Predictive Dynamic Model of the Negative Lightning Discharge Based on Similarity with Long Laboratory Sparks – Part 2: Validation

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ABSTRACT

In this paper, a mathematical model, requiring only the cloud-ground geometry, applied voltage and some atmospheric parameters, described in the first part of our contribution, has been used to predict the main macroscopic parameters of the negative lightning discharge. The predicted parameters include the spatial and temporal evolution of the entire discharge, the current and the corresponding electrical charge, the power and energy injected into the gap and the velocity. Assessment of the temporal evolution of the return stroke current is yet another application of the model. The computed results are found to be in good agreement with data reported in the literature.

Index Terms — **Negative lightning discharge, modeling, propagation, simulation**

1. INTRODUCTION

NEGATIVE lightning discharges have been the subject of very intensive experimental Contrary to the positive lightning for which many theoretical models are available [3 - 6], research to derive models for the negative lightning is still at its earlier stages. This is due to the complexity of the mechanisms involved in the propagation processes. The development of a negative lightning discharge model allowing predicting the main macroscopic parameters will be very useful for the design and protection of engineering structures against direct and indirect strikes.

In the first part of our investigations [7], a predictive dynamic model of negative lightning discharge was proposed to predict the main macroscopic parameters of the negative lightning discharge. The work presented in this second part of these investigations is mainly focused on the validation of this model. Assuming the discharge channel to be a long conductor and by considering criteria for instabilities and some atmospheric conditions, this model enables the computation of the macroscopic parameters of the discharge such as the current evolution and the corresponding charge, the instantaneous propagation velocity, the potential drop along the discharge channel, the power and energy injected into the gap, and a trajectory of the discharge plotted in 3D in real time using a probabilistic distribution.

2 SIMULATION RESULTS AND DISCUSSION

It is well-known that before a cloud-to-ground discharge, the field at the ground level is of about 10 to 15 kV/m [8]. Assuming that this field is roughly uniform between the cloud base - earth, the voltage difference (before the discharge inception) between them can be estimated to a few tens megavolts. Thus, for the validation of the model, three cloud – ground distances were considered, namely 2000, 5000 and 7500 m submitted to 35, 45 and 50 MV respectively, under a given atmospheric conditions: P=100 kPa and T=20°C at the ground level; these values being in the range of those used in the literature [9, 10]. Concerning the cloud diameter, 1 km constitutes a good dimension order [1]. The initial radius r_0 of the negative leader is taken equal to 0.75 cm [1, 2, 11].

The set of equations describing the mathematical model, proposed in the part 1 [7] were derived for long sparks in laboratory. They are therefore valid for any kind of applied voltage characteristics. For instance, in the laboratory, an impulse voltage is applied to the gap and it is known that the development of the discharge is conditioned by the rate of rise of the applied voltage. For lightning discharges, these equations simplify since the applied voltage is constant.

