Human Operating Risk Assessment for Outdoor Terminal Box of Electric Power

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Human Operating Risk Assessment for Outdoor Terminal Box of Electric Power

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Abstract: In the process of maintenance and repair for outdoor terminal box of electric power, safety accidents often occur due to human factors. For the correct evaluation of operation process of man-made factors on the failure and the effect of outdoor terminal box, in this paper, the common performance condition of the CREAM (Cognitive Reliability and Error Analysis Method) model be used to analyze the human behavior mechanism and behavior reliability of the terminal box operation process. Moreover, the SLIM (Success Likelihood Index Method) model is used to calculate the probability of human error, and the proportional hazard model is used to calculate the outdoor terminal box's own failure rate. Taking a circuit breaker terminal box as an example, the simulation results show that the corresponding probability of human error is 1.56%, the equipment failure rate is 0.84%, the risk value of the system is 10.7%, and the risk level of the system is 3. From the probabilistic perspective, the effects of human error are higher. Hence, if management department controls the influence factors, the risk level of system can be decreased.

Key words: Cognitive Reliability and Error Analysis Method; Success Likelihood Index Method; Proportional Hazard Model； Operating Risk Assessment for Outdoor Terminal Box

0 Introduction

As the intermediate link between outdoor electrical equipment and indoor monitoring, protection, communication and other equipment, outdoor terminal box is an important part of modern power system.[1]Due to outdoor terminal boxes and terminals must be on-site checked, loop tested, retrofitted, and equipment replaced,human error has become one of the major risks of power system accidents.For example, on September 12, 2013, a circuit breaker mistakenly closed at Nuozhadu power plant. The reason for the accident was that the workers misconceived the external lines of the terminals of the two loops. On May 17, 2016, a bus trip accident occurred in Qujing Substation. The reason was that the wrong connection caused too much current. Therefore, it is of great significance to study the reliability of outdoor terminal box operators to reduce the risk of the power system.

At present, the research on the reliability of outdoor terminal box of power system at home and abroad only focuses on environmental factors, mainly analyzing the influence of humidity, box rust and foreign matter on the reliability of terminal box, and designing the device including monitoring, dehumidification and other functions. Some scholars at home and abroad also have analyzed the reliability of terminals. In terms of machinery, literature [6] analyzed the reliability of terminals from the perspective of terminal plug and pull force, and found that the contact area was the direct cause affecting the reliability.Literature [7] analyzed the influence of pressure, temperature, lubricant and other factors on the contact performance of terminals. The influence of vibration stress on the reliability of terminals is analyzed and simulated in literature [8]. These studies are aimed at the physical reliability of the terminal box. However, the reliability and failure risk rating of outdoor terminal box operators are rarely involved.

In this paper, firstly, SLIM(Success Likelihood Index Method) model is used to calculate Human error probability, and the weight problem is solved by Analytic Hierarchy Process (AHP).Proportional Failure model (PHM) was then used to compute the equipment failure rates. Finally, the function decomposition method is adopted to fuse the probability of human error and equipment failure rate into system failure probability, and the value concept is adopted to evaluate the loss of failure consequence. Failure consequence loss and failure probability jointly determine the risk level of the system. According to the risk level of the system, the management and scheduling department can make better decisions.

1 Probability of human error and equipment failure rate

1.1 Probability of human error

The CREAM model[9] believes that the behavioral output of people depends on the situational environment in which people complete tasks. It ultimately determines the behavioral output of people by influencing people's cognitive control mode and its effects in different cognitive activities. The CREAM model takes into account many influencing factors such as environment, people themselves and organizations, so it is more in line with the actual situation. This model proposes nine classes of Common Performance Condition (CPC), which are often used as factors influencing the output of human behavior. Due to the needs of the actual scenario, it is not enough to only rely on CPC to measure the human operation factor impact factor of a specific problem, it must be subdivided.

