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B2 Overhead Lines
PS 3 Environmental and Safety Aspects from Overhead Lines

Development of a novel conductive garment for protecting linemen against transmission line induction

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SUMMARY

Electric and magnetic field induction pose a hazard to linemen working in transmission line corridors. When the lines are worked disconnected and with temporary grounding applied, adjacent energized lines may induce voltage and current in the circuit worked upon. Injury or death may happen to line workers when the induced voltages and currents exceed tolerable thresholds, and the individual is in series with an induction path. Common causes are human error due to fatigue, distraction, inappropriate methods, and insufficient training.

This paper explains the development of a new type of conductive clothing that can be used as personal protective equipment to protect against induction hazards. The clothing protects linemen from electric shock and reduces the body current under the let-go threshold during contact. It prevents thermal burns due to heat dissipation from the flow of current. It is also flame resistant and prevents ignition.

This paper contains accident statistics both from American and Central-European networks, which were used in developing the AC induction clothing. Technical considerations during the

development process are summarized; they confirm that AC induction clothing can be applied effectively as a personnel protective equipment against electromagnetic induction. The clothing shall be rated based on a garment current limit and duration of exposure per a design test. A production test should be conducted to ensure performance prior to sale. Once in operation, periodic testing shall ensure garment readiness. As part of the research, test methods were developed and future standardization under ASTM International is underway.

The field application of the clothing shall be accompanied by a risk assessment. Electric utilities should identify transmission corridors and applications prone to induction. Typically, workers shall follow traditional company procedures during de-energized work with use of temporary grounding practices. The use of the suit is additional protection in case the worker makes a mistake and becomes in series with the induction current.

Induction current may have two different components. One is capacitive current due to electric field coupling which is in the order of a few amperes. The other is magnetic induced current and could reach up to the order of 50 amperes. Both components could be lethal based on time of exposure without the use of special clothing. The conductive suit is resistive in nature and it has a dynamic rating over an induced current range. For example, if the current is rated 50 amperes at 30 seconds, it may protect against a larger current for a shorter duration. At higher intensity, the protection level reduces with duration of exposure. IEEE 80 may be used as a reference for determining the tolerable current. Typically, six milliamperes is a good basis to ensure the worker won't experience muscle contraction and could decouple from the circuit. The clothing should be selected so the let-go current threshold is not surpassed in hand-to-hand, hand-to-foot, and foot-to-foot configurations.

The clothing was developed to sustain very stringent tests including resistance to several washing cycles. Typical testing includes fabric flammability, fabric resistance, fabric shielding efficiency, electric field screening efficiency of garment, garment resistance, and through-current.

KEYWORDS
Conductive clothing, AC induction, induced voltage, induced current, proximity work, vicinity work, temporary protective grounding, TPG, capacitive coupling, magnetic field coupling, body current, OSHA, electric shock, flame resistant clothing

INTRODUCTION

This paper presents the new concept of a conductive suit that can be used for protecting transmission line workers from AC induction hazards. The suit offers a shielding effect so during accidental contact, the suit deviates most of the current through the conductive fabric and straps so the body current is minimal and not fatal.
The paper covers philosophy for suit design and laboratory testing. This personal protective equipment is recommended during vicinity work on de-energized lines with temporary protective grounding that run in in the vicinity of other energized circuits. IEEE is currently incorporating the suit concept in IEEE 1048 [1], and IEEE 1067 [2]. ASTM International is developing a new performance specification standard under task group WK 70226.