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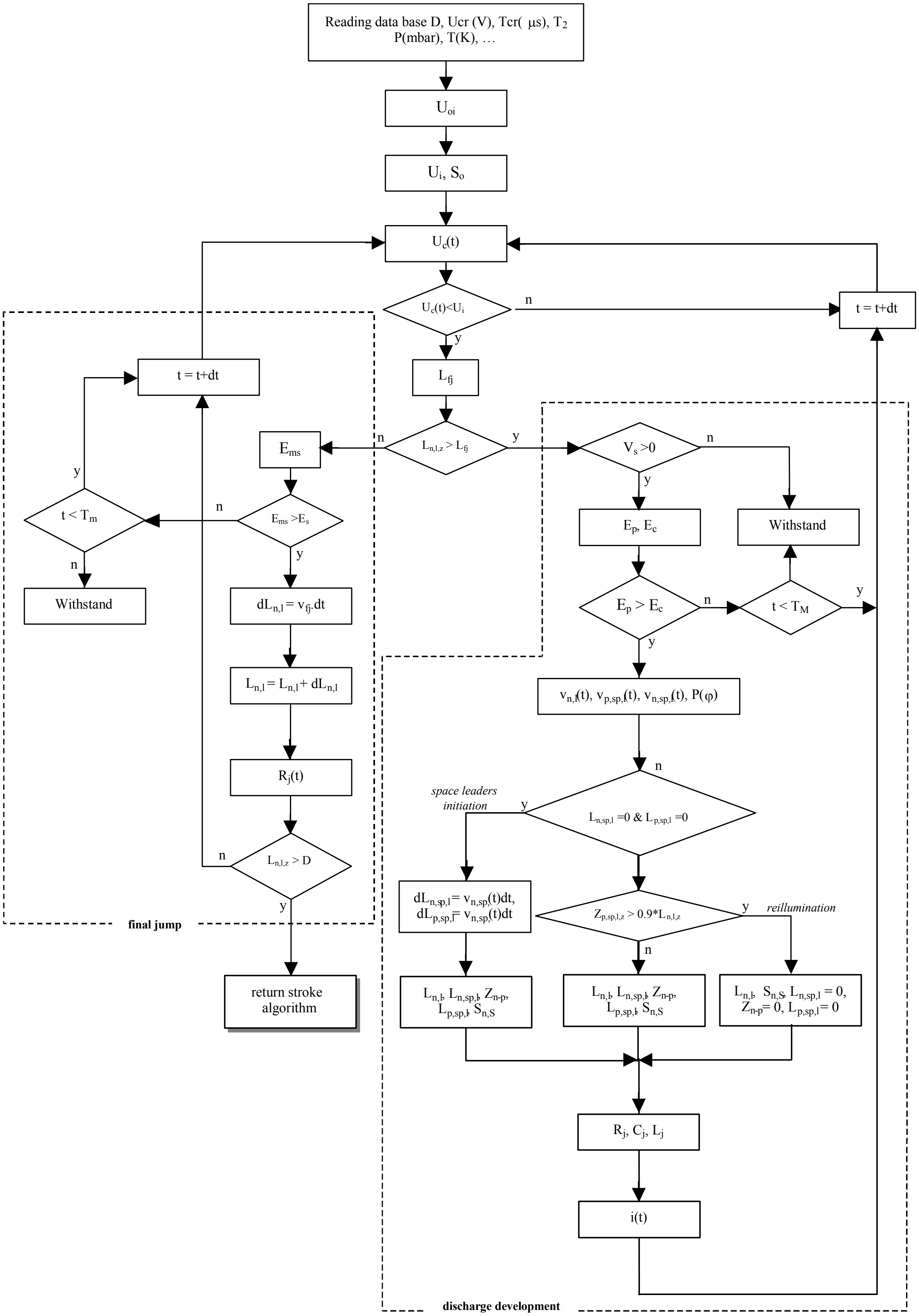


Figure 1. General flowchart of the model [7].

The simulations were performed using a software codes written in MATLAB. The block diagram is similar to that to that we used in a previous work [12] is given in Figure 1. The only input data are cloud – earth height, voltage and ambient air pressure and temperature. The sampling-time for simulation is 0.1 µs.

