Substation Reliability Evaluation Considering the Failure Events

Sung Hun Kim[1] and Dong Ju Lee[2]

1 Professor, Kongju National University, Republic of Korea
2 PhD candidate, Chungnam National University, Republic of Korea
E-mail: shkim3456@kongju.ac.kr; david1973.lee@gmail.com

Abstract. In this paper, bus and breaker structures of typical two substations were modelled by graph circuit to evaluate each reliability considering the various failure events and compare them each other. Passive failure event, active failure events, breaker stuck conditions and overlapping failure events in substation were conceptually explained and the reliability equations were presented to calculate the failure rate, repair rate and unavailability of each failure events. Also, deduction algorithms were implemented as a software programming to find the minimal cut sets for passive failure events and active minimal cut sets for active failure events. In the case study, reliability indices of each failure events and entire reliability indices (failure rate, annual outage time and MTTR) of typical two substations were calculated and quantitatively compared.

1. Introduction

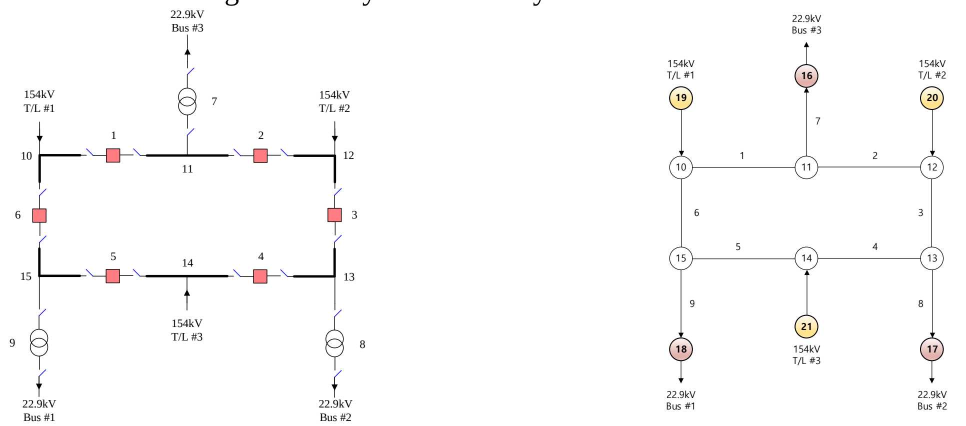
A substation consists of buses, transformers, breakers, and diverse protective devices for safe operation of the system. When a failure has occurred in a component of a substation, relatively complicated switching actions occur. The evaluation of the reliability of a substation considering such switching actions requires clear inference of failure events including passive failures, active failures, breaker stuck conditions and overlapping failures. In addition, minimal paths are inferred from failure events in the bus system to calculate failure rates, annual repair time, and unavailability, which are reliability indices, based on the minimal cut set and the active minimal cut set.

To infer failure events of substations, a method to prepare circuit graphs for substation components and infer the minimal path from the circuit graphs to determine the minimal cut set and the active minimal cut set was proposed [1]. For reliability index calculation considering substation's switching states, a new technique was proposed that is setting a two state model and a three state model to obtain minimal cut sets for passive failures and active failures and determining active minimal cut sets among the selected minimal cut sets[2]. A technique was presented that is to prepare an array of access of components by finding and storing all minimal paths between the power supply point and all load points and determine the minimal cut set as the cut set to which power supply is stopped through combinations of the paths[3].

In this paper, bus and breaker structures of typical substations were modelled by graph circuit to infer the failure events (passive failure events, active failure events, breaker stuck conditions and overlapping failure events) in substation and these failure events are conceptually explained. Deduction algorithms were implemented as a software programming to find the minimal cut sets for passive failure events and active minimal cut sets for active failure events. As a case study, reliability indices of each failure events and entire reliability indices (failure rate, annual outage time and MTTR) in the ring bus substation and double bus double breaker substation were calculated and quantitatively compared. The results of analysis of the reliability indices of typical two substations can be utilized as basic data in the design and maintenance schedule planning of substations with diverse bus structures hereafter.

