Application of Fault Tree Analysis on Smart Meter Fault Diagnosis

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Abstract. It is of great significance to study and analyze the fault causes and rules of smart meter, quickly and accurately judge the fault location of smart meters, and improve the reliability of smart meter. Based on the analysis of smart meter's structure, the fault tree of smart meter is established. The quantitative and qualitative analysis methods of fault tree are used to sort out the characteristics and rules of smart meter's fault, and the weak links and key parts of smart meter are determined. The application results show that the fault tree analysis can effectively help technicians to locate faults quickly and reduce the processing time of faults, which has a good practical value.

1. Introduction

In today's information age, various smart devices can be seen everywhere. Smart devices are gradually recognized and favored by everyone, and smart meters are no exception. As a statutory measuring instrument, the electric energy meter can quickly obtain detailed information on electricity consumption, which is convenient and safe. According to the national statistics, during the 13th Five-Year Plan period, the number of smart meters purchased by the State Grid is more than 200 million each year, and the number is still growing. It can be seen that smart meters have become an inevitable trend to replace traditional mechanical meters in an all-round way. As the smart terminal of smart grid, smart meter not only has the basic measurement function of electricity consumption as traditional meter, but also has the function of bidirectional multi-rate measurement, user terminal control function, bidirectional data communication function of various data transmission modes and anti-stealing function. The emergence of smart meters has effectively solved the problem of on-site reading meters and collecting electricity charges for power departments; for users, it is convenient and time-saving to deliver electricity charges or pre-purchase electricity on the Internet, and can receive prompt signals in emergencies. Smart meter has become a necessary equipment for power departments and users to communicate effectively in the intelligent manufacturing environment, but once the smart meter fails, it will also cause great losses to power departments and users [1,2]. Therefore, it is particularly important to study and analyze the causes and rules of the fault of smart meters, quickly and accurately judge the fault location of smart meters, and effectively improve the reliability and stability of smart meters.

2. Fault tree analysis

2.1. Basic concept of fault tree

The fault tree starts from the root node of the tree, analyses a fault of an instance, and assigns the reasons to its child nodes according to the actual situation, connects them with logic gates, and establishes them recursively. Establishing a complex fault tree is usually a process of repeated thinking, continuous
deepening and gradual improvement. In order to establish a fault tree, the top event should be determined first, usually according to the occurrence frequency of the results of accident investigation and statistics. Secondly, the direct cause of the top event is analyzed as the intermediate event. Then, we can find out the causes of the intermediate events, and decompose them in turn until the events can no longer be divided, and call these causes as basic events. The main purpose of building a fault tree is to enable the staff to make fault prediction of the system and quickly and accurately discover the weak links of the system, so as to provide a basis for future fault diagnosis and improvement of the system [4].

2.2. Advantages and disadvantages of fault tree analysis

2.2.1 Advantages of fault tree analysis
(1) Comprehensive and intuitive. Fault tree analysis is a step-by-step decomposition method of complex systems, which generally decomposes from systems to components and then to parts, so that engineers can find the fault of the system directly and quickly.

(2) Flexible. Effective elimination and prevention of potential faults will provide effective information and basis for those who do not know the design, use and maintenance of the system.

(3) Computable and simple. Using computer software can automatically generate analysis results, and can also complete more complex and larger fault tree analysis.

2.2.2 Disadvantages of fault tree analysis
(1) The task of building a fault tree is too heavy and it is difficult to analyze. Therefore, the analyst's analytical ability is highly demanded, which limits its popularization and application.

(2) The frequency of fault events is not easy to collect and the accuracy and reliability are difficult to guarantee.

(3) In the process of building fault tree, a large number of logical operations are needed. If the analysts do not master the calculation method, it can easily lead to the negligence and omission of events.

2.3. Establishment process of fault tree
Figure 1 shows the process of establishing fault tree. The general analysis steps of the fault tree analysis method determined by the process are as follows:

(1) Determine the top event. Be familiar with analysis system to determine top events based on actual problem and failure frequency.

(2) Determine the analysis boundary and scope. Determining the scope and boundary of the analysis is the premise of quantitative and qualitative analysis. Only by defining the boundary and scope can a standardized fault tree be established. If the boundary is not clear, it is not conducive to the downsizing of fault tree.

(3) Identify intermediate and basic events. After defining the top event, find out all the reasons that lead to the occurrence of the event, including human error, environmental factors, software factors and so on. Every fault-related cause is identified as an intermediate event and a basic event in the tree.

(4) Determining the scope and boundary of analysis is the premise of quantitative and qualitative analysis. If the boundary is not clear, the fault tree will be very complex and huge, which is not conducive to analysis and diagnosis.

(5) Draw the fault tree. Starting from the top event, all the cause events are found from the top down of the tree. The cause events are linked together in the form of logic gates. A top event represents a fault tree.

