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EXAMINATION OF CONDUCTIVE CLOTHING FROM THE ASPECT OF ARC PROTECTION

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SUMMARY

On high voltage, the use of bare-hand method spread out in Hungary, based on the development of Dr. Béla Csikós in the end of the 1960s. Through his work, the live-line maintenance technology was developed as the forth all over the world to the Hungarian 120 kV, 220 kV, 400 kV and 750 kV transmission lines. One of the essential equipment needed for the that working technique is the conductive clothing, which exempts the wearer from the electric field in the vicinity of high voltage parts of the network. The basic requirements about the conductive clothes are included by the IEC 60895 [1], in which there is no criterion for the arc protecting ability of the cloth.
Basically with regard to the national regulations, significant differences can be found in case of various nations on the field of arc protection on low and medium voltage systems also.
While these works are carried out in the close environment of high voltage systems during live-line maintenance, in which the probability to occur a flashover or sparkover is low because of the well-defined working techniques and clearances, despite this unfortunately in the past serious accidents happened, which raise the question about the necessity and usability of arc protection during that work. Another questionable case would be the installation of portable protection air gap (PPAG), in which the power line worker is in the close vicinity of an equipment, of which the operating principle to form dielectric breakdown of the air.
The paper highlights the arc protectional point of view of the live-line maintenance on high voltage systems especially about the conductive clothing, and examines the usability of related regulations, guidelines.

Introduction

Worldwide many live line working techniques were developed for the electric distribution and transmission network as well, to keep the network reliable and do not causes power outage for the consumers as well, in fact, the device or segment of the network is live during the repair or maintenance. This kind of work needs increased requirements and criterion regarding to the employees, trainings, tools and technologies compared with the de-energized works, but the advantages of these works are reflected in not only the financial and technical aspects, but in the occupational safety also. This special kind of work can be done in high voltage systems based on general methods – namely hot stick method or bare hand method –, but the basic principle of the use of tools are similar in the most cases, such as the various platforms and conductive clothes, in turn the exact working technologies and practice can be different in case of the different nations. During this kind of work, not only the possibility of on electric shock must be excluded, another thing to take into consideration the possibility of the occurrence of an electrical arc flash [2, 3, 4]. If it is required, steps have to be done to use the proper arc protection, and within this task to define the adequate personal protective equipment for the worker in the vicinity of an eventual arc flash. For that selection, the knowledge of the level of hazard is essential, which can be done via the use of standardized methods.

Existing methods for calculation of incident energy on high voltage

In case of low and medium voltage levels (approximately below 1 kV and 35 kV, but it can differ in each nations and regions) several existing methods are available for the calculation of the incident in the vicinity of an electric arc such as the followings according to the American OSHA regulation [5, 6, 7, 8]:

- NFPA 70E – Lee equation
- Doughty, Neal and Floyd
- IEEE 1584 standard
- ARCPRO software

In addition other alternative calculations are also available, such as the calculation method shown by French authors' [9]. The Electric Power Research Institute among others has written a research about "arc flash issues in transmission and substation environments" [10], in which via a comprehensive overview it is showed, in case of high voltage systems – such in case of the Hungarian and also in European nominal high voltage levels, 120 kV, 220 kV, 400 kV and 750 kV – the most of existing methods are not applicable to high voltage levels and with long arc gaps regarding to the incident energy. Our aim is to develop a mostly theoretical – not empirical model from the aspect of geometric arrangement, which means not with the use of direct measured method of incident energy in the environment of an electric arc – calculation method of incident energy at any point in the environment of an eventually initiated electric arc in high voltage system, in case of bare hand method also.

Developed method

A main purpose was to develop a method which is usable in case of high voltage networks, where the length of the arc – which is approximated by the gap length, in between the electric arc exists, therefore the meandering behaviour is neglected – can be several meters, like the power line worker's distance from the arc. In this case the arc cannot be modelled like a point heat or energy source [11].

Basically the method contains several steps. The input parameters are the following:

- Bolted fault current of the network at the assumed point of arc initiation, as the arc current

- Duration of the arc: basically it depends on the operational characteristics and adjustments of the protective devices of network. It is commonly regulated by the national safety code of live-line maintenance. For example in case of Hungary, during live-line maintenance the maintained segment of the network must be in a special condition, so-called “hold-off state”, with special adjustments of protective devices. It means that reclosers are deactivated and the tripping time is immediate.
- The geometrical arrengement of a situation, in which the arc initiation is expected, included the arc gap length and the worker’s exact position from the arc.

