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Evaluation Of Lightning Current Parameters Using Measured Lightning Induced Voltage On Distribution Power Lines

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Abstract- **In this paper, an algorithm had been proposed to evaluate the lightning current parameters using measured voltage from overhead distribution lines based on lightning location obtained from lightning location system. Moreover, the performance of algorithm had been considered using different samples of induced voltage. The results showed that the proposed algorithm could determine the lightning current parameters in an acceptable accuracy range. The proposed method is based on the measured values of lightning induced voltage as collecting this parameter is easier and more accessible than electromagnetic field components that had been widely used in past researches.**

Keywords- Lightning, Lightning induced voltage, Channel base current

I. INTRODUCTION

Lightning is a natural phenomenon that can affect on the stability of power system and other electrical systems[1]. In order to protect the electrical equipment against lightning one of important steps is classification of lightning current wave shapes and using them in the standards on the lightning protection[2]. As lightning is a natural phenomenon and striking point is not exactly predictable, preparing the data bank of lightning current parameters is an important challenge. Several studies have been done to create lightning artificially through triggered lightning experiment[3] as it can provide lightning current and lightning electromagnetic fields data limitary[4-6]. On the other hand, a number of studies had been done to estimate lightning current parameters using inverse procedure algorithms as they were based on measured values of lightning electromagnetic fields components[7][8]. Moreover, they had set few assumptions on the algorithms and they can evaluate the lightning current magnitude only in a limited range of frequencies[4]. One of important issue in measuring the lightning electromagnetic field components is extraction of the electromagnetic fields from local pollutions due to other EMF sources. Therefore, evaluation of lightning current parameters using measured induced voltage from overhead distribution lines has been targeted in this research paper.

By striking the lightning to the ground, due to following the lightning current in the channel, electromagnetic fields associated with lightning channel will be propagated around channel and by coupling between lighting electromagnetic fields and nearby overhead power lines, the lightning induced voltage will be created on the line. Therefore, in this study by measuring the lightning induced voltage on the line (setting the location of measuring point) and also by using lightning location obtained from lightning location system, the lightning current wave shapes at different levels of lightning channel will be evaluated through the proposed inverse procedure algorithm. Measuring the induced voltage on the line is easier and accessible than field components however the main signal(lightning induced voltage) should be extracted using a proper method. The mother wavelet method can be applied to extract the lightning induced voltage signal from measured voltage on the line.

II. LIGHTNING RETURN STROKE CURRENT

Lightning return stroke current should be considered into two different parts i.e. channel base current (at connection point between lightning channel and ground and also by assuming the current source has been located at this connection point), at different height along channel (above the ground surface). It should be mentioned that the current models consider on the current behavior at different heights along channel as the engineering current model has been used in this study.

The widely used channel base current functions have been listed in Table. I as follows[11];

TABLE.I. THE WIDELY USED CHANNEL BASE CURRENT FUNCTIONS

Function name	Channel base current function
Bruce and Golde	$I_p[\exp(-At)-\exp(-Bt)]$
Improvement of Uman and McLain on Bruce and Golde function	$\frac{I_p}{\eta}[\exp(-At)-\exp(-Bt)]$
Improvement of Jones on Bruce and Golde function	$\frac{I_p}{\eta}\left[\exp\left(-\frac{t^*}{\Gamma_1}\right)-\exp\left(-\frac{t^*}{\Gamma_2}\right)\right]$ $t^*=\frac{\Gamma_2^2}{\Gamma_1}+t$
Pierce and Ciones	$I_{p1}[\exp(-A_1t)-\exp(-B_1t)]+I_{p2}[\exp(-A_2t)-\exp(-B_2t)]$
Heidler function	$\frac{I_p}{\eta_1}\frac{\left(\frac{t}{\Gamma_1}\right)^{n_1}}{1+\left(\frac{t}{\Gamma_1}\right)^{n_1}}\exp\left(\frac{-t}{\Gamma_2}\right)$
Improvement of Diendorfer and Uman on Heidler function (DU)	$\frac{i_{01}}{\eta_1}\frac{\left(\frac{t}{\Gamma_{11}}\right)^{n_1}}{1+\left(\frac{t}{\Gamma_{11}}\right)^{n_1}}\exp\left(\frac{-t}{\Gamma_{12}}\right)+\frac{i_{02}}{\eta_2}\frac{\left(\frac{t}{\Gamma_{21}}\right)^{n_2}}{1+\left(\frac{t}{\Gamma_{21}}\right)^{n_2}}\exp\left(\frac{-t}{\Gamma_{22}}\right)$
Improvement of Nucci on Heidler function (referred as Nucci)	$\frac{i_{01}}{\eta_1}\frac{\left(\frac{t}{\Gamma_{11}}\right)^{n_1}}{1+\left(\frac{t}{\Gamma_{11}}\right)^{n_1}}\exp\left(\frac{-t}{\Gamma_{12}}\right)+i_{02}[\exp(-\Gamma_{21}t)-\exp(-\Gamma_{22}t)]$

