Substation Reliability Evaluation including Switching Actions with Redundant Components

by

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Abstract-**Failure events in substations often result in multiple outages of generators, lines and/or loads in power systems. The simulation of substation originated outages for practical substation configurations is difficult, due to the complex switching actions with disconnect switches and circuit breakers that can take place. A digital computer program has been developed at the Delft University of Technology, which simulates these complex switching actions following substation failures. The simulation algorithms, which deduce the contingencies before and after switching actions with their corresponding reliability indices, are described in detail in the paper. The paper reports on results obtained from analyzing six different busbar schemes with redundant components.**

1. Introduction

Many studies of substation reliability have been conducted in the past. The majority fall into one of two categories [1]. The first [2,3] has been concerned with deducing system states, their likelihood and the impact they have on connectivity including the modelling of active and passive failures. The second [4,5,6] has been concerned with the deduction of station-originated outages in a composite generation and transmission system due to active and passive failures in substations. Few, if any, have dealt with the assessment of the sequential complex reconfiguration events that can be used to recover energy supply following component failures and protection relay responses [1]. This paper describes an approach to incorporate such complex switching actions with disconnect switches and circuit breakers in the reliability evaluation of substation topologies.

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A station-originated outage is a forced outage of any number of system generators, lines and/or loads, caused by a failure inside a switching station or substation [5]. The probability and frequency of a station-originated outage can be high and can contribute significantly to the reliability indices of electricity supply [3,5,6,7].

The various failure modes in substations which can cause station-originated outages are [5,6]:
* Passive failure events
* Active failure events
* Stuck-condition of breakers
* Overlapping failure events

Passive failure events are referred to as all component faults that do not cause operation of protection breakers. Examples are undetected open-circuits and inadvertent operations of circuit breakers.

Active failure events are all component faults that cause the operation of the primary protection zone (breakers) around the failed component. An example is a short-circuit fault.

Stuck-condition of breakers arise when circuit breakers in the primary zone fail to operate following 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 previously failed substation component. The overlapping failure events usually considered are those involving only two station components. The probability of higher-order outages is normally negligible [5].

A previously proposed approach [5,6] applied to Dutch substation configurations appears to have certain limitations. Therefore, a computer program has been developed at the Delft University of Technology which contains a set of enhanced algorithms.