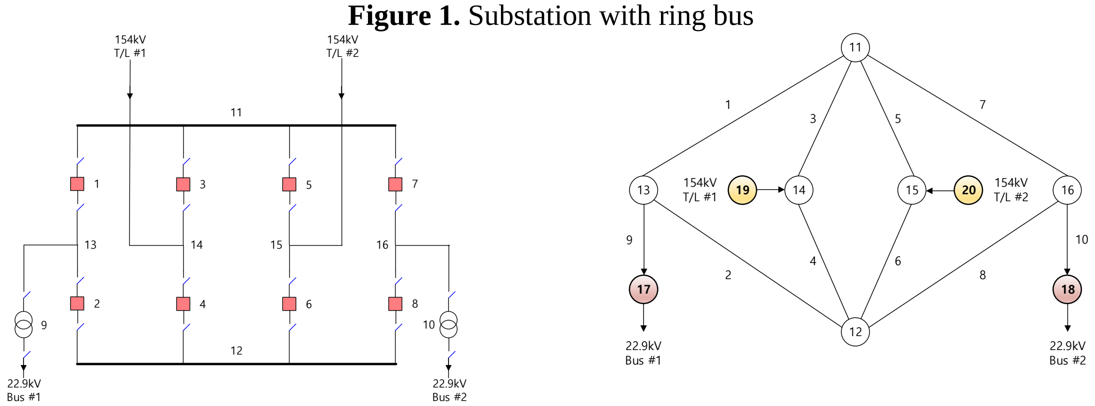
2. Failure events in substation

2.1. Graph modelling of typical substation
Figure 1 and 2 shows the system configuration and graph circuit of a substation with a ring bus structure and a substation with double bus double breaker structure, which are widely used in modern substations because of its high flexibility and reliability.



(a) System configuration (b) Graph circuit

Figure 1. Substation with ring bus



(a) System configuration (b) Graph circuit

Figure 2. Substation with double bus double breakers

The substation shown in Figure 1 consists of six breakers (branch 1~6), three transformers (branch 7~9), and ring bus (node 11~15), Three supply points (node 10, 12, 14) are connected to the transmission lines and two transformers (branch 9, 10) are connected to user load points (node 17, 18).
The substation shown in Figure 2 consists of eight breakers (branch 1~8), two transformers (branch 9, 10), and two buses (node 11, 12). Two supply points (node 14, 15) are connected to the transmission line and three transformers (branch 7~9) are connected to user load points (node 16~18)
In these substations, there are various failure events of internal components for each status transitions among the normal, switching and repair status.

2.2. Passive failure events
Passive failure events mean all failures that do not induce the actions of protective breakers located around the component where failure occurred and do not affect normally operating components where no failure occurred. Since a passive failure event generally causes first order contingency, power

outage occurs at one load point. The probability and frequency of occurrence are relatively low and in the case of bus and transformers, passive failures are ignored because the passive failure frequency is very close to zero.

2.3. Active failure events

Active failure events refer to all failures that induce the actions of protective breakers adjacent to the component where failure occurred and affect normally operating components where no failure occurred. For instance, when a failure has occurred due to a short-circuit accident, the component where the failure occurred may be separated or switching action may be taken and the function of the component can be continuously performed by other normally operating components. The system may be restored by repairing or replacing the component where the failure occurred.

2.4. Breaker stuck condition

A state where a breaker does not act despite that trip signals have been sent because a failure has been detected by the protective system is called stuck condition. A breaker stuck condition occurs when a breaker failed to act due to an abnormal action of the protective system or due to any trouble in the relay or the breaker per se. Stuck conditions lead to more serious effects on switching substations and provide causes of high order contingency. Therefore, the simulation and analysis of stuck conditions may be more important even if the probability of occurrence of stuck may be low.

2.5. Overlapping failure events

An overlapping failure event is a case where at failures occur sequentially in at least two components, that is, a case where a failure occurs first in a component and failures continuously occur in other components during the recovery time of the component where the failure occurred. In the case of overlapping failure events, usually up to second order overlapping failure events in two components are considered and higher order failure events may be disregarded.

3. Calculation of reliability indices

3.1. Minimal cut sets

The various efficient algorithms for finding the minimal cut sets for the output nodes of any network to find the passive failure events were presented and the algorithm in reference [3] are applied in this study.

3.2. Active minimal cut sets

The various algorithms to infer the active minimal cut sets to find the active failure events were presented and the algorithm in reference [4] are applied to find the following three failure events. The concept of these three failure events can be summarized as shown in Figure 4.

