Arc Protection During High Voltage Live Work

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Abstract* – The bare-hand technique is a common work method applied in high voltage power grids. Rules, guidelines, and recommendations must guarantee an appropriate level of protection against electric shock, electric field stress, open flames, and arc flash incident energy. Traditionally, conductive clothing has been used by line workers for protection against electric fields of extra-low frequency. Most conductive clothing designs offer high efficiency as Faraday-cages. Although screening efficiency of a well-designed clothing is high enough to significantly decrease electric fields for prevention against electric shock, other hazards should be addressed. Transmission line geometries may guarantee required clearances between conductive parts at different potentials. However, additional protection measures may be required. Several accidents occurred to line workers using hot sticks, insulating boom trucks, insulating scaffolds, and helicopters. During flashover, the incident energy of the arc may be high and exceed the threshold of a second-degree burn. This requires risk assessment and mitigation of arc flash and other thermal hazards. The most effective way of protecting against electric arcs is the integration of arc protective protection into conductive clothing. The improved design doesn't compromise worker's comfort. This paper presents an example on how to estimate arc incident energy for the transmission network of an electric utility, where protection from electric arcs and flames is mandatory. A procedure for selecting arc-rated conductive clothing is presented. The applications cover bare-hand work, and hot sticking.

***Keywords*—arc protection, live-line maintenance, bare hand method, conductive clothing**

I. Introduction

This paper covers how to protect line workers against arc flash incident energy while conducting bare hand and hot stick work in transmission systems. Historically, there has been a debate on whether arc protection should be accounted or not in these applications. This work intends to address the technical component of arc protection from the point of view of a region with a regulation that states that electric arcs and flammable hazards need to be included. Conductive suit technology can be manufactured as flame resistant and arc resistant. The US has federal regulations 29 CFR 1910.269 and 29 CFR 1926.960 that require employers to protect bare-hand workers against flammable hazards and arc flash hazards. Both regulations include information on how to estimate arc incident energy during bare-hand and hot stick work. After the publication of the regulations in 2014, an electric utility in California filed a request for an exemption of considering bare-hand work not applicable under 1926.960(g)(4). Article (g)(4) requires clothing to be flame resistant (FR) and arc resistant (AR). OSHA ruled that bare-hand work is not exempt from the requirement. Similarly, in 2014 the Edison Electric Institute (EEI) filed an exemption for bare-hand work suggesting that there is no basis for estimating electric arcs that can ignite a material that in turn can ignite the clothing of the employee. In response, OSHA ruled against the statement and gave no exemption. Currently, electric utilities in USA must estimate arc flash incident energy and provide AR/FR PPE [1], [2], [3], [4], [5], [6]. Standard IEEE C2, National Electric Safety Code, regulates electric utility practice in the US. The code is mandated at a State level, and it requires electric utilities to estimate arc flash incident energy for bare-hand and hot stick work under rule No. 410, if the exposure of the employee is greater than 2 cal/cm^2. An arc flash hazard analysis shall be conducted, or the employer can use Table 410-3 (based on clearing times for incident energies of 4, 8, and 12 cal/cm^2). Furthermore, the 2022 edition of NESC will include the necessary arc gaps, minimum approach distances, and distance to arc values for calculating incident energy of single-phase, open air arcs [7], [8], [9], [10], [11].

II. Bare-hand work – Risks and hazards

The bare-hand technique is one of the safest live work practices. However, it is not exempt from thermal hazards produced by open flames, electric arcs, and from the ignition of combustible materials. In the US, OSHA considers testing insulators with a live tool a hazardous arc prone activity as the minimum approach distance (MAD) is encroached. In Europe, regulations vary in a wide range because of the difference between the countries' legal systems; a future common guide needs to be published to harmonize practices (e.g. CIGRE WG B2.87). Table 1 contains a list of examples of typical thermal hazards, their cause, and means of control in the field. It is worth mentioning that arc flash may occur due to human error, equipment failure, equipment manufacturing defects, environmental conditions, lack of training, and deficiencies while planning of the job.

III. Properties of electric arcs

Electric arcs can produce heat via radiation, convection, and conduction. In open air applications with fast clearing time (e.g. transmission systems), most of the thermal energy of the arc is radiated. Radiated energy can heat up the surface of the body of a worker, ignite the clothing, and cause burns. Therefore, flame resistant (FR) and arc resistant (AR) clothing is the best protection against thermal hazards. ASTM F1506 is a standard that ensures that garments are FR and AR. The standard has pass criteria for the vertical flame test ASTM D6413 (Figure 1a), and for the fabric arc test, ASTM F1959 (Figure 1b). ASTM F1506 gives an arc rating to the garment, in cal/cm^2, which is the arc thermal performance value (ATPV) or the energy breakopen threshold (EBT). ASTM International is currently developing a new standard specification for flame resistant and arc resistant conductive clothing.

