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Online Monitoring and Early Warning Technology of Repeated Multiple Blackouts in Distribution Network Based on Multi-source Information Fusion and Delphi Method

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Abstract

The service-oriented architecture model (SOA) is highly open, hierarchical, and can support parallel / distributed information interaction. Through well-defined interfaces and contracts to contact different services of applications, it has many applications in the field of power system. The SOA architecture is used to realize multi-source power outage information fusion and provide data support for power outage risk assessment and hierarchical early warning.For the problem of repeated multiple blackouts in the distribution network, based on the SOA framework design, the multi-source information fusion technology of the distribution network is used to provide data exchange for online monitoring and early warning technology. By analyzing the factors affecting the repeated multiple blackouts risk and the blackout grading warning of the distribution network, every impact factor scoring standards are given respectively. The Delphi method is used to establish an indicator evaluation system to evaluate the repeated multiple blackouts risks and the indicators of power outage classification warnings in the distribution network, and calculate the weights of each indicator. A repeated multiple blackouts assessment was conducted for an actual blackouts instance, and the comprehensive probability value and hierarchical warning level of repeated multiple blackouts are obtained to realize online monitoring and early warning, which provided a new technology for dealing with repeated multiple blackouts.

Keywords: Delphi; Repeated multiple blackouts; grading early warning; multi-source information fusion; Service-Oriented Architecture.

1. Introduction

Many problems exist in the distribution network, such as weak grid, low equipment reliability, backward information level, insufficient scheduling capability and so on. Thereby, repeated multiple blackouts led to frequent accidents and frequent user complaints, which seriously affected the service quality and social image of the power supply company.According to the “Clear description of the acceptance criteria for low-voltage and frequent blackout complaints” by the marketing department of State Grid Corporation, Repeated Multiple Blackouts is defined as: 3 or more power blackouts occurred in a station for two consecutive months. Domestic and foreign research gaps on Repeated Multiple Blackouts, lack of effective governance methods. The causes for power blackouts can be divided into two categories: Planned blackouts and Fault blackouts. Planned blackouts can be known in advance through announcements, etc. Therefore, the Fault blackouts is studied mainly.

There is a lot of Equipmentin distribution network, the current operational and historical data come from multiple systems. It is difficult and inaccurate to evaluate the status of a certain area or line based on a single information. Compared with the single source information evaluation method, multi-source information fusion technology can improve the robustness and accuracy of the system. It is the basic links of realizing blackouts monitoring and early warning to achieve integration of multi-source blackouts information in distribution networks and the cross-system service linkage mechanism. This study adopts the SOA architecture based on Web Service to realize the fusion of multi-source information and online detection and early warning.

The causes of Repeated Multiple Blackouts are complex, including human factors, external factors, natural factors and equipment factors. How to target different causes, it is the key and difficult point of solving repeated Multiple Blackouts effectively to govern blackouts differently. Index weights are used to reflect the influence of various factors on the blackouts and the relative importance of the indicators. Determining the weight of the indicators is an important issue in the comprehensive evaluation. At present, the methods for determining the weight coefficient are: subjective weighting method,

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objective weighting method, and subjective and objective comprehensive weighting method.

In reference [2], OPA model is applied to power grid outage accident simulation to calculate the risk value of power grid security events, which is suitable for high-voltage transmission system. Literature [3] Based on fault tree and analytic hierarchy process (AHP), established four levels of indicators based on large-scale outage fault tree, and analyzed structural risk, technical risk and equipment risk layer by layer, so as to calculate the comprehensive risk degree of large-scale outage risk. In reference [4], by analyzing the outage probability caused by various emergencies, the outage risk of distribution network under emergencies is calculated, and the emergency warning level is determined based on this criterion. In reference [5], a risk assessment model of distribution network considering various factors is proposed. In the model, a new method is adopted to calculate the outage cost of distribution network. This method reflects the comprehensive influence of outage frequency, outage duration and outage power on outage cost. In the existing research results of distribution network risk assessment, the assessment method combining empirical analysis and qualitative analysis based on subjective factors is more common, there is no standard unified assessment system, and some quantitative assessment methods consider relatively single risk factors [1-5], and most of them are not applied in practice, only stay in theoretical analysis. In this paper, based on the SOA architecture to achieve multi-source outage information fusion, the Delphi evaluation system is used to evaluate and analyze the indicators of various influencing factors, and the risk and classification early warning model of repeated multiple outage in distribution network is constructed to realize online monitoring and early warning, providing new help for the governance of repeated multiple outage in distribution network.

