Multi-source information classification evaluation and status monitoring of Synchronous condenser excitation system

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Abstract. The excitation system of the synchronous condenser plays a significant role in reactive power regulation and maintaining voltage stability. The existing information classification of the excitation system is not perfect and the comprehensive analysis of multiple variables is insufficient, making it difficult to evaluate the operating status of synchronous condenser. Based on the basic structure of the synchronous condenser excitation system, the working mechanism of the excitation system is analyzed, and the internal signal transmission path is sorted out. The multi-source information of the excitation system is classified from the dimensions of functional application and data type, the original data is cleaned and filtered, the key characteristic variables are screened, and the data storage, transmission and invocation architecture of the excitation information monitoring system is constructed to achieve the state monitoring and intelligent diagnosis of the excitation system.

Keywords: Synchronous condenser excitation system; reactive power; condition monitoring.

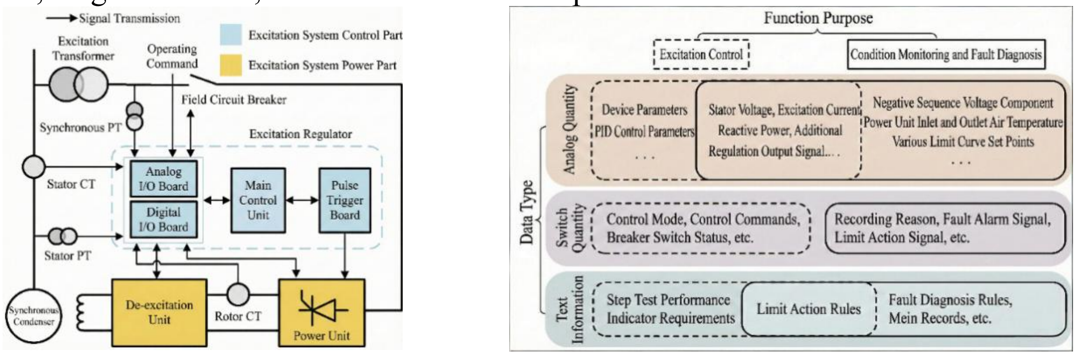
1. Introduction

To address the instability of the power grid caused by ultra-high voltage direct current transmission, synchronous condenser with large-capacity dynamic reactive power output play a significant role in the power system [1], and the rapid regulation of reactive power relies on the excitation system of the synchronous condenser [2]. Studying the fault diagnosis technology of the excitation system and designing the excitation information monitoring system are of great significance for maintaining the safe and stable operation of the synchronous condenser and the power grid [3]. Excitation system monitoring technology can be classified into three stages according to its development: manual inspection, microcomputer excitation device monitoring, and Internet remote monitoring [4]. With the expansion of the scale of the power system and the continuous improvement of its intelligence level, remote monitoring technology has become a key research direction [5, 6]. The network architecture of remote monitoring can be divided into Browser/Server (B/S) architecture and Client/Server (C/S) architecture [7]. Compared with the C/S architecture, the B/S architecture has advantages such as cross-platform compatibility and convenient deployment and maintenance, and has become a common choice for large-scale monitoring systems [8].

Following the design ideas of existing monitoring systems, this paper deeply analyzes the multi-source information of the excitation system, and starts from the functional requirements of the monitoring system to present the overall architecture and database design method of the excitation information monitoring system. The functional test results verify the practicability and reliability of the designed excitation information monitoring system. It can achieve real-time monitoring of the operating status of the synchronous condenser excitation system and fault location.

2. Analysis of the Characteristics

A self-shunt excitation mode is adopted in the synchronous condenser. Its basic structure and information classification are shown in Fig. 1 (a), including the synchronous condenser, excitation transformer, excitation regulator, power unit and demagnetization unit, etc. Fig. 1(b) presents the classification results of multi-source information based on functions and data types. From the perspective of functional application, the information used for excitation control directly participates in the regulation and operation of the system. The information used for condition monitoring and fault diagnosis focuses on the real-time perception of the system's operational status and anomaly detection. From the perspective of data type dimensions, different types of data have different forms of presentation and processing methods. Analog quantities can continuously reflect the changes of physical quantities, while switch quantities represent the system state in discrete states. Text information includes various descriptive contents such as performance index requirements, diagnostic rules, and maintenance and repair records.



