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A New Computational Method for Study of Corona Generated Electric Field Environment of HVDC Transmission Lines

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SUMMARY

UHVDC transmission plays a vital role in transmission of bulk amount of power over longer distances. Construction of the UHVDC transmission lines with minimal environmental impacts [1] and optimal cost needs more attention before designing the transmission lines. Consequently, to design the HVDC Transmission lines at UHV levels, various problems associated with it are being studied extensively elsewhere in the world. Presently in India +/-500 kV HVDC transmission lines are in operation and construction of ± 800 kV UHVDC bipolar transmission line is in progress. The Electric field environment under a DC line is significantly different from that existing under AC lines. One of the critical criteria in the design of HVDC transmission lines is their corona performance. It is not only the economic importance because of power losses resulting from the occurrence of corona on conductors, but is also associated with additional undesirable effects such as electromagnetic interference, audible noise, radio noise and space charge effected electric field [2, 3]. The electric field environment under a DC line may be characterized by the electrical field distribution, Space charge density and ionic current density. From the point of view of assessing the environmental impact, it is necessary to characterize the electric field environment of UHVDC transmission line. It is reported in literature that, the ionized field due to the corona effects of UHVDC transmission lines results in biological effects on human or any living organisms under and near the lines. Considerable experimental efforts have been put in to determine the corona behavior of HVDC lines on the basis of measurements conducted on short and long test sections of actual lines for different weather conditions elsewhere in the world [4]. However, evaluation of alternate line design based on entirely experimental means proved to be costly and time consuming. On account of this fact, a study of the electric field environment of HVDC transmission lines using computational analysis with supporting practical experimental results can provide significant support for alternate line design.

Few researchers have done work on computing the electric field environment parameters based on analytical methods such as Charge Simulation Method (CSM), Finite Element Method (FEM), Flux Tracking Method (FTM), Flux Integral Method and Integral Algorithm Method [5-11] etc. In all published literature, the analytical techniques were based mostly on steady state models and differed mainly in the computational techniques used. It is observed from the literature [5-11] that, it is possible to compute the electric field environment of HVDC lines using modelling of physics involved in the corona phenomenon of line conductor. In this context, the authors have made an attempts to evolve the computational method using the physics of the corona phenomenon around the line conductor considering impacts of atmospheric parameters such as temperature, pressure and humidity

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to study the electric field environment of unipolar HVDC transmission lines. The computation procedure involves calculation of space charge ion concentration, ionic current and space charge effected electric field at ground levels for a given atmospheric temperature and pressure. This paper presents the details of experimental investigations carried out for different experimental configurations, computational method to study the electric field environment of unipolar HVDC lines and comparison of both experimental and computational results.

KEYWORDS

Corona, HVDC transmission lines, Electric field environment, Ionic current, Space charge, Computational method, Unipolar

INTRODUCTION

The electric field environment under the HVDC line is significantly different from that existing under HVAC lines. At voltages above corona inception, the breakdown of air results in generation of space charge around the conductors. On a unipolar DC transmission line, ions having the same polarity as the conductor voltage that fill the entire inter-electrode space between the conductors and ground. On a bipolar HVDC transmission line, corona occurs almost simultaneously on conductors of both positive and negative polarities. The ions generated on the conductors of each polarity subject to electric field are drifts either towards the conductor of opposite polarity or towards the ground plane [12], as shown in Figure 1. As a result, the gradient at the conductor surface is decreased, whereas the gradient at the ground plane is increased. The drifting of these space charge ions towards the ground or towards the conductor of opposite polarity gives rise to a current flow in the entire inter electrode space between the conductors and the ground plane. Not only the ionic current flow at ground levels, the existence of space charge also exerts a significant influence upon the static electric field surrounding the line and at the ground levels. Hence, the electric field environment under a DC line may be characterized by Electrical field distribution, Space charge ion density, and Ionic current density.