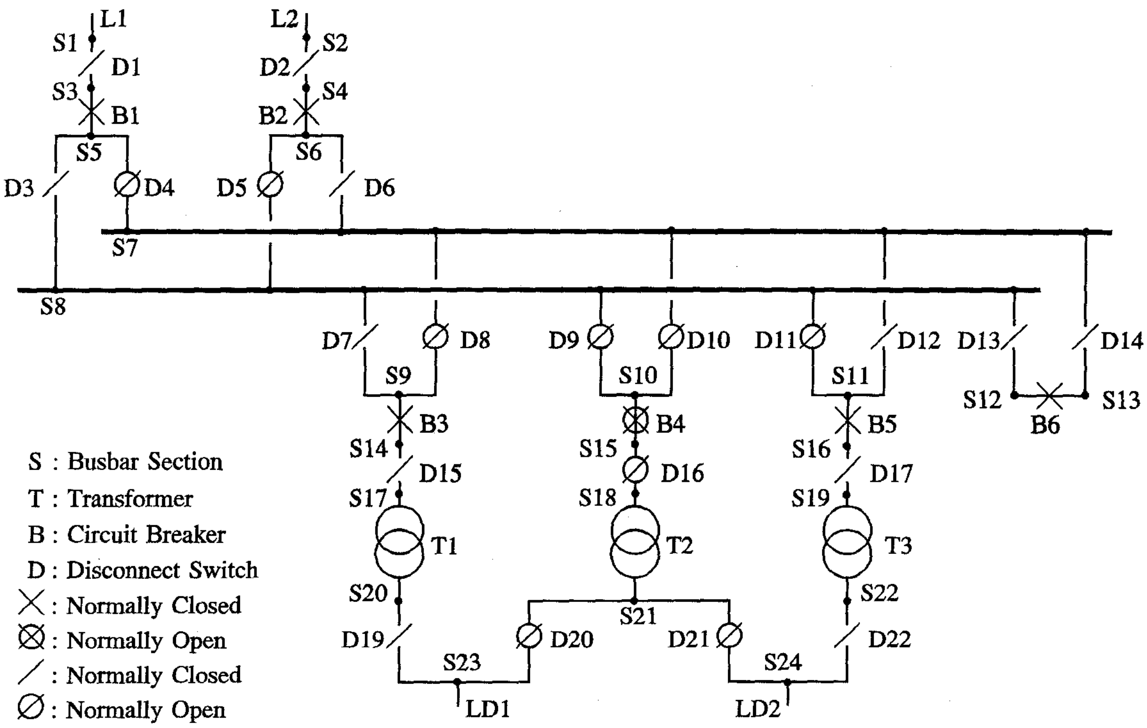

Figure 1. Single line diagram of a duplicate busbar scheme

2. Improvements

The first improvement to existing methods is to include both normally open and normally closed disconnect switches and/or circuit breakers in the analysis. This was impossible in the models previously used. To illustrate the impact of the incorporation of normally open and normally closed disconnect switches and/or circuit breakers, consider the single line diagram of a typical Dutch duplicate busbar substation configuration, as shown in figure 1.

Assume that breaker B3 suffers a short-circuit (active failure) which causes the operations of the surrounding breakers B1 and B6. This event causes L1 and LD1 to be outaged and this is a station-originated outage. After the operation of the breakers, the faulted breaker B3 is disconnected from the other healthy components, by opening the disconnect switches D7, D18 and D15. Simultaneously, the disconnect switches D9, D16 and D19 are commanded to close, followed by closing commands on the circuit breakers B1 and B4. Therefore, after these switching operations, the load LD1 is again supplied. This example demonstrates that the contingency caused by a fault on breaker B3 can be alleviated by switching operations with several breakers and disconnect switches.

In the models previously used, active (and passive) failure modes have been modelled together using the three-state model, shown in figure 2. The three states are:

* State before the fault (U)
* State after the fault but before isolation (S)
* State after isolation but before repair (R)

When the three-state model of figure 2 is used, an active failure on breaker B3 lead indirectly to state R. According to the model of figure 2, this state causes the contingency of LD1 during the whole repair time of breaker B3 (a passive failure on B3 lead directly to state R).

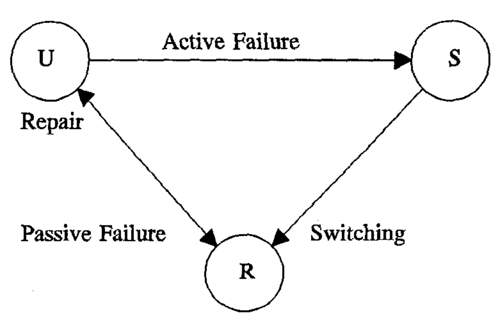

Figure 2. Three-state failure model

Therefore, the three-state model can not be used in reliability evaluation studies of substation configurations with redundant components (which are associated with normally open disconnect switches and/or circuit breakers). One of the assumptions in the concepts previously developed was that all circuit breakers (and disconnect switches) are normally closed. It should be clear that more detailed simulation algorithms, which take switching operations with redundant components into account, are necessary.

A second improvement to existing methods is to consider also failures on transmission lines in combination with stuck circuit breakers. From experience, it is a well known fact that failure rates of transmission lines are usually higher than failure rates of substation components. Therefore, it is not consistent to simulate active failures on substation components in combination with a stuck circuit breaker and to ignore active failures on transmission lines plus a stuck circuit breaker.This paper extends the present techniques by describing a set of enhanced algorithms which simulate several failure modes of substation components and the following switching actions, using principles of network reliability and failure mode and effects analysis. The resulting contingencies for each substation failure event are deduced and their corresponding reliability indices are evaluated.

