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Risk Assessment of Main Electrical Connection in Substation With Regional Grid Safety Constraints

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ABSTRACT To ensure the safe and stable operation of the power grid, it is necessary to carry out the risk assessment of the main electrical connection in the substation. In traditional methods, the influences of the regional power grid on the main electrical connection scheme are ignored. This paper aims to propose a new method of main electrical connection risk assessment considering the regional grid safety constraints. Firstly, the traditional risk indexes are modified by considering the load shedding in the regional grid, and safety constraints indexes are built by using severity functions. Secondly, the analytic method is adopted to analyze the faults in the substation and determine the consequences, and the external equivalent of the substation is conducted. Finally, the regional grid's power flow and optimal scheduling are calculated, and the risk assessment results are obtained. To verify the effectiveness of the proposed method, the IEEE-RTBS system and a real 220kV substation and its adjacent grid are taken for analysis. The results show that compared with the traditional method, the risk indexes obtained by the proposed method are more conservative, and the weakness of the main electrical connection under maintenance conditions can be obtained, which proves the proposed method's feasibility and effectiveness.

INDEX TERMS Main electrical connection, risk assessment, power grid safety constraints, optimal power flow.

I. INTRODUCTION

The substation is one of the key components in the power grid, which mainly plays an important role in collecting and distributing electric energy. Its operation will directly affect the safety and economy of the power grid [1]–[3]. It has always been a research central issue to conduct the risk assessment on the main electrical connection scheme in the substation to obtain the scheme with the least influences on the safe and stable operation of the power grid [4], [5].

Many achievements have been made in the study of the main electrical connection risk assessment in substations at present [6]–[8]. As the intermediate link of power transmission, the risk assessment for main electrical connection in substations is regarded as a special case of the transmission system or distribution system risk assessment in most research literatures. Therefore, the fault tree analysis [9], the time series analysis [10], the Monte Carlo method [11], the analytical method [12], and the neural network algorithm [13], which are often adopted in power system risk assessment, have been successfully applied in the main electrical connection risk analysis in substations. However, due to the limitations of the calculation scale, the risk assessment results are generally carried out only considering the main electrical connection of the substation itself, and its adjacent grid is often ignored. And it is difficult to find the connection scheme's weakness from the view of regional grid safety constraints. However, the generation system, the transmission system, the distribution system, and the substation system are closely related and interact with each other, so the risk assessment of a single part obviously cannot guarantee the comprehensiveness and accuracy of the assessment results. Therefore, some scholars proposed a joint risk assessment method for transmission and substation system, which was successfully applied in the optimization design of the main electrical connection scheme in a substation [14].

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With this method, the components in the substation such as circuit breakers were incorporated into the Jacobi matrix of the power flow equation by adding some virtual bus and branches. However, when the scale of the substation is large, the method proposed in [14] would largely increase the dimension of the power flow equation, Furthermore, some equipment and branches may be disconnected from the system when fault occurred, and the isolated island would appear, additional measures would be taken to deal with such situation to ensure that power-flow calculations are performed correctly.

This paper aims to propose a new method for the main electrical risk assessment in the substation considering the influences of regional safety constraints such as bus voltage and transmission line capacity and to overcome deficiencies in [14]. First, this paper modify the traditional risk indexes by considering the load shedding in the regional grid and build safety constraints indexes by using severity functions. Then, the external equivalent of the substation is obtained through fault enumeration and consequence analysis, which is conducted by using the accessibility matrix connectivity discrimination. And the load reduction of the regional grid is obtained by power flow calculation and optimal power flow scheduling. Finally, the risk indexes of the main electrical connection in the substation with regional grid safety constraints are obtained. In this paper, the interactions between the substation system and the regional grid are considered with the proposed method, and it is convenient for quantitative analysis of the risk indexes from the perspective of grid safety constraints. This paper also provides a new way of thinking for the risk assessment of the main electrical connection in substations.

II. RISK ASSESSMENT INDEXES

A. MODIFICATION OF TRADITIONAL RISK INDEXES

The purpose of the risk index is to quantify the degree of risk. In the relevant research literatures, different risk indexes are used to quantify the risk degree of the main electrical connection, such as the probability of loss of load (LOLP), the expected frequency of load curtailments (EFLC), and the expected energy not supplied (EENS). In this paper, the traditional risk indexes above are modified, so the load reduction within the substation and the load reduction of the regional grid caused by the topological changes are both taken into account. The indexes are shown as follows.

1) PROBABILITY OF LOSS OF LOAD (LOLP)

This index represents the system state frequency that produces load reduction, as shown in (1).

$$\mathrm{LOLP} = \sum_{i\in S} P_i + \sum_{j\in G} P_j - \sum_{k\in W} P_k \tag{1}$$

where P_i, P_j and P_k respectively represent the frequency of system states i, j, and k; S represents the collection of system states with load reduction in the substation, G represents the collection of system states with load reduction in regional grid, and W represents the collection of system states with simultaneous load reduction in the substation and the regional grid.