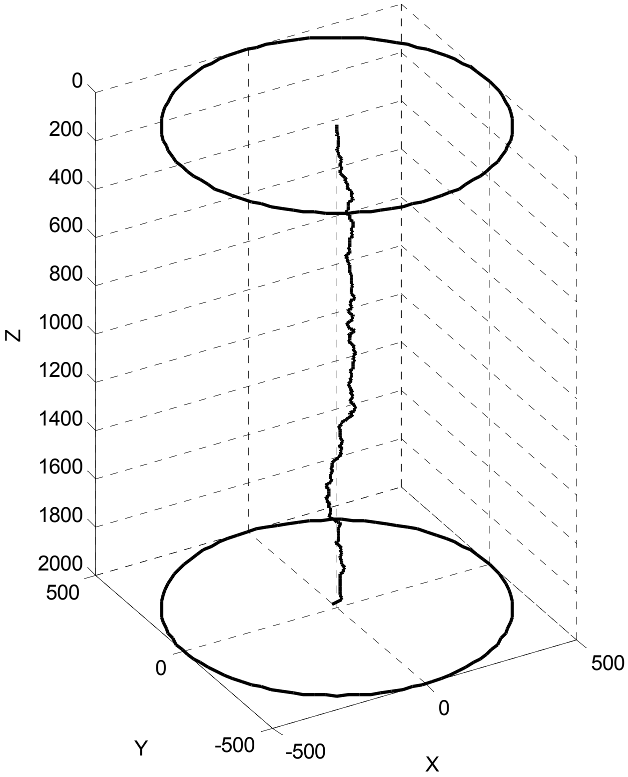
Figures 2 to 4 show some simulated results of the downward negative lightning leader characteristics. An example of trajectory is given in Figures 2a, 3a and 4a. From those results, it can be observed that the simulated current (Figures 2b, 3b and 4b), the charge (Figures 2d, 3d and 4d) and energy injected into the gap (Figures 2c, 3c and 4c) depict a real stepping. This is a well known phenomenon concerning the propagation of negative lightning. The current values are in the same range as those observed experimentally [1, 13]. Indeed, the simulated pulse currents of steps can reach a few kA. According to experimental results reported in literature, the currents depict stepwise pulses of at least 1 kA [13]. The current pulses correspond to re-illuminations. The number of these later depends on the voltage, the gap length and thence on the energy injected in the gap. It increases non-linearly with the cloud – earth gap. Moreover, the repetition time of stem occurrence lies between 0.1 and 1 µs and the time duration, between two re-illuminations, lies between 0.125 and 0.5 ms (Figures 2b, 3b and 4b). These results are of the same order as those estimated experimentally [14, 15]. The electrical charge injected during the propagation can reach several Coulombs. The simulated stepped leader duration seems to be higher by about one order dimension than the average one obtained experimentally. The characteristics of the thermal radius are reported in Figures 2e, 3e and 4e. Its growth is of a few centimetres as observed for natural lightning. It varies with the injected charge; the higher the injected charge, the larger the radius is. The simulated leader instantaneous velocities are of a few 10^5 m/s (Figures 2f, 3f and 4f) and the simulated average value is of about 3 10^5 m/s. Such a value is in a good agreement with that obtained experimentally from streak camera recordings, at the bottom of stepped leaders channel (i.e., near ground) during natural lightning discharge [1, 14-17]. Rubinstein et al. [14] obtained 4.0 10^5 $m.s^{-1}$ near cloud base and 5.2 10^6 $m.s^{-1}$ near earth with an average value of about 2 10^6 $m.s^{-1}$. Figures 2g, 3g and 4g depict the predicted return stroke currents. Its peak value can reach 18.5, 20.5 and 30.5 kA respectively for 2000, 5000 and 7500 m. Such values are in the range of those reported in literature [1, 18, 19]. For instance, the mean first-stroke peak current measured by K. Berger [19] for negative discharges, on Mount San Salvatore (Switzerland), is of 30 kA. Table 1 summarizes the main parameters obtained for three cloud –earth distances.

For a given voltage, the relationship giving the velocity of negative and positive discharges [7] shows that the current (i_L) and velocity (v_L) of the leader are related as $v_L \sim i_L^{1/3}$. Such a relationship has been reported by Bazelyan and Raizer for the positive discharge [2, 20].