TABLE 1 – THERMAL HAZARDS AND CONTROLS DURING BARE-HAND LIVE WORK

	Hazard	Cause(s)	Controls
	Hazards related to conductive clothing		
A	Overheating and ignition of conductive clothing - General	Broken/non-continuous fabric threads High resistance between fabric threads Inappropriate laundering	Wear AR/FR clothing Visual inspection of clothing Field continuity measurement of bonding Regular measurement of bonding resistance at shop Compliance with industry standards Follow washing instructions
B	Nearby arc flash melts conductor/equipment and hot metal droplets fall onto clothing	Equipment failure Accidental dropping of tools/hardware Breaking of conductors, shield/guy wires	Wear AR/FR Clothing Manipulate/secure tools with caution Check equipment alarms Use safety nets to catch fallen conductors
C	Bonding issues cause capacitive current to flow through the worker	Loose, missing, or inappropriate worker bonding to live conductor may cause capacitive current to ignite the clothing	Visual inspection of suit and line hardware Bond to a live conductor with a wand connected to aerial lift first Verify worker is bonded to aerial lift grid, and that grid is properly bonded to conductor
D	Conductive suit is contaminated with flammables	Tracking and arcs can ignite flammable vapor or flammable contaminants on conductive suit (E.g., hydraulic fluid, wood pole resin, insect repellent, gasoline)	Visual inspection of suit components Replace suit components as needed during work based on level of contamination Use approved insect repellent Follow washing instructions Periodical testing
	Hazards related to failures in the grid		
E	Switching transients cause insulator flashover	No TOV study available Line transients exceed TOV study prediction Line breaker reclosing function is not disabled	Test for minimum number of good insulators that matches maximum TOV Use PPAG Block line reclosing function Avoid system switching during work Add line arresters Wear AR/FR conductive clothing
F	Live conductor breaks and it contacts a grounded item; shield wire breaks and contacts live conductor	Visual inspection lacks criteria for level of acceptable mechanical damage of tower/hardware Polymer insulators with weakened inner rod are difficult to assess Inadequate use of mechanical equipment	Assess extent of mechanical damage with a visual inspection and field guide (e.g., acceptable quantity of conductor broken strands) Use safety nets/ropes to catch broken conductor(s) Check conductor tension with sag tables in drawings; consult engineering
G	Insulator flashover	Manufacturer defect Mechanical overloading Contamination causes a conducting surface across the insulator High TOV System switching	Perform visual inspection with field guide Test insulator with a live tool Clean insulator Block reclosing function Prohibit line switching operations Use PPAG Wear AR/FR conductive clothing
H	Arcs produced by interrupting a line loop	Arc extends and moves towards worker; risk of heat exposure or electric contact	Do not cut line loops if they carry more than 5 A If interrupting greater than 5 A, use a portable line switch Adjust worker positioning Wear AR/FR conductive clothing
	Hazards related to technology or equipment		
I	Ignition of hydraulic fluid of aerial lift and insulating boom	Boom contamination Vacuum/leaks in hydraulic lines Hydraulic fluid aging/contamination	Wear AR/FR clothing Perform pre-job aerial test Monitor boom leakage current online Perform regular hydraulic fluid sampling, testing, and analysis Periodical testing
J	Flashover of insulating live tools (e.g., ladder, hot stick, live rope, conductor cradle)	Manufacturing defect Inadequate testing or storage of live tool Mechanical overloading Contamination	Perform regular testing of live tools Acceptance and periodical tests in independent laboratory Check loading instructions Clean live tools

