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Arc Flash Calculation for 110/20 kV HV/MV Substation

Viktor Milardić, Amir Tokić, Anamari Nakić

***Summary* —This paper presents arc flash calculation for 110/20 kV HV/MV substation that follows IEEE 1584:2018 Standard. The IEEE 1584:2018 standard has been completely revised compared to the IEEE 1584:2002 standard, and according to the IEEE 1584:2002 standard, the calculation of an electric arc can no longer be performed. The paper shows how calculating the risk assessment to identify potential electrical hazards and implement appropriate safety measures and ultimately to protect workers from arc-flash hazards. Arc flash calculation for the case of real 110/20 kV substation is shown.**

***Keywords* — Calculation, Arc flash, IEEE 1584:2018 Standard.**

I. Introduction

An arc flash is a dangerous electrical explosion caused by an arc fault, which occurs when electrical current leaves its intended path and travels through the air between conductors or from a conductor to ground. This can happen due to various reasons, such as equipment failure, improper installation, or maintenance errors. Arc flashes can be triggered by factors like dust, corrosion, condensation, or accidental contact with live parts.

The explosion can reach temperatures up to 20 000 °C, causing severe burns, hearing loss, and even fatalities. It can also vaporize metal parts and create a pressure wave that can damage equipment and injure personnel.

Implementing proper safety measures, such as regular maintenance, using arc-resistant switchgear, and ensuring proper training and use of personal protective equipment, can significantly reduce the risk.

Compliance with standards IEEE 1584: 2018 [1] [2], NFPA 70E: 2024 [3] and paper [4] is crucial for ensuring safety and minimizing arc flash hazards.

II. Basic of IEEE Standard 1584

IEEE 1584 Standard helps protect workers from arc-flash hazards. The standard provides mathematical models to calculate the arc-flash hazard distance and the incident energy to which workers could be exposed during their work on or near electrical equipment.

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In relation to IEEE 1584:2002 standard, the IEEE 1584:2018 standard has been completely changed, and according to the IEEE 1584:2002 standard, arc flash calculation can no longer be performed.

For more details, see the changes in the document IEEE 1584_2018-2002_redline.

It defines the amount of thermal energy impressed on a surface at a certain distance from the source of an arc flash. This helps in determining the appropriate level of personal protective equipment (PPE) required.

IEEE 1584 Standard includes equations to calculate the arcing fault current, which is essential for understanding the potential severity of an arc flash.

The standard considers different electrode configurations and enclosure sizes, which significantly impact the arc-flash hazard calculations.

The latest version, IEEE 1584-2018, includes new equations and guidance for more accurate arc-flash hazard assessments, reflecting extensive testing and model development.

NFPA 70E, Standard for Electrical Safety in the Workplace, is a critical standard to ensure electrical safety for employees in the workplace.

NFPA 70E defines approach boundaries to protect workers from electrical hazards. These boundaries establish safe working distances around energized electrical conductors or circuit parts.

The standard requires a thorough risk assessment to identify potential electrical hazards and implement appropriate safety measures. This includes evaluating the likelihood of an arc flash and its potential severity.

NFPA 70E specifies the types of PPE required for different levels of electrical exposure. This includes flame-resistant clothing, gloves, face shields, and other protective gear. Employees must be trained in safe work practices and emergency procedures. The standard emphasizes the importance of regular training and drills to ensure workers are prepared for potential electrical incidents.

IEEE 1584 provides empirical formulas for determining arcing fault currents, incident energy and arc-flash boundary. This Standard establishes a ten-step procedure for gathering data and calculating arc flash hazard as follows:

- Collect the system and installation data
- Determine the system modes of operation
- Determine the bolted fault currents
- Determine typical gap and enclosure size based upon system voltages and classes of equipment
- Determine the equipment electrode configuration
- Determine the working distances

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- Calculation of arcing current
- Determine the arc duration
- Calculate the incident energy
- Determine the arc-flash boundary for all equipment

In the next part of the text, simplified calculation procedures for calculation of the arc currents, incident energy and arc-flash boundary are presented.