2) EXPECTED FREQUENCY OF LOAD CURTAILMENTS (EFLC)

This index represents the number of transfer times (times /a) from the system state with load reduction to the system state without load reduction, as shown in (2).

$$\mathrm{EFLC} = \sum_{i\in S} F_i + \sum_{j\in G} F_j - \sum_{k\in W} F_k \tag{2}$$

where F_i, F_j, and F_k represent the frequency of leaving the system state i, j, and k respectively, whose expressions are shown in (3).

$$F_m = P_m \sum_{n\in N} \lambda_n \tag{3}$$

where $m = \{i, j, k\}$, and λ_n represents the departure rate of system state m, and N represents the number of components in the system.

3) EXPECTED ENERGY NOT SUPPLIED (EENS)

This index represents the product of the system state frequency with load reduction and the reduced load, reflecting the potential power loss amount (MW · h/ a) of the system, as shown in (4).

$$\mathrm{EENS} = 8760(\sum_{i\in S} P_i C_i + \sum_{j\in G} P_j C_j) \tag{4}$$

where C_i and C_j respectively represent the load reduction in the substation and the regional power grid.

B. GIRD SAFETY CONSTRAINTS INDEXES

To reflect the influences of regional grid safety constraints on the main electrical connection in the substation, it is necessary to build corresponding indexes for quantitative analysis of grid safety constraints. In this paper, the regional grid safety constraints mainly refer to the static safety constraints of the power grid, which mainly include bus voltage over-limit and transmission line overload. In this paper, the severity function is adopted to represent the safety over-limit degree. The grid safety constraint indexes include the voltage over-limit severity index and the transmission line overload severity index.

1) VOLTAGE OVER-LIMIT SEVERITY INDEX

The evaluation object of this index is the bus in the regional grid, and the bus voltage determines the value of the voltage over-limit severity index. Generally, bus voltage over-limit includes the cases where the voltage is higher than the upper limit and the voltage is lower than the lower limit. Therefore, the index is quantified by the segmental continuous severity function, as shown in (5).

$$\mathrm{Sev}(U_n) = \begin{cases} \dfrac{U_n - 1}{U_{\min} - 1}, & U_n \le 1 \\ \dfrac{U_n - 1}{U_{\max} - 1}, & U_n \ge 1 \end{cases} \tag{5}$$

where $U_{\min} < 1 < U_{\max}$. The voltage over-limit severity function is shown in Fig. 1, when the bus voltage is 1(p.u.), the severity of over-voltage is 0; when the bus voltage is Umin or Umax, the severity is 1; when the bus voltage is over the upper or lower limit, the severity is greater than 1. Equation (5) represents the voltage over-limit severity index of a single bus in the regional grid. For the whole regional grid, its system voltage over-limit severity function can be expressed as (6).

$$\mathrm{Sev}_{\text{sys-U}} = \sum_{n \in N} \mathrm{Sev}(U_n) \tag{6}$$

where N represents the number of buses in the regional power grid.

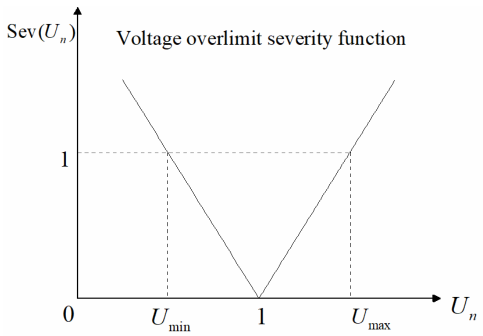

FIGURE 1. Voltage over-limit severity function.

2) TRANSMISSION LINE OVERLOAD SEVERITY INDEX

The evaluation object of this index is the transmission lines in the regional grid, and the actual transmission capacity on the components determines the value of this index. The severity function shown in (7) is adopted to quantify the transmission line overload severity index.

$$\mathrm{Sev}(S_l) = \begin{cases} \dfrac{S_l - S_{\text{lim}}}{1 - S_{\text{lim}}}, & S_l \geq S_{\text{lim}} \\ 0, & S_l \leq S_{\text{lim}} \end{cases} \tag{7}$$

where Slim represents the control capacity of the transmission line, which is generally 90% of the rated capacity, and Sl represents the actual transmission capacity of the transmission line. The transmission line overload severity function is shown in Fig. 2. When the actual transmission capacity of the branch is 1 (p.u.), the severity index is 1, and when it is less than the power flow control capacity of the transmission line, the severity index is 0.

Similar to the voltage over-limit severity index, for the whole regional power grid, the transmission line overload severity index can be expressed in (8), Where L represents the number of transmission lines in the regional grid.

$$\mathrm{Sev}_{\text{sys-S}} = \sum_{l \in L} \mathrm{Sev}(S_l) \tag{8}$$

III. METHOD FOR RISK ASSESSMENT OF MAIN ELECTRICAL CONNECTION IN SUBSTATION WITH REGIONAL GRID SAFETY CONSTRAINTS

The risk assessment method proposed in this paper presents typical layered structure characteristics, as shown in Fig. 3.