The general form of engineering current models can be expressed by equation(1) as follows[11,12];

$$I(z',t)=I\left(0,t-\frac{z'}{v}\right)\times P(z')\times u\left(t-\frac{z'}{v_f}\right) \quad (1)$$

Where:

z' is the temporary charge height along lightning channel,

I(z',t) is current distribution along lightning channel at any height z' and any time t,

I(0,t) is channel base current,

P(z') is the attenuation height dependent factor,

v is the current-wave propagation velocity,

v_f is the upward propagating front velocity,

u is the Heaviside function defended as

$$u\left(t-\frac{z'}{v_f}\right)=\begin{cases}1 & \text{for } t\geq\frac{z'}{v_f}\\ 0 & \text{for } t<\frac{z'}{v_f}\end{cases}$$

Moreover, based on equation (1) , the most important engineering current models have been mentioned in Table.II as follows[11];

TABLE. II. THE INTERNAL PARAMETERS OF ENGINEERING CURRENT MODELS

Model	P(z')	v
Bruce and Golde (BG)	1	∞
Traveling Current Source (TCS)	1	-c
Transmission Line (TL)	1	v_f
Modified Transmission Line with Linear Decay (MTLL)	$(1-\frac{z'}{H_c})$	v_f
Modified Transmission line with Exponential Decay (MTLE)	$\exp(-\frac{z'}{\lambda})$	v_f

It should be mentioned that c is speed of light in free space, λ as a decay constant (1~2km) and H_c is cloud height (channel height). likewise, the return stroke velocity is normally set as a constant value between c/2 to 2c/3.

III. LIGHTNING INDUCED VOLTAGE ON THE OVERHEAD POWER LINES

In order to evaluate the lightning induced voltage on the distribution line, the geometry of model has been illustrated in Figure.1 as follows;

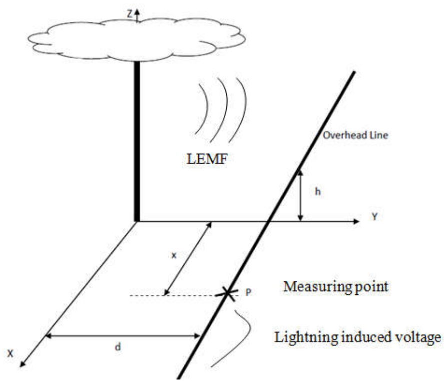

Fig.1. The geometry of problem

In this study the sum of two Heidler function (DU function) has been set as a channel base current function and also the MTLE model has been set as a current model. Noted that the parameters of current function and model are unknown and will be evaluated using proposed inverse procedure algorithm. It should be mentioned that the x and d parameters will be evaluated based on the data from lighting location system[9-10]. The values of lightning induced voltage on the line at different time steps and different points along line can be evaluated using analytical expression as presented by equation (2). Noted that the internal parameters of equation (2) should be evaluated for both terms of DU function and by superposition law will be taken into account [10].