3. Enhanced simulation algorithms

In the algorithms it is assumed that only the following substation components can fail: breakers (B), transformers (T) and certain busbar sections (S). Failures on other substation components are neglected. The fundamental concepts on which the algorithms are based are described in detail in Reference 1. A summary with certain modifications is given in this section.

Some realistic assumptions are adopted in the algorithms. These are:

* All the analysis is performed for a single weather condition
* Circuit breakers actively failing cannot clear their own faults
* Circuit breakers can operate due to faults in either direction
* Passive failures only occur on circuit breakers

The basic structure of the computer program is:

(i) Read the substation data.
(ii) Simulate passive events on breakers.
(iii) Simulate active events on breakers, transformers and busbars.
(iv) Simulate active events on breakers, transformers and busbars, followed by a stuck-condition of the circuit breakers that should have operated.
(v) Simulate overlapping failure events involving two substation components. These include passive and active failures overlapping the failure of another component.
(vi) Classify contingencies by order, group the failure events leading to the same contingency and evaluate the total probability and frequency of each contingency.

Reading substation data
In this step, the data defining the substation topology, the normally open or closed positions of circuit breakers and disconnect switches and the reliability parameters of the substation components are read.

Simulating passive events
The substation shown in figure 1 can be used to illustrate a passive event. Assume breaker B1 in figure 1 suffers a passive failure event. This failure event results in the isolation of line L1. From the figure, it appears that repair of breaker B1 can only take place when the disconnect switches D1, D3 and D4 are open. From figure 1, it can also be seen that switching operations with disconnect switches cannot lead to energizing of line L1, before the faulted breaker B1 is repaired. Therefore, the probability of being found in the passive contingency state and its frequency of occurrence is equal to the probability and frequency of the passive failure event which leads to it. These two indices can be approximated by:

$$P_{pc} \simeq \lambda^{p} \cdot r \tag{1}$$

$$f_{pc} \simeq \lambda^{p} \tag{2}$$

where:

P_{pc} the probability of the passive contingency
f_{pc} the frequency of occurrence of the passive contingency
λ^{p} the failure rate of a passive failure event
r the repair time of the substation component

Assume now that breaker B3 in figure 1 suffers a passive failure event. This failure event results in the isolation of load LD1. From the figure it appears that repair of breaker B3 can take place when the disconnect switches D7, D8, D15 and D18 are open. After the opening of these disconnect switches, the disconnect switches D9, D16 and D19 are manually closed, followed by the closing of circuit breaker B4. Therefore, load LD1 is energized, before the passively faulted breaker B3 will be repaired. The probability (P_{pc}) of being found in the passive contingency state and its frequency (f_{pc}) of occurrence can be evaluated by a modified form of (1) and (2):

$$P_{pc} \simeq \lambda^p \cdot s \qquad (3)$$

$$f_{pc} \simeq \lambda^p \qquad (4)$$

where:

s the switching time of the substation component

The algorithm to simulate passive failure events is as follows:

(i) Select a circuit breaker.

(ii) Open this circuit breaker.

(iii) Identify whether generators, lines and/or loads are disconnected and set the value of the number of isolated generators, lines and/or loads before switching, N_{bs}, to the total number of generators, lines and/or loads on outage due to this failure event.
 (a) If $N_{bs}=0$, go to step (viii).
 (b) If $N_{bs}>0$, go to step (iv).

(iv) Open all neighboring disconnect switches around the breaker which has passively failed.

(v) Close all other disconnect switches.

(vi) Close all healthy circuit breakers.

(vii) Identify the generators, lines and/or loads which are now disconnected and set the value of the number of isolated generators, lines and/or loads after switching, N_{as}, to the total number of generators, lines and/or loads on outage after these switching actions.
 (a) If $N_{as}=N_{bs}$, determine the probability and frequency of this outage, using the equations (1) and (2).
 (b) If $N_{as}=0$, determine the probability and frequency of the outage, using the equations (3) and (4).

