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Possibilities of Expanding Working Safety during Live-Line and Vicinity Working

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SUMMARY

Live overhead line work has become a popular work method and keeps increasing its use in the industry. However, in some instances maintenance work is carried out on de-energized lines. As vicinity work has less regulation than live work, many serious accidents happened over the last decades. This paper discusses both high voltage live work and vicinity work from personnel safety point of view, and it presents the newest developments and recommendations as part of research in these areas.

Linemen may wear special protective garments when carrying out live-line maintenance and when encroaching minimum approach distances of live lines. During live-line maintenance, conductive suits work as a Faraday cage. They protect workers against high electric field strength. Using conductive clothing allows line workers to perform live-line maintenance of energized networks; the suit guarantees safe and comfortable conditions. The principle of live work (barehand, hotstick) is well-known and strict regulations, standards, and detailed instructions are available for work procedures, but there are open questions regarding long-term effects of electric and magnetic fields. New applications are emerging. Workers must be adequately protected so that the occupational field exposure limit be met. There are two test methods in IEC 60895 to determine the screening efficiency of garments against electric fields. The methods are revied in depth in this article to ascertain which method can be better implemented with best results to ensure compliance.

The magnitude of voltages and currents occur has a wide range of values during live-line maintenance, but also in vicinity work due to the AC induction phenomenon. As the conventional conductive suit is designed to protect against electric fields only during the application of the barehand work method, the clothing can also be adapted for vicinity work. Numerous accidents prove that a conductive suit must be flame resistant, electrically arc-resistant and carry relatively high currents during vicinity work contrarily to live work. With appropriate material and construction, the specially designed conductive garment can protect against electric arcs and induced currents resulting from AC induction phenomena, working as additional personal protective equipment during vicinity work. To verify this specially designed type of conductive clothing, a new laboratory testing method both for the type testing process and at the acceptance level was developed and introduced in this paper in detail.

This paper presents examples of accidents due to AC induction. It also covers importance of protection against electric arcs. The paper shows the difference and the importance of the discrepancy between the screening efficiency inspection methods in the standard from a physiological perspective. It presents a newly developed conductive garment that protects against induced current. Laboratory test methods are explained with a discussion of the design phase and the essential characteristics of the conductive suit.

KEYWORDS

Live-Line Maintenance - Barehand Work - Vicinity Work - AC Induction - Conductive Clothing - Arc Flash

INTRODUCTION

During the operation of an electric system, maintenance can be performed with live work methods or with de-energized circuit methods. The protection of line workers during both work methods is critical. Testing of personal protective equipment (PPE) is not well regulated in the previous case, while the development of the PPE for the latter case is ongoing. First, the paper goes through the safety concerns of live work on high voltage power lines, including the use of conductive clothing as PPE, electric field exposures, and accidents statistics. All these aspects are accounted for proposing changes in the testing of conductive garments for worker safety.
Second, the safety concerns during vicinity working are presented, which were the motivation for the development of a new special conductive suit against AC induction. The laboratory test method is under standardization. Field applications of the new design of conductive garments are presented.

SAFETY DURING BAREHAND LIVE WORK

Barehand is a common live work method used over the world on high voltage power lines. Line workers are bonded electrically with the live phase conductor on which they perform maintenance, while they also maintain adequate distance from other energized phase conductors and grounded structures. To protect the line workers from the physiological effect of high electric fields, conductive clothing is used as a Faraday cage. To investigate how effective the garment shielding is against electric fields (attenuation), conductive clothing is tested and inspected per standard IEC 60895 [1]. However, the screening efficiency measurement (ECC) described by IEC 60895 has some inconsistencies in the testing arrangement, which should be investigated.

Safety concerns during barehand work

During barehand work, the line worker is exposed to the electric field (E). The magnitude of E depends on the line geometry, nominal voltage, and working distance. Conductive clothing is PPE that maintains occupational exposure level on the surface of the body of the worker under recommended limits. An accepted safety directive was published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [2], that determines the occupational electric field exposure level as 10 kV/m at 50 Hz (or 8.33 kV/m at 60 Hz) during an 8-hour work day. The occupational limit is larger than the 5 kV/m limit for public safety. Annual medical examination of individuals facilitates a higher occupational exposure limit compared to the public limit.

