Research and Demonstration of Intelligent Multi-Physical Quantity Integration Sensor for Transmission Lines

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Abstract—The digital grid requires sensors to be widely deployed, safe, and reliable. At present, the single functional sensors suffered from redundant sensing system, repeated construction and low utilization rate. Therefore, this paper researched the multi-physical quantity integration sensor for a quad-bundle spacer on 500kV transmission lines. The sensor was composed of self-supplying rings and the monitoring host. Based on the non-contact current measurement technology, energy supply technology, intelligent sensing technology, low power consumption technology, reliability design technology, and other advanced technologies, this paper designed the hardware, software, and protective structure of the sensor, which can monitor the current and temperature of bubbles, channel side image and infrared image on transmission lines, ambient temperature, humidity, and air pressure. Finally, the multi-physical quantity integration sensors have been used on transmission lines in China Southern Power Grid, and the functions were verified. The sensors promote the automation, information, and digitization of monitoring transmission lines.

1. INTRODUCTION

In China, transmission lines have the characteristics of large dispersion, long-distance, crossing many areas with complex terrain and climate due to unbalanced distribution of energy resources and power demands. Monitoring operation conditions of transmission lines are important in the construction of a smart grid. At present, the transmission line monitoring technology has transitioned from the traditional ‘Human Patrol’ to ‘Human Patrol + Machine Patrol’. However, unmanned aerial vehicle (UAV) Patrol has some shortcomings, such as being vulnerable to weather, a short distance of continuous line patrol, only image monitoring volume, and so on. With the development of the Internet of things, artificial intelligent technology, and the needs of power grid digital transformation, it is necessary to establish the IoT monitoring system of perception layer, transmission layer, and platform layer for transmission line operation status monitoring. Besides, the intelligent sensing of multi-parameters is the core and basic technology of the transmission line sensing layer.

Many scholars have done a lot of research on monitoring conditions of transmission lines. In Ref.[2-4], the equivalent icing thickness of the conductor was calculated by insulator tension for monitoring transmission line icing conditions. Ref. [5] predicted transmission line mountain fires based on satellite images. Ref. [6-7] studied the image recognition algorithm of deep learning based on the images of transmission line channels and conductors and realized the fault early warning of the transmission line.
Ref. [8-9] realized conductor galloping monitoring based on Beidou technology and image technology. The above Reference monitored conditions of the transmission line by configuring different sensors, however, the single sensing terminal only has a single state monitoring function and lacks integrated sensing equipment. To sense transmission lines in the overall view, many different types of single-function sensors need to be installed, which face the problems of the redundant sensing systems, repeated construction, and low utilization rate.

In this paper, multi-physical quantity integrated sensors were proposed for the needs of power grid digital transformation. The sensors overcome the difficulties of sensor energy acquisition, integration, and structural protection technology, which realized the acquisition and transmission of multiple state parameters by a single integrated sensor terminal. This technology improved the efficiency of data acquisition and promotes the goal of automation, informatization, and digitization of intelligent monitoring of transmission lines.

2. TRANSMISSION LINE OPERATION CONDITION AND SENSING DEMAND ANALYSIS

There are various abnormal conditions in transmission line operation. Generally, the operation conditions of equipment gradually deteriorate with time. The monitoring of the operation state is the basis of line operation and maintenance. Monitoring equipment on transmission lines is usually divided into real-time monitoring and non-real-time monitoring. Common monitoring technologies are shown in TABLE 1.

The non-real-time monitoring equipment needs to be operated by maintenance personnel. Its advantages are high patrol accuracy, low misjudgment rate of human observation, however, its disadvantages are high labor cost and difficult operation in complex terrain areas. At present, non-real-time monitoring gradually adopts human-machine collaborative patrol. Based on the cycle and operation cooperation of human patrol and machine patrol, the patrol information interaction is opened up, which improves the efficiency of transmission line patrol. However, the technology still fails to quickly warn the fault.

| Classification | Monitoring technology | Function |
|----------------|-----------------------|----------|
| real-time      | UAV patrol            | Channel patrol inspection |
|                | Human Patrol          | Fine patrol inspection |
|                | Monitoring device     | Daily monitoring |
|                | Distributed fault location | Fault location |
|                | Galloping monitoring  | Abnormal galloping alarm |
|                | Icing monitoring     | Icing thickness alarm |
| non-real-time  | Sag monitoring        | Sag alarm |
|                | Insulator monitoring  | Monitoring tension and zero value of insulator |
|                | Tower inclination monitoring | Inclination and settlement monitoring |

The monitoring equipment senses operation conditions by the sensing device, and the data information is transmitted to the background terminal by the power communication network. The advantages are real-time online and rapid fault early warning. However, the disadvantages are a large amount of data, unstable power supply, and so on. At present, many separate and single sensors are used to monitor the operating conditions of the power system, which cannot realize effective integration and information sharing at the sensing level. Therefore, the development of multi-parameter information fusion and diagnosis technology is slow, which cannot meet the development requirements of the digital power grid.

