

Simulation study on transient electric shock characteristics of human body under high voltage ac transmission lines

Tao Huang^{1,2}, Yanhui Zou^{1,2}, Jianhong Lv¹, Jinchun Yang¹, Li Tao¹, Jianfei Zhou¹

¹ Electric Power Research Institute of State Grid Hunan Electric Power Company, Changsha 410007, China

² Hunan Xiangdian Test & Research Institute. CO. LTD, Changsha 410007, China

Abstract. Human body under high-voltage AC transmission lines will produce a certain induced voltage due to the electrostatic induction. When the human body contacts with some grounded objects, the charges transfer from the body to the ground and produce contact current which may cause transient electric shock. Using CDEGS and ATP/EMTP, the paper proposes a method for quantitatively calculating the transient electric shock characteristics. It calculates the human body voltage, discharge current and discharge energy under certain 500kV compact-type transmission lines and predicts the corresponding human feelings. The results show that the average root value of discharge current is less than 10mA when the human body is under the 500kV compact-type transmission lines and the human body is overall safe if the transmission lines satisfy the relevant design specifications. It concludes that the electric field strength above the ground should be limited to 4kV/m through the residential area for the purpose of reducing the electromagnetic impact.

1 Introduction

Due to the electric field effect, there are two types of electrostatic induction effects when the human body is under AC transmission lines. One is the long-term physiological effect caused by the steady electrostatic induction current in the human body due to long time exposure in the electric field, and the other one is the short-term physiological effect caused by transient current flowing through the human body when contacting the low potential objects. The steady effect is not obvious as the electric field near the residential area is usually less than 4kV/m. However, the transient current flowing through the human body may cause strong electric shock which causes a serious public concern. Therefore, this paper mainly focuses on the short-term transient shock effect under AC transmission lines.

When the human body is under the AC transmission lines, the body potential will be higher than ground potential due to the electrostatic induction. When the human body contacts a grounded metal object such as a grounded metal rail, charges transfer quickly from the human to the ground in a short time which produces the transient current and causes the transient electric shock.

Foreign and domestic scholars have made a lot of researches on the transient electric shock problem. Early theoretical and experimental researches on the discharge process from high-potential objects to the human body under transmission lines were made in Ref [1-5]. The single transient shock current of the vehicle to the human body under the uniform electric field was calculated and an effective equivalent circuit model was proposed in Ref [6-7]. The electric current and electric field induced in the human body when exposed to an incident electric field were calculated by analytical



method in Ref [8-9]. The steady induced voltage and single maximum transient shock energy under AC transmission lines were calculated by two-dimensional FEM in Ref [10] while the induced current in the human body was calculated by three-dimensional FEM in Ref [11]. The test which simulated the discharge process from high-potential object to the human body was carried out and the discharge current was collected in Ref [12-13]. However, all the references mentioned above failed to build a complete electric field and circuit analysis model for the body-to-ground discharge process under the transmission lines.

In this paper, an electrostatic field model of the human body under certain 500kV compact-type transmission lines (non-uniform electric field) is established by CSM (charge simulation method), and the field model is transformed into a circuit model. Finally, the arc discharge model is introduced to the equivalent circuit to truly reflect the instant discharge process of the human body when contacting the grounded objects.

2 Mechanism of the transient electric shock in the human body

When the human body is under the AC transmission lines, its potential is higher than the ground potential due to the power frequency electric field and only micro-level steady-state induction current flows in the human body. If the human body suddenly touches the grounded metal object, the charges will transfer to the ground and form the amperometric level of pulse current, which is the main reason causing electric shock sensation.

In fact, when the human body effectively contacts the grounded metal object, the human body surface is gradually getting close to the surface of metal object. In this process, when the air gap between the human body and the metal object is less than a critical point, the potential difference can produce a strong enough electric field strength so that the air gap breaks down and forms conductive arc, that is, the formation of the discharge pulse. Then the potential difference between the human body and the metal object is almost zero. Further, when the arc current is less than the critical value, the arc discharge can not maintain and then extinguishes. The human body is recharged and the potential difference becomes larger until the air gap breaks down again and forms conductive arc. This is a cycling process which may last tens of milliseconds and forms multiple times of breakdown - discharge - arc extinguishing process. Therefore, when the human body contacts the metal object, multiple transient electric shocks occur and the total energy is much higher than the energy of a single transient electric shock resulting in a more intense sensation of the human.

