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Protection of maintenance workers in the vicinity of energized grids

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SUMMARY

High voltage overhead lines are core elements of the power system. According to this, their operational reliability and regular maintenance have an absolute priority from the aspect of transmission system operators (TSOs). In the power transmission system, several double-circuit overhead lines operate all around the world. These line structures are applied at almost all high voltage levels, including 220 kV, 400 kV, and 500 kV. One advantage of these line structures is that the circuits are independent of each other. According to this, in those countries where the bare-hand live working method is not applied, maintenance work can be performed on the de-energized side of the line while the other circuit is under normal operating conditions.

On the other hand, it is essential to mention that induced voltage can also appear in the de-energized circuit due to different coupling methods. Due to the induced voltage, the potential risk of any electrical discharge process between the linemen and the de-energized conductive parts of the OHL could increase. Another critical issue is that the electric field could also reach the intervention level in the vicinity of the de-energized parts, which is unfavourable due to safety and legal issues from the aspect of linemen. Due to the potentially hazardous nature of low frequency electric and magnetic fields, in several parts of the world, directives are applied for public and occupational exposure. Based on numerous medical experiments, limit values are stated for these field strengths that cannot be exceeded even in a short period.

In practice, there are different possible solution methods to protect the workers against the effects of induced voltage and electromagnetic fields. If the temporary protective ground is applied around the work stage within a proper distance (depending on the voltage level and line geometry) in full time of the maintenance work, the induced voltage does not appear, which reduces the risk of any electrical discharge processes. On the other hand, it is essential to mention that the magnitude of the electric field strength could still exceed its limit value near the grounded parts despite the protective ground. To avoid these electric field exposures, the necessity of another solution is highly required. To fulfill the criteria of the complete protection of the worker, the application of appropriate conductive suits could lead to a result. These kinds of suits equipped with proper face mesh are made of conductive material and cover the whole body of the worker.

Conductive suits have been applied widespread for bare-hand live working methods since the 1980s. The protection method of the conductive suits is based on the so-called Faraday-cage phenomenon, which results in zero electric field strength inside the suits. Due to this, wearing a conductive suit during the maintenance work could protect the worker against the hazards of the electric strength. This paper aims to investigate the magnitude of the evolving electromagnetic field during maintenance work on the de-energized circuit of the double circuit line, and to present how the conductive suit protects the workers against them.

KEYWORDS

Overhead line, power line, transmission system, induced voltage, induced current, electric field, electric field protection.

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 from the aspect of system TSOs and consumers. On the other hand, several risk factors may occur during maintenance activities, as in the 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 diverse, there are cases when the working position is on the grounded high voltage tower, while in the case of other maintenance works, there is a direct connection between the phase conductors and the linemen. The common point of these maintenance tasks is that the safety of the linemen needs to be ensured in all circumstances. The protection of the worker is essential due to several risks of potential induced voltage, and electromagnetic field could occur by the alternating electromagnetic field of an energized AC line. 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 disappears. However, the current generated by EMF flows through the grounding, still providing the inductive component of the induced voltage. In the case of a grounded situation, the capacitive component can be characterized with a large magnitude of induced voltage (up to 10 kV) and a relatively low current level through the grounding (no more than 100 mA). These voltage and current values mainly depend on the voltage level of the influencing line and its distance. The inductive component can be characterized as 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 essential to mention that 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 grounding resistance and may reach extremely high values even just near the protective grounding [1]-[5].

Another critical issue is the problem of low-frequency electromagnetic fields in the vicinity of the overhead power lines. In the case of a properly grounded passive system, the induced voltage does not appear. However, due to the active system in operation, electric field strengths could exceed the limit values even on the grounded structure such as a high voltage tower. In unfavourable cases, linemen working on the tower can be exposed to electric field strength over the limit value [3].

