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The Minimum Approach Distance Concept for Live Work at Voltages above 72,5 kV

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Abstract

This paper presents and discusses the definition, calculation methods and application of the Minimum Approach Distance concept (MAD) for Live work at system voltages above 72,5 kV. Both IEC and IEEE equations for calculation of MAD and their historical development are discussed.

MAD is based on the withstand voltage of airgaps stressed by switching surges that are expected at the worksite. Reasons for neglecting lightning surges are presented.

1. Recent changes in the calculation of voltage stresses and of the resulting MAD values are presented and their possible impact on live work is described. Methods of reducing the voltage stresses – and thereby offering the opportunity to calculate new smaller MAD values – are presented. Examples are provided in a companion paper “Procedures for Safe Operation of Helicopters in an Energized Wire Environment”.

Effects on MAD of special situations, such as breaker restrike, extremely hot and extremely cold climates, and contaminated insulators also need to be considered.

1. Introduction

Live work (or live working) is defined in the IEV (International Electrotechnical Vocabulary as: “activity in which a worker makes contact with energized parts or encroaches inside the live working zone with either parts of his or her body or with tools, devices or equipment” [1].

Similar definition is contained in the IEEE Std 516-2021: “Work on or near energized or potentially energized lines (i.e., grounding, insulating tool work, gloving, barehand work)” [2].

Four general live working scenarios or methods are considered, see Figure 1:

- Hot stick working – used typically for voltage levels between 50 kV and 500 kV (diagrammatically shown as Method 2 in Figure 1)
- Insulating glove working – used below about 50 kV (diagrammatically shown as Method 1 in Figure 1)
- Barehanding – typically used between above 200 kV and 1000 kV (diagrammatically shown as Method 3 in Figure 1)
- De-energized working (diagrammatically shown as Method 4 in Figure 1)

Two comments are in order:

- Both hot stick working and barehanding are used at voltages between 345 kV and 1000 kV, depending on work type, line configuration, and other factors.
- De-energized work often requires considerations similar to those of live work for two fundamental reasons:

- Before the line or object to be contacted is fully and safely de-energized, it may be at a significant voltage with respect to ground/earth or the worker, and must be treated as “live”
- After the grounding/earthing connections are removed, the object can acquire significant voltage with respect to ground/earth or the worker, and thus must be treated as “live.

Many accidents have occurred while performing de-energized work when the above-described hazards were not recognized and mitigated.

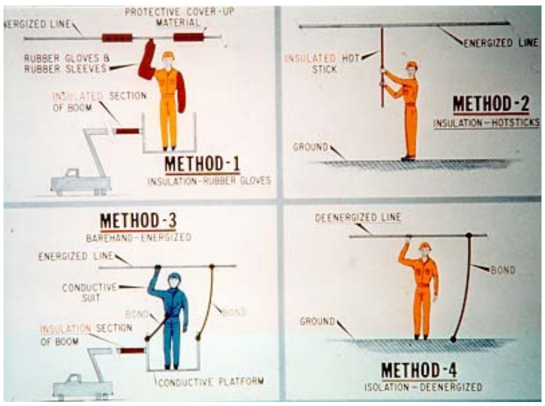


Figure 1. Schematic representation of four types of live working situations.

This paper considers the live working above 200 kV, i.e., the hit stick and the barehanding scenarios.

Safety of the worker during live working is attained by ensuring that the worker does not make contact with, and does not approach closely, parts at different potential that the worker’s body. In general, this requires that sufficient insulation must always be maintained between the worker and parts at other potentials **with respect to the worker**. For the voltage range discussed in this paper (i.e., above 200 kV), the insulation consists of the air gap between the worker and parts at other potentials (called the MAD – Minimum Air Distance), and the insulating tools used by the worker.

For barehanding working that requires contact by a worker with energized parts (barehand work), the required MAD must be maintained between every part of the worker’s body and all objects at potentials that are different from the potential of the worker. For hot stick working, the length of the insulating tools (and its surface finish and properties) must be equal to or greater than the MAD. Insulating tools include various types of hot sticks, ladders, rope, slings, etc.

Calculation of the required MAD includes an additional factor, called the “ergonomic distance” or “inadvertent movement factor”, which accounts for the movement of worker’s hand and body while performing live working tasks. In other words, the concept of MAD is not limited to a single measurable distance, but rather to a three-dimensional envelope around the worker. Also, the presence of tools and their effects are included.

Numerical calculation MAD is based on the withstand of air gaps when subjected to switching impulse.

These concepts and their details are presented in subsequent section of this paper.

Development of MAD values for use in helicopter-based is more complicated and is not addressed in this paper. This is the subject of a companion paper.

2. Two methods of calculating MAD

The two most commonly used method to calculate MAD are the IEC method [3], [4] and the IEEE method [5]. These two methods are described in detail next.

