‘Modelling Linesmen’s Potentials in Proximity to Overhead Lines’

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Modelling linesmen's potentials in proximity to overhead lines

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***Abstract*— A test object which can represent the human body in experiments near energised HV conductors has been developed. Induced potentials of the object have been measured inside an HV laboratory and at an outdoor 400 kV substation. The experimental arrangements have been modelled using the commercial software package CDEGS to compute the induced voltages and compare it with the actual measurements. Calculations show an excellent agreement with measurements. Predictions of the induced voltage of the object along the climbing route of 400 kV tower has also been developed and these show good agreement with the induced voltage levels of real linesmen while climbing such a tower. The human model developed within the software package has proved to be an accurate tool to predict the induced voltage level in a linesman's working environment. CDEGS will be useful for predicting the likelihood of linesmen experiencing microshocks in new working practicies.**

Index Terms—software tools, power transmission lines, voltage measurement, modelling, gas discharges, electric shock, occupational health and safety, personnel

I. Introduction

Overhead line workers (linesmen) become exposed to high electric and magnetic fields on a regular basis as a result of working close to high voltage (HV) transmission lines. These fields can cause induced currents and voltages. The electric fields induce currents on the body surface while the magnetic fields induce internal body currents [1]. The capacitance coupling the body to the HV lines combined with its capacitance to ground dictates the induced voltage levels.

In the UK, routine checks and inspections of overhead lines are carried out by linesmen during non-outage conditions. A typical task which exposes them to such fields is tower condition assessment where linesmen climb a 400 kV tower to its peak while maintaining the safety distances to the live conductors. However, these conditions occasionally lead linesmen to experience unpleasant discharges that may reach levels that require them to postpone their working activity.

A linesman becomes capacitively coupled to the energised conductors and his body voltage potential will rise subject to its distance to the HV conductors and nearby objects. If an ac charge is built up on the body due to this coupling, and a small air gap is maintained between ,say, a fingertip and a grounded metallic object, discharges will occur if the induced voltage across the gap exceeds the breakdown voltage of the air gap [2]. These discharges are known by different terms such as microshocks [3], spark discharges [4], capacitive discharges [5] and nuisance shocks [6]. These discharges are not known to cause any health hazard [7].

For microshocks to occur, the body must reach a substantial voltage and the gap must be small, although the voltages concerned may be large enough to breakdown gaps of a few millimetres in size [8]. An induced voltage as low as 500V may be sufficient for a person to experience discharges [9]. In practice, a person's sensitivity and perception to microshocks may be influenced by different factors including the skin condition [9] and body size [10].

The purpose of the work presented here is to determine the suitability of the commercial software package CDEGS (Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis) and in particular the sub package HIFREQ [11] to model the voltages induced on a human body, an application for which it was not designed. The CDEGS package is based on a series of mathematical equations referred to both field theory and circuit analysis. To facilitate verification of the model developed, a test object that represents the shape of the human body was developed for use in experiments.

II. Concept Development

Initially, a simplified two dimensional test object 'Stickman' was designed to represent the human body in experiments that took place inside the HV laboratory. This has been reported previously [2,8]. These experiments aimed to examine how the induced voltage levels of a test object change according to its distance from an energised overhead line and a relatively large grounded object such as the 6 m tall tower placed inside the laboratory. The following step was to develop a model in CDEGS to represent the experimental setup and predict the induced voltage levels on Stickman at different locations around the tower in which actual induced voltage levels have been recorded. By verification of the software model through actual measurements of simplified situations, much more complicated models of high electric field exposure scenarios may be relied upon without the need to physically measure each case.

The 3-dimensional test object with a structure equivalent to the human body has been developed in CDEGS object-based

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graphical software. This ‘Cylinderman’ has been manufactured and replaced Stickman in the initial experimental setup. Measurements in the HV laboratory with a single bus-bar were modelled using the software package before moving on to conduct outdoor experimental activities in a 400kV substation.

