Induced Voltage: A Major Risk Not Only During Live Working

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***Abstract*— Working in the vicinity of live parts is an effective working method on the high voltage power system. However, AC induction poses a threat to the linemen during vicinity working. The aim of this paper is to introduce the induction phenomenon on high voltage equipment, including the different coupling types, and also the magnitude of the evolving induced voltage and current. Moreover, a summary of accidents due to AC induction, their cause and outcome are also presented.**

One effective protection method against AC induction is the use of personnel protective equipment. For that purpose, some conductive clothing manufacturers developed specially strengthened garments against AC induction. The working philosophy of conductive clothing against AC induction is presented in detail, moreover the developed laboratory testing methodology is also discussed in this paper.

***Keywords*— live working, live-line maintenance, bare hand method, AC induction, conductive clothing, working safety**

I. Introduction

While working live, there is no concern about the necessity of conductive clothing as electrical and mechanical contact, that is established between the lineman and the energized parts of the grid through the conductive garment. Based on the principle of Faraday-cage, these clothing provide an efficient way of protection against extra-low frequency electric fields. However, from another aspect, a well-designed conductive clothing is also an essential protective equipment against electric shocks as well, caused by inductive or capacitive coupling between the energized and floating conductive structural parts. Although proper grounding at both ends of a line and at the worksite together guarantees adequate safety, lack or damage of grounding may cause direct hazards for the worker as high voltage and current occur. This major risk must be taken into account especially while working on double-circuit power lines, substations and railways. This paper introduces a properly designed conductive clothing that is effective for induced voltage-caused electric shock prevention. A special arrangement is also introduced at the High Voltage Laboratory of Budapest University of Technology and Economics (BME-HVL) to determine the efficiency against induced voltage of conductive garments by determining the body-to-clothing current ratio.

II. Potential Risks During Maintenance Work on a Double Circuit Line

One of the advantages of maintaining double-circuit power lines is that, while one system is in operation (active side), maintenance work can be carried out on the de-energized system (passive side). Thus, the period of unnecessary power outages can be limited which is favourable both from the aspect of transmission system operators (TSOs), distribution system operators (DSOs) and consumers. On the other hand, several risk factors may occur during maintenance activities with vicinity working method, as in case of these lines, the two systems are parallel to each other increasing the possibility of any induction phenomenon. Maintenance works on a double-circuit power line are diverse, there are cases when the working position is on the grounded high voltage tower below the phase conductors, while in case of other maintenance works, there is a direct connection between the phase conductors and the linemen even if it carried out on the active or the passive side. The common point of these maintenance tasks is that the safety of the linemen needs to be ensured in all circumstances. In the previous case, as the worker only be able to get in contact with different parts of the grounded high voltage tower, only the protection against electric field is required, which can be achieved by using conventional conductive suits. However, in the latter case if the maintenance is carried out on the passive side of the double circuit power line, the protection of the worker is essential due to several risks of potential induced voltage also. The key for a complex risk assessment is to simplify the physical background of the phenomenon and focus on those circumstances where electromagnetic induction may significantly exceed safe levels, so its risks can be high. The first important thing is to conditionally divide the phenomenon into components such as capacitive and inductive ones. There are different cases whether the conductor and metal parts located in the vicinity of the energized line are grounded or not. If there is no protective grounding, the conductor parts are induced with a non-zero electrostatic potential of capacitive nature and an electro-motive force (EMF) of inductive nature. When the ground connection of the de-energized part is proper, the non-zero electrostatic potential becomes zero and, in this way, the capacitive component disappear. However, the current generated by EMF flows through the grounding still providing the inductive component of the induced voltage. The capacitive component can be characterized with a large magnitude of induced voltage (up to 20 kV without proper grounding) and a relatively low current level when grounding (no more than 100 mA). These voltage and current values mostly depend on the voltage level of the influencing line and its distance. The inductive component can be characterized a relatively large current through the grounding (up to 30 A) of which magnitude depends on the current level in the influencing line, the distance to it and the length of the closed loop, located under the influence of the energized AC line. It is important to mention the level of the voltage level of the inductive component is a function of the induced current and the resistance of the grounding. Therefore, measured values of the induced voltage highly depend on the resistance of the grounding and may reach extremely high values even just near the protective grounding [1]-[5].

Another important issue is the problem of low-frequency electromagnetic fields in the vicinity of the overhead power lines. In case of a proper grounded passive system the induced voltage does not appear, however electric field strengths due to the active system in operation could exceed the limit values even on the grounded structure such as a high voltage tower. In unfavorable cases linemen working on the tower can be exposed to electric field strength over the limit value [6],[7].