According to research of the IEEE electrostatic induction work group, when the discharge energy is 0.1mJ, the electric shock reaches the level of sensibility. When the discharge energy ranges from 0.5mJ to 1.5mJ, the electric shock will not cause physical damage directly, but can make people upset and cause unnoticed muscle reaction. When the discharge energy reaches 25mJ, the electric shock may cause damage to people.

3 Electrostatic induction analysis of human body under AC transmission lines

3.1 Parameters of Transmission Lines

In order to analyze the transient electric shock level of the human body under high voltage transmission lines quantitatively, a certain 500kV compact-type transmission lines is chosen. The specific parameters of the transmission lines are shown in Figure 1.

3.2 Human body model in AC electric field

Based on the HIFREQ module of CDEGS, the induced voltage and induced current are calculated when the human body is under the transmission lines mentioned in 3.1. The model of the human body and transmission lines in CDEGS is shown in Figure 2 and the detailed human body model is shown in Figure 3. The human body model is in typical size, composed by head, trunk, arms, legs and feet^[14]. Considering that CDEGS is suitable for cylindrical conductor, the five parts of the human body model

is equivalent to several cylindrical conductors respectively and equivalent column structures of each part are shown in Figure 4 and Table 1.

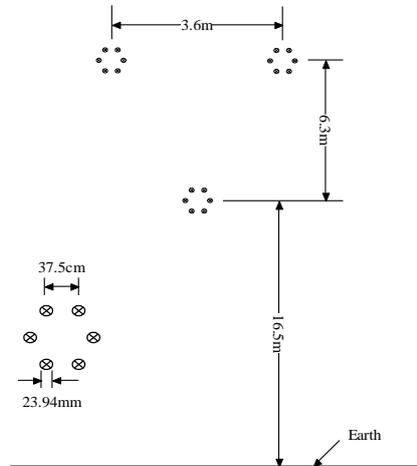


Figure 1: Parameters of certain 500kV compact-type transmission lines.

Table 1: Geometric parameters of the human body equivalent model.

Body parts	Diameter(mm)	Length(mm)
Head	160	170
Trunk	300	500
Legs	80	810
Other connecting parts	/	200

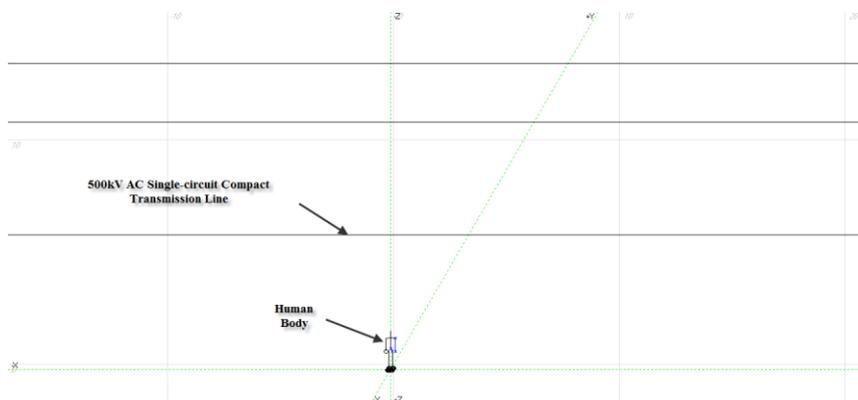


Figure 2: Human body-transmission lines model in CDEGS.

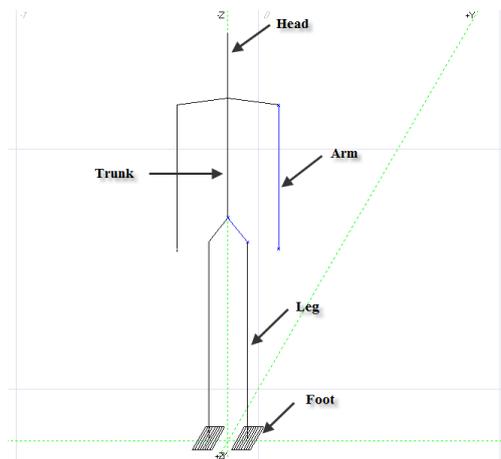


Figure 3: Detailed human body model in CDEGS.