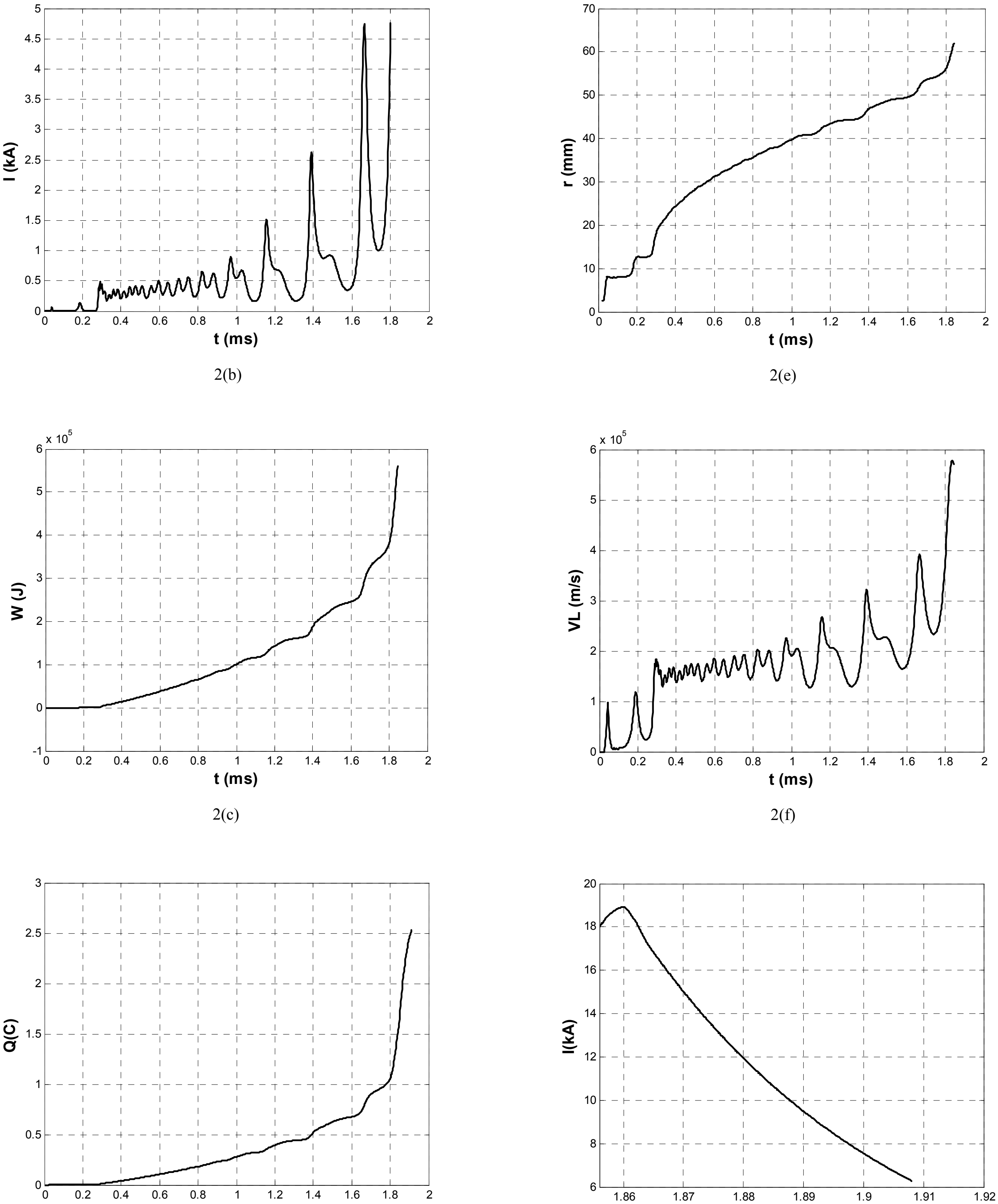
The proposed model may be considered as a good tool in predicting the characteristics of the negative lightning discharge. The simulated temporal evolution of the negative lightning discharge depicts the step-like propagation as well as the different sequences of the propagation as reported in literature. Moreover, the simulated values of the characteristic parameters are generally in the same range as the experimental ones estimated during natural lightning and reported in literature. The model emphasizes also the randomness aspect of the negative leader trajectory (Figures 2a, 3a and 4a). Indeed, for the same input parameters, one can have different simulated trajectories. Since the results vary randomly from one simulation to the next, one cannot expect agreement in detail between a single run of the simulation and a given experimental discharge.