Statistics of AC induction accidents

Accidents in linemen performing vicinity work due to AC induction hazards are common in USA. A review of the data from the US Bureau of Labor Statistics (BLS) [3] shows 81 accidents between 1985 and 2021. The events involved 93 workers in total. 33 workers are survivors (35%), and 60 workers are fatalities (65%). Most of the workers were experienced individuals (91%); the rest were apprentices. The main causes of the accidents were attributed to distraction, fatigue, and failure to follow company procedures for applying temporary protective grounding (TPG) on lines. In 33 of the accidents (41%), TPG were not applied at all, whereas in 39 of the accidents (48%), TPG were applied incorrectly. Based on the data, 2.6 people have induction accidents per year (average) during transmission and distribution operations. The average fatality rate is 1.7 workers per year. 1995 is the year with the most recorded fatalities, 5 people. Between 2011 and 2019 [3], the total number of fatalities in Transmission and Distribution remained under 20 people per year (all causes of death, including AC induction). AC induction fatalities are a significant portion of the total.
A review by the authors of the Central-European proximity work practice found three accidents registered in the last three years in Hungary. Two accidents happened on the transmission system and the other on the distribution network. Two line workers were hospitalized and one had a minor injury.
In the US, OSHA regulation 1910.269 [4] requires employers to conduct assessments of field conditions and determine induced voltage hazards. TPG shall be applied if the lines are not treated as energized or when the employers don’t demonstrate that the lines are free from induction. TPGs shall be placed so the workers won’t be exposed to dangerous voltages. A hazard exists if the resultant current would be more than 6 mA, which is the recognized let-go threshold for workers [5]. IEEE 1048 [1] is the most common guide for line work with TPG.

DEVELOPMENT OF A LABORATORY INSPECTION METHOD FOR AC INDUCTION CONDUCTIVE GARMENTS

The purpose of a test method for AC induction conductive garments is to determine what amount of Joule-energy can flow through the clothing, while maintaining the current flowing through the worker’s body below the safety level (e.g., 6 mA). According to literature, simulations and field measurements, the magnitude of line induced current is in the range of 1 A to 40 A in practice. For safety reasons, the garment should be inspected for a current level of 50 A for a 30 s time period. The measurement time accounts for a worker to enter the circuit, to perceive the heating effect of the induced current, and then remove himself/herself from the circuit.

In order to replicate this condition in a laboratory, an AC generator provides the test current between different parts of the clothing according to how the worker can be connected to the circuit with induced current (e.g., hand-to-hand, hand-to-foot, and foot-to-foot arrays). During the measurement, both the current waveforms flowing through the clothing (I_{suit}) and a mannequin representing the human body (I_b) should be recorded. The ratio of the currents defines the shielding efficiency of the clothing (I_b / I_{suit}). During measurement, the body current should not exceed the safety limit, and the test current cannot interrupt (because it indicates permanent degradation or rupture of the sample). Moreover, as a test current of 50 A has a high Joule-heating effect, the temperature of the surface of the mannequin which represents the human skin should be monitored. The maximum skin temperature recorded should not exceed the threshold of a second-degree burn.
The test arrangement and measurement points are shown in Figure 1.

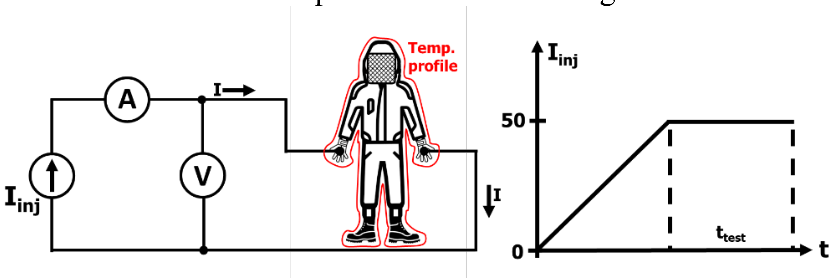


Figure 1 – Schematic of test arrangement for the induced current test

Determination of the accepted body current level

The performance of an AC induction suit is determined by the ability of line workers to survive direct contact of electrical current for a long duration. Limits are determined according to worst-case scenarios based on calculations and field measurements. Case studies show that induced current in the circuit worked upon may reach 30 to 40 Amperes [9]. The purpose of a low body current threshold value is to give an opportunity to the worker to disconnect from the electrical circuit. Body current should not exceed let-go current any time, which is defined as 6 mA according to IEEE 80 [6] and OSHA [5]. This value prevents the contraction of hand and limb muscles and reduces the probability of entanglement with the circuit. This current threshold prevents the worker from losing consciousness due to asphyxia. Duration should also encompass the possibility of a person touching the circuit twice by accident.
Accidental electrical contact on AC induced lines usually lasts for several seconds. It is reasonable to set the time of exposure for the laboratory test to 30 seconds.
In the European Union, Directive 2013/35/EU applies to electric hazard protection. It is based on the study of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the World Health Organization (WHO) [1],[2],[6],[7],[8].
IEEE 80 [6], defines the let-go current (I_b) of a person (e.g., a 3 s exposure leads to I_b of 90 mA for a 70 kg body). The calculation is valid for a maximum exposure of 3 s, but AC induction events may last longer than that. A more stringent criterion is to establish a body current limit determined by the perception threshold of 6 mA [1], [9].