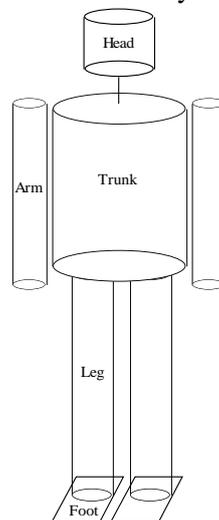


Figure 4: Equivalent human body model in CDEGS.

3.3 Calculation of human body open-circuit voltage and short-circuit current

Corresponding voltage sources are set to each phase conductor of the 500kV transmission lines and the human body is in suspended state which means that the human body is insulated to the ground and in open-circuit state. The open-circuit voltage of the human body U_0 can be obtained by calculating the human body to ground potential. By keeping the voltage source the same, the short-circuit current I_{sc} can be calculated when the human body is grounded. Different open-circuit voltages and short-circuit currents can be obtained when the distance between the human body and the center of the transmission lines changes, as shown in Table 2 and Table 3.

4 Transient electric shock calculation based on ATP/EMTP

4.1 Transformation of electrostatic field model to circuit model

As CDEGS is based on field analysis, only steady-state parameters of the transmission lines and human body system such as partial capacitance, open-circuit voltage, short-circuit current can be calculated. As shown in Table 2 and Table 3, the phase of the short-circuit current is always ahead 90° than the open-circuit voltage which means the transmission lines and human body system is a linear distributed parameter system and can be equivalent to a capacitive centralized parametric circuit.

In order to avoid complicated calculation of partial capacitances, the Thevenin equivalent circuit model is adopted to converse the field model to the equivalent circuit model rapidly. Then the equivalent capacitance can be calculated as follow:

$$C_{eq} = \left| \frac{\dot{U}_0}{\dot{I}_{sc}} \right| \quad (1)$$

4.2 Transient circuit model of human body discharge

When the human body contacts the grounded metal object, the centralized parametric system composed by the grounding resistance (R_g), the human body's internal impedance ($R_b + jL_b$) and the discharge gap capacitance (C_{gap}) can be seen as a external circuit and connect to a port of the original equivalent capacitance network formed by the transmission lines and human body. And finally the two parts form the transient equivalent circuit model to simulate the process of human body to ground discharge as shown in Figure 5.

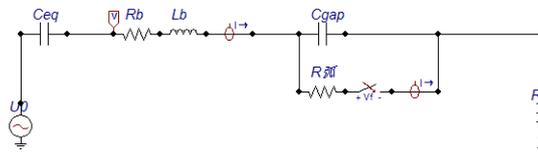


Figure 5: Equivalent circuit model of human body to ground discharge.

In the human body impedance model, R_g is 5Ω , R_b is 1750Ω ^[12], and L_b is $1\mu\text{H}$ ^[7].

In the arc discharge model, C_{gap} is the equivalent capacitance of the air gap between the human body and the grounded metal object which varies with the distance of the human body and the grounded object. As the gap is very small, the capacitance of the gap can be calculated by parallel plates capacitance formula as shown in Equation 2 and the electric field of the gap can be obtained by Equation 3.

$$C_{gap} = \frac{\epsilon S}{d} \quad (2)$$

$$E_{gap} = \frac{U_{gap}}{d} \quad (3)$$

As shown in Figure 5, V_f represents the voltage control switch to simulate the air breakdown and insulation recovery. When E_{gap} is larger than E_{break} , V_f closes and the charges in the human body release to the ground through the arc discharge channel. When the charges release too much, the arc current is less than certain threshold and the arc channel could not maintain resulting in the extinction of the arc and the disconnect of V_f . The air gap may produce several “breakdown - discharge - extinction” processes with the voltage of the human body changes in a frequency cycle. In this paper, the breakdown electric field is taken to be 25kV/m , the extinction arc current is 0.1A and the resistance of the arc is 1Ω .

5 Simulation results of transient electric shock

5.1 Sectional distribution of transient electric shock

The coupling capacitance between transmission lines and human body and the discharge characteristics changes with the human body's position under the transmission lines. This section simulates the discharge process when the human body contacts the grounded metal object at different position under 500kV compact-type transmission lines. In the calculation, the height of the

transmission line is 16.5m, the gap between human body and the grounded metal object is 0.5mm and the contacting process lasts for about 1s. Calculation results are shown in Table 2 and Figure 6.