3.2.1. Active minimal cut sets

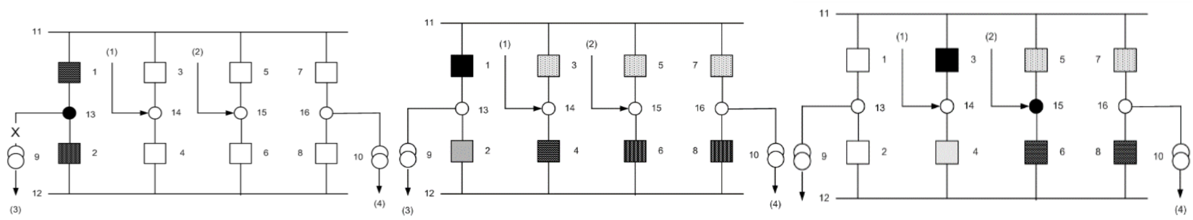
In Figure 3(a), when the first order minimal cut set is transformer 9 and the first order failure event has occurred at node 13, breaker 1 and breaker 2 correspond to the first order active minimal cut set.

3.2.2. Active failure event + total failure event

In Figure 3(b), the second order active minimal cut set for the second order minimal cut set for breaker 1 is 4A, 6A, and 8A and the second order active minimal cut set for breaker 2 is 3A, 5A, and 7A, which are in the state of active failures.

3.2.3. Active failure event + active failure event

In Figure 3(c), when the breaker 3 and the supply point (2) (node 15) are in the state of active failures, 6A and 8A are in the state of active failures and when the breaker 4 and the supply point (2) (node 15) are in the state of active failures, 5A and 7A are in the state of active failures.



(a) (b) (c)

Figure 3. Active minimal cut sets

3.3. Calculation of reliability indices

The reliability indices for load points can be calculated using the minimal cut sets and active minimal cut sets for the load points [5].

In the case of total failure events in which a failure of one component leads to total failure, the reliability indices can be obtained from the first order and second order minimal cut sets. Reliability indices for first order passive failures of a component are given as the reliability data value of the component. On the other hand, the reliability indices for the second order passive failure events due to passive failures of two components can be calculated regarding that the two components are in the state of parallel connection.

In cases where individual maintenance works for individual components are not considered, the failure rate (λ_{pp}) for second order passive failure events can be indicated as shown by equation (1). In general, when $\lambda_i r_i \ll 1$, the repair rate(r_{pp}) and unavailability(U_{pp}) can be obtained with equations (2) ～ (3).

$$\lambda_{pp} = \frac{\lambda_1\lambda_2(r_1+r_2)}{1+\lambda_1 r_1+\lambda_2 r_2} = \lambda_1\lambda_2(r_1 + r_2) \quad (1)$$

where, λ_1,λ_2: failure rates of components 1 and 2

r_1,r_2: repair time of components 1 and 2

$$r_{pp} = \frac{r_1 r_2}{r_1+r_2} \quad (2)$$

$$U_{pp} = f_{pp} r_{pp} = \lambda_{pp} r_{pp} = \lambda_1\lambda_2 r_1 r_2 \quad (3)$$

In cases where individual maintenance works for individual components are considered, the failure rate (λ_{pm}), repair rate(r_{pm}), and unavailability(U_{pm}) for second order passive failure events can be obtained with equations (4) ～ (6).

$$\lambda_{pm} = \lambda_1^{''}\left(\lambda_2 r_1^{''}\right) + \lambda_2^{''}\left(\lambda_1 r_2^{''}\right) \quad (4)$$

where, $\lambda_1^{''}$,$\lambda_2^{''}$: numbers of times of maintenance of components 1 and 2

$r_1^{''}$,$r_2^{''}$: numbers of times of maintenance of components 1 and 2

$$r_{pm} = U_{pm}/\lambda_{pm} \quad (5)$$

$$U_{pm} = \lambda_1^{''}\left(\lambda_2 r_1^{''}\right)\frac{r_1^{''} r_2}{r_1^{''}+r_2} + \lambda_2^{''}\left(\lambda_1 r_2^{''}\right)\frac{r_1 r_2^{''}}{r_1+r_2^{''}} \quad (6)$$

The reliability indices for active failure events for which switching actions are considered can be calculated from the first order and second order active minimal cut sets.

