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**Surge Arrester Separation Distance Considerations for High-Voltage  
Substation Circuit Breakers**

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**SUMMARY**

The surge voltage at a protected piece of equipment is always greater than that located at the arrester terminals, based on the traveling wave theorem. This rise in voltage is called a separation effect, which occurs with increasing steepness of the incoming surge and increasing distance between the arrester and the protected equipment. The distance between an arrester and a protected piece of equipment is termed separation distance. It is evaluated against the maximum allowable separation distance that is based on the voltage increase at the terminal of the protected equipment and its insulation strength. Among all substation equipment (e.g., transformers), the lightning surge protection of circuit breakers lacks clarity, comparatively. Therefore, this paper focuses on the theory of calculating the maximum allowable separation distance from an arrester to a circuit breaker, the method of considering various breaker operation scenarios, and the procedure for analyzing and determining arrester placements for lightning surge protection of circuit breakers.

**KEYWORDS**

Substation, surge arresters, lightning surge, traveling wave, circuit breakers

## INTRODUCTION

Surge arresters protect insulation systems throughout a substation. Proper coordination should exist between the insulation withstand capabilities of a piece of equipment and the overvoltage protection provided by its arrester. Whenever an arrester clamps a surge, any remaining surge will continue to grow as it travels. Once the surge reaches shunt equipment, such as a transformer winding, the surge is reflected. This reflection can result in voltage doubling if the separation distance is long enough. In most cases, the reflected voltage only adds a few percent to the incoming surge. It is this traveling wave phenomenon and its associated reflection that create the separation distance issue. As a result, surge arresters should be installed as close as possible to the equipment to be protected. The protective margin provided by the arrester to the equipment decreases as the separation distance between the arrester and the equipment increases.

Since most utilities sufficiently protect power transformers using transformer-mounted arresters next to bushings, this paper will not focus on transformers. Conversely, surge protection for circuit breakers lacks the attention of industry if:

- 1) The number of circuit breakers per a substation is typically large.
- 2) The cost of repairing or replacing a circuit breaker is relatively low.
- 3) The risk of damaging a circuit breaker from a lightning surge is not clear.

However, the above judgements are in comparison to a power transformer. The likelihood and negative impact of failing or degrading an opened or closed circuit breaker due to a lightning surge are generally underestimated. Negative impacts may include required breaker replacement and harm to substation personnel due to breaker misoperations. Therefore, this paper focuses on the lightning surge protection of circuit breakers.



Figure 1. An example of lightning surge protection for circuit breakers in an AEP substation.

In this paper, we will discuss the formulation and derivation of the equation for calculating the maximum allowable separation distance for circuit breakers. We will also discuss how to apply the calculated separation distance into an arrester placement decision-making process, while considering various breaker operation scenarios.

## SEPARATION DISTANCE CALCULATION

Annex C of IEEE Standard C62.22 [1] (henceforth referred to as IEEE-C62.22) provides a variety of equations to help utility engineers calculate the maximum allowable separation distances to transformers (or non-self-restoring-insulation equipment) and breakers (or self-restoring-insulation equipment). Fig. 2 shows an illustration of a single-breaker-single-transformer substation layout, which is used to explain the traveling wave theorem and the derivation of the IEEE-C62.22 equations.

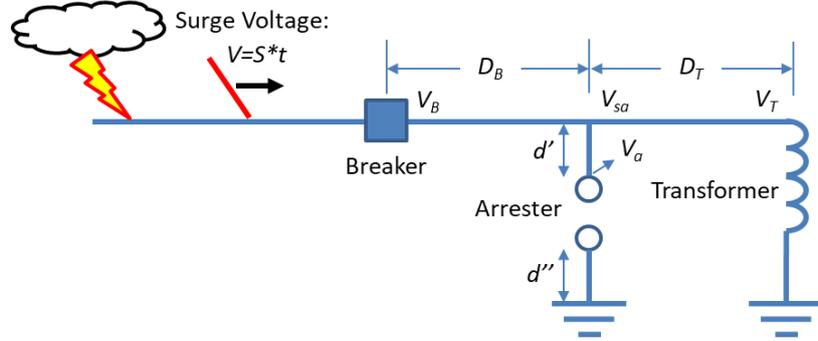


Figure 2. A simple substation layout

The maximum allowable separation distance for circuit breakers ( $D_B$ ) may be determined using the equation below from Annex C of IEEE-C62.22. Note that some parameters used to calculate  $D_B$  are illustrated in Fig. 2.

