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PROBABILITY-BASED SEISMIC RESILIENCE ASSESSMENT METHOD FOR SUBSTATION SYSTEMS

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Abstract

Electricity has substantial effects on rescue and relief responses after severe earthquakes. As one of the most important components of electric power networks, it is necessary to study the seismic performance of substations. Among many performance indices of substation systems, the recovery capacity from external events has caught much concerns recently. It is referred to as the seismic resilience, defined as the ability of a system to resist, restore, and adapt to an earthquake impact, and quantified as the variation of functionality along the time. In this paper, a new probability-based method is proposed to assess the seismic resilience of complex systems such as substations. A case study is conducted on a typical 220-kV substation in China. Three important parts are discussed in detail: the definition of system functionality, the system model which takes into account the correlations among components, and the optimized recovery strategy to restore system functionality.

Substations are complex systems consisting of various interconnected equipment, such as transformers, current/potential transformers, circuit breakers, and disconnecting switches. To better illustrate the composite of the substation, all components were separated into five functional units, namely as, line-in unit, bus-220 unit, transformer unit, bus-110 unit and line-out unit. In a single path, only all the five functional units operate normally, power is accessible at the end of the line-out unit. Accordingly, the substation's system functionality is defined as the number of available line-out units over the total amount, ranging from 0 to 1, which is able to quantify the residual serviceability.

Substations are always parallelly designed, thus several paths exist to deliver power. The substation's system model is established adopting the proposed state tree method, which integrates the merits of the fault tree and the success path method. The fault trees of the aforementioned five functional units are firstly constructed, then assembled together based on the success paths which represents the possible directions of power flow in these functional units. With this model, the operational state of the substation can be evaluated directly according to those of components.

Monte Carlo simulation is used to calculate the substation's resilience curve based on fragility and recover parameters of components. In one simulation at a given PGA, a random number distributed between 0 and 1 is generated for each bottom component of the system model. If the generated number is less than or equal to the failure probability as defined by the corresponding fragility curve, the component is considered as a failure, otherwise as a success. From the bottom to the top, the operational state of the whole substation system can be evaluated. For a damaged system, the improved functionality of repairing different components varies due to its complexity. Therefore, an optimized recovery routine is determined by repairing the component that improves the system functionality most one by one. If N components are damaged, $N(N-1)/2$ calculations are needed to obtain one resilience curve. This simulation is repeated many times at the given PGA, and the median resilience curve can be computed.

Keywords: seismic resilience; substation system; system functionality, state tree; recover strategy;

1. Introduction

Electricity has substantial effects on rescue and relief responses after severe earthquakes. As one of the most important components of electric power networks, substations are key to transforming and distributing power and play vital roles in the stability, controllability, and serviceability of power systems [1]. However, extensive damage to equipment in substations has been observed in past earthquakes [2][3], which make substations the most vulnerable component within a power grid.

Substations are complex systems consisting of various interconnected equipment. The seismic performance of individual pieces of equipment and structures has recently undergone extensive study [4]. Nevertheless, the seismic performance of an entire substation from the perspective of functionality remains unclear because of its high degree of redundancy and functional interaction.

Among many performance indices of substation systems, the recovery capacity from external events has caught much concerns recently. It is referred to as the seismic resilience, defined as the ability of a system to resist, restore, and adapt to an earthquake impact [5], and quantified as the variation of functionality along the time (Fig.1). Three major properties are implied in the resilience curve: the definition of system functionality, the system model which takes into account the correlations among components, and the recovery strategy to restore system functionality.