2. Multi-source Information Fusion and Literature Review

The source system related to the multi-source information of the distribution network includes:PMS2.0（Lean management system for equipment (property) operation and maintenance）, Distribution Automation System（A kind of automation system that can make the distribution enterprise monitor, coordinate and operate the distribution equipment in real time in the distance）Power Collection System（Through the collection and analysis of power consumption data of distribution transformers and end users, the power consumption monitoring, step pricing, load management and line loss analysis are realized）, OMS（A scheduling integrated management system which integrates scheduling production, professional management and scheduling business processing.）, and the like. Multi-source information fusion technology was launched in the 1970s to study the comprehensive processing and utilization of multi-source uncertainty information[5]. Common information fusion methods are: Artificial Neural Network method [6-8], Bayesian Network method [9], Fuzzy Reasoning method [10-11], Dempster-Shafer Reasoning method, etc. [12].Service-Oriented Architecture (SOA) is a highly open, hierarchical, component model that supports parallel/distributed information interaction and loose coupling [13].It links the different services of the application through well-defined interfaces and contracts between these services, it links the different services of the application through well-defined interfaces and contracts between these services, whose interface specifications generally complying with the IEC61968 and IEC61970 protocols. And has been applied widely in the field of power systems [14-16].The SOA architecture solves the coupling problem of the subsystem to the greatest extent and minimizes the coupling degree of each subsystem. It is an effective mechanism to solve the encapsulation, interaction, integration, and reuse of each subsystem.

Web Service is used to implement the SOA architecture, the Web Service interface adopts Apache Axis2 technology. The client and the server interact with each other with the SOAP protocol through HTTP. The client generates a SOAP request message according to the WSDL description document and sends it to the server. The client generates a SOAP request message according to the WSDL description document and sends it to the server, the server parses the received SOAP request, invokes the Web Service, and then generates a corresponding SOAP response and sends it back to the client.

The Web Service server adopts the dual-system hot backup mechanism. Through the dynamic IP drift mechanism, when the running machine fails, the IP automatically drifts and points to the hot backup machine to achieve trouble-free operation. Web services are published in the JBOSS server using the Axis2 framework.

All source system data (model, real-time data, fault information, etc.) is pushed to the enterprise information bus through the Web Service, and pushed to the data adapter from the bus to the multi-source blackouts information buffer pool to perform model checking, model conversion, model splicing and model fusion. Then it is stored in the multi-source blackouts information database to provide data support for the risk assessment, prevention and control application of the distribution network Repeated Multiple Blackouts, as shown in Figure 1.