Determination of current injection levels for laboratory inspection

One of the main advantages of the suit is that it gives time to the worker to release from the energized circuit when there is conductive current. Per [6], a range between 1 mA and 6 mA exposure, or let-go current, allows a person to release an energized object. Currents between 9 to 25 mA are very painful and make it very difficult or impossible to release a live object. 60 to 100 mA is a lethal range in which ventricular fibrillation, heart stoppage, and no breathing is possible. Many papers indicate that the typical AC induced current, whether capacitive or inductive, commonly exceeds all those current thresholds. A large issue regarding the duration of exposure is that AC induction cannot be cleared by a protection system as the line is out of service already. If the let-go current threshold is exceeded, then the rate of survival decreases greatly as the time of exposure is high and a relative low current may be fatal.

The suit produces an attenuation of the electrical current portion “seen” by the body of the worker. This is called a shielding effect. For example, if a suit limits the body current to 6 mA or less when 50 A flows through the suit (e.g., hand-to-hand exposure), then the attenuation is at least 99.988%, or 78 dB.

Another advantage of the suit is the handling of thermoelectric heating while current flows through the suit. Conductive clothing reduces thermal as most of the current flows through the metallic fabric and straps. However, the temperature of the metallic thread increases, and the suit needs to be rated in the laboratory to ensure the metal layer will not cause serious burns.

During testing, it is ensured that thermal markers indicate a maximum temperature that can cause curable burns. For example, ASTM C1055 [12] and C1057 [13] have a curable burn threshold ‘B’ of 54°C for exposure of conductive heat, for 30 seconds. The burn areas are monitored to ensure they are small; that is about 5 cm^2 or less. The American Burn Association determined that a body burn of 25% or less gives over 95% chance of survival for workers between 20 to 60 years old. Per the rule of nines, the front and back of each arm and hand equal 9% of the total body surface area (TBSA). A small burn on each hand is less area than that. The Palmer method estimates that the palm of a hand plus fingers are equal to only 1% TBSA.

The Electric Utility involved in the development of the suit determined through study that a limit of 50 A of induced current was sufficient for design. The object of analysis was transmission line corridors. This was based on engineering calculations and field measurements. It is recommended that end users conduct a risk assessment and choose an expected induced current limit for design of their suits. AC induced current and voltage on a line changes per conductor phase and per time of the day [9]. It is recommended to issue simple instructions of when to use the suit and to avoid field monitoring of induced current [9].

Measurement of induced voltage serves only as a reference; the induced current parameter is more important for suit design as it has a tolerable limit that can be calculated and compared. An open line with induction may have several hundreds to several thousands of volts, but once it is shorted through portable grounds or through a worker, the voltage decreases abruptly and the current increases considerably. [9] covers an example with a 345 kV line where the capacitive coupling was 18 kV with each line end open, which changed to only 30 V when one end was grounded with TPG. However, with both ends open, the induced current was 3.3 A with one end grounded, but it increased to 37.7 A when both line ends were grounded 550 m away between TPGs (about 10 times increase in current).

Assumed working positions during laboratory testing

The physiological effect of electric shock depends on the exposure time, the magnitude of the current flowing through the human body, and the path of the current inside the human body. The latter has a higher impact on the outcome. It is important to cover all the body configurations (how the line worker can get into the circuit) during laboratory testing. In practice, there are a wide range of possibilities on how the worker can connect to the circuit with different limbs. Examples include the installation or removal of TPG, work from aerial devices, structure climbing, and installation of shield wires.