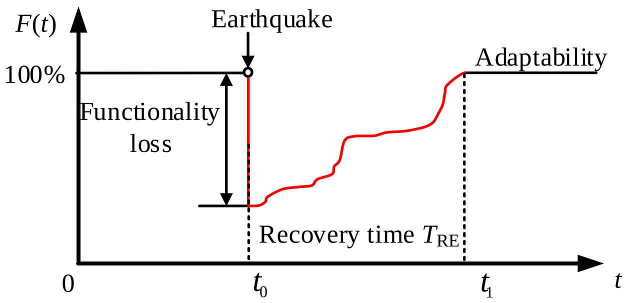

Fig. 1 – Typical model of seismic resilience

Li et al. [12] summarized insufficiencies of the commonly used methods for system assessment, including the binary test method, the fault tree method, the event tree method, and the success paths method, and proposed a new probability-based method, namely the state tree method to evaluate complex systems. The new method explicitly considers the interconnection of all associated components to achieve system functionality and integrates the merits of the fault tree method and the success path method. Unlike the seismic marginal assessment method [6], all success paths (If all components in the success path remain operational, the entire system survives; otherwise, it fails.) are required to be identified and clearly defined to construct the system model in the state tree method. A strong logical relationship inherently exists within the state tree model and it is much more manageable than the minimal cut set method used in fault tree analysis.

In this paper, the state tree model based probabilistic method was illustrated to quantitatively assess the seismic resilience of complex systems such as substations. Two different recovery strategies are proposed to restore the damaged system. Based on a typical 220-kV substation in China, effects of the recovery strategies were discussed.

2. Framework of the method

The proposed method includes four steps: (1) definition of system functionality according to specific demand from users, engineers, or regulators; (2) system analysis with the state tree method representing the network topology of the system; (3) assessment of system performance adopting Monte Carlo simulation; (4) assessment of system resilience with different recovery strategies considering different priorities. The components' fragility functions and recovery parameters, i.e., recovery time and cost, are basic data thus needs to be determined prior to the calculation.

3. System model

3.1 Overview

A typical 220/110/10-kV substation [10] (hereafter referred to as a 220-kV substation) is selected as the study case. The layout is shown in Fig.2. The power comes into the substation from the 220-kV portion, passes through the transformer, and goes out through the 110-kV portion. There are 8 lines in the 220-kV portion and 12 lines in the 110-kV portion. Each line works independently and is connected to the bus, which is used to gather and distribute the electric power. The transformers are also connected to the bus rather than to these lines. For the sake of reliability, two buses are adopted for the 110-kV portion. The 220-kV portion also has two buses, and one of the two is separated into two segments to further improve reliability. Note that the control house must be operational to guarantee the substation's functionality.

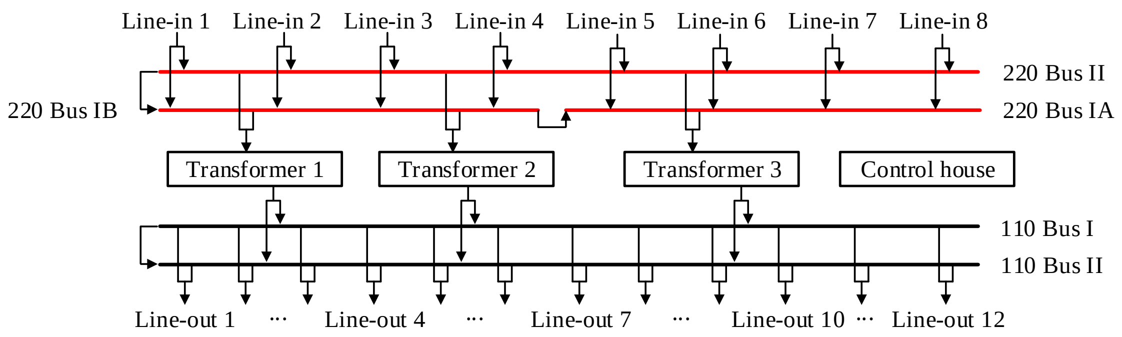

Fig. 2 – Layout of a typical 220-kV substation

Substations are complex systems consisting of various interconnected equipment, such as transformers, current/potential transformers, circuit breakers, and disconnecting switches. To better illustrate the composite of the substation, all components were categorized into five functional units (Fig.3), namely as, line-in unit, bus-220 unit, transformer unit, bus-110 unit and line-out unit. In a single path, only all the five functional units operate normally, power is accessible at the end of the line-out unit.