The IEC method of calculating MAD

The IEC method is based on data from laboratory sparkover tests of rod-plane gaps energized with the standard 250/2500 µs switching impulses. The up-and-down procedure is used most often to determine the 50% sparkover voltage, U_{50}, and the standard deviation of the air gap, σ. [6]

This published information is then converted to withstand value as shown in Equation (1):

$$U_{90} = K_s U_2 \quad (1)$$

Where :

K_s is the statistical safety factor, usually take as $K_s = 1{,}0$

U_2 is the is the highest (maximum) expected phase-to-phase rms voltage of the system, in kV

Recalling that the magnitude of a switching surge on a transmission system is related to the PEAK of the ac voltage, we define the highest (maximum) expected phase-to-ground PEAK voltage of the system U_{e2} as:

$$U_{e2} = (/)\ U_s u_{e2} \quad (2)$$

Where:

U_s (/) is the highest (maximum) expected phase to ground peak voltage, of the system expressed in kV,

u_{e2} is the statistical overvoltage phase to ground expressed in per unit (of the rated system phase to-ground voltage).

The value of u_{e2} is determined from overvoltage studies of the system. Examples of typical values of u_{e2} are listed in Annex A of Reference [3].

Combining Equations (1) and (2), the highest (maximum) expected phase-ground peak voltage is:

$$U_{e90} = K_{s\,(}/)\ U_s u_{e2} \quad (3)$$

An analogous derivation provides the equation for the highest (maximum) expected phase-to-phase peak voltage:

$$U_{p90} = K_{s(}/)\ U_s u_{p2} \quad (4)$$

Where u_{p2} is derived from u_{e2} as:

$$u_{p2} = 1{,}35\, u_{e2} + 0{,}45 \quad (5)$$

2. 2.1 Calculation of MAD, D_A, IEC method

The minimum approach distance D_A is determined as the sum of the electrical distance, D_U, needed to assure withstand of the maximum expected overvoltage calculated from Equations (3) or (4), and the ergonomic distance D_E:

$$D_A = D_{U(1)} + D_E \quad (6)$$

Where

$D_{U(1)}$ is determined with K_s = 1,0.

D_E is the ergonomic distance and is dependent on work procedures, level of training, skill of the workers, type of construction, and such contingencies as inadvertent movement, and errors in appraising distances.

The expression for D_U is:

(7)

where

F sum of all lengths, in the direction of the gap axis, of all floating conductive objects in the air gap (in metres)

U_{90} is the phase to earth (U_{e90}) or the phase to phase (U_{p90}) statistical impulse withstand voltage in kV;

K_t is given by:

$$K_t = k_s k_g k_a k_f k_i \quad (8)$$

Where:

k_s is the standard statistical deviation factor which accounts for the statistical nature of the breakdown voltage, and usually the value of 0,936, based on a standard deviation of 5 %, for positive impulses, is appropriate

k_g takes into account the effect of the gap configuration on the dielectric strength of air. The value of 1,45 is typically used [8], [9].

k_a is the atmospheric factor which takes into account the effect of air density.

k_f is the floating conductive object factor.

Floating conductive objects can decrease, or increase, the electric strength of a gap by field distortion.

k_i is the damaged insulator factor [3], [10].

The IEC method does not explicitly account for presence of insulating live working tools.

The “ergonomic distance” or “inadvertent movement factor”, D_E, is added to the calculated D_U.

Example, IEC method

The following basic parameters are used:

K_s = 1,0; k_s = 0,936; k_g = 1,2; k_a = 0,941 (value for 1 000 m), k_f and k_i = 1,0, U_s= 525 kV, u_{e2}= 2,2, F = 0 and D_E = 0,3 m.

Substituting these values into above equations, we obtain:

D_U = 2,787 m (2,8 m)

And D_A = 2,8 m + 0,3 m = 3,1 m

3. 2.2 Calculation of MAD, IEEE method

The IEEE method of calculation of MAD (Minimum Approach Distance) is different from the IEC method. It is considerably simpler to use and understand but is does not explicitly account for factors used in the IEC equations.

However, for the same worksite conditions represented by the parameters K_t in Equation (8) and parameter F in Equation (7), the final calculated values of MAD (D_A) are practically the same [11], [12]. Also, the IEEE method accounts explicitly for effects of insulating live working tools at the worksite.

The IEEE method is derived from switching impulse (surge) tests on rod-rod gaps performed in 1960s at 13 laboratories. The test data were collected, plotted on a common graph and the lowest (worst-case) envelope was drawn to obtain a locus the withstand voltage values. The worst-case curve includes the effect of tools at the worksite tests (tools were installed at the worksite during the tests). The results, redrawn from the original plot for clarity, are shown in Figure 2. The abscissa represents distance (length of the gap) in ft., i.e., the unit of length that was used during the original tests [13]. The ordinate is in units of kV.

