High Frequency Analysis of Single Overhead Line Terminated to Grounded Arrester Using Fuzzy Inference Models

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***Abstract*— In this paper, intelligent models based on fuzzy inference are proposed to analyze single overhead line terminated to arrester. This paper consists of two parts. The first one is modeling overhead line; and the second one is related to modeling grounding system. In each part, the behavior of the problem is first represented as simple and unchanged membership functions. After then, effects of parameters of the problem such as height of overhead line, and lightning-strike point are extracted as simple curves. As a result, these achieved models in despite of transmission line model (TLM) is applicable for high frequencies created by lightning strikes.**

***Index Terms*—**Overhead line, Arrester, Fuzzy inference.

I. INTRODUCTION

The transient analysis of overhead lines is of importance because through it, one can find where and what arrester should be placed along overhead line to suppress the lightning-induced voltage [1-3]. A schematic diagram of a single overhead line connected to arrester is shown in figure 1.

In figure 1, the ground is characterized by electromagnetic parameters $\varepsilon_{rg}, \sigma_g$ and μ_g and h is the spacing between transmission line and ground surface. It is also assumed that the lightning arrester is connected to a simple grounding rod buried in a lossy ground. The arrester behaves as a nonlinear load with following i–v characteristic:

$$i_a = p v_a^{\alpha} \tag{1}$$

Where i_a is the arrester current and v_a is the arrester voltage and p is a real coefficient. For silicon carbide (SiC) arresters, the value of α varies between 2 and 6 while it takes a value between 10 and 60 for MO arresters [5].

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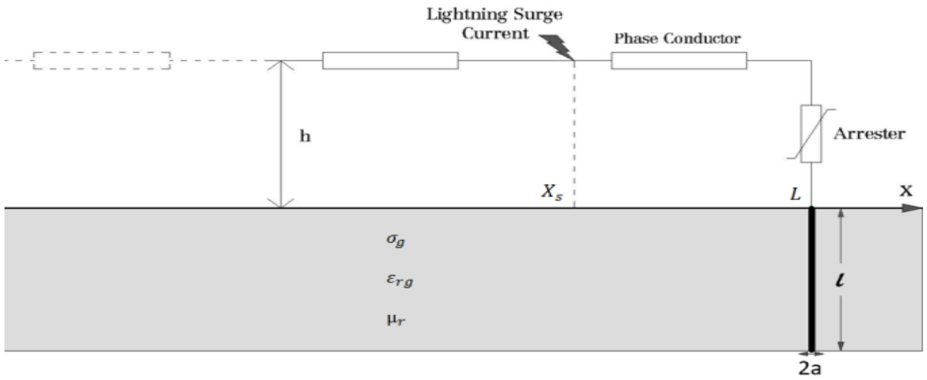


Fig.1. Schematic diagram of a single-conductor transmission line above a lossy ground with a grounded lightning arrester.

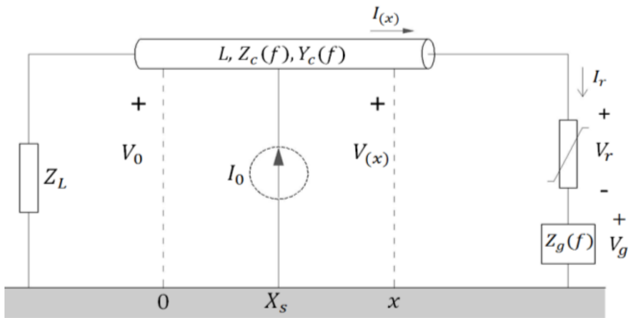


Fig.2.Representation of problem of figure 1(a) by transmission line model.

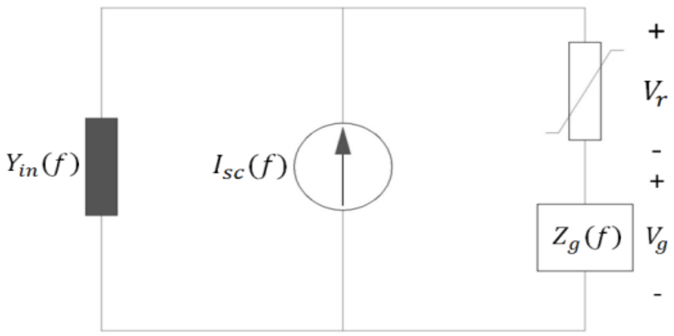


Fig. 3.Equivalent circuit model of the problem shown in figure 1 (a) and (b) ignoring the ionization of soil.