The line worker can become in series with the circuit with a hand-to-hand, hand and foot, or foot-to-foot configuration. The resistance of human skin in the palms and soles varies greatly. For conservatism, the skin resistance is disregarded and a body resistance of 1000 Ω represented by a resistor is used for laboratory testing on a mannequin with conductive skin. The skin resistance of the mannequin is negligible compared to the body resistance (Figure 3). The shielding efficiency (current attenuation) of the clothing (I_b/I_{suit}) should be guaranteed for all the body configurations shown in Figure 2. The 1000 Ω value is based on experiments conducted by Dalziel [11] on people with saltwater on hands and feet where he measured resistances hand-to-hand (around 2000 Ω) and hand-to-feet (around 1000 Ω). Soaking skin on saltwater eliminated skin resistance (which could be in the order of hundreds to thousands of ohms) effects on the measurement. Hand-to-feet resistance was selected as worst-case as it is the lower of the two [10]. During laboratory tests, it was confirmed that the conductive garment has a purely resistive behaviour as no phase angle difference between current and voltage was detected.

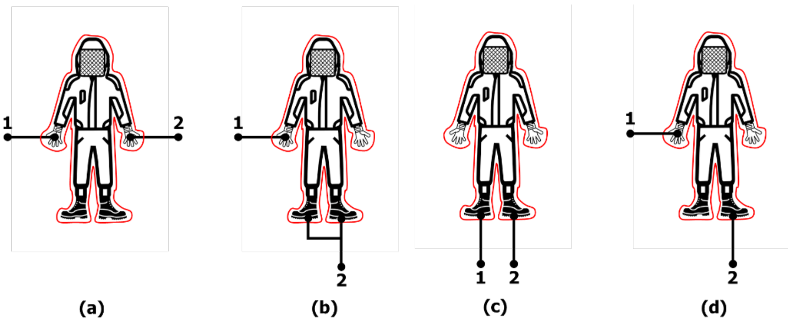


Figure 2 – Body configurations for induced current testing

During current injection, the resistance of the suit causes an increase in temperature. This in turn increases the resistance of the suit and test circuit and reduces the injected current. The source output voltage must be increased so the target current injection is kept. See examples of injected current in Figure 6.

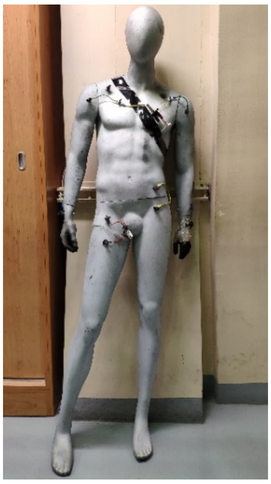


Figure 3 – Conductive skin mannequin with resistor for AC induction testing

The best way to record the thermal response is to visually monitor the garment and to place thermal indicators (Figure 4). Visual inspection includes reporting of flames, smoke, breakopen, melting and dripping. It also includes thermal monitoring of hot spots with a special camera. Thermal indicators include irreversible thermal stickers which can read temperatures in the 40°C to 80°C range. They change color and typically respond within one second which is good for the application as the induced current injection was sustained for 30 seconds. For example, 44°C is the pain onset temperature and 54 °C is the threshold for a reversible epidermal injury for 30 s exposure [12]. 100 % cotton undergarments of 4 oz/yd^2 fabric weight were used for evaluating charring and scorching which may indicate burn marks at around 2 cal/cm^2 exposure or higher.

Figure 4 – Thermal indicators: camera (left), 100% cotton clothing (center), irreversible temperature sticker (right)

Results with the proposed test method

The laboratory tests were carried out in the High Voltage Laboratory of Budapest University of Technology and Economics. Data showed that the highest current density occurred at the connection points to the AC generator (e.g., glove surface for hand-to-hand test). These points have the highest electrical and thermal stress on the garment. See results in Figure 5.