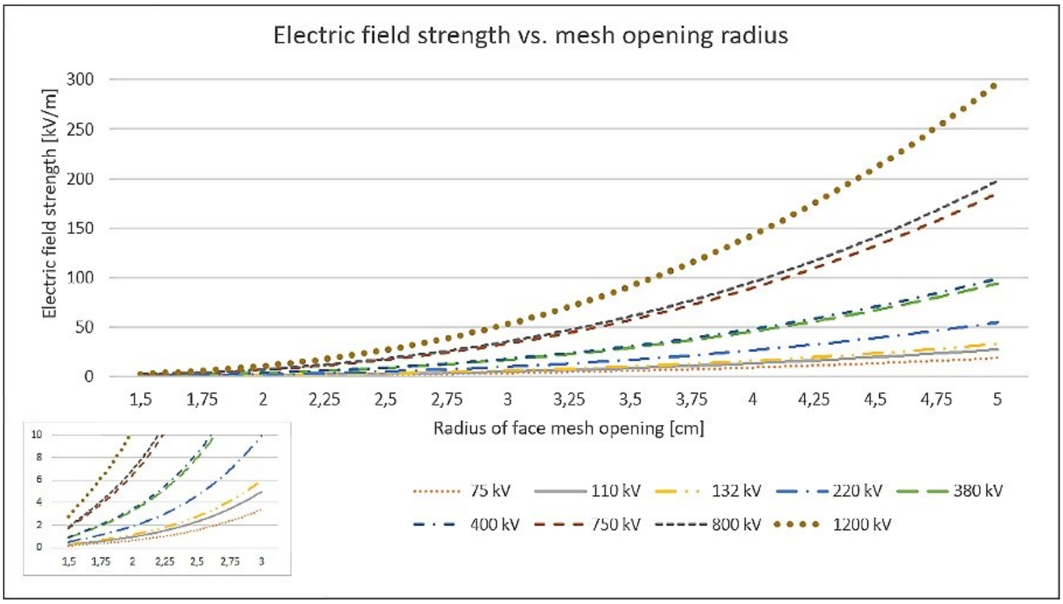

Figure 1. Electric field magnitude at the worker's face based on line's voltage level and radius of the face mesh opening [3]

Conductive clothing designs vary in the marketplace, and several manufacturers offer options worldwide. Designs, materials, accessories, and the overall quality and performance (e.g., resistance, screening efficiency, arc rating) vary in a wide range. From a long-term physiological perspective, the openings of conductive face screens and the coverage of the face area are critical. Finite element simulations are performed to determine whether the magnitude of the electric field exceeds the occupational limit at face of the worker. Figure 1 shows examples of simulations at various line voltage levels for different face mesh designs, from which the size of the critical face mesh opening can be determined. A critical opening of 1.75 cm (0.69 inches) may be applied in the manufacturing process of face meshes to guarantee worker safety at any line voltage level up to 1200 kV. [3], [4], [5]

Barehand work is a very safe practice when compared to other methods such as hotstick work, rubber gloving, and vicinity work. [6] covers examples of accidents during barehand work, and hotstick work on high voltage lines in several countries. As a result, it is beneficial for conductive clothing to be flame resistant (flame retardant) to protect from failure of live line tools [7], mechanical equipment flashover (e.g., insulating aerial lifts) [6], insulating scaffolding flashovers [8], helicopter emergency landing accidents, and others. Some regulations, such as OSHA in the USA [9] and IEEE C2 or NESC [10], require conductive clothing also to be arc rated (e.g., per ASTM F1506 [11]). Arc rated PPE is required at exposures of 2 cal/cm^2 or greater during live work.

