Research on Influencing Factors of Power Grid Security Risk Based on "Cognitive-Constraint" Model

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Abstract. With the improvement of the intelligent level of the power grid, the operation safety of the power system has received extensive attention. The current accident analysis mostly relies on the experience of personnel, which is prone to omissions. Firstly, this article analyzes the safety risk factors of power grid accidents from four aspects: man factors, equipment factors, management factors, and environmental factors based on the accident causes theory. Secondly, the fault tree model is used to explore the mechanism of each failure factor and quantify the structural importance of each event. Finally, summarize the rules of accidents and make reasonable suggestions for scientifically and reasonably avoiding similar accidents and building a safe power grid.

1. Introduction
In recent years, the State Grid has been continuously deepening the reform of smart grids and large-scale regional interconnection. The development of HVAC-HVDC hybrid transmission has made the topology and operating status control of the power grid more and more complicated, and the organization has undergone significant changes. The access to new energy sources and the reform of the power market have caused the uncertainty of the power grid to increase. Due to the complexity of the structure and the increase of uncertainty, the issue of power grid operation safety is of great concern. Therefore, in the new situation, related issues such as the identification and early warning of key risk factors need to be resolved urgently.

Literature[1] proposed a method of transformer status based on clustering and time series analysis to determine the fault type of faulty equipment. Literature[2] first quantified the main risk factors, and then combined the quantified event possibility. Risk assessment of real-time operating lines in the system. Literature[3] builds an AC and DC same-tower model based on the detailed DC engineering PSCAD/EMTDC simulation platform, studies the characteristic quantities and influencing factors caused by the line fault, and analyzes its potential challenges to the AC and DC protection action characteristics. Literature[4] Established a multi-region interconnected power grid security constraint unit commitment model involving multi-scenario operation risks. Literature[5] applied fuzzy sets and fuzzy inference methods in power system fault diagnosis, so as to better solve such problems. Most of the existing methods for determining factors affecting the safe operation of power grids focus on a single factor, and risk early warning mainly relies on manual experience. In order to avoid the impact of subjective judgments, taking into account the increase in the complexity of modern power grid
systems, this article first applies the "cognitive-constraint" model to deal with accidents from four aspects: Man factors, Equipment factors, Management factors, and Machine factors. Mechanism analysis. Secondly, a suitable fault tree model is constructed to systematically sort out the safety risk factors, and explain the correlation between the failure factors. Finally, it explores the structural importance of different influencing factors, and gives reasonable suggestions for building a digital safety production supervision business system and preventing power system operation risks.

2. Analysis of the mechanism of power grid accidents based on the "cognitive-constraint" model

The "cognitive-constraint" model is a system theory model for the analysis of the cause and evolution of modern complex system accidents[6], as shown in Figure 1. To make the complex system achieve a controllable state, it is necessary to solve the maximum degree of overlap between the security constraint domain and the security cognitive domain[7]. This paper applies the accident analysis model based on "cognitive-constraint", through the summary and refinement of the current grid accident analysis, the accident handling report, literature reading and power plant visits and inquiries on potential impacts on grid safety production. Summed up the internal factors, and constructed a risk analysis model based on "man-equipment-management-environment" as shown in Figure 2. The potential or inherent factors that may cause power plant accidents are sorted out, and the characteristic factor diagram (fishbone diagram) of the key factors of power grid security risk is drawn, as shown in Figure 3. This diagram can intuitively describe each failure factor.

![Figure 1](image1.png)

**Figure 1.** Broad connotation of "cognitive-constraint" model.

![Figure 2](image2.png)

**Figure 2.** Accident analysis model based on "cognitive-constraint" model.

The "Grid accident" in the picture is the final result. The safety risk factors are analyzed logically and progressively according to the logical system of large bones, medium bones, and small bones. Among them, the big bones are four analysis angles: man factors, equipment factors, management factors, and environmental factors. Middle bone spreads based on the direction of the big bones. According to incident cases, it summarizes the important factors affecting the safe operation of the power grid in various risk sources. The ossicles are used to conduct a more detailed analysis of the middle bones and implement the underlying events that explain the middle bone factors.

3. Risk factor association model based on fault tree

3.1. Fault tree analysis method

The characteristic factor diagram only conducts a basic analysis of the key factors that lead to the unsafe state of power grid operation, and does not clarify the causal linkage mechanism between the factors. Therefore, the fault tree model is further used for analysis on the basis of the above. The specific analysis steps are shown in Figure 4.

![Figure 3](image3.png)
Figure 3. Characteristic factor analysis of power grid accident safety risk factor analysis.

![Figure 3](image)

Figure 4. Analysis steps of the accident tree.

At present, there are two commonly used methods to quantify the structural importance of incidents at the bottom of the accident tree[8].