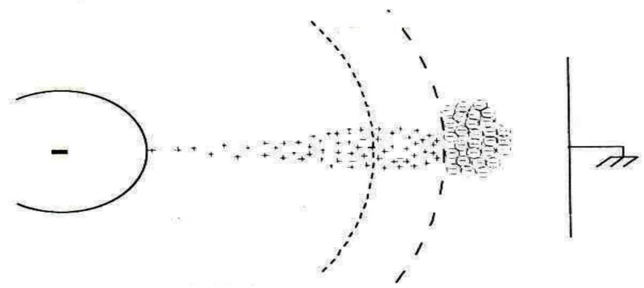


Fig. 1: Ionic current flow of a unipolar HVDC transmission line.

METHOD OF CALCULATION FOR ELECTRIC FIELD ENVIRONMENT OF UNIPOLAR HVDC LINES

To calculate the parameters of the electric field environment of unipolar HVDC transmission lines such as space charge density, ionic current and electric field, a computational method with an analytical technique of the physics of corona phenomenon is used. The major equations used to estimate the parameters of the electric field environment of unipolar HVDC lines are current continuity equation and passions equation and the governing equations of current continuity and Poission’s equations are given below:

$$\mathbf{J} = \rho b \mathbf{E} \quad \text{..................} \quad (1)$$

$$\nabla.\mathbf{E} = ((\rho/\varepsilon) + \mathbf{E}') \quad \text{..................} \quad (2)$$

Where **E** is space charge effected electric field, **E´** is space charge free electric field, **J** is ionic current density, ρ is ion space charge density and b is the mobility of the ions. The average mobility of ions considered is 1.5 m^2/s although, the mobility of positive ions is higher than negative ions. The corona inception electric field for a given line configuration is calculated by the method of successive images. It is very clear that equations (1) and (2) are dependent on ion space charge density (ρ), this suggests that, it is necessary to determine the magnitude of space charge density ρ to solve the equations (1) and (2). The present method of analytical technique aims at the determination of the magnitude of space charge ion density (ρ) corresponding to a given applied DC voltage using physical modelling of corona phenomenon. In order to achieve this, few assumptions are made to compute ion space charge density which is given below:

1. The electric field stress on the conductor surface is constant.
2. The effect of wind is neglected.

From the equations related to the parameters of the electric field environment of HVDC transmission lines, it is very clear that the ion space charge density at ground level is dependent on ionization of air molecules in the ionization region. Therefore, the computational procedure to estimate the ion space charge density at ground level shall take into account the ionization of air molecules from the ionization region. The formation of an ionization region around a conductor when a higher DC voltage is applied to the conductor is shown in Figure 2.

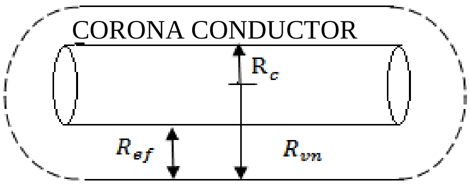


Fig. 2: Ionization region formation around the HVDC conductor.

Where, R_c is the conductor radius, R_{vn} is the virtual radius of the conductor and R_{ef} is effective radius of ionization region. At a given temperature, pressure and humidity, the air molecules present within the ionization volume of radius R_{ef} are only responsible for the generation of space charge ions within the space between the conductor and ground. The basic collision reaction process which ionizes the air molecule result in an electron avalanche in ionization volume of radius Ref and is given by:

$$[A] + [B] \longrightarrow P; \qquad P = k\,[A]\,[B] \qquad (3)$$

Where [A] = free electron or positive ion.
[B] = Air molecule.