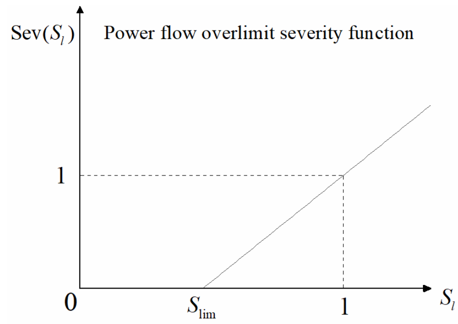

FIGURE 2. Transmission line overload severity function.

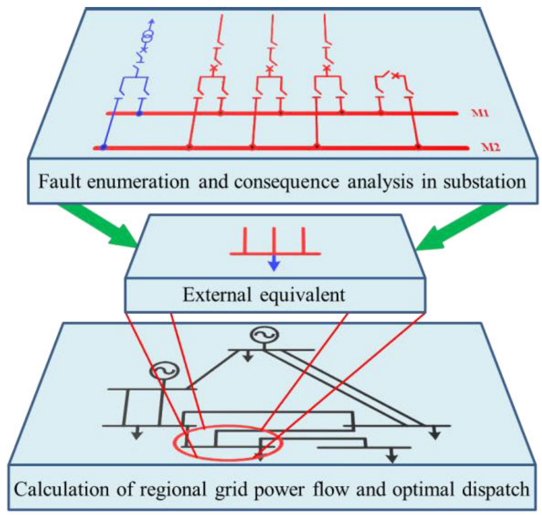

FIGURE 3. The hierarchical structure of the method.

The first layer of the method is the fault enumeration and consequence analysis in the substation: The analytical method is adopted to enumerate the fault components in turn, and the fault scope is obtained according to the electrical connection topology and protective relaying configuration. The load reduction and outage time in the substation are also obtained. The second layer of the method is the external equivalent: The adjacency matrix of the substation main connection is generated and the corresponding reachable matrix is obtained, and the connectivity between the transmission lines and the load points within the substation under various system states is identified. The third layer of the method is the calculation of regional grid power grid power flow and optimal scheduling: the external equivalent of the substation (detailed in III.*B*) is incorporated into the regional power flow equation, and the bus voltage and transmission line capacity are calculated to obtain the severity indexes of the regional grid. When there is an over-limit condition, optimal scheduling is also required to ensure the safe operation of the regional grid.

A. FAULT ENUMERATION AND CONSEQUENCE ANALYSIS IN THE SUBSTATION

We assume that all components in the regional grid are 100% reliable, only the faults of the components in the substation are enumerated. Therefore, the risk assessment results mainly

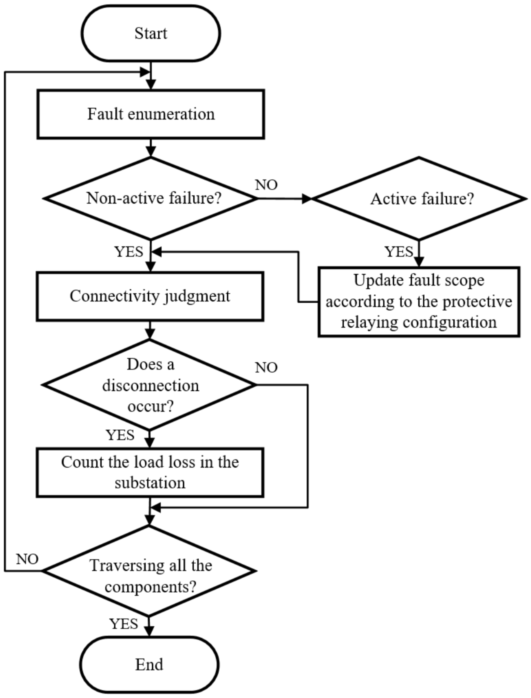

FIGURE 4. Flow chart of fault enumeration and consequence analysis for components in the substation.

reflect the influences of regional grid safety constraints on the substation system. The main steps are shown in Fig. 4.

1) Enumerate fault of components in the substation. In general, the probability of simultaneous failure of more than two components in a substation is very rare, which is usually ignored. Therefore, the maximum number of components that fail simultaneously in the enumeration method is set as 2.

2) Determine the fault type of the component and the fault scope. Components failure is divided into active and non-active failure. Active failure refers to the faults that resulting in other circuit breakers tripping, such as a short-circuit fault. And non-active failure refers to the faults that only affect the faulty component itself, such as an open circuit fault. When an active failure occurs, the tripping circuit breakers and the fault scope should be judged according to the protective relaying configuration in the substation.

3) Connectivity judgment. Judge whether there is no electrical connection between the load points and any transmission line in the substation after the component failure occurs. And if there is, record the amount of load loss and the probability of the system state.

4) Repeat the steps above until all components in the substation have been enumerated.

B. EXTERNAL EQUIVALENT OF THE SUBSTATION

The adjacency matrix and the reachable matrix are adopted to obtain the external equivalent results of the evaluated substation, and it is specifically explained with the simple power transmission and transformation system shown in Fig. 5. There are three substations in the regional grid as shown in the figure, and the lower part is the main electrical connection expansion of the evaluated substation. There are two incoming transmission lines and two transformers in the evaluated substation, and the transformers can be regarded as the load points within the substation. When in normal operation, the transmission line L_1 and 1# transformer are connected to bus I M, and the transmission line L_2 and 2# transformer are connected to bus II M, and the bus-tie switch is closed.