$$D_B = \frac{c}{2S} \left( \frac{1.15 \cdot \delta \cdot BIL}{1.05} - V_{sa} \right) \quad (1)$$

where:

$c$ : Velocity of light, 300 m/ $\mu$ s

$S$ : Steepness or rate of rise of the incoming surge,  $S = \frac{K_c}{d_m}$

$K_c$ : Corona constant that determines steepness of incoming surge (kV – km/ $\mu$ s)

$d_m$ : Distance from a lightning stroke occurrence on a line to a substation, in km,  $d_m = \frac{100}{MTBF \cdot FOR}$

$MTBF$ : Mean time between failures (years)

$FOR$ : Flashover rate of lines (flashovers/100 km-year)

$\delta$ : Altitude adjustment factor,  $\delta = e^{\frac{A}{8.6}}$

$A$ : Altitude, in km

$BIL$ : Basic lightning impulse insulation level

$V_{sa}$ : Voltage across the surge arrester, from junction  $J$  to ground (kV),  $V_{sa} = V_a + 1.3 \mu H/m * (d' + d'') * (2 * S/Z)$

$V_a$ : Surge arrester FOW protective level at 0.5  $\mu$ s (kV)

$d'$ : Conductor length between arrester-bus junction and arrester terminal (m)

$d''$ : Conductor length between ground and arrester grounding terminal (m)

$Z$ : Line surge impedance ( $\Omega$ )

The derivation of equation (1) has not been described in Annex C of IEEE-C62.22. Therefore, we use the method in [2] to interpret how (1) is derived and expand its applicability to different scenarios. For the scenario depicted in Fig. 2, the surge voltage at the breaker location can be derived as illustrated in Fig. 3.