The reliability indices for first order active failures of a component can be easily obtained using the switching time value for the component. That is, when one component is in the state of active failure, in cases where individual maintenance works for individual components are not considered, the failure rate (λ_{ap}) and repair rate (r_{ap}) for passive failure events are as shown by equations (7) and (8).

$$\lambda_{ap} = \lambda_1^a \quad (7)$$

$$r_{ap} = s_1 \quad (8)$$

where, λ_1^a : active failure rate of component 1

s_1 : switching time of component 1

In cases where components are in the state of second order active failures, there may be cases where an active failure of component 1 and the total failure of component 2 overlap with each other and cases where an active failure of component 1 and an active failure of component 2 overlap with each other.

First, cases where an active failure of component 1 and the total failure of component 2 overlap with each other are cases where an active failure of component 1 occurs during the repair time of component 2. The failure rate (λ_{ap}) and repair rate(r_{ap}) in such cases can be calculated as shown by equations (9) and (10).

$$\lambda_{ap} = \lambda_1^a(\lambda_2 s_1) + \lambda_2(\lambda_1^a r_2) = \lambda_1^a \lambda_2(s_1 + r_2) \tag{9}$$

$$r_{ap} = \frac{s_1 r_2}{s_1 + r_2} \tag{10}$$

Since the repair time of a component is generally sufficiently larger compared to the switching time ($r_2 \gg s_1$), the probability of failure of component 2 during the switching time of component 1 may be ignored. Therefore, equation (9) can be approximated into equation (11) and equation (10) can be approximated into equation (12).

$$\lambda_{ap} = \lambda_1^a(\lambda_2 r_2) \tag{11}$$

$$r_{ap} = s_1 \tag{12}$$

Cases where two active failures overlap with each other are cases where active failure of component 1 occurs during the maintenance time of component 2 and the failure rate (λ_{am}) and repair rate (r_{am}) in such cases can be calculated as shown by equations (13) and (14).

$$\lambda_{am} = \lambda_2''(\lambda_1^a r_2'') \tag{13}$$

$$r_{am} = \frac{s_1 r_2''}{s_1 + r_2''} \tag{14}$$

Since the maintenance time of a component is generally sufficiently larger compared to the switching time ($r_2'' \gg s_1$), equation (14) can be approximated into equation (15).

$$r_{am} = s_1 \tag{15}$$

When the active failure of a component overlaps with the breaker stuck condition (breaker stuck condition occurrence probability (P_C), the failure rate (λ_{ap}) and repair rate (r_{ap}) can be obtained with equations (16) and (17).

$$\lambda_{ap} = \lambda_1^a \times P_C \tag{16}$$

$$r_{ap} = s_1 \tag{17}$$

4. Case study

As a case study, substation with ring bus and substation with double bus double breakers were selected to analyse the reliability indices of each failure events and total reliability indices (failure rate, annual outage time and MTTR) in these substations

4.1. Minimal cut set and active minimal cut set

Based on the results of implementation of the software programming, the minimal cut sets and active minimal cut sets can be summarized as shown in Table 1 and Table 2.

4.2. Reliability indices

For the evaluation of the reliability of a ring bus substation as shown in Figure 1 and evaluation of the reliability of a double bus double breaker substation as shown in Figure 2, in the states of overlapping total outage and maintenance outage based on the load point, a passive failure model, an active failure model, an active failure and passive failure model, indices for failure rates, repair time, and unavailability considering the passive failure model and the active failure model were obtained. To calculate the reliability of substations, input data for the accident rate, repair time, and switching time of major facilities are important. However, in reality, since failure rate data recorded at the site were insufficient, the reliability data as shown in Table 3 from Hamze's paper, which is the most frequently cited, were used[6]. In addition, individual maintenance works for components were assumed to be performed for 8 hours every year for each component.

Table 1. Minimal cut set at Bus # 3 (node 16) in ring bus substation.