4. 2.2.1 Calculation of line-ground MAD, IEEE method

It is observed in Figure 2 that the relation between withstand voltage and length is not linear. In particular, the slope of the curve **decreases** as gap length **increases**. In other words, and gap lengths must be considerably greater as surge voltage increases. This phenomenon is a property of air gaps and it is called “air saturation” in [5]. The effect of saturation is accounted for by the chancing value of the factor *a*, which increases (disproportionately) as voltage increases.

The mathematical formula shown in Figure 2 is:

$$D = (0{,}011 + a) \cdot V_{L\text{-}G} \cdot S \quad (9)$$

The number 0.011 in Equation (9) includes the effect of tools in the airgap (see inserts in Figure 2). The number 0,011 is the product of 0,01 ft./kV and 1,1 (dimensionless). That is, D is related to 10% of the system voltage $V_{L\text{-}G}$, in kV_{rms}, modified by the effect of live working tools, further modified by the non-linearity of the curve, and the pe-unit switching surge factor S.

The more general form of Equation (9) is:

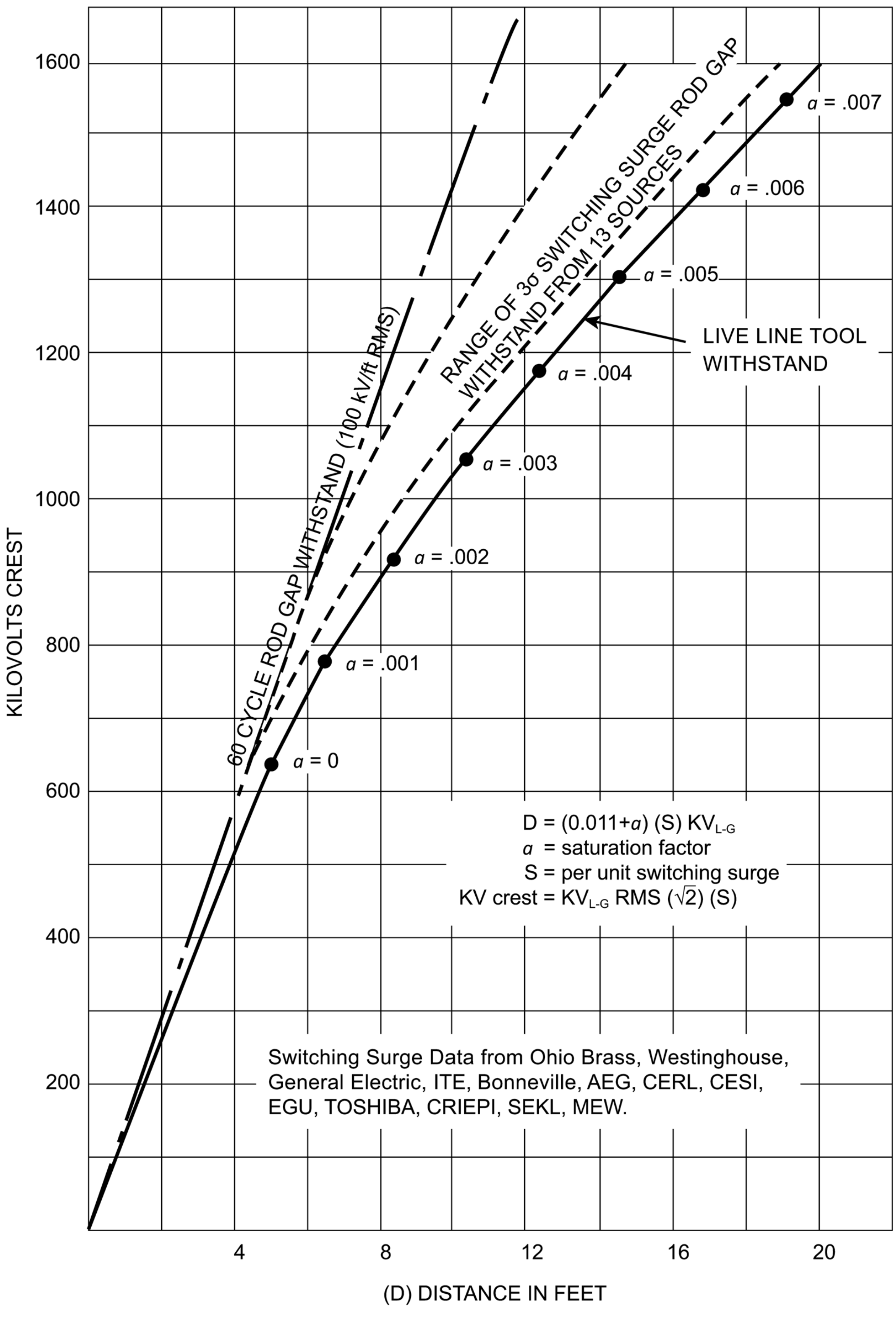
$$D = (C_1C_2 + a) \cdot V_{L\text{-}G} \cdot S \quad (10)$$