(a) Basic structure (b) Multi-source information classification

Fig. 1 The basic structure and multi-source information classification of the pumped storage unit

For state monitoring variables, they can be classified into μs-level, ms-level and s-level data according to the monitoring accuracy. μs-level data is generally used to monitor excitation voltage and excitation current, analyze and process the fundamental and harmonic signals of voltage and current. ms-level data is generally used to record the performance status of the excitation system, various restricted actions and fault waveforms of the excitation system. s-level data is long-term condition monitoring data to analyze the operational development trend of the excitation system and identify potential equipment deterioration. Switch quantities are used to reflect the control logic and operational status changes of the excitation system. Input switch quantities include control commands and control modes, which are used to change the control mode of the excitation system to meet the operational requirements under different working conditions. The output switch quantities include signals such as recording causes, restricted actions, and fault alarms, and are mainly used for system status monitoring and fault diagnosis. Text information is an important data type in the excitation information monitoring system, recording various fault types of the excitation system.

3. Screening of key characteristic variables of the excitation system

3.1 Data preprocessing

To enhance data quality and reduce the impact of noise on the performance of subsequent diagnostic algorithms, it is necessary to clean the data by methods such as eliminating outliers, interpolating missing values, moving average filtering, and standardization processing. Sort the original sequence in ascending order to obtain the first quartile Q1 (at 25%) and the third quartile Q3 (at 75%). The formula for calculating the interquartile range I_{QR} is as follows:

$$I_{QR} = Q_3 - Q_1 . \tag{1}$$

Set the upper and lower limit thresholds of the confidence interval for data using (2) and (3).

$$U_{th} = Q_3 + k_{th} \times I_{QR} . \tag{2}$$

$$L_{th} = Q_1 - k_{th} \times I_{QR} . \tag{3}$$

It is determined as abnormal data and eliminated when the data is outside the threshold range. For the missing data after elimination, the linear interpolation method is used to fill in. The original data is processed by using moving average filtering. Let the original sample sequence be $\boldsymbol{X}^{\text{org}} = \left\{x_1^{\text{org}}, x_2^{\text{org}}, \ldots, x_{N_{\text{org}}}^{\text{org}}\right\}$, and N_{org} be the length of the original sample sequence. The formula for moving average filtering is as follows:

$$x_t^{\text{filter}} = \frac{1}{k_{\text{org}}} \sum_{i=0}^{k_{\text{org}}-1} x_{t-i}^{\text{org}} . \tag{4}$$

where, x_t^{filter} is the value at time t after filtering, and k_{org} is the size of the filtering window, $k_{\text{org}} = 5$ based on reference [9].

The filtered data is standardized by using maximum and minimum value normalization. All data are scaled to the unit interval through linear mapping. The specific formula is as follows:

$$\boldsymbol{x}^{\text{norm}} = \frac{\boldsymbol{x}^{\text{filter}} - x_{\min}}{x_{\max} - x_{\min}} . \tag{5}$$

where, $\boldsymbol{x}^{\text{norm}}$ are the normalized values, $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of the filtered data $\boldsymbol{x}^{\text{filter}}$, respectively.

Adopt the data standardization processing method, and the specific formula is as follows:

$$\boldsymbol{x}^{\text{st}} = \frac{\boldsymbol{x}^{\text{filter}}}{x_{\text{base}}} . \tag{6}$$

where, $\boldsymbol{x}^{\text{st}}$ represents the result after standardization processing, x_{base} represents the average value of the variable $\boldsymbol{x}^{\text{filter}}$ under normal operating conditions.