A. *The magnitude of the induced voltage on a double circuit power line*

In order to implement proper protection against induced voltage it is important to know its magnitude on the inspected power line. Several articles focus on modelling of this phenomenon applying different equivalent circuits and parameters for the same phenomenon [1]-[5].

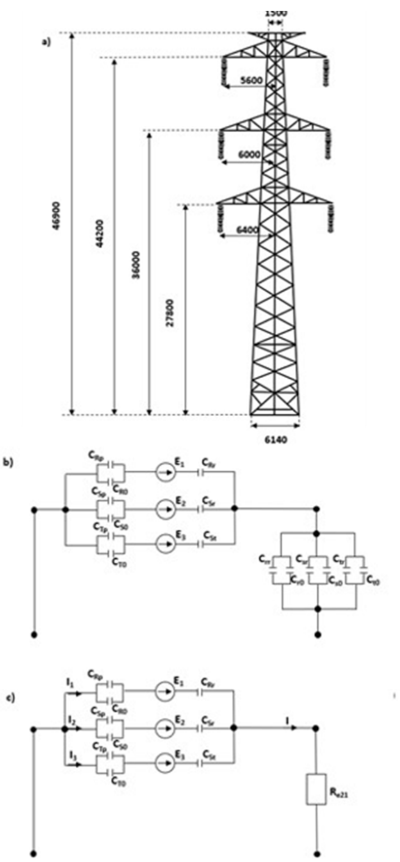

Fig. 1. a) dimension of the tower applied in the simulation, b) and c) equivalent circuit for the calculation of induced voltage [4]

To present an unfavorable case, simulations were carried out for a 400 kV power line with lattice towers. In case of high voltage power lines presented in Fig. 1, the induced voltage generated by capacitive coupling is significant, thus the most important parameters for the calculation are the partial capacities between the phase conductors and between the phase conductors and the ground points.

In Table I the partial capacity values calculated from the given geometry can be seen. G1 and g2 represent the ground wires on the top of the tower, R, S, and T represent the phases of the active side, while r, s, t are the phase conductors of the passive side of the OHL.

TABLE I. CAPACITY VALUES CALCULATED WITH THE CHOSEN 400 KV LATTICE TOWER PARAMETERS

Partial capacities between phase conductors [nF/km]	**G1**	**g2**	**R**	**S**	**T**	**r**	**s**	**t**
V1	-	25.27	35.22	22.76	18.81	21.44	19.55	17.66
V2	25.27	-	21.44	19.55	17.66	35.22	22.76	18.81
R	35.22	21.44	-	26.78	20.07	19.55	18.77	17.45
S	22.76	19.55	26.78	-	26.76	18.77	19.21	18.48
T	18.81	17.66	20.07	26.76	-	17.45	18.48	18.81
r	21.44	35.22	19.55	18.77	17.45	-	26.78	20.07
s	19.55	22.76	18.77	19.21	18.48	26.78	-	26.76
t	17.66	18.81	17.45	18.48	18.81	20.07	26.76	-

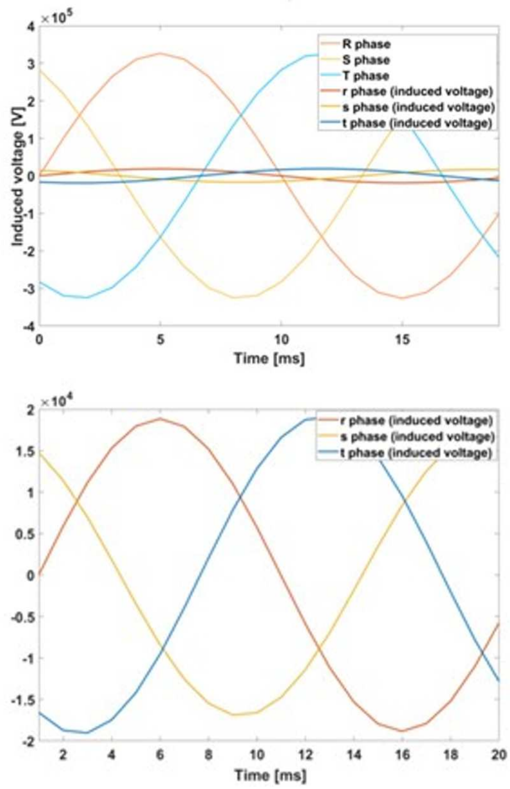

Fig. 2. Induced voltage in the de-energized side compared to voltages in energized system

Knowing the capacitance values and the phase voltage magnitudes, the induced voltage values in the passive side can be determined.