where

a is air saturation factor (dimensionless) a = 0 for the surge voltage levels ($V_{L\text{-}G} \cdot T$) ≤ 635 kV_{peak}
C_1 = 0,011 ft./kV
C_2 = 1,1 (dimensionless)
S (now called T) is the per-unit switching surge
$V_{L\text{-}G}$ is maximum anticipated line-to-ground voltage in kV_{rms}

For line-to-ground surges with peak values ($V_{L\text{-}G} \cdot T$) ≤ 635 kV_{peak}m the parameter a = 0. For surge values ($V_{L\text{-}G} \cdot T$) ≥ 635 kV_{peak}, values of a are read off (interpolated) from the graph in Figure 2.

IEEE Std 516:2021 also tabulates values of a versus the quantity ($V_{L\text{-}G} \cdot T$). [5]



1600
1400
1200
1000
800
600
400
200
KILOVOLTS CREST
4
8
12
16
20
(D) DISTANCE IN FEET
60 CYCLE ROD GAP WITHSTAND (100 kV/ft RMS)
RANGE OF 3σ SWITCHING SURGE ROD GAP
WITHSTAND FROM 13 SOURCES
LIVE LINE TOOL
WITHSTAND
a = .007
a = .006
a = .005
a = .004
a = .003
a = .002
a = .001
a = 0
D = (0.011+a) (S) KVL-G
a = saturation factor
S = per unit switching surge
KV crest = KVL-G RMS (√2) (S)
Switching Surge Data from Ohio Brass, Westinghouse,
General Electric, ITE, Bonneville, AEG, CERL, CESI,
EGU, TOSHIBA, CRIEPI, SEKL, MEW.

Figure 2. Test data for the IEEE method of determining MAD.

To emphasize that Equation (10) includes effects of live working tools at the worksite, the result of this calculation is termed MTID (Minimum Tool Insulation Distance). For situations where tools are not present at the worksite, the factor C_2 in Equation (10) is set to C_2 = 1,0, and the result of the calculation is termed MAID (Minimum Air Insulation Distance), which somewhat smaller than MTID. This may be useful for climbing inspections, for example, but for additional safety reasons MTID is commonly used.

Two additional acronyms are used:

MAD: Minimum Approach Distance, which is obtained as:

$$\text{MAD} = \text{MAID} + \text{M} \quad (11)$$

$\text{MAD}_{\text{tools}}$: Minimum Approach Distance with Tool, which is obtained as:

$$\text{MAD}_{\text{tools}} = \text{MTID} + \text{M} \quad (12)$$

Where M is the "ergonomic distance" or "inadvertent movement factor".

For live working at elevations above 900 m, the MAID (MTID) values are multiplied by the appropriate adjustment factor.

5. 2.2.2 Calculation of line-line MAD, IEEE method

The general procedure for determining line-line MAD in the IEEE method is similar that for the line-ground procedure. Calculation line-line MAID is of course based on switching impulse line-to-line gap test data determined by tests performed on line conductor-to-line conductor gaps.

A fundamental parameter in determining the line-to-line insulation strength is the proportion, α, of negative switching voltage impulse to the total line-to-line voltage impulse [14]:

$$\alpha = U_{\text{Neg}}/(U_{\text{Neg}} + U_{\text{Pos}}) \quad (13)$$

where

U_{Pos} is the crest (peak) value of the positive voltage impulse

U_{Neg} is the value of the negative switching voltage impulse at the instant of the crest of the positive voltage impulse

The most interesting range of the parameter α is $0,33 < \alpha < 0,5$. It should be noted that the total line-line voltage impulse magnitude is NOT equal to (in fact, it is significantly less than) the sum $|U_{\text{Pos}}| + |U_{\text{Neg}}|$. Therefore, the test data used for determining the line-to-ground MAID cannot be used to obtain the line-to-line MAID.

For determining the line-to-line MAID, test data for the line-to-line gap for conductor-to-conductor configuration are used [15]. The tests data are fitted with a modified Gallet equation. After considerable manipulation, the equation for line-line MAID = $D_{\text{L-L}}$ is:

(14)

In the presence of a conductive object(s) that are electrically floating between phases, $\text{MAID}_{\text{L-L}}$ is the sum of the air gaps on both sides of the conductive object(s).

