Research and implementation of condition monitoring and evaluation for process switch of intelligent substation

Haitao Liu¹,², Shuang Zhang¹,², Fei Xue³, Jian Niu¹, Zhongnan Xu⁴* and Yehong Han⁴

¹State Grid Ningxia Electric Power Co., Ltd. Electric Power Research Institute, Yinchuan, Ningxia, 750002, China
²Ningxia Key Laboratory of Power and Energy Security, Yinchuan, Ningxia, 750002, China
³Suqian Power Supply Branch of State Grid Jiangsu Electric Power Co., Ltd, Suqian, Jiangsu, 223800, China
⁴Wuhan Kemov Electric Co., Ltd, Wuhan, Hubei, 430223, China
*E-mail: jiangzhuoyan@kemov.com

Abstract. There are some problems in the regular inspection of switch, such as lack of real-time, lack of maintenance and over maintenance, this paper proposes a method for monitoring and evaluating the status of process layer intelligent switches. According to IEC61850 standard, the information model of switch is established to obtain the status information of the switch. The status information data is analyzed through the monitoring model of over-limit, synchronization, mutation and trend warning, and the status of switch is quantitatively evaluated by the fuzzy comprehensive evaluation algorithm. The example shows that this method can effectively evaluate the state of switch, which provides application technical support for state maintenance of process layer intelligent switches.

1. Introduction
The switch is an important communication hub for information transmission in network, whether the switches work normally is crucial to the safety, reliability and effectiveness of data and information in intelligent substation automation monitoring system[1-2]. At present, the switch maintenance mostly adopts the means of planned maintenance and accident maintenance, which has the disadvantages of lack of real-time, lack of maintenance or excessive maintenance, which can not meet the requirements of intelligent development of switch.

In recent years, State Grid Corporation of China (SGCC) has successively issued the technical specifications for ethernet switch in smart substation[3] and the notice of the state dispatching center on printing and distributing safety measures for on-site maintenance of relay protection and automatic safety devices in smart substations ([2015] No. 92)[4], which creates good technical conditions for condition monitoring and maintenance of switches. In addition, scientific research institutions have also carried out relevant research. Reference [5] established the switch information model based on IEC61850 standard, which realized the operation status monitoring and parameter unified management of the switch; reference [6] realized the acquisition and data processing analysis of switch status information based on SNMP protocol; reference [7-9] proposed fuzzy evaluation based on partial
monitoring amount and historical information, and introduced and discussed the key technologies of secondary equipment monitoring and operation and maintenance technology operation. These studies can not effectively obtain the state monitoring information data of switches, and can not provide effective technical support for condition based maintenance of switches.

From the practical application, this paper puts forward a method for monitoring and evaluating the status of intelligent switches, and based on this, develops the intelligent substation process layer switch status monitoring and evaluation system. The system can monitor and analyze the state information of the switch; combined with the status information and monitoring analysis results, select reasonable indicators, and use fuzzy evaluation algorithm to carry out quantitative evaluation on the status of the switch.

2. State monitoring and evaluation scheme of intelligent switch

The IED equipment of intelligent substation can continuously monitor the state information of key analog quantities and transmit them in the way of communication. By identifying and analyzing the long-term change law of state information, and combining the state characteristics of the analog quantity when the device is abnormal, the monitoring and evaluation of state information can be realized.

The intelligent switch condition monitoring and evaluation scheme is as follows: firstly, the information model of intelligent switch is established to describe the state monitoring data of intelligent switch; secondly, the state monitoring model of intelligent switch is established to analyze the state information data of intelligent switch; combined with the analysis results, the appropriate index is selected to establish the state evaluation model of intelligent switch, as shown in figure 1.

1) Establish the information model of intelligent switch. Establish the switch information model based on the IEC61850 standard to provide a data source for condition monitoring and evaluation of process layer switches in intelligent substation.

2) Automatically associate mapping state information. According to the technical specification of intelligent substation network switch, the association model file is established to realize the automatic association mapping of switch status monitoring items.

3) Establish the intelligent switch state monitoring model. For different state information, the analysis methods are different due to different characteristics. According to the type of state information, the state monitoring model of out-of-limit, mutation, synchronization and trend warning is established.