(6) Qualitative and quantitative analysis. Fault tree species and data and contents related to fault events are analyzed by computer.

(7) Conclusion. Constructing a correct and reasonable fault tree is the precondition for the analysis of smart meter faults. Fault analysis is used to determine the sequence of fault analysis and diagnosis process to improve the safety and reliability of the system.
3. Establishment of fault Tree for smart meter

3.1. Structural analysis of smart meter

Although smart meter is a new product in the era of smart manufacturing, its essential attributes of energy measurement have not changed. Smart meter is still based on traditional electronic energy meter, and has been improved and expanded in function to meet the needs of smart grid construction. As shown in figure 2, the schematic diagram of the smart meter structure is presented. The current signal of the current sampling transformer and the voltage signal of the voltage sampling transformer are received and processed by the metering chip. The time is measured by the metering pulse. The power signal and the time signal are sent to the MCU to obtain the electric energy metering value. The security authentication module mainly completes the secret key function, and the cost control module mainly completes the prepayment and power cut control functions. The peripheral circuits of the micro-control unit include clock circuit, display circuit, communication circuit, data storage and alarm button. Power management mainly includes two parts: the main power supply and the backup battery. The main power
supply is used for MCU and its peripheral circuit, and the backup battery is used to supply power to the clock circuit when power is off [6-8].

3.2. Fault tree of smart meter

According to the schematic diagram of smart meter structure and the operation data of smart meter in State Grid and smart meter manufacturer, the main failure modes of smart meter whose failure rate exceeds 900PPM mainly include metering, communication, display and power supply [9]. The fault tree established by these failure modes is shown in figures 3, 4, 5, 6 and 7.

![Fault tree for failure mode of electric energy meter.](image3)

![Fault tree for metering faults in electric energy meter.](image4)

![Fault tree for communication faults in electric energy meter.](image5)
4. Quantitative analysis of fault tree of smart meter

Quantitative analysis of fault tree of smart meter system is mainly to calculate the probability of fault of the meter, and to quantitatively explain the key degree of the cause of the fault. Fault prediction of smart meters can be carried out in a timely, accurate and true way.

4.1. Probability analysis of basic events

The probability of basic event is the basis of quantitative analysis of fault tree in smart meter system. It represents the possibility of occurrence of the event. It is an objective demonstration, not a subjective verification. In the fault tree analysis, according to the actual operation of each component, the basic event number, the time name, and considering the severity factor, the probability is calculated. The closer the probability is to 1, the more likely the event will occur. There are 30 basic events in the fault tree. The probability statistics of each event are shown in Table 1.

Table 1. Probability statistics of basic events.

| No. | Probability | No. | Probability | No. | Probability | No. | Probability |
|-----|-------------|-----|-------------|-----|-------------|-----|-------------|
| X1  | 0.0005      | X7  | 0.001       | X13 | 0.001       | X19 | 0.001       | X25 | 0.0005      |
| X2  | 0.0005      | X8  | 0.0005      | X14 | 0.002       | X20 | 0.0005      | X26 | 0.002       |
| X3  | 0.0005      | X9  | 0.0005      | X15 | 0.002       | X21 | 0.001       | X27 | 0.0005      |
| X4  | 0.001       | X10 | 0.0005      | X16 | 0.0005      | X22 | 0.001       | X28 | 0.002       |

Figure 6. Fault tree for display faults in electric energy meter.

Figure 7. Fault tree for power supply faults in electric energy meter.
4.2. Probability calculation of top event

In the fault tree of smart meter system, all basic events from X1-X30 are independent, and the probability of top event "smart meter system fault" can be calculated according to equation (1):

\[ g = \sum \phi(X) \prod_{i=1}^{n} q_i^{x_i} (1-q_i)^{1-x_i} \]  

(1)

In equation (1), \( g \) represents the probability calculation function of the top event; \( q_i \) is the probability of the occurrence of the \( i \)th basic event; \( \prod_{i=1}^{n} \) is the probability product of \( n \) basic events; and \( \Phi(X) \) is the structure function of the fault tree, which is defined as follows:

\[ \phi(x) = \begin{cases} 1 & \text{Top event occurrence (fault)} \\ 0 & \text{Top events do not occur (normal)} \end{cases}, X = (X_1, \ldots, X_n) \]

According to the probability of basic events in Table 1 and equation (1), the probability of smart meter fault is 0.0327.