6. 2.3 Consideration of circuit breaker restrike in the calculation of MAD, IEEE method

Calculation of MAD is based on the TOV (Transient Overvoltage, symbol *T*). Values of *T* for a particular transmission line are determined by calculations or tests. In case results of calculations or tests are not available, the industry has determined typical maximum values for use in determining MAD, see Table 1 [5]. Note that Table 1 shows the maximum nominal line voltages, rather than rated line voltages. Maximum nominal line voltages account for Ferranti effect on energized but unloaded or lightly loaded lines. As an additional level of safety, maximum nominal line voltage is typically taken as about 5% to 10% higher than the rated voltage. For example, the maximum nominal voltage of a 345 kV line is taken as 362 kV (362/345 = 1,049 rounded up to 1,05) and of a 765 line is taken as 800 kV (800/765 = 1,0457 rounded up to 1,05).

TABLE 1

AC line-to-line voltage	*T* for live work
At and below 362 kV	3,0 p.u.
363 to 550 kV	2,4 p.u.
551 to 800 kV	2,0 p.u.

The highest values of *T* typically are produced when a circuit breaker **opens** (de-energizes) and then **recloses** at the opposite peak of the sinusoidal voltage wave. This opening action followed by re-energization action is used commonly because experience has shown that many line events that cause beaker operation are temporary single-phase faults that are self-cleared (for example, a tree branch falling on a phase and burning off quickly). In case the breaker detects a persistent line-ground or another type of fault, the breaker remains open after one or two unsuccessful reclosure attempts.

However, it is recognized that the reclosing actions often produces transient overvoltages (*TOV*) which are greater in magnitude than the overvoltages resulting from the opening actions. Hence, many line operators block (disable) breakers from reclosing after the first opening operation, as an attempt of preventing the possibility of a very high reclosing *TOV*. While this approach has been deemed successful in reducing the *T* factor and thus providing the possibility of calculating needed MAD, concern is that there is no guarantee that a circuit breaker will not suffer restrike during the first (or subsequent) opening action.

7. 2.3.1 What is circuit breaker restrike

Restrike is an event that may occur during an *opening* operation when the contact opening is not successful but results in a momentary re-energization of the line. Restrike is different from prestrike.

Prestrike

Prestrike is a normal operating mode of a breaker. It occurs during the closing operation of the breaker before contacts are fully closed. Before the initiation of the closing operation, opposing contacts are at different potentials, i.e., full AC voltage exists between the contacts.

In the simplest terms, the breaker and the insulation between them are designed to withstand this condition. As the closing operation is initiated, contacts approach each other and the insulation between then *decreases*. Depending on the instantaneous voltages at the opposing contacts, the remaining insulation may break down and result on an arc between the closing contacts. This is schematically illustrated in Figure 3.

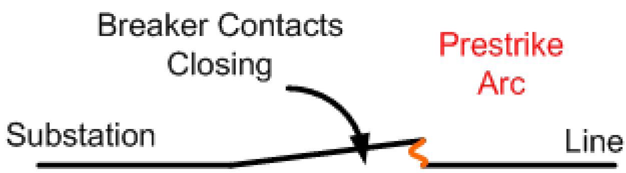


Figure 3. Diagram showing prestrike during closing of circuit breaker contacts

The situation shown in Figure 3 is a normal operating mode of the circuit breaker and modern beakers are designed to survive a certain number of such events. Each event, however, may result in some damage or pitting of the breaker contacts.

Restrike

Restrike is not considered a normal operating mode of a breaker. It can occur during an *opening* operation of the breaker. Before the initiation of the *opening* operation, the voltage between opposing contacts is zero.

As the opening operation is initiated, contacts move apart and the insulation between then *increases*. Depending on the instantaneous voltages at the opposing contacts, the buildup of insulation may not be sufficiently rapid to withstand the voltage between the contacts. In that case, the insulation may break down and result on an arc between the *opening* contacts. This is schematically illustrated in Figure 4.

Figure 4. Diagram showing restrike during *opening* of circuit breaker contacts

This results in re-energization of the line. If this event takes place on the first opening of the breaker, planned blocking breaker reclosure is ineffective and cannot be considered as a practical means of reducing *T*. In fact, restrike can produce very high *T* factors which are similar to those produced by intentional reclosing into a trapped charge on the line. Consequently, Occupational Health and Safety Administration (OSHA) of the USA issued a requirement in 2014 for use of higher *T* values to ensure worker safety for cases where *T* values are not known [17].

Table 2 lists the new *T* factors.

TABLE 2

AC line-to-line voltage	*T* for live work
72,6 to 420 kV	3,5 p.u.
420,1 to 550 kV	3,0 p.u.
550,1 to 800 kV	2,5 p.u.

Can the probability of restrike be minimized?