Laboratory testing methodologies of conductive clothing

The research group of High Voltage Laboratory is an independent and accredited laboratory for testing of live line tools and PPE. With more than 10 years of experience in conductive clothing inspection, the laboratory identified drawbacks of the IEC 60895 [1] testing process. This standard does not require a face mesh during the test and inspection of conductive clothing, which is critical from the medium- and long-term physiological effects point of view. During screening efficiency inspection, which is carried out to find out how good is a conductive clothing in the shielding of electric field, the established electric field lines for testing are vertical. The electric field lines run parallel with the mannequin face used to simulate the line worker's body. The effect of the face mesh is negligible on the screening efficiency results. Conductive clothing without a face mesh may be able to pass the shielding efficiency test due to this issue. For correcting this flaw in the test, a new methodology for shielding efficiency testing was included in the latest version of the standard (Method 2, Figure 2– right). However, only the original screening efficiency test is mandatory (Method 1, Figure 2– left). Method 2 is optional in the standard [1]. In Method 2, an energized conductor at chest height establishes the electric field for the screening efficiency inspection. In this arrangement, the electric field lines are radial; therefore, they reach the face of the mannequin almost perpendicular. The effect of the face mesh on the screening efficiency with this setup is higher than with the original Method 1. Therefore, conductive clothing can pass the new screening efficiency test under Method 2 only with a face mesh. A revision of IEC 60895:2020 [1] and making Method 2 mandatory is necessary and critical. The measurement arrangements of the two screening efficiency test methods are shown in Figure 2.

Figure 2. Screening efficiency tests of conductive clothing with the original Method 1 (left) and the new Method 2 (right) [1]

Another deficiency of the current shielding testing process of conductive clothing is the roughly defined measuring apparatus and arrangement. During the mandatory screening efficiency measurement with Method 1, not only the design, material and the overall quality of the clothing influence the measured screening efficiency, but the formation of measurement arrangement too. Based on the measured screening efficiency, the conductive garment can be classified into the following three options:

- *Fail*: if screening efficiency is 40 dB or less,
- *Pass as Class 1*: if screening efficiency is between 40 dB and 50 dB, or
- *Pass as Class 2*: screening efficiency is 50 dB or greater.

The classifications determine the maximum voltage that the conductive clothing can be used on. Class 1 type of conductive garments can be used up to 800 kV_{AC}, while Class 2 qualification enables to use it up to 1000 kV_{AC}. Due to the roughly defined measurement arrangement, the classification of the conductive clothing is not unequivocal. To find out how the different parameters in the test setup affect the resulted screening efficiency, six different specifications have been inspected, namely the:

- effect of conductive mannequin type,
- effect of mannequin size,
- effect of insulation between the mannequin and the garment under inspection,
- effect of body current connection,
- effect of face mesh, and
- effect of electrode position.

Laboratory inspections were carried out by two independent measurement groups at different days, while five different types of conductive garment designs from over the world have been included in the sensitivity analysis. The tests were performed at voltage levels of 50, 75, 87.5, 100 and 125 kV. The results carried out at 100 kV are presented. To get a comprehensive picture about the results, the two most significant cases are shown in Figure 3.

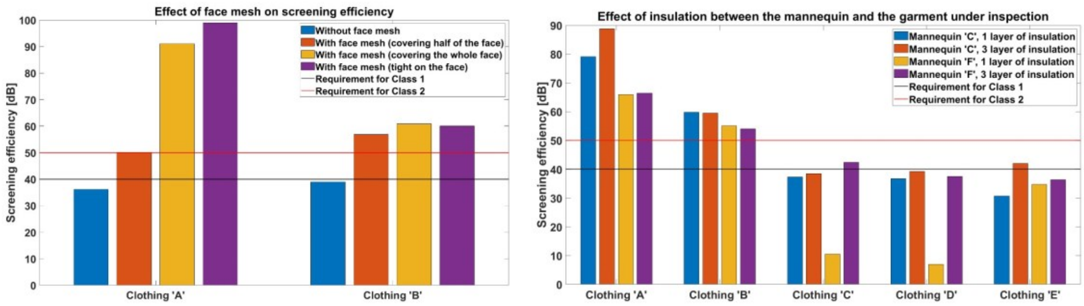

Figure 3. Sensitivity analysis of screening efficiency measurement according to IEC 60895:2020, the most significant parameters

Only a general insight of the sensitivity analysis results was presented in Figure 3. However, the whole test contained hundreds of measurements. The results are summarized in Table 1.