(1) The intermediate average arcing currents can be determined using the relation:

$$I_{\mathrm{arc\_Voc}} = 10^{k_1 + k_2 \log I_{\mathrm{bf}} + k_3 \log G} \sum_{i=4}^{10} k_i I_{\mathrm{bf}}^{10-i} \quad (1)$$

where are:
I_{bf} - the bolted fault current for three-phase faults (symmetrical rms) $[kA]$
$I_{\mathrm{arc\_Voc}}$ - the average rms arcing current at $V_{\mathrm{oc}} = 600\ V$ $[kA]$
$I_{\mathrm{arc\_Voc}}$ - the average rms arcing current at $V_{\mathrm{oc}} = 2700\ V$ $[kA]$
$I_{\mathrm{arc\_Voc}}$ - the average rms arcing current at $V_{\mathrm{oc}} = 14\,300\ V$ $[kA]$
G - the gap distance between electrodes $[mm]$
$k_1, \ldots, k_{10}$ - the coefficients regard to [1]

(2) The reduced arcing currents, including the variation correction factor, are calculated from relations:

$$VarC_f = \sum_{i=1}^{7} k_i V_{\mathrm{oc}}^{7-i} \quad (2)$$

$$I_{\mathrm{arc\_min}} = I_{\mathrm{arc}}\left(1 - 0.5 VarC_f\right) \quad (3)$$

where are:
$VarC_f$ - the arcing current variation correction factor
I_{arc} - the final or intermediate rms arcing current(s) $[kA]$

$I_{\mathrm{arc\_min}}$ - the second rms arcing current reduced based on the variation correction factor $[kA]$
V_{oc} - the open-circuit voltage between 0.208 and 15.0 (20.0) $[kV]$
$k_1, \ldots, k_7$ - the coefficients regard to [1]

(3) The final arcing current can be determined using the next equations:

$$I_{\mathrm{arc\_1}} = \frac{I_{\mathrm{arc\_2700}} - I_{\mathrm{arc\_600}}}{2.1}(V_{\mathrm{oc}} - 2.7) + I_{\mathrm{arc\_2700}} \quad (4)$$

$$I_{\mathrm{arc\_2}} = \frac{I_{\mathrm{arc\_14300}} - I_{\mathrm{arc\_2700}}}{11.6}(V_{\mathrm{oc}} - 14.3) + I_{\mathrm{arc\_14300}} \quad (5)$$

$$I_{\mathrm{arc\_3}} = \frac{I_{\mathrm{arc\_1}}}{2.1}(2.7 - V_{\mathrm{oc}}) + \frac{I_{\mathrm{arc\_2}}}{2.1}(V_{\mathrm{oc}} - 0.6) \quad (6)$$

where are:
$I_{\mathrm{arc\_1}}$ - the first I_{arc} interpolation term between $600\ V$ and $2700\ V$ $[kA]$
$I_{\mathrm{arc\_2}}$ - the second I_{arc} interpolation term used when V_{oc} is greater than $2700\ V$ $[kA]$
$I_{\mathrm{arc\_3}}$ - the third I_{arc} interpolation term used when V_{oc} is less than $2700\ V$ $[kA]$
V_{oc} - the open-circuit voltage (system voltage) $[kV]$

(4.a) The equivalent height and width are determined using the next relations:

$$\mathrm{Width}_1 = \frac{1}{25.4}\left(660.4 + (\mathrm{Width} - 660.4)\frac{V_{\mathrm{oc}} + A}{B}\right) \quad (7)$$

$$\mathrm{Height}_1 = \frac{1}{25.4}\left(660.4 + (\mathrm{Height} - 660.4)\frac{V_{\mathrm{oc}} + A}{B}\right) \quad (8)$$

where are:
Width_1 - the equivalent enclosure width
Height_1 - the equivalent enclosure height
Width - the actual enclosure width $[mm]$
Height - the actual enclosure height $[mm]$
V_{oc} - the open-circuit voltage (system voltage) $[kV]$
A - constant equal to 4 for VCB and 10 for VCBB and HCB
B - constant equal to 20 for VCB, 24 for VCBB and 22 for HCB
The following electrode configurations (test arrangements) are defined.
VCB: Vertical conductors/electrodes inside a metal box/enclosure
VCBB: Vertical conductors/electrodes terminated in an insulating barrier inside a metal box/enclosure
HCB: Horizontal conductors/electrodes inside a metal box/enclosure
VOA: Vertical conductors/electrodes in open air
HOA: Horizontal conductors/electrodes in open air.

The general guidelines to determine the equivalent enclosure height and width for different ranges of enclosure dimensions and electrode configurations are presented in [1].