(viii) Restore the original topology, and repeat steps (i) to (vii) until all circuit breakers have been considered.

Simulating active events

The substation configuration in figure 1 can also be used to illustrate active events. Assume that busbar S8 suffers an active failure event. The breakers B1, B3 and B6 should operate. Therefore, line L1 and load LD1 are forced out. The faulted busbar S8 is then isolated by opening the disconnect switches D3, D7 and D13. After this isolation all disconnect switches connected to busbar S7 are closed, followed by the closing of the breakers B1 and B3. By doing so, the line L1 and load LD1 are only on outage for a short duration, defined by the switching time of the faulted substation component. Therefore, the equations (3) and (4) are valid, provided that λ^p is replaced by λ^a (active failure rate).

From figure 1, it appears also that it is possible that some severe outages can be alleviated but not totally relieved. Such an event occurs when for example breaker B1 actively fails. The breakers B3 and B6 will trip and line L1 and load LD1 are on outage. By opening the disconnect switches D1 and D3, the faulted breaker B1 is isolated and after this, the healthy breakers B3 and B6 will be closed again. After these switching actions, the contingency is alleviated from L1,LD1 to L1. Therefore, in the situation before switching, the equations for the probability ($P_{ac,bs}$) and frequency ($f_{ac,bs}$) of such a contingency created by an active failure on a component are given by:

$$P_{ac,bs} \simeq \lambda^a \cdot s \qquad (5)$$

$$f_{ac,bs} \simeq \lambda^a \qquad (6)$$

For the situation after switching, the probability ($P_{ac,as}$) and frequency ($f_{ac,as}$) of this contingency can be evaluated by:

$$P_{ac,as} \simeq \lambda^a \cdot (r-s) \qquad (7)$$

$$f_{ac,as} \simeq \lambda^a \qquad (8)$$

The algorithm for simulating active failure events is as follows:

(i) Select a substation component.

(ii) Open all neighboring circuit breakers around this component.

(iii) Identify whether generators, lines and/or loads are disconnected and set the value of N_{bs} to the total number of generators, lines and/or loads on outage due to this failure event.
 (a) If $N_{bs}=0$, go to step (viii).
 (b) If $N_{bs}>0$, go to step (iv).

(iv) Open all neighboring disconnect switches around the substation component which have actively failed.

(v) Close all other disconnect switches.

(vi) Close all healthy circuit breakers.

(vii) Identify the generators, lines and/or loads which are now disconnected and set the value of N_{as} to the total number of generators, lines and/or loads on outage due to these switching actions.
 (a) If $N_{as}=0$, determine the probability and frequency of the outage, using the equations (5) and (6).
 (b) If $N_{as}=N_{bs}$, determine the probability and frequency of this outage, using the equations (1) and (2) with λ^a in stead of λ^p.
 (c) If $0<N_{as}<N_{bs}$, determine the probabili-

ties and frequencies of both outages, using the equations (5), (6) and (7), (8) respectively.

(viii) Restore the original topology, and repeat steps (i) to (vii) until all substation components have been considered.

Simulating stuck-condition of breakers

Again, figure 1 is used to illustrate such failure events. If line L1 suffers an active failure, breaker B1 should operate. Suppose B1 fails to operate (stuck) and therefore, B3 and B6 respond causing the removal of line L1 and load LD1. Therefore, in this situation before switching, the equations for the probability ($P_{sc,bs}$) and frequency ($f_{sc,bs}$) of this contingency created by a stuck condition of a circuit breaker are given by:

$$P_{sc,bs} \simeq \lambda^a \cdot P_s \cdot s \tag{9}$$

$$f_{sc,bs} \simeq \lambda^a \cdot P_s \tag{10}$$

where:

P_s the probability of a stuck condition of a circuit breaker

The probability, P_s, can be evaluated from a data collection scheme and is given by [8]:

$$P_s = \frac{\text{number of failures to operate}}{\text{number of commands to operate}} \tag{11}$$

