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SIMPLIFIED ASSESSING OF SUBSTATION-ORIGINATED OUTAGES IN ANALYSIS OF TRANSMISSION SYSTEM RELIABILITY

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In order to minimize the effects of substation-related outages on performance of the composite system, the power system planners have to assess their effects. The present paper is specifically concerned with a relatively simple method of substation reliability analysis based on failure modes and effect analysis. More influential failure events are screened basing on reliability indices of substation components. The further analysis considers only a relatively small number of screened events. So the method enables to analyze and compare different substation configurations, to elaborate measures to improve system operation, to incorporate substation-related outages in evaluation of the reliability of the composite system etc. relatively simply without using special complicated computer programs.

Introduction

The quality and availability of power supply to customers is highly dependent on the performance of a large number of generators, transmission lines and substation equipment. Substation-related outages can have considerable impact on the reliability of the power system. Substation components, substation configuration and terminal connection topologies are important factors in system reliability evaluation.

Assessment of reliability of substations or their switchgears is substantial in evaluating the reliability of the existing network and availability of supply to customers, as well as in choice of configuration of new substations.

There are numerous studies and publications in this area concerning detailed probabilistic or imitation methods [1–2]. These methods are most labor-consuming and not applicable without corresponding computer programs. While the assessment of reliability of substation arrangements is

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relatively complicated and labor-consuming, the use of suitable computer program packages in reliability studies are assumed in most cases. For practical analysis, such as, for example, testing the effect of substation equipment faults to power system reliability, special testing systems like IEEE Reliability Test System (IEEE-RTS) [3] or Roy Billinton Test System (RBTS) [4] are often used.

In situations where such systems are not available, the necessity for approximate methods to assess the reliability of substation configuration may arise. In such cases one can use simplified analytical methods where the assessments of reliability indices of an electric network or a part of it are calculated on the basis of reliability indices of the network components by corresponding formulas [1, 5].

In principle, the observation of substation reliability would be correct in conditions of a definite power system. However, in approximate analysis more simplified approaches, focusing mainly on the reliability of the substation itself without considering the effect of the whole system, have to be used. Nevertheless, the influence of power lines connecting the substation to the system can be taken into account roughly. In such case the main problem is how to assess the effect of faults of substation components on the outages and supply interruptions, as well as how to determine reliability characteristics of the substation.

This paper presents a relatively simple analytical method for assessment of the reliability of substation switchgear configuration based on standpoints known from the publications [1, 2, 5, 6]. The paper regards straightforwardness and transparency of the method and interpretation of the results. The method is in essence an enumeration method or analysis of failure modes and effects [1], which is based on modeling of single components of the substation and on evaluation of the resulting contingencies of connected lines and transformers and their reliability indices.

The method employs an inductive approach that systematically details, component-by-component basis, all possible failure modes and identifies their resulting effects on the substation reliability. A final list of failure events is formed to evaluate the indices of basic connections. The failures and outages of substation components are considered as independent events.

In the case of every failure mode, interrupted connections are identified and the corresponding interruption rate and average annual duration of interruptions are determined. Finally the resulting outages of connections (lines and transformers) and their reliability indices are deduced.

Failure modes of substation components

Substation-related outages or contingencies are substantially dependent on failure events of substation components. For assessment simplicity, the number of components considered should be reduced as much as possible. In simplified approach it is enough to consider circuit breakers and busbars and, if the whole substation is observed, also transformers. When consideration of connection with the system is requested, the incoming lines should be taken into account as well.

A substation-originated event is a forced outage of any number of transformers or lines, caused by a failure inside the substation. These outages depend on occurrence of failures and the reliability indices of the failed substation component.

The modes of failures which can occur in a substation and may cause a substation-originated outage are usually passive and active failure events, stuck-condition of breakers and overlapping failure events [1, 5].