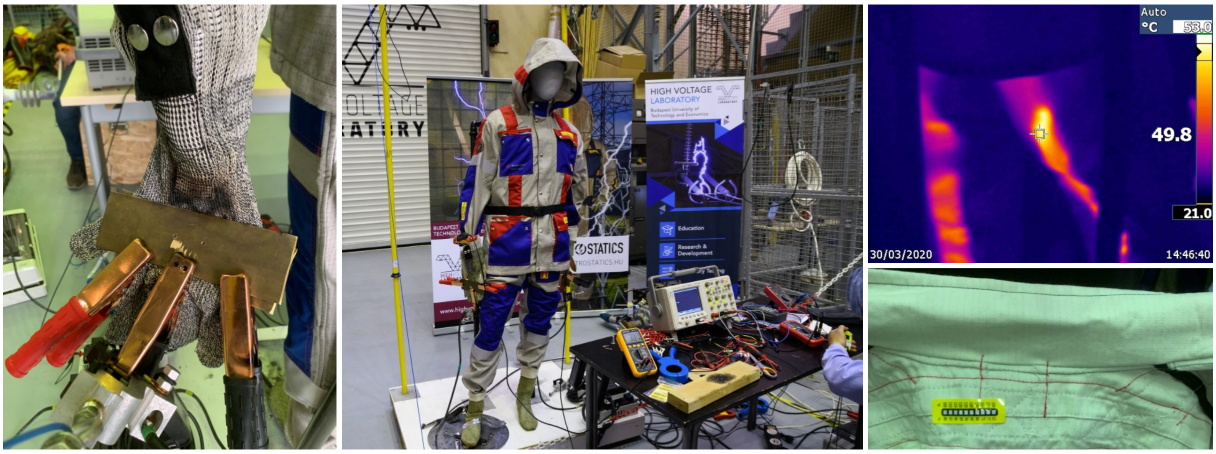
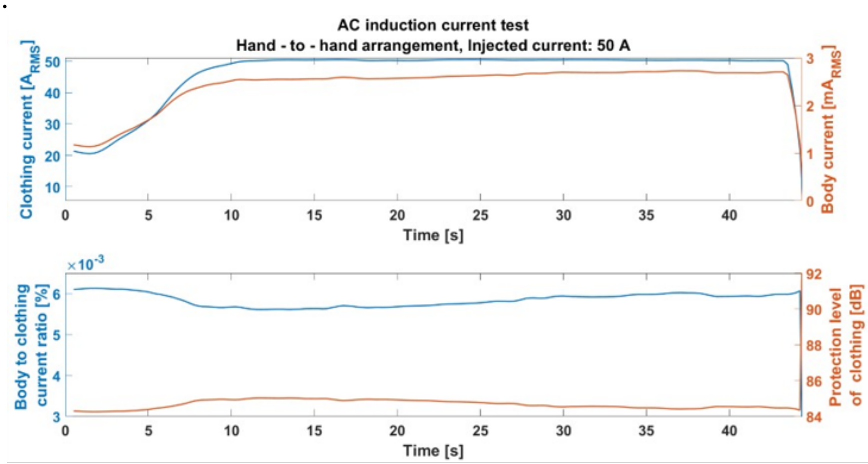


Figure 5 – Carbonization on the conductive glove surface as the result of high current density (left), performing AC induction measurement in hand-to-hand arrangement (center) and thermal tracking methods during the inspection (right)

The body configuration applied during the test has a medium impact on the shielding efficiency of the clothing (I_b/I_{suit} ratio). The measured current ratios for hand-to-hand and foot-to-foot arrangements are compared in Figure 6. The foot-to-foot array has a slightly higher body current value.