THE MAGNITUDE OF THE INDUCED VOLTAGE ON A DOUBLE CIRCUIT POWER LINE

To implement proper protection against induced voltage, it is vital 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 problem [1][2][4][5].
The development of any new methods is not the object of this paper, the aim is to present the magnitude of the induced voltage that can occur in the case of a high voltage OHL. To submit an unfavourable circumstance, simulations were performed on a 400 kV power line with lattice towers. In the case of high voltage power lines presented in Figure 1, the induced voltage generated by capacitive coupling is significant. Thus the most critical parameters for the calculation are the partial capacities between the phase conductors and between the phase conductors and the ground points.

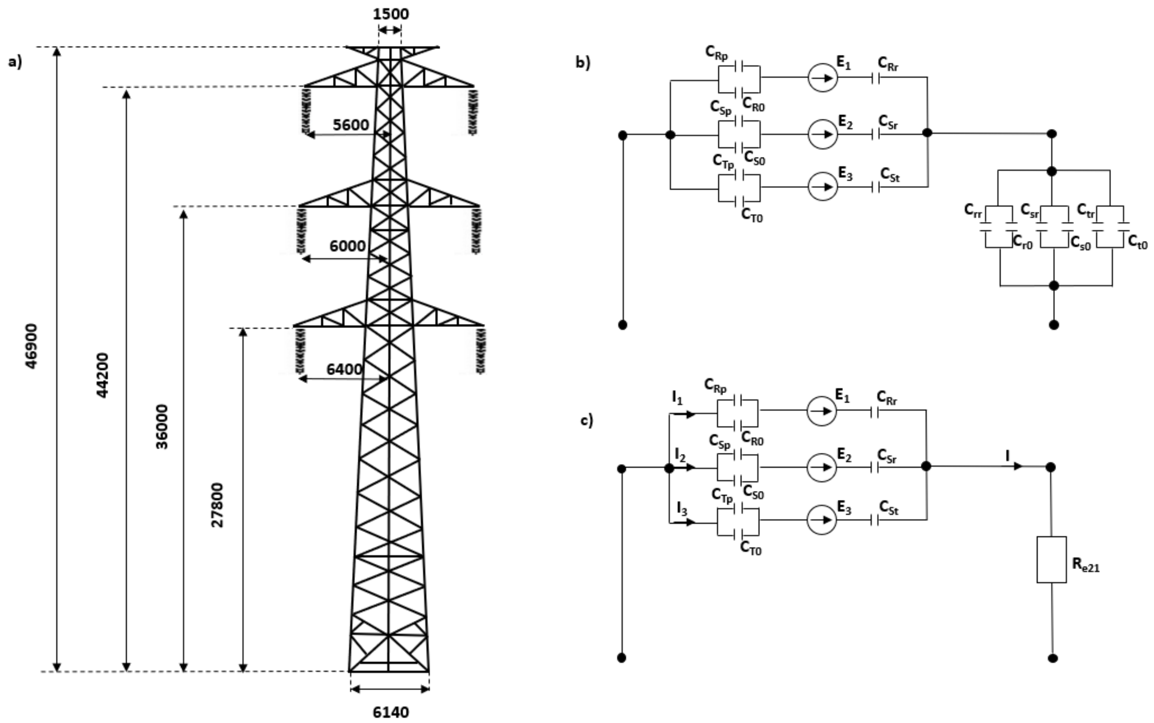


Figure 1 a, illustration of the tower applied in the simulation, b,c equivalent circuit for the calculation of induced voltage [5]

In Table 1, the 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, T represent the phases of the active side, while r, s, t are the phase conductors of the passive side of the OHL.

Table 1 Capacity values calculated with the chosen 400 kV lattice tower parameters

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	-

Knowing the capacitance values, the induced voltage values in the de-energized phases can be determined.