It is assumed that the ionization of soil is ignorable, hence the input impedance of the rod buried in the soil can be represented by linear impedance $Z_g(f)$ and the transmission line can be represented by transmission line of length L and characteristics impedance Z_c as shown in figure 2. Meanwhile in this figure, current source I_0 represents current due to lightning strike at lightning-strike point X_s.

Accordingly the equivalent circuits of single overhead line from point of view of the arrester and the ground impedance can be represented as figure 3(a).

In figure 3, Y_{in} is input admittance of the transmission line, I_{sc} is Norton equivalent current, and $Z_g(f)$ is input impedance of grounding system. These quantities are computed through accurate methods such as the method of moments (MoM) [6] or approximations ones such as transmission line models (TLM) [7-11].

With reference to [4], accurate evaluation of the overvoltage is based upon combining approximate method of TLM and nonlinear technique of AOM. Since the lightning-induced current along the line include frequencies up to 10MHz, the TLM [1] which is restricted to frequencies at which $kh << 1$ is failed and the overvoltage is not consequently correctly computed. On the other hand, MoM gives accurate results at arbitrary frequency; but it demands long run-time.

To the best our knowledge, there is no closed-form solution for $Y_{in}(f)$, $I_{sc}(f)$, and $Z_g(f)$, at high frequencies created by lightning strikes. To achieve close forms for them, intelligent models such as neural networks (N.N) [12, 13] and conventional fuzzy inferences [14, 15] can be used. It is however well known that these models require too many initial input-output data to create the model and also training process is too long especially when the number of inputs is increased.

In contrast with these intelligent models, the fuzzy-based approach proposed only for modeling electromagnetic problems [16-18] can be used.

This model has two main advantageous against the other ones such as N.N that makes it more efficient for instance one can compare this model with N.N in analyzing nonlinear antennas [19-21]. The first is extracting behavior of the problem as a moving circle using a few input-output data, and the second is dividing multi input-multi output system to single input-multi output sub systems, then extracting knowledge base of each sub system separately as simple curves and finally combining them through spatial membership functions [22]. Further information about this approach is explained in the next section.

This paper is organized as follows. In section II, behavior of the overhead line by the proposed approach, is represented, and then in section III the input admittance including the effect of height as very simple curves is modeled. In section IV, the short circuit current is modeled and effect of lightning-strike point on it is extracted. Fuzzy model of the input impedance of the buried rod are presented in section V. Finally conclusion is in section VI.

II. BEHAVIOR OF THE OVERHEAD LINE

Consider an overhead line of length 600 m and above the ground surface with $h = 18m$, $\varepsilon_{rg} = 10$ and $\sigma_g = 1(mS/m)$. In order to model input admittance of a general transmission line is first computed by MoM (via Feko software) in the frequency interval [1- 2] MHz. Figure 4(a) shows the amplitude versus phase of the input admittance in polar plane.