Two approaches may be used to help reduce the probability of restrike, thus allowing recalculation of MAD (i.e., obtaining reduced MAD values) based in reduced *T* factors.

Assuming that, by design, a circuit breaker is capable of passing the required standardized tests, proper breaker application and maintenance can minimize the probability of restrike occurrence. Reference [16] concluded that it is impossible to determine a standard probability level related to restrike performance of a circuit breaker in-service. As such, restrike probability can only be minimized.

Based on the findings in [16], there are three primary factors affecting the probability of breaker restrike as follows:

- Breaker design,
- Breaker application, and
- Breaker maintenance.

Properly applied circuit breakers should be carefully inspected and maintained based on manufacturer’s recommendations, industry standards, operational history, and testing history.

Also, control of overvoltages at the worksite may be achieved with installation of devices such as Portable Protective Air Gaps (PPAG) or specific surge arresters for the duration of live working or permanently. Figure 5 shows a PPAG and its installation on a structure for the duration of live working, and Figure 6 shows a surge arrester installed permanently on a structure.

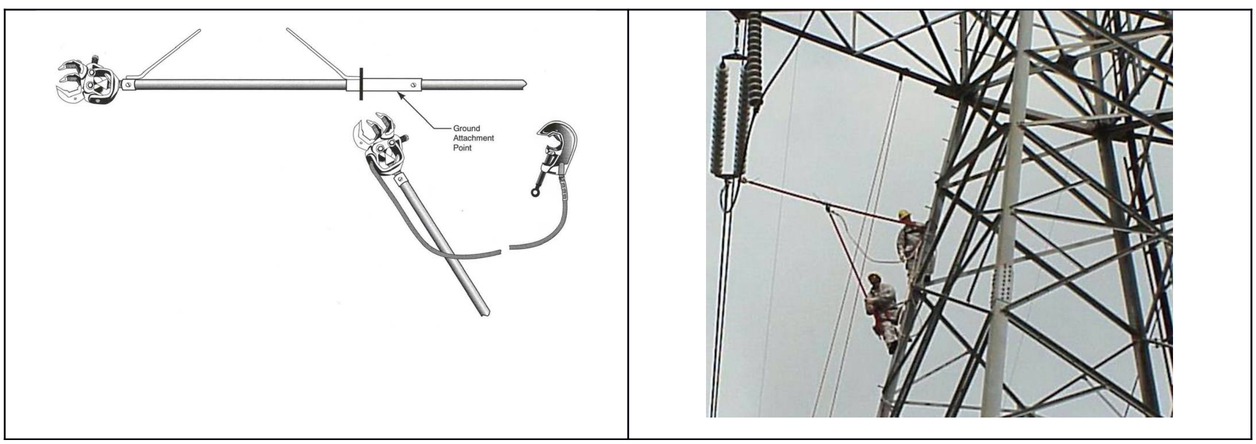


Figure 5. Example of a Portable Protective Air Gap (PPAG) (left) and installation of PPAG (right)

Figure 6. Example surge arrester installed between line conductor and structure.

8. 3. Relating MAD to voltage stresses at the worksite – concept of insulation coordination

In the science of insulation coordination, the strength of electrical insulation, $U_{\text{insulation}}$, must equal or, preferably exceed, the expected voltage stresses, U_{stress}, as sown in Equation (15):

$$U_{\text{insulation}} \geq U_{\text{stress}} \tag{15}$$

For live working applications, three types of voltage stresses are of importance:

- Steady-state AC operating line voltages at power frequency
- Short-duration lightning overvoltages, characterized by the standard lightning impulse 1.2/50 μs
- Intermediate-duration switching overvoltages, characterized by the standard switching impulse 250/2500 μs