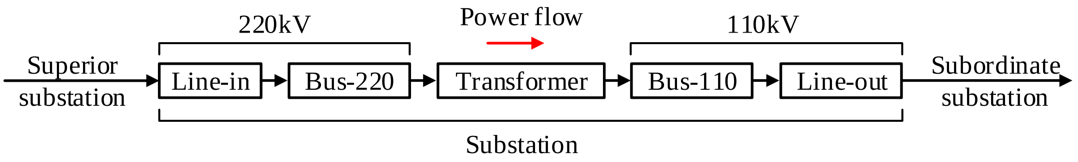

Fig. 3 – Layout of a typical 220-kV substation

3.2 Definition of functionality and system model

The substation's functionality, F_s, is defined as the number of available line-out units over the total amount. The values for F_s are 0 to 1 in increments of 1/12. Considering the redundancy of the design, it is supposed that two transformers in full operation are sufficient to sustain the power supply. It is also assumed that one line-in unit is capable of sustaining two line-out units. Therefore, the functionality of the substation can be calculated with Eq. (1).

$$F_s = \frac{\min\left(N_{line-out}, 6N_{transformer}, 2N_{line-in}\right)}{12} \tag{1}$$

where $N_{\text{line-out}}$ denotes the number of available line-out units, $N_{\text{tranformer}}$ is the number of available transformers, and $N_{\text{line-in}}$ represents the number of available line-in units.

Substations are always parallelly designed, thus several paths exist to deliver power. The substation's system model is established adopting the proposed state tree method. The fault trees of the aforementioned five functional units are firstly constructed, then assembled together with the success paths which represent the possible directions of power flow in these functional units. With this model, the operational state of the substation can be evaluated directly according to the component states. More details are presented in the previous study [7].

4. Fragility functions and recovery paramters of components

The double lognormal model was used to define equipment fragilities in this paper to consider both the aleatory randomness and the epistemic uncertainty [6][11], as shown in Eq. (2) and Eq. (3). The median capacity $\bar{x}_m$ of the electrical equipment varies following a lognormal distribution with median $\hat{x}_m$ and logarithmic standard deviation β_u.

$$\bar{x}_m = \hat{x}_m \cdot e^{-\Phi^{-1}(Q)\cdot\beta_u} \tag{2}$$

$$F_{ds}(edp) = \Phi\left(\frac{\ln(edp/\bar{x}_m)}{\beta_r}\right) \tag{3}$$

where Q represents the probability that the median capacity of the component exceeds a given value $\bar{x}_m$.

Table 1 – Fragility parameters of electrical equipment

Component	110-kV			220-kV		
	$\hat{x}_m$ (g)	β_r	β_u	$\hat{x}_m$ (g)	β_r	β_u
Transformer	0.43	0.68	0.49	0.59	0.47	0.30
Circuit breaker	0.62	0.45	0.45	0.46	0.37	0.61
Disconnect switch	0.66	0.41	0.54	0.55	0.38	0.37
Current transformer	0.82	0.40	0.45	0.41	0.27	0.58
Potential transformer	0.93	0.38	0.48	0.49	0.22	0.28
Lightning arrester	0.65	0.42	0.45	0.65	0.28	0.26
Bus bar	1.00	0.25	0.25	1.00	0.25	0.25
Insulator	0.80	0.30	0.30	0.70	0.30	0.30
Bus-insulator	0.80	0.30	0.30	0.70	0.30	0.30
Steel frame	1.5	0.25	0.25	-	-	-
Control house	1.0	0.25	0.25	-	-	-

Fragility parameters for different components are listed in Table 1 [12]. It is noted that parameters for transformer, circuit breaker, disconnect switch, current transformer, potential transformer and lightning arrester are obtained based on series of existing data of either experiential, numerical or experimental results. On the other hand, few studies have focused on the insulator, bus bar, steel frame, or control house; therefore, assumed parameters were used for these components.

The recovery parameters for components are listed in Table 2. Recovery time and cost are two main parameters for resilience assessment. Considering the difficulties to quantify the real cost and time to repair the components, including purchase, transport and installation, these values are assumed taking into account opinions from manufactories and engineers. Detailed works are still needed to make them more accurate.