III. Cylinderman Development and Design

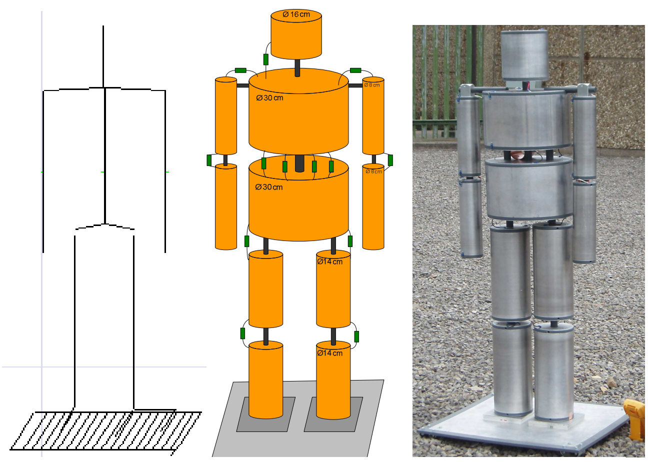
As detailed in [8], Stickman was made of hollow cylindrical copper tubes with an external radius of (14 mm) and internal radius of (12 mm). Unlike Stickman, Cylinderman’s parts were designed to reflect the variation in proportions between its elements similar to the human body.

Cylinderman’s parts have been fabricated from customized aluminium cylinders with specific dimensions (Table.1). The distance between cylinders may be adjusted according to requirements. Each cylinder can be linked to its adjacent one either through a physical component such as a resistor, as illustrated in the schematic of Fig. 1, or through a piece of wire, as shown in Fig. 2, so the impedance between any two parts can be controlled. In all the work reported here the adjacent elements are shorted together using copper wire.

Cylinderman is placed on an aluminium plate fixed to a PVC base to form a controlled ground plane. Cylinderman’s feet are formed by two aluminium plates (150 mm x 150 mm), separated from the ground plane by a 10 mm thick PMMA sheet. This provides a capacitance of 85 pF for each foot, typical of a real shoe value, giving an impedance of 18.7 MΩ between both feet and ground at 50 Hz.

TABLE I.
Cylinderman’s Body Part Dimensions

	Diameter (mm)	Height (mm)
Head	160	170
Upper Trunk	300	200
Lower Trunk	300	200
Upper Arm	80	300
Lower Arm	80	300
Upper Leg	140	360
Lower Leg	140	360



(i) (ii) (iii)

Fig. 1. (i) CDEGS model, (ii) design, (iii) physical realisation

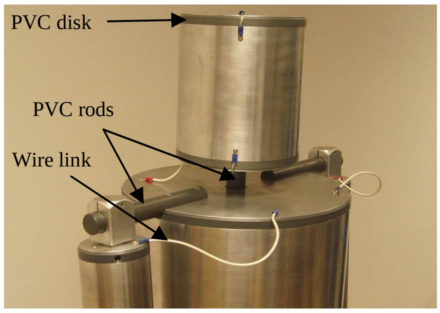


Fig. 2. A photo illustrating the connections between the head, upper trunk and arms

Modelling Cylinderman in CEDEGS proved to be extremely challenging, because the package is designed for use with systems of long conductors. Conductors, regardless of their diameters, can only be displayed in 2-dimensional straight line segments (as illustrated in Fig. 1), which does not facilitate recognition of the borders of adjacent conductors. For example, joining the upper trunk with the head and arms through a resistor is a difficult task primarily due to size differences. As a result, each part has to be assigned as a different conductor type. This problem is reduced if all conductors representing resistor components are replaced with short-circuit ordinary conductors. When necessary, to maintain a body resistance, each body part can be assigned with an internal resistance so that the total resistance on a certain path for example left to right arm or left arm to left foot, remain unchanged in comparison to the original design. What appears on paper as simple structure is in fact a complicated conductor network of different conductor types in the model.

IV. Laboratory Experiment

A. Experimental Setup

An experiment was conducted within the HV laboratory to observe the induced voltage and leakage current levels on Cylinderman at 15 different locations around a 6 m high steel tower. Cylinderman was positioned at distances 0.1, 0.5, 1, 1.5 and 2 m from the tower structure on three sides (E, W and S) with his shoulders parallel to the tower face concerned in each case. 18 m of 28 mm diameter copper tube formed the overhead conductor which was energised at 200 kV rms. Fig. 3 shows the experimental schematic diagram with a photograph of the tower section. The north direction shown is to aid description of the experiment and does not represent the true magnetic north.