Where P is proportional to the product of [A], [B] with k as the proportionate rate constant. The rate constant k can be predicted by considering the physical requirements for successful collision reaction. According to the bimolecular collision reaction theory [13], the rate constant k is proportional to the rate of collisions or collision density (Z) and is given by:

$$k \; \alpha \; Z \qquad (4)$$

However, a collision will be successful only when kinetic energy gained from electric field exceeds a minimum value called the activation energy (Ea) [14] of the collision reaction. Hence the rate constant k should also be proportional to the activation energy (Ea). Thus, the equation (4) can be written as

$$k \; \alpha \; Z \times Ea \qquad (5)$$

It is to be noted that, not every collision leads to successful ionization reaction, even if the energy requirement is satisfied. This is because the collision of electrons should be in a certain relative orientation to eject another electron from a molecule. This relative orientation suggests the steric requirement [13], that a further factor, 'S', should be introduced into the equation below:

$$k \; \alpha \; Z \times Ea \times S \qquad (6)$$

From the literature [13], steric requirement is a parameter which depends on the experimental measurement only and can be used to calculate from the measured values directly. It will vary for each measured value.

Equation (6) is a similar expression of successful collision of ions specified in collision theory [13]. Therefore, rate constant k gives the concentration of electron density, which moves from the ionization region and drifting toward the ground plane in the direction of the electric field. The drifting of these electrons towards the ground plain attaches with air molecules results in the formation of negative ion space charge density. As a result, electron attachment decreases the number of free electrons, unlike ionization which increases the free electrons. The electron attachment during the drifting of ions can be calculated from J J Thomson's electron attachment theory [15]. When this negative ion space charge density drifts towards the ground, diffusion of ions also take place which results in a decrement in magnitude of negative ion space charge density and the diffusion (D) of the ions can be calculated from [16]. The resulting magnitude of negative ion space charge density by taking into account the collision rate constant, attachment coefficient and the diffusion coefficient at ground level is given by

$$\rho = (k - A - D)\, e \qquad C/m^2 \qquad (7)$$

Substituting equation (7) in (1) and (2) for ionic current in amperes and space charge affected electric field distribution at ground levels are being computed.

RESULTS & DISCUSSION

Case A:

An outdoor experimental setup was arranged for measurement of ionic current and electric field. In this experimental setup a monopolar DC conductor of radius 1.015 mm was strung above ground at a height of 1.73 m. The conductor was energized with positive DC voltage in the range of 70kV to 150kV in steps of 20kV. At each applied voltage, the ion current and electric field is measured directly under the line and also at a lateral distance of 1m, 2m, 3m and 4m from the center of the line using the digital DC nano ammeter and a DC electric field meter.