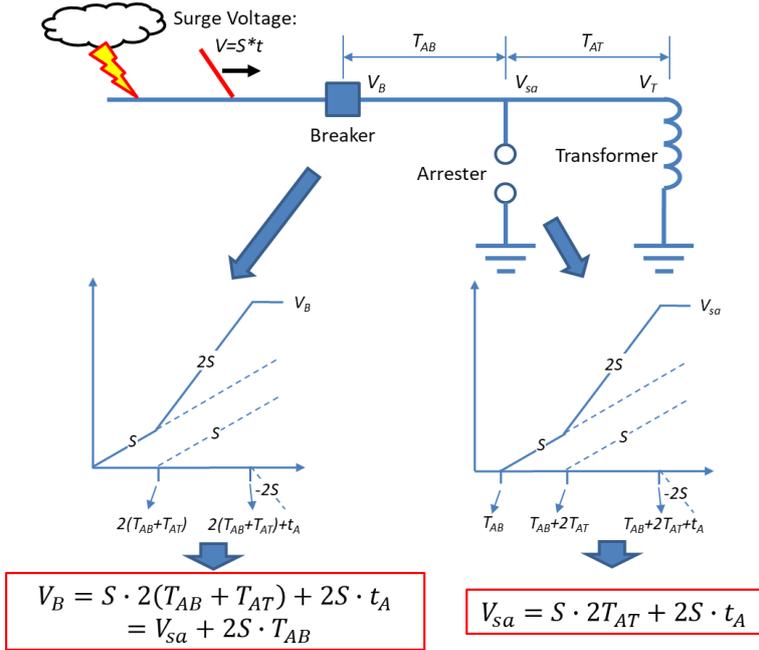


Figure 3. Traveling-wave analysis for breaker-in-front-of-arrester scenario

In this scenario, the breaker is closed and the arrester is installed between the breaker and the power transformer. A lightning surge travels from the incoming line, with a steepness of its rising voltage ( $S$ ) into the substation. This surge arrives at the breaker at time zero and continues traveling until reaching the transformer terminal. The travel time between the arrester and the breaker is defined as  $T_{AB}$  and the travel time between the arrester and the transformer is defined as  $T_{AT}$ . Since we consider the transformer an open circuit, the steepness at the transformer doubles, and a reflected surge having a steepness of  $S$  travels back toward the arrester and breaker. Upon arrival to these other locations, the steepness doubles. Therefore, the voltage at the breaker location increases at a steepness of  $S$  for a duration of  $2(T_{AB} + T_{AT})$  until the reflected surge arrives at the breaker. Then, the steepness at the breaker location doubles ( $2S$ ) and the voltage at the breaker increases at a steepness of  $2S$  for a duration of  $t_A$ . The term  $t_A$  represents the time from when the reflected surge reaches the arrester junction to when the arrester operates. At the time  $2(T_{AB} + T_{AT}) + t_A$ , another reflected surge at a steepness of  $-2S$  produced by the operating arrester (treated as a closed circuit) arrives at the breaker and cancels out the previous surge, with a steepness of  $2S$ . As a result, the worst-case  $V_B$  is obtained and keeps constant. The equations for both  $V_{sa}$  and  $V_B$  are shown at the bottom of Fig. 2. The surge voltage at the breaker ( $V_B$ ) equals the discharge voltage of the arrester ( $V_{sa}$ ) plus the increase of the surge at a steepness of  $2S$  for the duration of  $T_{AB}$  ( $2S \cdot T_{AB}$ ). Note that  $T_{AB}$  equals the separation distance ( $D_B$ ) divided by the speed of light ( $c$ ). Therefore, we obtain:

$$V_B = V_{sa} + 2S \cdot \frac{D_B}{c} \quad (2)$$

It can be observed from equation (2) that  $D_B$  is proportional to  $V_B$ . In other words, the greater the surge voltage allowed at the breaker translates to a longer maximum allowable separation distance. Regarding the allowable surge voltage at the equipment location, it should be related to the BIL of the corresponding equipment (i.e., circuit breakers). Typically, we assume the time to crest of an arrester discharge voltage is shorter than that used for BIL testing. In addition, the insulation strength of a piece of equipment with a shorter time to crest is higher, based on typical equipment insulation volt-time curves. Therefore, BIL is multiplied by a factor (1.15) to represent an appropriate insulation strength. Furthermore, the altitude adjustment factor ( $\delta$ ) should be considered since the insulation strength decreases as altitude increases. Lastly, a protection margin of 5-percent is considered, resulting in a factor of 1.05 in the denominator of equation (3). As a result,  $V_B$  in (2) is substituted by (3) as below:

$$V_B = \frac{1.15 \cdot \delta \cdot BIL}{1.05} \quad (3)$$

Then, (1) is derived and obtained, as expected.

If the arrester is placed in front of a breaker as shown in Fig. 4, it is important to know if (1) is still applicable. A similar derivation is provided in Fig. 4. The surge travels to the transformer and is reflected back. The reflected surge arrives at the arrester junction and increases the surge steepness at the arrester to  $2S$ . Then, the surge grows until the arrester operates and reflects a surge at a steepness of  $-2S$  toward the breaker at the time  $2(T_{AB} + T_{AT}) + t_A$ . This reflected surge arrives at the breaker after a duration of  $T_{AB}$  and cancels out the previous surge at a steepness of  $2S$  at the time  $2(T_{AB} + T_{AT}) + t_A + T_{AB}$ . The equations for both  $V_{sa}$  and  $V_B$  are shown at the bottom of Fig. 4. Thus, (1) is still applicable.