TABLE II. MAXIMUM INDUCED VOLTAGE VALUES ON THE DE-ENERGIZED PHASE CONDUCTORS

Phase	r	s	t
Maximum induced voltage	18.8 kV	18.5 kV	19.0 kV

As it can be seen in Table II and Fig. 2, the voltage levels induced in the de-energized conductors of the OHL is significant, the peak of them could even reach 19 kV. The difference between the maximum induced voltage values is due to the geometrical particularities.

B. The magnitude of the induced current on a double circuit power line

There are basically three scenarios for calculating the induced current, depending on how the work ground is located. In the first case no protective work ground is contacted to the de-energized system thus, the induced voltage generated by electrostatic coupling will be the significant. Due to the lack of the work-site grounding, the magnitude of induced current in this case is negligible in the passive system [4].

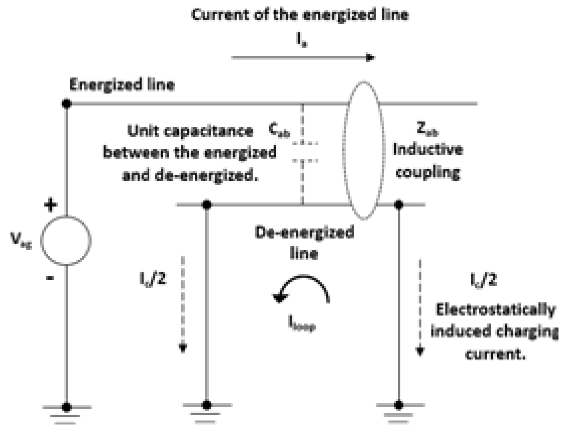

Fig. 3. Schematic equivalent circuit for AC induction with two work-site groundings [3]

In the second case, one work-site grounding is placed on the de-energized side, and at this contact point the potential of the passive system equals the ground potential. It can be stated, that when one work-site grounding is installed, both electrostatic and electromagnetic coupling needs to be considered. In the third case, two work groundings are installed on the de-energized system as it is shown in Fig. 3. As in the second case, both electrostatic and electromagnetic induction are present and as a result of the two-connection points, a loop could be formed in which current flows. The induced current, as in the previous case, is generated by electrostatic coupling, but by electromagnetic induction it is supplemented by the loop current. In order to present the magnitude of the current a simulation was carried out on the same 400 kV power line for the third case, when two work grounding is in connection with the passive side [4].

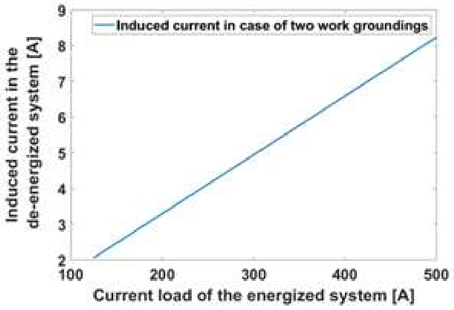

Fig. 4. Induced current level depending on active side load with two work-site groundings [4]

The loop current generated on the de-energized system as a function of the energized side load is shown in Fig. 4. According to the results, at a current load over 500 A, the induced current can be as high as 10 A, which is significant from the safety aspect of linemen.

III. MAIN PRINCIPLES OF WORKING SAFE IN THE VICINITY OF LIVE PARTS

Protective grounding at the work site of de-energized line minimizes the level of the induced voltage. Creating an equipotential zone around workplace eliminates possibility of potential differences between any parts of human body and, as a result – current flowing through the body. The existing working methods are safe for linemen and if they would strictly follow the rules no accident could happen. However, sometimes workers make mistakes that can cause accidents, from which unfortunately, the AC induction related accidents are mostly fatal [8].

Fig. 5 shows the statistics about the causes of AC induction related accidents.

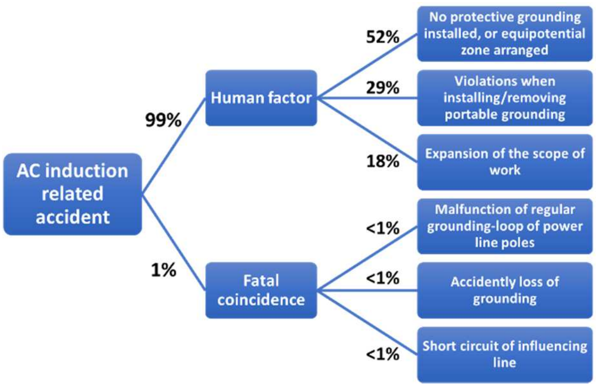

Fig. 5. Causes of AC induction related accidents

There is a study carried out for the AC induction related accidents, which investigates 81 accidents happened in the USA between 1985 and 2021 [9]. This statistic shows, that 89% of the accidents was happened due to the incorrectly applied or absence of temporary protective grounding (TPG).