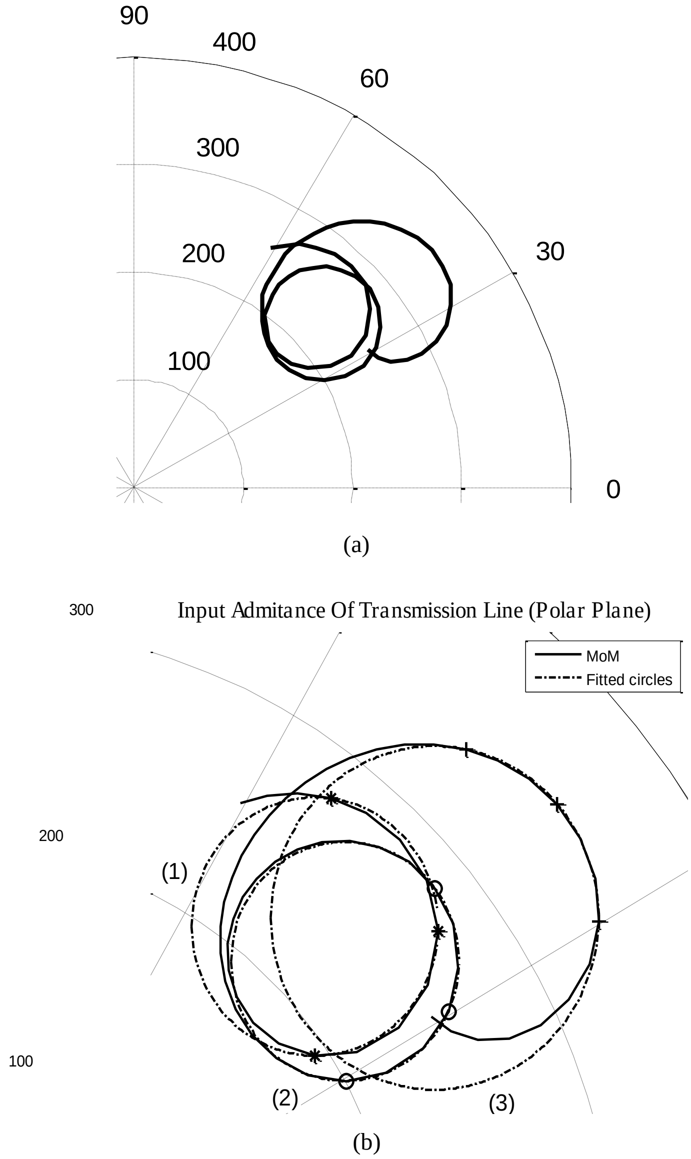


Fig. 4. (a): Amplitude versus phase of the input admittance in polar plane by MoM (b) figure (a) in zoomed form in addition to starting points (stars, circles and pluses) for defining fitted circles.

This curve may be interpreted as three basic circles converting to each other smoothly by increasing L/λ . This circular movement is represented as the following if-then rules:

$$\begin{cases} if \quad L/\lambda \quad is \quad small \quad \rightarrow \quad first \quad Circle \\ if \quad L/\lambda \quad is \quad medium \quad \rightarrow \quad second \quad Circle \\ if \quad L/\lambda \quad is \quad large \quad \rightarrow \quad third \quad Circle \end{cases} \qquad (2)$$

In order to model this circular movement, we use the method introduced in [16-18]. Therefore at first we fit circles on the basic circles of the circular movement of figure 4 by selecting three sets of input-output data (circles, pluses, and stars) around $L/\lambda = 2.2, 2.8, 3.5$ as shown in figure 4(b).

Assigning a membership function or belongingness for each fitted circle, is the second step as shown in figure 5.

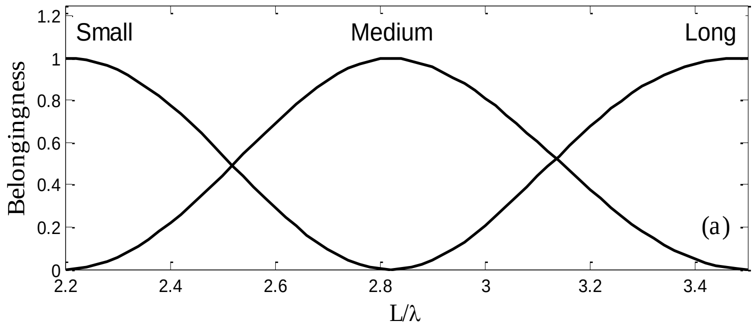


Fig.5. Membership functions for modeling partial locus.

The general form of this membership functions in figure 5, is expressed as equation (3):

$$\alpha_i\left(L/\lambda\right)=\begin{cases}\frac{1}{2}\left(1+\cos\left(\pi\left(\frac{L/\lambda-a}{b-a}\right)^{\beta_1}\right)\right)\Rightarrow L/\lambda : a\to b\\ \frac{1}{2}\left(1-\cos\left(\pi\left(\frac{L/\lambda-a}{b-a}\right)^{\beta_2}\right)\right)\Rightarrow L/\lambda : b\to a\end{cases} \tag{3}$$

Where $\beta_{1,2}$ are optimizing parameters, and a,b are boundary points where the circular movement is separated from the fitted circles. As shown in figure 6, these three membership functions have belongingness one on the fitted circles and are smoothly decreasing to zero on the neighbor fitted circle. This kind of membership function is defined by Bagheri Shouraki et al [23] and is selected because of its flexibility and also its adaption with circular movement.