Assumptions of the model:

- The power factor of electric arc is 1, that means the arc is a resistive part of the circuit.
- In case of high voltage systems, the voltage of an electric arc is negliegable compared to the nominal voltage of the network, therefore the bolted fault current is assumed to be equivivalent with the arc current in contrast to the case of low and medium voltage levels [7].
- During the definition of the duration of the electric arc, only the primer arc is taken into consideration from the initiation to the switching off the fault.
- The medium around the electric arc is lossless from the aspect of heat transfer. It is not the same with some approach, when it is assumed the heat is only emitted by radiation.
- The total energy of the arc is emitted, the additonal energy consuming phenomena are neglected, like the vaporization of electrods and the heating of the vaporizated metal.
- The energy is emitted to the environment in all the direction

The first step of the methodology is to collect the input parameters accoding to the properties of the examined electric network. After that the voltage of the arc have to be calculated according to the literature. In an article from Goda [12], measurements were shown about the voltage gradient of electric arc in a 3.4 m long gap up to 50 kA.

$$U_{arc} = \left(0{,}95 + \frac{0{,}005}{I}\right) * l$$

(Equation 1)

I: arc current [kA]

l: gap length (m)

That was the first used equation in addition to the EPRI research [10], were also empirically developed equation was shown about the voltage gradient.

$$U_{arc,rms} = \frac{(0{,}000012 * G^{-8} + 1{,}19 + (0{,}0069 * G^{-1{,}239} - 0{,}0126) * I_{arc}) * G}{1{,}1255}$$

(Equation 2)

$U_{arc,rms}$: arc voltage [kV, rms]

G: gap length [m]

I_{arc}: arc current [kA]

With the use of calculated voltage of electric arc in function with the arc current and the gap length, the total energy of the electric arc can be defined, it is the multiplication of the arc current, arc voltage and the duration.

$$E_a = I_{arc} * U_{arc} * t$$

(Equation 3)

E_a: total generated energy in the arc [J]

I_{arc}: arc current, same as the bolted current [A, rms]

U_{arc}: calculated arc voltage [V, rms]

After that the total energy is calculated, the electric arc has to be geometrically converted to a line energy source, in which the sum of the homogeneously divided heat energy is equal to the calculated arc energy. During the calculation, the line energy source is devided to infinitesimal point energy sources, and the main principles of calculation are the following:

- The point sources emits the energy in all direction
- The energy of any point is devided on a sphere with equal radius to the examined point
- The volume is lossless from the aspect of heat transfer

According to these, the effect of all of the point energy sources can be summarized in the examined point, and that will be the estimated incident energy.

Correction factors

Because of the assumptions and neglects of the basic model, corrections have to be done because of the physical processes and stochastic behaviour of an electric arc. It is well known, the electric arc meanders, especially if we think of the long electric arcs. After the dielectric breakdown of the air, the arc getting bigger, it starts to meander as it is shown on the 3. Figure, which is from the EPRI study [10]..

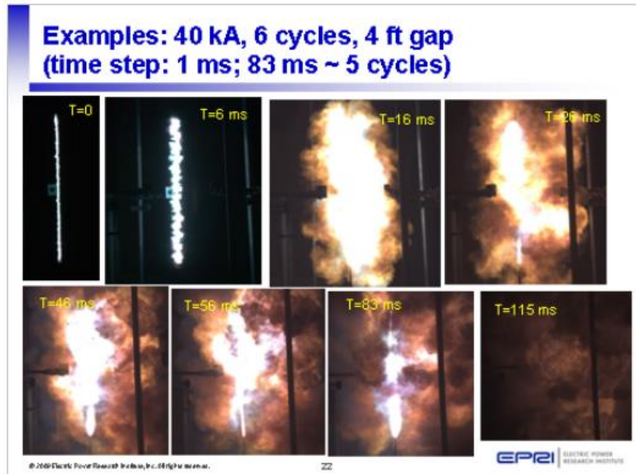

Fig. 3. Behavior of a high voltage and high current electric arc with approximately 100 ms duration [10]

As it can be seen, the initiative properties are not valid ever, like the distance from the arc. To take into account this phenomenon, the model take into consideration that change in the arrangement via the use of two line energy sources instead of one, which is used at the initiative condition. The modification in the arrangement is done after the first 20 ms. The correction is based on the radius of the dielectric arc in addition to the meandering behaviour. Because of that the cross section of arc and the electromagnetic forces – which also affect the path of the arc – are changing in function of the arc current as well, therefore the proper correction also depends on the current. For the definition of the radius of an electric arc the existing methods give various results, but these methods have different limits. Because of that the following formula is the base of the correction [13]:

$$d = 0{,}041 * \sqrt{I} - 0{,}18 \qquad \text{(Equation 4)}$$

d: radius of the arc [cm]

I: arc current

In case of the definition of geometrical places of two line energy sources – which represent the total generated energy of the electric arc – this calculation estimate the extension of the electric arc. Because of the meandering behaviour, in case of vertical gaps, this calculation method should be used until 100-200 ms duration. In hundreds of miliseconds, probably the electric arcs path can be significantly different from the initiative state, moreover in case of horizontal gaps.