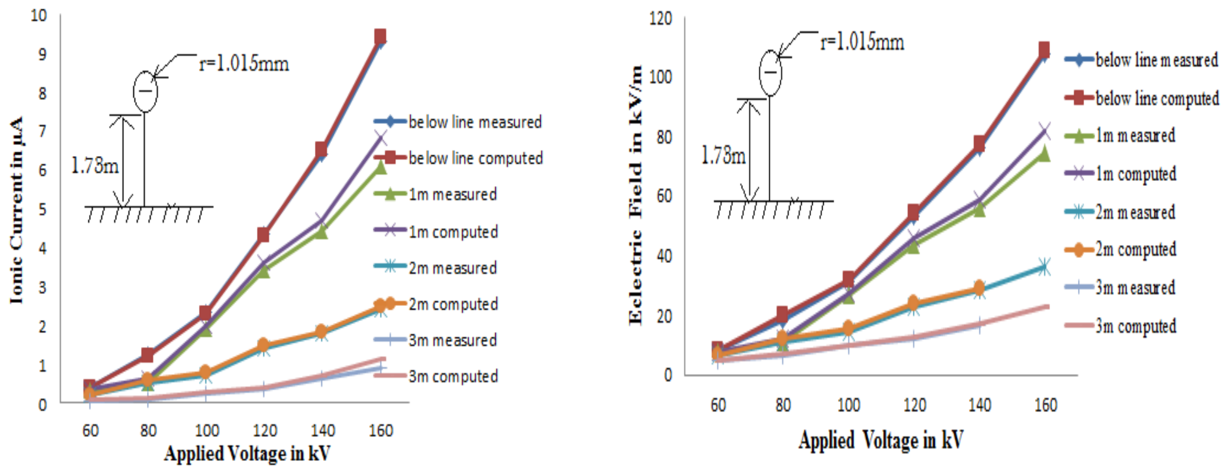


Fig. 3: a) Variation of ionic current b) Variation of electric field

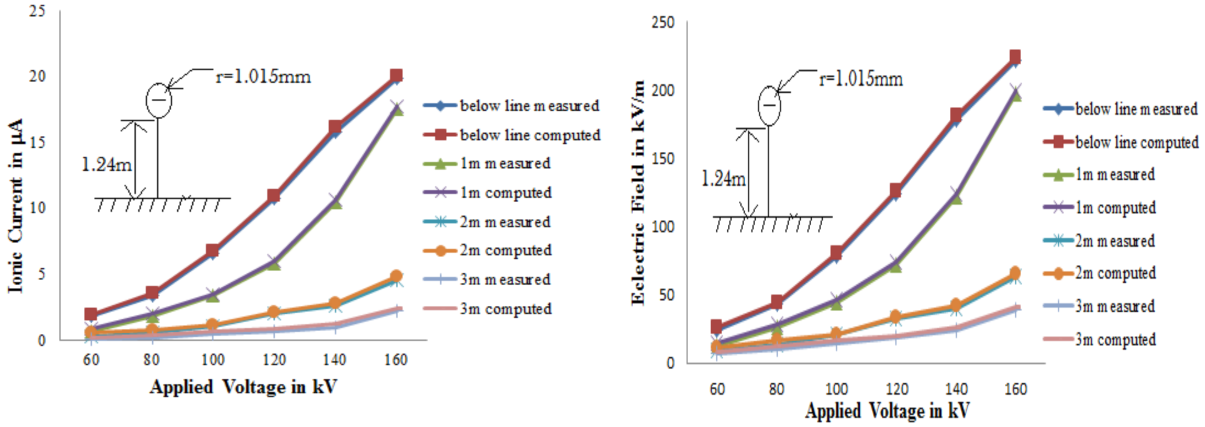


Fig. 4: a) Variation of ionic current b) Variation of electric field

Figures 3 (a) -4 (b) gives the variation of ionic current and electric field of a given line configuration for both positive and negative polarities. It is observed from Figures 3 (a) -4 (b), the computational results of the proposed method are very close to the experimental results and both computational and experimental results are nonlinear in nature.

During the ionic current measurement, it is observed that, the ionic current magnitudes have wide variations from maximum to minimum value due to atmospheric wind velocity. It is also observed that, the maximum magnitude was recorded at lower wind velocity and lower magnitudes at higher wind velocity. This may be due to the fact that the life span of the ions generated during the corona discharge [17], have significant influence in magnitude of the ionic current flow at ground levels. The same variation of ionic current measurements at ground levels can be attained from computational results by varying steric requirement from 0.1 to 0.95, as strict requirement is dependent on measured values explained in earlier sections. Hence, for easy analysis of results, graphs are drawn by taking the average value of the each variation of both electric field and ionic current.

Case B:

Similarly, the ionic current measurement was also carried out for another line conductor configuration comprising of aluminium material having a radius of 1.78 mm strung at a height of 1.24m in outdoor experimental setup. The line conductor was energized with the DC negative polarity in the range of 100 kV to 200 kV with increment of 20 kV. The ionic current was measured directly under the line and also at a lateral distance of 1m, 2m and 3m from the center of the line at all the different voltage levels using the digital DC nano ammeter. Figures 5 (a) - 6 (b) shows the variation of computed and measured values of ionic current and electric field distribution.