A passive failure event is a component fault that does not cause operation of protection breakers (undetected open-circuits and inadvertent operation of breakers) and so does not have any impact on the remaining components. An active failure event is referred to as any component fault that causes the operation of primary protection breakers around the failed component – for example a short-circuit. The service can be restored to the healthy parts of the substation after isolation of the failed component (i.e. after the so-called switching time). Restoration of the failed component takes place after its repair or replacement. The repair time is usually many times longer than the switching time.

Assuming for simplicity that outage durations in the case of both failure modes are equal, the timing of the process can be presented as given in Fig. 1. In the case of substation configurations with comparatively low reliability, relatively long-lasting contingencies (connection interruptions), whose duration is determined by repair duration *r* of the components, may take place. To reduce durations of that kind of contingencies, normally opened circuit-breakers and disconnectors are often used. Owing to such redundance components, the interruption time can be reduced to switching time many times shorter than repair durations [2]. It means that assessing substation reliability, the repair duration *r* of a passive failure can be divided into two phases or states: switching state *s* and repair state *r*-*s*, as shown in Fig. 1 for active failures.

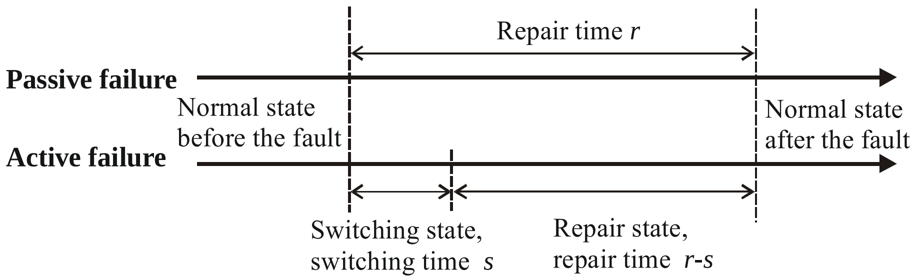

Fig. 1. Failure time-model.

A breaker can become stuck when the circuit-breaker in the primary zone fails to operate after an active failure event. Back-up protection must then respond, and a larger section of the substation may become isolated.

Overlapping failure events arise when substation components fail during the restoration time associated with a substation component failed previously. The overlapping failure events usually considered are those embracing only two substation components. In principle, failures during the time when some other component is removed from service to perform preventive maintenance can also be considered as overlapping failure events. However, substation-related maintenance outages are ignored here, which is quite common practice in reliability studies.

To simplify reliability studies of substations, different realistic assumptions are widely adopted [1, 2, 5, 6]. In this paper the following ones are applied:

- circuit-breakers actively failing cannot clear their own faults;
- circuit-breakers can operate, due to faults, in either direction;
- only passive failures occur on circuit-breakers;
- overlapping outages of three or more substation components are neglected;
- from overlapping failures only so-called total failure events (i.e. combining of passive and active failure events) and active failure events whose duration is determined by repair or replacement time *r* are considered. Overlapping of the switching state, corresponding to a relatively short switching time, with failure of any other component is not considered;
- a component is not taken out for preventive maintenance if it causes the outage of a customer load point;
- preventive maintenance on busbars is not considered.

Aforesaid failure events and corresponding component outages with their switching and repairing states are depicted graphically as sets and subsets of events in Figures 2 and 3. In the figures the following symbols are used:

B, S, L – breakers, busbars and transmission lines;

superscripts *t, p, a* – total, passive and active failures. Such classification is needed only for circuit-breakers, as passive failure events for other components are neglected;

superscripts *st, ma* – breaker stuck and maintenance;

subscripts *s, r, s-r, m* – switching time, repair times (Fig. 1) and maintenance time.

Symbol $\bigcap$ denotes intersection of event sets.

For example, in Fig. 2*a* expression $B_s^a \bigcap B_s^{st}$ represents the failure events where the switching state of a circuit-breaker active failure is accompanied by a stuck of primary-zone breaker. Such failure events form a subset of the set B_s^a of switching states of active failures. The set B_s^a, in turn, is a subset of active failures of the circuit-breaker B_r^a. The active failures form a subset of total failures of the circuit-breaker B_r^t.