		Environmental conditions Flying debris	Suspend work during rainy, foggy, and other conditions Wear AR/FR conductive clothing
Hazards related to weather or environment			
K	Weather conditions cause flashover Failure to maintain MAD	Low barometric pressure, temperature, and humidity may reduce insulation properties of insulators and live tools Old line designs with very low clearances Distraction, fatigue Wind moves aerial lift/helicopter towards conductor	Suspend operations due to bad weather Inspect live tools Use insulating sheds on live tools Maintain live tools in weather conditioned trailer Discuss MAD in pre-job brief Use non-conductive tools to measure MAD Add a buffer distance for wind or suspend operations Regulate period of work shifts for personnel to avoid fatigue
L	Flashover produced by lightning	Lightning activity in the area	Check weather conduction forecast prior to work Suspend live work in case weather conditions worsen Wear AR/FR conductive clothing
M	Flying debris cause flashover	Contamination High wind Trash hanging on the line hardware	Perform visual inspection Improved live working tool preparation procedures Suspend operations due to high wind Remove trash/debris on conductor
N	Ignition of wood pole or vegetation	Defective (high resistance) hardware connections exist in the presence of ac induced current, and arcing ignites wood pole or vegetation Smoke/heated air is conductive and could cause flashover	Visually inspect pole hardware prior to climbing or commencing work Measure continuity of structure grounds Cut a clear buffer of no vegetation around the base of the wood pole Carry water container/extinguisher for fire mitigation

CIGRÉ has recently started working group B2.87, which will provide guidelines and collect international regulations for PPE used for bare-hand work. Electric utilities can also arc test complete garments using the manikin test, ASTM F2621 (Figure 2). In this test, the garment can be evaluated for ignition, melting and dripping of garment components, and evaluation of clothing indicators. The target arc incident energy can be setup under 120% of the rated ATPV/EBT value of the garment label. Components of importance are fabric, zippers, snaps, visibility enhancements, trim, thread, and heraldry. Other standards, such as IEC 60895:2020, evaluate flame retardancy, but do not include arc performance. The flame retardancy test per IEC 60895:2020 is like ASTM D6413 in terms of assessing resistance to ignition [12], [13], [14]. Per OSHA/NESC, the arc flash boundary (AFB) defines the area around a live conductor where AR/FR clothing is required while conducting live work. Outside the AFB, AR/FR clothing is not required. AFB is defined as the area where the incident energy at the body of the worker is 2.0 cal/cm^2 or greater. Some electric utilities use a more stringent value, 1.2 cal/cm^2, based on the Stoll curve, or onset of a second-degree (curable) burn. The US Department of Energy (DOE) adopted NFPA 70E which uses 1.2 cal/cm^2 for arc flash boundary and State-owned electric utilities shall abide by that value [15], [16].

Fig. 1a, 1b – Examples of conductive fabric samples exposed to a vertical flame test

Electric arcs produce arc jets that can melt and evaporate the metal of the electrodes. Droplets of hot molten metal are propelled and could ignite clothing upon contact. In transmission system applications, more research is needed to better estimate the incident energy of electric arcs. EPRI conducted a study on long arcs. The study concluded that long arcs are comprised of five regions. Two regions are ionization and vaporization of the metallic electrodes, two regions are due to the arc jets (low voltage gradient), and one central region corresponds to the free arc (low voltage gradient). A model for incident energy was produced, but it is preliminary, it is not ready for field application [17], [18]. There is also a detailed research on the incident energy of electric arcs, especially during high voltage live work, using a novel approach to assess risks [19]. The Kinectrics laboratory in Canada created a semi-empirical model for arcs in open air for arc gap lengths up to 60 inches (1.5 m). The model is based on thermodynamic equations and laboratory testing data. The model was used by OSHA and NESC for estimating arc incident energy for systems up to 765 kV AC. These regulations use reduced arc gap lengths that when applied to the model, provide an acceptable but conservative arc incident energy value. For example, a transmission line rated at 345 kV with an insulator string of 22 bell-type insulators has a dry arc distance of about 126.5 inches long (3213 mm). Similarly, a substation post insulator for a 345 kV bus (e.g. 1550 kV BIL) measures 128 inches (3251 mm) in total length. OSHA/NESC assumes a value of arc gap of 20.9 inches (530.1 mm) instead of using the values of 126.5 or 128 inches. The insulator's physical length is not used in the calculation but instead the arc over distance in an air gap for the respective line-to-ground voltage. In addition, for the distance to arc (worker-to-arc), OSHA/NESC assumes MADL-G minus the arc reach. Arc reach, in inches, is defined as (2 x kVL-L/10) [20].