(4.b) The equivalent enclosure size (*EES*) is determined using the equivalent width and height from relation:

$$EES = \frac{\mathrm{Height}_1 + \mathrm{Width}_1}{2} \quad (9)$$

where are:
Width_1 - the equivalent enclosure width
Height_1 - the equivalent enclosure height
EES - the equivalent enclosure size

(4.c) The correction factor (*CF*) for a “Typical Enclosure” is obtained by using relation:

$$CF = b_1 EES^2 + b_2 EES + b_3 \quad (10)$$

The correction factor (*CF*) for a “Shallow Enclosure” is obtained by using relation:

$$CF = \frac{1}{b_1 EES^2 + b_2 EES + b_3} \quad (11)$$

where are:
b_1, b_2, b_3 - the coefficients refer to [1]
CF - the enclosure size correction factor
EES - the equivalent enclosure size (for typical box enclosures the minimum value of EES is 20)

(5) The intermediate incident energy values are calculated using the next relations:

$$E_{600} = \frac{12.552}{50} T \cdot$$

$$\cdot\ 10^{k_1 + k_2 \log G + \frac{k_3 I_{\mathrm{arc\_600}}}{\sum_{i=4}^{10} k_i I_{\mathrm{bf}}^{11-i}} + k_{11} \log I_{\mathrm{bf}} + k_{12} \log D + k_{13} \log I_{\mathrm{arc\_600}} + \log \frac{1}{CF}} \quad (12)$$

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$$E_{2700} = \frac{12.552}{50} T \cdot 10^{k_1 + k_2 \log G + \frac{k_3 I_{arc\_2700}}{\sum_{i=4}^{10} k_i I_{bf}^{11-i}} + k_{11} \log I_{bf} + k_{12} \log D + k_{13} \log I_{arc\_2700} + \log \frac{1}{CF}} \quad (13)$$

$$E_{14300} = \frac{12.552}{50} T \cdot 10^{k_1 + k_2 \log G + \frac{k_3 I_{arc\_14300}}{\sum_{i=4}^{10} k_i I_{bf}^{11-i}} + k_{11} \log I_{bf} + k_{12} \log D + k_{13} \log I_{arc\_14300} + \log \frac{1}{CF}} \quad (14)$$

where are:
E_{600} - the incident energy at $V_{oc} = 600\ V$ [J/cm^2]
E_{2700} - the incident energy at $V_{oc} = 2700\ V$ [J/cm^2]
E_{14300} - the incident energy at $V_{oc} = 14\ 300\ V$ [J/cm^2]
T - the arc duration [ms]
G - the gap distance between conductors (electrodes) [mm]
I_{arc_600} - the rms arcing current for $600\ V$ [kA]
I_{arc_2700} - the rms arcing current for $2700\ V$ [kA]
I_{arc_14300} - the rms arcing current for $14\ 300\ V$ [kA]
I_{bf} - the bolted fault current for three-phase faults (symmetrical rms) [kA]
D - the distance between electrodes and calorimeters (working distance) [mm]
CF - the correction factor for enclosure size ($CF = 1$ for VOA and HOA configurations)

$k_1, \ldots, k_{13}$ - the coefficients regard to [1]

(6) The final incident energy values are estimated using the next equations:

$$E_1 = \frac{E_{2700} - E_{600}}{2.1} (V_{oc} - 2.7) + E_{2700} \quad (15)$$
$$E_2 = \frac{E_{14300} - E_{2700}}{11.6} (V_{oc} - 14.3) + E_{14300} \quad (16)$$
$$E_3 = \frac{E_1}{2.1} (2.7 - V_{oc}) + \frac{E_2}{2.1} (V_{oc} - 0.6) \quad (17)$$

where are:
E_1 - the first E interpolation term between $600\ V$ and $2700\ V$ [J/cm^2]
E_2 - the second E interpolation term used when V_{oc} is greater than $2700\ V$ [J/cm^2]
E_3 - the third E interpolation term used when V_{oc} is less than $2700\ V$ [J/cm^2]
V_{oc} - the open-circuit voltage (system voltage) [kV]