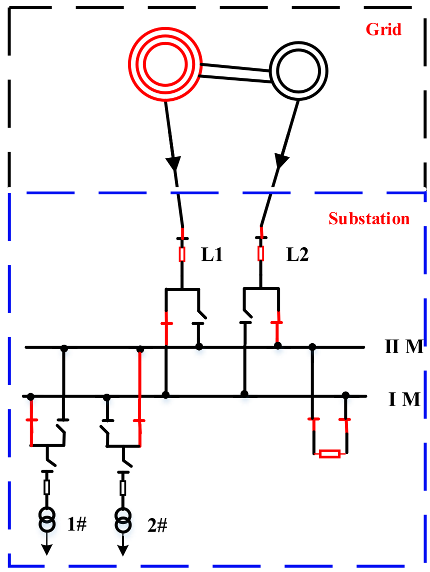

FIGURE 5. Diagram of a simple power transmission and substation system.

1) Convert the power transmission and substation system diagram shown in Fig. 5 into the equivalent node diagram shown in Fig. 6. Every branch in Fig. 6 (blue numbers) represents a certain component in Fig. 5. For example, branch 1, 2, 3, and 4 represent the transmission lines in the regional grid, branch 18 and 23 represent 1# and 2# transformer respectively, branch 14 and 19 represent bus I M and bus II M respectively, branch 6, 9, 12, 16 and 21 represent the circuit breakers, other branches represent isolating switches. A virtual node (red numbers in the circles) is added on both sides of each branch in the substation to help distinguish the connection relation.

2) Generate the adjacency matrix of the system according to the Fig. 6, and the adjacency matrix of Fig. 6 is shown in (9):

$$A_{22\times 22} = \begin{bmatrix} 0 & 1 & 0 & 0 & \cdots & 0 \\ 1 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 1 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \tag{9}$$

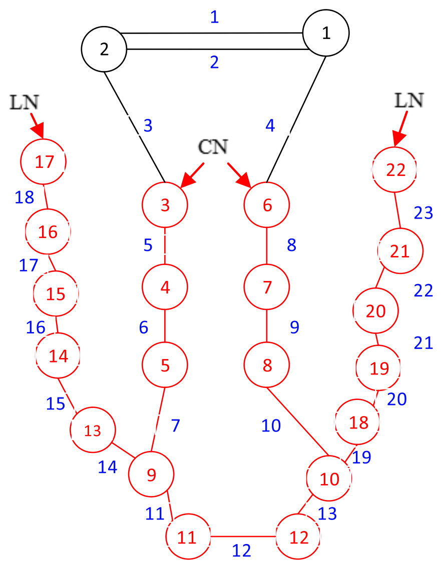

FIGURE 6. Equivalent node diagram.

the values of each element in the adjacency matrix are shown in (10) :

$$a_{ij} = \begin{cases} 0, & \text{no connection between node i and j} \\ 1, & \text{there is a connection between node i and j} \end{cases} \tag{10}$$

3) Transform the adjacency matrix into the reachable matrix with the Warshall algorithm, as shown in (11):

$$B = (A + I)^2 = I + A + A^2 + \ldots + A^n \tag{11}$$

where I is the unit diagonal matrix with dimension n, and matrix B is the reachable matrix, in which the value of each element b_{ij} represents the number of branches that node i needs to go through to connect with node j, and each non-zero b_{ij} in the matrix B indicates that there is a connection between node i and j, otherwise, there is no connection.

4) Judge the connectivity between load nodes (defined as LN, as nodes 17 and 22 in Fig. 6) and substation internal/external connection nodes (defined as CN, as nodes 3 and 6 in Fig. 6) under various system states according to the reachable matrix. On this basis, the external equivalent rules of the substation are shown in Table 1.

5) In additional, many substations need to be reconfigured in different working conditions of the power system, and the equivalent node diagram of the main electrical connection in the substation needs to be regenerated after being reconfigured according step 1) to step 4) above.

According to the rules shown in Table 1, several external equivalent cases of the substation are listed in Fig. 7, and the external equivalent results of the substation is shown in the red dotted box. Fig. 7 (a) corresponds to the case shown serial number 1 in Table 1, and the simultaneous disconnection of two incoming line circuit breakers in Fig. 5 (branch 6 and 9 in Fig.6) May lead to this result. Fig. 7 (b) corresponds to the case shown serial number 2 in Table 1, and simultaneous disconnection of the two transformers in Fig. 5 (branch 18 and 23 in Fig.6) may lead to this result. Fig. 7 (c) corresponds to the case shown serial number 3 in Table 1, and the short circuit fault in bus I M in Fig. 5 (branch 14 in Fig.6) may lead to this result. Fig. 7 (d) corresponds to the case shown serial number 4 in Table 1, and the disconnection of the bus-tie switch in Fig.5 (branch 12 in Fig.6) may lead to this result.

TABLE 1. External equivalent rules of the substation.