4) Establish the state evaluation model of intelligent switch. Considering the fuzziness of the influence of various evaluation factors on the results of the switch, the state monitoring information parameters are selected as the evaluation index to establish a perfect evaluation system to evaluate the status of the switch.
5) Intelligent switch status monitoring and evaluation. Evaluate the state of the switch with the evaluation model. According to the evaluation results, the switches are divided into four different levels: good, general, attention and abnormal, which are the basis for maintenance decision.

3. Establishment of intelligent switch state monitoring model
The state information model of the switch is the basis of the state monitoring and evaluation of the intelligent substation switch. The state information model includes public information and port information, as shown in Table 1.

| Logical Node    | Data Object | Data Description          |
|-----------------|-------------|---------------------------|
| Public Information (LLN0) | VoltSv | Device voltage            |
|          | BoardTmpSv | Power supply temperature  |
|          | CpuTmpSv  | CPU temperature           |
|          | lfspeed   | Port rate                 |
|          | lhInOcts  | Input port bytes          |
|          | lhInUnPs  | Input port unicast frames |
|          | lhInMulPs | Input port multicast frames |
|          | lhInBroPs | Input port broadcast frames |
|          | lhOutOcts | Output port bytes         |
| Port Information (APST) | lhOutUnPs | Output port unicast frames |
|          | lhOutMulPs| Output port multicast frames |
|          | lhOutBroPs| Output port broadcast frames |
|          | lhInRate  | Input port real time rate |
|          | lhOutRate | Output port real time rate |
|          | TmpSv     | Port module temperature   |
|          | LightSvT  | Port transmit light intensity |
|          | LightSvR  | Port received light intensity |

According to the switch's device voltage, power supply temperature, CPU temperature, port rate, port module sending and receiving light intensity and other status information, the state monitoring model is established, including the out-of-limit, mutation, synchronization, trend warning model [10-12].

According to “The technical specifications for ethernet switch in smart substation”, the threshold control character is established. The control word has three states: acquisition, calculation and exit.

The meanings of the three states are as follows;

- Acquisition: alarm signal analysis according to the monitoring items of the switch;
- Calculation: Analysis the sampling value according to the state monitoring items; when the threshold control character is calculation, the alarm threshold value of monitoring information needs to be designed.
- Exit: the status monitoring entry does not participate in the analysis.

1) Out of limit model
If the value of the current sampling point is greater than the set upper limit threshold, the upper limit alarm will be given; if it is less than the set lower limit threshold, the lower limit alarm will be given, as shown in figure 2.

The calculation formula of overrun is shown in formula (1)

\[ V_{al} > V_{max} \text{ or } V_{al} < V_{min} \]  (1)

In formula (1), \( V_{min} \) is the threshold value of the lower limit, \( V_{max} \) is the threshold value of the upper limit and \( V_{al} \) is the value of the current sampling point.
2) Mutation model

If the difference ratio between the current sampling point and the previous sampling point is greater than the set mutation threshold value, the sudden change alarm will occur, as shown in figure 3.

3) Same period model

If the difference ratio between the current sampling point and the sampling point on the Nth day ago is greater than the set synchronization threshold value, the synchronization alarm will be given.

Same period comparison is a calculation method based on the above mutation model. The difference between mutation model and same period model is the choice of the previous point. The last point of the mutation model refers to the sampling point which is one sampling compartment away from the current sampling point, while the last point of the synchronous model refers to the sampling point on the Nth day ahead of the current sampling point.

4) Trend warning model

Take days as the unit, such as the Nth day, take the period from the current time to the Nth day ago as the trend statistical time period, "trend warning threshold" takes days as the unit, such as the Mth day, take the period from the current time to the Mth day later as the trend warning time period. The sampling points on the Nth day ago will automatically be fitted into a straight line. It can calculate how many days the straight line can intersect the data straight line of upper and lower limits according to its slope and current value. If the calculated days are less than the Mth day, it will tend to Potential warning, as shown in figure 4.

