Reliability Study of HV Substations Equipped With the Fault Current Limiter

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***Abstract*—Of particular interest to restrict the short-circuit level of interconnected power systems is to exploit fault current limiter (FCL) technologies. FCLs let the system planners devise new reliable and rather economical substation configurations and provide the possibility of proposing a promising cost-effective and prompt solution to the fault current over duty problem in the existing substations. This paper attempts to assess reliability of substation architectures accommodating the FCL operation and, besides, numerically investigates the FCL's impacts on the substation reliability indices. In order to clarify the proposed approach, two case studies with and without FCL are analyzed and compared. Although the discussions raised here are applicable for reliability modeling of all structures, five common substation configurations, namely: 1) single-bus single-breaker; 2) double-bus single-breaker; 3) ring bus; 4) one breaker and a half; and 5) double-bus double-breaker are considered in this paper. Numerical studies reveal that FCL deployment, while keeping the maximal flexibility of substation, may deteriorate the reliability indices of the substation due to the possible failures of FCLs.**

***Index Terms*—Failure mode and effect analysis (FMEA), fault current limiter (FCL), reliability evaluation, substation configuration.**

I. Introduction

CONTINIOUS growth of the electricity demand, specifically in developing countries, makes expansions of power generation, transmission, and distribution facilities indispensable. Besides, either or both stability and reliability concerns lead to the interconnected operation of neighboring grids, which also eventuates in the dimension expansion of power systems. To this end, Thevenin impedance of transmission substations drops more and more and, as a direct consequence, the short-circuit levels intensify. These conditions put the power system apparatus under greater fault currents with stronger and rather intolerable thermal and electromagnetic stresses [1]. Accordingly, a wide spectrum of conventional solutions has been so far suggested which mainly consist of: 1) construction of new substations; 2) bus splitting; 3) multiple circuit-breaker (CB) upgrades; 4) current-limiting reactors and high impendence transformers; and 5) sequential breaker tripping [2]. The operation philosophy and investigation over pros and cons of these methods, from both technical and economical facets, have also been accomplished in [2]. Fault current limiter (FCL) technologies, as a promising solution, exploit the same principle as that associated with group 4 which consists of an impedance increase seen by the faulted section. In contrast with the components in group 4, FCLs play their vital role only upon occurrence of short circuits and are invisible during healthy conditions of the power system. Hence, they do not suffer from significant voltage drops and constant power losses, as reactors do.

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Many studies have been carried out concerning different type of FCLs [3]; their structural designs [4], [5]; and their impacts on static and dynamic behavior of faulted systems [6]–[8]. Reference [9] investigated the reliability of FLC as a single component by studying its internal elements while [10]–[12] illustrated the impacts of implementing FCL on the reliability of power systems. Reference [10] has studied reliability of a simple substation in the presence of the FCL at three different locations (i.e., incoming feeders, bus-tie position, and outgoing feeders). A similar study has been carried out in [11], but with a FCL in the just bus-tie position. In that paper, a discussion has been raised over various failure modes of three types of FCLs. Reference [12] has addressed the reliability impact of FCL installation from the distribution system perspective. In [12], no particular substation configuration is assumed, and the FCL is located in a distribution network. Based on the aforementioned discussions, the lack of comprehensive studies on FCL reliability impacts considering different substation configurations is necessarily evident.

The objective of this paper is to cover the introduced requirement, going to be fulfilled with presenting the reliability evaluation process of FCL-equipped substations. Different configurations including single-bus single-breaker, double-bus single-breaker, ring bus, one breaker and a half, and double-bus double-breaker are taken into account. The broadly used approach, namely, failure mode and effect analysis (FMEA) is employed to assess the reliability. The assessment methodology is thoroughly elaborated in such a way that the possibility of studying some other substation configurations, not covered here, would be viable. The installation of an FCL in a substation, where the short-circuit problem restricts the operational flexibility, introduces some new failure modes. As a consequence, the substation reliability would be accordingly deteriorated compared with the original layout which suffers from the fault over duty problem. It is hence concluded that the FCL allocation necessitates a thorough reliability study in addition to the usual short-circuit modeling. Numerical studies are conducted based on reasonable typical data. An analysis on the variation of FCL reliability data is also fulfilled to demonstrate the results sensitivity to the most uncertain parameters.

This paper is organized as follows. Section II discusses the substation configurations and short-circuit problem. In Section III, component failure modes and fundamental reliability principles are reviewed. The reliability evaluation of substation arrangements is probed in Section IV. Numerical studies are examined in Section V. Conclusions are given in Section VI.

II. Substation Bus Configuration and Short-Circuit Challenge

Several well-known substation configurations have been implemented in power systems. Generally, these configurations are different from two conflicting aspects of reliability and cost and, as such, any decision is made by compromising these two factors. Some configurations, such as double-bus double-breaker and one breaker and a half, are more reliable and offer appropriate operational flexibility. On the contrary, some other configurations, such as single-bus single-breaker and ring bus are less complicated and the number of apparatus required for each bay is fewer compared to that of other configurations. The operating procedure of a substation is an important factor in the reliability of load points which are connected to the electricity sources through the substation. Though the methodology presented here is general, results associated with five configurations that are commonly used by power utilities are presented and discussed here.