The next step is modeling partial locus that is inference of a circle for each L/λ using Takagi-Sugeno's method [14] as following:

$$\begin{cases}x(L/\lambda)=\sum_{i=1}^{3}x_i\alpha_i(L/\lambda)\\ y(L/\lambda)=\sum_{i=1}^{3}y_i\alpha_i(L/\lambda)\\ r(L/\lambda)=\sum_{i=1}^{3}r_i\alpha_i(L/\lambda)\end{cases} \tag{4}$$

in which $\alpha_i s$ are membership functions (belongingness) in figure 5, x_i, y_i and $r_i\,(i=1,2,3)$ are centre coordinates and radius of the fitted circles, and $x(L/\lambda)$, $y(L/\lambda)$, $r(L/\lambda)$ are centre coordinates and radius of inferred-fuzzy circles for each L/λ. A few inferred-fuzzy circles are shown in figure 6.

To determine the input admittance (output) on the inferred circles, the partial phase (phase with respect to the centre of inferred circles) should be defined, and then modeled. The partial phase for the problem under consideration is shown in figure 7.

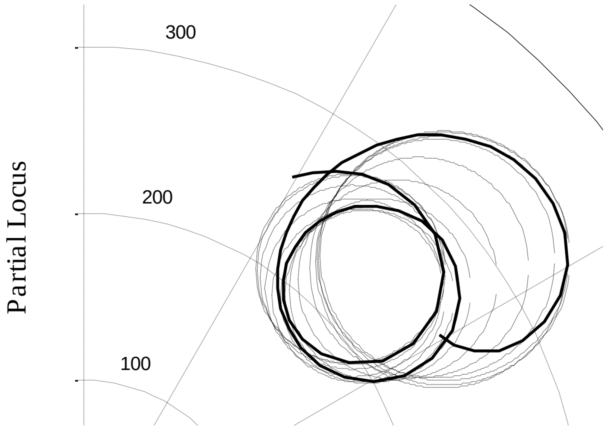


Fig. 6.Inferred fuzzy circles in polar plane.

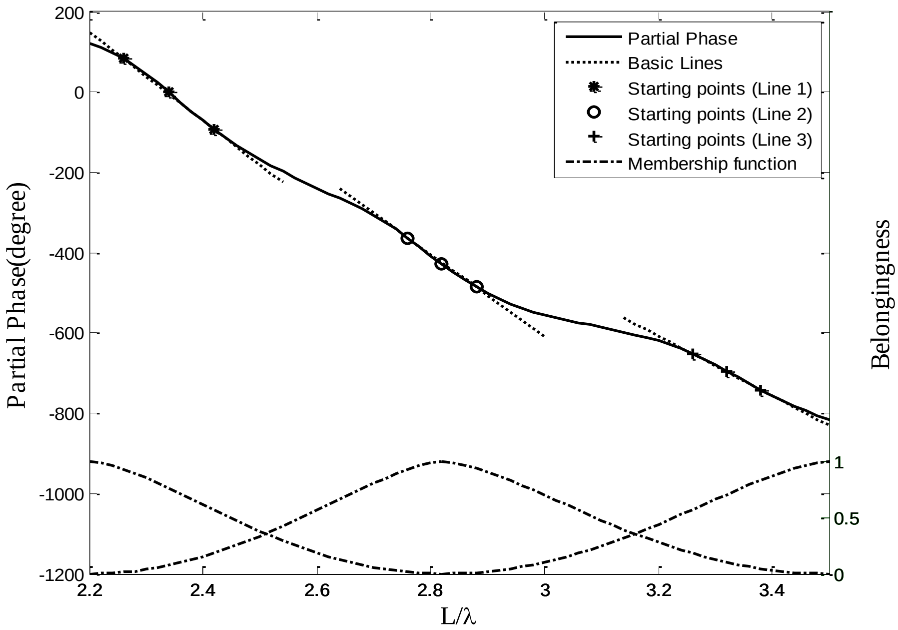


Fig. 7. partial phase, fitted line and membership functions for modeling partial phase.