As shown in Figure 6, the human body to ground discharge is actually pulse current discharge which has a periodic repetition characteristics and repeats every half frequency cycle and the pulse current peak can reach amperometric level. With the horizontal distance between the human body and the center of the transmission lines decreases, the discharge frequency increases. When the contacting gap keeps the same, the peak of the discharge current remains unchanged because of the limit of the breakdown voltage of the discharge gap.

It can be seen from Table 2 that when the human body is directly under the transmission lines, the discharge energy and the average root value of discharge current reaches the maximum value, 18.96mJ and 3.29mA. The discharge energy and the average root value of discharge current decrease with the horizontal distance between the human body and the center of the transmission lines increases. Transient electric shock no longer happens when the distance is more than 25m.

According to the results, when the horizontal distance between the human body and the center of the transmission lines is more than 15m, the human body has no feeling of electric shock; When the distance is 0m~10m, the human body has an obvious electric shock feeling which makes people upset and cause unnoticed muscle reaction but does not reach the level of causing physiological damage.

Table 2: Characteristics of transient electric shock with different position of human body.

Horizontal distance from the center of the line X/m	Measured value of electric field E/V/m	Calculated value of electric field E/V/m	Calculated value of open-circuit voltage U_o/V	Calculated value of short-circuit current $I_{sc}/\mu A$	Calculated value of equivalent capacitance C_{eq}/pF	Discharge frequency	Discharge energy during 1s Q/mJ	Average root value of discharge current I_{eq}/mA
0	4242.9	4184.8	1882.0 \angle -120.00°	55.4 \angle -30.02°	93.75	500	18.96	3.29
5	3775.3	3581.8	1611.7 \angle -106.88°	47.4 \angle -16.90°	93.66	400	15.35	2.96
10	2840.2	2455.1	1105.2 \angle -88.95°	32.5 \angle 1.03°	93.65	200	8.13	2.15
15	1694.3	1633.9	737.8 \angle -66.01°	21.7 \angle 23.97°	93.67	1	0.036	0.14
20	1178.8	1196.9	541.2 \angle -44.28°	15.9 \angle 45.70°	93.56	1	0.036	0.14
25	925.4	923.0	424.6 \angle -28.18°	12.5 \angle 61.80°	93.75	No pulse current		