Table 2 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

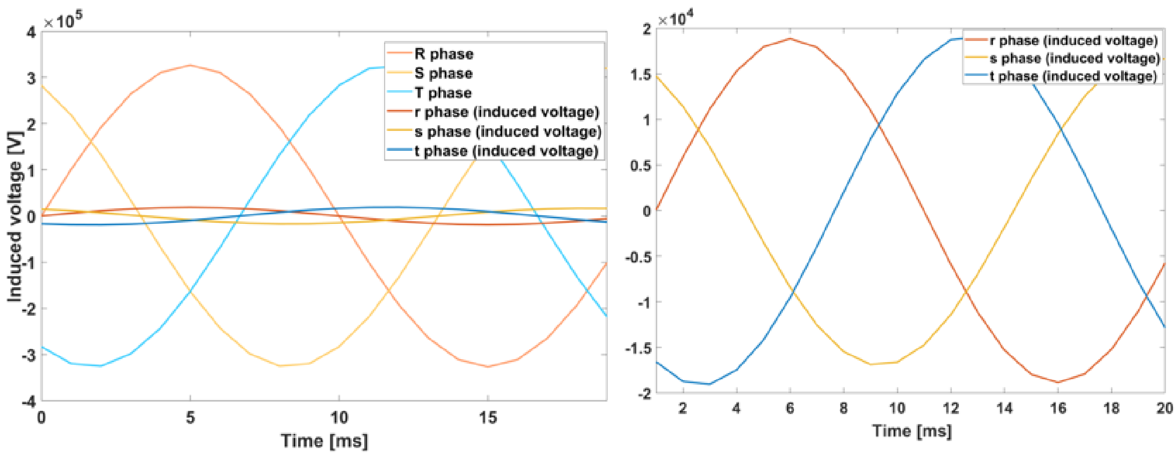


Figure 2 Induced voltage in the de-energized side compared to voltages in the energized system

As shown in Table 2 and Figure 2, the voltage levels induced in the de-energized conductors of the OHL are significant; their peak could even reach 19 kV. The difference between the maximum induced voltage values is due to the geometrical particularities.

THE MAGNITUDE OF THE INDUCED CURRENT ON A DOUBLE CIRCUIT POWER LINE

There are 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 significant. Due to the lack of grounding, induced current does not flow through the passive system [4].
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 shown in Figure 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. As in the previous case, the induced current is generated by electrostatic coupling, but by electromagnetic induction, it is supplemented by the loop current. To present the magnitude of the current, a simulation was carried on the same 400 kV power line for the third case, when two work grounding is in connection with the passive side [4].

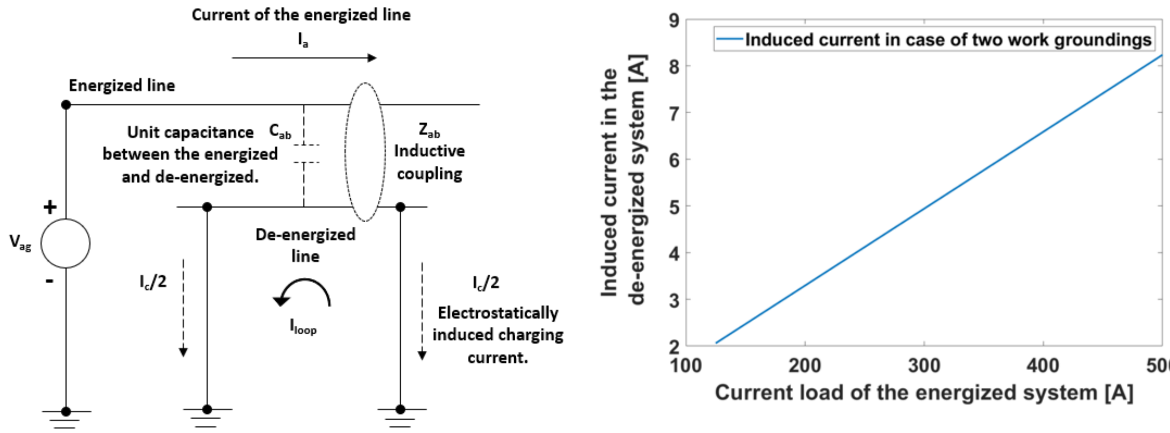


Figure 3 Schematic equivalent circuit and the magnitude of the induced current for two work groundings case [4]

The loop current generated on the de-energized system as a function of the energized side load is shown in Figure 3. 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.