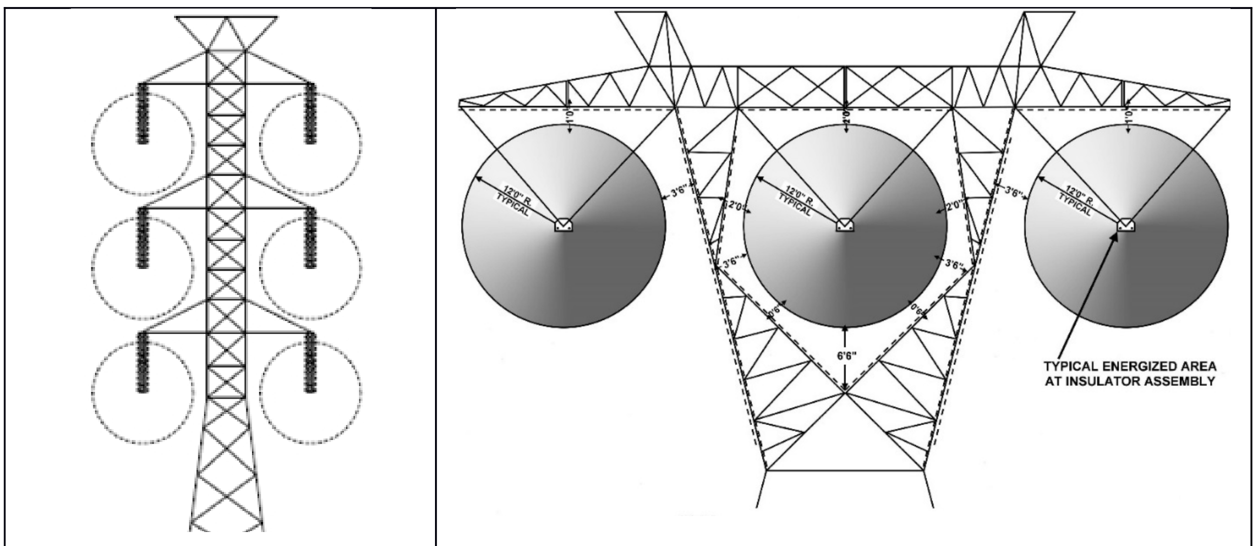
As described earlier, steady-state AC operating live voltages are taken to be the maximum nominal levels which are typically 5% or 10% higher than the rated line voltage.

Lightning overvoltages are not included explicitly in the calculation of MAD because, based on lightning surge studies on transmission lines, the surge produced by a lightning strike far away from the worksite is attenuated and slowed down as it propagates on a lossy transmission line [18]. These results indicated that a lightning surge becomes to look like a typical switching surge after having travels about 10 miles along the line. This led to the development of the “10-mile” rule-of thumb. These days, weather and lightning activity are monitored continuously during live work and work is interrupted when a thunderstorm approaches the worksite to within the specified distance. This led to the “10-mile” rule-of thumb.

The last requirement – overvoltages produced on a line due to switching operations – requires the knowledge on resulting overvoltages. This information can be obtained by performing computations (for example, using the EMTP software) or may be derived from historical knowledge or comparison with overvoltages on similar lines.

Practical application of Equation (15), consists in the simplest form in drawing contours (circles) around the location of the worker. The contours must not overlap or touch any object at potential that is different from that of the worker.

Figure 7 shows circular contours drawn on structures with I-strings and V-strings of insulators. In the simplest analysts, the radius of the circular contour (or spherical envelope) is equal to or greater than the length of the insulator string. Only insulators in good condition can be used to determine the size and extent of the envelope.



Contours for I-string insulators	Contours for V-string insulators

Figure 7. Example of application of Equation 15.

In more complicated worksite scenarios, such as work from an elevating work platform (MEWP), which includes electrically floating metallic parts, the envelope is not a circle or sphere but a three-dimensional “bubble” as shown in Figure 8.