As shown in Fig. 4, Cylinderman is capacitively coupled to the energised overhead line and tower as represented by C_{CL} and C_{CT} respectively. C_s represents Cylinderman’s combined shoe capacitance while the capacitance between the overhead line and tower is represented by C_{LT}. A totally conductive Cylinderman has been formed by electrically connecting the adjacent parts as shown in Fig. 2.

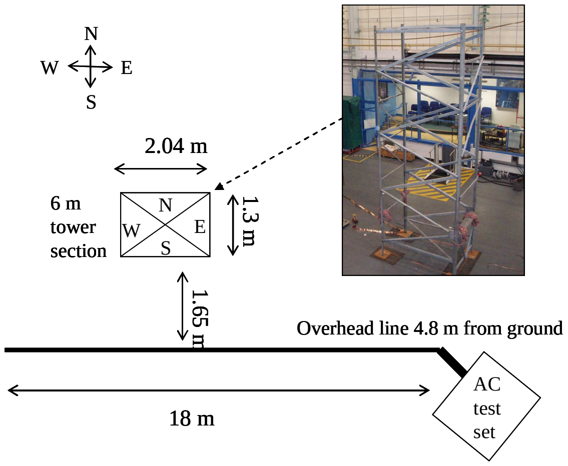


Fig. 3. A schematic plan of the experiment (not to scale).

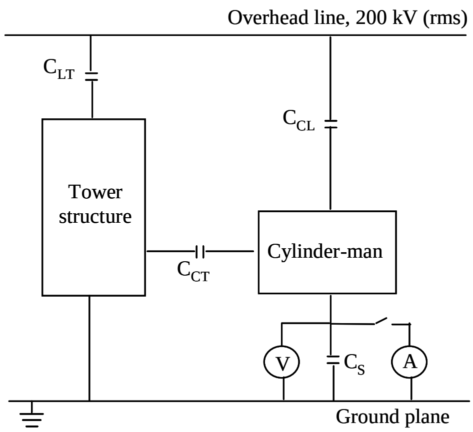


Fig. 4. Experiment equivalent circuit diagram

B. *Induced Voltage Measurements and Software Predictions*

Cylinderman's potential has been measured using a resistive divider (HV probe- Fluke 40k-8) associated with a digital voltmeter. This HV probe has an ac accuracy of ±5% at 50 Hz with and input resistance of 1 GΩ. It has been found necessary to use a metallic box to shield the measurement equipments to prevent recording false measurements as a result of the high electric fields in which the whole experiment was conducted. More experimental detail including calibration is given in [2].

Induced voltages on the totally conductive Cylinderman have been recorded in the various positions around the tower structure and modelled using the HIFREQ module of the CDEGS software. Measured and predicted induced voltages are shown in Fig. 5.

On the south-side, an average of 6% difference has been recorded between measured and predicted voltages with a maximum of 9% recorded at 0.1 m from tower. On the west-side of the tower an 8% average difference has been recorded compared to only 3% on the east-side. In general, a good agreement has been achieved between measured and predicted voltages with a maximum difference of 10% recorded on the west-side, 2 m away from tower.

C. *Leakage Current Measurements vs. Software Predictions*

To further verify the model, the maximum leakage ac current to ground was predicted and measured. To enable this measurement, an ammeter was inserted between one foot and ground while the other foot left isolated from ground. This measurement collapses the voltage to near zero. Measured and predicted currents are shown in Fig. 6. The highest leakage current (93 μA) was measured 2 m from tower on the south-side while HIFREQ has under-predicted the current by 3%. The average difference between measured and predicted currents was 5% on the south-side compared to 4% and 2% on the west and east sides respectively.