Validation with measured values

For the validation of the model, hundreds of measured value was used, which were available in the EPRI study about arc flash [10]. In these cases the exact properties of the arrangements were shown:

- Used arc currents: 8, 20, 40 kA
- Arc durations: 33 ms, 100 ms, 200 ms
- Gap lenghts: 1, 2, 4, 5 ft

During the measurements, calorimeters were placed in various places, and in case of the validation, calculations were done for each exact measurement for each sensor, based on the measured current (RMS) and duration. In each case, the incident energy calculation was done with the use of eq. 1. and eq. 2. as well, and the higher value was chosen to achieve higher safety.

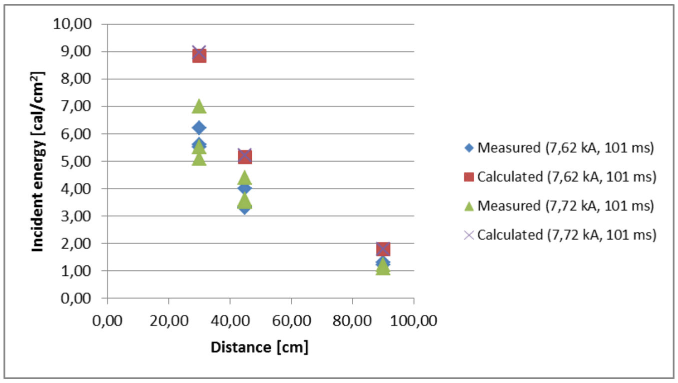

Fig. 3. An example comparison of the measured and calculated values – 4 ft gap distance, at the center line of the arc

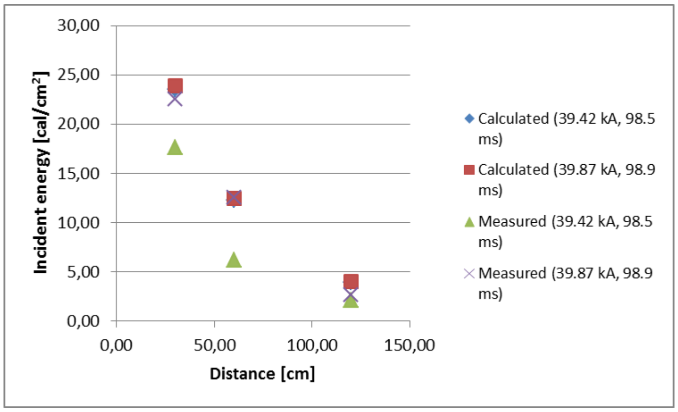

Fig. 4. An example comparison of the measured and calculated values – 4 ft gap distance, at the end line of the arc

The evaluation contains more than 500 measured energy values, and the following conclusions can be maden based on them:

- In case of the use of stainless steel and aluminium electrodes, the calculated values are consequently 1-2 times higher than the measured values
- In case of graphite electrodes, the calculated values are consequently 3-5 times higher than the measured values

Case studies

I. Flashover on hot stick

The motivation of this case study to make an evaluation about two accidental arc initiations, which were happened in 1997 and 2002 in Canada, during live-line work on 500 kV AC transmission line.