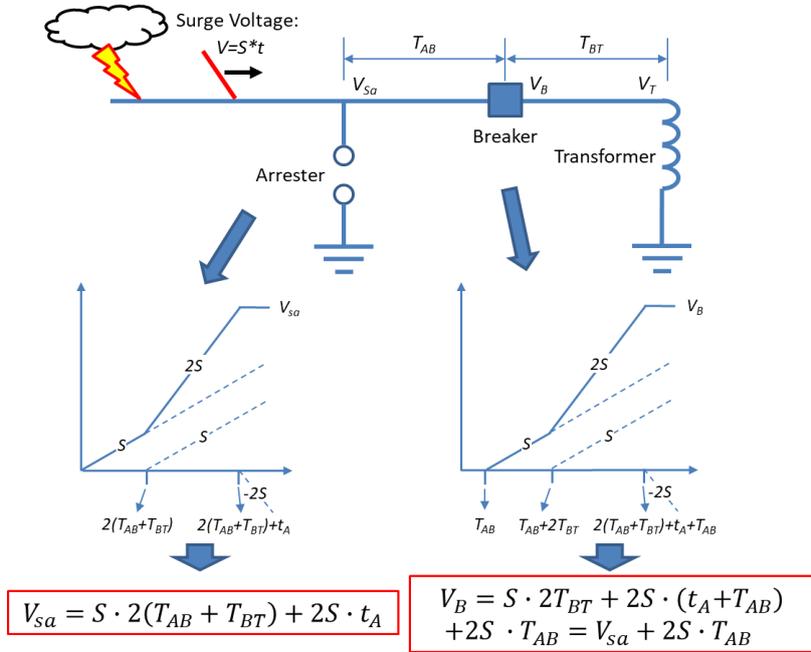


Figure 4. Traveling-wave analysis for breaker-behind-arrester scenario

Another scenario is illustrated in Fig. 5, in which the breaker is tripped due to a previous fault. Therefore, the incoming surge arrives at the breaker and is reflected back. The reflected surge arrives at the arrester junction at the time  $2T_{AB}$  and results in the steepness increasing to  $2S$ . The surge voltage at the arrester junction remains increasing at a steepness of  $2S$  until the arrester operates at the time  $2T_{AB} + t_A$ . On the other hand, the surge voltage at the breaker remains increasing at a steepness of  $2S$ , since the original surge arrives at the time  $T_{AB}$ . This increase is stopped when the reflected surge with a steepness of  $-2S$  from the operated arrester arrives. Therefore, the increase of the surge voltage at the opened breaker lasts from  $T_{AB}$  to  $2T_{AB} + t_A + T_{AB}$ . with a steepness of  $2S$ . The equations for both  $V_{sa}$  and  $V_B$  are shown at the bottom of Fig. 4. Furthermore, (1) is proven applicable for this scenario, as well.

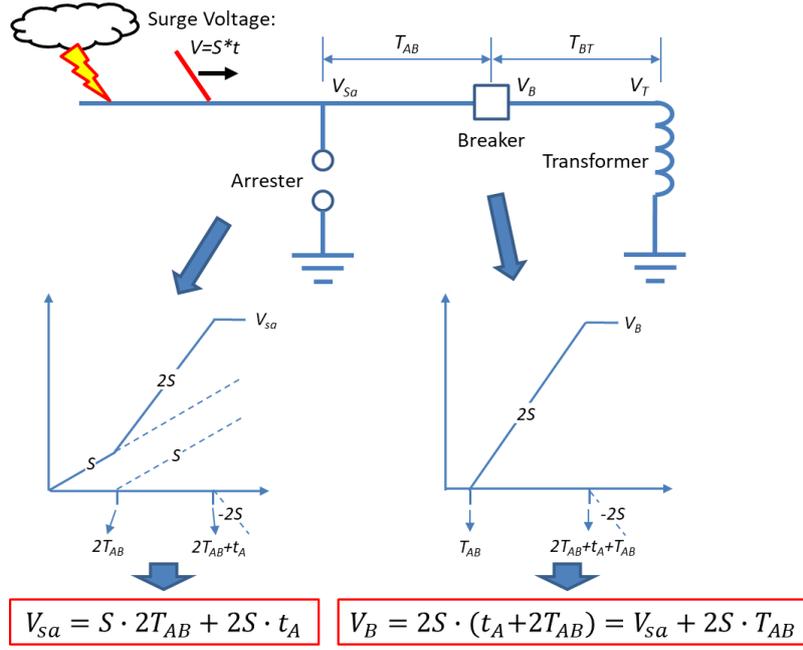


Figure 5. Traveling-wave analysis for opened-breaker-behind-arrester scenario

Thus, we have proven that (1) is applicable for various scenarios involving breaker-arrester positions and closed or opened breaker status. Once the maximum allowable separation distance for a breaker is determined based on (1), the next step is to assess if the breaker is within the maximum allowable separation distance to its nearest arrester. However, a breaker can be opened that results in one side of the breaker being disconnected from the other. In other words, if an arrester is installed within the maximum allowable separation distance to one side of a breaker, it does not protect the other side of the breaker when the breaker is opened. Therefore, various breaker operation scenarios due to a previous fault or scheduled maintenance should be studied. Such details are discussed in the following section.