Table 1. Results of the repeatability analysis of screening efficiency measurement according to IEC 60895:2020 Method 1

Effect of …	Deviation range [%]	Effect on screening efficiency
Insulation layers	8-45%	High
Conductive mannequin	4-11%	Medium
Mannequin size	4-13%	Medium
Face mesh	16-38%	High
Body current connection	3-20%	Medium
Electrode position	4-8%	Low

According to the results of the sensitivity analysis, conductive clothing not only can fail or pass the screening efficiency test depending on which laboratory, which apparatus, and personnel performed the

test, but in extreme cases a conductive garment may pass the screening efficiency test as a Class 2 type, while the same garment may fail on the same test at a different laboratory.
Based on results, the following proposals are recommended for the next revision of IEC 60895 [1]:

- Ensure that the conductive mannequin and the garment are similar in size, to reduce its effect on the screening efficiency, and
- Require the use of a face mesh as a mandatory accessory of conductive clothing to reduce the medium- and long-term physiological risk of live work with the barehand method.

Although, some initial considerations during the revision process of the standard formed in the previous points, further evaluation of the results and the elaboration of the revision is in progress.

SAFETY DURING VICINITY WORK

In the case of vicinity work, work conditions and processes are not well regulated compared to live work. Accordingly, work safety is assured by the application of worksite temporary protective grounding (TPG) to form an equipotential work zone (EPZ), instead of using PPE, like conductive clothing in the case of live work. The EPZ is used in order to prevent potential rise due to AC induction. Electric shock due to contacting parts at different potentials is minimized. Properly placement of worksite TPG provides safety, however, accident statistics shows that serious – often fatal – accidents can happen mainly due to human failure, such as the inappropriate application of TPG [12]. In such cases, lack of PPE can result in serious accidents, which was the motivation for the development of a special design of conductive clothing.

Accidents during vicinity work

[12] covers statistics of accidents during vicinity work due to AC induction in USA (81 accidents, 60 workers killed and 33 injured). Today, especially designed conductive clothing exists for AC induction protection. The clothing is designed to maintain a body current of 6 mA or less at a given AC induced current rating (e.g., 50 A), for a given duration (e.g., 30 s). The design is flame resistant. The following are examples of typical AC induction accidents.


Figure 4. Location of AC induction related accidents: crew erecting a transmission lattice tower near a live 345 kV substation in NM, USA (left), crew replacing a 115 kV circuit breaker on a de-energized line that runs parallel with a 230 kV line CO, USA (right)

Case 1 – In 2015 in a substation in Dora, NM, USA, a civil crew was erecting a new 195-foot (60 m) transmission lattice tower 75 feet (23 m) near an energized 345 kV substation yard and live lines (Figure 4 - left). After erecting the 60-foot (20 m) base of the tower, a crew of three climbed the structure and proceeded to aid and align the second lattice section suspended from a crane when they received electric shock due to induced current. The climbers had fall protection and experienced muscle related symptoms due to the shock and alerted the crane operator. They were able to climb down and received medical attention. The crane used a synthetic sling for holding the load. While touching the top lattice structure, the workers became in series with the induced circuit of the two tower sections. As a result, the work practices were modified to add bonding jumpers between structures for this activity. Also, ac induction protective suits may be applied in addition to proper bonding jumpers.

Case 2 – In 2021 in a substation in Colorado, USA, a substation crew was replacing a 115 kV circuit breaker (Figure 4 – right). The 115 kV line had TPG at the substation terminal, and the line ran parallel to an energized 230 kV line for several miles. During work, the TPG had to be repositioned to accommodate and position mechanical equipment. A worker on a 60-foot aerial platform loosened a TPG clamp with his hands with the intent to slide it through and reposition it, without a live line tool. OSHA requires workers to use live line tools [9]. The clamp lost contact with the conductor, and it detached. The worker sustained electric shock due to induced current and had hand-to-hand contact in series. The worker sustained injuries on the tip of the fingers of both hands, where the electric current entered and exited and had to go to the hospital for medical care. The worker had assumed that a visual disconnect from the live substation (circuit breaker and disconnects were open) was a sign of a visual "open" to the line and didn't recognize the risk of induced current on the line through the TPG. The crew suffered from distraction and fatigue from getting the bay ready for another contractor. Typical training in the US covers AC induction hazards in overhead lines and not inside substations. Proper TPG removal with live line tools could prevent this incident. Conductive clothing was not used at the time but could have served as a backup protection and averted the injury. The utility is considering field trials for substation applications in the near future.