The calculation formula of trend analysis is shown in formula (3).

\[ y' = ax + b \] (3)

To determine the regression linear equation, it is necessary to establish the regression coefficient. Take a set of data \((x_i, y_i) i=1,2,3,.....n\), when \(x=x_i (i=1,2,3,.....n)\), the observed value of \(y\) is \(y'_i\), and \(y_i-y'_i (i=1,2,3,.....n)\) describes the deviation between the actual observation value and the ordinate of the corresponding point on the regression line.
The total deviation is shown in formula (4)

$$\sum_{i=1}^{n} y_i - \hat{y}_i$$

The general practice is to use the sum of squares of the deviations to represent the total deviation, as shown in the formula (5).

$$\sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

The calculation formula of the least square method is as follows:

$$\hat{a} = \frac{\sum_{i=1}^{n} x_i y_i - nx\bar{y}}{\sum_{i=1}^{n} x_i^2 - n\bar{x}^2}$$

In formula (6), $\bar{x}$ is the average value of $x_i$ ($i=1, 2, 3, ..., n$) and $\bar{y}$ is the average value of $y_i$ ($i=1, 2, 3, ..., n$).

$$\hat{b} = \bar{y} - \hat{a} \bar{x}$$

In formula (7), $\bar{x}$ and $\bar{y}$ are the average values of $x_i$ and $y_i$, respectively. $\hat{a}$ and $\hat{b}$ are estimated values obtained from the observed values according to the least square method.

4. Establish the intelligent switch state evaluation model

It is necessary to select reasonable evaluation indicators, establish a perfect evaluation system, and evaluate the state of the switch. The analysis of switch state information about out-of-limit, mutation, synchronization and trend warning, reflects the switch status within the statistical period. The state information alarm in the statistical period can be regarded as the historical value and the historical index of intelligent switch state evaluation. The real-time index is the current value of voltage, light intensity and temperature of switch. The flow chart of switch state evaluation is shown in Figure 5.

![Figure 4. Trend warning model](image-url)
Fuzzy comprehensive evaluation

Get the evaluation results

Determination of membership function

Determination of weight

Calculation of deterioration degree

Establishment of evaluation system

Figure 5. State assessment process

1) Establishment of evaluation system

Select reasonable evaluation indexes, and engineers will evaluate the selected evaluation indexes to form a comment set.

Evaluation indexes set \( U \)={device voltage, electric temperature source, CPU temperature, port speed, sent light intensity of the port module, received light intensity of the port module, status information alarm}; state comment set \( V \)={good, general, attention, serious}.

2) Determination of weight

After establishing the evaluation indexes, the weight is given according to the importance of each evaluation indexes. Define the fuzzy subset of evaluation indexes \( \mathbf{A} = [a_i] \), \( a_i \) is the weight of \( u_i \) in the overall evaluation \(^{[13]}\).

\[
\sum_{i=0}^{n} a_i = 1
\]  \hspace{1cm} (8)

3) Calculation of deterioration degree

Due to the different characteristics of each evaluation index, the degradation rate calculation method is different. Taking the received light intensity of the port as an example, the calculation model of degradation rate is as follows:

\[
u = \frac{P_{\text{Normal}} - P_{\text{Current}}}{P_{\text{Normal}} - P_{\text{AllowMin}}} \]  \hspace{1cm} (9)

In formula (9), \( P_{\text{Normal}} \) is the good value of the received light intensity of the port; \( P_{\text{Current}} \) is the current value of the received light intensity of the port; and \( P_{\text{AllowMin}} \) is the minimum allowable value of the received light intensity of the port.

4) Determination of membership function

Typical membership functions include normal distribution, Cauchy distribution, trapezoidal distribution, triangle distribution, etc. The membership function used in this paper is an improved triangular trapezoidal state distribution model, as shown in Figure 6.
Fig. 6. Triangular trapezoidal membership distribution

In Figure 6, according to different evaluation indexes, the values of deterioration rate $v_1, v_2, v_3, v_4$ will be different according to different evaluation indexes.

5) Fuzzy comprehensive evaluation

According to the membership function, the state fuzzy relation matrix $R_{n\times m}$ is established

$$R_{n\times m} = \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{bmatrix}$$

(10)

In formula (10), $n$ is the number of the evaluation indexes, $m$ is the state comment group, and $r_{nm}$ is the membership value of the $n$ evaluation index to the $m$ state comment set.

A fuzzy linear transformation from the evaluation index to the state comment set can be induced from $R_{n\times m}$

$$B = A \circ R_{n\times m}$$

(11)

In formula (11), “$\circ$” is the generalized fuzzy operation symbol; $B$ is a fuzzy subset of the state comment set, that is, fuzzy comprehensive evaluation.

5. System design

The overall architecture of the state monitoring and evaluation system of process layer switch in intelligent substation is shown in Figure 7, which mainly includes acquisition unit and condition monitoring and evaluation unit.