## SEPARATION DISTANCE APPLICATION SCENARIO ANALYSIS

A 138-kV breaker-and-a-half bus is used to illustrate various application considerations in Figs. 6 and 7, which target breaker maintenance and tripping scenarios, respectively.

As shown in Fig. 6a, Breaker A is taken out of service for scheduled maintenance by opening disconnect switches on both sides to isolate the working zone. Assuming a lightning surge originates on Line 1, this surge travels through Breaker A1 and is blocked by the opened disconnect switches of Breaker A. In this scenario, the arresters on either side of Breaker A1 can provide effective protection if they are within the maximum allowable separation distance to Breaker A1. Note that breaker-mounted arresters for Breaker A (if they were installed) cannot be relied upon in this case, since they are isolated by the neighboring disconnect switches. In addition, for this scenario, note that it is not needed to install arresters on both sides of Breaker A1, but this may be necessary for the following scenarios.

Next, we consider the scenario shown in Fig. 6b, in which Breaker A1 is taken out of service for scheduled maintenance. Therefore, the breaker-mounted arresters installed on both sides of Breaker A1 are isolated and unable to protect Breaker A. However, the breaker-mounted arresters on Breaker A2 can protect Breaker A if they are within the maximum allowable separation distance to Breaker A.

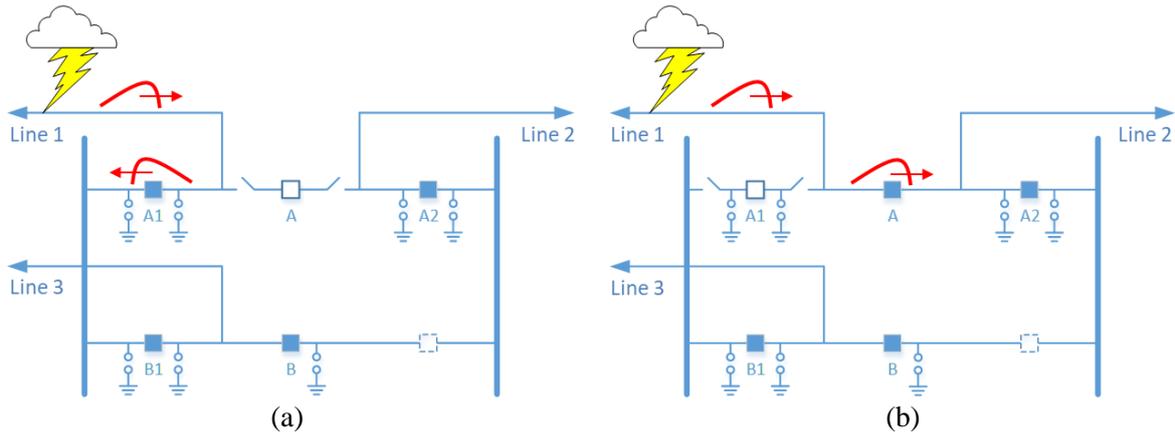


Figure 6. Lightning surge traveling for breaker maintenance scenarios

Now, we will consider the breaker tripping scenarios illustrated in Fig. 7. In Fig. 7a, a fault occurs on Line 1 due to either a lightning strike or other inadvertent contacts (e.g., a flying debris or a fallen tree caused by strong winds), and trips breakers A1 and A. Note that the breaker disconnect switches are closed in this scenario since they typically require manual operation and remain closed until station personnel arrives at the station. In this scenario, there should be arresters within the maximum allowable separation distance to both sides of breakers A1 and A. Note that each side of the breakers are treated separately since the breakers are opened and both sides are vulnerable to surge voltage. We assume that the breaker-mounted arresters on the line-side of breaker A1 are within the maximum allowable separation distance to both sides of breakers A1 and A neighboring Line 1. The bus-side of Breaker A1 is protected by an additional set of breaker-mounted arresters. Similarly, the side of Breaker A neighboring Line 2 is within the maximum allowable separation distance to the arresters on the Line 2 side of Breaker A2. As a result, this scenario is addressed by the proposed arrester placements. In Fig. 7b, the fault on Line 1 trips breakers A1 and A. Considering that Line 1 and Line 3 share the same towers, there is a chance that a direct lightning strike or a backflash can occur on Line 3. In this scenario, the surge travels from Line 3 through Breaker B1 and the bus to the bus-side of Breaker A1. Therefore, we propose installing a set of breaker-mounted arresters on the bus side of Breaker A1, which will clamp the surge and protect Breaker A1. Otherwise, the bus-side of Breaker A1 is exposed to a destructive surge voltage that exceeds the withstand capability of the equipment, since the distance between Breaker A1 and the arresters near Breaker B1 likely exceeds the maximum allowable separation distance.