$$V_{ind}(x, t = t_n) = [A'_1 + A'_2 + A'_3]U(t_n - \frac{\sqrt{x^2+d^2+h^2}}{c}) \qquad (2)$$

Where:

V_{ind} is the value of lightning induced voltage

$$A'_1 = \frac{-1}{2\Delta h}\sum_{m'=1}^{k'+1} h_m \times [\vec{E}_z(x, y, z = (m'-1)\times\Delta h, t_{n-1}) + \Delta t \times \sum_{i=1}^{n}\sum_{m=1}^{k+1} a_m\{F_2(x, y, z = (m'-1)\times\Delta h, t = t_n, z' = h_{m,i}) - a'_m F_2(x, y, z = (m'-1)\times\Delta h, t = t_n, z' = h'_{m,i})\}U(t - \frac{\sqrt{r^2+z^2}}{c})]$$

$$A'_2 = -\frac{1}{4\Delta x}\times\sum_{m'=1}^{q+1} c_m \times [\vec{E}_x(x = x_{m'}, y = d, z = h, t_{n-1} - \frac{x_{m'}-x}{c}) + \Delta t \times \sum_{i=1}^{n}\sum_{m=1}^{k+1} a_m\{F_1(x = x_{m'}, y = d, z = h, t = t_n - \frac{x_{m'}-x}{c}, z' = h_{m,i}) - a'_m F_1(x = x_{m'}, y = d, z = h, t = t_n - \frac{x_{m'}-x}{c}, z' = h'_{m,i})\}U(t_n - \frac{x_{m'}-x}{c} - \frac{\sqrt{x_{m'}^2+d^2+h^2}}{c})]$$

$$A'_3 = \frac{1}{4\Delta x'}\times\sum_{m'=1}^{q+1} c_m \times [\vec{E}_x(x = x'_{m'}, y = d, z = h, t_{n-1} + \frac{x'_{m'}-x}{c}) + \Delta t \times \sum_{i=1}^{n}\sum_{m=1}^{k+1} a_m\{F_1(x = x'_{m'}, y = d, z = h, t = t_n + \frac{x'_{m'}-x}{c}, z' = h_{m,i}) - a'_m F_1(x = x'_{m'}, y = d, z = h, t = t_n + \frac{x'_{m'}-x}{c}, z' = h'_{m,i})\}U(t_n + \frac{x'_{m'}-x}{c} - \frac{\sqrt{[x'^2_{m'} + d^2 + h^2}}{c})]$$

$$\Delta x' = \frac{x + \frac{(ct-x)^2 - h^2 - d^2}{2(ct-x)}}{q},$$

$$x'_{m'} = -\frac{(ct_n - x)^2 - h^2 - d^2}{2(ct_n - x)} + (m'-1)\times\Delta x',$$

q is division factor (>=2) ,

$$c_m = \begin{cases} 2 & \text{for } m' = 1 \text{ and } m' = q+1 \\ 1 & \text{for others} \end{cases}$$

$$F_1 = \frac{I_{01}P(z')x(z-z')A_2}{4\pi\varepsilon_0\eta_{01}\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]}\left\{\frac{\left(\frac{A_1}{t_1}\right)^n(3c^2t_2^2 - 3ct_2R + R^2)}{c^2t_2^2R^5} + \frac{2n^2\left(\frac{A_1}{t_1}\right)^{3n-2} + n(n-1)\left(\frac{A_1}{t_1}\right)^{n-2}\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]^2 + (-3n^2+n)\left(\frac{A_1}{t_1}\right)^{2n-2}\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]}{c^2t_1^2R^3\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]^2} + \frac{3n\left(\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]\left(\frac{A_1}{t_1}\right)^{n-1} - \left(\frac{A_1}{t_1}\right)^{2n-1}\right)}{ct_1R^4\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]} + \frac{2n\left(\left(\frac{A_1}{t_1}\right)^{2n-1} - \left[\left(\frac{A_1}{t_1}\right)^n + 1\right]\left(\frac{A_1}{t_1}\right)^{n-1}\right)}{c^2t_1t_2R^3\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]}\right\}$$

