the characterization signals of the control actions of high voltage circuit breakers, and the fault types of circuit breakers can be judged by measuring the current values, such as the jamming of the operating mechanism, the blockage of the iron core, the excessive travel of the mechanism and other related problems.

2.3 Travel-Time Curve Monitoring

The travel-time curve of the circuit breaker operating mechanism refers to the relationship curve of the travel of the moving contact with time during the opening and closing operation of the circuit breaker. Figure 3(a) shows the standard travel-time curve for closing contact. It can effectively evaluate the following aspects of equipment failure: opening asynchronization, over-travel and opening distance [10].

![Travel-Time Curve Monitoring](image)

(a) travel-time standard curve for closing contact  
(b) current curve of typical energy storage motor

Figure 3. Two kinds of typical curve diagrams in the process of circuit breaker state monitoring

The closing and opening travel-time characteristics of high voltage circuit breaker are obtained by monitoring the travel signals of moving contacts. Through the travel-time signal of the contacts, the time of each event occurring during the contact movement can be extracted, and the fault can be diagnosed according to the time of the event. This method can diagnose the wear, fatigue aging and fatigue of the mechanical part of the circuit breaker.

2.4 Energy Storage Motor Current Monitoring

Usually, the energy storage device of high voltage circuit breaker is energy storage spring. Under the condition of current conduction, the energy storage motor will operate and drive the energy storage spring to pull, forming deformation energy storage. Pressure monitoring refers to the use of pressure sensors to measure the pressure conditions of energy storage spring, and to evaluate the state of spring under the condition of circuit breaker closing. The current signal of energy storage motor is measured by current sensor, and the spring state is indirectly evaluated by current signal [11].

Among the two methods mentioned above, the application of pressure sensor is limited and needs to be involved in the structure of circuit breaker. Therefore, the current measurement method of energy storage motor is usually used to obtain the state characteristics of energy storage spring. Figure 3(b) shows the current curve of typical energy storage motor. The time characteristic of motor current can indicate the running state of energy storage mechanism.

3. Terminal Node Architecture for Deep State Sensing of High Voltage Breaker

3.1 Terminal Node Deployment

Figure 4 shows the sensor deployment diagram for circuit breaker condition monitoring. The terminal nodes are deployed at four locations, namely, the switch-on/off control wire, the power supply of energy storage motor, the primary bus and the linear mechanism. At the primary bus side, Hall-current sensor is used to measure three-phase bus current. The current of switching coil and the motor is also monitored by Hall sensor, and non-direct contact is measured by passing through the middle ring of Hall sensor. Displacement sensor is installed to monitor the travel time characteristic curve of circuit breaker and
connected with the tail of the insulating pull rod and fixed in the outer shell.

Figure 4. Miniaturized depth sensing node architecture of high voltage breaker

3.2 Integrated sensors Architecture

The schematic diagram of integrated sensor architecture is shown in Figure 5. The deep state sensing architecture of high voltage circuit breaker is composed of three parts: sensor signal transmission, local acquisition data collection and data remote transmissions. Firstly, the signal transmission session refers to the use of different sensors to collect parameters such as opening and closing coil current, contact displacement, primary breaking current, etc. Sensor’s signals need to be converted, amplified and filtered through conditioning circuit module before acquisition by AD module. Therefore, the local signal collecting unit is mainly used to collect and acquire the original signals of each sensor. Considering the influence of high voltage primary side and the difficulty of layout and wiring, this Hall-current sensor integrates wireless communication functions, which can directly transmit the collected primary current data to the collection unit by 2.4 GHz wireless.

Figure 5. The schematic diagram of integrated sensor architecture of high voltage breaker

All coil current sensors and angular displacement sensors are directly connected to the signal collection unit. The current of the opening coil, closing coil, and the energy storage motor coil are collected by a direct current sensor respectively. Furthermore, it is necessary to transfer the state of circuit breaker reliably to the analysis system by means of data wide-area remote transmission such as LPWAN. In particular, a low power wide area communication technology called LoRa (Long Range) is used in our design. LoRa uses LFM (Linear Frequency Modulation) and SSM (Spread Spectrum Modulation) to maintain the same low power characteristics as FSK (Frequency-Shift Keying) modulation, increase communication distance, and change the mode of both transmission distance and power consumption. In our design, a LoRa DTU (Data Transfer Unit) is used to send data from the concentrator unit to the remote analysis system.
4. Conclusion
Aiming at the state-depth fusion sensing system of substation switchgear based on intelligent operation and inspection, a miniaturized multi-parameter sensing monitoring architecture is proposed, which can implement on-line monitoring of switching coil, closing coil and motor’s current, contact travel monitoring of key nodes. The primary-side current sensing monitoring terminal of switch buses is used to measure the switch on and off current. LoRa technology under complex electromagnetic environment of substation is used for the fast-real-time transmission of monitoring data. The reliability and intelligence level of on-line monitoring sensors in substations can be improved by deep fusion of state perception of switchgear, which is helpful to improve the construction level of IoT (Internet of Things) technology system for intelligent operation and inspection of power grid.

References
[1] Franck, C. M . HVDC Circuit Breakers: A Review Identifying Future Research Needs[J]. IEEE Transactions on Power Delivery, 2011, 26(2):998-1007.
[2] Song G, Gu N. Analysis of operation and fault of HV switchgear[J]. Distribution & Utilization in China, 2007, 24(1):6-9.
[3] Fei M, Zhu K, Zheng J, et al. Design of high voltage vacuum circuit breaker’s on-line monitoring and fault diagnosis system[C]// Advanced Information Management, Communicates, Electronic & Automation Control Conference. 2017.
[4] Yu Z, Pulong G, Chunyu X U, et al. Fault Feature Extraction Method for the Circuit Breaker with Permanent Magnetic Mechanism Based on Control Loop[J]. High Voltage Apparatus, 2017.
[5] Hou C, Yu X, Cao Y, et al. Prediction of synchronous closing time of permanent magnetic actuator for vacuum circuit breaker based on PSO-BP[J]. IEEE Transactions on Dielectrics & Electrical Insulation, 2018, 24(6):3321-3326.
[6] Cai Y, Wang Y, Chen W, et al. Reliability assessment of monitoring device for mechanical failure of high voltage circuit breaker based on FTA[C]// International Conference on High Voltage Engineering & Application. 2015.
[7] Yan H, Du L, Tan Y, et al. Transient Characteristic Parameters Monitoring and Diagnosis of the Hybrid HVDC Circuit Breaker[C]// International Conference on High Voltage Engineering and Application, 2018.
[8] Strachan S, Macarthur S, McDonald J, et al. Trip coil signature analysis and interpretation for distribution circuit breaker condition assessment and diagnosis[C]// International Conference & Exhibition on Electricity Distribution. 2005.
[9] Fan X M, He J M, Pan Y C, et al. Review of monitoring and diagnosis methods for vacuum circuit breaker electrical wear[J]. High Voltage Apparatus, 2011, 47(10):81-86.
[10] Zhang X, Yu D, Yang L, et al. Application study of the displacement sensor used for testing the mechanical properties of medium voltage circuit breaker[J]. High Voltage Apparatus, 2015, 51(7):37-41.
[11] Sun S G, Zhao L Y, Du T H, et al. Diagnosis on the mechanical fault of universal circuit breaker based on motor current analysis[J]. China Journal of Scientific Instrument, 2017, 38(4):952-960.