In figure 8, smoothly decreasing curves as well as three sets of starting points (stars, circles and pluses) are seen. These points are those used for defining basic circles in modeling process of circular movement, and here three lines are fitted on them (dotted lines in figure 7). Modeling partial phase is the same as partial locus except that circles are replaced with lines. The fuzzy inference equations for modeling partial phase are as following:

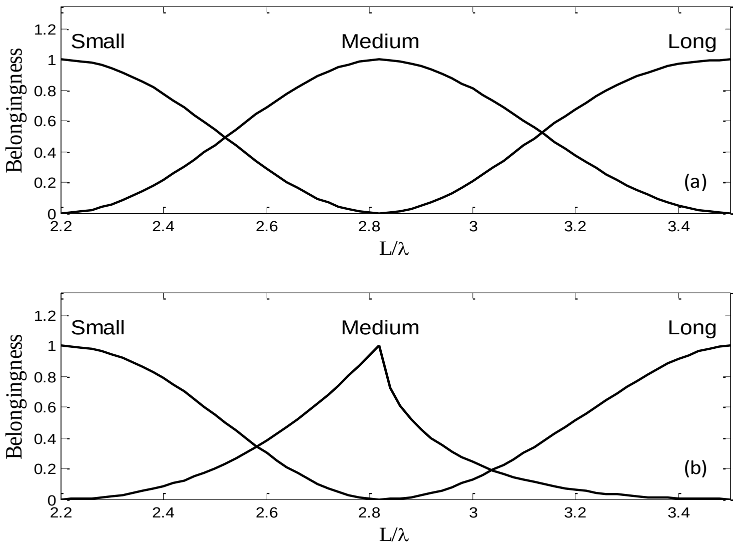


Fig. 8.Optimum Membership functions for (a) partial Locus, and (b) partial Phase.

$$\begin{cases} m(L/\lambda) = \dfrac{\sum_{i=1}^{3} m_i \alpha_i'(L/\lambda)}{\sum_{i=1}^{3} \alpha_i'(L/\lambda)} \\ n(L/\lambda) = \dfrac{\sum_{i=1}^{3} n_i \alpha_i'(L/\lambda)}{\sum_{i=1}^{3} \alpha_i'(L/\lambda)} \end{cases} \tag{5}$$

In which m_i and n_i are slope and bias of fitted lines, and $m(L/\lambda)$ and $n(L/\lambda)$ are slope and bias of inferred fuzzy lines for each L/λ . Also $\alpha_i s$ are membership functions in figure 7. These membership functions are again expressed in such a way that they have belongingness one on each fitted line and are smoothly decreasing to zero on the neighbor fitted lines.

Finally, the real and imaginary part of the input admittance versus input value is computed through the proposed model using below equation:

$$output(\frac{L}{\lambda}) = x(\frac{L}{\lambda}) + j.y(\frac{L}{\lambda}) + r(\frac{L}{\lambda}).e^{j(m.\frac{L}{\lambda}+n)} \tag{6}$$

Where x, y, r are computed by equation (4), and m,n by equation (5). To reach an acceptable amount of error, optimizing loop can be performed for $\beta_i s$ for both partial locus and partial phase. Notice that in the modeling process totally 8 parameters should be optimized.

By optimizing the all 8 β_i for the sample transmission line, the optimum membership functions and the input admittance are obtained and shown in figure 8 and 9 respectively.

As it is seen in figure 9, comparing model of fuzzy (MoF) with accurate one (MoM) an excellent agreement is achieved.