Order of failure events	Number of events	Components
1st order total failure	2	7, 11
2nd order total failure	4	1+2, 1+12, 2+10, 10+12
Active failure	2	1A, 2A
Active failure + Total failure	4	6A+2, 3A+1, 6A+2, 3A+10
Active failure + Active failure	1	3A+6A

Table 2. Minimal cut set at Bus # 1 (node 17) in double bus substation

Order of failure events	Number of events	Components
1st order Total failure	2	9, 13
2nd order Total failure	5	1+2, 1+12, 11+2, 11+12, 14+15
Active failure	2	1A, 2A
Active failure + Total failure	16	3A+12, 5A+2, 7A+2, 4A+1, 6A+1, 8A+1 3A+12, 5A+12, 7A+12, 4A+11, 6A+11 8A+11, 3A+15, 4A+15, 5A+14, 6A+14
Active failure + Active failure	6	3A+6A, 3A+8A, 5A+4A, 5A+8A, 7A+4A, 7A+6A

Table 3. Substation components reliability data.

Component Name	Total Failure Rate λ [failure/yr]	Repair Time r [hour]	Active Failure Rate λ_a [failure/yr]	Switching Time s [hour]	Stuck Breaker Probability P_c
Breaker	0.010	12	0.010	1	0.06
Transformer	0.040	40	0.040	1	-
Bus	0.010	4	0.010	-	-

Note 1. Uncoordinated Maintenance outage rate λ'' = 1 [time/year], Uncoordinated Maintenance time r'' = 8 [hours]

As shown in Table 4 and Table 5, the failure rate in cases where the individual maintenance works for individual components were not considered is 0.05[failure/yr], and the failure rate in cases where individual maintenance works were performed is 0.000457 [failure/yr] in case of ring bus substation and is 0.000283 [failure/yr] in case of double bus double breaker substation indicating that the failure rate drastically decreased when individual maintenance works were performed so that the improvement of overall operation reliability can be quantitatively identified.

Table 10 and Table 11 show a summary of the reliability indices for events where two active failures overlapped with each other and the total failure rate of those events was calculated as 0.0000000806 [failure/yr] in case of ring bus substation and 0.000000137 [failure/yr] in case of double bus double breaker substation. From these results, it can be quantitatively identified that the events shown in Table 6 and Table 7 are first order active failure events and have larger effects on the reliability of the entire system than the other overlapping failure events shown in Tables 8 ~ 11.

Table 4. Overlapping total outages and a maintenance outage in ring bus substation.

Failure Event	λ_{pp} [failure/yr]	r_{pp} [hour]	U_{pp} [hour/yr]	λ_{pm} [failure/yr]	r_{pm} [hour]	U_{pm} [hour/yr]
7	4.00E-02	40.00	1.60E+00	-	-	-

11	1.00E-02	4.00	4.00E-02	-	-	-
1 + 2	2.74E-07	6.00	1.64E-06	1.83E-05	4.80	8.77E-05
1 + 12	3.15E-07	6.00	1.89E-05	1.14E-04	4.99	5.70E-04
2 + 10	3.15E-07	6.00	1.89E-05	1.14E-04	4.80	5.48E-04
10 + 12	3.62E-05	6.00	2.17E-04	2.10E-04	4.80	1.01E-03
Total	5.00E-02	32.78	1.64E+00	4.57E-04	4.85	2.21E-03

Table 5. Overlapping total outages and a maintenance outage in double bus substation

Failure Event	λ_{pp} [failure/yr]	r_{pp} [hour]	U_{pp} [hour/yr]	λ_{pm} [failure/yr]	r_{pm} [hour]	U_{pm} [hour/yr]
9	4.00E-02	40.00	1.60E+00	-	-	-
13	1.00E-02	4.00	4.00E-02	-	-	-
1 + 2	2.74E-07	6.00	1.64E-06	1.83E-05	4.80	8.77E-05
1 + 12	1.83E-07	3.00	5.48E-07	1.83E-05	3.33	6.09E-05
11 + 2	1.83E-07	3.00	5.48E-07	1.83E-05	3.33	6.09E-05
11 + 12	9.13E-08	6.00	5.48E-07	1.83E-05	2.00	3.65E-05
14 + 15	3.62E-05	6.00	2.17E-04	2.10E-04	6.00	1.26E-03
Total	5.00E-02	32.78	1.64E+00	2.83E-04	5.32	1.51E-03

Table 6. Active failure in ring bus substation

Failure Event	λ_{ap} [failure/yr]	r_{ap} [hour]	U_{ap} [hour/yr]
1A	1.00E-02	1.00	1.00E-02
2A	1.00E-02	1.00	1.00E-02
Total	2.00E-02	1.00	2.00E-02