As the main cause of fatal accidents is human factor, it indicates the demand for personal protective equipment that is able to reduce the risk AC induction accidents, to have linemen the possibility to survive. However, the most important aspect of safe working in the vicinity of live parts is making an equipotential work zone (EPZ) around the work site, while the AC induction clothing is working as an additional safety factor in the case of human errors.

IV. Conductive clothing against AC induction

When the lineman gets into the circuit by accidental touch of parts with differential potentials due to AC induction, an induced current flow through his body. The magnitude of this current varies according to the potential difference between the touched parts, which can be reached 30-40 A in worst-case scenario. The concept of the new type of conductive clothing developed against AC induction, is the usage of it as a personal protective equipment in order to shunt this hazardous induced current which without the PPE flowing through the human body. During the design of the special conductive clothing against AC induction the following criteria was taken into account in order to protect workers against current shock of induced voltage:

- Ability to minimize the level of current flowing through the worker's body down to 6 mA (threshold of let-go current [10]) or below. For this purpose, the required level of electric resistance for conductive suits should be below 0.5 Ω.
- Ability to conduct high current of minimum 50 A for minimum 30 seconds without any damage of the material, while not cause 2nd degree burn on the human body.
- Conductive fabric used should be not only flame retardant but also arc protective with minimum the ATPV level of 8 cal/cm^2.
- All conductive materials and accessories used must be resistant to multiple washing and to human sweat.

To fulfil the first two requirements a special highly conductivity strap is implemented in the conductive suit. The strap goes through the whole suit, electrically connecting all the tailoring elements of the conductive fabric among each other. The electrical resistance of the strap is less than 0,1 Ω/m and it can conduct current up to 100 A for more than a minute without breaking the electrical continuity [11]. The design of the strap in the jacket of the conductive clothing against AC induction is shown in Fig. 6.

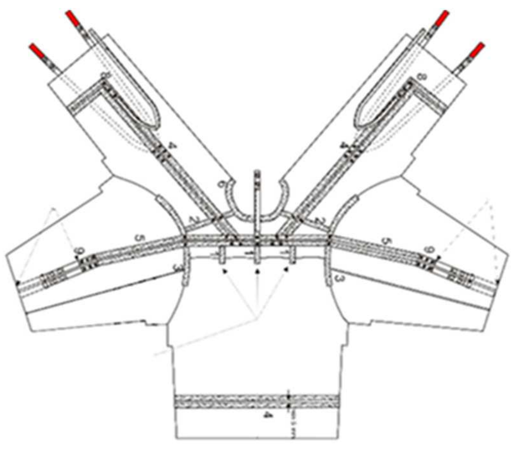

Fig. 6. Highly conductive strap implementation into the AC induction clothing's jacket

If something goes wrong with equipotentiality of the workplace and a lineman gets under induced voltage, conductive clothing makes equipotential arrangement around him, and leads away the current from the human body as it is shown in Fig. 7.

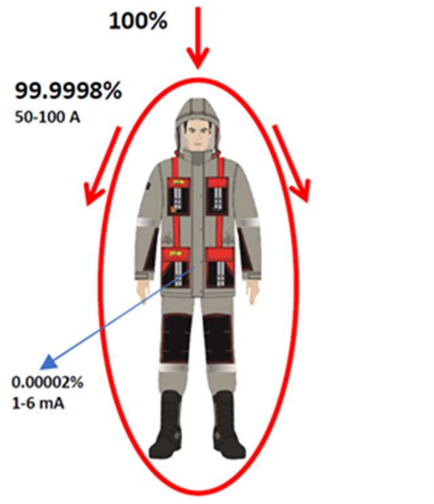

Fig. 7. Philosophy of conductive suit as a PPE against AC induction

Workers usually do not even recognize the problem and do not stop working with the induced current flowing through the garment. However, if the induced current through the garment reaches 20 A or higher, it can be felt due to its heating effect. Then work should be immediately stopped, the electric scheme of the workplace arrangement checked and equipotentiality of the workplace provided.