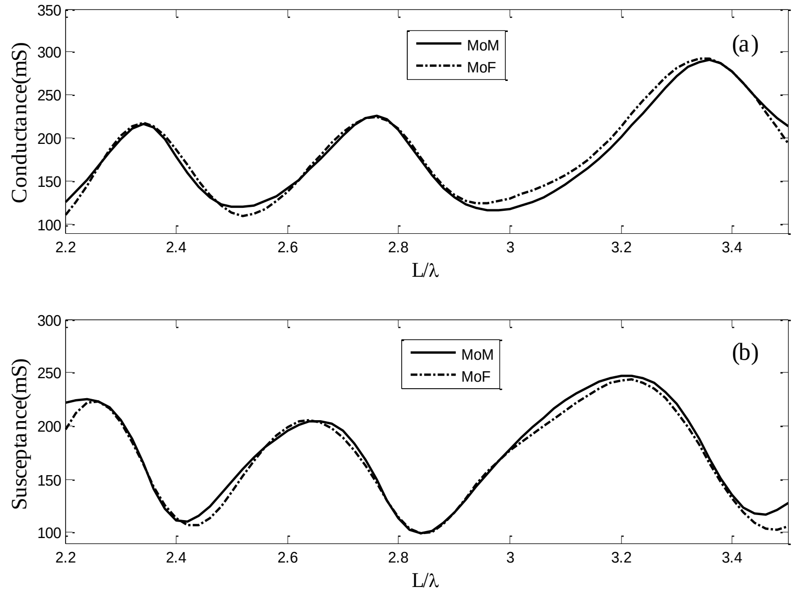


Fig. 9. Output Comparing the modeled input admittance with the MoM. (a) Real part. (b) Imaginary part.

From now on, these membership functions are considered as behavior of overhead line. In the next section, effect height on the input admittance is investigated.

III. FUZZY MODEL OF THE INPUT ADMITTANCE

One of the assumptions on the TLM approximation is low frequency (less than 1MHz) i.e., $kh << 1$ where k is wave number in free space.

In the previous section, all parameters of the overhead line were unchanged. Extracting the height effect lonely is carried out as follows. At first it is assumed that the membership functions in figure 9 for different values of height are constant, and then the centre coordinates and radius of three fitted circles for a few values of height for instance $h = 18,20,22,25m$ are computed (through selecting three sets of input-output data around $L/\lambda = 2.2, 2.8, 3.5$ by MoM). The centre coordinates and radius of three fitted circle for these samples are shown as stars, circles, and pluses in figure 10.

Figure 10 shows the centre coordinates and radius of three fitted circles versus height. As seen in figure 10, there is almost linear relation between these points and height that can be used simply to extract the effect of height. In fact, using these simple curves, centre coordinates and radius of fitted circles for arbitrary height such as $h = 19m$ is simply computed (without needing to MoM), and then using the membership functions of the figure 8, the input admittance based on equation (6) is efficiently computed and shown in figure 11.

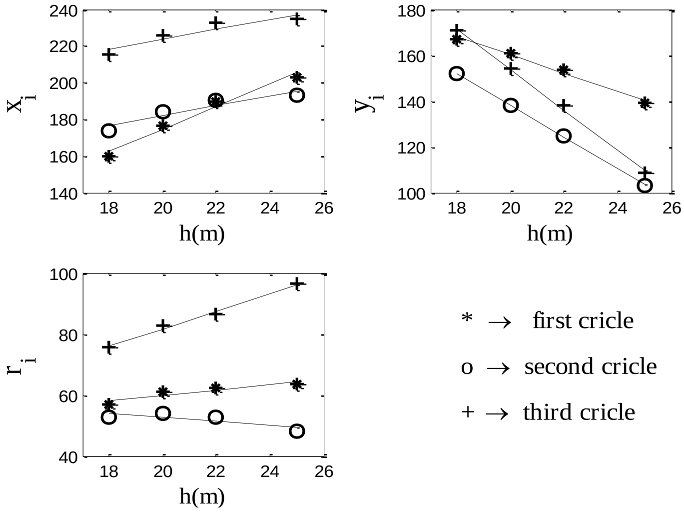


Fig. 10. Centre coordinates and radius of fitted circles versus height and the fitted lines on them.