Along with growing the network dimensions, either due to the system expansion or because of interconnections, short-circuit levels of the network are inescapably increased. So the components that have been installed in the past, particularly CBs, as equipment in charge to interrupt fault currents, might not be compatible with the new fault levels. The likelihood of this situation is high particularly in the substations having stronger connections with the entire network. The mismatch between the fault current level and interruption capability of CBs is commonly referred to as the over duty condition and is a potential hazard to equipment health as well as system operational security. A catastrophic damage in HV facilities unavoidably imposes further stress on system healthy components and, thus, is deemed to be an extremely dangerous threat to the staff.

Among different solutions to restrict the short-circuit level of substations, FCL technologies have more potential. The reason lies in the fact that the installation process of an FCL is prompt and does not oblige long outage times. Also, substation yard lands are usually large enough and the solution is cost-effective. Keeping the system operational flexibility is another superiority of these technologies. FCLs available to date are the HV current limiting fuse, pyrotechnic FCL (Is-limiter [13]), liquid-metal FCL, thyristor–control series compensator with current limitation capability, solid-state limiter, and superconductor FCL (SCFCL or SFCL) [3]. A comprehensive investigation on technical characteristics of FCL technologies, such as being either a passive or active element, triggering method, current interruption, and voltage level, has been reported in [3].

One disadvantage associated with the FCL is that having deployed it in a substation, the reliability of the substation might decline. This finding is demonstrated in the numerical studies conducted in this paper.

III. Failure Modes and Reliability Principles

Substation equipment failure modes are generally categorized into two separate groups of passive and active failure modes [14]. A failure mode is considered to be *passive* if it manifests itself only on the failed component and does not stimulate the protection system. Therefore, a passive failure mode does not have any impact on the remaining healthy components. Uninstructed opening of a CB is an example for this type of failure mode. A failure mode is called *active* if it activates the protection system and can therefore cause the removal of other healthy components. For example, a short circuit on a component is considered an active failure, and the protection system must respond and consequently isolate the faulty section. Compared to the passive failures, active failures are more dominant in component failures [14]. There is another failure mode specific to CBs and it is commonly referred to as the *stuck breaker* condition. Under this situation, a closed CB fails to open due to the malfunction of the protection system or the breaker itself [14].

From the failure modes' point of view, an FCL is very similar to the CB whereas the stuck mode is recognized as the inability of the FCL in performing current-limiting action when required. Other types of failure modes, namely active and passive, could also be dedicated to the FCL. An internal short circuit in the FCL, probably caused by the breakdown in insulation materials, is considered as an active failure and, thus, motivates the protection system to respond. A passive failure mode means unnecessary action of FCL, inserting high series impedance when there is no fault. This failure can occur due to malfunction of the triggering system (in external triggered FCL) or because of transient high currents when the device setpoint is not properly adjusted. A comprehensive investigation on the FCL failure modes has been carried out in [11].

In order to have a quantitative sense of the reliability level, all failure modes related to a given substation configuration are determined and the average failure rate (*total* λ expressed in f/yr), and annual outage time (*total* U expressed in hrs/yr) are calculated. These two indices are used as the benchmarks to evaluate the impacts on the overall substation reliability of implementing FCL. The systematic approach in the reliability evaluation of substation configurations is basically associated with failure modes and effect analysis of components. It is not possible to enumerate all of the states as the number increases exponentially with the number of components and their associated states. In this paper, up to the third-order simultaneous outages are considered. The probabilities of higher order failure events for substation components are very low [15] and, hence, are ignored in the analysis conducted here.

The following mathematical expressions can be used to calculate the risk indices associated with substation configurations. Detailed formulations are available in [14] and [15]. For a first-order failure event, if λ_i (f/yr) and Tr_i (hrs/f) are, respectively, the failure rate and repair time of component i, (1) yields the annual outage time associated with that failure event

$$U_i = \lambda_i \times Tr_i. \tag{1}$$

The equivalent failure rate ($\lambda^{\rm eq}$), the average outage time (T^O), and the annual outage time ($U^{\rm eq}$) for the case of simultaneous outages of components 1 and 2 are expressed as follows:

$$\lambda^{\rm eq} = \lambda_1 \times \lambda_2 \times (Tr_1 + Tr_2) \quad (2)$$

$$T^O = \frac{Tr_1 \times Tr_2}{Tr_1 + Tr_2} \quad (3)$$

$$U^{\rm eq} = \lambda^{\rm eq} \times T^O = \lambda_1 \times \lambda_2 \times Tr_1 \times Tr_2. \quad (4)$$

And the indices associated with the third-order failure events of components 1, 2, and 3 are given by

$$\lambda^{\rm eq} = \lambda_1 \times \lambda_2 \times \lambda_3 \times (Tr_1 \times Tr_2 + Tr_1 \times Tr_3 + Tr_2 \times Tr_3) \quad (5)$$

$$T^O = \frac{Tr_1 \times Tr_2 \times Tr_3}{Tr_1 \times Tr_2 + Tr_1 \times Tr_3 + Tr_2 \times Tr_3} \quad (6)$$

$$U^{\rm eq} = \lambda^{\rm eq} \times T^O = \lambda_1 \times \lambda_2 \times \lambda_3 \times Tr_1 \times Tr_2 \times Tr_3. \quad (7)$$