ELECTRIC FIELD DISTRIBUTION IN THE VICINITY OF GROUNDED PARTS OF THE POWER LINE

The electrical stress of the commonly used power line structures can be effectively calculated, measured and simulated. As mentioned, an electric field that exceeds the limit values could occur in case of proper ground connection of phase conductors or in the vicinity of the tower. In order to present a possible case, an electric field distribution simulation based on finite element method (FEM) was performed on a 3D model of a 400 kV lattice tower. As a result of simulation, it is possible to examine the electric field graphically, with high accuracy [3].

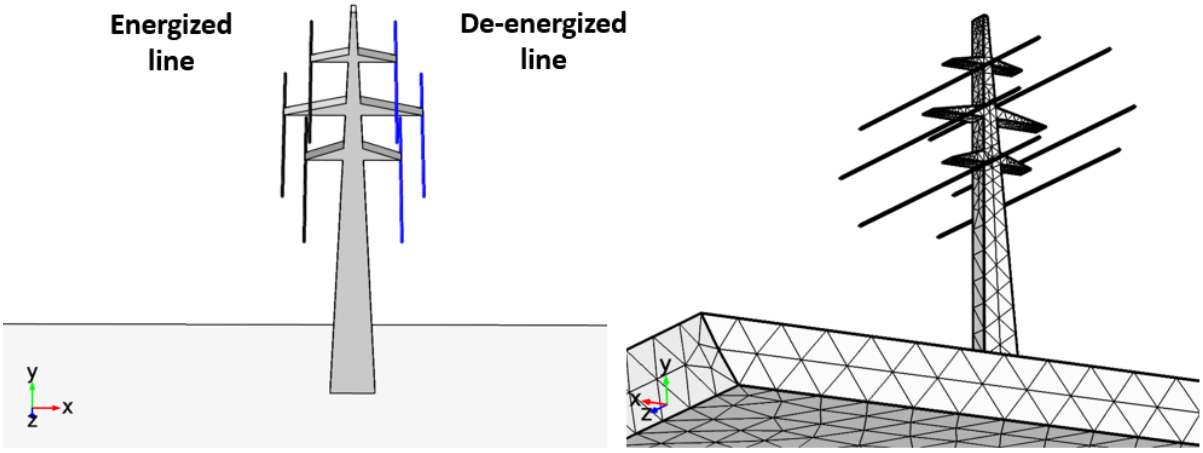


Figure 4 Scaled drawing of the modeled tower structure and 3D model of the tower

The complex 3D model contains the 3D CAD model of a 400 kV lattice tower structure with three conductors in a vertical arrangement on both sides. The tower structure was considered solid and grounded through the tests. On the active side, the voltage of the conductors was the phase-to-ground voltage of a 400 kV system with a phase angle of -120°, 0°, and +120°, respectively. The other system was supposed to be grounded. A grounded conductive plate modeled the surface of the ground at the bottom of the model. Figure 4 represents the shape and 3D model of the applied tower.

In several parts of the world (in most European countries), Directives of the European Parliament and of the Council apply for both public and occupational exposures regarding extra-low frequency electric and magnetic fields. Most of these regulations are based on numerous medical experiments executed by, e.g., the International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) or an independent organization, the International Commission on Non-Ionizing Radiation Protection (ICNIRP). ICNIRP's 2010 guidelines for 50 Hz are summarized in Table 3 [3][6][7][8].

Table 3 Current limits for electric and magnetic field strength based on ICNIRP's guidelines [6][7]

	Limits of electric field strength [kV/m]	**Limits of magnetic flux density [µT]**
Public	5	200
Occupational (max. 8 hours/day)	10	1000

In Figure 5 illustrates the results, the top of the range of electric field strength colour map was chosen as 10 kV/m, which is the current occupational limit by ICNIRP 2010.

Figure 5 shows the electric field distribution around the conductors while the left-side system is energized and the right-side system is grounded.