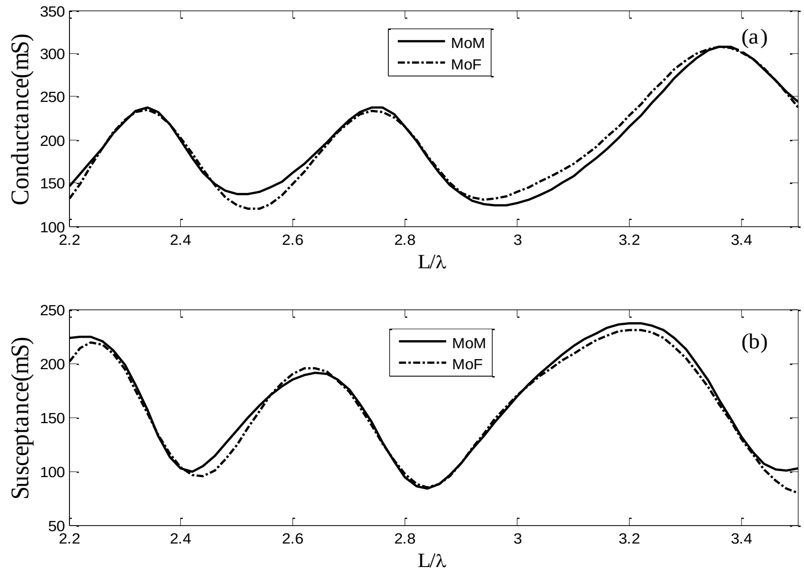


Fig. 11. Predicted input admittance of the overhead line compared with the MoM for $h = 19m$.

(a): Real part. (b): Imaginary part.

In this sub-section for the same transmission line, a model for short circuit current for various lightning-strike points (X_s)is presented. Figure 12 shows the amplitude versus phase of the short circuit current (I_{sc}) for two values of lightning-strike points in polar plane.

As it is seen in figure 12, the circular movement similar to figure 4 is kept, and only difference is the centre coordinates and radius of fitted circles. It means that the membership functions in figure 8 can model the circular movement related to short circuit current.

Now if the centre coordinates and radius of fitted circles for a few samples ($X_s = 20,40,60,80m$) and then curves of second order are fitted on them, the effect of the lightning-strike point on the short circuit current is easily extracted as shown in figure 13.

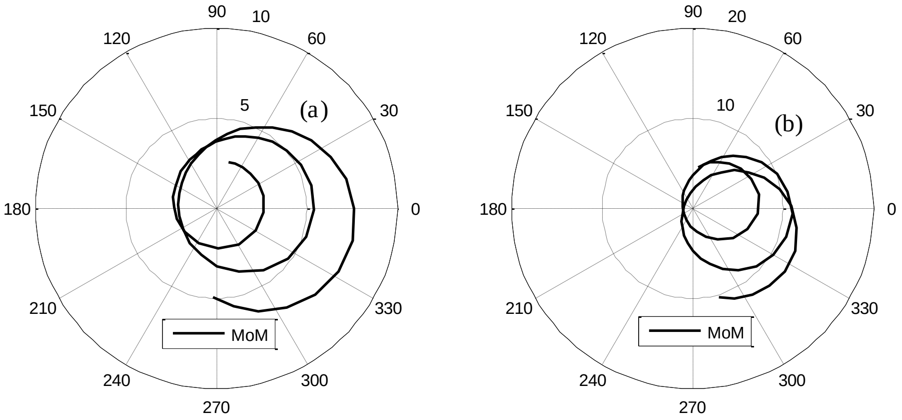


Fig. 12. Short circuit current in polar plane. (a) $X_s = 60m$. (b) $X_s = 80m$.

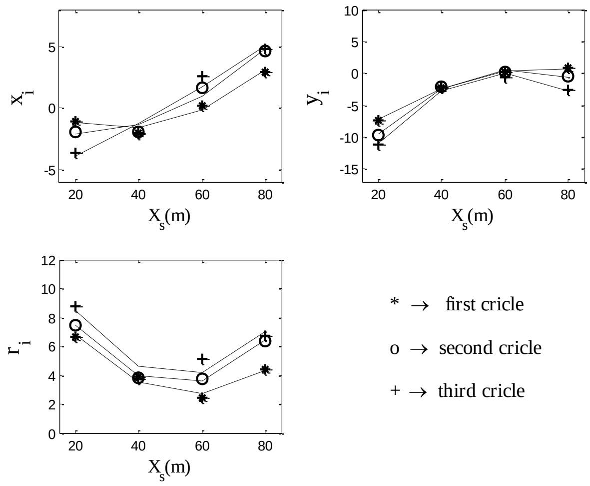


Fig. 13. Centre coordinates and radius of three fitted circles versus X_s in meter as the fitted curves of second-order.