$$F_2 = \frac{I_{01}P(z')A_2}{4\pi\varepsilon_0\eta_{01}[\left(\frac{A_1}{t_1}\right)^n + 1]}\left\{\frac{(x^2+y^2)\left[\left(\frac{A_1}{t_1}\right)^n(-3c^2t_1t_2^2 + 3ct_1t_2R - t_1R^2) + n\left(\frac{A_1}{t_1}\right)^{n-1}(-3ct_2^2R + 2t_2R^2)\right]}{c^2t_1t_2^2R^5} + \frac{2\left(\frac{A_1}{t_1}\right)^n(ct_1t_2 - t_1R) + 2n\left(\frac{A_1}{t_1}\right)^{n-1}t_2R}{ct_1t_2R^3} - \frac{n(n-1)(x^2+y^2)\left(\frac{A_1}{t_1}\right)^{n-2}}{c^2t_1^2R^3} + \frac{(x^2+y^2)\left[2n^2t_2R\left(\frac{A_1}{t_1}\right)^{2n-2} + 3nct_1t_2\left(\frac{A_1}{t_1}\right)^{2n-1} + n(n-1)t_2R\left(\frac{A_1}{t_1}\right)^{2n-2} - 2nt_1R\left(\frac{A_1}{t_1}\right)^{2n-1}\right] - 2nct_1t_2R^2\left(\frac{A_1}{t_1}\right)^{2n-1}}{c^2t_1^2t_2R^4\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]} - \frac{2n^2(x^2+y^2)\left(\frac{A_1}{t_1}\right)^{3n-2}}{c^2t_1^2R^3\left[\left(\frac{A_1}{t_1}\right)^n + 1\right]^2}\right\}$$

$$R = \sqrt{x^2 + y^2 + (z-z')^2}$$

$$A_1 = t - \frac{R}{c} - \frac{|z'|}{v}$$

$$A_2 = \exp(\frac{\frac{R}{c} - t + \frac{|z'|}{v}}{t_2})$$

$$\vec{E}_x(x,y,z,t_n) = \vec{E}_x(x,y,z,t_{n-1}) + \Delta t \times \sum_{i=1}^{n}\sum_{m=1}^{k+1} a_m\{F_1(x,y,z,t=t_n,z'=h_{m,i}) - a'_m F_1(x,y,z,t=t_n,z'=h'_{m,i})\}U(t - \frac{\sqrt{r^2+z^2}}{c})$$

$$\vec{E}_z(x,y,z,t_n) = \vec{E}_z(x,y,z,t_{n-1}) + \Delta t \times \sum_{i=1}^{n}\sum_{m=1}^{k+1}\{a_m F_2(x,y,z,t=t_n,z'=h_{m,i}) - a'_m F_2(x,y,z,t=t_n,z'=h'_{m,i})\}U(t - \frac{\sqrt{r^2+z^2}}{c})$$

$\vec{E}_x$ is the electric field at x-axis due to Heidler return stroke current function,

$\vec{E}_z$ is the electric field at z-axis due to Heidler return stroke current function,

Δt is the time step,

n is the number of time steps,

$$t_n = (n-1)\Delta t \qquad n = 1,2,\dots,n_{max}$$

$$a_m = \begin{cases} \frac{\Delta h_i}{2\times k} & \text{for } m=1 \text{ and } m=k+1 \\ \frac{\Delta h_i}{k} & \text{for others} \end{cases}$$

$$a'_m = \begin{cases} \frac{\Delta h'_i}{2\times k} & \text{for } m=1 \text{ and } m=k+1 \\ \frac{\Delta h'_i}{k} & \text{for others} \end{cases}$$

