IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 9, Issue 6 Ver. I (Nov. - Dec. 2017), PP 77-80
www.iosrjournals.org

Attenuation of Lightning Generated VLF Electromagnetic Waves Between Mixed Sea-Land Path And Ionosphere

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***Abstract**: Cooray and Ming [1] have studied that the path of propagation affects the shape and amplitude of the electric fields generated by lightning return strokes. However, in this study no attempt is made to examine the attenuation of electromagnetic waves generated by lightning return strokes as they propagate from the source to the measuring station through reflections from - (i) Ionosphere, (ii) Sea-water, and (iii) small strip of land. It would therefore be of more important to investigate the propagation effects caused due to the presence of mixed sea-land and ionosphere. In this paper it is shown that the path of propagation, between mixed sea – land and ionosphere, influences the attenuation factor and it depends up on the inclination of the lightning return stroke.*

***Keywords:** Attenuation factor, Complex reflection coefficient, Electromagnetic wave, Ionosphere, Lightning return stroke.*

Date of Submission: 01 -11-2017 Date of acceptance: 29-11-2017

II. Introduction

Current is the primary source for all thermal and damages caused by lightning. Besides that, the rate of rise of the lightning currents may induce over voltages in electric and electronic systems or devices. The lightning threat is associated with the current parameters. The easiest way to derive return stroke current parameters is by measuring electromagnetic fields emitted by the return stroke. There are number of engineering models that relate fields and currents for geometries similar to that of a cloud to ground return stroke [2, 5].The electromagnetic fields change in various degrees depending on the electrical characteristics of the propagation path. Many workers [6, 13] have been shown that the amplitude of the electromagnetic field decreases with increasing propagation distance over land. Therefore any attempt to derive return stroke current parameters from the measured fields without correcting for these propagation effects may lead to significant errors.

To avoid the propagation effects caused by finitely conducting ground, many researchers have measured the electromagnetic fields from lightning flashes striking the sea, so that the path of propagation of the electromagnetic fields is over sea – water [7, 8, 14, 15]. Since sea-water is a better conductor than soil, electromagnetic waves propagating over sea-water are subjected to much less severe propagation effects compared with the electromagnetic fields propagating over land. Cooray [20] studied the propagation effects caused by a finitely conducting and rough sea on the lightning generated electric fields. In some of the experimental investigations the electromagnetic fields recording sites were situated several tens to several hundreds of meters inland [3, 7, 14, 15]. In such situations the path of propagation of electromagnetic fields generated by lightning return strokes striking the sea is entirely over sea – water except for the last few tens or hundreds of meters. However, in these studies no attempt is made to examine the propagation effects on the electric field generated by the return stroke as they propagate from the source to the measuring station through reflections from – (i) ionosphere, (ii) sea – water, and (iii) small strip of land. Singh and Singh [16] have studied about the propagation effects of ground and ionosphere on electromagnetic waves generated by oblique return stroke. They have not attempted to study the propagation effects of mixed sea – land path and ionosphere.

In the present study an attempt is made to examine the propagation effects, on lightning generated electromagnetic waves, caused by the mixed sea – land path and ionosphere.

II. Expression for the Attenuation factor

In the measurement of many researchers [3, 14, 15] the measuring stations were situated on land at several meters from the sea-land boundary. In these experiments the path of propagation of the electric fields is entirely over sea water except for the last few tens to few hundreds of meters on the land. The electromagnetic waves radiated from the lightning return stroke may reach the measuring centre through many possible paths, some of which are:

(i) Waves reflected from ionosphere,
(ii) Direct waves, and
(iii) Mixed sea-land reflected waves - waves reflected from: (a) sea-water, and (b) land.

Propagation of these lightning generated waves are illustrated in Fig. (1). Jayratne and Cooray [17] estimated the propagation effects caused by mixed sea - land path by developing an approximate equation on the basis of theory reported by Wait [18, 19] by neglecting the displacement current in the ground. Cooray and Ming [1] argued that the approximation used by Jayratne and Cooray can lead to significant error for higher frequencies. In that study the propagation effects caused by mixed sea - land path are calculated without taking the effect of reflection from ionospheric boundaries.

The precise measurements and analysis of field data associated with lightning return stroke situated on land at several tens to several hundreds of meters from the sea - land boundary should account for the attenuation factor introduced by the mixed sea-water-land below and the ionospheric layer above. At the reception point P (r, θ, φ) in addition to the direct field component, three indirect components arrive. One component is reflected from the sea-water, second is reflected from the strip of homogeneous land and other one is reflected from the ionospheric boundary. The correct phase of the four components and their resultant value are determined by:

(i) The distance of the point of measurement ,
(ii) Angle of incidence at the sea- water, land and at the ionospheric boundary.