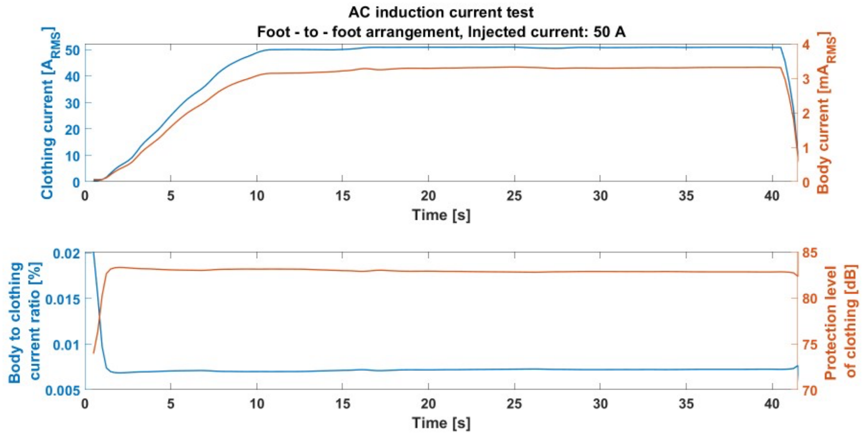


Figure 6 – Shielding efficiency of AC induction suit in case of hand-to-hand arrangement (upper) and foot-to-foot arrangement (bottom)

Conductive clothing can lead away most of the current when a line worker contacts two points at different electric potential. The suit construction has low resistance fabric strengthened with highly conductive bands in a network pattern.

In order to model how the current divides between human body and clothing, the resistance values of the whole clothing between the contact points, between the human body and the clothing, and the human body should be known. A "current divider" model can be established where body current is estimated as a function of the total current flowing through the suit. The resistance of the human body should be 1000 Ω according to the literature [6], [14]. The authors are currently working on a model that will be based on a four-wire technique for resistance measurement. The four-wire method is necessary, as it eliminates the contact and lead resistances, which, in this case, may be higher than the roughly 0.1 Ω garment resistance to be measured. Body current will be estimated based on the injected clothing current without performing any destructive tests on the garment. The first results of the model show about 20% overestimation of the body current. However, the fine-tuning of the model with other mannequins, and different type of conductive suits in laboratory conditions is still in progress.

ADDITIONAL TESTING METHODOLOGY OF CONDUCTIVE GARMENTS

Electrical and thermal testing of conductive clothing

Evaluation of AC induction clothing requires performing standard electrical tests. Many test methods are in IEC 60895:2020 [15]. Other tests for this type of clothing are being developed under ASTM WK 70226. Tests include fabric resistance, fabric shielding efficiency (SE), garment screening efficiency of electric field strength (ECC), resistance of garment components, resistance of bonding, and current shielding of garment. Table 1 shows examples of measured values from tests conducted on an AC induction suit.

Clothing evaluation includes tests for fabric flammability and ignition. If a garment ignites and continues to burn, survivability is minimal. During electric contact, arcing and overheating can occur. Conductive fabric that meets flame retardancy criteria per IEC 60895:2020 [15] and flame resistance per ASTM F1506 (tested according to ASTM D6413) does the job.

It is recommended that conducive clothing is arc resistant. Nowadays, there are conductive fabrics that meet criteria per ASTM F1506 (tested per ASTMF1959) or IEC 61482-2 (tested per IEC 61482-1-1) and have an arc protective value. Conductive fabrics in the market range between 7 and 13 cal/cm^2 of ATPV.

During vicinity work, there is a risk of flashover due to electrical contact with nearby live parts, arcing due to induced current, or arcing due to accidental energization or TPG failure. Events recorded in the US BLS database show ignition of clothing due to arcing when FR clothing was not worn.

Durability test of conductive garment with large number of washing cycles

Laundering can increase the electrical resistance of conductive clothing which in turn could raise the body current during electric contact with induced current. For this reason, it is recommended to test the fabric and the garment after a given amount of washing cycles.
The utility who partnered in the development of the suit determined that 50 washing cycles were sufficient. They assumed a line worker would work in parallel circuit applications 30% of the time. Then suits could be washed weekly around 4 months per year. The overall life of the suit could be 3 years or longer. Suits can be used all time or mainly on occasion in some specific work scenarios when AC induction is suspected on the lines.