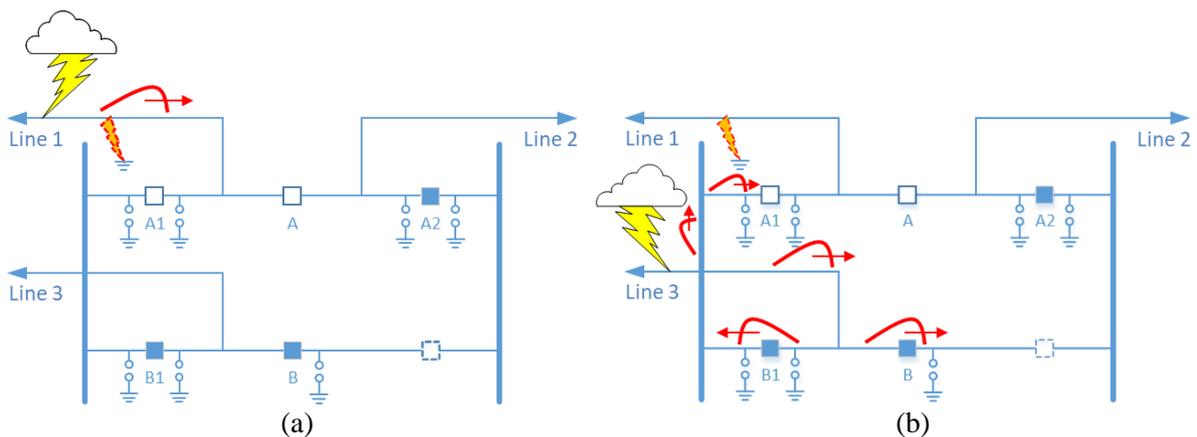


Figure 7. Lightning surge traveling for breaker tripping scenarios

Based on the previous scenarios, we propose installing breaker-mounted arresters on both sides of bus breakers (e.g., A1 and A2) in each branch of a breaker-and-a-half bus layout, as shown in Figs. 6 and 7. Note that the breaker with dashed lines (Breaker B2) in Figs. 6 and 7 does not exist and is considered a future development. A single set of breaker-mounted arresters needs to be installed on the bus-side of

Breaker B, to ensure that the bus-side of Breaker B has arresters within the maximum allowable separation distance when Breaker B trips due to a fault on Line 3.

In addition to the proposed arrester placement solution, there are alternative solutions that include placing arresters at the line entrance locations (illustrated in Fig. 8a) or installing breaker-mounted arresters on both sides of a center breaker (e.g., A and B), as shown in Fig. 8b. However, both solutions cannot address all situations. For the scenario depicted in Fig. 8a, we assume the line entrance arresters are within the maximum allowable separation distance to the Line 1 sides of Breakers A1 and A, which are tripped due to a fault on Line 1. The surge travels from Line 3 to the bus-side of Breaker A1, which does not have any arresters protecting it. Therefore, this scenario disqualifies the placement solution of installing only line entrance arresters (as shown in Fig. 8a). Nonetheless, if such a scenario is deemed unlikely, for instance line 1 and line 3 do not share the same towers or a corridor, then it may not be considered. Thus, using only line entrance arresters may be a cost-effective solution if the risk is deemed acceptable. For the scenario illustrated in Fig. 8b, the breaker-mounted arresters for Breaker A are isolated due to scheduled maintenance. As a result, Breaker A1 is exposed to high surge voltages without effective surge protection.