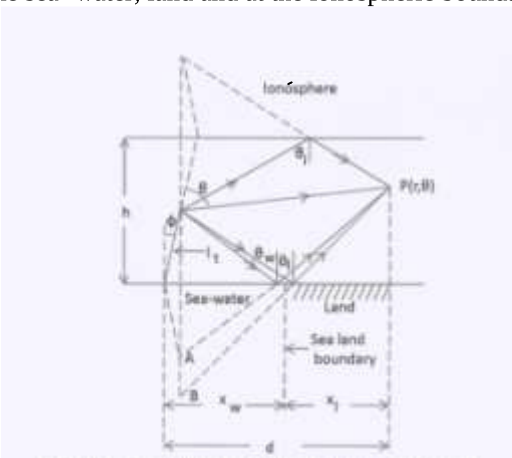

Fig.(1) Geometry showing propagation of electromagnetic waves between mixed sea-land path below and ionosphere above.

Fig. (1) shows the propagation paths of electromagnetic waves before and after reflections from sea water surface and land. In deriving the expression for the attenuation factor, it is assumed that the reflections from the points at sea water surface and land are very close to the boundary separating the sea water and the land. In this consideration the images formed due the reflections from the both points are approximately equal and image formed, due to the reflection from the land is overlapped up on the image formed due to the reflection from the sea water.

The angles of incidence θ_w, θ_l and θ_i are related with the angle of direct observationθ, angle of inclination φ of lightning return stroke. θ_w, θ_l and θ_i are determined from the geometry shown in Fig. (1) as:

$$\theta_w = \sin^{-1}\frac{rsin\,(\theta+\phi)}{r+(\Delta r)_w} \tag{1}$$

$$\theta_l = \sin^{-1}\frac{rsin\,(\theta+\phi)}{r+(\Delta r)_l} \tag{2}$$

$$\theta_i = \sin^{-1}\frac{rsin\,(\theta+\phi)}{r+(\Delta r)_i} \tag{3}$$

Where,

$(\Delta r)_w$ = geometric path difference with respect to the direct wave of the sea-water reflected wave,
$(\Delta r)_l$ = geometric path difference with respect to the direct wave of the land reflected wave, and
$(\Delta r)_i$ = geometric path difference with respect to the direct wave of the ionospheric reflected wave,

In terms of the ionospheric height, h and the average channel lengthl_t, the expressions for $(\Delta r)_w$, $(\Delta r)_l$, and $(\Delta r)_i$ are written as:

$$(\Delta r)_w = [\{2l_t\cos\emptyset + r\cos(\theta+\emptyset)\}^2 + \{rsin(\theta+\emptyset)\}^2]^{1/2} - r \tag{4}$$

$$(\Delta r)_l = [\{2l_t\cos\emptyset + r\cos(\theta+\emptyset)\}^2 + \{rsin(\theta+\emptyset)\}^2]^{1/2} - r \tag{5}$$

$$(\Delta r)_w = [\{2(h - l_t\cos\emptyset) - r\cos(\theta+\emptyset)\}^2 + \{rsin(\theta+\emptyset)\}^2]^{1/2} - r \tag{6}$$

Equations (4), (5) and (6) are derived for potential ray paths [21]. These are approximate relations but very near to their exact value.

The observation distance r is related with average channel length, observation angle, θ and angle of orientation, $\emptyset$ as:

$$r = \frac{d - l_t \sin\emptyset}{\sin(\theta + \emptyset)} \tag{7}$$

Where, d = $x_w + x_l$,

x_w= sea water path length, and

x_l = land strip length

The attenuation factors under different propagation conditions are:

(i) $$F_w = \frac{r^2 R_w \exp\left[-i\left(\frac{2\pi}{\lambda}\right)(\Delta r)_w\right]}{\{r + (\Delta r)_w\}^2} \tag{8}$$

In expression (8), R_w is complex reflection coefficient for sea water and is given as:

$$R_w = \frac{\left(\epsilon_{rw}' + \frac{\sigma_w}{i\omega\epsilon_0}\right)\cos\theta_w - \sqrt{\left(\epsilon_{rw}' + \frac{\sigma_w}{i\omega\epsilon_0}\right) - \sin^2\theta_w}}{\left(\epsilon_{rw}' + \frac{\sigma_w}{i\omega\epsilon_0}\right)\cos\theta_w + \sqrt{\left(\epsilon_{rw}' + \frac{\sigma_w}{i\omega\epsilon_0}\right) - \sin^2\theta_w}}$$

Where,

ϵ_{rw}' = dielectric constant of water,

σ_w = electrical conductivity of sea-water, and

ω = angular frequency of radiated electric field

(ii) $$F_l = \frac{r^2 R_l \exp\left[-i\left(\frac{2\pi}{\lambda}\right)(\Delta r)_l\right]}{\{r + (\Delta r)_l\}^2} \tag{9}$$