After such severe failure events, the operators of the power system should try to restore the substation topology as far as possible. This means in the present case that line L1 and circuit breaker B1 are isolated by opening the disconnect switches D1, D3 and D4. After this fault isolation, the breakers B3 and B6 are closed. In this new situation, both loads LD1 and LD2 are again supplied and only line L1 is on outage. For the new situation after switching, the probability ($P_{sc,as}$) and frequency ($f_{sc,as}$) indices of this contingency can be evaluated by:

$$P_{sc,as} \simeq \lambda^a \cdot P_s \cdot (r-s) \tag{12}$$

$$f_{sc,as} \simeq \lambda^a \cdot P_s \tag{13}$$

The algorithm for simulating an active failure on a transmission line or a substation component in combination with a stuck breaker, is a slight modification of the algorithms presented earlier. Therefore, it is not presented here.

Simulating overlapping events

The probability (P_{oc}) and the frequency (f_{oc}) of occurrence of an overlapping contingency state of two components are evaluated from network reliability concepts and can be approximated by:

$$P_{oc} = \lambda_1 \lambda_2 r_1 r_2 \tag{14}$$

$$f_{oc} = \lambda_1 \lambda_2 (r_1 + r_2) \tag{15}$$

In equations (14) and (15), λ_1 is the total failure rate ($\lambda_1^p + \lambda_1^a$) of the first component of the overlapping event to fail; r_1 is its repair or replacement time. The parameters λ_2 and r_2 are similarly defined.

The algorithm for simulating overlapping failures of substation components, is a slight modification of the algorithms presented earlier.

Classifying contingencies

In this step, the different substation failure events leading to the same contingency are identified. From the previous examples it appears, that many distinct failure events (passive failures, active failures and stuck-condition of breakers) might cause the same station-originated outage or contingency.

The total probability, P_{ck}, and frequency, f_{ck}, of each specific contingency can be determined by:

$$P_{ck} = \sum_{i \in k} P_{ik} \tag{16}$$

$$f_{ck} = \sum_{i \in k} f_{ik} \tag{17}$$

where:

- P_{ck} the probability of contingency k
- f_{ck} the frequency of contingency k
- P_{ik} the probability of event i leading to contingency k
- f_{ik} the frequency of event i leading to contingency k
- $i \in k$ the failure events leading to contingency k

The mean duration of contingency k, D_{ck}, is given by:

$$D_{ck} = \frac{P_{ck}}{f_{ck}} \tag{18}$$

These three indices constitute the information required for composite system reliability evaluation studies. They take into account station-originated outages and switching actions, performed by the operators, after faults in substations. However, the algorithms can also be used for reliability assessment