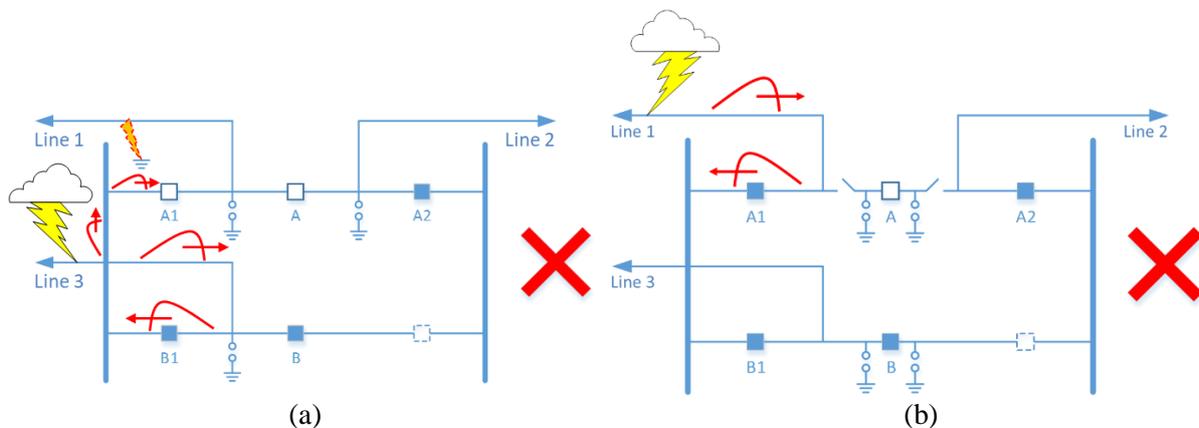


Figure 8. Analysis of breaker operation scenarios for arresters installed at (a) the line entrance terminals and (b) both sides of the center breaker

## SEPARATION DISTANCE APPLICATION PROCEDURES

A summary of the separation distance (SD) application procedure is presented via flowchart in Fig. 9. The procedure:

- 1) Use (1) to calculate the maximum allowable SD.
- 2) Identify a breaker to be analyzed and select the breaker operation scenario (i.e., open due to maintenance or fault, or closed).
- 3) If the breaker is closed, search and verify if there are arresters placed within the calculated SD to the breaker from both directions. If the breaker is opened, search and verify if there are arresters placed within the calculated maximum allowable SD to the breaker from a single direction. Refer to Figs. 10 and 11 for illustrations of separation zones and maximum allowable SD for the closed and opened breaker scenarios, respectively.
- 4) If no arresters can be found based on the previous step, additional arresters need to be placed.
- 5) If not all breaker operation scenarios have been considered, loop back to Step 2.

Note that Fig. 10 illustrates a single separation zone in both directions of Breaker A, which is closed. Fig. 11 illustrates separation Zones 1 and 2 for lightning surge protections of left- and right-hand sides of Breaker A, which is opened due to a fault on Line 1. The separation zones are defined based on the calculated maximum allowable separation distance.