k is division factor(>=2) ,

$$\Delta h_i = \begin{cases} \beta\chi^2\{(ct_i - ct_{i-1}) - \sqrt{(\beta ct_i - z)^2 + (\frac{r}{\chi})^2} + \sqrt{(\beta ct_{i-1} - z)^2 + (\frac{r}{\chi})^2}\} \\ \beta\chi^2\left\{-(\beta z - ct_i) - \sqrt{(\beta ct_i - z)^2 + \left(\frac{r}{\chi}\right)^2}\right\} & \text{for } i=1 \end{cases}$$

$$\Delta h'_i = \begin{cases} \beta\chi^2\{(ct_{i-1} - ct_i) + \sqrt{(\beta ct_i + z)^2 + (\frac{r}{\chi})^2} - \sqrt{(\beta ct_{i-1} + z)^2 + (\frac{r}{\chi})^2}\} \\ \beta\chi^2\left\{-(\beta z + ct_i) + \sqrt{(\beta ct_i + z)^2 + \left(\frac{r}{\chi}\right)^2}\right\} & \text{for } i=1 \end{cases}$$

$$h_{m,i} = \begin{cases} \frac{(m-1)\times\Delta h_i}{k} + h_{m=k+1,i-1} \\ \frac{(m-1)\times\Delta h_i}{k} & \text{for } i=1 \end{cases}$$

$$h'_{m,i} = \begin{cases} \frac{(m-1)\times\Delta h'_i}{k} + h'_{m=k+1,i-1} \\ \frac{(m-1)\times\Delta h'_i}{k} & \text{for } i=1 \end{cases}$$

IV. PROPOSED ALGORITHM

Based on equation(2) and Figure.1, the values of lightning induced voltage at measuring point at different time steps can be evaluated using analytical expression as the parameters of current function (DU) and current model (MTLE) have been set as unknown parameters. Therefore, by using data from lightning location system the values of x and d (location of lightning with respect to measuring point) will be determined as illustrated in Figure.1. Likewise, by using measured lightning induced voltage on the line in the same time with respect to lightning location system, the parametrical equation of lightning induced voltage at different time steps will be equal to the corresponding measured values and the unknown current parameters can be calculate by solving the nonlinear equations system as presented by equation (3). The lightning induced voltage will be extracted from using mother wavelet. Noted that the particle swarm optimization algorithm had been used in this study as minimization of all sub-equations of equation(4) with a multi objective function has been targeted(minimization of any equations to zero).

$$\begin{cases} V^{ind}_{Measured}(x,t=t_1) = [A'_1(x,t=t_1) + A'_2(x,t=t_1) + A'_3(x,t=t_1)]U\left(t_1 - \frac{\sqrt{x^2+d^2+h^2}}{c}\right) \\ V^{ind}_{Measured}(x,t=t_2) = [A'_1(x,t=t_2) + A'_2(x,t=t_2) + A'_3(x,t=t_2)]U(t_2 - \frac{\sqrt{x^2+d^2+h^2}}{c}) \\ \vdots \\ V^{ind}_{Measured}(x,t=t_n) = [A'_1(x,t=t_n) + A'_2(x,t=t_n) + A'_3(x,t=t_n)]U(t_n - \frac{\sqrt{x^2+d^2+h^2}}{c}) \end{cases} \quad (3)$$

$$\begin{cases} V^{ind}_{Measured}(x,t=t_1) - [A'_1(x,t=t_1) + A'_2(x,t=t_1) + A'_3(x,t=t_1)]U\left(t_1 - \frac{\sqrt{x^2+d^2+h^2}}{c}\right) = 0 \\ V^{ind}_{Measured}(x,t=t_2) - [A'_1(x,t=t_2) + A'_2(x,t=t_2) + A'_3(x,t=t_2)]U\left(t_2 - \frac{\sqrt{x^2+d^2+h^2}}{c}\right) = 0 \\ \vdots \\ V^{ind}_{Measured}(x,t=t_n) - [A'_1(x,t=t_n) + A'_2(x,t=t_n) + A'_3(x,t=t_n)]U\left(t_n - \frac{\sqrt{x^2+d^2+h^2}}{c}\right) = 0 \end{cases} \quad (4)$$

Where:

$V^{ind}_{Measured}(x, t = t_n)$ is the measured induced voltage at the measuring point and time step of t_n.