Based on the actual outdoor terminal box scenario, CPC was subdivided into secondary influencing factors: organizational integrity, working conditions, availability of plans, available time, physiological rhythm, adequacy of training and experience, and quality of teamwork. Each secondary influencing factor represents the factors that may affect human behavior during terminal box operation, and seven corresponding decisive factors are selected: rules and regulations, equipment condition, operation difficulty, personnel arrangement, physiological state, experience level and teamwork. Under different working scenarios, each secondary influencing factor has different influences on people. This paper uses a weighted method to calculate the total influence index of these factors on people (hereinafter referred to as the success likelihood index).

According to Vestrucci's SLIM model 2[10], each influencing factor should contain two attributes: weight and value. The success likelihood index *SLI*, and the relationship between the Probability of failure(*Pf*) and success likelihood index *Pf* were represented by equation(1) and (2):

$$SLI = \sum_{i}^{N} \omega_i r_i, 0 \le SLI \le 100 \qquad (1)$$

$$Pf = \exp(aSLI + b) \qquad (2)$$

where, ω_i is the importance weight of the influential factor in the item *i*; r_i is the value of the influencing factor in item *i*, which is determined by the actual situation; N is the number of influencing factors; A and B are constants. When r_i is 0, the corresponding influencing factor is in the worst case. Different compromise situations can be endowed with different values, which are determined by the actual scenario.

Combining CPC in CREAM method, the probability of human error can be obtained by AHP-Slim[11] method. To be specific, first consider the actual working scene, select the appropriate CPC, and then analyze the secondary influencing factors contained in it. Secondly, in the form of expert questionnaire, the value of second-level influencing factors of a certain practical operation is judged and the judgment matrix is obtained, and then the weight vector is obtained. Finally, consistency check is carried out. If it passes, the human error probability is calculated according to equations (1) and (2). Otherwise, the discriminant matrix needs to be adjusted repeatedly until the consistency test is satisfied.

1.2 Equipment failure rate

Research on equipment failure rate is of great significance for making maintenance plan, normal operation of equipment and resource allocation [12]. In this paper, the proportional failure probability model proposed in literature [13] is adopted to analyze the terminal box equipment failure rate. Assuming the the time before the equipment failure was denoted by the random variable T , and the probability density function of T was assumed to be *F(T)*. Then,the reliability function [14] was defined by the following equation:

$$R(t) = 1 - F(t) \tag{3}$$

According to the proportional failure rate model, the calculation formula of the failure rate function was given by:

$$h(t) = \lim_{\Delta t \to 0} \frac{R(t) - R(t + \Delta t)}{\Delta t \times R(t)} = \frac{f(t)}{R(t)} \tag{4}$$

where, $h(t)\Delta t$ represents the probability of failure within time period Δt under the condition of normal operation before time. Weibull distribution is generally used as the model of failure rate function,is given by:

$$h(t) = \frac{\beta}{\gamma} \times (\frac{t}{\gamma})^{\beta - 1} \times e^{\sum_{i=1}^{n} \alpha_i \times S_i(t)} \tag{5}$$

In this formula, $e^{\sum_{i=1}^{n} \alpha_i \times S_i(t)}$ is called the connection function and represents the influence of the state $S(t)$ of the device at time T on the device failure rate. $S(t)$ is the vector, and the dimensions are N. α_i is the coefficient (or weight) of each state, β is the shape parameter, and γ is the characteristic parameter. They can be understood as constants to be fitted and obtained by simulation. According to Equation (3) and (4), there are:

$$f(t) = h(t) \times e^{-\int_0^t h(t)dt} \tag{6}$$

In practice, maximum likelihood estimation in statistics is often used to obtain the results. For simplicity, this paper believes that a state will affect the circuit breaker equipment. The likelihood function is as follows:

$$\begin{aligned} L(\alpha,\beta,\gamma,T_i) &= \prod_{i=1}^{n} f(T_i,\alpha,\beta,\gamma) \\ &= \prod_{i=1}^{n} \frac{\beta}{\gamma} \times \left(\frac{T_i}{\gamma}\right)^{\beta-1} \times e^{\alpha S(T_i)} \times e^{-\int_0^{T_i} h(t)dt} \\ &= \left(\frac{\beta}{\gamma}\right)^{n} \times \left(\frac{1}{\gamma}\right)^{n\times(\beta-1)} \times \left(\prod_{i=1}^{n} T_i\right)^{\beta-1} \times e^{\alpha\times\sum_{i=1}^{n} S(T_i)} \times \exp(-(\sum_{i=1}^{n}\int_0^{T_i} h(t)dt)) \end{aligned} \tag{7}$$