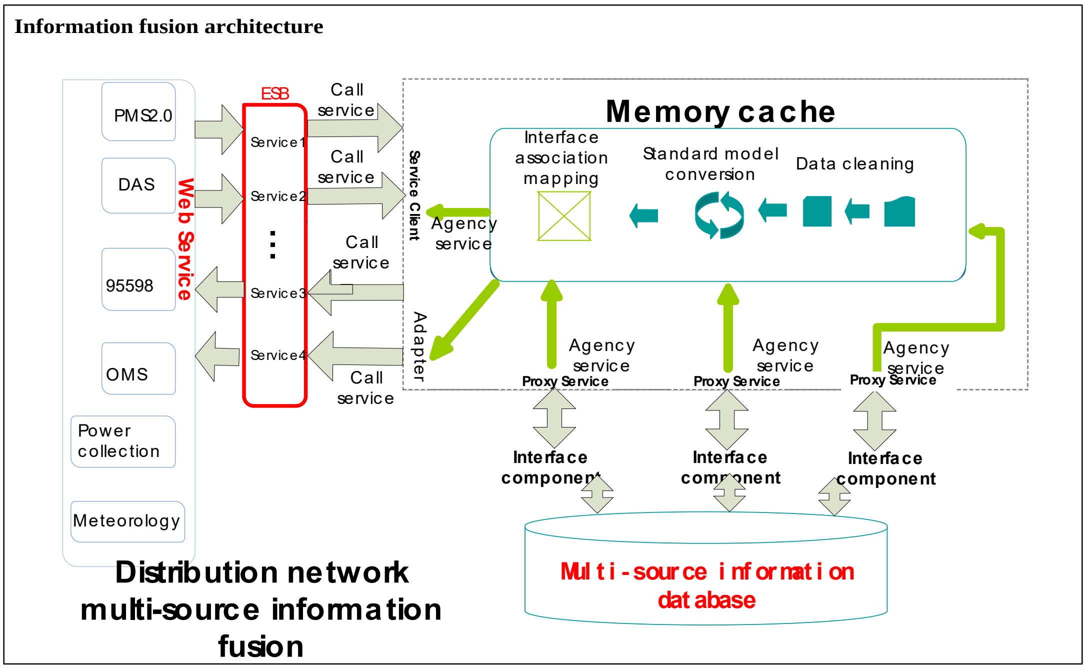

Figure1. Information fusion architecture

3. Delphi method evaluation system

Delphi is a method that fully integrates expert knowledge, experience and information in the field, also known as expert scoring. The key of Delphi's method is that it seeks expert opinions in an anonymous manner, and the decision opinions tend to be consistent and approximate the actual value through information communication and cyclic feedbackexperts, n indicators (assuming each expert evaluates all indicators).

3.1. Delphi method main statistical analysis function

3.1.1. Expert authority level

Expert authority level has an important influence on the accuracy of the weight coefficient judgment results. The higher the authority of the pert, the more reliable the weight coefficient obtained. Expert authority level is generally decided by the basis of expert judgment and expert familiarity with the index. The calculation formula is:

$$C_{Ri} = \frac{C_{ai} + C_{si}}{2} \quad (i = 1, 2 \ldots m) \qquad (1)$$

3.1.2. Weighted arithmetic mean C_{Ej}

C_{Ej} reflects the concentration of expert ratings. The larger the C_{Ej}, the more important the indicator. The calculation formula is:

$$C_{Ej} = \frac{1}{m}\sum_{i=1}^{m} C_{Ri} * C_{ji} \,(i = 1, 2 \ldots m,\ j = 1, 2 \ldots n) \qquad (2)$$

C_{Ej} : the weighted arithmetic mean of indicator j,

C_{ji} :the score of expert i on indicator j.

3.1.3. Coefficient of variation

The coefficient of variation v_j mainly reflects the volatility of the experts' evaluation of the indicators, that is the degree of coordination. The calculation formula is:

$$v_j = \frac{S_i}{C_{Ei}} \qquad (3)$$

S_i : the standard deviation of the evaluation index i score.

$$S_i = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}(C_{ji} - C_{Ej})^2} \qquad (4)$$

3.1.4. Coordination coefficient of expert opinion w

The expert opinion coordination coefficient W reflects the coordination degree of the expert group's weighting coefficients for all indicators, ranging from 0 to 1. Generally, after 2 to 3 rounds of consultation and coordination, the coordination coefficient generally fluctuates within the range of 0.5 and the error control is better.

$$w = \frac{12}{(m^2(n^3 - n) - m\sum_{j=1}^{m} T_j)}\sum_{j=1}^{n}(R_j - R)^2 \quad (j = 1, 2 \ldots n) \qquad (5)$$

n: the total number of indicators; R_j : the index i evaluation level and; R: the evaluation level and the mean value of all indicators;

$$T_j = \sum_{l=0}^{L}(t_l^3 - t_l) \qquad (6)$$

L: the number of groups having the same evaluation value among the expert evaluation values;

t_l : the same number of levels in the L group.

3.1.5. Expert positive coefficient

k_j is the interest level of experts on indicator i. The calculation formula is:

$$k_j = \frac{m_j}{m} \tag{7}$$

m_j : the number of experts who evaluated the indicator j. Under the assumption of this paper, k=1.

3.1.6. indicator weight

The indicator weight is the weight coefficient of the index j:

$$k_{wj} = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{8}$$

4. Risk model of distribution network Repeated Multiple Blackouts

4.1. Risk indicators of distribution network Repeated Multiple Blackouts

The repeated multiple blackouts risk assessment of the distribution network accounts for the main characteristics of the repeated multiple blackouts scenarios. There are three main factors affecting the repeated multiple blackouts in the distribution network: equipment level, operation and maintenance level, and grid structure level. At the same time, it also takes into account the influence of external factors such as meteorological and historical blackouts, and makes full use of the current situation data and historical data of the distribution network in the multi-source information fusion system, which effectively reflects the comprehensive probability level of repeated multiple blackouts in the distribution network.