Fig. 2 – Example of a conductive garment arc test per ASTM F2621

IV. Overview of Arc-Related Accidents

This section covers examples of typical events in which workers have been exposed to arc flash during bare-hand or hot stick work. Flashovers can occur due to the poor condition of the insulating parts of mechanical equipment. In 1980, a bare-hand crew was conducting training on an aerial lift on a high voltage line. A flashover occurred between the conductor and the insulating boom. The cause was a partial vacuum that created ionization after oil leaked from the boom hydraulic lines. The arc caused an explosion that ruptured the boom and one employee fell 75 feet (22.9 m) from the bucket; another worker was paralyzed. The failure was attributed to a design issue. Today, OSHA 1910.269 mandates fall protection harnesses, and worker protection from arc and flames. Also, OSHA 1926.964(c)(12) mandates a pre-flight test and bonding with leakage current monitoring prior to commencing work. OSHA does not have a requirement for inspecting hydraulic lines. However, OSHA and ANSI A92.2 require insulating bucket trucks to be tested periodically every 12 months at a high voltage laboratory. In cases like this accident, hydraulic fluid could fall on the worker's clothing and ignite; FR clothing is needed. Also, the arc can radiate heat towards the worker and cause burns; AR/FR conductive clothing and ASTM F887 arc tested fall protection harnesses are best protection. In 2018, a bare-hand crew was conducting a boom leakage current test on a 500 kV line in Arizona, USA. No workers were in the aerial lift during the test. There was a flashover across the boom and the aerial platform. The job was to remove a jumper between a bus and a disconnect switch. The cause was unknown. The fault current was 65 kA based on oscillography. There was no operation of switching equipment during the failure. During laboratory testing, it was unable to replicate flashover of the same boom from the incident. This case shows that the risk of flashover of insulating booms is not zero. AR/FR clothing is best protection. In 2019, while conducting field inspection in Colorado, USA, an electric utility found issues on truck insulating booms including damage from dragging conductors, surface chipping, and use of decals with company logo. Work was suspended and the trucks were sent for repair and re-testing. Similarly, in 2020 in USA, an instructor noted that a 500 kV insulating boom in a truck had a vinyl logo that covered two thirds of the boom. It was installed by the leasing company. It compromised the safety of the equipment due to risk of arc flash. Live tools can cause flashover if they are not tested, used, or maintained properly. Other causes are design issues or environmental conditions that produce air ionization and tracking. In California, USA (2019) a crew was working on a 500 kV line on an insulating ladder that flashed over. Several workers with AR/FR conductive clothing were using the ladder to access the conductor from the tower and sustained minor injuries. There are several reported accidents in which insulating hotsticks flashed over during live work. Two events happened in 500 kV lines in 1997 and 2002 in Manitoba, Canada. Two events occurred in 230 kV lines in Saskatchewan, Canada, in 2012. In the US, there was an event on a 345 kV line in Texas in 2002, and one event with a flashover on a strain pole on a 500 kV line in California in 2017. In France, an insulating stick flashed over in a substation in Bézaumont in 1995; in 1997, in a substation in Boismorand, two sticks in an insulating scaffold flashed over and caused burns on several workers [21]. Helicopter bare-hand work is not exempt from thermal hazards, too. Future research is needed for PPE improvement. Several incidents include contact with conductor and flashover (e.g., phase-to-helicopter, phase-phase, phase-to-ground). Ignition and fires inside the aircraft during the emergency landing, and subsequent fires on vegetation and in the aircraft after landing/crash are typical. AR/FR clothing is recommended. In the future, integration with other standards such as NFPA 2112 and ASTM F1930 may add extra protection for surviving short and long duration thermal events.

V. Possible Ways of Protection

It is important to develop a field program that encompasses work methods, approved tools, mechanical equipment, and personal protective equipment (PPE). First, for each job task it is recommended to identify the hazards, and assign a level of risk. Then the work method is evaluated, and the hazards are either removed or mitigated with controls. Finally, personal protective equipment shall be selected. Table 1 is an example of hazard identification and the application of controls. Table 2 is an example of calculation of arc flash incident energy in transmission line applications. Table 2 is based on the OSHA/NESC method of calculation. It is based on typical protection clearing times, fault current magnitude, and MAD used by a US electric utility. Other calculation methods are available too. Table 2 shows that for a typical total fault clearing time of 4.5 cycles, AR/FR conductive clothing with a rating of 14 cal/cm^2 covers 230 to 500 kV applications for fault current up to 50 kA. Similarly, if the rating of the conductive clothing is 10 cal/cm^2, all the table scenarios are acceptable except for a fault current greater than 40 kA at 230 kV systems. In that case, a simple solution is to instruct personnel to add 4 inches to MAD (68 + 4 = 72 inches total) to maintain the exposure at 10 cal/cm^2 or under. Currently, there are several designs of conductive clothing in the marketplace ranging between 1 and 11 cal/cm^2. A same rationale may be applied to conductive clothing rated at other values like 7 cal/cm^2, 10 cal/cm^2, etc. (e.g., increase of MAD).