V. RESULTS AND DISCUSSION

In order to evaluate the proposed algorithm, three samples of lightning induced voltage on the power line (at different distances with lightning) have been used to determine the current parameters and the results have been compared with the corresponding measured one.

Figure.2 shows the wave shape of lightning induced voltage at measuring point(based on Figure.1) as it has been used as an input data of proposed algorithm beside the radial distance with respect to lightning channel(500m).

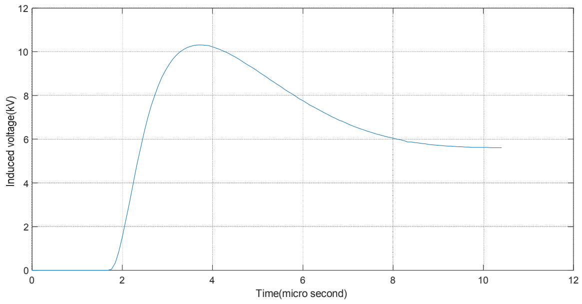

Fig.2. Induced voltage on the measuring point (x=0;d=500;h=10)

Figure.3 illustrates the comparison between actual channel base current and the corresponding evaluated current obtained from propose algorithm with average error percentage about 1.5%. The result shows that the evaluated current is in a good agreement with respect to actual one. Noted that the current parameters are t11=1μs,t12=2 μs, t21=8 μs, t22=30 μs,n1=2, n2=2, I01=19.5kA,I02=12kA and also the evaluated return stroke velocity is c/3 and λ=1500[11].

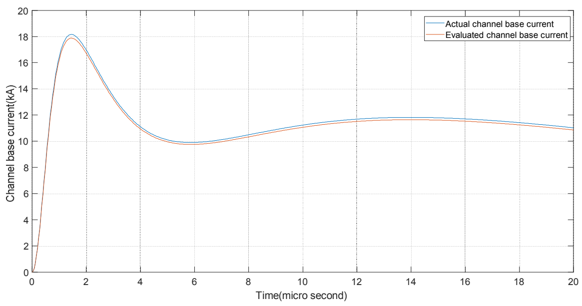

Fig.3. Comparison between actual channel base current and corresponding evaluated one(first data)

Moreover Figure.4 demonstrates the second wave shape of lightning induced voltage at measuring point(based on Figure.1). It should be mentioned that the radial distance with respect to lightning channel had been set on 50m.

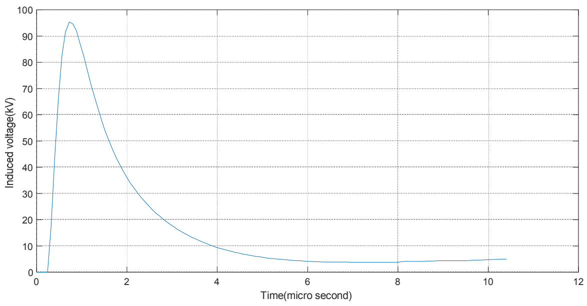

Fig.4. Induced voltage on the measuring point (x=0;d=50;h=10)

Figure.5 shows the comparison between actual channel base current and the corresponding evaluated current obtained from proposed algorithm with average error percentage about 1%. The result shows that the evaluated current is in a good agreement with respect to actual one. Noted that the current parameters are t11=0.25μs, t12=2.5 μs, t21=2 μs, t22=230 μs,n1=2, n2=2, I01=10.7kA,I02=6.5kA and also the evaluated return stroke velocity is c/2 and λ=2000[11].