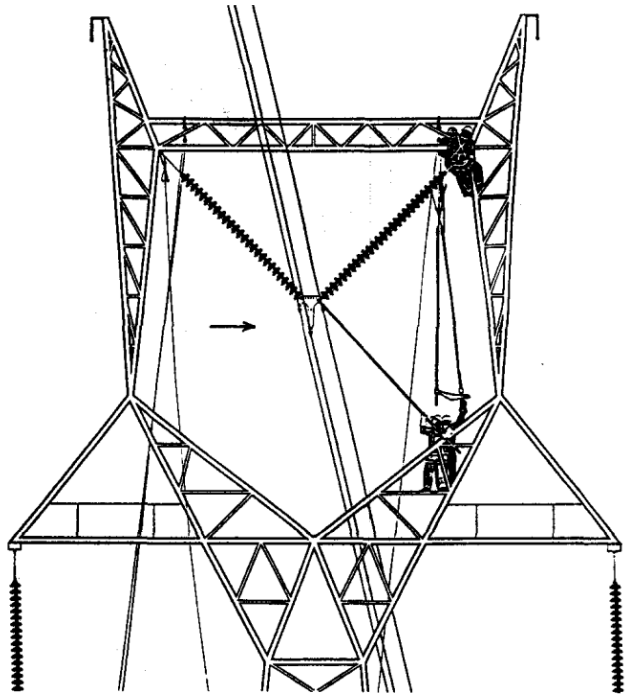

Fig. 5. The arrangement of the situation when an FRP hot stick was flashed over on 500 kV [4]

The arrangement of the situation can be seen in the Figure 5.. The lineman was standing in the window of the tower and holding a hot stick to the center phase, when the used fibreglass re-inforced plastic (FRP) rod (hot stick) – with 4,88 m of clear insulation– flashed over. The phase bundle contains of three sub-conductors, having diameter of 33-35 mm and spaced at 457 mm [1, 2, 3].

Input parameters of the calculation:

- Arc current: 5,8 kA peak, 4,1 kA rms
- Arc length: 3,5 m
- Primer arc duration: 50 ms
- Position of the arc is on Figure 5.

Based on the input parameters of calculation, the calculated arc voltage with the use of equation 1 and 2, and the total generated energy:

- eq I.: 3.325 kV rms, 681.625 kJ
- eq II.: 3.558 kV rms, 729.5 kJ

For the calculation of the incident energy it was expected the end of the arc was 10 cm away from the nearest point of the power line worker. In this case the calculated incident energy is 2.55 cal/cm^2 (based on eq. 1.) and **2.73 cal/cm^2 (ep. 2.)**. It has to be noted, the magnitude of the bolted fault current significantly depends on the place of the work on the power line. In case of 10 kA,rms bolted current the calculated incident energy with the same circumstances would be 6.23 cal/cm^2 (ep. 1.), **6.28 cal/cm^2 (eq. 2.).**

Case studies

II. Use of portable protective air gap

To carry out live line works on novel high voltage networks can be a difficult task from many aspects. One of them is the reduced distances, why new technologies and equipment are needed for the work, not to violate the required clearances. The portable protective air gap is an overvoltage limitter device, which works like a spark gap [14, 15, 16]. By the use of this device during live-line work, the minimal approach distance can be reduced by the reduction of transient overvoltage (TOV). During the installation, after that the high voltage electrode is connected to the phase conductor, finally the grounding take place with the use of a hot stick manipulated by a power line worker, and during the remove of the device, firstly the grounding is disconnected. In these cases the worker is close to the device, in which the occurring of the dielectric breakdown is the basic principle of working. The question is that how high is the estimated incident energy at the assumed place of the worker.

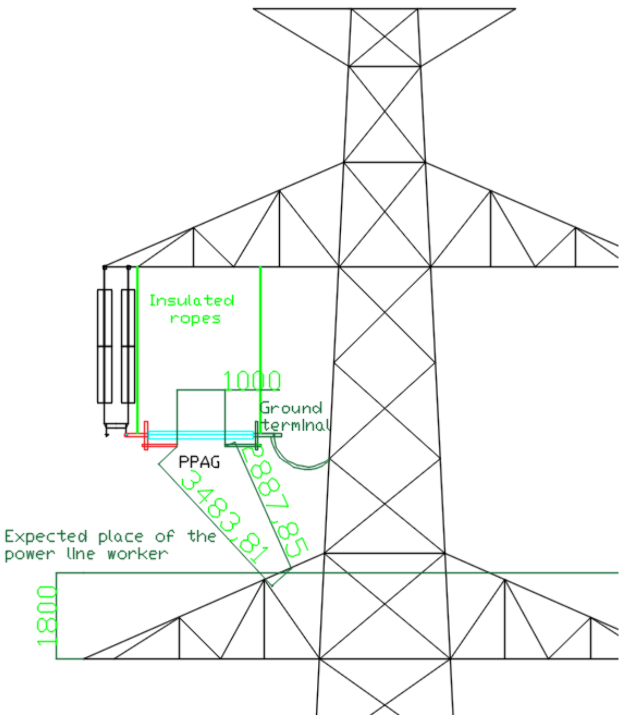

Fig. 6. Installed PPAG on a 400 kV double circuit high voltage tower

The arrangement of the installation can be seen on the Fig. 6. with one of the theoretically possible place of the worker. The dark green line shows the height of the power line worker, which is 1800 mm. The gap distance of the PPAG is 1000 mm, and it is suspended to the arm of the tower. The calculated incident energies can be seen in the following table.