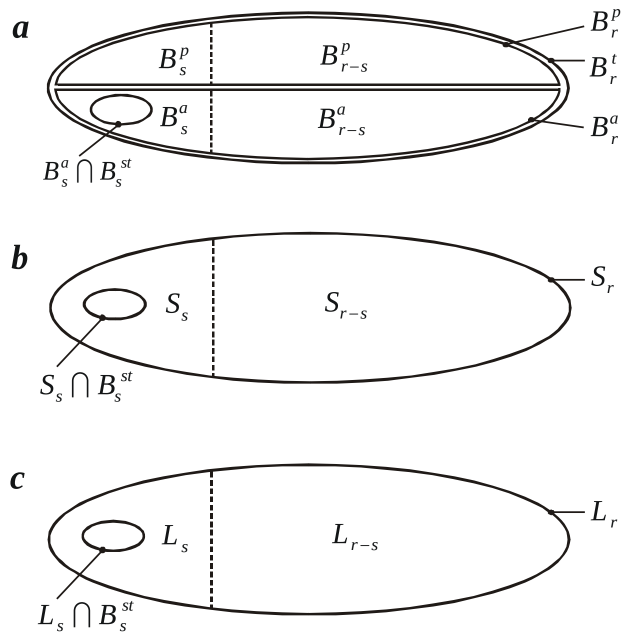

Fig. 2. Failure events and states of components: (a) breaker; (b) busbar; (c) line.

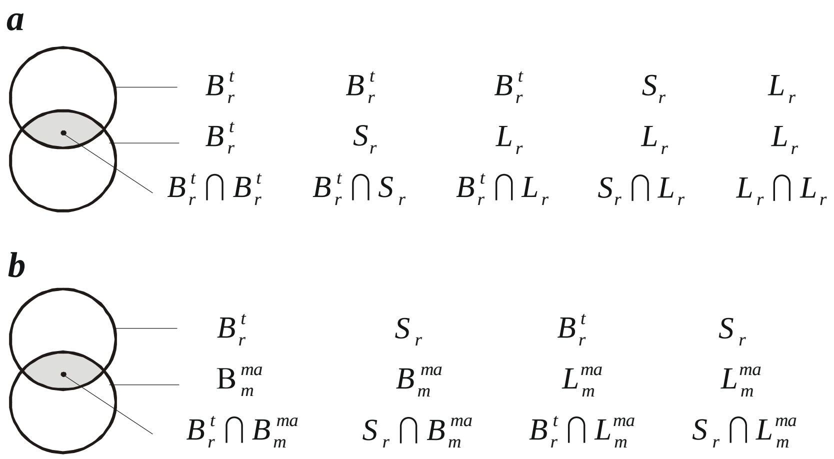

Fig. 3. Overlapping failure events including maintenance outages: (a) overlapping failure events; (b) maintenance outages overlapped by a component-forced outage.

Outage rate and annual outage time

If there are available statistical data on average failure and maintenance rates, switching times, and repair and maintenance durations of substation components and on probabilities of circuit-breaker stuck, it is possible to assess rates and total annual durations of failure-related outages for every failure event of every substation component. Corresponding basic formulas are well known [1].

Knowing passive failure rate of a component, for example of a circuit breaker λ_B^p, the corresponding outage rate will be

$$\lambda(B_r^b) = \lambda_B^b. \tag{1}$$

Further, if the average repair time r_B is known, the average annual outage time or unavailability can be determined as product of the failure rate and repair time

$$U(B_r^p) = \lambda_B^p \cdot r_B. \tag{2}$$

Corresponding indices for all possible outages and outage states shown in Fig. 2 can be calculated similarly.