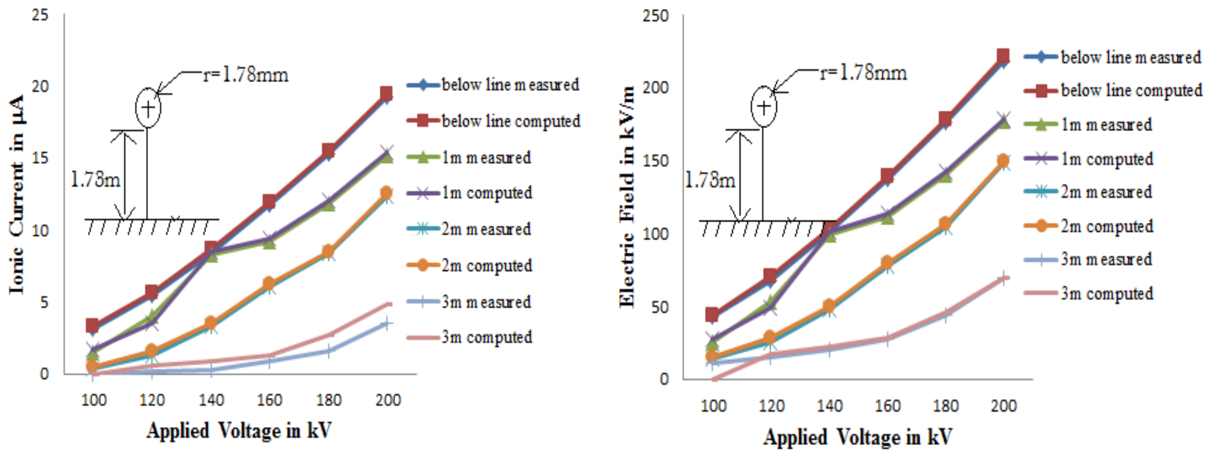
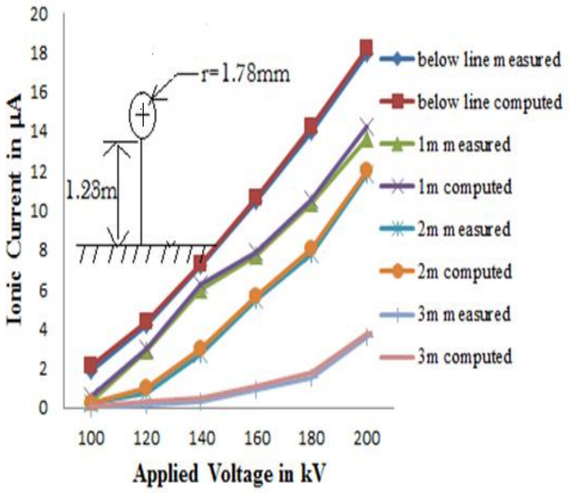


Fig. 5: a) Variation of ionic current b) Variation of electric field



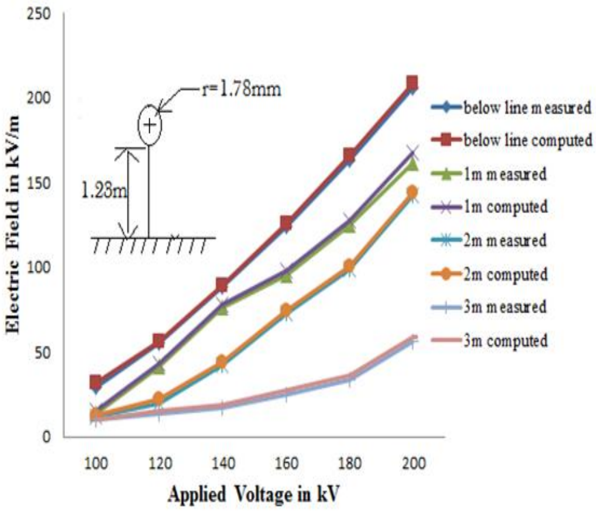


Fig. 6: a) Variation of ionic current b) Variation of electric field

Similar to case A, it is observed from figures 5 (a) -6 (b), the calculations based on the proposed method carried out in case B are matching closely with the experimental results. It is also observed from figures 5 (a) -6 (b) that, the variation of both ionic current and electric field are nonlinear in nature.