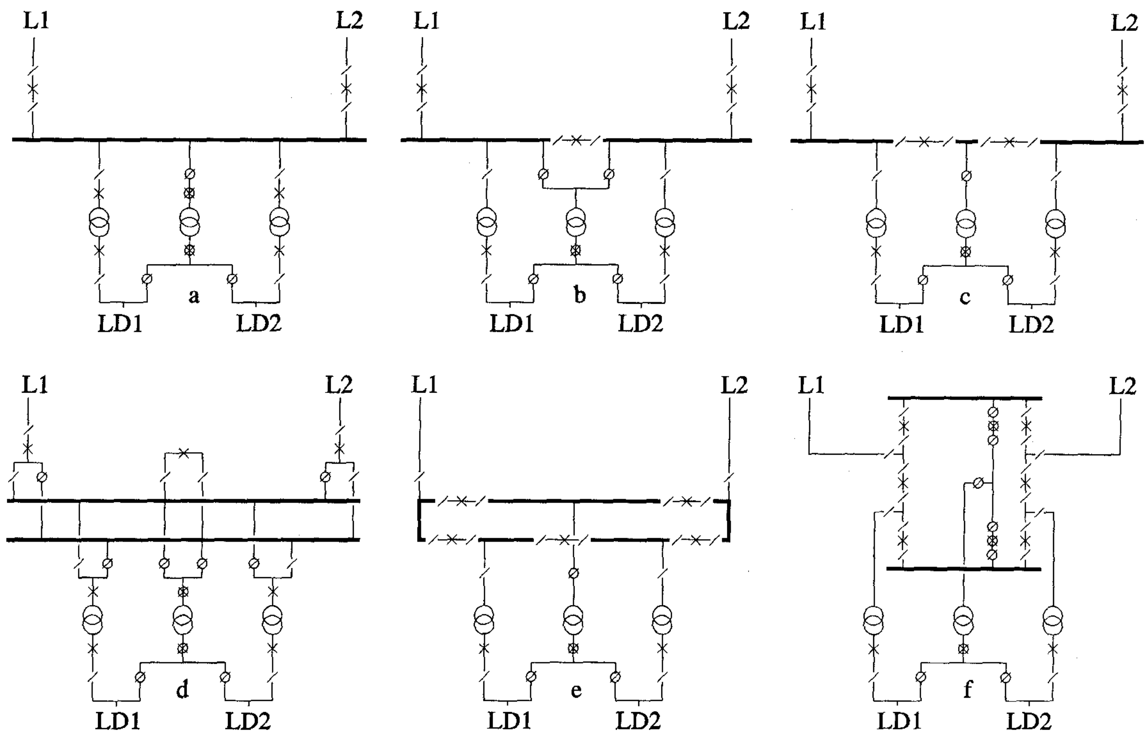

Figure 3. Single line diagrams of six different busbar schemes which are often used in (sub)transmission networks

studies of individual busbar schemes, as will be shown in the next section.

4. Numerical examples

Consider the six different busbar schemes of figure 3 which are often used in (sub)transmission networks and the reliability data in table 1. These data are taken from References 1 and 2 but more actual data could have been used as well. In each configuration, the loads LD1 and LD2 are supplied by two transmission lines L1 and L2 via three transformers, where the third transformer is a spare transformer. The interlaying busbar schemes are different.

Component	λ^a [f/yr]	λ^p [f/yr]	s [hr]	r [hr]	P_s
Breaker	0.01	0.01	1	12	0.06
Busbar	0.025	--	2	25	--
Transformer	0.10	--	1	150	--
Line	1.00	--	1	10	--

Table 1. Reliability data

The busbar-data given in table 1 are only valid for the thick busbar sections in figure 3. The corresponding active failure rates of the thin busbar sections in figure 3 are assumed to be equal to zero.

Figure 4 shows the frequency and duration indices, F and D respectively, of load LD1 being disconnected, for all six busbar schemes. These indices are calculated using the enhanced simulation algorithms. Because all substation configurations are symmetric, the values of F and D for load LD2 are identical. For each contingency, the total probability, P_{ck}, frequency, F_{ck}, and mean duration, D_{ck}, is calculated, using equations (16) to (18). Then, for each contingency a check is performed to assess the connection of the load with at least one of the feeding transmission lines L1 and L2.

The results presented in figure 4 show the difference in reliability indices as a result of ignoring switching actions with redundant components (which are associated with normally open and normally closed disconnect switches and/or circuit breakers). From these differences, it can be seen that switching actions with redundant components have considerable effect on the mean duration (and probability) of load being disconnected. This influence is mainly due to the large repair times and the relatively small switching times of substation components. The frequency indices are not influenced by modelling