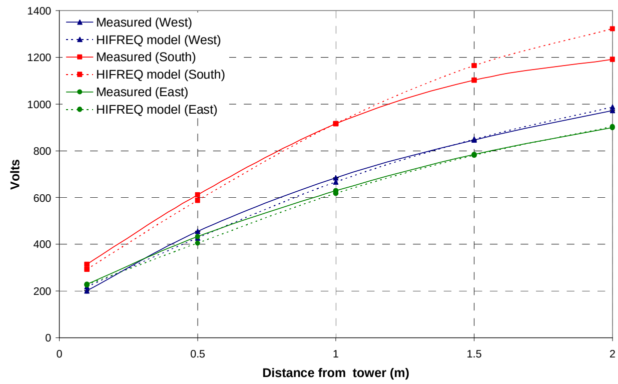


Fig. 5. Induced voltage measurements on Cylinderman (solid lines) and CDEGS predictions at various locations around the tower.

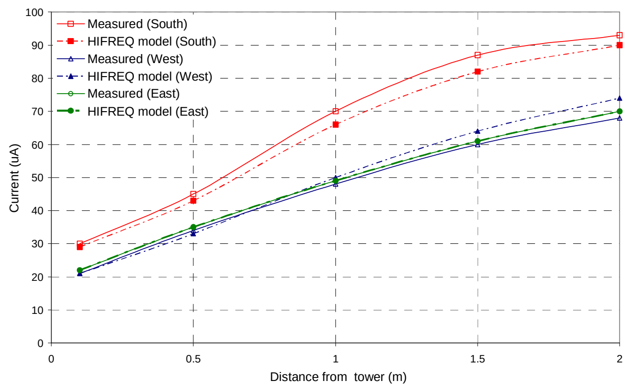


Fig. 6. Measurements and predictions of the current flowing through an earthed foot of Cylinderman. Solid lines represent the measured current.

V. Outdoor Measurements & Predictions

A. *Measurements and Predictions at a Substation*

Controlled outdoor experiments have been carried out under three 400 kV bus-bars passing above a fenced area approximately 15 m x 7 m. These bus-bars have a diameter of 220 mm, are 8.75 m from ground and 4.5 m apart. The software schematic and a photograph illustrating the test location are shown in Fig. 7. In order to allow the induced voltage on Cylinderman to rise to similar levels measured under the energised conductor inside the HV laboratory, the shoe capacitance to ground was reduced by thickening the PMMA layer between the two aluminium plates. By doubling the thickness the capacitance was reduced to 42 pF per foot.

Cylinderman was located at different positions at ground level as shown in Fig. 7. The highest measured induced voltage was found to be under bus-bar A, and this dropped considerably as Cylinderman moved toward the end of the fenced region, under bus-bar C.

According to the model, the highest voltage is predicted when Cylinderman is moved from under busbar A 0.5 m away from the bus-bars. However, the actual measured voltage drops 7% when Cylinderman moved to that location. Apart from this mismatch, predictions showed a good agreement with the actual measurements. Moreover the model has predicted accurately the leakage current under bus-bar A.

B. *Induced Voltage Predictions along a Climbing Route*

A model in HIFREQ has been developed to predict the induced voltage levels along the climbing route of a tower. A Cylinderman leaning back with a straight upper body posture represented the human body. A detailed structural model of the tower was generated in CDEGS for this activity. Voltage computations have been generated at 3 m intervals from the tower base to its peak with Cylinderman's trunk 0.3 m from tower. Fig. 8 presents the distribution of induced voltages. The highest voltage is predicted at the location directly opposite the bottom conductor level. The induced voltage decreases significantly along the climbing route between the top and bottom cross-arms as a result of the superposition of the fields produced by the different phases.

The change in Cylinderman's potential as a result of relatively small movements in relation to the closest conductor and tower was computed. Voltage predictions have been produced 0.5 m above, below, to the left and away from the position with the highest voltage prediction (3503 V). The computations, illustrated in Fig. 9, show the sensitivity of the voltage to Cylinderman's position. Moving away from the bottom conductor reduced his potential by 40% while a movement to his left cut his voltage by 20%. However, predicted voltages have decreased by only 7% by moving Cylinderman downwards and increased by 1% moving him upwards.