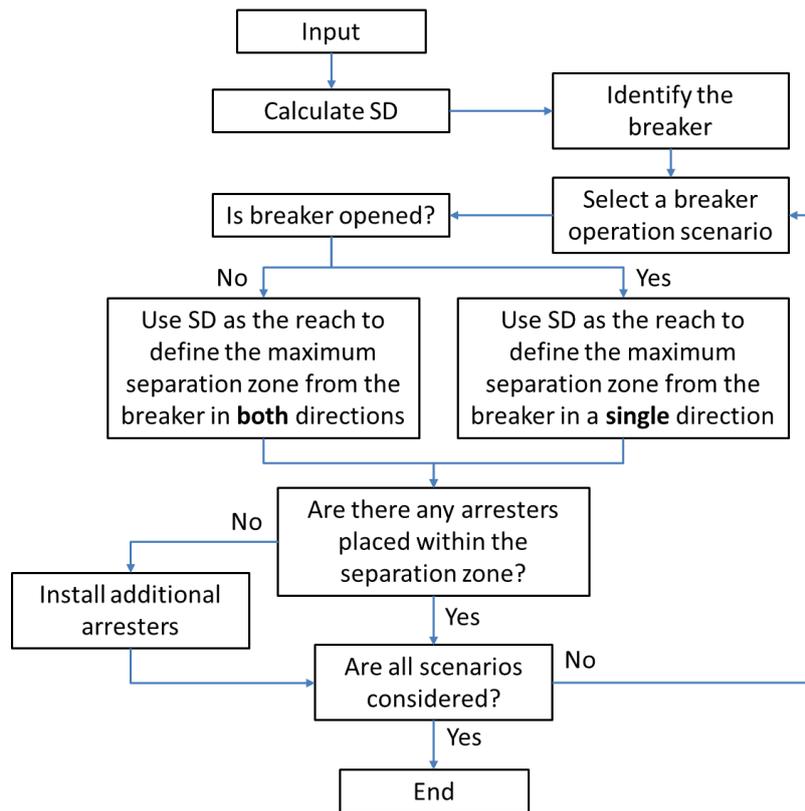


Figure 9. Flowchart of determining surge arrester placements for circuit breakers

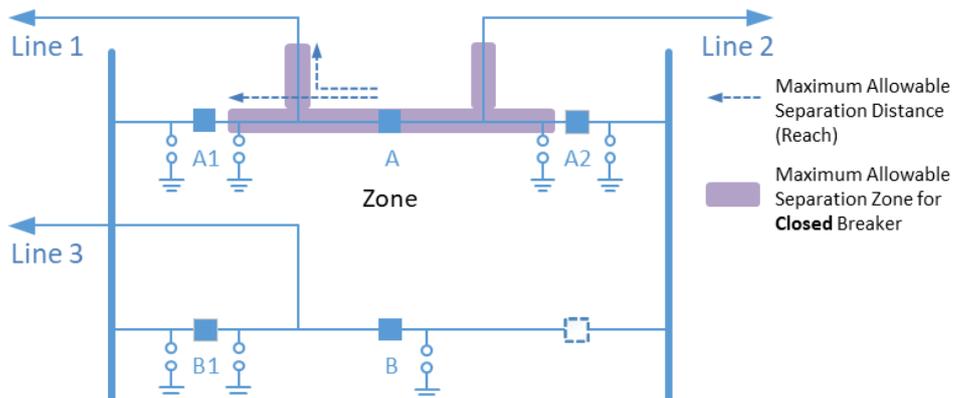


Figure 10. Illustration of a separation zone and maximum allowable separation distance for a closed breaker

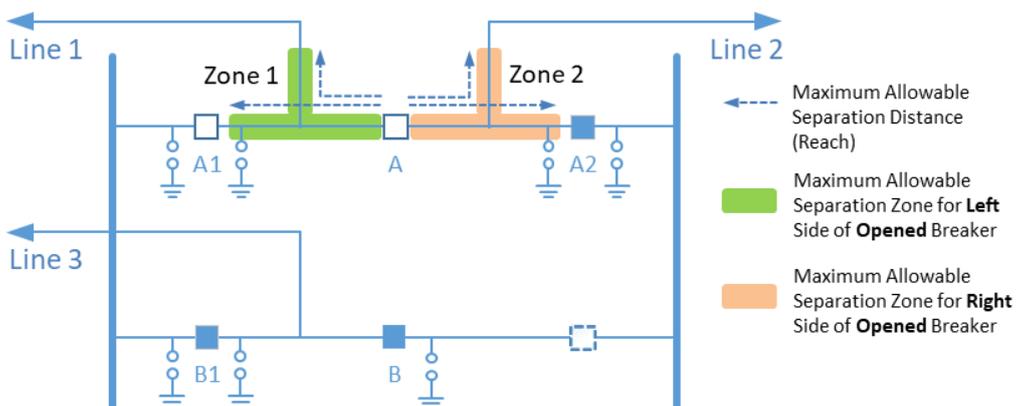


Figure 11. Illustration of separation zones and maximum allowable separation distance for an opened breaker

## **SUMMARY AND CONCLUSIONS**

In this paper, we proved and verified that the equation is valid for calculating the maximum allowable separation distance for substation circuit breakers recommended by IEEE-C62.22 for various breaker-arrester positions and breaker closed/opened statuses. This exercise also helps explain the fundamentals of separation effects and the importance of installing arresters as close as possible to the equipment they are intended to protect. In addition, we explore various breaker operation scenarios including removing a breaker due to scheduled maintenance or a fault, which may influence the placement of surge arresters. Furthermore, we propose an optimal surge arrester placement solution for a typical 138-kV breaker-and-a-half station bus. Lastly, a procedure for determining arrester placements for lightning surge protection of circuit breakers is recommended.

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