Table 1. Simulated results for the three different cloud – earth distances.

Gap D(m)	Crest voltage U_{cr} (MV)	Maximum velocity v_{max} (m/s)	Leader average current I_m (kA)	Maximum current of return stroke I_{arc} (kA)
2000	40	4.0 10^5	1	18.5
3500	45	4.5 10^5	1.5	20.5
5000	50	5.2 10^5	2	30.5



2(a)

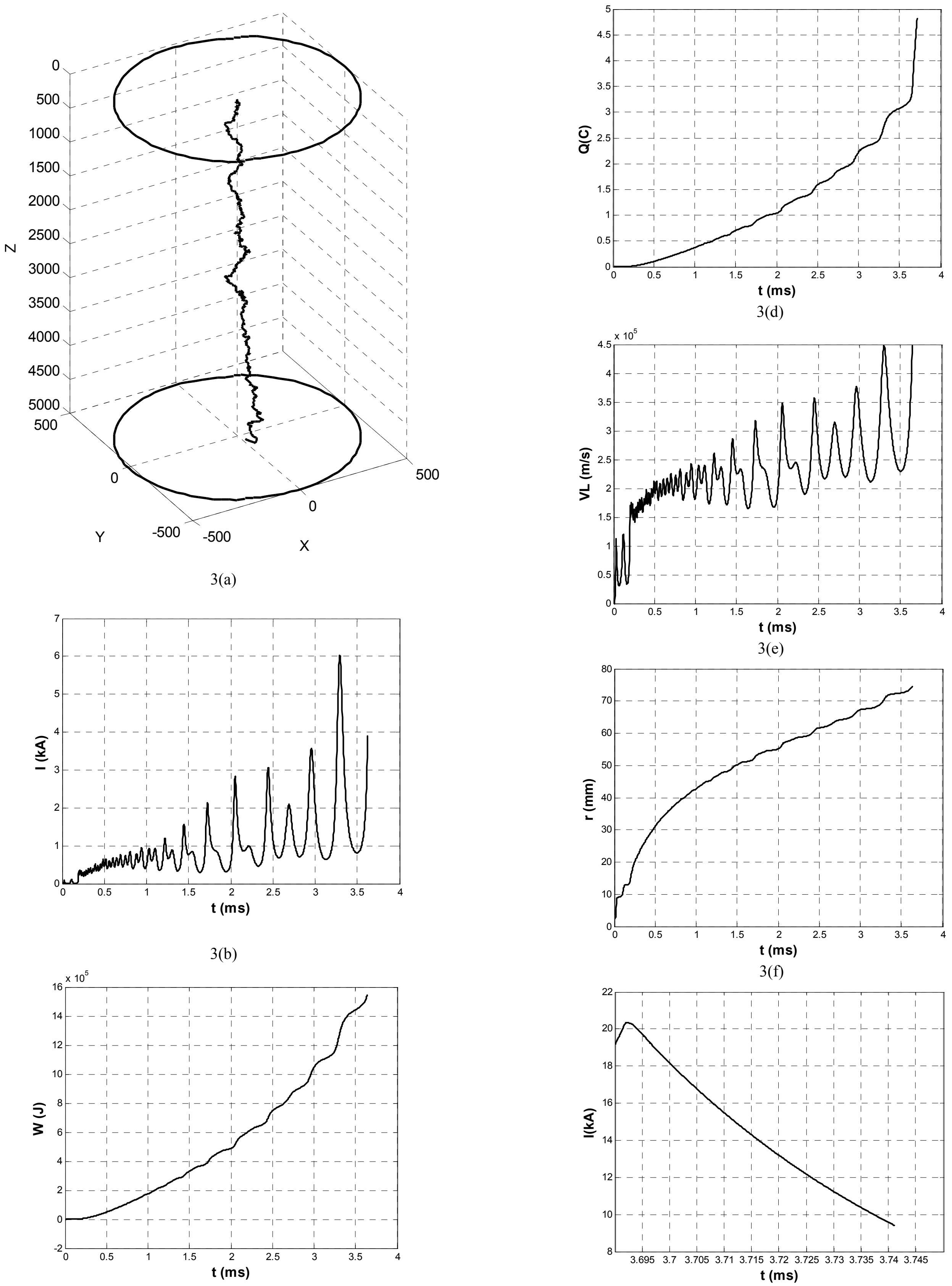


2(b) 2(e)

2(c) 2(f)

2(d) 2(g)

Figure 2. Simulation of cloud – earth distance *D=2000 m* under a constant voltage *Uc=30 MV*, and atmospheric conditions of *P=100 kPa* and *T=20°C.