Once the failure modes associated with a given load point are finalized, the indices of that load point are calculated as follows:

$$\text{Total } \lambda = \sum_{j \in \rm FM} \lambda_j^{\rm eq} \quad (8)$$

$$\text{Total } U = \sum_{j \in \rm FM} U_j^{\rm eq} = \sum_{j \in \rm FM} \left(\lambda_j^{\rm eq} \times T_j^O\right) \quad (9)$$

where FM stands the set of failure modes considered. $\lambda_j^{\rm eq}, U_j^{\rm eq}$, and T_j^O are, respectively, the equivalent failure rate, annual outage time, and average outage time of the failure mode j. These parameters are determined through (1)–(7) depending on the outage order of the failure mode.

IV. Reliability Evaluation of Substations Without/With FCL

To find out the FCL performance in alleviating the over duty fault current problem without interfering with the normal operation of the system, it is necessary to analyze the substation according to a standard protection scheme and recognize failure modes which cause supply interruption. In the next step, FCL's effect in introducing new failure modes is studied.

In this analysis, it is assumed that a substation is energized by transformer circuits. Therefore, if a failure mode results in a circuit losing its connection to the transformers, the circuit service is consequently interrupted.

In the following text, five typically used substation configurations [16] are considered and the reliability modeling and analysis of each structure are carried out for two cases without and with FCL installation.

A. Single-Bus Single-Breaker

Fig. 1 shows the single-line diagram of a single-bus single-breaker substation configuration. B0 denotes the bus-tie breaker of the substation and could be normally open or closed depending on the permitted short-circuit level and the operation policy. Each line is connected to its corresponding bus just through a single CB and the number of apparatuses for each circuit is minimal.

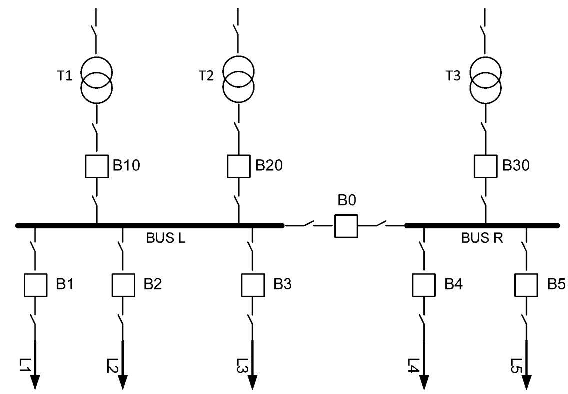

Fig. 1. Single-line diagram of a single-bus single-breaker configuration.

TABLE I
FAILURE MODES CORRESPONDING TO LOAD POINT L1 IN THE CONFIGURATION OF FIG. 1

Row number	Failed #1	Failed #2	Failed #3	TE
1	{$B1_T$, $BUSL_T$}	-	-	2
2	{$B10_a$, $B20_a$, $B0_a$, $B2_a$, $B3_a$}	-	-	5
3	$T1_a$	$B10_s$	-	1
4	$T2_a$	$B20_s$	-	1
5	{$B4_a$, $B5_a$, $B30_a$, $BUSR_a$}	$B0_s$	-	4
6	{$T1_T$, $B10_T$}	{$T2_T$, $B20_T$}	{$T3_T$, $B30_T$, $B0_T$, $BUSR_T$}	16
7	$T3_a$	$B30_s$	$B0_s$	1

In the analysis conducted that will be shown, it is assumed that each of the three transformers in Fig. 1 is able to feed the total circuits connected to the substation. This assumption is justified since in substation and distribution reliability assessments, the network and terminals' connectivity is of modeling interest.

Since all circuits connected to the substation are identical (load point L1 with L2 and L3 and load point L4 with L5), performing the analysis on one load point in each set, one from the left bus and another from the right bus, is sufficient to examine the overall substation performance from the reliability point of view. Owing to the aforementioned conditions and without any FCL in use, all failure modes that lead to outage of circuit L1 are listed in Table I. Note that in the events shown in Table I and forward tables, subscripts "a," "p," "T," and "s" stand for active failure, passive failure, total failure, and stuck break mode, respectively. It should be noted that the active and passive failures of a component can be combined to produce the associated total failure.

Table I indicates that the total number of failure events (TE) associated with load point L1 is 30 from which there are seven first-order failure events (rows 1 and 2), two first-order active failures with stuck breaker condition (rows 3, 4), four second-order failure events (row 5), 16 third-order failure events (rows 6), and one first-order active failure event with two stuck breaker conditions (row 7). Those rows that contain "{}" are compressed representations of multiple failure modes. For instance, row 6 includes 16 failure events ($2 \times 2 \times 4$) shown in Table II.