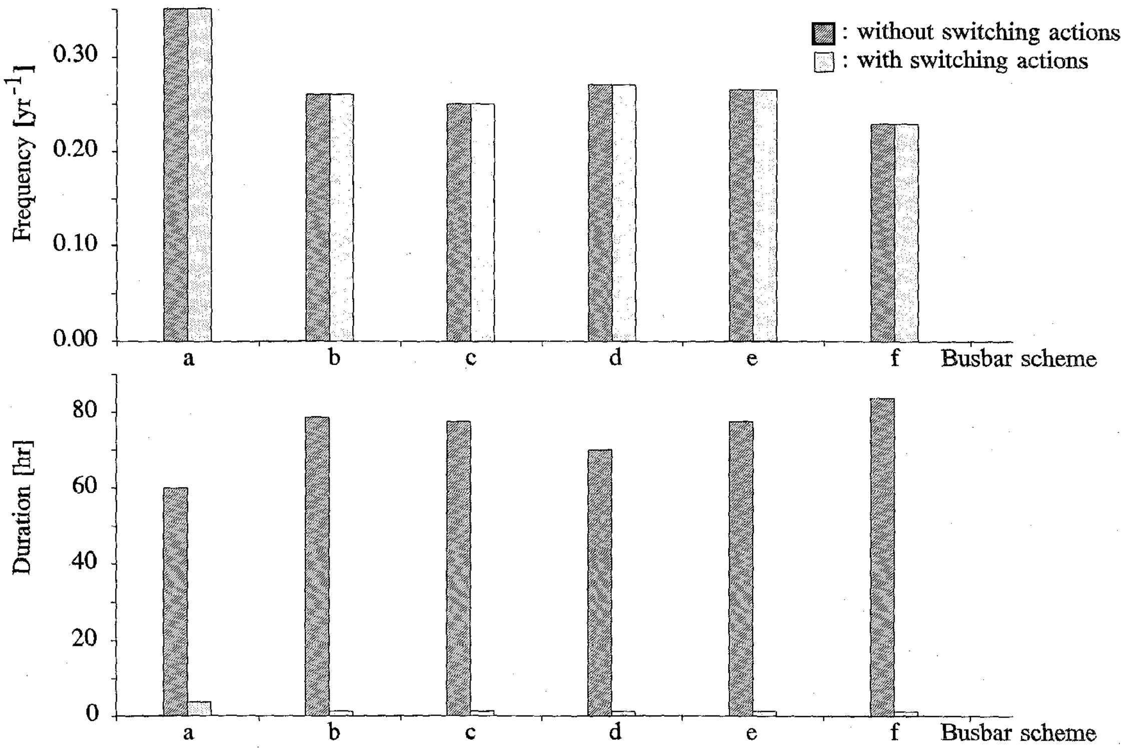

Figure 4. Frequency and duration indices of the load points LD1 and LD2 for the busbar schemes presented in figure 3

these switching actions, which is clear. Figure 4 shows that modelling techniques can have significant effect on the calculated reliability indices. For example: the mean duration of load point LD1 being disconnected in substation configuration *a* reduces from 59.11 hours to 3.26 hours and the mean duration of load point LD1 being disconnected in configuration *f* reduces from 83.35 hours to 1.12 hours, which is approximately equal to the switching time of several substation components (table 1).

The proposed concepts in this paper improve considerably previously developed concepts. In previously developed concepts [5,6], the assumption was made that all circuit breakers (and disconnect switches) are normally closed. However, this assumption is not always valid, and in order to incorporate switching actions with redundant components, a set of enhanced algorithms was developed, resulting in a more realistic simulation approach.

5. Conclusions

The contingencies caused due to failures in substation configurations are an important aspect in the reliability evaluation of electricity supply. It is very important to simulate these contingencies in the most appropriate manner. For such simulations, a thorough understanding of system behavior and operation is essential.

This paper demonstrated the effect of switching operations with normally open and normally closed disconnect switches and/or circuit breakers on the frequency and duration indices of contingencies, caused by station-originated outages. The paper has described the simulation aspects in detail. The proposed concepts in this paper improve considerably previously developed concepts.

The enhanced simulation algorithms described in this paper are currently used in a decision-making process to determine appropriate busbar schemes for the PNEM, a utility in the southern part of the Netherlands. In the project, called 'Substation-2000', several new substation concepts are compared to their costs and reliability.

Acknowledgement

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Biographies

Jos Meeuwsen was born in Goes, the Netherlands, on December 29, 1971. He received his M.S.-degree in electrical engineering from the Delft University of Technology in 1994. Since then he has been with the Power System Laboratory of the same university. He is presently working on a Ph.D.-degree. His main research interests are reliability assessment of electric power systems and power system protection.

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