Where, F_l is attenuation factor for the land. In this equation R_l is the complex reflection coefficient for the land and is expressed as:

$$R_w = \frac{\left(\epsilon_{rl}' + \frac{\sigma_l}{i\omega\epsilon_0}\right)\cos\theta_l - \sqrt{\left(\epsilon_{rl}' + \frac{\sigma_l}{i\omega\epsilon_0}\right) - \sin^2\theta_l}}{\left(\epsilon_{rl}' + \frac{\sigma_l}{i\omega\epsilon_0}\right)\cos\theta_l + \sqrt{\left(\epsilon_{rl}' + \frac{\sigma_l}{i\omega\epsilon_0}\right) - \sin^2\theta_l}}$$

In this expression, ϵ_{rl}' and σ_l are the dielectric constant and electrical conductivity of the land, respectively. The attenuation factor for ionosphere is given as:

(iii) $$F_i = \frac{r^2 R_i \exp\left[-i\left(\frac{2\pi}{\lambda}\right)(\Delta r)_i\right]}{\{r + (\Delta r)_i\}^2} \tag{10}$$

The expression for the complex reflection coefficient is written as:

$$R_i = \frac{\left(\epsilon_{ri}' + \frac{\sigma_i}{i\omega\epsilon_0}\right)\cos\theta_i - \sqrt{\left(\epsilon_{ri}' + \frac{\sigma_i}{i\omega\epsilon_0}\right) - \sin^2\theta_i}}{\left(\epsilon_{ri}' + \frac{\sigma_i}{i\omega\epsilon_0}\right)\cos\theta_i + \sqrt{\left(\epsilon_{ri}' + \frac{\sigma_i}{i\omega\epsilon_0}\right) - \sin^2\theta_i}}$$

Where, ϵ_{ri}' and σ_i are the dielectric constant and electrical conductivity of the ionosphere, respectively.

Total attenuation factor [16,22] is written as:

$$F = 1 + F_w + F_l + F_i \tag{11}$$

In this expression 1 appears as an attenuation factor for direct wave.

Using Eqs (8),(9),and (10) into Eq.(11), the expression for the attenuation factor is modified as:

$$|F| = \left| \frac{r^2 R_w \exp\left[-i\left(\frac{2\pi}{\lambda}\right)(\Delta r)_w\right]}{\{r + (\Delta r)_w\}^2} + \frac{r^2 R_l \exp\left[-i\left(\frac{2\pi}{\lambda}\right)(\Delta r)_l\right]}{\{r + (\Delta r)_l\}^2} + \frac{r^2 R_i \exp\left[-i\left(\frac{2\pi}{\lambda}\right)(\Delta r)_i\right]}{\{r + (\Delta r)_i\}^2} \right| \tag{12}$$

It is clear from Eq.(12) that the attenuation factor depends on electrical properties of reflecting surfaces, angle of incidence at reflecting surfaces, angle of inclination of the return stroke and the nature of polarization of electromagnetic waves generated from the lightning flash.

III. Results and Discussions

To illustrate the quantitative effect of propagation of the radiated VLF electromagnetic waves generated from lightning return stroke in presence of the sea water, small strip of the land and the ionosphere, the variation of $|F|$ with frequency for θ = 30^0 and 90^0 at different angle of orientation of return stroke channel is computed. In this computation, the illustrative values of conductivities of the ground, ionospheric reflecting layer and sea water are taken respectively as 10^{-3}, 10^{-5} and 4 mho m^{-1} , their relative permittivities are taken respectively as 10, 1, 81, and the ionospheric height and average channel length as 90 km and 5 km, respectively.

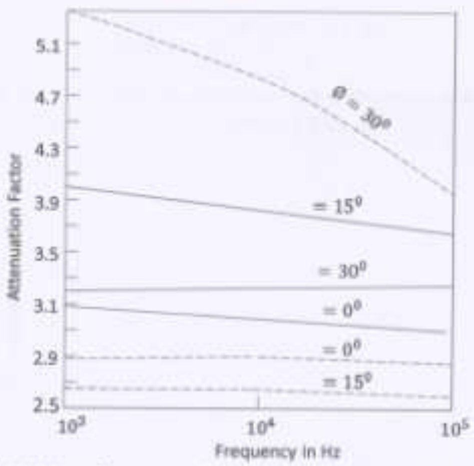

Fig.(2) Variation of attenuation factor for propagation over a mixed sea-land path.
(1) Solid curve, θ = 30°
(2) Dashed curve, θ = 90°
(3) Observation distance = 100 km

In the development of Eq. (12) it is assumed that potential rays generated by lightning channel reflected from infinite number of points at sea-land mixed path and ionospheric reflecting layer reached at receiving point [20] The variation of attenuation factor arises due to the propagation of lightning generated electromagnetic wave between mixed sea-land path below and ionospheric layer above with frequency in the frequency range from 1 kHz to 100 kHz is depicted in Fig. (2). It is obvious from this figure that attenuation factor decreases from maximum value as frequency varies from 1 kHz to higher values.

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