The first is to use the minimum cut set (minimum path set) to find the structural importance. It can be calculated and solved by the approximate formula of structural importance as shown below.

Where $I_{\phi(i)}$ is the structural importance coefficient of the $i$ basic event; $k$ is the total number of minimum cut sets; $k_j$ is the $j$ minimum cut set; $n_j$ is the total number of basic events in the $k_j$ minimum cut set where the $i$ basic event is located.

$$I_{\phi(i)} = \sum_{x_j \in k_j} \frac{1}{2^{n_j-1}}$$

The second method is the structural importance coefficient method to obtain the structural importance. Use formula (2) to calculate the structural importance coefficient of each basic event, and get the important sequence of each basic event.

\[ I_{\phi(i)} = \frac{1}{2^{m-1}} \sum [\phi(Y, x(i) = 1) - \phi(Y, x(i) = 0)] \]  

(2)

Where \( \phi(Y, x(i) = 1) \) is the number of all permutations and combinations in which the state of the grid accident \( T \) is also 1 when the state of the \( i \) bottom event is 1 (the event occurs); \( \phi(Y, x(i) = 0) \) is the state of the \( i \) bottom event under the condition of \( (Y, x(i) = 1) \). When 0 (the event does not occur), the number of possible event \( T \) status is still 1.

Using the minimum cut set to solve can only approximate the structural importance of the event at all levels. The structure of the structural importance coefficient method is more accurate, and the grid risk can be analyzed more objectively and accurately, and reliable analysis results can be obtained. Therefore, according to the actual application scenarios of this article, the second method is selected for analysis.

3.2. Grid Safety Fault Tree

Based on the analysis results in Figure 3, combined with the actual operation scenarios of the power system, this paper constructs the fault tree of unsafe state events in the power grid as shown in Figure 5. The specific mechanism is as follows:

(1) When the operation of the power plant is in an unsafe state (event X) and the staff fails to investigate and deal with it (event Y), it will lead to grid accidents (event T).

(2) Environmental issues (event Xa), equipment issues (event Xb) and unsafe human behavior (event Xc) may all induce an unsafe state of the power grid.

(3) Environmental issues are often also important reasons for safety risks. Environmental problems are not only natural weather causes (event Xa1) of severe weather (event C2) such as strong wind, heavy snow, heavy rain, but also geographic conditions (event Xa2) and the operating environment of the staff (event Xa3). The wooded areas of mountains (incident C3) need to pay special attention to fire prevention measures, and the dimly lit environment with complicated wiring (incident C4) also requires extra attention from operators to ensure the safety of the power plant. The staff's insufficient consideration of these hazards (event C1) is also one of the main reasons for the accident.

(4) Equipment operation problems (incident C6) and other equipment operation problems (incident Xb1) and safety protection measures such as lightning protection facilities, fire protection facilities, and waterproof facilities (event Xb4), as well as weak power grid structure and insufficient monitoring equipment coverage (event Xb4) C7) Defects such as insufficient operating mechanism (event Xb2) will reduce the safety of production and the speed of accident discovery. Failure to investigate potential hazards of power plant operating equipment (event C5) and quality problems of the equipment itself (event C8) will cause equipment failure (event Xb3). The sealing strip of the terminal box falls off, the guide bearing is broken, the quality of the busbar switch does not meet the requirements, the service life of the circuit breaker exceeds the service life, the main transformer, high-resistance, busbar, switch, CT and other important equipment in the station malfunction, which seriously threatens the safety of the main network.

(5) Man factors are mainly composed of four types of power plant workers, criminals, surrounding residents, and power plant management personnel, which are expressed by Xc1, Xc2, Xc3, and Xc4, respectively. Among them, criminal activities such as arson and theft and destruction of power facilities (incident C11) can also cause grid operation failures. The staff's main influences are physical, psychological, and experience and ability. Incorrect behaviors of users living around the power plant include: discarding plastic films, waste garbage, straw poles, colored strips and other floating objects at will, or flying kites in places not allowed around the power plant (Event C12), leading to grounding A trip occurs when the discharge channel is formed. Staff and management personnel who do not follow the regulations to make operational arrangements (incident C10) can easily lead to accidents. In
addition, it is also necessary to pay attention to the publicity of power grid safety to all types of personnel to reduce the hidden dangers of power grid risks caused by lack of safety awareness (event C9).

(6) After the unsafe state was induced, the power grid company failed to investigate the accident signal (event Y) for the following reasons: ① The staff did not find the unsafe signal in time (event Ya1). Failure to find out in time may be due to insufficient monitoring equipment and lack of information sources (incident C13) or unreasonable personnel allocation and failure to conduct a full and comprehensive accident investigation on the operation of the power plant (incident C14); it may also be due to inspection work but due to accident handling by staff Insufficient experience (incident C15) or insufficient information to prove the occurrence of the accident (incident C16). ② The accident signal was discovered in time, but effective measures were not taken to organize the risk spread (event Ya2). The accident signal is discovered, but due to the lack of management mechanism, failure to adopt a reasonable emergency plan, or the professional standard of maintenance personnel needs to be improved, the accident cannot be prevented in time.