Fig. 7. System architecture

The data acquisition unit is connected to MMS network and obtains the status information data of the switch in real time based on IEC61850-8 protocol.
Condition monitoring and evaluation unit mainly includes configuration module, data processing and analysis module, condition monitoring and early warning module, state evaluation and diagnosis module, and visual graphic display module. The specific functions of each module are as follows:

1) Configuration module
   The configuration module obtains the configuration data of the whole station by importing SCD file, which mainly includes the configuration of association model file, state information configuration, alarm information classification configuration, alarm threshold configuration of state monitoring, etc.

2) Data processing and analysis module
   The data processing and analysis module makes a comprehensive analysis about the out-of-limit, mutation, synchronization and trend warning of the state information sent by the acquisition unit according to the change of the status information index and the alarm threshold value.

3) Condition monitoring and early warning module
   The state monitoring and early warning module monitors the continuous change process of the state data of the switch in real time, and receives the results of the comprehensive analysis of the state information of the switch by the data processing and analysis module, so as to monitor the over-limit, sudden change, synchronization, and trend warning of the switch status information.

4) Condition evaluation and diagnosis module
   According to the relevant guidelines and standards, the condition evaluation and diagnosis module evaluates the state of the switch with the results of comprehensive analysis of the state information of the switch by the data processing and analysis module as the index of state evaluation and diagnosis. And according to the evaluation results, the switches are divided into four different levels: good, general, attention and abnormal, which are the basis for maintenance decision.

5) Visual graphic display module
   The visual graphic display module can display the output results of the state assessment and diagnosis module, as well as the real-time data and historical statistical data monitored by the state monitoring and early warning module. The real-time data display is to display the data at the current time; the historical data statistical display is to count the data within a period of time. It supports multi condition real-time query by time, data type, single condition or other combination, and supports display in table, tree view, pie chart, etc.

6. Application examples and analysis
Based on QT platform, the condition monitoring and evaluation system of process layer switch in intelligent substation is developed. The evaluation index data of a certain switch monitored by the system is shown in table 2.

Table 2. Switch evaluation index data

| Type                | Monitoring Quantity       | Value |
|---------------------|---------------------------|-------|
| Current value       | Device voltage            | 5V    |
|                     | Power supply temperature  | 46 ºC |
|                     | CPU temperature           | 50 ºC |
|                     | Port rate                 | 30%   |
|                     | Port transmit light intensity | -17dBm |
|                     | Port received light intensity | -35dBm |
| Historical value    | Alarm of condition monitoring | 134   |

According to the "technical specification for intelligent substation network switch", the scope of each evaluation index is shown in table 3.

Table 3. Range of evaluation indicators

| Index                | Upper Limit | Lower Limit |
|----------------------|-------------|-------------|
| Device voltage       | 5.5V        | 4.5V        |
| Power supply temperature | 85 ºC      | -55 ºC      |
Taking the received light intensity of the port module as an example, the good value of port received light intensity is -17dBm, and the minimum allowable value of port received light intensity is -40dBm, according to formula (9), the degradation rate $v$ is obtained as follows:

$$\frac{-17 + 33.1}{-17 + 40} = 0.7$$

According to historical experience, the selected values of port light intensity degradation rate $v_1$, $v_2$, $v_3$ and $v_4$ are 0.2, 0.4, 0.6 and 0.8 respectively.\cite{14-15} Put the degradation rate of the light intensity received by the port module into the membership function formula (11), then the fuzzy relation matrix $R_6 = [0 \ 0.5 \ 0.5]$ can be obtained. The other state fuzzy relation matrix can be calculated respectively, and finally the state fuzzy relation matrix of switch can be obtained

$$R_{7 \times 4} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0.75 & 0.25 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0.5 & 0.5 \\
0 & 0 & 0.3 & 0.7
\end{bmatrix}$$

Using the expert scoring method to determine the weight proportion of each evaluation index, the final result is $A = [0.1 \ 0.1 \ 0.15 \ 0.15 \ 0.15 \ 0.15 \ 0.2]$.