	Arc voltage [kV]		Total energy [kJ]		Incident energy [cal/cm]	
Curr.	**eq I.**	**eq II.**	**eq I.**	**eq II.**	**eq I.**	**eq II.**
10 kA	0,95	1,006	950,7	1006,9	0,185	0,196
20 kA	0,95	0,956	1900	1912	0,371	0,373
40 kA	0,95	0,854	3801	3419	0,742	0,668

Case studies

III. Flashover during insulator changing

The use of composite insulators is spread worldwide, instead of glass and porcelain insulators, but not only the construction of the insulator has been changed, but many times the length of the insulator also. Sometimes the length of insulators and the gap distance between the corona rings are smaller than the required minimal approach distance. This case study has been done to examine a situation, when a new type of insulator is being changed in live condition, and a flashover occurs on the added relieving insulators surface. It has to be highlighted: this case study can be useful from the aspect of arc protection, and to show the magnitude of an occurring flashover in case of bare hand method, but not because of the exact arrangement and technology. The showed insulated moving is based on the old Hungarian practice, developed by Dr. Béla Csikós, and it has to be noted, there were no accidents in the past during the use of it [17].

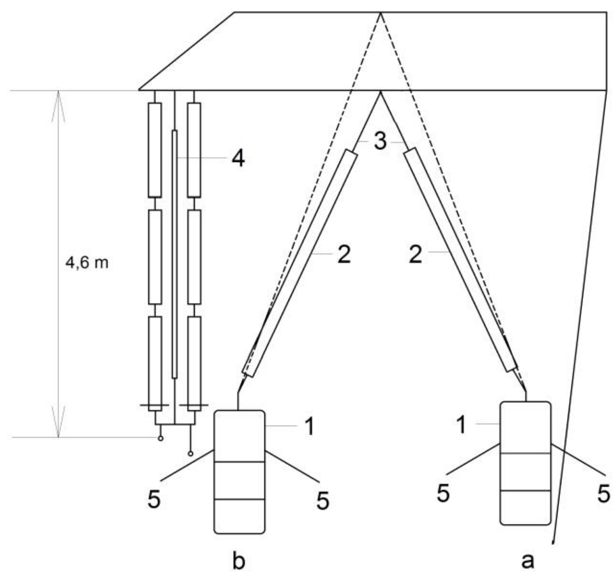

Fig. 7. Insulated moving by Dr. Béla Csikós's technology on 400 kV [17]

In this arrangement, the power line worker is sitting in a so called mounting chair, which is suspended by an insulator to the arm of the high voltage tower structure. The working position is the position "b", close to the fittings of the insulator. In this case it is assumed, a flashover occurs on the insulator marked by "4". Because of that the arc current depends on the properties of the line and the system, the calculation was executed for 10, 20 and 40 kA arc currents. The duration of the primer arc is assumed to be 100 ms. The length of the arc is 4 meters, and the vertical and horizontal distance from the arc was 0,2 m.

	Arc voltage [kV]		Total energy [kJ]		Incident energy [cal/cm]	
Curr.	**eq I.**	**eq II.**	**eq I.**	**eq II.**	**eq I.**	**eq II.**
10 kA	3,8	3,8	3800	3825	**6,1**	6,1
20 kA	3,8	3,4	7600	6843	**12,2**	10,9
40 kA	3,8	2,6	15200	10456	**24,3**	16,7

Conclusion

A new methodology was used to estimate the incident energy in case of high voltage systems, during live-line maintenance in various scenarios with different arrangements, in case of hot stick method and potential work as well.

According to the NFPA 70E 130.7(C)(1), “when an employee is working within the arc flash boundary, he or she shall wear protective clothing and other personal protective equipment” [18]. It means, if the estimated incident energy is higher than 1,2 cal/cm^2, the proper PPE has to be worn by the working personnel. Basically the following conclusions can be taken according to the evaluated cases:

- The magnitude of the occurring incident energy in case of high voltage can be handled with existing arc protective materials
- It is feasible to produce effective PPE for high voltage work also
- In case of the happened incidents showed in the first case study, the power line worker probably suffered higher thermal load then 1.2 cal/cm^2
- In case of the third case study, the estimated incident energy is significantly higher than the 1.2 cal/cm^2 threshold.

The described case studies showed that, in case of the use of bare hand or hot stick method, the use of arc protective clothing can be required, because of that the electric arc can be at a close place to the power line worker, and the arc current can reach several kiloampers.

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