Table 2 – Recovery time and cost of substation's components

Component	**110-kV**		**220-kV**	
	Time (day)	Cost (10000 RMB)	Time (day)	Cost (10000 RMB)
Transformer	0.50	3.2	0.60	6.6
Circuit breaker	0.25	4.3	0.35	8.8
Disconnect switch	0.40	1.8	0.50	4.0
Current transformer	0.20	2.5	0.25	4.5
Potential transformer	0.20	2.3	0.25	4.3
Lightning arrester	0.15	2.0	0.20	3.8
Bus bar	1.00	3.6	1.20	6.8
Insulator	0.10	1.5	0.15	3.2
Bus-insulator	0.10	0.8	0.15	1.5
Steel frame	0.25	5.0	-	-
Control house	1.00	10.0	-	-

5. Resilience assessment

5.1 System functionality

The averaged system functionality in terms of peak ground motion acceleration (PGA) with 1000 realizations of Monte Carlo simulation is shown in Fig.4. The Chinese code [13] requires that the substation needs to maintain its functionality at the design basis earthquake, i.e., 0.10g. However, the system's functionality starts to fall at PGA less than 0.1g and lost most of its functionality at 0.25g. More than 80% functionality will be lost under maximum considered earthquake (MCE) with the PGA of 0.2g. It implies that the redundancy of substation is insufficient to improve the seismic reliability, further improvements are needed.

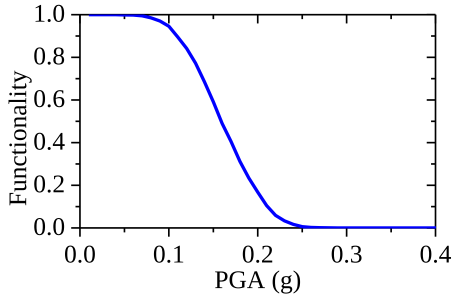

Fig. 4 – System functionality in terms of PGA

5.2 Pre-determined repair procedure

Seismic resilience is a dynamic process of the functionality variation over time for a system after earthquakes. A pre-determined repair procedure is used first to restore the system's functionality as shown in Fig.5. Seven major steps are determined to repair steel frames, line-in units, bus-220 units, transformer units, bus-110 units, line-out units and control house in series.

In engineering practice, the recovery time of a system is determined by human resources, number of standby equipment, and working schedules, etc. For simplicity, the total time to repair a functional unit is assumed as the sum of the time to repair the damaged components belonging to the functional unit, i.e., the components are repaired one by one. Sequential strategies are also used to repair the same groups of functional units.

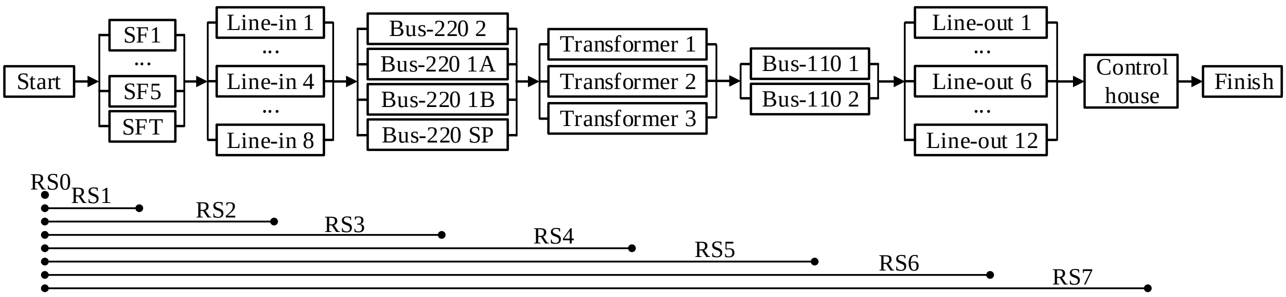

Fig. 5 – System functionality in terms of PGA

Seven recovery sequences namely RS1 to RS7 were defined. RSi means that components belonging to the first to the *i*-th functional units have been repaired. For example, RS3 represents that all steel frames, line-in units and bus-220 units have been repaired. For each recovery sequences in the simulation, a large enough value was set as the component's median capacities. Then system functionality was calculated (Fig.6). It shall be noted that not every repair sequence could increase the system functionality. The transformer units have large effect on the substation's functionality because obvious improvement was observed between the results of RS4 and RS3.