According to the weight of the evaluation index, the weighted average fuzzy evaluation is adopted, $B = A \odot R_{7 \times 4} = [0.6125, 0.0375, 0.135, 0.215]$. The fuzzy evaluation result B shows that the good ratio is 0.6125, the general ratio is 0.0375, the attention ratio is 0.315, the abnormal ratio is 0.215, and the good ratio is the highest. Therefore, the overall status of the switch is good. However, the system detected that the port module exceeded the lower limit alarm, and the historical alarm value recorded by the state monitoring is higher than that in the previous period. The maintenance personnel should immediately check whether the fiber link is broken, whether the port module of the opposite end equipment is normal, and whether the port module of the switch is normal. Through the investigation, it is found that the sensitivity of the switch port module is not enough, which leads to the lower limit alarm, so the port module should be replaced in time.

7. Conclusion

In this paper, the realization method of switch condition monitoring and evaluation is proposed. By analyzing the information model of intelligent switch, a variety of state monitoring models, such as out-of-limit, mutation, synchronization and trend, are established to analyze the information of the switch. Considering the diversity and perfection of the evaluation index, the basic information and information analysis result data are taken as the evaluation index, and the triangular trapezoid membership distribution is selected. The evaluation index weight is determined by expert scoring method, and the fuzzy comprehensive evaluation algorithm is applied to quantitatively evaluate the condition monitoring information of the switch. The results show that the evaluation method can accurately reflect the state of the switch and provide decision-making basis for the maintenance of the switch.
References

[1] Huang Xin, (2015) Development overview and technical verification of intelligent substation network switch. Electric power information and communication technology, 13: 6–11.

[2] Niu Yuan, (2019) Analysis of state maintenance of relay protection in power system. Science and innovation, 23: 134–135.

[3] Feng Ziquan, (2019) Research on power switch maintenance technology based on static multicast search. Power system protection and control, 2019,47(2): 182–187.

[4] China Southern Power Grid, (2012) Q/GDW1429-2012, Technical Specification for Network Switch of Intelligent Substation, Beijing China.

[5] Li Feng, Xie Jun, Zhao Yinfeng, Zhang Xiaobo, Feng Yong, Li Yong, (2012) IED information model of Intelligent Substation Switch Based on IEC61850. Power system automation, 36: 76–79.

[6] Zhu Lin, Wang Pengyuan, Shi Dongyuan, (2013) State monitoring information model and configuration description of intelligent substation communication network. Power system automation, 37: 87–92.

[7] Qi Jianhuai, Deng Shuai, (2018) Construction of auxiliary decision system for state maintenance of relay protection based on multi information collection. Automation and instrumentation, (04): 179–182.

[8] Wang Tongwen, Liu Hongjun, Shao Qingqing, Yu Bing, (2020) Research on intelligent early warning and fault diagnosis technology of secondary circuit in intelligent substation. Electrical measurement and instrumentation, 57: 59–63+98.

[9] Wu Jie, Jiang Zhenchao, (2019) Research on online diagnosis and prediction method of protection and control obstacles in intelligent substation. Electrical measurement and instrumentation, 56: 70–76.

[10] China Southern Power Grid, (2017) Q/DW 11361-2017, Technical specification for protection equipments' on-line monitoring and diagnosis device in smart substation, Beijing China.

[11] Liu Kun, Huang Minghui, Li Yiquan, Chen Zhiguang, Zheng Genghui, Liu Wei, Su Zhongyang, (2018) Intelligent substation fault information model and relay protection online monitoring method. Power automation equipment, 38: 210–216

[12] Xiao Fan, Wang Ziwei, Zhang Zhe, Yin Xianggen, Zhang Kanjun, Li Hengxuan, (2018) Study on maintenance strategy of relay protection system based on condition monitoring. Power system protection and control, 46: 74–83.

[13] Sun Hui, Zhang Guoqing, Gao Bo, Wang Yu, Li Yuansong, (2020) Fuzzy comprehensive evaluation of relay protection equipment status of intelligent substation by using combined weighting method. Electrical measurement and instrumentation, 57: 23–28+34

[14] Wu Junjie, Chen Cheng, Cheng Lin, Jiang Yi, Han Qin, Feng Liang, (2018) Study on condition evaluation of secondary equipment in intelligent substation based on fuzzy comprehensive evaluation method. Electrical measurement and instrumentation, 55: 72–76.

[15] Zhou Hubing, Wang Yulei, Zhang man, Zhang Huanqing, Zhang Hao, Wang Liwei, (2018) Fuzzy comprehensive evaluation of secondary equipment efficiency of intelligent substation empowered by entropy method. Electrical measurement and instrumentation, 55: 73–79.