The last product term of the above formula contains integral and state variable. In order to obtain its specific value, continuous monitoring of the state of the device must be carried out. However, monitoring is generally non-continuous, so the exact value of the integral cannot be obtained. Assuming that the monitoring time interval does not change and its relative scale is negligible, it can be basically considered that there will be no change. Then, as long as the sum of it is obtained:

$$\int_0^{T_i} h(t)dt = \sum_{j=1}^{k_i} h(t_{ij}) \times \Delta t_i \tag{8}$$

In the above formula, when is the time of equipment failure, and the monitoring times of the equipment; Represents the time when the equipment fails, and the time series for monitoring the equipment.

According to Equation (8), the logarithm of the result obtained by equation (7) is taken and the partial derivative of each parameter is calculated, making it 0. A system of equations containing three equations, including three unknowns, can be solved by matlab program, or numerical solution can also be obtained by quasi-Newton method.

2 Failure risk assessment model

In order to take the hardware and human factors of the terminal box into account the failure risk of the system, the method of functional decomposition [16] is adopted to grade the risk level of the terminal box of outdoor circuit breaker.First, define the system as a collection of entities that perform a series of task functions.And define the functions completed by the circuit breaker terminal box or part of the device; Logical nodes are defined as the smallest part of data exchange and abstract the whole or part behavior. Logical connection is defined as the communication line between logical nodes with directivity. Define communication information chip as the information attribute of communication connection; Function tree is defined as the system function structure chart formed based on functions if there are multiple functions in the system and the functions are independent of each other and do not affect each other.

When the definition condition of the function tree is satisfied, the total function failure risk level of the system can be calculated according to the sub-function failure risk level:

$$RISK = \sum_{i=1}^{RN} \omega_i^{\,r} \times risk_i \tag{9}$$

In the formula, RISK is the failure RISK level of the parent function, RISK is the failure RISK level of the sub-function it contains, RN is the number of sub-functions it contains, ω^{r} is the RISK transfer weight of each sub-function, indicating the degree of influence of sub-function failure on the total function failure, which can be obtained by analytic hierarchy process. The total failure risk level of the system can be obtained by layering the weighted sum of the function tree.

Below, introduce the calculation method of risk level.

Since the circuit breaker in the terminal box needs to be checked manually, the failure probability of the circuit breaker with human factors taken into account should be calculated:

$$p^{'}(t) = 1-(1-p(t))(1-Pf) \tag{10}$$

Where, $p(t)$ is the failure probability of the circuit breaker without considering human factors, namely the equipment failure rate, and $p^{'}(t)$ is the failure probability of the circuit breaker after considering human factors.

In order to fuse the failure probability of each logical node of the system considering human factors into the total failure probability of the system, it is assumed that there are only two working states of logical nodes and logical connections, namely, effective and failure. Logical node pair, logical connection pair, logical connection pair and logical nodes have no interaction and are independent of each other. Communication delay is 0, that is, assume that the speed of information transmission is infinite. The function can be considered as a series system of logical nodes and logical connections, from which the function failure probability can be obtained:

$$p_F = 1-\prod_{i=1}^{n}(1-p_{1i})\prod_{j=1}^{m}(1-p_{2j}) \tag{11}$$

In the formula, p_{1i} and p_{2i} are logical nodes, error probability of logical connections (corrected by using human error probability), n and m are logical nodes, number of logical connections, and p_F is the total probability of system failure.