An exception is a circuit-breaker stuck. Knowing the stuck probability p^{st}, the formulas for the circuit-breaker stuck accompanied by a busbar failure, for instance, will be

$$\lambda(S_s \cap B_s^{st}) = \lambda_S \cdot p^{st} \tag{3}$$

and

$$U(S_s \cap B_s^t) = \lambda_S \cdot p^{st} \cdot s_B. \tag{4}$$

In the case of overlapping failures (Fig. 3*a*) the formulas for overlapping the total failure of a circuit-breaker and a busbar fault, for example,will be

$$\lambda(B_r^t \cap S_r) = \lambda_B^t \cdot \lambda_S (r_B + r_S)/8760 \tag{5}$$

and

$$U(B_r^t \cap S_r) = \lambda_B^t \cdot \lambda_S \cdot r_B \cdot r_S /8760, \tag{6}$$

where the total failure rate $\lambda_B^t = \lambda_B^p + \lambda_B^a$. Here the failure rates are measured in events per annum (1/yr), and average repair times in hours (hr) per failure.

The formulas for other overlapping failure events are analogous.

Formulas will differ from the previous ones, if the failure of a component occurs during the maintenance of another component. It is so because during a forced outage of a component the maintenance of any other component will not be initiated. For instance, in the case of a busbar fault during the maintenance of a breaker the corresponding formulas will be

$$\lambda(S_r \cap B_m^{ma}) = \lambda_S \cdot \lambda_B^{ma} \cdot m_B /8760 \tag{7}$$

and

$$U\,(S_r \cap B_m^{ma}) = \lambda_S \cdot \lambda_B^{ma} \cdot m_B \frac{r_S\,.m_B}{(r_S + m_B)8760}\,. \tag{8}$$

If reliable local statistics on the initial data needed for calculations is not available, the data for neighbouring countries, at least for a rough assessment, can be used. In this study the average data from different publications on failure rates and durations of substation components are employed (Table 1).

On the basis of data in Table 1, the values of reliability indices for all failure events and states shown in Figures 2 and 3 can be calculated by formulas analogous to (1)–(8). The results for failure events with higher values of failure rate and unavailability are presented in Table 2. At that, the failure rates of 20-km transmission lines were assumed to be 20×0.01 = 0.2.

Table 1. **Average reliability indices of substation components used in sample calculations**

Component	Passive failure rate λ^p, f/yr	Active failure rate λ^a, f/yr	Repair time *r*, hr	Switching time *S*, hr	Maintenance duration $\lambda^{ma} \cdot m$, hr/yr	Probability of a breaker failure, due to stuck, p^{st}
Circuit-breaker	0.01	0.01	50	1	20	0.06
Busbars	–	0.02	15	1	3	–
Transmission line	–	0.01 f/km/yr	10	1	4	–

Table 2. **Reliability indices of failure events and states of the components**

Failure event		Outage	
Component	State	Failure rate λ, f/yr	Unavailability U, hr/yr
Circuit-breaker	B_r^p	0.01	0.5
	B_s^p	0.01	0.01
	B_{r-s}^p	0.01	0.49
	B_r^a	0.01	0.5
	B_s^a	0.01	0.01
	B_{r-s}^a	0.01	0.49
	$B_s^a \cap \mathbf{B}_s^{st}$	0.0006	0.0006
Busbars	S_r	0.02	0.3
	S_s	0.02	0.04
	S_{r-s}	0.02	0.26
	$S_s \cap B_s^{st}$	0.0012	0.0012
Transmission line	L_r	0.2	2.0
	L_s	0.2	0.2
	L_{r-s}	0.2	1.8
	$L_s \cap B_s^{st}$	0.012	0.012

Reliability indices for remaining overlapping failures and failures which overlap with maintenance outage of a circuit-breaker or transmission line are less than the values in Table 2 ($\lambda \leq 0.0001$ and $U \leq 0.0006$). The unavailability 0.0006 means that the annual outage is only 2.2 sec. In analysis of substations of lower reliability such failures can be neglected. This will simplify the analysis substantially.