4.1.1. Equipment level

The probability of distribution network blackouts is closely related to the equipment level. The advanced and reliable power equipment is the hardware guarantee for safe operation of the distribution network. The indicators affecting the equipment level and scoring criteria are shown in Table 1

4.1.2. Operation and maintenance level

In the operation and management of the distribution network, whether the inspection is in place and whether the defects are eliminated is in time, which is related to whether the hidden dangers of the equipment can be detected and solved in time, thus affecting the failure rate. The index scores that affect the level of operation and maintenance are shown in Table 2.

Table 1. Scoring standard of sub-indicators affecting the level of equipment

Score / Sub indicator	10-20	30-40	50-80
Protection level against lightning	Lightning arrester Perfectly installed	Install lightning arrester only on the high voltage side of the power transformer	No lightning arresters
Insulation level	All lines are insulated	Some lines are insulated	Unused insulated wire
Number of old equipment	No old equipment	Small amount of old equipment	Large quantity of old equipment
Distribution network protection device configuration	All configured	Partial configured	No configured

Table 2. Scoring standard of sub-indicators affecting the level of operation and maintenance

Score / Sub indicator	10-20	30-40	50-80
Uninterruptible operation level	Third and fourth types of operational capabilities	Only the first and second types of simple operation capabilities	No ability
Repair ability	Stronger	Medium	Insufficient
Live detection and online monitoring technology	Stronger	Medium	Not possess

4.1.3. Grid structure level

Many problems exist in the distribution network, such as weak grid, and the repeated multiple blackouts led to frequent accidents and frequent user complaints. So, the grid structure needs to be strengthened. The index scores that affect the level of the grid structure are shown in Table 3.

Table 3. Scoring standard of sub-indicators affecting the level of grid structure

Score / Sub indicator	10-20	30-40	50-80
Line "N-1" pass rate	Stronger transfer ability	Medium transfer capacity	No ability
Section switch installation	3 paragraphs and above	Less than 3	None
Power supply radius	Standards compliant	——	Exceeding provisions

4.2. Distribution network repeated multiple blackouts risk indicator weight

4.2.1. Indicator weights

Figure 2 shows the process of determining the weight coefficient of each index. According to the statistical analysis function of the Delphi method in Section 2.1, the scores of all experts are analyzed and summarized circularly. Synthesizing many power experts' understanding for the importance of distribution network repeating multiple blackouts risk assessment indicators and the ratio of complaints held by the comprehensive management department, combined with the multi-source information fusion platform. After corresponding mathematical calculations, the weights of each indicator are obtained, and finally the weights of the 10 indicator features in the indicator system can be obtained, as shown in Table 4.

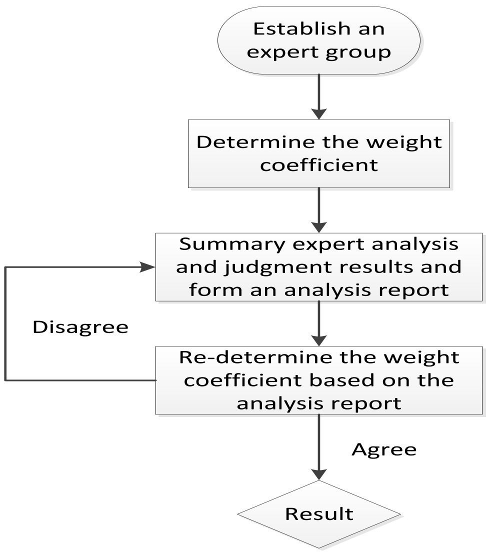

Figure 2. Process to get the index weight

Table 4. The coefficient of each index weight

Specific indicators	Weights
Protection level against lightning	0.12
Insulation level	0.08
Number of old equipment	0.08
Distribution network protection device configuration	0.12
Uninterruptible operation level	0.06
Repair ability	0.06
Live detection and online monitoring technology	0.08
Line "N-1" pass rate	0.16
Section switch installation	0.16
Power supply radius	0.08
Note：Number of experts：10	

4.2.2. External factors

External factors mainly include meteorological conditions and repeated power outages. The value of the repeated power outage factor is 1 for the power outage in the previous month and 1.5 for the power outage last month.