TABLE 2 – ESTIMATED ARC INCIDENT ENERGY FOR BARE-HAND AND HOTSTICK WORK [1]

System Voltage (kV-L)	Total Clearing Time (cycles, 60 Hz)	Total Fault Current SLG 3I0 (kA)	MAD (inches)	Distance to Arc (inches)	Arc Incident Energy (cal/cm^2)
230	4.5	10	68	22	1.86
		20	68	22	4.24
		30	68	22	6.88
		40	68	22	9.84
		50	68	22	13.10
345	4.5	10	110	40	0.85
		20	110	40	1.95
		30	110	40	3.16
		40	110	40	4.52
		50	110	40	6.01
500	4.5	10	143	43	1.09
		20	143	43	2.48
		30	143	43	4.03
		40	143	43	5.76
		50	143	43	7.67

Arc resistant PPE can be applied in different ways. Historically, in regions where arc protection is mandated for bare-hand work like in the US, conductive clothing that was flame retardant only was used on top of non-conductive arc resistant clothing. The main problem is that this solution provides a heavy weight of the garment system to the worker. For example, a worker with flame resistant clothing of 0.24 kg/m^2 (7.0 oz/yd^2) and conductive clothing of 0.31 kg/m^2 (9.0 oz/yd^2) on top will feel an increase of 77% in weight in a combined layer fabric weight. This can jeopardize comfort, and cause heat exhaustion to the employee, especially in hot weather conditions like in New Mexico and Texas (US). Nowadays, there are several designs of AR/FR conductive clothing that can be used stand-alone without the need of an extra layer of non-conductive AR clothing. In applications where there are cold weather and wind chill conditions, it is acceptable to add layers for warming up of the worker. In that case, FR winter liners/underwear can be used underneath the conductive clothing. Another option is to wear AR/FR winter jackets and trousers on top of the conductive clothing (only some manufactures allows it!). The addition of non-conductive AR/FR layers under or over the conductive clothing do not affect the Faraday effect of the suits for attenuating electric field strength. Finally, when working aloft, fall protection is necessary. Currently, there are fall protection harnesses and lanyards that are arc tested per ASTM F887 that become the perfect combination with AR/FR conductive clothing. The harness protects the worker after an arc flash event in case of a fall and makes sure that the harness or the lanyard will not fail mechanically. Per ASTM F887, fall protection systems are arc tested at 40 cal/cm^2 exposure and then a drop test is applied with a standard weight. Harnesses can be used under or over the AR/FR conductive clothing.

VI. CONCLUSION

Bare-hand work is statistically a very safe work practice, but it is not exempt from arc flash and flame hazards. This paper covered examples of multiple field incidents where protection from arcs and flames was needed. Incidents covered cases where there was failure of insulating booms of bucket trucks, hot sticks, and insulating scaffolds. Thermal hazards during helicopter work were presented along with a future need of further research on survival of emergency landing after helicopter accidental contact. Currently, there are conductive suit designs that are flame resistant and arc resistant that become a suitable option for field implementation. Arc flash during bare-hand work is preventable and there are AR/FR PPE options available. PPE can be arc rated per the ASTM F1506 performance specification, where flame resistance is tested per ASTM D6413 and arc rating is tested per ASTM F1959. Furthermore, ASTM International is working on a performance specification standard on conductive clothing. This paper provided a summary of situations where bare-hand and hot stick work could expose workers to arc incident energy and some controls were recommended (Table 1). Furthermore, a method of estimating arc flash incident energy, as interpreted in the US per OSHA/NESC was presented with a working example at 4.5 cycles clearing time (Table 2). If a conductive clothing solution has a limitation due to arc rating based on system fault clearing time and fault current magnitude, there is a possibility to make the clothing be compliant by adding distance to MAD. Finally, AR/FR conductive clothing can be complimented with the use of arc tested fall protection systems rated ASTM F887. Arc

[1] SLG: single line-to-ground fault
Total clearing time: assumed 15 ms relay pickup time, 4 ms protective element time delay, 6 ms relay output, and 50 ms circuit breaker open time, for a total of 75 ms (4.5 cycles)
Arc gap: assumed 13.97 inches for 230 kV systems, 20.90 inches for 345 kV, and 31.75 inches for 500 kV.

protection, as an additional layer of safety protocol while conductive live work may significantly increase the protection and survival of line workers.

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