TABLE II
EXPENDED VIEW OF ROW #6 IN TABLE I

State number	Failed #1	Failed #2	Failed #3
1	$T1_T$	$T2_T$	$T3_T$
2	$T1_T$	$T2_T$	$B30_T$
3	$T1_T$	$T2_T$	$B0_T$
4	$T1_T$	$T2_T$	$BUSR_T$
5	$T1_T$	$B20_T$	$T3_T$
6	$T1_T$	$B20_T$	$B30_T$
7	$T1_T$	$B20_T$	$B0_T$
8	$T1_T$	$B20_T$	$BUSR_T$
9	$B10_T$	$T2_T$	$T3_T$
10	$B10_T$	$T2_T$	$B30_T$
11	$B10_T$	$T2_T$	$B0_T$
12	$B10_T$	$T2_T$	$BUSR_T$
13	$B10_T$	$B20_T$	$T3_T$
14	$B10_T$	$B20_T$	$B30_T$
15	$B10_T$	$B20_T$	$B0_T$
16	$B10_T$	$B20_T$	$BUSR_T$

TABLE III
FAILURE MODES CORRESPONDING TO LOAD POINT L4 IN THE CONFIGURATION OF FIG. 1

Row number	Failed #1	Failed #2	Failed #3	TE
1	$\{B4_T, BUSR_T\}$	-	-	2
2	$\{B5_a, B30_a\}$	-	-	2
3	$B0_a$	-	-	1
4	$T3_a$	$B30_s$	-	1
5	$\{B10_a, B20_a, B1_a, B2_a, B3_a, BUSL_a\}$	$B0_s$	-	6
6	$\{T3_T, B30_T\}$	$\{B0_T, BUSL_T\}$	-	4
7	$\{T3_T, B30_T\}$	$\{T2_T, B20_T\}$	$\{T1_T, B10_T\}$	6
8	$T1_a$	$B10_s$	$B0_s$	1
9	$T2_a$	$B20_s$	$B0_s$	1

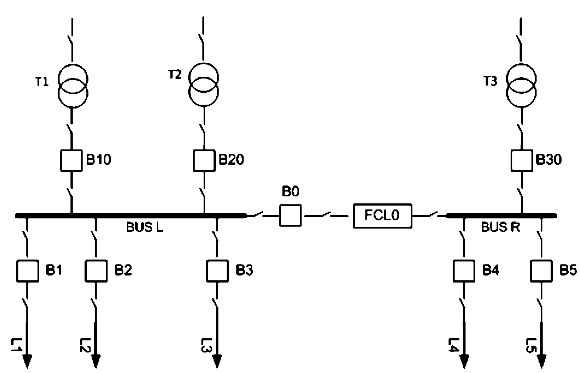

Fig. 2. Single-line diagram of a single-bus single-breaker configuration with an FCL in the bus-tie location.

TABLE IV
NEW FAILURE MODES CORRESPONDING TO LOAD POINT L1 IN THE CONFIGURATION OF FIG. 2

Failed #1	Failed #2	Failed #3	TE
$\{T1_T, B10_T\}$	$\{T2_T, B20_T\}$	$FCL0_T$	4
$FCL0_a$	$B0_s$	-	1

TABLE V
NEW FAILURE MODES CORRESPONDING TO LOAD POINT L4 IN THE CONFIGURATION OF FIG. 2

Failed #1	Failed #2	Failed #3	TE
$\{T3_T, B30_T\}$	$FCL0_T$	-	2
$FCL0_a$	-	-	1

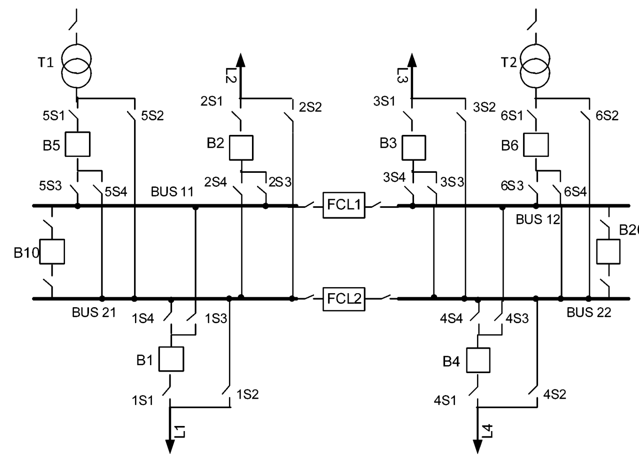

Fig. 3. Single-line diagram of the double-bus single-breaker configuration.

In the next step, the same analyses are performed for the right-hand side bus (i.e., BUS R), and failure modes associated with load point L4 are determined. These failure modes are illustrated in Table III.

Now, reconsider the analyses associated with L1 and L4 when an FCL is implemented on the bus-tie location as depicted in Fig. 2.

With regards to L1 failure modes, some new failure modes, which originate from the FCL failures, are introduced. These new failure modes are presented in Table IV. As shown in this table, five failure modes associated with the FCL are added to the already determined failure modes shown in Table I. To clarify the issue, one of the added failure modes is illustrated. Consider that an active failure occurs on the FCL while Breaker B0 is in the stuck condition. Under this condition, B10, B20, and B30 are opened, resulting in the switching state in which L1 is interrupted from the source.

The same analysis is performed to evaluate the impacts of implementing FCL on the reliability of load point L4. Table V shows the modifications required in Table III when the bus-tie FCL is added to the analyses.