Conductive clothing design for AC induction protection

By inspecting the magnitude of induced voltages and currents in the most common vicinity work cases, which is the maintenance activity on the passive side of a double circuit power line, the magnitudes of both the induced current and voltage is dangerous from a safety point of view. Table 2 summarizes field measurements from North America carried out in different configurations of double circuit power lines. The lines consist of different tower configuration, however, the exact type of towers and line loads are sensitive information.

Table 2. Examples of measured induced voltage and current magnitudes during vicinity work [13]

Case explanation	Line nominal voltage	Induced current [A]	Induced voltage [V]
Measurement – both ends open	345 kV	-	18 kV
Measurement – both ends grounded	345 kV	35-40 A	-
Measurement – both ends grounded	115 kV	8-20 A	-

According to Table 2, the magnitude of induced voltage can reach tens of kilovolts without TPG grounding, while the maximum of induced current level can be observed in the case of two TPGs (at the substation or at the worksite), which magnitude is in the range of tens of amperes.

By considering that conductive clothing design is acting as a Faraday-cage, it can protect the worker against induced voltage. On the other hand, the current-carrying capacity of the conductive clothing material should be 1.0 A according to IEC 60895:2020 [1], which is not appropriate for AC induction application. In order to cover the range of induced current in the current-carrying capacity of conductive clothing, a special design with strengthened conductive straps was introduced. The philosophy of the specially designed conductive suit against AC induction, is to shunt the current, which flows through the PPE, while limiting actual body current under 6 mA. The 6 mA current level was chosen according to research carried out in the area of the physiological effects of alternating current [14]. Under 6 mA, there is no loss of muscle control, therefore, this limit is referred as let-go current level. The philosophy of the conductive suit for vicinity work is shown in Figure 5.

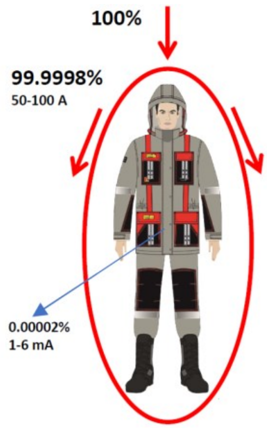

Figure 5. Philosophy of conductive suit designed against AC induction in reducing body current under 6 mA

Laboratory test method of conductive clothing against AC induction

During the laboratory testing of a live working equipment, type, acceptance and periodical testing are defined. While the type testing process can be destructive, until then, the latter two cannot cause any degradation on the tested apparatus. In the case of conductive garments against AC induction, the two-testing philosophy occur. The type testing of an AC induction garment is destructive, as in this case 50 A was injected into the arrangement. See Figure 6.