The total time and cost to repair the system are calculated directly according to all damaged components. Then the total time and cost to repair the functional units can be calculated by Eq. (4). For example, the time to repair all line-in units can be calculated as the differential of $Time_{RS1}$ and $Time_{RS2}$. The resilience curve of the substation is shown in Fig.7 by combining the curves of system functionality, recovery time and cost at 0.2g (MCE). The functionality of the system decreases 83.1% when earthquake happens. The total time and cost to completely recovery the functionality are 7.18 days and 0.93 million yuan. It is noted that the functionality depicts little improvement at the first five days, although more than half of the total money have been used. Such a pre-determined repair sequence cannot meet the requirement of the rescue works, and a smarter strategy is needed.

$$(Time, cost)_{RS_i} = (Time, cost)_{RS_i} - (Time, cost)_{RS_{i+1}} \quad (4)$$

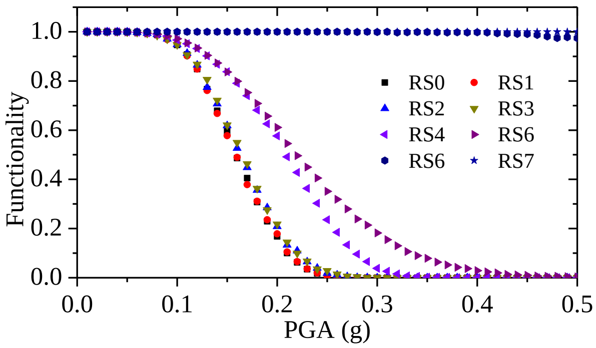

Fig. 6 – System functionality in terms of PGA

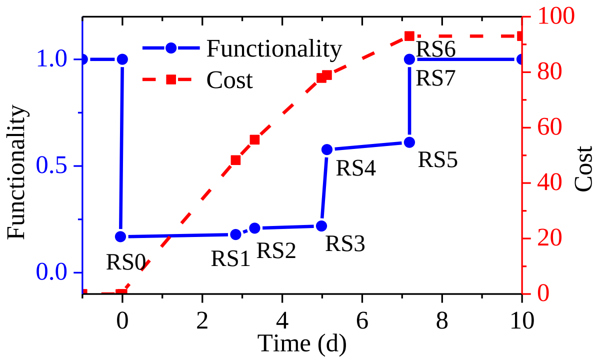

Fig. 7 – System functionality in terms of PGA

5.3 Functionality prioritized recovery strategy

For the complex substation system, several components form a basic functional unit, the reparation of a single component cannot affect the system's functionality, therefore the recovery strategy is determined at functional unit level. Considering the importance of power supply after earthquake, functionality is used as the priority to recovery the substation.

In one simulation at 0.2g, 10 functional units were damaged. The improved system functionality, time and cost to repair each functional unit separately are shown in Table 3. Either line in unit 1, 2, 4, 5, 6 or 7 can be repaired first because the system's functionality increases 16.7% after the reparation. However, it is better to repair line-in unit 3 because its less repair time, i.e. 0.25 days. It is also noted that the reparation of one functional unit may not improve the system's functionality. For such cases, the less time, the prior to repair the functional unit. If the repair time are the same, then the functional unit with less cost will be repaired first.

With this priority strategy, the resilience curve can be obtained. Fig.8 shows the resilience curve in one simulation. The detailed recovery path is shown in Table 4. The system will loss 66.6% of the functionality when earthquake occurs. It took 2.95 days to fully recover the system's functionality while 6.65 days to repair the system completely.