B. Double-Bus Single-Breaker

Fig. 3 shows the single-line diagram of this configuration. It is worthwhile noting that this arrangement is synonymously called the *transfer bus* or *transfer breaker* configuration. Compared to the single-bus single-breaker, this structure consists of more components and, therefore, is more voluminous. However, a superior balance between the cost and operational flexibility associated with this configuration exists.

While in the original configuration the two side buses are directly connected to each other, two FCLs connect the left and right sides of the substation when FCLs are implemented.

TABLE VI
FAILURE MODES CORRESPONDING TO LOAD POINT L1 IN THE CONFIGURATION OF FIG. 3

Row number	Failed #1	Failed #2	Failed #3	TE
1	$B1_T$	-	-	1
2	$B10_a$	-	-	1
3	{$BUS11_a$, $B2_a$, $BUS21_a$, $B5_a$}	$B10_S$	-	4
4	{$BUS12_a$, $BUS22_a$, $B4_a$, $B3_a$, $B6_a$, $B20_a$}	$B10_S$	-	6
5	$BUS11_T$	$BUS21_T$	-	1
6	{$B2_a$, $B5_a$ }	{$BUS21_T$, $BUS11_T$}	-	4
7	{$B3_a$, $B6_a$, $B4_a$ }	{$BUS12_T$, $BUS22_T$}	-	6
8	$T1_T$	$T2_T$	-	1
9	$T1_T$	$B6_T$	$BUS22_T$	1
10	$T1_T$	$BUS12_T$	$BUS22_T$	1
11	$T1_T$	$BUS11_T$	$BUS22_T$	1
12	$T1_T$	$BUS21_T$	$BUS12_T$	1

TABLE VII
NEW FAILURE MODES CORRESPONDING TO LOAD POINT L1 IN THE CONFIGURATION OF FIG. 3

Failed #1	Failed #2	Failed #3	TE
$T1_T$	{$BUS12_T$, $FCL1_T$}	$FCL2_T$	2
$T1_T$	$FCL1_T$	$BUS22_T$	1
$T1_T$	$FCL2_T$	$BUS11_T$	1
$T1_T$	$FCL1_T$	$BUS21_T$	1
$FCL1_a$	{$B10_S$, $B20_S$}	-	2
$FCL2_a$	{$B10_S$, $B20_S$}	-	2

In the normal operation, switches S1, S3, and S4 in all circuits are normally closed, resulting in all circuits to be simultaneously connected to both BUS1 and BUS2. Meanwhile, all bypass switches S2 are kept open and the only way to preserve the circuits energized is through CBs. The protection scheme of this configuration is flexible, albeit quite complicated [17].

Two different studies are conducted; with and without implementing FCL. The list of failure modes associated with Load point L1 without FCL is listed in Table VI.

By adding two FCLs, additional failure modes would effectuate serving L1. The list of failure modes to be added is given in Table VII.

C. Ring Bus

As shown in Fig. 4 in this configuration, the number of CBs is equal to the number of circuits, but each circuit is supplied from two paths.

In this configuration, the short circuit on a bus results in the interruption of only one circuit. In response to the occurrence of any short-circuit failure, two CBs must be opened to clear the fault. Although this configuration is strong enough against single failure events, it is vulnerable against the second-order failures. The reason is due to the fact that the substation integrity may be lost if such failure events occur. In addition, if an active failure occurs in a CB and the protection system is not successful in isolating the faulty part, two circuits are lost. Table VIII shows the failure modes associated with Load point L4 when no FCL is deployed.

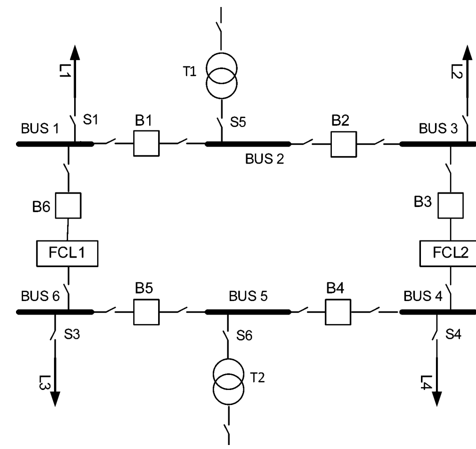

Fig. 4. Single-line diagram of the ring-bus configuration.

TABLE VIII
FAILURE MODES CORRESPONDING TO LOAD POINT L4 IN THE CONFIGURATION OF FIG. 4

Row number	Failed #1	Failed #2	Failed #3	TE
1	{$B3_a$, $B4_a$, $BUS4_T$}	-	-	3
2	{$T2_T$, $BUS5_T$, $B4_T$}	{$T1_T$, $BUS2_T$, $B2_T$, $BUS3_T$, $B3_T$, $L2_a$}	-	18
3	{$L2_a$, $BUS3_a$, $B2_a$}	$B3_S$	-	3
4	{$T1_a$, $BUS2_a$, $B1_a$}	$B2_S$	$B3_S$	3
5	{$T2_a$, $BUS5_a$, $B5_a$}	$B4_S$	-	3
6	{$L3_a$, $BUS6_a$, $B6_a$}	$B5_S$	$B4_S$	3

TABLE IX
NEW FAILURE MODES CORRESPONDING TO LOAD POINT L4 IN THE CONFIGURATION OF FIG. 4

Failed #1	Failed #2	Failed #3	TE
{$BUS5_T$, $B4_T$, $T2_T$}	$FCL2_T$	-	3
$FCL2_a$	-	-	1
$FCL1_a$	$B5_S$	$B4_S$	1

By installing FCLs at the locations designated in Fig. 4, the failure modes listed in Table IX are added to those presented in Table VIII.