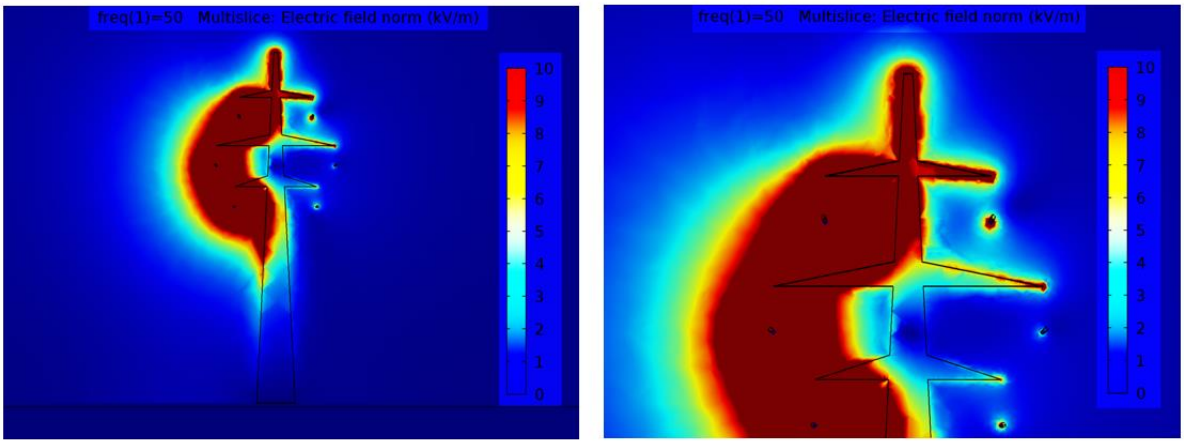
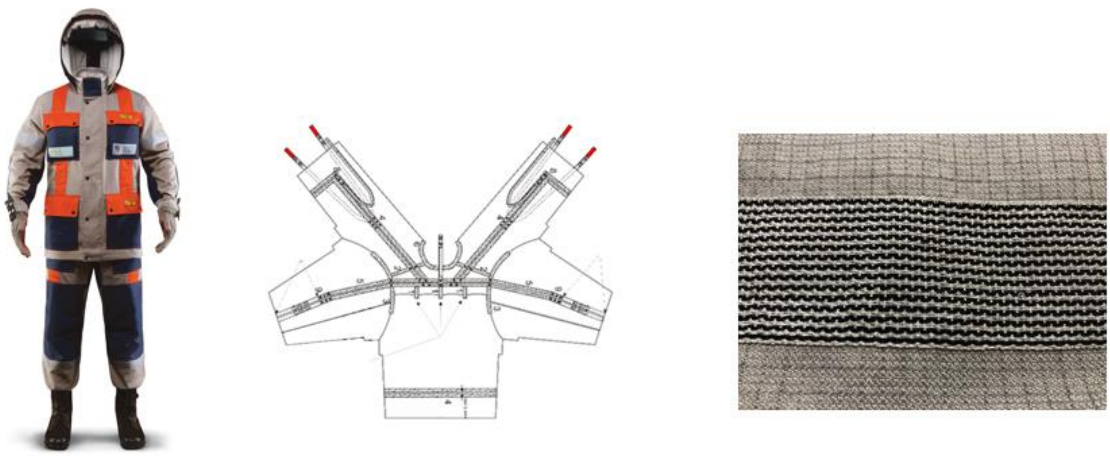


Figure 5: Electric field distribution around the structure (right-side system grounded) and the same structure with zoom

As it can be determined to form the results, electric field strength may reach its limits even when one system of a double-system power line is grounded. To guarantee the necessary level of safety of working personnel, it is always required to wear conductive clothing – acting as a Faraday-cage – to shield the electric field properly. Electric field strength may endanger the safety of workers even on de-energized elements of the grid (e.g., tower structure, conductors on the grounded side).