The value of a logical node should be determined by the value and number of logical connections it outputs, and the value of logical connections should be determined by the security attribute level of the communication information chip. Based on this, logical connections and logical nodes are defined, and the system value calculation formula is as follows:

$$V_1 = \ln \frac{e^{SE} + e^{IN} + e^{US}}{3} \tag{12}$$

$$V_2 = (V_1)_{\max} + \sum_{i=1}^{s-1} \frac{(V_{1i}{}^{n\max})(9-(V_1)_{\max})}{9s} \tag{13}$$

$$V_3 = (V_2)_{\max} + \sum_{i=1}^{q-1} \frac{(V_{2i}{}^{n\max})(9-(V_2)_{\max})}{9q} \tag{14}$$

Where, V_1, V_2, V_3 are respectively logical connections, logical nodes, and the quantified value of the system. They have no unit and are only used to reflect the severity of functional failure. Superscript 5 represents the element remaining after the maximum value of the output logical connection value contained by the logical node is removed; 7,8 respectively represent logical connections and the number of logical nodes; *SE,IN,* and *US* respectively represent the confidentiality, integrity, and availability quantization levels of logical connections.

According to the above contents, the total failure probability and the total value of the system are calculated. The value of risk depends on the two values. The calculation formula is as follows:

$$R = \frac{p_F \times V_3}{9} \tag{15}$$

However, the risk value is only a percentage, which cannot be used to give real guidance. Only the risk level can give people certain psychological hints and enhance people's vigilance. In order to calculate the risk level by using the risk value, the 9-level assessment standard and the exponential function model are adopted. When the risk value is assumed to be 20%(after human factors are taken into account, the risk value is slightly increased compared with that before human factors are not taken into account), the risk level reaches the maximum, which is 9. When the risk value is 0, the risk level is at least 1. The relationship between risk level and risk value is:

$$Level = \min\{round(e^{11\times R}), 9\} \tag{16}$$

Where, *Level* is the risk Level of the system to be evaluated, and *round* is a rounding function. The description of each *Level* is shown in Table 1:

Table 1 Interpretation of Risk Level

Level	Instructions
1	The consequential loss is 0~3.6%, Acceptable,Without any adjustment,Can be operated
2	The consequence loss is 3.6%~8.3%, Slightly smaller,Can be adjusted or not, Can be operated.
3	The consequential loss is 8.3%~11.3%, Slightly smaller, Needs to be adjusted slightly, Can be performed
4	The consequential loss is 11.3%~13.6%, Small medium,Needs minor adjustment, Can be operated
5	The consequential loss is 13.6%~15.4%, Medium,Requires moderate adjustment, Can be operated,Need to be careful

6	The consequential loss is 15.4%~17.0%， Medium to large,Slightly tweaked, Can be operated, Need to be careful
7	The consequence loss is 17.0%~18.3%, Medium to large,Needs to be adjusted moderately. Can be operated,Need to be careful
8	The consequential loss is 18.3%~19.4% Much more than average，Need substantial adjustment， Can not be operated
9	Can be operated19.4%~20.4%，Too serious，Severe adjustment，Can not be operated

The entire evaluation process is shown in Figure 1.

1) Get the actual scene;

2) Calculate the probability of human error according to AHP-Slim;

3) The proportional fault model is adopted to obtain the equipment failure rate;

4) Use the human to correct the equipment fault probability to obtain the system fault probability;

5) Conduct value assessment and risk rating according to the functional decomposition method.