* Initial radius of equivalent electrode $r_i = 6$ *m* [21]: (a) Simulated main leader's trajectory in space; (b) Simulated main leader's current; (c) Simulated energy injected into the gap; (d) Applied voltage between cloud – ground; (e) Simulated charge injected into air gap; (f) Main leader thermal radius evolution; (g) Main leader instantaneous velocities; (h) The gradient in the main leader; (i) Simulated discharge's return strike current.



3(a)

3(b)

3(c)

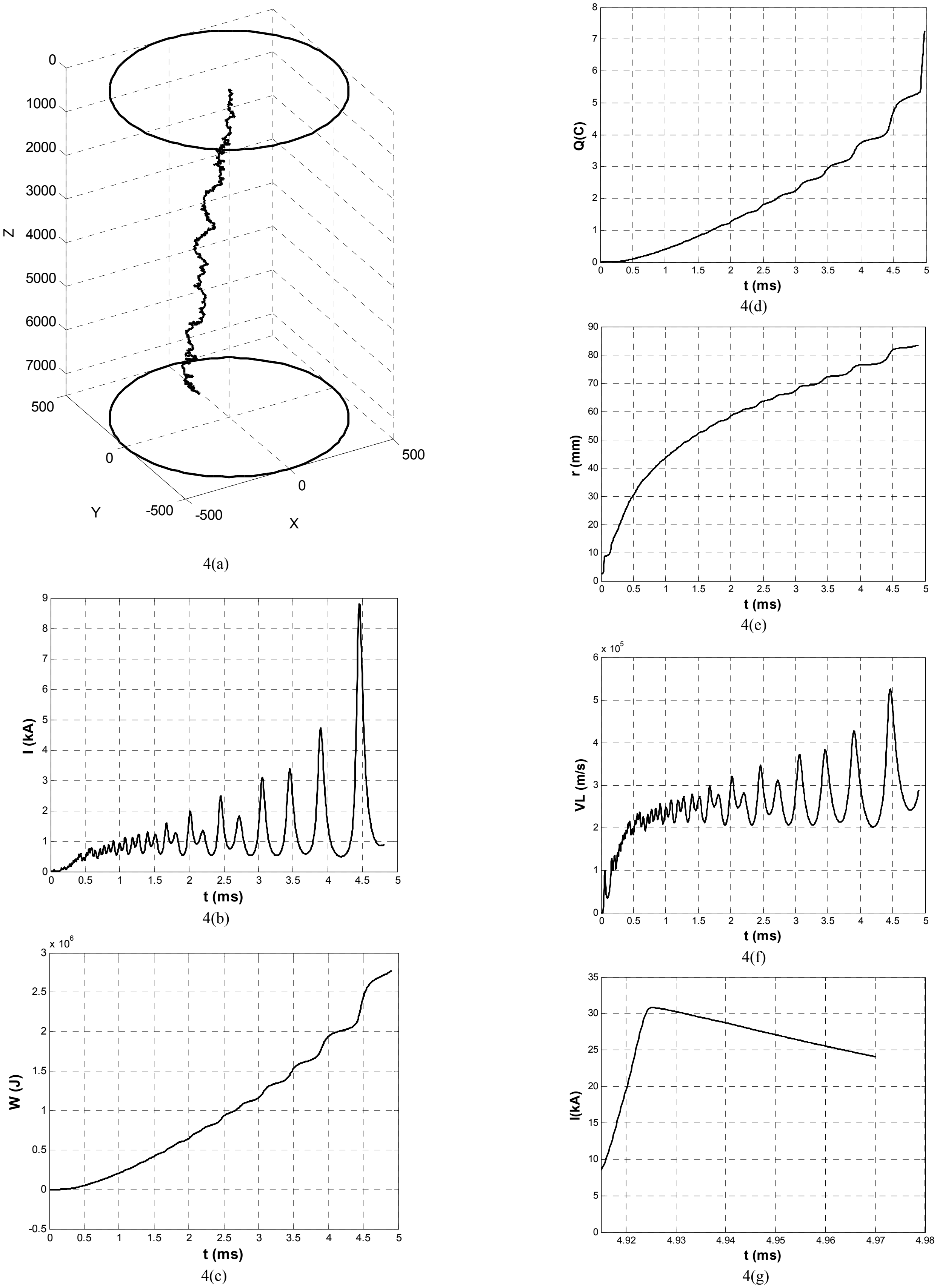
3(d)