CONDUCTIVE SUIT AS A POTENTIAL PROTECTIVE EQUIPMENT

The proper grounding of the work zone provides widespread protection against induced voltage and current in the de-energized parts of the OHL. However, in case of not adequate grounding or any accidental re-energization the worker's safety is limited. This was the reason to introduce a specially designed conductive suit that functions as personal protective equipment (PPE) while working on a passive side in the vicinity of the high voltage conductors. The main advantage of the conductive suit is that it shunts the currents and provides equipotential bonding to the energized parts. Thus, if the human body is exposed to the unfavourable induction effects, the bypass could provide additional protection.



a) b) c)

Figure 6 a, special conductive suit, b, high conductivity tape, c, material of the high conductivity tape

However, it is essential to note that conductive suit as equipotential bonding is not applicable on its own; it must always be supplemented with other PPE specially designed for this purpose, such as portable bases, shunt rods, connectors etc. In case of unexpected re-energization, equipotential bonding ensures that the suit's potential increases with the conductor's potential. The suit also protects against induced current shock; the effect of 15 A current cannot be recognised inside the suit. In the case of 20 A current, the heating of the garment is already perceptible, but in these cases, work must be stopped immediately, and safe conditions must be ensured. In order to fulfill the requirement of the strictest standard (30 A for 1 minute without damage), a particular high conductivity tape is implemented in the conductive suit. The tape goes through the whole suit, electrically connecting all the tailoring elements of the conductive fabric among themselves. The electrical resistivity of the tape is less than 0,1 Ohms per meter, and it can conduct current up to 60 A for more than 2 minutes without breaking the electrical continuity.
Another critical issue is the problem of low-frequency electromagnetic fields in the vicinity of the overhead power lines. In the case of a properly grounded passive system, the induced voltage and current do not pose concerns for human health. However, due to the active system in operation, electric field strengths could exceed the limit values even on the grounded structure such as a high voltage tower. In these cases, equipotential work grounding is not sufficient for the full protection of the worker and the wearing of a conductive suit can provide the necessary protection. In this case, the conductive suit operates in analogy to the faraday cage; the electric field strength inside the suit takes up a value of zero, thus protecting the worker from a field strength above the limit in the vicinity of the conductor.
To present the protection level of a conductive suit, a screening efficiency test was performed on a new conductive suit in the High Voltage Laboratory of Budapest University of Technology and Economics.