D. One Breaker and a Half

In view of the good flexibility and high level of reliability, one breaker and a half configuration is very attractive for the system planners and is broadly used for prominent substations in HV grids. In this configuration, demonstrated in Fig. 5, each circuit is connected to the substation via two CBs where one is in common with another circuit in the same diameter. So a circuit will be disconnected if two CBs are opened. Active failure on the common breaker affects both circuits. For instance, if an active failure occurs on B5, both Load points L1 and L3 are interrupted. In contrary to the ring-bus configuration, an active failure on a bus does not lead to any circuit interruption in one breaker and a half configuration.

Table X shows the failure events associated with Load point L4 without implementing FCLs. It should be noted that the

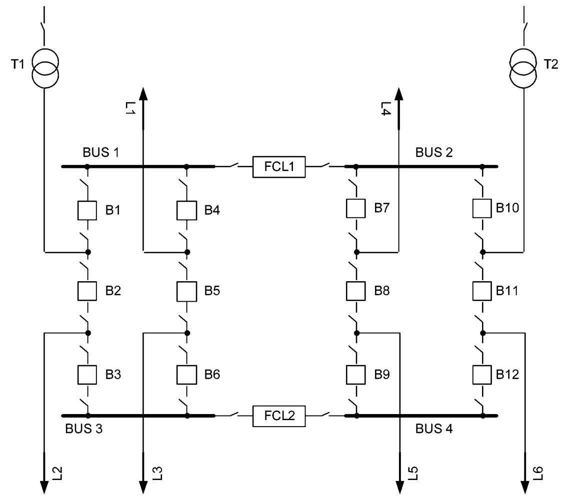

Fig. 5. Single-line diagram of one breaker and a half configuration.

TABLE X
FAILURE MODES CORRESPONDING TO LOAD POINT L4 IN THE CONFIGURATION OF FIG. 5

Row number	Failed #1	Failed #2	Failed #3	TE
1	{$B7_a$, $B8_a$}	-	-	2
2	{$B7_T$, $BUS2_T$}	{$B8_T$, $B9_T$, $BUS4_T$}	-	6
3	$T1_T$	$T2_T$	-	1
4	{$B10_a$, $BUS2_a$}	$B7_S$	-	2
5	{$L5_a$, $B9_a$}	$B8_S$	-	2
6	{$B1_a$, $B4_a$, $BUS1_a$}	$B7_S$	-	3
7	{$B12_a$, $BUS4_a$}	$B9_S$	$B8_S$	2
8	{$T2_a$, $B11_a$}	$B10_S$	$B7_S$	2
9	$T1_T$	{$B11_T$, $B12_T$, $BUS4_T$}	$B10_T$	3
10	$T1_T$	$B11_T$	$BUS2_T$	1
11	$T2_T$	{$BUS3_T$, $BUS4_T$}	$BUS1_T$	2
12	{$T1_a$, $B2_a$}	$B1_S$	$B7_S$	2
13	{$L1_a$, $B5_a$}	$B4_S$	$B7_S$	2
14	{$B3_a$, $B6_a$, $BUS3_a$}	$B9_S$	$B8_S$	3
15	$T2_T$	$BUS2_T$	$BUS3_T$	1
16	$T2_T$	{$B2_T$, $B3_T$, $BUS3_T$}	$B1_T$	2
17	$T2_T$	$B2_T$	$BUS1_T$	1

TABLE XI
NEW FAILURE MODES CORRESPONDING TO LOAD POINT L4 IN THE CONFIGURATION OF FIG. 5

Failed #1	Failed #2	Failed #3	TE
$T2_T$	{$BUS3_T$, $FCL2_T$, $BUS4_T$}	$FCL1_T$	4
$T2_T$	$FCL2_T$	$BUS1_T$, $BUS2_T$}	2
$FCL1_a$	$B7_S$	-	1
$FCL2_a$	$B9_S$	$B8_S$	1

right- and left-hand sides of the substation are directly connected to each other when FCLs are not employed.

If the substation is equipped with the FCLs at the locations shown in Fig. 5, depending on the load point under consideration, some new failure modes are created. The newly added failure modes associated with Load point L4 are listed in Table XI.

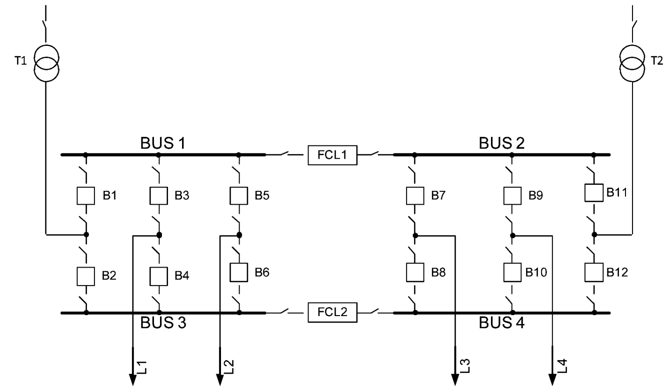

Fig. 6. Single-line diagram of the double-bus double-breaker configuration.