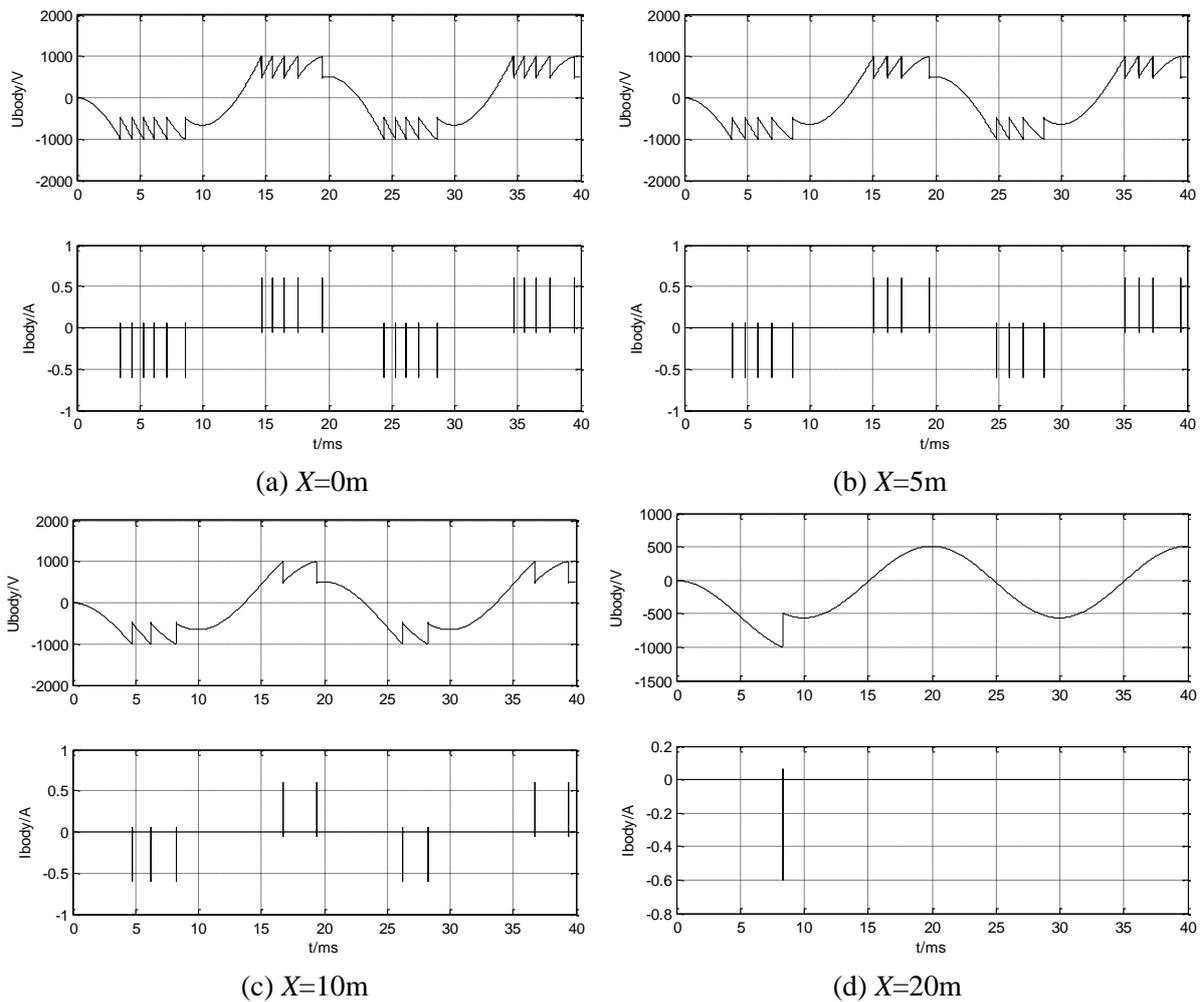


Figure 6: Discharge voltage and current waveforms at different X .

5.2 Characteristics of transient electric shock with different height of transmission lines

The coupling capacitance between transmission lines and human body and the discharge characteristics changes with the height of the transmission lines. This section simulates the discharge process when the human body contacts the grounded metal object under 500kV compact-type transmission lines of different heights. In the calculation, the gap between human body and the grounded metal object is 0.5mm and the contacting process lasts for about 1s. According to the code for design of 110~750kV overhead transmission line (GB 50545-2010), the minimum height of the transmission lines shall not be less than 14m when it crosses through the residential area and shall not be less than 10.5m when it is triangular arranged and cross through the non-residential area. So the lower limit in Table 3 is 10.5m.

As shown in Table 3, the maximum electric field under the line, the discharge energy and the average root value of discharge current increase with the decrease of the height of the transmission lines. When the height is lower than 17m, the maximum electric field exceeds 4kV/m. When the height is lower than 14m, the maximum electric field exceeds 5.6kV/m and the discharge energy exceeds 25mJ, which reaches the level that may cause damage to the human body.

Table 3: Characteristics of transient electric shock with different heights of transmission lines.

Height H/m	Maximum electric field under the line $E/kV/m$	Calculated value of open- circuit voltage U_o/V	Calculated value of short- circuit current $I_{sc}/\mu A$	Calculated value of equivalent capacitance C_{eq}/pF	Discharge energy during 1s Q/mJ	Average root value of discharge current I_{eq}/mA
36.0	1	461.15 \angle - 120.00°	13.6 \angle -30.02°	93.92	No pulse current	
24.6	2	922.2 \angle - 120.00°	27.1 \angle -30.02°	93.59	4.52	1.61
19.8	3	1361.9 \angle - 120.00°	40.1 \angle -30.02°	93.77	11.74	2.59
17.0	4	1784.7 \angle - 120.00°	52.5 \angle -30.02°	93.68	15.35	2.96
14.0	5.6	2505.8 \angle - 120.00°	73.7 \angle -30.02°	93.67	26.18	3.87
10.5	9.3	4099.1 \angle - 120.00°	121.0 \angle - 30.02°	94.01	47.84	5.23

5.3 Characteristics of transient electric shock with different contact gap

The air gap between the human body and the grounded metal object is not constant in the contact process. This section simulates the discharge energy and average root value of discharge current at different length of air gap when the height of the transmission line is 17m and the human body is directly under the line.

As shown in Table 4, when the length of the air gap between human body and grounded metal object is more than 2mm, the potential difference is not enough to breakdown the air so that transient electric shock will not happen. When the length of the air gap is less than 1mm, the discharge energy and average root value of discharge current decrease with the decrease of the length. When effective stable contact is built between human body and grounded metal object, the transient electric shock does not occur and the current flows in human body is power frequency steady current.