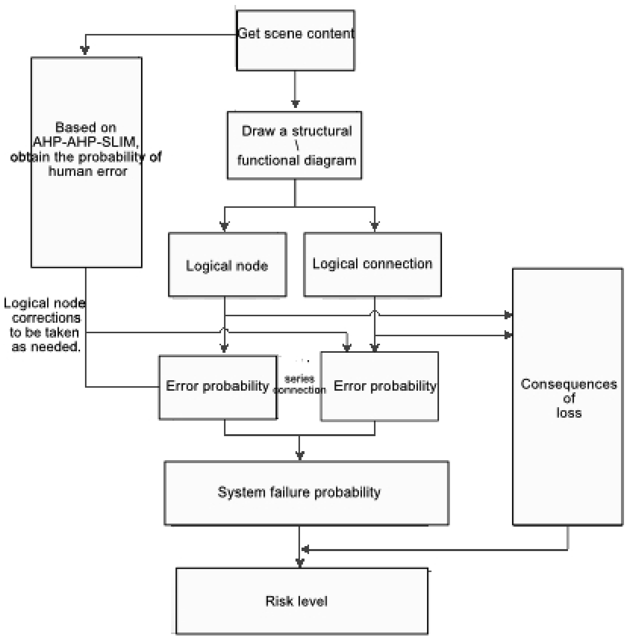

Fig 1 Process of assessing risk level of terminal box

3 Simulation Analysis

The test is carried out with a circuit breaker terminal box as the object. The device contained in the specification file is indicated as: current terminal 1, voltage terminal 1, common terminal 1, circuit breaker 3, temperature and humidity controller 1, heater 1, and in-box floodlight 1. In order to highlight the main content of the algorithm for simple analysis, this paper assumes that both voltage terminals and current terminals are considered as common terminals with the same properties and are collectively called terminals. The same terminal box contains the same breaker nature (such as material, aging degree, etc.); Auxiliary equipment such as temperature and humidity controller, heater and floodlight has the same failure probability, and human does not interfere with its operation. Therefore, they can be regarded as a whole, which is collectively referred to as auxiliary equipment. Information transfer between terminals, circuit breakers and auxiliary equipment only, without any other interaction or influence.

3.1 Failure consequence loss analysis

Based on the above assumptions, the properties of logical connections in the terminal box of a circuit breaker are shown in Table 1.

Table 1 Properties of logical link of terminal box

Logical connection	Message type	*SE*	*IN*	*US*
The circuit breaker->Terminal	Type 1-2	2	8	8
Auxiliary equipment->Auxiliary equipment	Type 4-2	5	8	6
The circuit breaker->Auxiliary equipment	Type 4-2	5	8	6

According to Eqs.(12)-(14), the value of each logical connection, logical node and system was respectively calculated as V_1^{1-2}=7.5957, $V_1^{2-3}=V_1^{1-3}$=7.0712, V_2^1=8.1427, V_2^2=7.0712, V_3=8.34795.Where the V_1^{1-2}, V_1^{2-3}, V_1^{1-3} respectively represent the value of the three logical connections of circuit breaker to terminal, terminal to auxiliary equipment and circuit breaker to auxiliary equipment .The V_2^1 and V_2^2 respectively represent the value of the circuit breaker and the terminal (since the auxiliary equipment has no output logical connection, there is no value of the logic node).The V_3 represents the total value of the system.

3.2Human error probability analysis

The influencing factors in this scenario include rules and regulations, equipment condition, operation difficulty, personnel arrangement, physiological status, experience level and teamwork, which are respectively expressed as U_1, U_2, U_3, U_4, U_5, U_6 and U_7.

For a practical scenario, the judgment matrix constructed by the judgment given by experts is shown in Table 3:

Table 3 Discriminate matrix of one practical situation

	U_1	U_2	U_3	U_4	U_5	U_6	U_7
U_1	1	1/2	1/2	1	1/5	1/4	1/6
U_2	2	1	1	2	1/4	1/2	1/5
U_3	2	1	1	2	1/4	1/2	1/5
U_4	1	1/2	1/2	1	1/5	1/4	1/6
U_5	5	4	4	5	1	4	1/5
U_6	4	2	2	4	1/4	1	1/6
U_7	6	5	5	6	5	6	1

According to the discriminant matrix, the weight vector is: $\omega^T=[0.0420\quad 0.0719\quad 0.0719\quad 0.0420\quad 0.2290\quad 0.1230\quad 0.4202]$. The matrix passes the consistency test and the weight vector obtained can be directly used to calculate the probability of human error.