TABLE XII
FAILURE MODES CORRESPONDING TO LOAD POINT L1 IN THE CONFIGURATION OF FIG. 6

Row number	Failed #1	Failed #2	Failed #3	TE
1	$T1_T$	$T2_T$	-	1
2	$B3_T$	$B4_T$	-	1
3	$BUS1_T$	$BUS3_T$	-	1
4	$T1_T$	{$BUS4_T$, $B12_T$}	$B11_T$	2
5	$T1_T$	$BUS4_T$	$BUS1_T$	1
6	$T1_T$	{$BUS4_T$, $BUS3_T$, $B12_T$}	$BUS2_T$	3
7	$T2_T$	{$BUS3_T$, $B2_T$}	$B1_T$	2
8	$T2_T$	$BUS1_T$	$B2_T$	1
9	{$B3_a$, $B4_a$}	-	-	2
10	{$B11_a$, $B9_a$, $B7_a$, $BUS2_a$, $B5_a$, $B1_a$, $BUS1_a$ }	$B3_S$	-	7
11	{$B2_a$, $BUS3_a$, $B6_a$, $BUS4_a$, $B8_a$, $B10_a$, $B12_a$ }	$B4_S$	-	7
12	$T2_a$	$B11_S$	$B3_S$	1
13	$B12_a$	$B11_S$	$B3_S$	1
14	$B10_a$	$B9_S$	$B3_S$	1
15	$B8_a$	$B7_S$	$B3_S$	1
16	$B6_a$	$B5_S$	$B3_S$	1
17	$B2_a$	$B1_S$	$B3_S$	1
18	$T1_a$	$B11_S$	$B3_S$	1
19	$B1_a$	$B2_S$	$B4_S$	1
20	$T1_a$	$B2_S$	$B4_S$	1
21	$B5_a$	$B6_S$	$B4_S$	1
22	$B7_a$	$B8_S$	$B4_S$	1
23	$B9_a$	$B10_S$	$B4_S$	1
24	$B11_a$	$B12_S$	$B4_S$	1
25	$T2_a$	$B12_S$	$B4_S$	1

E. Double-Bus Double-Breaker

This configuration offers maximum operational flexibility and profits from an extensive level of reliability point of view. However, since it requires a vast place to locate numerous components, it is not very desirable to planning engineers. A single-line diagram of this configuration is depicted in Fig. 6.

Without any FCL, the failure modes resulting in the interruption of load point L1 are those listed in Table XII. By employing two FCLs at the specified locations shown in Fig. 6, new failure events that bring about service interruption to load point L1 are introduced. These new failure events are stated in Table XIII.

TABLE XIII
NEW FAILURE MODES CORRESPONDING TO LOAD POINT L1 IN THE CONFIGURATION OF FIG. 6

Failed #1	Failed #2	Failed #3	TE
$T1_T$	{$BUS3_T$, $FCL2_T$, $BUS4_T$ }	$FCL1_T$	3
$T1_T$	{$BUS1_T$, $BUS2_T$}	$FCL2_T$	2
$FCL1_a$	$B3_s$	-	1
$FCL2_a$	$B4_s$	-	1

TABLE XIV
RELIABILITY DATA ASSOCIATED WITH COMPONENTS

Component type	λ_a [f/yr]	λ_p [f/yr]	P_s	T_R [hr]	T_S [hr]
Transformer	0.04	0.001	-	40	1
Breaker	0.05	0.05	0.06	12	1
Bus	0.01	-	-	4	1
FCL	0.04	0.001	0.001	30	1

V. NUMERICAL STUDIES

As discussed in the preceding sections, the FCL installation creates some new failure modes that reduce the overall reliability of the substation. This section aims to numerically conduct such analyses. The reliability data of components are given in Table XIV, where those of all components but the FCL are adopted in appropriate ranges based on relevant textbooks such as [14], research papers, and domestic databases. There is, however, no reference presenting the FCL reliability data. Having conducted an exhaustive investigation, the FCL reliability data are adopted the same way as the transformer due to the similar structural analogy between these two components.

The parameters shown in Table XIV are defined as follows

λ_a active failure rate;

λ_p passive failure rate;

P_s stuck failure mode probability;

T_R repair time;

T_S switching time.

The reliability indices associated with the different substation configurations are calculated based on the failure modes identified through Tables I– XIII. Two cases, namely without and with FCL, are considered to illustrate the impacts of FCL employment. Tables XV and XVI, respectively, present the average failure rate and annual outage time obtained for different simulations.

The following discussions are raised based on the results presented in Tables XV and XVI.

- Both indices of the average failure rate and annual outage time are increased following FCL installation. Accordingly, the effects of FCL utilization on the substation reliability are adverse in all configurations.
- FCL application has not changed the reliability merit order among the configurations. That is, with the given configurations and reliability parameters, L1 in the single-bus single-breaker configuration and L1 in the double-bus single-breaker arrangement are, respectively, the least and most reliable load points regardless of FCL deployment.
- When the substation layout is unsymmetrical (e.g., single-bus single-breaker and ring bus configurations), the impacts of FCL on different circuits are not necessarily the same.
- In the single-bus single-breaker arrangement, the reliability associated with both left- and right-hand-side circuits degrades with FCL installation, while load points connected to the left-hand-side bus (e.g., L1) experience greater impact.