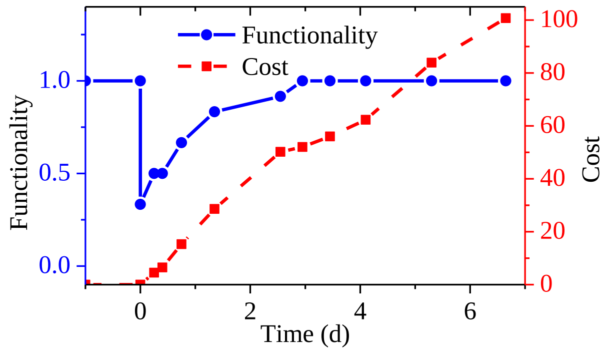

Fig. 8 – System functionality in terms of PGA

Table 3 – Functionality, repair time and repair cost to repair one functional unit at 0.2g

Functional unit	Increased functionality	Repair time	Repair cost
inline_1	0.167	0.25	4.50
inline_2	0.167	1.20	21.60
inline_4	0.167	0.35	8.80
inline_5	0.167	0.60	13.30
inline_6	0.167	1.20	21.60
inline_7	0.167	1.35	16.80
220bus_2	0.000	0.50	4.00
transformer_1	0.000	0.65	6.30
transformer_3	0.000	0.15	2.00
outline_4	0.000	0.40	1.80

Table 4 –Functionality, recovery time and cost through functionality prioritized recovery strategy at 0.2g

Recovery path	Increased functionality	Repair time	Repair cost	Functionality	Total repair time	Total repair cost
Before EQ	1	0	0	1	0	0
EQ	0.333	0.00	0.00	0.333	0.00	0.00
inline_1	0.167	0.25	4.50	0.500	0.25	4.50
transformer_3	0.000	0.15	2.00	0.500	0.40	6.50
inline_4	0.167	0.35	8.80	0.667	0.75	15.30
inline_5	0.167	0.60	13.30	0.833	1.35	28.60

inline_2	0.083	1.20	21.60	0.917	2.55	50.20
outline_4	0.083	0.40	1.80	1.000	2.95	52.00
220bus_2	0.000	0.50	4.00	1.000	3.45	56.00
transformer_1	0.000	0.65	6.30	1.000	4.10	62.30
inline_6	0.000	1.20	21.60	1.000	5.30	83.90
inline_7	0.000	1.35	16.80	1.000	6.65	100.70

With 1000 times calculation, the averaged resilience curves of the substation with the pre-determined (PD) recovery path and functionality prioritized (FP) strategy at 0.1g, and 0.2g are obtained (Fig.9). Once an earthquake occurs, the functionality of the system is affected and decreased by approximately 0.6%, and 83% for the two intensities, respectively. The total time and cost to repair the system at different intensities are similar for both strategies because the number of damaged components is similar. At a small PGA of 0.1g, few components have been damaged thus the difference between PD and FP results is very small. However, it is obviously that the system's functionality can be restored much faster with the FP strategy at larger PGAs. For example, the substation's functionality is 51%, 67%, and 80% for the first three days with FP strategy, while the system's functionality shows almost no improvement for the same period with the PD strategy.

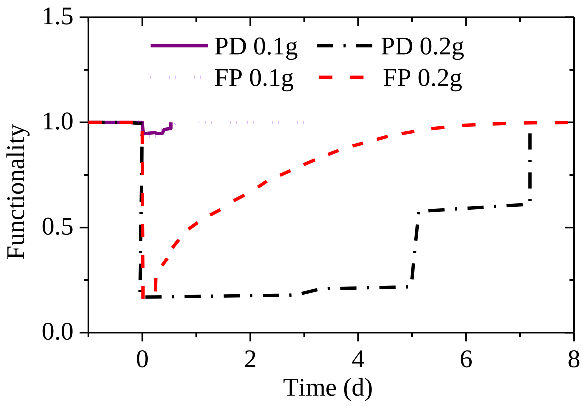

Fig. 9 – Averaged resilience curve of the substation with PD and FP recovery strategies

6. Conclusions

A new probabilistic method based on the state tree model was developed to assess the seismic resilience of substation systems. The advantage of the state tree method is that the operational state of the system and the components are one-to-one corresponded, which enables the use of Monte Carlo simulation to comprehensively consider the dynamic recovery process to restore a damaged system. The method was illustrated through a typical 220-kV substation. The substation's resilience curves of different recovery strategies were discussed.

The resilience of systems in real world are very difficult to evaluate due to limitation of manpower, financial and material resources. Nevertheless, the state tree method provides an effective tool to evaluate systematically the seismic resilience of such systems.

7. Acknowledgements

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8. Copyrights

9. References

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