Therefore, to fully coverage monitor location information of transmission lines, it is necessary to establish a perfect and systematic monitoring system through the environment, conductor, channel, and tower monitoring. The specific monitoring data are as follows:
(a) Environmental monitoring. The volume of micrometeorological monitoring devices (i.e. wind speed and rainfall) is large, which is mostly installed on the tower. While, temperature, humidity, wind speed, and air pressure sensors can be installed on various positions of the transmission line by integrated design;

(b) Wire monitoring. Its monitoring quantity is the electrical quantity and mechanical quantity of the conductor. By measuring the current and temperature of the conductor, the energy transmission state of the conductor can be monitored. By monitoring the galloping, sag, and vibration on the conductor, the mechanical characteristics can be evaluated, and the operation risks (e.g., wire breakage and strand breakage) can be prevented;

(c) Channel monitoring. The channel monitoring network of the transmission line can be constructed by visible and infrared images. The mountain fire, external damage, tree barrier, and bird's nest are quickly diagnosed based on AI recognition algorithm;

(d) Tower monitoring. By installing displacement, tilt, and other sensors on the tower, the stress state and the stability of the tower are monitored for preventing tower tilt and other faults.

According to the above monitoring requirements of transmission lines, multi-physical quantity integrated sensors are designed, which make the best of the sensor, video monitoring, communication, and image recognition technology. The integrated sensor will carry out real-time monitoring and control on the site for replacing human inspection.

3. INTEGRATED SENSOR DESIGN

3.1. Architecture Design
In this paper, the multi-physical quantity integrated sensor were designed based on 500kV four bundle conductor structure from hardware development, software development and application scenario.

The multi-physical quantity integrated sensor was proposed to collect the current of each split conductor, which supports the subsequent development of fault location and other functions. In addition, the sensor integrates various sensing functions and wireless long-distance communication modules, which causes large system power consumption. Therefore, it is necessary to design the measuring power claw (ring) to realize the self-power supply. Therefore, the independent measuring power ring was designed, which can be installed on each conductor and measure conductor current and temperature. The monitoring host was installed in the middle of the spacer, which did not affect the mechanical performance of spacer fittings. The host was connected with the measuring power rings by flexible connecting lines, as shown in Figure 1(a).

During operation, the measuring power ring was in contact with the conductor for measuring the current and temperature. Besides, the monitoring host was responsible for the data acquisition, processing and, energy management of the system.

![Architecture of sensor and Measuring power ring](image)

Figure 1. Architecture of sensor and Measuring power ring

3.2. Sensor Integration

3.2.1. Measuring power ring design
The measuring power ring is divided into three functional modules, i.e., coil energy acquisition module, current acquisition module, and temperature acquisition module.
(a) Coil energy acquisition module. The sensor obtains electric energy from the conductor by coil power acquisition and processes electric energy for supplying to the acquisition module. Specifically, the output voltage of the coil energy acquisition module is 12V, with a maximum output of 7.2W. The output voltage is larger than the power consumption of 1.9W, so the monitoring host is supplied by excess energy by cables.

(b) Current acquisition module. The current on a conductor is measured by a microsensor. Then, the current is processed into an analog signal and transmitted to the host.

(c) Temperature acquisition module. the temperature on the conductor surface is measured and processed into an analog signal for transmitting to the host.

To prevent the failure of the energy extraction module and ensure stable operation, the adaptive work management strategy was designed between the main power supply and standby battery. The battery is a lithium battery with a capacity of 3200 mAh, which can provide the system to work continuously for more than 8h. The working temperature is between -10 and 80°C, which has strong environmental adaptability. The battery is charged under high current, and the standby battery works under low current, which improves the stability and reliability of the sensing system. The structure of the measuring power ring is shown in Figure 1(b).

3.2.2 Hardware Design

The monitoring host is divided into five functional modules, i.e., power management module, sensing module, data acquisition module, main control module, and data encryption communication module. The hardware circuit architecture is shown in Figure 2.

In the design of sensor hardware, each data interface is reserved, and the standardized interfaces (e.g., SPI, I2C, or serial port) are used to transmit data. Therefore, the sensor module can be integrated standardized, which can replace the sensor module according to the application scenario. The standardized interface includes power terminal, enable terminal, function control terminal, data terminal, etc. Besides, the sensor hardware adopts a pin and cable layout design with a locking function.

The design can freely combine the sensor modules of the system. When monitoring functions are less, some sensor modules can be removed to reduce the sensor cost; When the monitoring function needs to be added, the number of sensors (such as cameras) can be increased to improve the monitoring accuracy.

To ensure stable and reliable data transmission, three communication interfaces are designed, i.e., Bluetooth, WiFi, and 4G. Bluetooth communication has the function of a communication relay, which can receive data from other monitoring devices near the sensor. The WiFi module is used for sensor debugging and configuration, which can support Ad Hoc network transmission. Besides, the 4G module is the main channel for sensor data transmission. It uses the special IOT network card of CSG for communication. The data is directly connected to the IoT platform, which is safe and reliable.
3.2.3. Software Design

The software system was developed in layers according to business, function, and hardware. As shown in Figure 3.