4.3. Calculation of probability importance

The probability importance is the degree to which the probability of the top event is affected by the change of the probability of each basic event. It is usually expressed by \( I_g(i) \). Since the probability function of top event occurrence \( g \) is a multiple linear function, the probability importance coefficient of the basic event can be obtained by calculating the first partial derivative of the independent variable \( q_i \). According to the calculation equation (2), that is:

\[ I_g(i) = \frac{\partial g}{\partial q_i} \]  

(2)

The results are shown in Table 2.

| No. | Probability | No. | Probability | No. | Probability | No. | Probability |
|-----|-------------|-----|-------------|-----|-------------|-----|-------------|
| X1  | 0.9678      | X7  | 0.9678      | X13 | 0.9683      | X19 | 0.9683      | X25 | 0.9678      |
| X2  | 0.9678      | X8  | 0.9683      | X14 | 0.9693      | X20 | 0.9678      | X26 | 0.9693      |
| X3  | 0.9678      | X9  | 0.9678      | X15 | 0.9693      | X21 | 0.9683      | X27 | 0.9678      |
| X4  | 0.9683      | X10 | 0.9678      | X16 | 0.9678      | X22 | 0.968      | X28 | 0.9693      |
| X5  | 0.9683      | X11 | 0.9683      | X17 | 0.9677      | X23 | 0.9678      | X29 | 0.9721      |
| X6  | 0.9683      | X12 | 0.9693      | X18 | 0.9683      | X24 | 0.9693      | X30 | 0.9676      |

4.4. Calculation of critical importance

The critical importance of basic events is expressed by the ratio of the relative change rate of the occurrence probability of basic events to the relative change rate of the occurrence probability of top events. It measures the importance of each basic event from two aspects of sensitivity and its occurrence probability. The calculation is as equation (3):

\[ I_g(i) = \frac{q_i}{g} I_g(i) \]  

(3)

The results are shown in Table 3.

| No. | Critical importance | No. | Critical importance | No. | Critical importance | No. | Critical importance |
|-----|---------------------|-----|---------------------|-----|---------------------|-----|---------------------|
| X1  | 0.0148              | X7  | 0.0148              | X13 | 0.0296              | X19 | 0.0296              | X25 | 0.0148              |
| X2  | 0.0148              | X8  | 0.0296              | X14 | 0.0593              | X20 | 0.0148              | X26 | 0.0593              |
| X3  | 0.0148              | X9  | 0.0148              | X15 | 0.0593              | X21 | 0.0296              | X27 | 0.0148              |
| X4  | 0.0296              | X10 | 0.0148              | X16 | 0.0148              | X22 | 0.0296              | X28 | 0.0593              |
Using the quantitative analysis results of fault tree of smart meter, the probability of fault occurrence can be found directly through the value, which provides directional guidance for fault diagnosis and formulation of reasonable fault removal scheme. It also avoids blind operation or no way to start when facing failure, and can effectively locate the fault location, thus making the implementation of fault removal measures more targeted.

### 5. Qualitative analysis of fault tree of smart meter

The purpose of qualitative analysis of fault tree of smart meters is to identify all the fault types that lead to the top events, find out the unknown faults and analyze the fault characteristics of smart meters, so as to improve and optimize the quality of smart meters. At the same time, it can provide other important information such as maintenance, replenishment, etc. [10].

#### 5.1. Calculation of the minimum cut set

Minimum cut set is essentially representing a set of basic events which cause top events to occur in the minimum number. The more the minimum cut sets are, the more dangerous and difficult to control the system is. According to the mathematical and statistical cut set calculation method, such as equation (4), 30 minimum cut sets in the top event "smart meter system fault" are calculated as follows:

$$T = K_1 + \cdots + K_m$$  \hspace{1cm} (4)

| \(X_5\) | \(X_{11}\) | \(X_{17}\) | \(X_{23}\) | \(X_{29}\) |
|---|---|---|---|---|
| 0.0296 | 0.0296 | 0.0118 | 0.0148 | 0.1487 |

| \(X_6\) | \(X_{12}\) | \(X_{18}\) | \(X_{24}\) | \(X_{30}\) |
|---|---|---|---|---|
| 0.0296 | 0.0593 | 0.0296 | 0.0593 | 0.009 |

Using the calculated minimum path set, combined with objective conditions and economic factors, the best scheme to control the occurrence of smart meter faults can be selected to reduce the occurrence frequency of smart meter faults.

#### 5.2. Calculation of minimal path set

The minimum path set is also a kind of set, which represents the minimum that the top event does not occur. By finding the minimal path set, it can effectively prevent the top event from happening. With more minimal path sets, there will be more ways to prevent the top event from happening and more flexible solutions, and the system will be safer. According to the mathematical and statistical cut set calculation method, the equation is (5). It is calculated that there are 30 minimal path sets in the top event "smart meter fault":

$$X_1*X_2*X_3*X_4*X_5*X_6*X_7*X_8*X_9*X_{10}*X_{11}*X_{12}*X_{13}*X_{14}*X_{15}*X_{16}*X_{17}*X_{18}*X_{19}*X_{20} *X_{21}*X_{22}*X_{23}*X_{24}*X_{25}*X_{26}*X_{27}*X_{28}*X_{29}*X_{30};$$

$$\bar{T} = P_1 + \cdots + P_i$$  \hspace{1cm} (5)
Using the calculated minimum path set, combined with objective conditions and economic factors, the best scheme to control the occurrence of smart meter faults can be selected to reduce the occurrence frequency of smart meter faults.