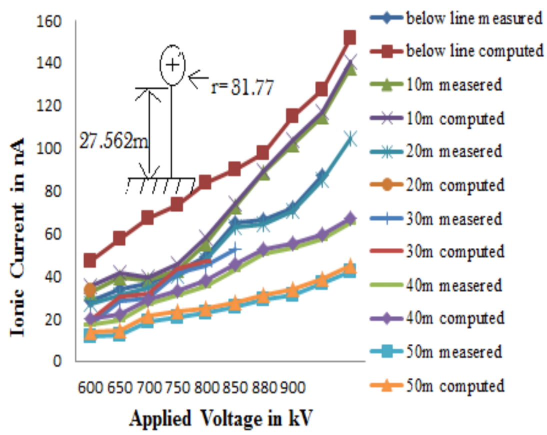
From figures 3 (a) -6 (b) of both case studies A and B, it is clear that, the ion current and electric field magnitudes of computed and measured values are higher with smaller conductor diameter for both applied voltage polarities under the line conductor and vice versa. Whereas in case of lateral profiles, the ionic current decreases as the lateral distance increases.

Case C:

Experimental measurements were also carried out with the single ACSR Moose conductor having an overall diameter of 31.77 mm hung at a height of 27 m above the ground. This experiment was conducted to validate the proposed computational method with the experimentally measured values strung at heights in the actual power transmission system and to ensure that this method is suitable for the actual HVDC transmission lines. Figure 7 and figure 8 shows the view of experimental line and ± 1200 kV HVDC source used in the study.

Fig. 7: View of experimental line

Fig. 8: View of ± 1200 kV HVDC source



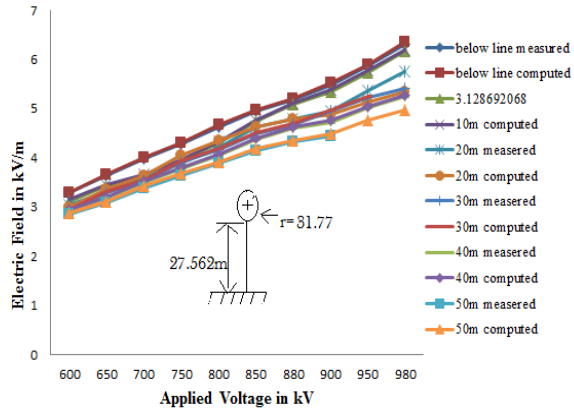
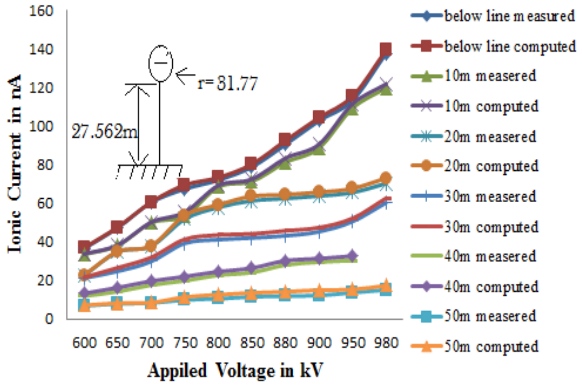