3.2 Feature quantity selection

Spearman correlation analysis was used to remove redundant features. For the given n-dimensional vectors R and S, the elements were arranged in ascending order to obtain the corresponding rank sequence $\{r_1, r_2, \ldots, r_n\}$, $\{s_1, s_2, \ldots, s_n\}$ and the rank difference sequence $\boldsymbol{d}^{\text{Sp}} = \{d_1, d_2, \ldots, d_n\}$ was calculated, where $d_i = r_i - s_i$ represents the rank difference at the i-th position. The calculation formula of the Spearman correlation coefficient ρ is:

$$\rho = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} . \tag{7}$$

After Spearman correlation analysis and eliminating redundant features, the key characteristic variables of the excitation system are shown in Table 1.

Table 1. Key Characteristic Variables of the Excitation System

Flag	Variable	Flag	Variable
F_1	stator voltage	F_9	power stabilizer_B output
F_2	excitation current	F_{10}	power stabilizer_
F_3	trigger Angle	F_{11}	negative sequence percentage of stator voltage
F_4	active power	F_{12}	negative sequence percentage of stator current
F_5	reactive power	F_{13}	inlet air temperature of the power cabinet
F_6	stator current	F_{14}	outlet air temperature of the power cabinet
F_7	power stabilizer_P output	F_{15}	temperature of the rectifier
F_8	power stabilizer_W output	F_{16}	temperature of magnetic field circuit breaker

4. Design of Excitation Information Monitoring System

4.1 Overall architecture design.

The overall architecture of the designed monitoring system of excitation information is shown in Fig. 2, which includes a four-layer structure: the field device layer, the data acquisition layer, the system application layer, and the user access layer.