When induced current through the garment is noticed, then changing the garment to a new one is highly recommended [12].

A. Laboratory testing methodology of conductive clothing against AC induction

Three categories of testing of AC induction suits can be distinguished:

- design (type) tests,
- production (acceptance) tests,
- in-service (periodic) tests.

Design tests determine the AC induction current withstand, which is a destructive test. During the inspection, an AC generator is used to inject 50 A current through the conductive clothing. The test configurations include hand-to-hand, hand-to-foot, and foot-to-foot exposure, in order to cover all possible compositions, how the lineman can get into the circuit. A conductive mannequin is used during the tests, and its limbs are insulated from each other. A 1.0 kΩ resistance represents the body resistance and it is placed in series with the investigated body parts. During the test, the total injected current and the body current have to be measured and monitored during a 30 s exposure time. The body current should not exceed 6 mA during the measurement. Also, hot spots of the conductive clothing should not cause a 2nd degree burn. To monitor the temperature distribution, temperature indicating labels and thermal cameras are used. Moreover, the test sample shall not melt or ignite during the test, and the current flowing through the arrangement cannot be interrupted.

The laboratory tests carried out in the High Voltage Laboratory of BME investigated different type of conductive clothing including the new design, which is specially developed against AC induction. Based on laboratory testing, it was determined that not all conductive clothing have proper current-carrying capacity to protect against AC induction hazards, however the newly developed suit is able to meet the requirements of ASTM WK70226.

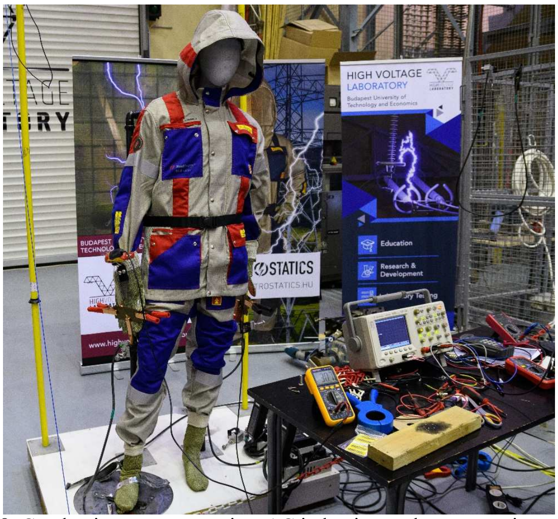

Fig. 8. Conductive garment against AC induction under type testing

B. *Regulatory environment of protection against AC induction*

Since the first design of an AC induction protection suit was developed, there has been some movement in industry standard organizations to incorporate the philosophy, which is summarized in the following:

- Cigré B2.87 working group was started in the beginning of 2021, one of the tasks is to review HVAC overhead lines grounding techniques and working in the vicinity of voltage including induced voltage and currents which could lead to fatalities.
- IEC 60895 was recently released under 2020, so AC induction clothing may be incorporated not until the next revision cycle, however several IEC country members are interested.
- ASTM International has task group WK 70226 which is developing a performance specification for conductive clothing which will incorporate AC induction protection as a Type 2 garment.
- IEEE 1067 has a task group which is incorporating the in-service use, care, maintenance, and field testing of different type of conductive suits.
- IEEE ESMO has plans to develop a paper on AC induction suits and their incorporation under standard IEEE 1048 for temporary protective grounding of power lines.

V. Conclusions

Generally, the maintenance interventions in the high voltage system can be performed on energized system components with live-line maintenance techniques, or on de-energized elements. In the previous case all the techniques and tools are available for safe work, while in the latter case the AC induction phenomenon poses a safety risk. Firstly, the paper introduces the AC induction forms categorized by coupling effects. Then, the magnitude of induced voltage and current is shown via case studies depending on the applied number of work-site groundings. Based on these analyses, the demand for a personal protective equipment for maintenance activities in the vicinity of live parts is justified. Accordingly, to reach the same safety level by working in the vicinity of live parts as during live working, a specially designed conductive suit is introduced in this paper. The philosophy of the developed garments is to shunt the magnitude of the induced current below the limit of let-go current flowing through the human body. In order to investigate how effective of that shunt effect, a laboratory testing method is proposed by ASTM WK 70226. The proposed inspection was carried out on conventional conductive suits and the newly design one, which showed that the current carrying capacity of the conventional suits in most cases do not provide proper protection against AC induction.

All in all, this paper points out, that the safety of working in the vicinity of live parts can be increased by using specially designed conductive garments, which laboratory testing method is also presented.

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