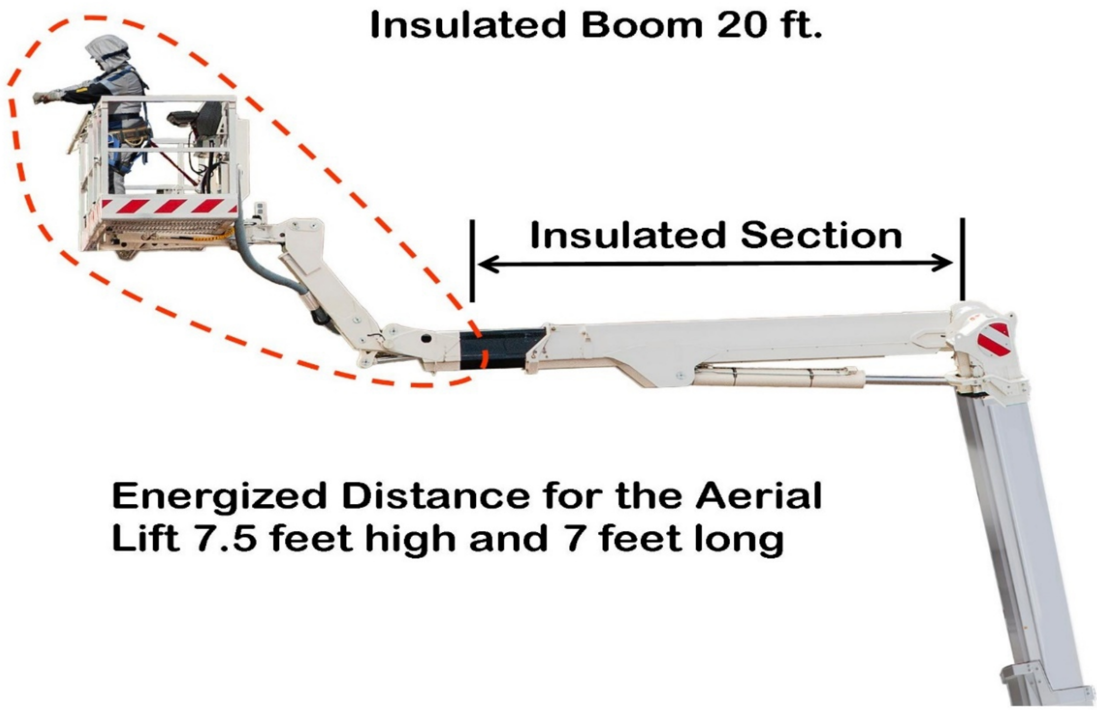


Figure 8. Example of an envelope for work from an elevated work platform with electrically floating metallic parts.

9. 4. Summary and conclusions

This paper presents calculation methods and application of the Minimum Approach Distance concept (MAD) for Live work at system voltages above 72,5 kV. Both IEC and IEEE equations for calculation of MAD and their historical development are discussed.

MAD is based on the withstand voltage of airgaps stressed by switching surges that are expected at the worksite. Reasons for neglecting lightning surges are presented.

This paper also discusses the circuit breaker restrike phenomenon that can cancel the advantages of blocking circuit breaker reclosure for the duration of work. Breaker restrike can result in high transient overvoltages at the worksite and must be considered during the preparatory phase of live working operations. Methods reducing worksite *T* with the use of overvoltage limiting devices (PPAG, lightning arresters), and of minimizing the probability of occurrence of undesirable restrikes are also discussed. Examples are provided in a companion paper "Procedures for Safe Operation of Helicopters in an Energized Wire Environment".

References

[1] IEV Entry 651-21-01, https://www.electropedia.org/

[2] IEEE 516-2021, https://standards.ieee.org/ieee/516/5911/

[3] IEC 61472:2013 "Live working - Minimum approach distances for a.c. systems in the voltage range 72,5 kV to 800 kV - A method of calculation", https://webstore.iec.ch/publication/5486

[4] IEC 61472:2013/COR1:2015 “Corrigendum 1 - Live working - Minimum approach distances for a.c. systems in the voltage range 72,5 kV to 800 kV - A method of calculation”, https://webstore.iec.ch/publication/23624

[5] IEEE 516-2021, “IEEE Guide for Maintenance Methods on Energized Power Lines”, https://standards.ieee.org/ieee/516/5911/

[6] IEC 60060-1:2010, “High-voltage test techniques - Part 1: General definitions and test requirements”, https://webstore.iec.ch/searchform&q=IEC%2060060-1, and other parts of 60060 series.

[7] IEEE Std 4-2013, “IEEE Standard for High-Voltage Testing Techniques”, https://standards.ieee.org/ieee/4/4777/

[8] CIGRÉ, Brochure No. 72:1992, *Guidelines for the evaluation of the dielectric strength of the external insulation*

[9] I EC 60071-2:2018, “Insulation co-ordination – Part 2: Application guidelines”

[10] CIGRÉ, Brochure No. 151:2000, *Guidelines for insulation coordination in live working*

[11] G. Gela, M. Charest, “IEC Method of Calculation of Minimum Approach Distances for Live Working,” in Proc. 1998 ICOLIM Conf., Lisbon, Portugal.

[12] G. Gela, P.W. Hotte, M. Charest, “IEC Method of Calculation of Minimum Approach Distances for Live Working”, IEEE Trans. Power Delivery, vol. 15, No. 2, pp. 635-640, Apr. 2000.

[13] IEEE paper “Recommendations for safety in live-line maintenance”, IEEE T&D, vol. PAS-87, no. 2, pp. 346–352, Feb. 1968.

[14] Gallet, G., and G. Leroy, “Expression for positive switching impulse strength suggesting a highest permissible voltage for ac systems,” IEEE Transaction on Power Apparatus and Systems, IEEE Conference Paper C73-408, vol. PAS-92, no. 6, pg. 1808, Nov./Dec. 1973.

[15] Vaisman, R., et al., “Switching impulse strength of compact transmission lines,” IEEE Transactions on Power Delivery, vol. 8, no. 3, pp. 1570–1578, July 1993.

[16] IEEE paper, Practical Approaches to Reducing Transient Overvoltages Factors for Live Work”, 2016 ESMO Conference, Columbus, OH, 2016.

[17] 29 CFR Parts 1910 and 1929, “Electric power generation, transmission, and distribution; Electrical protective equipment, Final rule, Federal Register, Vol. 79, No. 70, Part II. April 11, 2014.

[18] Everett, S.L. and Faust, C.M., “The Measurement of Surge Voltages on Transmission Lines due to Lightning”, Transactions A.I.E.E., February 1927, pp. 339-356.