Table 4: Characteristics of transient electric shock with different contact gap.

Length H/m	Capacitance C_{gap}/pF	Breakdown voltage U_{break}/V	Discharge energy during 1s Q/mJ	Average root value of discharge current I_{eq}/mA
0.1	4.98	200	5.33	1.75
0.2	2.49	400	9.47	2.33
0.5	1.00	1000	15.35	2.96
1	0.50	2000	22.32	3.57
2	0.25	4000	No pulse current	

6 Conclusion

(1) The discharge energy and discharge current of human body to ground is positive correlated with the position of the human body under the 500kV transmission lines which means the greater the original electric field strength, the greater the discharge current and energy.

(2) If the design of the transmission lines cross through the residential area meets the code for design of 110~750kV overhead transmission line (GB 50545-2010), the electric field strength above ground and the discharge energy is generally not over 4kV/m and 25mJ respectively, which means the human body is overall safe.

(3) When the maximum electric field under transmission lines exceeds 5.6kV/m, the discharge energy is larger than 25mJ which may cause damage to human body. It is recommended that the electric field

strength above the ground should be limited to 4kV/m in the residential area for the purpose of reducing the electromagnetic impact.

References

- [1] J Patrick Reilly. "Electric field induction of long objects - a methodology for transmission line impact studies", *IEEE Transactions on Power Apparatus and Systems*, **98**, pp. 1841-1852, (1979).
- [2] J Patrick Reilly. "Characteristics of spark discharges from vehicles energized by AC electric fields", *IEEE Transactions on Power Apparatus and Systems*, **101**, pp. 3178-3186, (1982).
- [3] J Patrick Reilly. "Electrocutaneous stimulation with high voltage capacitive discharges", *IEEE Transactions on Biomedical Engineering*, **30**, pp. 631-641, (1983).
- [4] J Patrick Reilly, V T Freeman, Willard D Larkin. "Sensory effects of transient electrical stimulation - evaluation with a neuroelectric model", *IEEE Transactions on Biomedical Engineering*, **32**, pp. 1001-1011, (1985).
- [5] J Patrick Reilly, Willard D Larkin. "Human sensitivity to electric shock induced by power - frequency electric fields", *IEEE Transactions on Electromagnetic Compatibility*, **29**, pp. 221-232, (1987).
- [6] C J Lin, H R Chaung, K M Chen. "Steady-state and shock currents induced by ELF electric fields in a human body and a nearby vehicle", *IEEE Transactions on Electromagnetic Compatibility*, **32**, pp. 59-65, (1990).
- [7] MA Aiqing, WANG Haibo, CHEN Lei, et al. "Electric shock effect on human body generated by car parked under HVAC transmission lines based on human body MSM model", *High Voltage Engineering*, **39**, pp. 2876-2881, (2013).
- [8] Ronold W P K. "Electric current and electric field induced in the human body when exposed to a incident electric field near the resonant frequency", *IEEE Transactions on Microwave Theory and Technique*, **48**, pp. 1537-1543, (2000).
- [9] Ronold W P K. "Currents and electric fields induced in the human body when the arms are raised", *Journal Application Physics*, **81**, pp. 7116-7128, (1997).
- [10] WU Jian, An Cuicui, Bai Xiaochun, et al. "Research on transient electric shock of human body under AC transmission lines", *High Voltage Apparatus*, **47**, pp. 37-46, (2011).
- [11] Wang Jianhua, WEN Wu, Ruan Jiangjun, et al. "Calculation of electric field induced currents in human body under 1000kV UHV", *High Voltage Engineering*, **33**, pp. 46-49, (2007).
- [12] A. Gunatilake, S. M. Rowland, Z. D. Wang, et al. "Modeling and management of microshocks under high voltage transmission lines", *IEEE Holm Conference*, **11**, pp. 63-68, (2005).
- [13] Aruna Gunatilake, Yasir Ahmed, S M Rowland. "Modeling of microshocks associated with high-voltage equipment", *IEEE Transactions on Power Delivery*, **24**, pp. 202-207, (2009).
- [14] Yasir Ahmed, Simon M. Rowland. "Modeling linesmen's potentials in proximity to overhead lines", *IEEE Transactions on Power Delivery*, **24**, pp. 2270-2275, (2009).