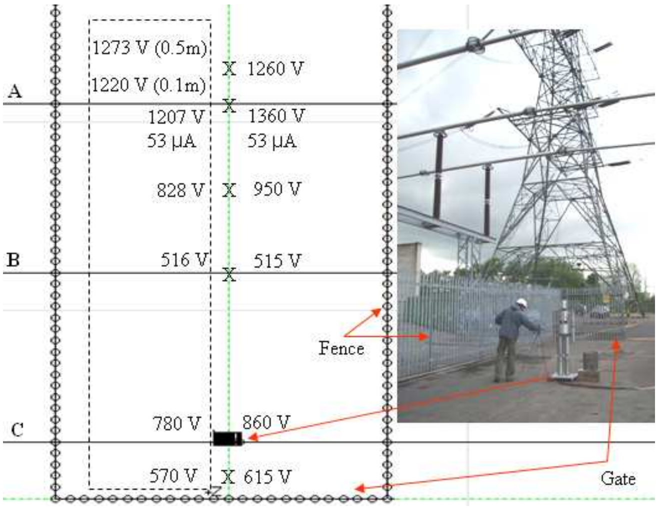


Fig. 7. Measured values under 400 kV busbars (A, B and C) at locations marked 'X'. Predicted values are contained within the dotted box to the left, measured values are printed on the right hand side of the positions.

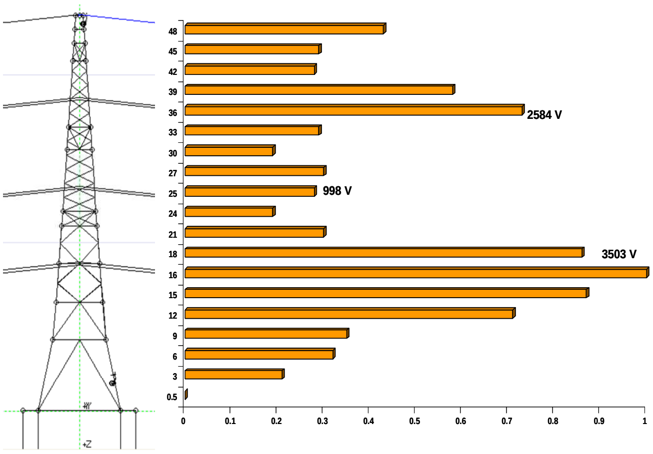


Fig. 8. Predictions of induced voltage on the climbing route of a standard 400 kV tower.

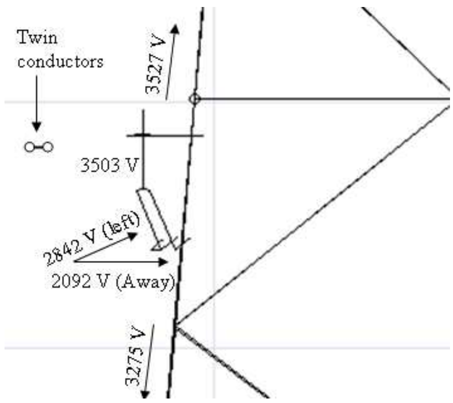


Fig. 9. Sensitivity analysis of the induced voltage on the tower opposite to bottom conductor region

C. Measurements on a Tower with Live Circuits

Measurements have been made on a tension tower similar to the one shown in Fig. 10. During the climb a copper adhesive tape was worn around one wrist to maintain a good electrical connectivity between the body and the HV probe connected to the voltmeter. Along the first few meters of the climb, microshock discharges were not felt, implying an induced voltage of less that 1 kV. Eventually, mild discharges were felt on the skin under the copper tape whenever the wrist came in close proximity to the tower frame. The intensity and frequency of discharges increased with height towards the bottom cross-arm, and were received at various points on the body as they came in close contact with the tower e.g. both hands and knees. Readily felt discharges implies a voltage of above 1 kV.