4.3. Evaluation results

The cumulative probability of repeated multiple blackouts can be derived from equations (9) and (10).

$$P = P_0 * Q * T \quad (9)$$

$$P_0 = \sum_{i=1}^{n} k_{wi} * U_i \quad (10)$$

P:the comprehensive probability of repeated multiple power outages;P_0:the base probability of repeated multiple blackouts; Q: the meteorological condition factor; T:the repeated blackouts factor; U_i: the score of each indicator. The comprehensive probability value of repeated multiple blackouts ranges from 0 to 100, and if the calculated value exceeds 100, it is calculated as 100.

According to the comprehensive probability value of repeated multiple blackouts in the distribution network, the probabilityof repeated multiple blackouts is divided into five levels(from large to small): I, II, III, IV, V, as shown in Table 5. The comprehensive probability value is a comprehensive score that takes into account various influencing factors, and reflects the repeated multiple blackouts probability level of the whole distribution network, and does not represent the percentage probability of repeated multiple blackouts.

Table 5. Repeated multiple outages of comprehensive probability of hierarchical and quantification

Level	I	II	III	IV	V
P	>70	40-70	20-40	10-20	<10

5. Classification early warning model of distribution network repeated multiple blackouts

According to the comprehensive probability value of repeated multiple blackouts, when the probability exceeds 70, that is, when repeated multiple blackouts occur "very likely", an early warning should be issued.

According to the different consequences of repeated blackouts, a grading warning is carried out. That is, the risk is quantified in combination with the consequences of repeated blackouts. According to the risk grading results, the corresponding level of early warning is issued, and the corresponding measures are taken to provide the basis for prevention and control.

5.1. Consequences of repeating multiple blackouts

The factors affecting the consequences of repeated multiple blackouts mainly include four aspects: the importance of power load, the repeated blackouts complaint rate, the time and scope of blackouts. Therefore, different impacts should be considered in the repeated multiple blackouts warnings, and graded warning should be implemented. Quantitative scoring of each influencing factor index is analyzed and calculated by Delphi method, and the effect value of repeated multiple blackouts is obtained finally. The risk level of repeated multiple blackout events is determined according to the magnitude of the consequence value, and a corresponding level of warning is issued.

5.1.1. Consequence indicators of repeating multiple blackouts

1. The importance of blackouts load

For the distribution network, the greater the proportion of important loads, the greater the loss caused by blackouts. The load factor will be determined based on the specific gravity of the level I and II loads, as shown in Table 6.

Table 6. The importance of the load

Proportion of level I and II load	30%	60%	80%	100%
Score	60	70	80	90

When the load weight data is not available, the distribution of the load has regional characteristics, which can be used to reflect the importance of the load. Four types of areas—the center of city, urban area, town, village— are selected. Each type of area corresponds to a load area characteristic factor, which is used to characterize the load importance factor, as shown in Table 7.

Table 7 .The importance of the load

Characteristics of load area	the center of city	urban area	Town	village
Score	90	80	70	60

2. Complaint information of repeated blackouts

The areas with more repeated blackouts complaint taking place will lead to more complaints, so consider the repeated blackouts complaint rate indicator in the region to characterize the region's tolerance to repeated blackouts, as shown in Table 8.

$$P_T = \frac{T_0}{T} \times 100\% \tag{11}$$

P_T: the repeated multiple blackouts complaint rate; T_0: the number of repeated power outage complaints in the region; T: the number of user complaints in the region.

Table 8. The index of outages complaint history information

Complaint rate (%)	0-10	10-20	20-30	30-40	40-50	>50
Score	50	60	70	80	90	100

3. Time of blackouts

The time factor considers three cases: general working days, holidays, and special power supply periods, as shown in Table 9.

Table 9. The index of time of occurrence of Repeated multiple outages

Time factor	General working days	Holidays	Special power supply periods
Score	50-60	70-90	90-100

4. The scope of blackouts

For the distribution network, the range of blackouts, such as the whole line outage and the branch line outage, have different effects on the repeated blackouts of the distribution network, as shown in Table 10.

Table 10. Influence sphere of Repeated multiple outages

Range of blackouts	Branch line outage	Whole line outage
Score	20-50	80-90

5.1.2. Consequences indicator weights of repeating multiple blackouts

The Delphi method is also used to derive the weight of each indicator, as shown in Table 11.