Software application is divided into three parts, i.e., configuration system, operation system, and upgrading system, as shown in Figure 4. Specifically, the configuration system is used for calibration, installation, and commissioning in the field. The operation system is the logic for the normal operation of the sensor. The upgrading system provides system function expansion with the remote wireless upgrade function. According to the adjustable working interval, the sensor can maintain a low-power standby state for the rest of the time.

3.2.4. Protective Structure Design

The multi-physical quantity integrated sensor often operates outdoor with high temperature, high humidity, icing, and other harsh environments for a long time. Therefore, the device must meet the high IP protection design, and heat dissipation, and insulation functions.
The host is protected by a multi-layer coil for IP67 protection grade. Because the internal heating component is mainly MCU, however, the total calorific value is not high, the overall heating of the device is mainly caused by external sunlight. Therefore, referring to the design of louvers, the mesh sunshade and ventilation hood were added to the shell on the host for dissipating heat. The structure is shown in Figure 5.

4. POWER GRID OPERATION TEST AND RESULTS
At present, the multi-physical quantity integrated sensors have been applied in the five provinces of the China Southern Power Grid. The device can be installed on energized or de-energized. Besides, special installation tools were developed for quick installation. Multiple key parameters can be measured at one installation which can reduce the total cost. The sensor was installed on the field as shown in Figure 6.

![Figure 6 Sensor installed on the line](image)

The images from the sensor installed in Diqing transmission line are shown in Figure 7.

![Figure 7 Images monitors by sensor](image)

The measurement images and data from the integrated sensor verify the pre-designed functions, which realized the image acquisition in front, behind, and below the transmission line channel. Besides, the current and temperature of the conductor can be measured, and the parameters (e.g., conductor galloping and sag) can be calculated. This technology established the foundation for the automation, informatization, and digitization of intelligent monitoring of transmission line.

5. CONCLUSIONS
For supporting the construction of digital power grid and build the new power system, a large number of micro intelligent sensors must be deployed. Therefore, an intelligent multi-physical quantity sensor was proposed in this paper. Relying on non-contact current measurement, energy supply, intelligent sensing, low power consumption, and reliability design technology, different types of sensing modules were integrated into one sensor for monitoring the condition of the transmission line conductor side and
channel side,. Finally, the pilot application and functions of the sensor were carried out in the field, which established the technical foundation for intelligent monitoring of transmission lines.

Nevertheless, the proposed intelligent sensors were performed on a few transmission lines. According to the plans, the intelligent sensors will widely apply in CSG for intelligent and digital monitoring transmission lines. In addition, there is a need for mathematical relationships between sensing data and operation conditions of transmission lines.

REFERENCES
[1] H. Bai, C. Zhou, Z. Yuan, and J. Lei, “Prospect and Thinking of Digital Power Grid Based on Digital Twin,” Southern Power System Technology, vol. 14, pp. 18-24+40, 2020.
[2] Y. Gan, Z. Du, W. Zhou, and et al., “Equivalent ice thickness calculation model of strain tower line based on icing tension monitoring system,” Electrical Measurement and Instrumentation, vol. 58, pp. 39-45, 2021.
[3] J. Li, Y. Tang, and Q. Wu, “On-line Monitoring Technology of High Voltage Transmission Cable Based on Temperature and Humidity Sensor,” Instrumentation and Measurement, vol. 40, pp. 108-111, 2021.
[4] W. Wang, L. Li, H. Li, and et al., “System for Monitoring Ice Thickness on Transmission Lines Based on Wavelet Transform and Morphological Processing,” Automatic Control Systems and Equipments, vol. 42, pp. 63-65, 2020.
[5] M. Sun, Q. Wang, Y. Sun, and Y. Chen, “Mountain Fire Monitoring and Positioning of Transmission Line Satellite Based on Image Recognition Technology,” Identification Modeling and Simulation, vol. 38, pp. 65-69, 2019.
[6] Y. Wang, H. Liu, L. Li, and et al., “Application of Image Recognition Technology Based on Edge Intelligence Analysis in Transmission Line Online Monitoring,” Electric Power ICT, vol. 17, pp. 35-40, 2019.
[7] J. Zhao, X. Zhang, J. Zhao, and et al., “Research on Icing Monitoring Method of Transmission Lines Based on Image and Stress,” Automation and Instrumentation, vol. 33, pp. 54-58, 2018.
[8] F. Guo, Z. Fan, W. Yu, “Research on 110kV Transmission Line Galloping Monitoring Technology Based on Power Internet of Things,” Electrical technology, vol. 22, pp. 113-115, 2020.
[9] Z. Zhang, L. Lang, J. Yan, and et al., “Transmission Line Galloping Monitoring System Based on Beidou Ground-based Augment System,” Electric Power ICT, vol. 18, pp. 42-47, 2020.