Serial number	connection between CN and LN	connection between CN and CN	Equivalent rule
1	There is no connection between this CN and any LN	There is no connection between this CN and any other CN	Delete the transmission line connected to the CN
2		There is a connection between this CN and other CN	All connected CN are combined into a bus without load, and the transmission lines connected to these CN are reserved
3	There is a connection between this CN and any LN	There is no connection between this CN and any other CN	This CN is combined into a bus with load, and the transmission lines connected to this CN are reserved
4		There is a connection between this CN and other CN	All connected CN are combined into a bus with load, and the transmission lines connected to these CN are reserved

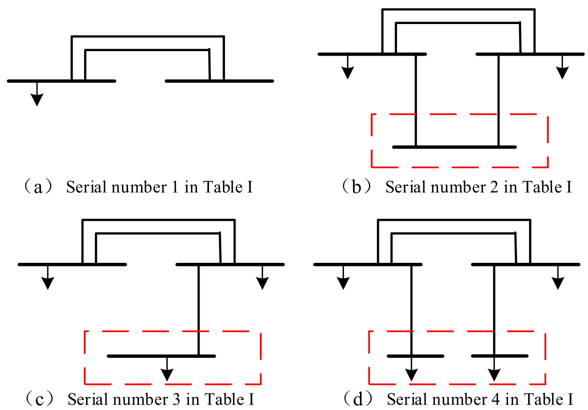

FIGURE 7. External equivalent results of the substation.

C. REGIONAL POWER FLOW CALCULATION AND OPTIMAL SCHEDULING

The substation's external equivalent nodes are incorporated into the Jacobian matrix of the regional grid for power flow calculation. When an over-limit situation which cannot be eliminated by adjusting the generator's output occurs in the regional grid, the optimal scheduling should be carried out. In the relevant studies, the minimum load reduction is generally taken as the optimal scheduling goal, and the optimal scheduling calculation model adopted in this paper is shown in (12) to (19).

$$\min \sum_{i \in ND} C_i \tag{12}$$

$$\text{subject to: } P_i(V,\delta) - P_{LDi} + C_i = 0 \quad i \in ND \tag{13}$$

$$Q_i(V,\delta) - Q_{LDi} = 0 \quad i \in ND \tag{14}$$

$$PG_i^{\min} \le P_i(V,\delta) \le PG_i^{\max} \quad i \in NG \tag{15}$$

$$QG_i^{\min} \le Q_i(V,\delta) \le QG_i^{\max} \quad i \in NG \tag{16}$$

$$0 \le C_i \le P_{LDi} \quad i \in ND \tag{17}$$

$$TR_k(V,\delta) \le TR_k^{\max} \quad (k \in L) \tag{18}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (i \in N) \tag{19}$$

where $P_i(V,\delta) = V_i \sum V_j(G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij})$ and $Q_i(V,\delta) = V_i \sum V_j(G_{ij}\cos\delta_{ij} - B_{ij}\sin\delta_{ij})$, G_{ij} and B_{ij} are the real and imaginary parts of the admittance matrix, row i, column j; V is amplitude of the bus voltage, and δ_{ij} is the phase difference between the two ends of the transmission line; C_i is the load reduction of node i; P_{LDi} and Q_{LDi} are the active and reactive power needs on node i; $PG_i^{\max}$, $PG_i^{\min}$, $QG_i^{\max}$ and $QG_i^{\min}$ are the upper and lower limits of injected active power and injected reactive power on generator node i respectively. TR_k is the actual transmission capacity of transmission line k, and $TR_k^{\max}$ is the max transmission capacity of transmission line k; $V_i^{\max}$ and $V_i^{\min}$ are the upper and lower limits of the voltage amplitude of bus i respectively; ND, NG, N, and L are the collection of load bus nodes, generator bus nodes, all bus nodes, and all transmission lines in the transmission system respectively. The minimum load reduced in the regional power grid under the safety constraints can be obtained by using (12) to (19). Combined with the load reduction in the substation, the risk indexes of substation main electrical connection under the safety constraints can be obtained by using (1) to (8).

Many devices and measures can be used to control the bus voltage and line power flow in the power grid. The effect of these devices and measures are considered in (12) to (19). For example, Capacitors and the OLTC correspond to V_i in the (19). By setting the bus as PV node in the power flow calculation, the bus voltage can be adjusted to the set value. And generation re-dispatch corresponds to $P_i(V,\delta)$ and $Q_i(V,\delta)$ in the formula (15) and (16), which can be adjusted between the maximum and the minimum values.

IV. CASE STUDY

A. AN IEEE RELIABILITY TEST SYSTEM WITH 6 BUSES

The risk assessment methodology proposed in this paper is tested by using IEEE-RTS6. As shown in Fig. 8, the BUS4 in RTS6 is replaced by the specific main electrical connection of a substation. There are four incoming transmission lines and two transformers in the substation. Double-bus scheme is adopted in this substation. Transmission line L4, L7, and 1# transformer are connected to BUS IM while transmission line L2, L8, and 2# transformer are connected to BUS IIM under the normal condition. And the bus-tie switch is closed. All of the components in the substation are marked by red