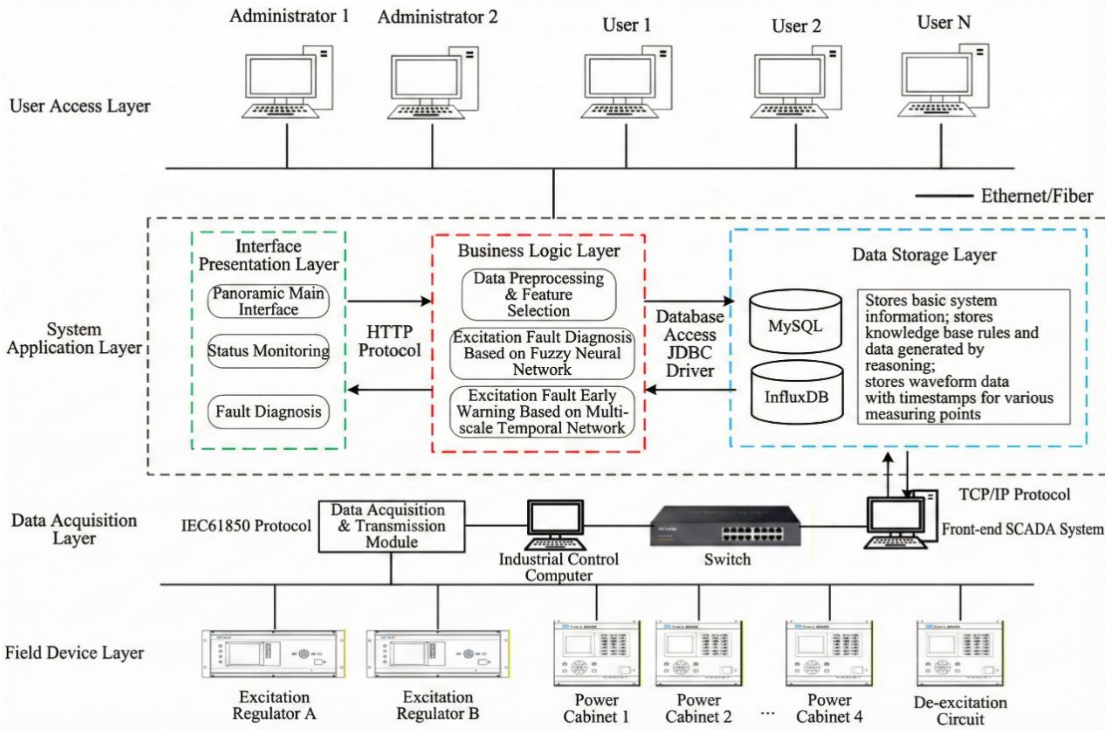


Fig. 2 Overall architecture of the excitation information monitoring system

The field device layer and the data acquisition layer form a complete data acquisition and transmission path. The system application layer adopts a B/S architecture design and is divided into interface display units, business logic units and data storage units. The interface display unit is the main interface of the monitoring system, responsible for visualizing the data to facilitate users' viewing of the operating status of the excitation system. This unit interacts with the business logic layer through the HTTP protocol for requests and responses, ensuring rapid data response and real-time updates. The business logic unit adopts Java as the development language, receives various requests from the web side, and interacts with the data storage layer through the JDBC driver at the same time. The data storage unit is used to store multi-source information of the excitation system, including operation monitoring data, equipment parameters and fault alarm records. The user access layer is responsible for connecting user devices to servers and completing identity verification.

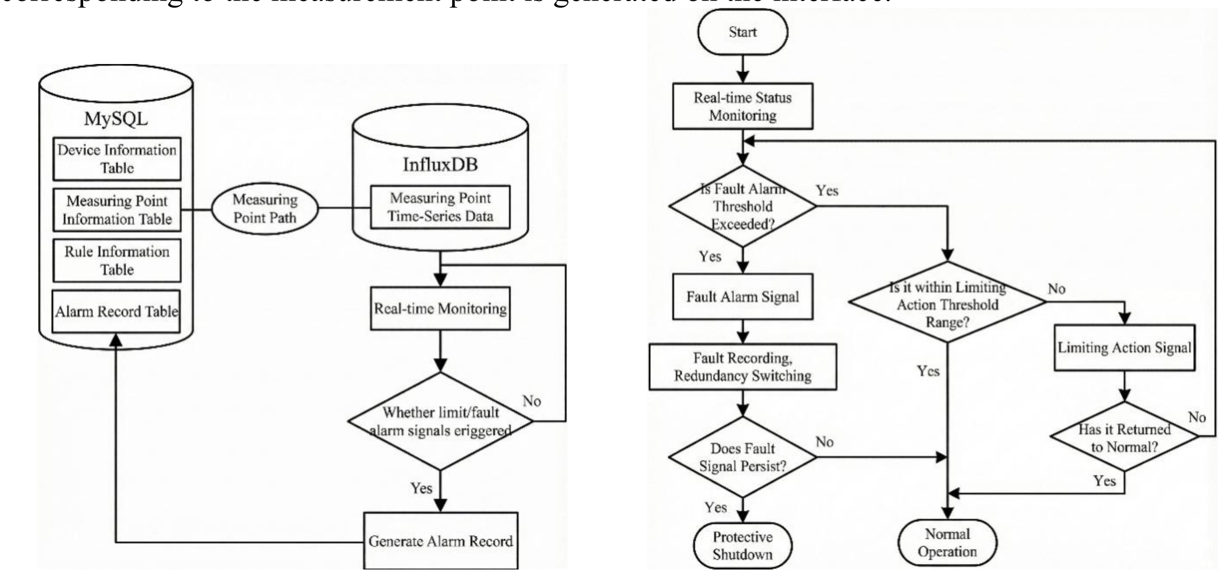
4.2 Database design.

The database design of the monitoring system adopts a dual-database collaborative storage architecture of MySQL and InfluxDB, fully leveraging the structured query capabilities of relational databases and the efficient storage characteristics of time series databases. The MySQL database stores structured data such as basic device information, measurement point information, diagnostic rules, and alarm records, while the InfluxDB database stores measurement point data with timestamps.