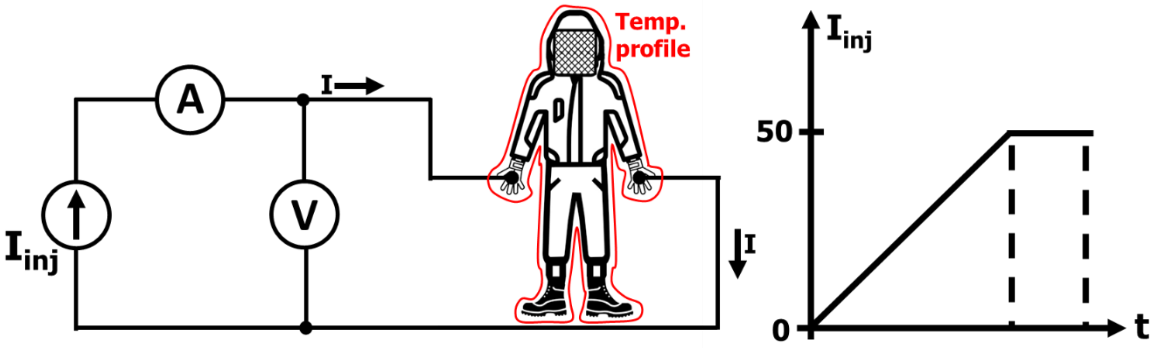

Figure 6. Type test arrangement of conductive garment against AC induction

According to Figure 6, the garment is placed on a conductive mannequin, which has a body resistance of 1000 Ω (representing the human body). Both the current flowing through the mannequin and the garment are recorded on an oscilloscope. The test duration is 30 s, because accidents due to AC induction showed that line workers may need several seconds to disconnect from the circuit. The garment passes the type test if the body current measured on the mannequin does not exceed the 6 mA let-go current limit, while maintaining 50 A injected current for 30 s. While the test current is injected, no flame, ignition or hot spots exceeding 2^{nd} degree burns are allowed during the test.
In the case of acceptance and periodical testing, the previously presented method cannot applied as it is destructive. For that purpose, a new testing method based on 4-wire resistance measurement was established. Based on the precision resistance measurement on the different parts of the clothing (and the contact resistance between the inspected clothing and the mannequin), the body current can be estimated with a current divider model. The laboratory tests showed that the deviation of the estimation regarding the measured body current is in the range of ±5-10%. Both the testing methods are in the standardization process by an ASTM International working group WK70226 in Subcommittee F18.65.

Field application of conductive clothing against AC induction

Case 1 – An electric utility in USA installed a new set of two OPGW wires of 24 pairs of fibres each on an existing 115 kV, 41 miles (66 km) length line in Texas during February of 2022. The line has H-frame wood pole structures with two 5/16" galvanized steel shield wires at the top of the wood poles (Figure 7). It runs through flat terrain on cattle farms with little vegetation. The length of new OPGW conductor to be installed was 4 miles (6.4 km).

Figure 7. Field trial for use of conductive clothing for installing OPGW under an energized 115 kV line with wood H-frame

The job was conducted with a crew of 30 people. The crew used two cranes for loading and unloading OPGW wire and equipment. Also, they used two insulating trucks (rated ANSI/SAIA A92.2, Category A [15]) with aerial lifts (with 18-foot insulating boom and 3-foot insulating insert at bottom of the boom). Seven line-workers donned special conductive suits designed for AC induction protection. The conductive suit design is flame resistant, arc rated (10 cal/cm^2), and rated to sustain 50 A of induced current for 30 s. Each conductive suit is comprised of a jacket, pants, gloves, and socks, all bonded together through braided bands with metallic snaps [15]. Weather conditions during work were sunny, windy, with a temperature between 30 to 40 degrees Fahrenheit. The work was performed in one week timeframe and there was snow (up to 12 inches) and thawing conditions.

A month before work, the company conducted a 2-hour session for introducing line workers to the concept of the suit and then a 4-hr training with demonstration was carried on with a classroom of 30 attendees. The course's curriculum included philosophy, use, inspection, care, and maintenance. It also included analysis of a few field ac induction incidents and general industry accident statistics [12]. The procedure of using the special suit was presented as secondary protection when line workers perform vicinity work and follow traditional industry [16] and company TPG practices. Workers were told during the training that TPG is the main (primary) control for protection. At the eventuality of equipment failure, or human error in work methods, the suit would provide additional protection against induced current.

First, during work the crews installed the angle dollys and other hardware ("R" type through bolts, etc.) on the wood poles in the tower structures for four miles. Then equipotential zones (EPZ) were established by bonding the angle dollys to the wood pole grounding conductors; a temporary jumper with a duckbill clamp was added between the exposed 3" of the "R" bolt to the pole grounding conductor. Later, once the OPGW was strung, the temporary bond between the R bolt and the wood pole grounding conductor was replaced with a fixed connection comprised of a "C" type crimp on each end of a new airplane type cable (1/4" winds line) of galvanized steel, fine braided.

Second, the new OPGW was installed starting at a central location and it was strung on both directions through the angle dollys towards the line ends (about two-mile runs each way). The angle Dolly design had Neoprene in the body of the wheels, so they were not conducting (insulating). While the conductor was being strung, six locations throughout the line had running grounds bonded to an anchor rod driven to the ground. Master TPG grounds (full fault current rated) were placed at the middle point of the line, and at both ends of the OPGW. Each master TPG set was connected from an anchor rod driven on the ground to each OPGW; then the anchor rod was bonded to the wood pole grounding conductor.