Table 7. Active failure in double bus substation

Failure Event	λ_{ap} [failure/yr]	r_{ap} [hour]	U_{ap} [hour/yr]
1A	1.00E-02	1.00	1.00E-02
2A	1.00E-02	1.00	1.00E-02
Total	2.00E-02	1.00	2.00E-02

Table 8. Active failure + total failure in ring bus substation

Failure Event	λ_{pp} [failure/yr]	r_{pp} [hour]	U_{pp} [hour/yr]
6A + 2	1.48E-07	0.92	1.37E-07
3A + 1	1.48E-07	0.92	1.37E-07
6A + 12	1.71E-06	0.92	1.58E-06
3A + 10	1.71E-06	0.92	1.58E-06
Total	3.71E-06	0.92	3.42E-06

Table 9. Active failure + Active failure in double bus substation

Failure Event	λ_{ap} [failure/yr]	r_{ap} [hour]	U_{ap} [hour/yr]
3A + 6A	2.28E-08	0.50	1.14E-08
Total	2.28E-08	0.50	1.14E-08

Table 10. Active failure + total failure in ring bus substation

Failure Event	λ_{pp} [failure/yr]	r_{pp} [hour]	U_{pp} [hour/yr]
3A + 2	1.48E-07	0.92	1.37E-07
5A + 2	1.48E-07	0.92	1.37E-07
7A + 2	1.48E-07	0.92	1.37E-07

Table 11. Active failure + Active failure in double bus substation

Failure Event	λ_{ap} [failure/yr]	r_{ap} [hour]	U_{ap} [hour/yr]
3A + 6A	2.28E-08	0.50	1.14E-08
3A + 8A	2.28E-08	0.50	1.14E-08
5A + 4A	2.28E-08	0.50	1.14E-08

4A + 1	1.48E-07	0.92	1.37E-07
6A + 1	1.48E-07	0.92	1.37E-07
8A + 1	1.48E-07	0.92	1.37E-07
3A + 12	5.71E-08	0.80	4.57E-08
5A + 12	5.71E-08	0.80	4.57E-08
7A + 12	5.71E-08	0.80	4.57E-08
4A + 11	5.71E-08	0.80	4.57E-08
6A + 11	5.71E-08	0.80	4.57E-08
8A + 11	5.71E-08	0.80	4.57E-08
3A + 15	1.71E-06	0.92	1.58E-06
4A + 15	1.71E-06	0.92	1.58E-06
5A + 14	1.71E-06	0.92	1.58E-06
6A + 14	1.71E-06	0.92	1.58E-06
Total	8.06E-06	0.92	7.40E-06

5A + 8A	2.28E-08	0.50	1.14E-08
7A + 4A	2.28E-08	0.50	1.14E-08
7A + 6A	2.28E-08	0.50	1.14E-08
Total	1.37E-07	0.50	6.85E-08

Table 12. Reliability indices

Reliability indices	Figure 1	Figure 2
Failure rate [failure/year]	0.070503	0.07005
Annual outage time [hour/year]	23.58013	23.7023
MTTR [hours/failure]	1.662474	1.66023

Table 12 shows the results of calculation of reliability indices for the entire system by synthesizing all the failure events shown in Tables 4 ~ 11 and the failure rate, annual down time, and MTTR of the entire system were calculated as 0.070503 [failure/yr], 23.58013 [hour/year], and 1.662474 [hrs/failure] in case of double bus double breaker substation and calculated as 0.07005 [failure/yr], 23.7023 [hour/year], and 1.66023 [hrs/failure] in case of double bus double breaker substation

The reliability indices calculated as described above are the results of qualitative calculations to see how much the reliability levels of internal components affect the reliability indices of entire system, which can be used as basic data for the establishment of maintenance plans for internal components to most economically maximize the reliability of the entire system.

5. Conclusion

Reliability indices of each failure events and entire reliability indices (failure rate, annual outage time and MTTR) in the ring bus substation and double bus double breaker substation were calculated and quantitatively compared. From these results, it can be quantitatively identified that the single active failure events have larger effects on the reliability of the entire system than the other overlapping failure. The reliability evaluation results of typical two substations can be utilized as basic data in the design and maintenance schedule planning of substations with diverse bus structures hereafter.

6. References

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