3(e)

3(f)

3(g)

Figure 3. Simulation of cloud – earth distance *D=3500 m* under a constant voltage *Uc=45MV*, and atmospheric conditions of *P=100 kPa* and *T=20°C*. Initial radius of equivalent electrode $r_i = 6\ m$ [21]: (a) Simulated main leader's trajectory in space; (b) Simulated main leader's current; (c) Simulated energy injected into the gap; (d) Applied voltage between cloud – ground; (e) Simulated charge injected into air gap; (f) Main leader thermal radius evolution; (g) Main leader instantaneous velocities; (h) The gradient in the main leader; (i) Simulated discharge's return strike current.



4(a)

4(b)

4(c)

4(d)

4(e)

4(f)

4(g)

Figure 4. Simulation of cloud – earth distance *D=5000 m* under a constant voltage *Uc=50MV*, and atmospheric conditions of *P=100 kPa* and *T=20°C*. Initial radius of equivalent electrode $r_i = 6\ m$ [21]: (a) Simulated main leader's trajectory in space; (b) Simulated main leader's current; (c) Simulated energy injected into the gap; (d) Applied voltage between cloud – ground; (e) Simulated charge injected into air gap; (f) Main leader thermal radius evolution; (g) Main leader instantaneous velocities; (h) The gradient in the main leader; (i) Simulated discharge's return strike current.

The results obtained are found to be in a good agreement with trends of results recorded during natural lightning. They display prominently the scale effects between the simulated results obtained for negative lightning discharges and long negative discharges in laboratory. The proposed simulator may therefore constitute a good tool in determining the characteristics of negative lightning discharge. This work emphasises once more the utility of equivalent electrical circuit model in modelling physical phenomena.

3 CONCLUSIONS

The model proposed in this contribution reproduces the negative lightning discharge propagation through a series of successive equivalent electrical circuit. The overall computed space-time characteristics of the negative lightning discharge show satisfactory agreement with experimental measurements/observations. The presented results have shown that the actual understanding of the physical mechanism of electrical discharge is good enough for the development of self consistent detailed models. Work is still in progress to improve the values of the physical parameters and to check the limits of accuracy over a wide range of experimental results. The authors are actually engaged in additional works to study the influence of some assumptions made on the lightning discharge parameters.

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