The value vector in a practical scenario was $r^T=[85\quad 30\quad 45\quad 65\quad 73\quad 77\quad 52]$ .Based on the weight and value of each influencing factor, the proportion of each factor in the success likelihood index was 5.98%, 3.61%, 5.42%, 4.57%, 28.0%, 15.8%, 36.5%, respectively. And the value of *a* and *b* were -0.07 and 0.02 .According to Eqs. (1) and (2),the *Pf* was calculated and the result was 1.56%. .

Therefore, in the case of good rules and regulations, poor equipment condition, medium operation difficulty, reasonable personnel arrangement, good physiological status, rich experience level, and general teamwork, the probability of human error is 1.56%.In fact, the following order of importance is first used to construct the above discriminant matrix: $U_1 = U_4 < U_3 = U_2 < U_6 < U_5 < U_7$. The order of weight vector size also accords with the above importance order, which explains the rationality of using AHP from this perspective.

3.3 Analysis of equipment failure rate

A reference result obtained in this paper is as follows:

α=2.665、β=6.697、γ=4500。

Thus the failure rate is expressed as follows:

$$h(t) = 1.488 \times 10^{-3} \times \left(\frac{t}{4500} \right)^{5.697} \times e^{2.665 \times S(t)}$$

After analyzing the failure rate expression, it can be concluded that the failure rate is very low in the case of a short time, and the change rate of failure rate can be ignored whenever the unit time is changed. However, when the time is longer, such as more than 5,000 days, the change of failure probability is very obvious. The failure rate reflects the aging condition and current state of the equipment. The longer the equipment is used, the higher the degree of natural aging and the higher the probability of failure.

The values of the above state variables are 1,2,3,4. These four values represent the device were in a good, attentive, severe, or extremely bad state respectively.

3.4 Classification of system risk

Assuming that a department is repaired every 1500 days and the equipment is in a serious state, the failure rate of circuit breakers, terminals and auxiliary equipment is the same, the failure rate of equipment can be obtained as follows：$h(1500) = 0.84\%$。Since the department is mainly repairing the circuit breaker, the fault rate of the circuit breaker must be corrected by employing the error probability, which can be obtained after correction according to Formula (10)：$p_1^{'} = 2.39\%$。Using SAS (substation automation system, substation automation system) steady-state failure probability of equipment, the example of the logical connection failure probability of 0.19%, and the failure probability of each logical connection are the same, according to the type (11) the general failure probability of system is $p_F = 11.6\%$. Therefore, the risk value of the system is 10.7%, the current risk level of the system is 3, and the operation can be performed. In other words, under the current situation, the management department can make some adjustments to personnel and then overhaul the outdoor terminal box.

It can be seen from the above scenario that the probability of human error is higher than the equipment failure rate, so the management department should focus on increasing the training of personnel, improving the management system, and reasonably choosing working hours to reduce the risk level.

4 conclusion

1) In this paper, the CPC quantified in THE CREAM model was applied to the actual working scene of the terminal box, and was subdivided into secondary influencing factors based on the specific scene;

2) The SLIM model 2 was adopted for quantitatively calculation of the probability of human error, and the analytic hierarchy process was used to determine the factor index's weight in the SLIM model 2;

3) As for the issue of the failure rate of outdoor terminal boxes without regard to human error, the proportional failure model was adopted in this research, which considered the aging condition of the equipment and the influence of the existing state on the failure rate of the equipment. At the same time, the failure probability of the system considering human factors was also calculated. The equipment in the

terminal box was divided into logical nodes and logical connections, and the failure rate of the equipment is corrected by using the probability of human error, and then the failure probability of the system as a whole was worked out.

4）To better judge the consequences of losses, with the method of the information assets, combined consequence loss and overall system failure probability, and get the system's overall level of risk, and risk level of the whole system one by one, is advantageous to the management in artificial maintenance scheduling department to make better decisions, such as adhering to the principle of "early discovery and maintenance", adjust the working time, targeted on personnel training, etc.