Table 1 - Example of measured values during electrical testing of conductive clothing

Parameter	Measured value	Parameter	Measured value
Fabric resistance, no washes	0.640 Ω [b]	Garment resistance, unused, hand-to-hand	0.045 Ω [b]
Fabric resistance, 50 washes	0.780 Ω	Garment resistance, after 50 washes, hand-to-hand	0.059 Ω
Fabric SE, no washes	44.16 dB [b]	Garment resistance, unused, hand-to-foot	0.131 Ω [b]
Fabric SE, 50 washes	42.18 dB	Garment resistance, after 50 washes, hand-to-foot	0.170 Ω
Garment ECC, unused	99.99 % [c]	Body current, unused @ 50 A	2.22 mA
Garment ECC, 50 washes	99.98 %	Body current, 50 washes @ 50 A	3.90 mA [d]

[a] Hand-to-foot; [b] Per IEC 60895:2020; [c] Per IEC 60895:2020, Method 2; [d] current shielding of 99.9922%

FIELD CASE EXAMPLE

Field measurements are required for validation in addition to modelling with mathematical and finite element method (FEM) of the electromagnetic induction on the power system. For this purpose, field measurements were carried out on two 220 kV power lines of the Hungarian transmission system. One line was a 120 km cross border line with a high current load. The other 7.5 km line, an internal line, was also highly loaded. Per Hungarian practice, ground switches also function automatically as grounding devices at both ends of the line when deenergizing a circuit. Measurement was carried out on the passive (de-energized) side of the double circuit lines. The lines were grounded at both ends in the substations. The results are in Table 2.

Table 2 – Measured induced current on the passive side of power lines in the Hungarian and American transmission systems

Power line	Measured induced current [A]		
	TPG both ends [a]	TPG current [b]	Without TPG [c]
Double Circuit, 220 kV, Internal, Hungary	11.0-12.6	0.1-0.4	1.6-11.2
Double Circuit, 220 kV, Cross-border, Hungary	8.6-11.6	0.1-5.7	8.5-10.5
345 kV line, two adjacent 345 kV lines, USA	37.7	37.7	-
115 kV line, adjacent 230 & 345 kV lines, USA	8.0-19.9	8.0-19.9	-

[a] total current ground switch plus TPG at line end; [b] only TPG contribution; [c] only ground switch contribution

According to Table 2, the field measurements in the Hungarian cases are in accordance with the mathematical models; FEM simulation results can be found in the international literature [16], [17]. In case of higher voltage levels and higher current loads, the induced current can

reach up to 20-30 A magnitude, which corresponds to the development aim of the AC induction clothing. Another study was conducted on 345 kV and 115 kV circuits in USA [9]. Values are in Table 2 for comparison.
The conclusion is a conductive suit rated at 50 A for 30 s will accommodate these case studies and many field applications. Further development is underway, a suit testing specification will be available under an ASTM International standard, and use, care, and maintenance of the suit guidance will be available in the next edition of IEEE 1067 [2].

CONCLUSION

When performing line construction and maintenance on the transmission system in the vicinity of live parts, line workers may be exposed to AC induction hazards. USA statistics and EU cases show that many fatal accidents happened in the last decades due to AC induction hazards. The appropriate application of work-site grounding and the creation of an equipotential work zone provide protection from electric shock during vicinity work; however, statistics show that human factors can lead to fatalities even in these conditions. Accordingly, the development of personal protective equipment, that improves worker protection in the event of human error is justified.
For this purpose, a special conductive clothing was developed, which can shunt body current if the line worker becomes in series with the circuit and AC induced current flows through his/her body. The AC induction protective suit conducts most of the induced current and reduces the current flowing through the body of the line worker and keeps it under the threshold of let-go current (6 mA). Therefore, the line worker can disconnect from the hazardous circuit, thus avoiding fatal electric shock. Moreover, the heating effect of the induced current on the conductive clothing is controlled and kept under the temperature limit that could lead to a 2nd degree burn. A way to accomplish this is by using highly conductive straps.
Because there is no technical background available for laboratory testing of AC induction garments, the development of the inspection procedure was introduced in detail. Currently, the type test is a destructive method, as it requires the injection of current in the order of tens of amperes that can cause irreversible mechanical damage. Development of non-destructive acceptance and periodical tests based on a current division model is underway and will be addressed in future technical papers.
The investigation of the effect of use on conductive garment performance was part of the scope of this work. A durability test with tens of washing cycles was carried out.
Field measurement of induced currents in real lines and case studies were also presented in this paper to rationalize the need of operating limits of AC induction protective garments. Recommended values of magnitude of current and duration were implemented in the laboratory type tests.

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