5.3. Calculation of structural importance

The structural importance means that, under the premise that the probability of each basic event is the same, the structure analysis of fault tree is used to explore which basic event is the main cause of the top event. The arrangement of all basic events according to the importance of structure is conducive to the selection of high-quality smart meter parts by technicians, and is conducive to more standardized management and control.

In the fault tree of smart meters, the calculation equation is as follows:

\[ I_{q}(i) = I_R(i)|_{q=0.5}, \quad i=1,2,\ldots,n \quad (6) \]

According to the calculation results and the field fault treatment report, the structural importance of the system is obtained as follows:

\[ I(X30)=I(X29)=I(X28)=I(X27)=I(X26)=I(X25)=I(X24)=I(X23)=I(X22)=I(X21)=I(X20)=I(X19)=I(X18)=I(X17)=I(X16)=I(X15)=I(X14)=I(X13)=I(X12)=I(X11)=I(X10)=I(X9)=I(X8)=I(X7)=I(X6)=I(X5)=I(X4)=I(X3)=I(X2)=I(X1). \]

6. Conclusion

Based on the analysis of the statistical investigation results of the fault history data of smart meters and the analysis of the structure of smart meters, the fault tree of smart meters is established. Through quantitative and qualitative analysis of fault tree of smart meter, the probability characteristics of fault occurrence of smart meter are sorted out. The fault characteristics of smart meter are explored from different angles, and the general rules of fault analysis of smart meter are formed using fault tree. The application results show that the fault tree analysis method can effectively help the relevant technical personnel to locate, diagnose and deal with the faults, reduce the time of fault treatment, and improve the quality management level of smart meter, which has good practical value [11,12].

References

[1] Ni, S.X., Zhang, Y.F., Yi, H., Liang, X.F. (2008) Intelligent Fault Diagnosis Method Based on Fault Tree. JOURNAL OF SHANGHAI JIAOTONG UNIVERSITY,42:1372-1386.
[2] Zhu, Y.N., Xu, Q., Liu, J., Tian, Z.Q., Zhou, C. (2016) Data Mining Application in Smart Meter Fault Analysis. Jiangsu Electrical Engineering, 35:19-23.
[3] Chen, G.H., Zhang, G.B., Ren, X.L., Zhao, X. (2009) Diagnosis Method and Simulation of Supply Chain’s Reliability Based on Fault Tree Analysis. Computer Integrated Manufacturing
Systems, 15:2305-2307.

[4] Barbara, T.C., Krzysztof, B. (2010) Analysis of Undesirable Events Scenarios in Water Supply System by Means of Fault Tree Method. Journal of Konbin, 35: 309-320.

[5] Luo, R.R., Long, L., Zhang, Y., Wang S., Chu, Y.W., Tian, C.M., Ji, Y.T. (2014) Research on the Fault Analysis Method for Black Screen of the Single Phase Smart Meter Based on the Fault Tree Theory. Electrical Measurement & Instrumentation, 51:6-10,17.

[6] Huang, Z.Q. (2012) Analysis of Black Screen Fault of Single Phase Electronic Energy Meter. GUANGXI ELECTRIC POWER, 35:78-80.

[7] Zhang, X., Duan, X.M., Jiang, X.Q., Cui, X.Y., Zou, Y. (2014) Fault Analysis and Preventive Measures for Smart Meter Battery. Electrical Measurement & Instrumentation, 51:24-27.

[8] Xu, Q., Zhou, C., Ji, F. (2013) Influence on Metering Error of Smart Meters Caused by Date Overflow of Metering Chip. Electrical Measurement & Instrumentation, 50:132-136.

[9] Purba, J.H. (2014) A fuzzy-based reliability approach to evaluate basic events of fault tree analysis for nuclear power plant safety assessment. Annals of Nuclear Energy, 70:21-29.

[10] Zhao, K., Cui H.P. (2018) Application of Fault Tree Analysis on Offshore Workover Platform Auto Drill Stem Processing System. Mechanical & Electrical Engineering Technology, 47:195-198.

[11] Chen, C. (2014) Intelligent Analysis on the Malfunction Meter Based on the Electric Energy Data Acquisition System. Electrical Measurement & Instrumentation, 51:18-22.

[12] Li, P., Yang, X., Chen, X., Gao, J.G., Li, S. (2017) Analysis of the undervoltage fault of single phase intelligent electric energy meter. Industrial Instrumentation & Automation, 4:113-114,120.