(7) The intermediate arc-flash boundary values are calculated using the next relations:

$$AFB_{600} = 10^{\frac{k_1 + k_2 \log G + \frac{k_3 I_{arc\_600}}{\sum_{i=4}^{10} k_i I_{bf}^{11-i}} + k_{11} \log I_{bf} + k_{13} \log I_{arc\_600} + \log \frac{1}{CF} - \log \frac{20}{T}}{-k_{12}}} \quad (18)$$

$$AFB_{2700} = 10^{\frac{k_1 + k_2 \log G + \frac{k_3 I_{arc\_2700}}{\sum_{i=4}^{10} k_i I_{bf}^{11-i}} + k_{11} \log I_{bf} + k_{13} \log I_{arc\_2700} + \log \frac{1}{CF} - \log \frac{20}{T}}{-k_{12}}} \quad (19)$$

$$AFB_{14300} = 10^{\frac{k_1 + k_2 \log G + \frac{k_3 I_{arc\_14300}}{\sum_{i=4}^{10} k_i I_{bf}^{11-i}} + k_{11} \log I_{bf} + k_{13} \log I_{arc\_14300} + \log \frac{1}{CF} - \log \frac{20}{T}}{-k_{12}}} \quad (20)$$

where are:
AFB_{600} - the arc-flash boundary for $V_{oc} = 600\ V$ [mm]
AFB_{2700} - the arc-flash boundary for $V_{oc} = 2700\ V$ [mm]
AFB_{14300} - the arc-flash boundary for $V_{oc} = 14\ 300\ V$ [mm]
T - the arc duration [ms]
G - the gap distance between conductors (electrodes) [mm]
I_{arc_600} - the rms arcing current for $600\ V$ [kA]
I_{arc_2700} - the rms arcing current for $2700\ V$ [kA]
I_{arc_14300} - the rms arcing current for $14\ 300\ V$ [kA]
I_{bf} - the bolted fault current for three-phase faults (symmetrical rms) [kA]
D - the distance between electrodes and calorimeters (working distance) [mm]
CF - the correction factor for enclosure size ($CF = 1$ for VOA and HOA configurations)
$k_1, \ldots, k_{13}$ - the coefficients regard to [1]

(8) The final arc-flash boundary values are calculated using the next relations:

$$AFB_1 = \frac{AFB_{2700} - AFB_{600}}{2.1} (V_{oc} - 2.7) + AFB_{2700} \quad (21)$$
$$AFB_2 = \frac{AFB_{14300} - AFB_{2700}}{11.6} (V_{oc} - 14.3) + AFB_{14300} \quad (22)$$
$$AFB_3 = \frac{AFB_1}{2.1} (2.7 - V_{oc}) + \frac{AFB_2}{2.1} (V_{oc} - 0.6) \quad (23)$$

AFB_1 - the first AFB interpolation term between $600\ V$ and $2700\ V$ [mm]
AFB_2 - the second AFB interpolation term used when V_{oc} is greater than $2700\ V$ [mm]
AFB_3 - the third AFB interpolation term used when V_{oc} is less than $2700\ V$ [mm]
V_{oc} - the open-circuit voltage (system voltage) [kV]

III. ARC FLASH CALCULATION

There are the following switchgears in the 110/20 kV HV/MV substation that is in Austria: 110 kV switchgears, power transformers 110/20 kV, earthing transformers and auxiliary transformers and MV switchgears. The real danger of arc flash exists only in rooms of MV switchgears.

110 kV switchgears are three-pole shielded GIS, and, in the event of a fault, there is no danger of the arc spreading outside the GIS.

Earthing transformers and auxiliary transformers are in a room where personnel do not stay, and rooms have large dimensions of 10.5 x 9.0 x 10.4 m. In case of transformer failure, i.e. failure of the cable terminations, there is no risk of high pressure.

There is a real danger of arc flash in rooms of MV switchgears and arc flash calculations need to be carried out.

If it is observed the design of the MV switchgear that will be installed, Figure 1., it contains three compartments in which there are live parts:

A – Switching-device compartment
B - Busbar compartment
C – Connection compartment

From experience with similar MV switchgear, the probability of arc flash in A and B compartments is very low. The highest probability of failure is in the C - Connection compartment, i.e. at the cable terminations. Therefore, the calculation will be carried out for the C - Connection compartment.

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The dimensions of the C compartment of some switchgears are approx. 80 x 70 x 114 cm. Input parameters are in Table I. Results are in Table II.