Fig. 9: a) Variation of ionic current b) Variation of electric field



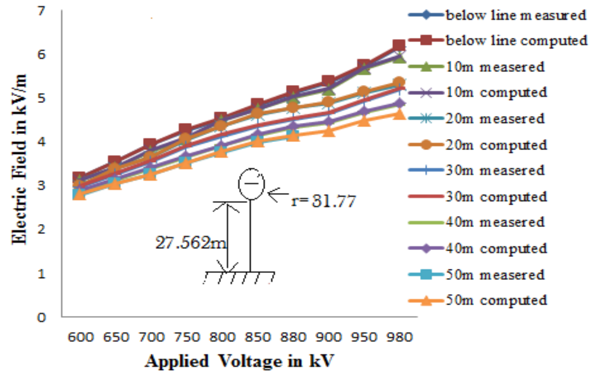
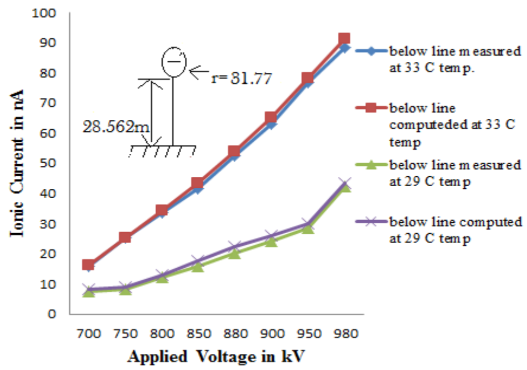


Fig. 10: a) Variation of ionic current b) Variation of electric field

In this case also, it is observed from figures 9 (a) -10 (b) that, the variation of both ionic current and electric field are nonlinear in nature. Also, it is found that, the calculations based on the proposed computational method are closely matching with the experimental results for a given height, irrespective of polarity of voltage applied.

Case D:

In order to check the sensitivity of the proposed computational method with atmospheric temperature, the experimental measurements are conducted with ACSR moose conductor arranged at a height of 28 m above the ground. The measurements were carried out under two different atmospheric conditions of 33˚C and 29˚C. Figures 11 (a) -11 (b) show the variation of computed and measured values of ionic current and electric field distribution.



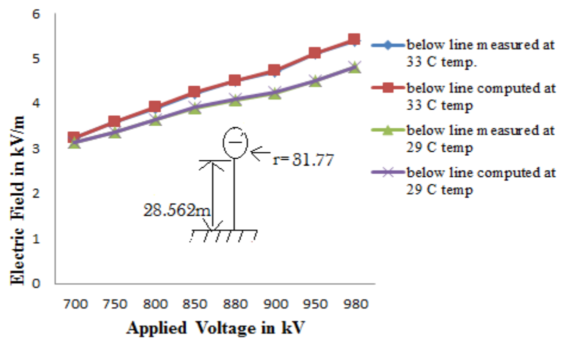


Fig. 11: a) Variation of ionic current b) Variation of electric field

It is observed from figures 11 (a) -11 (b) that, the calculations based on the computational method are matching very closely with the experimental results for two different weather conditions considered and also nonlinear in nature. It is also observed from figures 11 (a) -11 (b) that, the ion current and electric field magnitudes are higher at higher temperatures and vice versa. This may be attributed due to the fact that, the movement of ions is faster at higher temperatures as compared to the movement of ions at lower temperatures. The faster movement of ions may result in the generation of more number of ions in corona discharge due to more collisions in their expedition.

CONCLUSIONS

The electric field environment of unipolar HVDC transmission lines has been studied using the computational method evolved and compared with experimental results. The following conclusions are drawn from the results presented:

1. The calculations based on the proposed computational method are closely matched with experimental results, irrespective of height and diameter of the line conductor.

2. The variation of both ionic current and electric field distribution of unipolar HVDC transmission lines at ground level is found to be nonlinear in nature for both experimental and computational results.

3. The proposed computational method can react and calculates the parameters of the electric field environment of HVDC transmission lines at different atmospheric temperature, pressure and humidity conditions.

4. The computational method evolved considering the impact of atmospheric temperature, pressure and humidity can provide significant inputs in analyzing the electric field environment on unipolar HVDC transmission lines for different line conductor configurations with good computational accuracy.

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