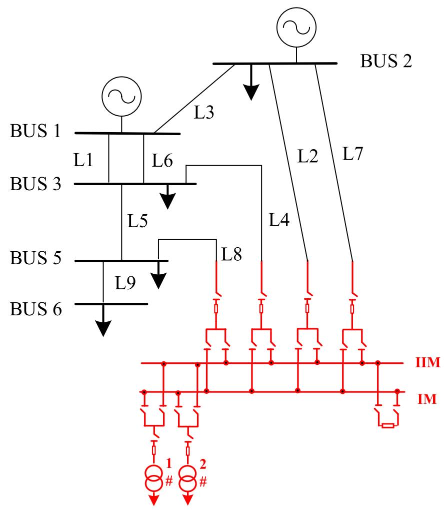

FIGURE 8. Diagram of IEEE-RTS6 system with BUS4 node expanded.

color in Fig. 8. The basic data for power flow calculation as well as the reliability data of circuit breakers, buses, transformers, and other components are shown in the paper [15]. Neglecting the normally opened isolating switches, there are 25 components in the substation. Therefore, there are 25 1-order failures (one component fails) and 300 2-order failures (two components fail at the same time) in total. The skeleton of the combinative system shown in Fig. 8 is transformed into the equivalent node diagram shown in Fig. 9. In the Fig.9, the branch set {12, 16, 20, 24, 40, 31, 36} represent the circuit breakers, the branch set {27, 28} represent buses, and the branch set {29, 34} represent the transformers in the substation. The remaining branches with blue numbers are all isolating switches.

The risk assessment indexes (1) to (8) are calculated with the method proposed in this paper. Besides, the traditional method (regional grid safety constraints are not considered) is also used for comparison. The risk indexes obtained by the two methods are shown in Table 2.

TABLE 2. Risk assessment results with different methods.

Risk assessment indexes	Traditional method	Method considering regional grid safety constraints
Number of system states with load reduction within substation	205	205
Number of system states with load reduction in regional grid	—	24
Total amount of load reduction（MW）	4600.00	5076.33
LOLP	0.00432836	0.00432841
EFLC（times/a）	0.00284892	0.00284895
EENS （MW·h/a）	759.149	759.171

According to Table 2, with the method proposed in this paper, the LOLP, the EFLC, and the EENS are both slightly increased compared with the traditional method. The reason

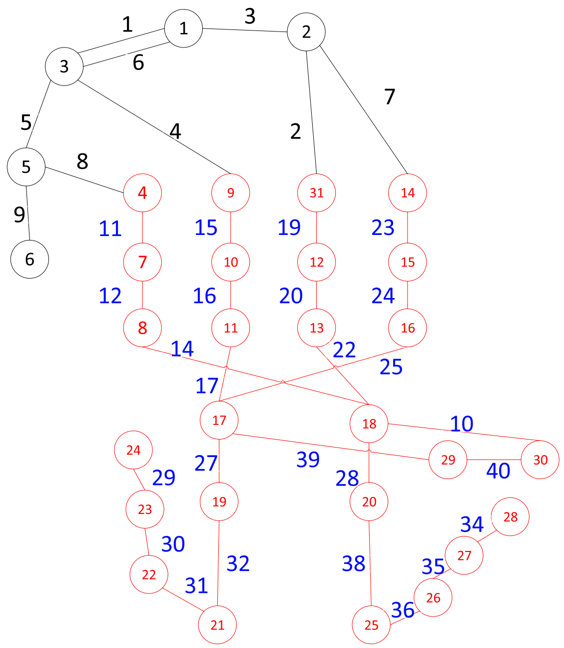

FIGURE 9. Equivalent node diagram.

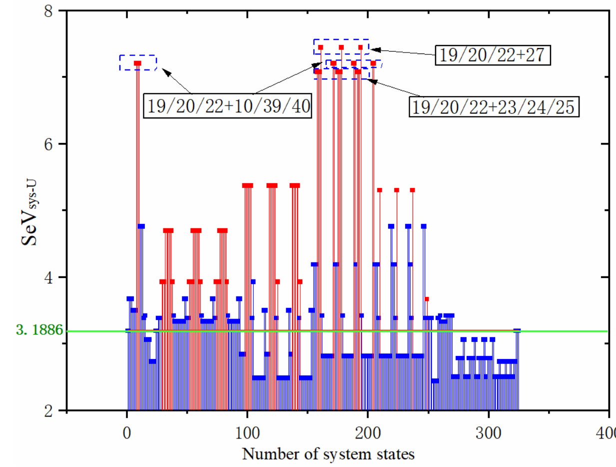

FIGURE 10. Diagram of voltage over-limit severity index.