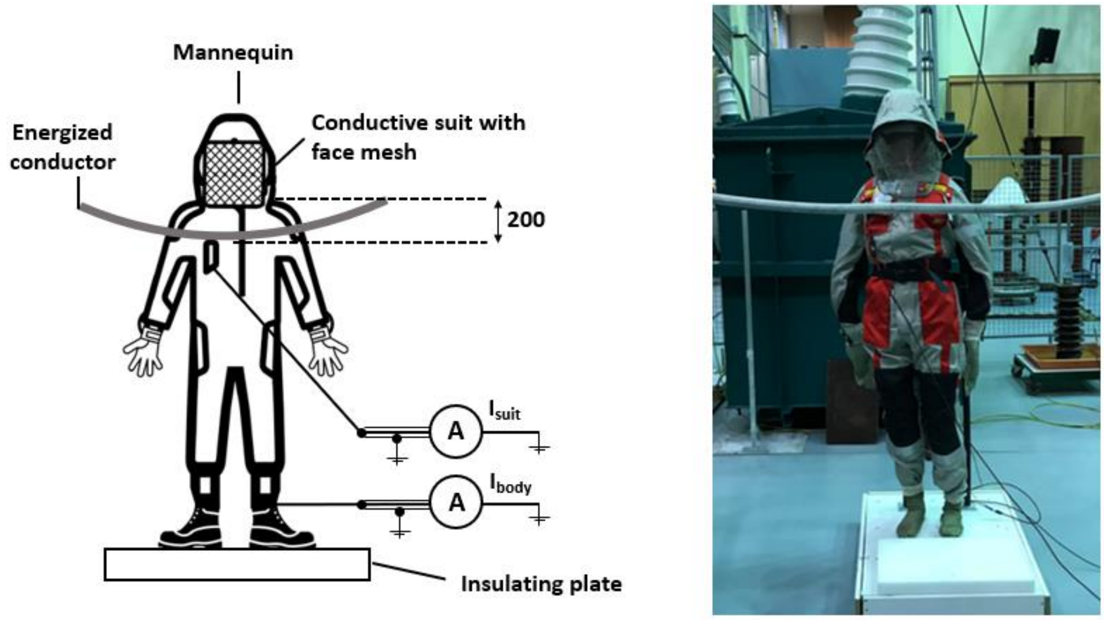


Figure 7 Schematic and real arrangement of the screening efficiency test

The essence of the measurement is that a conductor at high potential is in front of the mannequin's chest and induction current is measured at different voltage levels. As it can be seen in Figure 7, the electrode is connected to the mannequin while the other is to the suit. Thus the measured currents can be compared to each other. The earth (electrical ground) shall be at a distance D, in metres, given by Equation 1 (values in the formula are with ±2 % of tolerance):

$$D = \frac{U_{test}}{100} + 0.5 \tag{1}$$

Where U_{test} is the voltage, in kilovolts.
The efficiency of conductive clothing, ECC, in decibels, is given by Equation 2:

$$ECC = 20\ log_{10}\left(\frac{I_{suit} + I_{body}}{I_{body}}\right) \tag{2}$$

The compliance criterium is that the efficiency calculated from the rate of the two currents should be higher than 99% at all voltage levels [10][11].

Table 4 Result of the screening efficiency test

Voltage level [kV]	Efficiency level
50	99.9 % - 106.23 dB
75	99.9 % - 102.54 dB
100	99.9 % - 108.13 dB
125	99.9 % - 98.41 dB

According to Table 4, the screening efficiency test showed that a conductive suit equipped with face mesh could provide widespread protection against the harmful effects of the induction phenomena. Via the application of the suit, the electric field strengths are zero, which means primary protection for those cases when the field strengths exceed the limit value in the vicinity of the conductor. On the other hand, the conductive suit provides an equipotential bonding to the de-energized elements of the OHL and bypasses the current in the event of an accidental reenergizing, thus plays secondary, additional protection to the grounding equipment for those who wear them.

CONCLUSION

In the case of maintenance works, it is of utmost importance to fully ensure the worker's safety throughout the whole time of the work process. During the maintenance work in the vicinity of double-circuit power lines, several risk factors are present even in the surroundings of the de-energized parts of the power line. Those who work on the de-energized conductors are posed to induced voltage, induced current, and low-frequency electric field. In this article, simulations were carried out to present the magnitude of the induced voltage and current that could appear in the passive part of a double-circuit 400 kV OHL. Simulations have shown that the induced voltage value could reach even 19 kV in unfavorable cases, and the induced current can exceed 9 A in the de-energized phases. Against the induced voltage and current, proper use of different special work-site grounding equipment could lead to a result, as the current flows through the grounding connections via their application. Another critical issue is the electric field strength present in the vicinity of AC installations. Simulations were performed with a 400 kV power line tower to show electric field strength distribution for those cases when the

grounding is ensured. It can be seen from the results that in the vicinity of the grounded tower, the electric field strength could exceed the limit values, which is not acceptable from the aspect of safety and legal issues. A new conductive suit has been developed to ensure the workers' complete protection, which could act as primary protection against the electric field that may harm the linemen. The background of the protection method is the so-called Faraday-cage effect that results in theoretically zero electric fields inside the suit.
On the other hand, a conductive suit could function as secondary protection and grounding equipment. In case of accidental re-energization, the equipotential bonding ensures the protection against induced voltage, and the unique conductive material protects the worker's body by bypassing the induced current. To present the efficiency of the conductive suit, an electric screening efficiency test was carried out, which entirely consistent the theoretical background. All in all, it can be stated that a conductive suit could increase the complete protection of the worker and, in some cases, provides additional protection beyond the use of special grounding tools.

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