On a location directly opposite the jumpers connecting the bottom phase conductors, a safety belt was used to enable the climber lean back to with free hands, to isolate the body from the tower, in line with the diagram of Fig. 9. At this location the measured body potential was 2.5 kV. The exact voltage was found to be very sensitive to body position. By way of reference, 40 V was recorded at the ground level next to the tower leg.

VI. Discussion

Previously CDEGS has been shown to provide accurate models for Stickman. However Stickman was designed so that it could be readily modelled in the software [8]. The modelling of the Cylinderman is not a normal application for the software, however the HV laboratory experiments show an excellent correlation between measured and predicted induced voltages and leakage currents for Cylinderman. On the south side of tower, the average difference between measured and predicted induced voltages on Cylinderman was 6% compared to 5% average difference on Stickman at the five test locations. On the west side the average difference was 8% on compared to 4% for Stickman. On the east side, the average difference was 4% compared with 2% for Stickman.

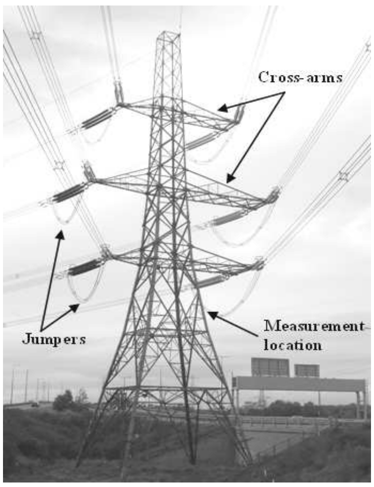


Fig. 10. A 400 kV transmission line tension tower highlighting the measurement location directly opposite the lowest live jumpers

The maximum difference was 10% on the south side, 2 m from tower. These variations are small in the context of the situation, and probably reflect uncertainties in geometry. Also the laboratory itself provides capacitive coupling to the Cylinderman and surroundings and so the geometric representation is not entirely accurate. Leakage currents flowing through Cylinderman's foot have also been predicted with excellent agreement to measured values with an average difference of 4% on the south and west sides and 2% at the east tower side. Measurements have not been recorded at the north tower side as this area falls at the tower 'shadow', where the electric field is shielded by the structure and therefore low induced voltage levels are seen, well below the values of interest.

This experimental verification suggests that any approximations used in the commercial software do not prevent it from being suitable for this application.

The HIFREQ model created for the HV laboratory and substation setups has produced accurate induced voltage and leakage current predictions. These results have encouraged the development of further models to predict the induced voltages at more complex locations. In general, the predicted induced voltage levels along the climbing route on a 400 kV tower shown in Fig. 9 are in-line with actual measured potentials on a similar location directly opposite the jumpers connecting the bottom phase conductors where the measured body potential reached levels between 2.5 kV and 5 kV. Exact verification has not been possible since the health and safety issues have prevented Cylinderman being raised up the tower. In addition both the experimental measurement on a linesman, and the HIFREQ analysis showed a high sensitivity of induced voltage to location. This is because the body's capacitance to the tower varies strongly with position in this situation and adds to the foot capacitance. HIFREQ is able to calculate these capacitance values but can only work with the geometric data provided.

Linesmen's reports of microshocks suggest the highest voltages are seen at the bottom cross arm level, giving further support to the model generated. The voltages measured on the particular tower climbed of up to 2.4 kV, and those predicted on the standard tower and illustrated in Fig. 8 of up to 3.5 kV are high enough to cause microshocks, as reported by linesmen.

VII. Conclusions

The methodology of developing simple but realistic test objects to represent the human body have worked well. Previously Stickman was developed to provide experimental data against which a CDEGS model could be thoroughly tested, and showed a high level of accuracy. CDEGS has now been shown to accurately model potential on a 3-dimensional, human shape in a variety of situations near high voltage plant. Cylinderman and its equivalent CDEGS model are reliable tools that can be utilised to assess the likely induced voltage and leakage current levels on a person's body close to HV equipment.

Developing further models of more sophisticated and realistic work exposure scenarios is expected to identify situation in which microshocks is to be expected. These models are further expected to assist with developing and verifying practical mitigation techniques.

VIII. ACKNOWLEDGEMENT

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X. BIOGRAPHIES

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