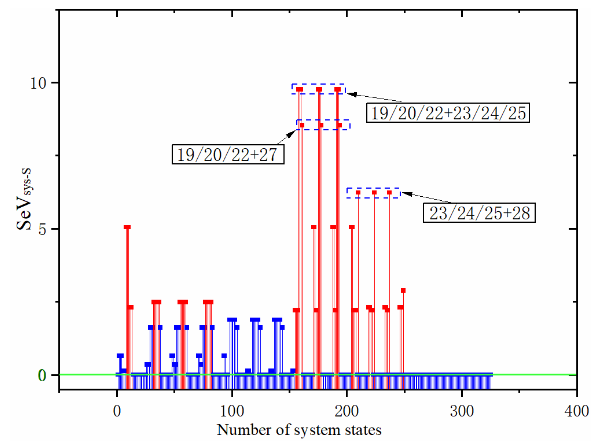

FIGURE 11. Diagram of transmission line overload severity index.

is that the load reduction caused by the topology changes of the regional grid is also taking into account with the new method. However, due to the probability of system states with load reduction in regional grid is very rare, the differences between the results is not obvious. As a reference, there are 205 system states with load reduction within substation and 24 system states with load reduction in regional grid among the total 325 enumerated system states. All of the system states with load reduction are caused by the 2-order failures, whose occurrence probability is very low (10^{-5} class). Therefore, although the total amount of load reduction using the proposed method is 476.33MW (the amount of load reduction in the regional grid) higher than the result obtained by the traditional method, the difference of EENS is slight.

To reflect the influences of the regional safety constraints on main electrical connection scheme, the voltage over-limit severity index and the transmission line overload severity index are calculated, and the results are respectively shown in Fig.10 and Fig.11.

The abscissa in Fig.10 represents the number of system states, and there are 325 system states in total, corresponding to 325 faults of components. The ordinate represents the value of voltage over-limit severity index, and the green line in Fig. 10 represents the index value in normal operation (no fault occurs). During the component faults enumeration, there are 177 system states where the value of voltage over-limit index is higher than the green line and 148 system states where the value of over-limit index is lower than the green line in Fig.10.

The red vertical lines represent the system states where the bus voltage exceeds the limitations, and there are 76 system states with bus voltage over-limit. The system states with maximum value of the voltage over-limit index are shown as follows, and the corresponding components fault combinations are "19/20/22 + 27", "19/20/22 + 10/39/40" and "19/20/22 + 23/24/25" in Fig.9. And the corresponding minimum bus voltages (p.u.) of the regional grid are 0.9455, 0.9497, and 0.9487, which all belong to the node BUS6 in Fig.8.

Although the probabilities of components 2-order faults shown above are low, in some special conditions such as maintenance condition, the probability cannot be ignored. As an example, when transmission line L2 is under maintenance (components 19/20/22 in Fig.9 are out of service), emphasis should be placed on strengthening the inspection of BUS IM (27 in Fig.9), bus-tie switch (10/39/40 in Fig.9), and transmission line L7 (23/24/25 in Fig.9) to prevent the voltage over-limit, according to results shown in Fig. 10.

Similarly, the abscissa in Fig.11 represents the number of system states. The ordinate represents the value of transmission line overload severity index, and the green line in Fig.11 represents the value of the index in normal operation, which is 0. During the component faults enumeration, there are 121 system states where the value of transmission line overload severity index is higher than the green line and

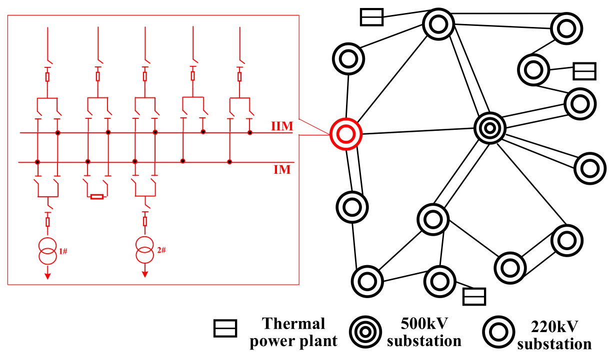

FIGURE 12. Diagram of a 220kV substation and its adjacent grid.

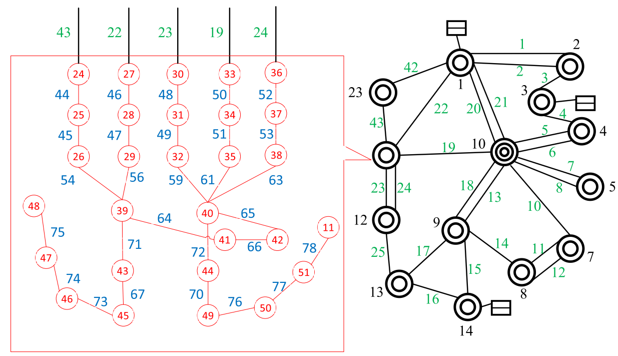

FIGURE 13. Equivalent node diagram of figure 12.

204 system states where the value of index is lower than the green line in Fig.11.

The red vertical lines represent the system states where the actual transmission line capacity exceeds the limitations, and there are 63 system states with transmission line overload. Similarly, the system states with maximum value of the transmission line overload severity index are shown as follows, and the corresponding components fault combinations are "19/20/22 + 23/24/25", "9/20/22 + 27" and "23/24/25 + 28" in Fig.9. And the corresponding maximum actual transmission line capacities (p.u.) of the regional grid are 1.3247, 1.1600, and 1.1482, which relatively belong to transmission lines L1 and L6 in Fig.8. And when transmission line L2 is under maintenance (components 19/20/22 in Fig.9 are out of service), emphasis should be placed on strengthening the inspection of BUS IM (27 in Fig.9), and transmission line L7 (23/24/25 in Fig.9) to prevent the transmission line overload, according to results shown in Fig. 11.