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Figures

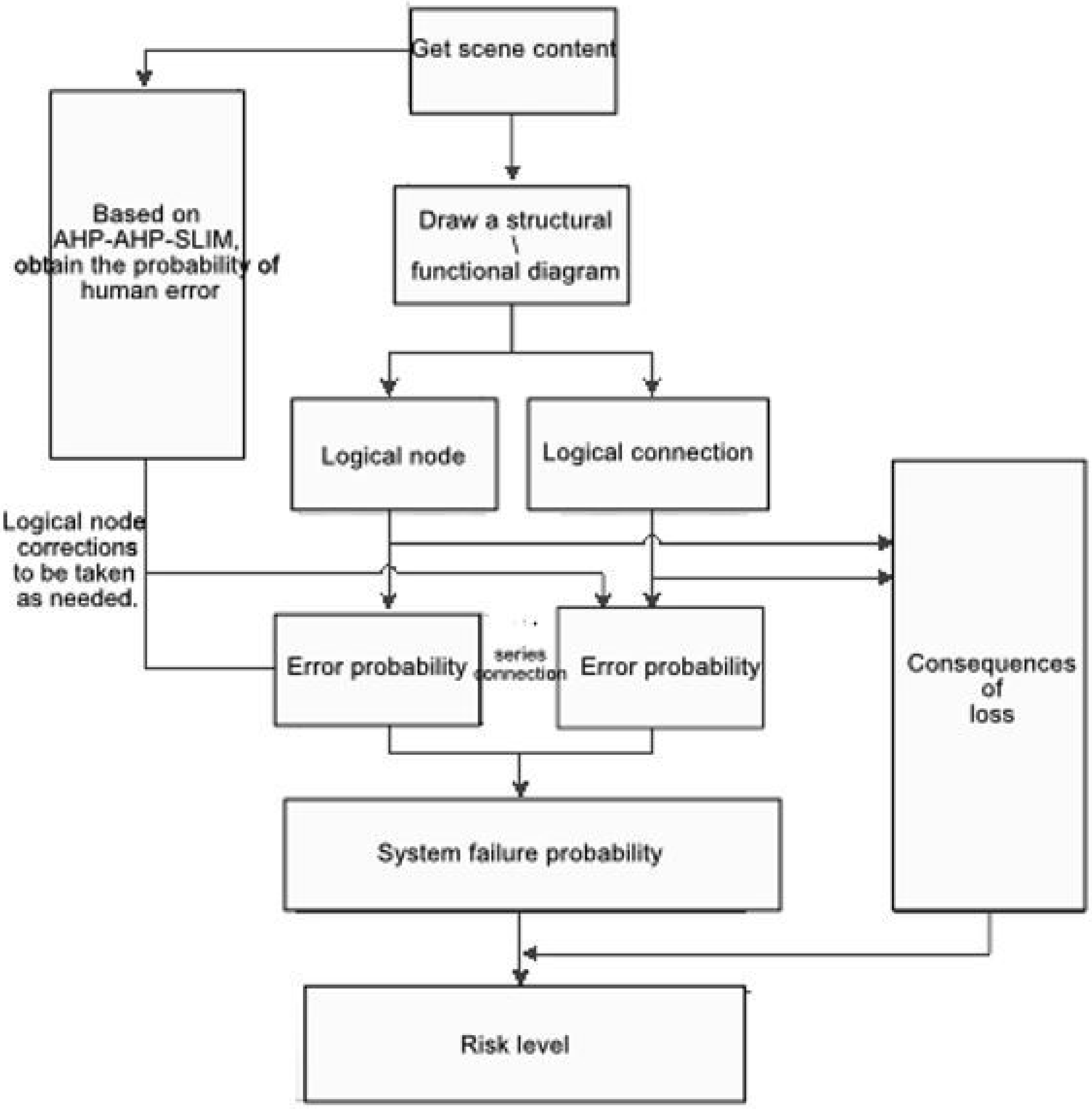

Figure 1

Process of assessing risk level of terminal box