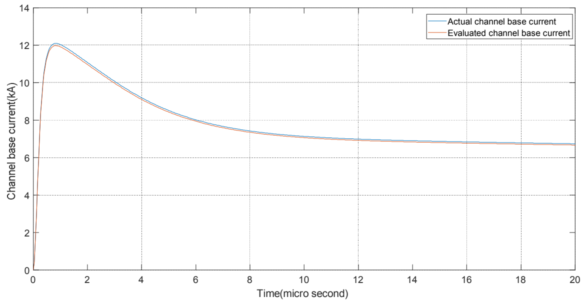

Fig.5. Comparison between actual channel base current and corresponding evaluated one(second data)

Figure.6 shows the third wave shape of lightning induced voltage at the measuring point (based on Figure.1). It should be mentioned that the radial distance with respect to lightning channel had been set on 2000m. In this study the general form of DU current function and MTLE current model had been used in the proposed algorithm however other current functions and models can be applied with the same approach.

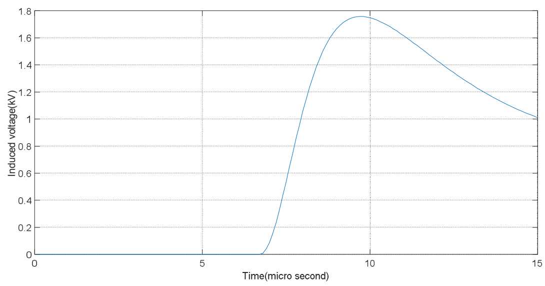

Fig.6. Induced voltage on the measuring point (x=0;d=2000;h=10**)**

Figure.7 illustrates the comparison between actual channel base current and the corresponding evaluated current obtained from proposed algorithm with average error percentage about 2%. The result shows that the evaluated current is in a good agreement with respect to actual one. Noted that the current parameters are t11=2μs, t12=4.8 μs, t21=20 μs, t22=26 μs,n1=2, n2=2, I01=10.5kA,I02=9kA and also the evaluated return stroke velocity is 1.8E8 m/s and λ=1500[11].

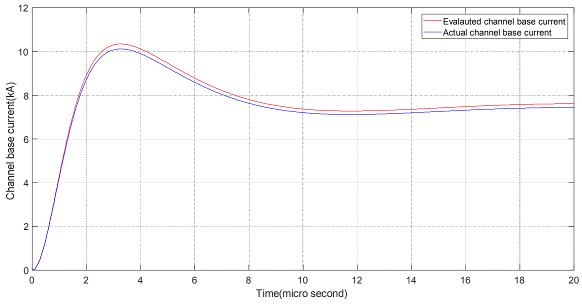

Fig.7. Comparison between actual channel base current and corresponding evaluated one(third data)

As mentioned in the results, the proposed method had been evaluated and validated using three different current samples as in the first stage, the lightning induced voltage had been evaluated using current parameters and in the second stage, the lightning induced voltage (obtained from first stage) had been used in the algorithm as an input data and the channel base current had been evaluated based on proposed method and the results had been compared with the corresponding original current. The results showed that the proposed method can evaluate the current parameters using measured induced voltage on the overhead line and radial distance from lightning obtained from lightning location system. The proposed method can cover a wide range of current functions and models and also can determine full of current as opposed with some of previous method that could evaluate current values at a limited frequency range. In this method the induced voltage has been used as an input data that measuring of this index is easier and accessible than electromagnetic field components that had been used in other previous methods[12]. By using the proposed algorithm a wide range of lightning events can be covered and the evaluated current wave shapes can be used to develop the lightning protection standards.

VI. CONCLUSION

In this paper, the return stroke current parameters had been determined using a proposed algorithm using measure voltage values from overhead distribution lines and lightning location that had been obtained from lightning location system. The algorithm performance had been studied using three different samples considered using different samples and the results had been discussed accordingly. The results showed that the proposed algorithm could determine the lightning current parameters in an acceptable range of accuracy. Likewise, the proposed method can prepare lightning current parameters using a wide range of lightning events based on their induced voltage on the line. The evaluated current parameters can be used in the lightning protection studies and by using them , the lightning protection standards can be developed.

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