As shown above, the method proposed in our paper could not only calculate the risk indexes of the main electrical connection, but also effectively find the weak point of the power system and the over-limit buses and transmission lines under all circumstances.

B. AN APPLICATION IN A REAL CASE

To test the effectiveness of the model proposed in this paper, the model is applied to a real 220kV substation and its adjacent grid. As shown in Fig.12, the topology of the power grid is on the right side of the figure, and the main electrical connection of the substation being evaluated is shown in the red box on the left side of the figure. By using the method described in section III.B of this paper, the power system shown in Fig. 12 is transformed into the equivalent node diagram shown in Fig. 13. And the risk indexes obtained by the traditional method and the method proposed in this paper are shown in Table 3.

It can be seen from Table 3 that after considering regional grid safety constrains, the total amount of load reduction increases from 2188.11WM to 2504.79WM. This is mainly because the fault of substation would cause the change of the power flow distribution in regional grid, which might lead to the overload of transmission lines, and additional load need to be cut off to eliminate the overload. In addition, the LOLP, the EFLC, and the EENS are slightly larger, which is because the probability of system states with load reduction in regional grid is very rare.

TABLE 3. Risk assessment results with different methods.

Risk assessment indexes	Traditional method	Method considering regional grid safety constraints
Number of system states with load reduction within substation	406	406
Number of system states with load reduction in regional grid	—	57
Total amount of load reduction（MW）	2188.11	2504.79
LOLP	0.00530012	0.00530315
EFLC（times/a）	0.00362846	0.00362911
EENS （MW·h/a）	3610.51	3616.89

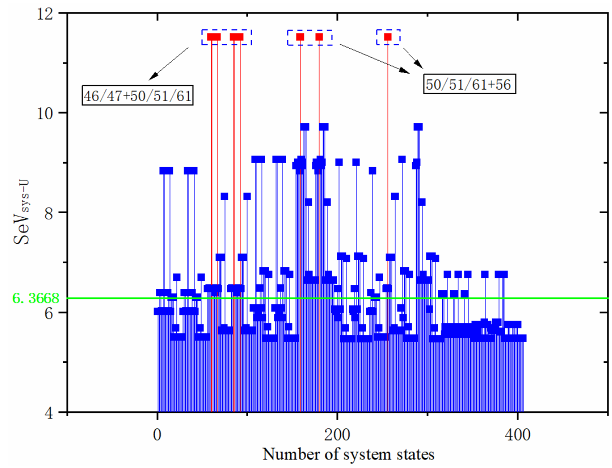

FIGURE 14. Diagram of voltage over-limit severity index.

The voltage over-limit severity index and the transmission line overload severity index are respectively shown in Fig.14 and Fig.15. The abscissa, the ordinate, and each element in the figure are the same with Fig.10 and Fig.11.

There are 406 system states in total. There are 9 system states with bus voltage over-limit, and 21 system states with transmission line over-limit, which represented by the red

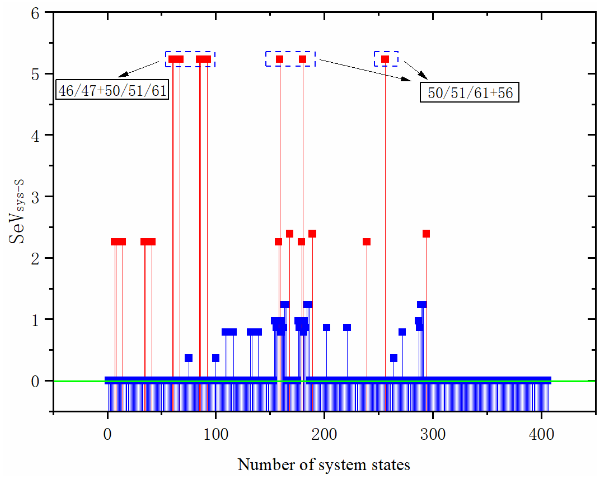

FIGURE 15. **Diagram of transmission line overload severity index.**

vertical lines in Fig.14 and Fig.15. The system states with maximum value of voltage over-limit index and the system states with maximum value of transmission line over-limit index are shown in Fig.14 and Fig.15, and the corresponding components fault combinations are both "46/47+50/51/61", "50/51/61+56".It means that the emphasis should be placed on transmission line 19 and 22 (green lines in Fig.13) to prevent the voltage over-limit and transmission line over-limit.

V. CONCLUSION

This paper has proposed a new method for risk assessment of main electrical connection in the substation considering the regional grid safety constraints. Combined with IEEE-RTS6 and a real 220kV substation with its adjacent grid, the risk assessment indexes are obtained, and the main findings are as follows:1)The load loss and the severity of voltage/current over-limit in the regional grid can be obtained by modifying the traditional risk indexes and constructing the grid safety constraints indexes, which are more comprehensive compared with the traditional method. 2) The method proposed in this paper can equate the main electrical connection of the substation with a bus, which solves the problem that components in the substation cannot participate in power flow calculation of the power grid. 3) By comparing risk indexes in different system states, the method in this paper can obtain the main wiring fault combination corresponding to the maximum risk, to find the weak point of the main electrical connection in the substation.

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