During the work, the crews measured how much induced current was flowing through the OPGW wire (Figure 8). The crew used a fork type ammeter mounted on a hotstick on the TPG jumpers and measured 1.5 A. That was the result of a "loop" of approximately two miles between two master grounds, OPGW wire, and soil. The OPGW wire was positioned approximately 15 feet (4.6 m) under the live phase conductors. The OSHA limit for requiring controls for induced current and voltage is when the worker exposure exceeds 6 mA, according to regulation 29 CFR 1910.269(q)(2)(iv) [9]. The reading of 1.5 A exceeds the occupational limit by 200 times. Therefore, TPG and special conductive suits were used as controls for worker exposure.

Figure 8. Measurement of AC induced current (1.5 A) with a live tool and a fork type ammeter on the TPG

It is not recommended to monitor induced current for work purposes as the level of current changes per phase conductor, and throughout the day. Therefore, no assumptions should be made based on readings. It is shown for illustrative purpose of this paper. Induction shall be treated as present no matter what values are recorded, and appropriate controls shall be put in place. After the job was completed, the transmission lines department in TX acquired 40 AC induction suits for future line construction operations.

Case 2 – The same utility from case 1 conducted another job at an existing 345 kV line with double circuit in USA in May of 2022. The double line 15 mile in length, had a failure in the OPGW wire support (broken shackle) at a tower and the conductor fell and contacted a phase conductor of one of the circuits at mid-span, causing an outage. The tower configuration is a single weathered steel pole with one circuit at each side of the pole. After the outage, one circuit remained in operation and the line was kept at full line rating after the contingency. The circuit is the main corridor that carries power from a large wind generation area in the Northwest part of Texas.

The repair job was completed by a 10-men crew, comprised mostly of dead-line crewmembers, two barehand line workers, plus one supervisor. All line workers donned special conductive suits for AC induction protection (same suit design as in case 1). The induced current on the OPGW wire was not measured, but it is estimated that it well exceeded 5 A based on previous experiences at that same line corridor. In the past, induced voltages of 8 kV were measured during construction.

The crews assumed that AC induction was present during the job and TPGs were applied, and special suits worn. The downed OPGW was inspected, and it didn't have broken strands, so it had to be raised and supported back into the tower where the hardware broke. The optical fibre was tested and had no damage and no alarms. The crews hung master grounds (TPG) on each structure, in a bracket ground configuration. The tower poles were 140 ft high, so the crews used two insulating cranes (ANSI/SAIA A92.2, Category A [15]) to reach out to the OPGW. The conductor was moved by using the aerial basket with its rolling type dolly. Prior to accessing the conductor, the crew in the aerial basket used live line tools for bonding the aerial lift to the OPGW and establish an EPZ. See Figure 9. The work was completed in one day.

Figure 9. Field trial 2: use of conductive clothing for repairing OPGW over a double circuit 345 kV line with single pole, weathered steel with one circuit deenergized (left); wildfire caused due to flashover of insulating aerial crane outrigger (right)

During the job, the crews observed a little fire caused by a flash through one of insulating crane outriggers. The cause was induced voltage flashover. The sparking from the arc caused vegetation to ignite and the crews had to attend the fire and extinguish it with no further consequences. The flashover started right after the first set of TPG was installed on the OPGW. The crew had grounded the crane chassis to the ground conductor on the metallic pole. Then that ground connection was bonded through another TPG jumper to the phase conductors and OPGW. Induction arced through pads placed under the outrigger on the crane (Figure 9). It is important to note that wildfires are another risk from AC induction that need to be accounted for by line workers.

CONCLUSION

Electric utilities use live and vicinity work on their networks in order to maintain the grid operational. Both live and vicinity work methods have different safety aspects that should be considered to protect the lives of line workers. This paper introduced these safety challenges on which based different simulations, laboratory testing processes and the development of new types of PPE against AC induction have been developed. The standardization and revision process of the laboratory test processes of the different conductive garments are in progress based on presented results. Moreover, the field testing of the conductive clothing against AC induction was successfully demonstrated by one of the major US utilities, that proved an effective protection in field conditions.

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