Figure 5. Analysis steps of the accident tree.

4. Structural Importance Coefficient Analysis
According to the analysis in Section 3, the basic set of events leading to grid accidents is: A={C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15, C16, C17, C18, C19}, n=19. According to the fault tree drawn in Figure 5, the structural importance is calculated, and each fault factor is quantitatively evaluated to obtain the key factors that threaten the safe production of power plants.

\[
T = X \cdot Y = (X_1 + X_2 + X_3) \cdot (Y_1 + Y_2)
\]

\[
= [(X_{1a} + X_{1b} + X_{1c}) + (X_{1d} + X_{1e} + X_{1f}) + (X_{1g} + X_{1h} + X_{1i})] \cdot [(Y_{1a} + Y_{1b} + Y_{1c})]
\]

\[
= [(C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 + C_{10}) + (C_{11} + C_{12} + C_{13} + C_{14})] \cdot [(C_1 + C_2 + C_3 + C_4 + C_{10} + C_{11} + C_{12})]
\]

(3)

According to Figure 5, the functional expression of the logical relationship between the factors of the power grid security risk fault tree can be obtained:

Relying on the expression, this article arranges and combines the possibility of occurrence or non-occurrence of the key safety risk factors of power grid accidents, and quantifies the structural importance of the 17 failure factors, and ranks the results from high to low, as shown in the Table 1.
| Risk factors | Structual importance | Risk factors | Structual importance | Risk factors | Structual importance |
|-------------|----------------------|-------------|----------------------|-------------|----------------------|
| C1          | 0.2682               | C5          | 0.2682               | C9          | 0.2682               |
| C13         | 0.0514               | C14         | 0.0514               | C15         | 0.0514               |
| C16         | 0.0514               | C17         | 0.0514               | C2          | 0.0383               |
| C3          | 0.0383               | C4          | 0.0383               | C6          | 0.0383               |
| C7          | 0.0383               | C8          | 0.0383               | C10         | 0.0383               |
| C11         | 0.0383               | C12         | 0.0383               |             |                      |

It can be seen from Table 1:

\[ C_1 = C_5 = C_9 > C_{13} - C_{14} = C_{15} = C_{16} = C_{17} > C_2 = C_3 = C_4 = C_6 = C_7 = C_8 = C_9 = C_{10} = C_{11} = C_{12} \]

5. Conclusion
Grid accidents have had a huge impact on the production and life of residents, as well as the industrial economy. This article starts with man factors, equipment factors, management factors, and environmental factors. Combined with the summary rules and characteristics of power accidents, it gives reasonable results for safe production of power grids. Suggested measures: (1)Pay attention to personnel safety awareness and strengthen the investigation of potential hazards. (2)Strengthen the process of power grid management and supervision, and formulate reasonable emergency plans. (3)Improve the power grid operation mechanism. Enhance operation and maintenance management, improve the quality of operation and maintenance personnel and inspection quality, and further enhance the efficiency of visual terminal use. (4)Organize personnel to clean up floating objects in line channels, pay close attention to local weather information, enhance monitoring of fire protection and lightning protection facilities, optimize personnel construction environment, and further build a modern safe power grid production environment with real-time data, intelligent management and control, and reasonable early warning.

References
[1] Xin J B, Kang C, Weng X L, Chen T, Xie B and Guo C X 2019 Power System Protection and Control. 47 (03): 64-70.
[2] Ji Y, Wang X D, Shen G Q, Sun H, Zhang S P and Wei Z B 2016 Journal of Electric Power System and Automation. 28 (10): 129-134.
[3] Li X H, Liang Z P, Feng J W, Zhang S F and Cao J, Ding Xiaobing 2020 Automation of Electric Power Systems:1-12.
[4] Zhang Q, Jia Y B, Song T H, Zhang B F, Zheng H P and Mao S J 2019 Electric Power Construction. 40 (05): 98-106.
[5] Zhou M, Ren J W, Li G Y and Xu K L 2001 Automation of Electric Power Systems. (24): 33-36.
[6] Wang S 2014 Safety and Environmental Engineering. 21 (06): 140-143.
[7] Wang Y and Wang S 2013 Industrial Safety and Environmental Protection. 39 (08): 83-86
[8] Wei C R, Li Y X, Sun J H, Gong Z C, Xing S R 2012 Journal of Heilongjiang Institute of Science and Technology. 22 (01): 84-88 + 92.

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