It is worth noting that since the conclusions drawn before depend on the reliability data, a sensitivity analysis with respect to the most uncertain or variant parameter, which here is the FCL reliability data, could somehow generalize the conclusions.

TABLE XV
AVERAGE FAILURE RATE [f/yr] FOR DIFFERENT CONFIGURATIONS

Configuration	Load point	Without FCL	With FCL	Variation [%]
A	L1	0.873335	1.012259	-15.91
A	L4	0.727365	0.847990	-16.58
B	L1	0.230166	0.277597	-20.61
C	L4	0.509716	0.690217	-35.41
D	L4	0.512866	0.553241	-7.87
E	L1	0.344813	0.387445	-12.36

A: Single-bus single-breaker B: Double-bus single-breaker
C: Ring-bus D: One breaker and a half
E: Double-bus double-breaker

TABLE XVI
ANNUAL OUTAGE TIME (h/yr) FOR DIFFERENT CONFIGURATIONS

Configuration	Load point	Without FCL	With FCL	Variation [%]
A	L1	4.460454	5.398893	-21.04
A	L4	4.379291	5.370868	-22.64
B	L1	0.823933	1.119983	-35.93
C	L4	3.325383	4.392368	-32.09
D	L4	2.656886	2.945879	-10.88
E	L1	1.697232	1.983681	-16.88

A, B, C, D, and E are defined in Table XV.

A. Sensitivity Analysis

The impacts on the reliability indices of FCL failure-rate variation are investigated. The results are shown in Figs. 7 and 8 in terms of different values for the FCL active failure rate. It is evident that in the single-bus, single-breaker, and ring-bus configurations, the substation reliability indices are more sensitive to the variation of the FCL active failure rate.

VI. CONCLUSION

FCL technology competes with the old-fashioned breaker upgrading solution as alternatives available for the fault current over duty problem in existing substations. As a matter of fact, reliability and economics are two conflicting aspects to be analyzed for the ultimate decision making. This paper focused on the reliability facet, and further investigations concentrating on the economical analysis are currently ongoing. The impacts of

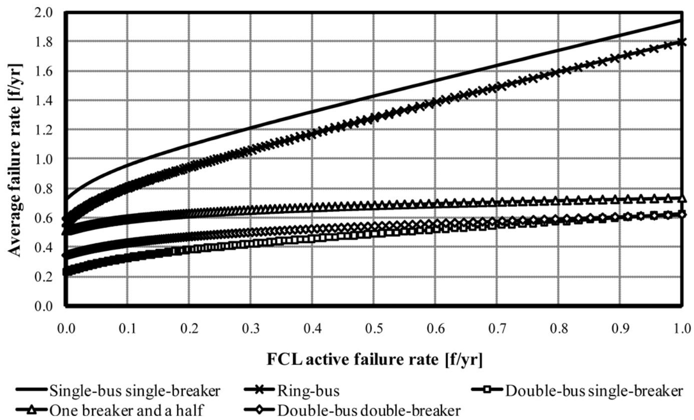

Fig. 7. Average failure rate for different configurations with respect to the variation of the FCL's active failure rate.

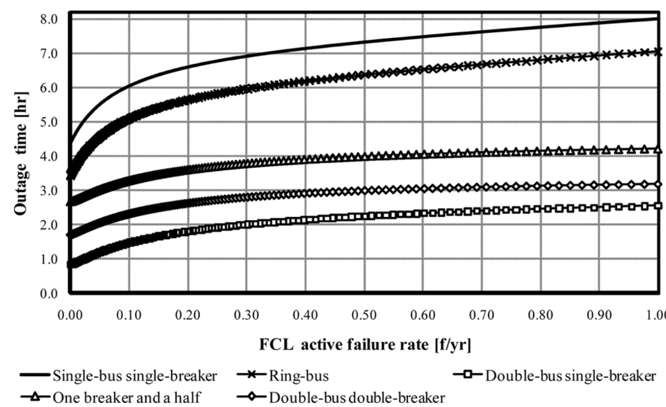

Fig. 8. Annual outage time for different configurations with respect to the variation of the FCL's active failure rate.

implementing FCL on the reliability of the five common substation configurations have been probed here including single-bus single-breaker, double-bus single-breaker, ring-bus, one breaker and a half, and double-bus double-breaker. Numerical results revealed that both indices of average failure rate and annual outage time of load points increased with the insertion of FCL. So FCL installation, because of adding some new failure events to those already existing, degrades the reliability of the original substation scheme. With numerical analysis, it was also deduced that configurations with less reliability, such as single-bus single-breaker, are more sensitive to FCL deployment and its reliability.

The point deserving specific attention is that the comparison of reliability indices conducted by this paper is against the original substation layout. So, expectedly, a slight reduction in the reliability is observed when the FCL is added as an additional component. The FCL is, however, employed by a necessity, and the reliability could be compared to other solutions available for the fault current limitation (such as bus splitting). This requirement might be an appropriate topic for future research.

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