TABLE I

INPUT PARAMETERS

Input parameters	
Configuration	1 VCB
Three-phase bolted fault current	13.537 kA [5]
Gap between conductors	160 mm
Working distance	914.4 mm
Enclosure dimension	
Width	800 mm
Height	1140 mm
Switch off time*	395 ms

TABLE II

RESULTS

Results	
Lower Boundary Arcing Current:	12.62 kA
Incident Energy:	6.01 cal/cm^2
Incident Energy:	25.14 J/cm^2
Flash-Protection Boundary	2554.54 mm

The dimensions of the C compartment of anothe switchgears are approx. 100 x 70 x 114 cm. Input parameter are in Table III. Results are in Table IV.

TABLE III

INPUT PARAMETERS

Input parameters	
Configuration	1 VCB
Three-phase bolted fault current	13.537 kA [5]
Gap between conductors	160 mm
Working distance	914.4 mm
Enclosure dimension	
Width	1000 mm
Height	1140 mm
Switch off time*	395 ms

TABLE IV

RESULTS

Results	
Lower Boundary Arcing Current:	12.62 kA
Incident Energy:	5.84 cal/cm^2
Incident Energy:	24.42 J/cm^2
Flash-Protection Boundary	2507.58 mm

*Switch off time includes relay protection setting time (300 ms), relay operating time (20 ms) and circuit breaker break time 75 ms.

The obtained value is greater than 1.2 cal/cm2 = 5.024 J/cm2 and less than 12 cal/cm2 or 50.24 J/cm2. According to [3] PPE 1 is required. In accordance with the calculated incident energy values, labels should be affixed to all fields in the MV plant as shown in Appendix.

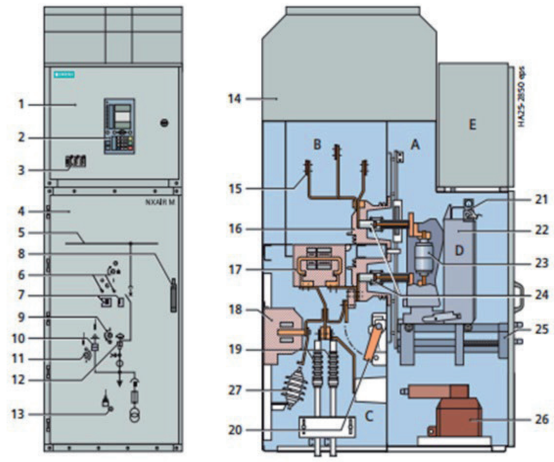

Fig. 1. Basic panel design – circuit-breaker panel [6].

IV. Conclusions

The paper is focused on arc flash calculations. Implementing proper safety measures, such as regular maintenance, using arc-resistant switchgear, and ensuring proper training and use of personal protective equipment, can significantly reduce the risk.

Compliance with standards IEEE 1584: 2018 [1],[2] and NFPA 70E: 2024 [3] is crucial for ensuring safety and minimizing arc flash hazards.

Results of arc flash calculation show that critical incident energy can be expected in the C compartment of all MV fields. Slightly smaller values can be expected in another MV fields due to the larger width.

If the medium-voltage switchgear will be equipped with pressure relief duct and meet internal arc classification according to IAC A FLR for all short-circuit currents up to 25 kA and an arc duration of 1 s arc flash labels are not required.

References

[1] IEEE Std 1584: 2018 IEEE Guide for Preforming Arc-Flash Hazard Calculation.

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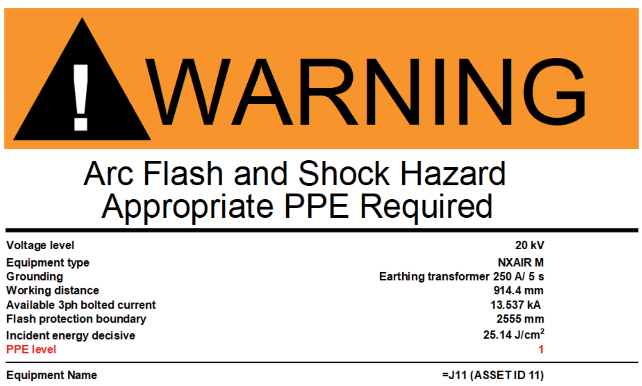
[5] A. Tokić, V. Milardić, "110/20 kV HV/MC substation", Short Circuit Study, AT-VIE017-Z-XX-SIE-CA-E-61101, October 2024.

[6] Medium-Voltage Switchgear Type NXAIR M up to 24 kV, up to 25 kA, Air-Insulated, Catalog HA 25.75 2024.

Appendix



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