The database storage architecture and signal transmission process are shown in Fig. 3. MySQL establishes associations with InfluxDB through the measurement point paths in the measurement point information table to achieve unified data management and efficient query.

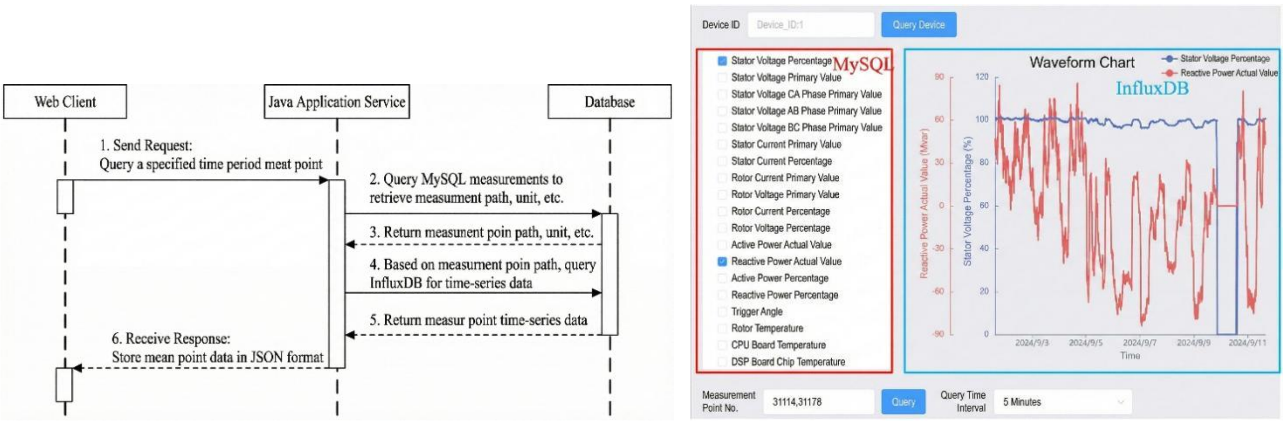
5. Evaluation of implementation effect

Taking the excitation system of a certain synchronous condenser as the research object, the main manifestations of condition monitoring are the reading and visualization of operation data. The functional sequence of data reading is shown in Fig. 4 (a). Based on the HTTP protocol, requests are sent from the web page to the backend Java service, and the JSON format data transmitted from the backend is received. Since MySQL and InfluxDB achieve data association through the measurement point path, it is necessary to first query MySQL to obtain the corresponding measurement point path, and then read the time series data stored in InfluxDB. Fig. 4 (b) shows the waveform curves of stator voltage and reactive power. The red box part is the measurement point name stored in MySQL, and the blue box part is the time series data of InfluxDB. After entering the device number, click the "Query Device" button to obtain the name of the measurement point corresponding to the queried device. The Java service can obtain the corresponding measurement point paths after selecting the required measurement points. Subsequently, by specifying the query time interval and start/end time, the user clicks the "Query" button, and the waveform curve corresponding to the measurement point is generated on the interface.



(a) Database storage architecture (b) Signal transmission process

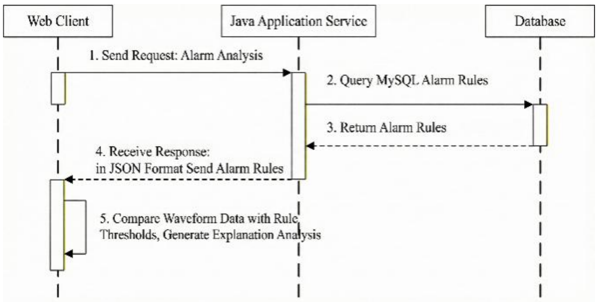
Fig. 3 Database storage architecture and signal transmission process