Table 11. Each index weight of consequence of Repeated multiple outages

Influencing factor indicator	Weights
The importance of load	0.3
Historical blackout complaint information	0.2
Time of blackouts	0.1
Range of blackouts	0.4

5.1.3. Quantitative assessment of the consequences of repeated multiple blackouts

After obtaining the scores of the indicators that affect the consequences of repeated multiple blackouts in the distribution network, according to the formula (3-1) (3-2), the scores of the repeated multiple blackouts are obtained. According to the magnitude of the consequences of the blackouts, the severity of the consequences is divided into five levels, as shown in Table 12.

Table 12. Hierarchical and quantification of consequence of Repeated multiple outages

Loss of LevelI	Loss of Level II	Loss of LevelIII	Loss of LevelIV	Loss of LevelV
>70	40-70	20-40	10-20	<10

5.2. Failure risk classification warning

According to the quantified distribution network failure consequence value, the risk of repeated multiple blackouts in the distribution network is classified, and the warning level is determined according to the classification of the corresponding risks, so that the risk response measures can be taken conveniently in management. According to the normal distribution network risk grading theory, the distribution network repeated multiple blackouts risk warning is divided into five levels, namely, level I, level II, level III, level IV and V, as shown in Table 13.

Table 13. Hierarchical and quantification of consequence of Repeated multiple outages

Alert level	Consequence value
Level I	≥70
Level II	[40-70)
Level III	[20-40)
Level IV	[10,20）
Level V	<10

6. Example analysis

6.1. Case introduction

In July 2016, a distribution network line in a county town suffered blackouts due to two lightning arrester breakdown accidents during the summer. This line supplies power to some enterprises in the county. Collecting basic data such as power equipment, network structure, operation and maintenance records, and fault records in the area where the blackouts occurred in the multi-source information system, the equipment with a long operating life in this area is put into operation early, most of the equipment is aging seriously, and the relay protection device is simple in configuration. The scores of the benchmark probability indicators for evaluating repeated multiple blackouts are given in four aspects: comprehensive equipment level, operation and maintenance level, external force protection level and grid structure level.

In the region, lightning was frequent in the summer of June-August, and the meteorological factor was 1.2. The blackouts had occurred 2 times last month, and the repeated multiple blackouts factor was 1.5.

6.2. Score of evaluation index

The collected distribution network basic data is processed, and the scores of the respective indicators are given. The results are shown in Table 14.

Table 14. Score of factors

Index	Score
Lightning protection level	70
Insulation level	80
Ratio of old equipment	80
Distribution network protection device	60
Uninterruptible operation level	30
Repair ability	30
Live detection and online monitoring technology	70
Line “N-1” pass rate	30
Section switch installation	60
Power supply radius	10

The calculated baseline probability index value is 52.8. After considering the meteorological factors and the repeated blackouts factor, the comprehensive probability value is 95.04. A repeated multiple blackouts warning should be issued.

Table 15. Score of consequence

Influencing factor indicator	Score
The importance of load	70
Historical blackout complaint information	50
Time of blackouts	60
Range of blackouts	30

The value of calculated repeated blackouts consequence is 48. Therefore, the warning level should be level II.

6.3. Analysis of case evaluation results

The probability of the event evolving into repeated multiple blackouts exceeds 70. The event is “very likely” for repeated blackouts, and an early warning should be issued. According to the calculation of the consequence indicator value, the early warning level is determined to be a level II. The event will evolve into repeated multiple events, and measures should be taken in time to avoid the occurrence of repeated multiple events. Therefore, the electricity sector should formulate corresponding measures according to different repeated multiple blackouts warning levels and consequence risk levels, and the operation and maintenance personnel can take corresponding measures accordingly to prevent the blackouts event from evolving into repeated multiple blackouts events, causing serious consequences.

7. Conclusion

1. Using SOA framework of WebService service, multi-source outage information fusion is realized, which provides data support for on-line monitoring, early warning and control of repeated multiple outages in distribution network;
2. Based on the analysis of multi-source information, the influencing factors, scoring standards and quantitative

scope of the two models are analyzed. Based on the Delphi method evaluation system, the risk model and outage classification early warning model of repetitive outage in distribution network are established to provide new technologies for the control of repetitive outage in distribution network.

3. In the future application process, the the risk model and outage classification early warning model of repeated multiple blackouts will be improved and improved

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