Assessment of substation-related outages

Substation-related outages or contingencies are substantially dependent on the configuration and the topology of terminal connections and failure events of substation components.

For further illustration of a substation reliability, let us analyse a substation in the H-connection of a high-voltage switchgear depicted in Fig. 4. From the total list of failure events, as an example of the contingencies related to failures of breaker B1, busbar section S1 and line L1 and corresponding connection interruption events (lines L1 and L2, transformers T1 and T2) with their rates and annual durations are presented in Table 3.

Every failure event can be divided into states (phases, Fig. 2) differently, depending on substation configuration and the aim of the analysis.

As outages of different components can cause interruption of the same connection, one has to summarize the values of indices for outages causing the interruptions to get the data about certain interruptions.

As an example, in Table 3 three interruption cases are observed: interruption of transformer connection T1, simultaneous interruption of transformer connections T1 and T2, and interruption of power transit through lines L1 and L2. Reliability indices must be summarized selectively, depending on

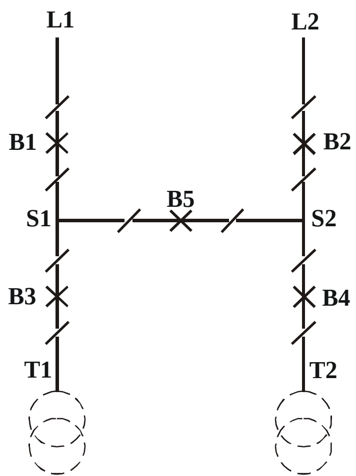

Fig. 4. A substation diagram in the H-connection.

affiliation of failure events and their states in event sets and subsets (Fig. 2). Correspondingly, columns 5–10 of Table 3 contain only the values belonging to be summed up. For instance, the active failure of breaker B1 with a simultaneous stuck of breaker B5 (row 4 in Table 3) causes an outage of the transformer T1 terminal. However, the corresponding values of λ and *r* must not be included in columns 4 and 5 for summation, because a stuck is a subevent of the active failure event of the breaker B1 considered already in row 2. For the same reason they will not be included in columns 9–10 for calculation of the transit interruption indices.

The box in row 3 and column 9 is empty as well, because the rows 3 and 4 present two states of the same failure event, and the corresponding interruption rate is considered already in row 2 (column 9).

In spite of summation problems, the columns 5–10 of Table 3 give a good overview of factors affecting substation reliability and their relative importance. Such tables enable to analyze and compare different configurations of substation and network, to elaborate measures to improve system operation, to incorporate outages of substations and switching stations into the evaluation of the composite system reliability etc.

Table 3. **Contingencies and their indices for the substation in Fig. 4**

Component failure, state	Contingency			Outage of terminal T1		Outage of terminals T1, T2		Interruption of transit through L1, L2	
	Outaged terminals	λ, 1/yr	*U*, hr/yr	λ, 1/yr	*U*, hr/yr	λ, 1/yr	*U*, hr/yr	λ, 1/yr	*U*, hr/yr
1	2	3	4	5	6	7	8	9	10
$B1_r^p$	L1	0.01	0.5					0.01	0.5
$B1_s^a$	L1 T1	0.01	0.01	0.01	0.01			0.01	0.01
$B1_{r-s}^a$	L1	0.01	0.49						0.49
$B1_s^a \cap B5_s^{st}$	L1 L2 T1 T2	0.0006	0.0006			0.0006	0.0006		
…………..									
$S1_r$	L1 T1	0.02	0.3	0.02	0.3			0.02	0.3
$S1_s \cap B5_s^{st}$	L1 L2 T1 T2	0.0012	0.0012			0.0012	0.0012		
…………..									
$L1_r$	L1	0.2	2.0					0.2	2.0
$L1_s \cap B1_s^{st}$	L1 T1	0.012	0.012	0.012	0.012				

The analysis is relatively simple and performable without specialized computer programs.

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