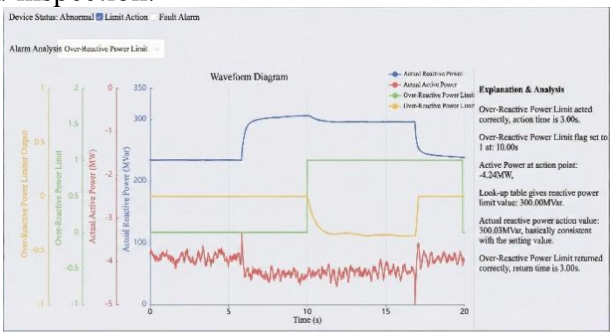
(a) Time sequence of data reading function (b) Information monitoring screen

Fig. 4 Normal data reading and status monitoring interface

The abnormal alarm module utilizes expert knowledge to interpret and analyze the restricted actions and fault alarm signals. Its functional timing diagram is shown in Fig. 5 (a). After the user sends an alarm analysis request through the web end, the trigger conditions in the MySQL alarm rule library is queried based on the alarm signal, and then compares the waveform data with the rule threshold of the trigger condition to generate a detailed explanation and analysis report. Take the over-reactive power limiting action as an example. The action time and return time, while the over-reactive power limiting happened, are used as the basis for evaluation to determine whether the limiter operates and returns correctly. When the restricted action conforms to the preset rules, the excitation system is in a normal control state and does not require manual intervention. When the restricted action is inconsistent with the preset rules, the excitation system is regarded as being in an abnormal state and requires timely maintenance and inspection.



(a) Time sequence of data reading function



(b) Analysis results of reactive power limiting actions

Fig. 5 Abnormal alarm reading and status monitoring interface

6. Conclusion

Based on functional application and data type dimensions, a multi-source information classification method for the synchronous condenser excitation system is proposed. Through data preprocessing and feature quantity selection, key feature variables are screened out, which is helpful to lay a high-quality data foundation for the excitation system state monitoring. The designed and developed architecture, data transmission and invocation mechanism of the synchronous condenser excitation information monitoring system can realize the remote monitoring and diagnosis of the synchronous condenser excitation system, and improve the automation level of the excitation system.

Acknowledgment

This research was funded by the State Grid Technology Project (No. 5500-202240497A-3-0-ZZ).

References

[1] Cheng, Ming Tian Weijie, Wang Wei, et al. Review on key technologies and latest development of new synchronous condenser [J]. Electric Power Engineering Technology, 2020, 39(2): 2-9.

[2] Hadavi Sajjad, Rathnayake Dayan B., Jayasinghe Gamini, et al. A robust exciter controller design for synchronous condensers in weak grids [J]. IEEE Transactions on Power Systems, 2022, 37(3): 1857-1867.

[3] Xiaowei Jia, Min Qin, Yingmeng Gu. Opinions for improving control functions of digital excitation regulator [J]. Automation of Electric Power System, 1999, 23(10): 45-46.

[4] Zhao Shuai, Blaabjerg Frede, Wang Huai. An overview of artificial intelligence applications for power electronics [J]. IEEE Transactions on Power Electronics, 2021, 36(4): 4633-4658.

[5] Lv Qi, Zhou Hualiang, Zhu Hongchao, et al. Development and application of new generation platform for excitation regulator [J]. Automation of Electric Power System, 2018, 42(20): 165-170.

[6] Zhang Yuandong，Liu Guangquan，Liu Chengxiang, et al. Application of NARI NES6100 excitation regulator in a Giant Hydropower Station [J]. Hydropower and New Energy, 2020, 34(9): 58-61.

[7] Ma Ning, Chen Li, Wang Xiaojun, et al. Remote monitoring system of power station [J]. Journal of Harbin Institute of Technology, 2009, 41(1): 216-218.

[8] Wu Zhifeng, Shu Jie, Cui Qiong, et al. Research on intelligent supervision platform for photovoltaic power generation system [J]. Chinese Journal of Power Sources, 2019, 43(3): 490-494.

[9] Shan Yanhao. Data-driven research on condition monitoring and fault diagnosis of offshore wind turbine[D]. Dissertation for Master's Degree of Shanghai University of Electric Power, 2021.