Now with the use of the above fitted curves and the behavior of transmission line (figure 8), the short circuit current (I_{sc}) for arbitrary lightning-strike point is obtained as shown in figure 14.

As it is seen in figure 14, close agreement is achieved; moreover the run-time is considerably reduced. Meanwhile in this figure, a bit error around $L/\lambda = 3.1$ is observed. This error by fitting curves of higher order in figure 13 is reduced.

IV. MODELING GROUNDING SYSTEM

According to [7-11], there are three methods for computing the input impedance of grounding system, i.e., RLC, TLM, and MoM. On one hand RLC and TLM lead to acceptable prediction as well as short run-time at frequencies less than 1 MHz, on the other hand MoM yields accurate result for arbitrary frequency, but run-time is too long.

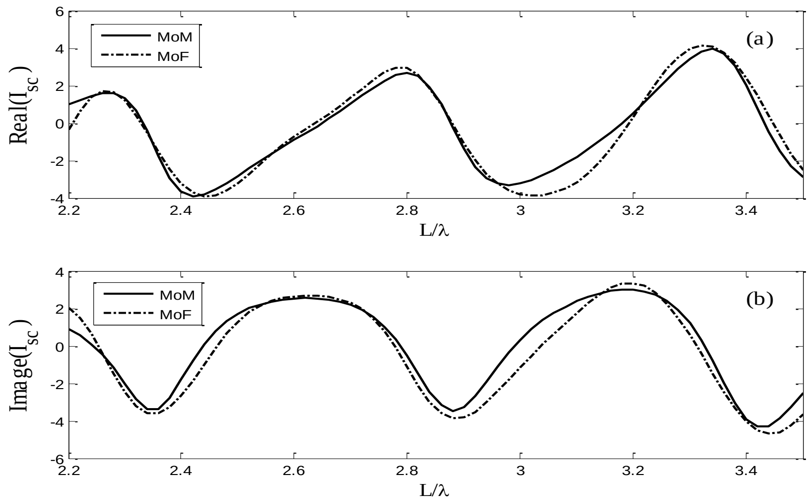
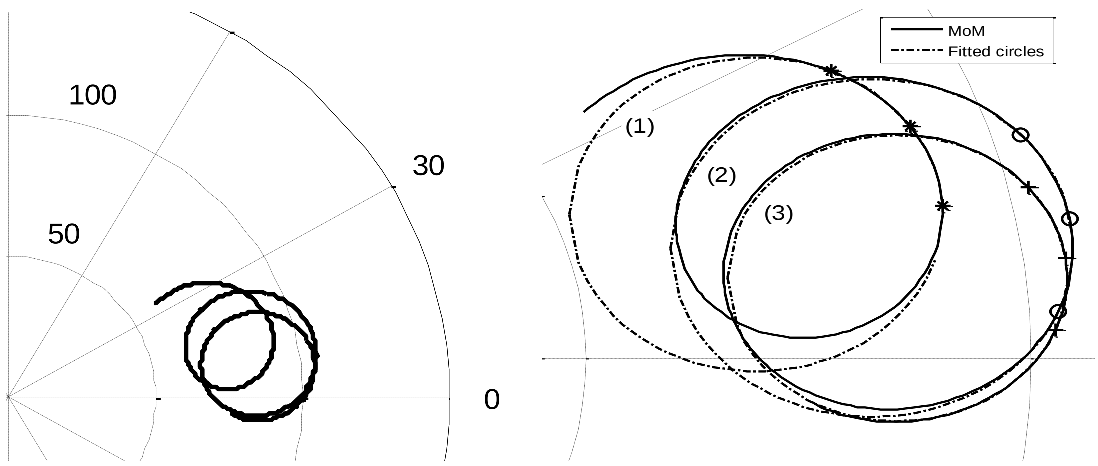


Fig. 14. Predicted lightning induced current for $X_s = 50m$ and comparing with MoM.

(a) Real part, (b) Imaginary part.



(a) (b)

Fig. 15. (a) Amplitude versus phase of the input impedance (ohm) of buried rod inside soil, (b) figure (a) in zoomed form in addition to starting points (stars, circles, and pluses) and fitted circles (dash-dotted).

To achieve a comprehensive model for input impedance, MoF can be again used. To this end, amplitude versus phase of input impedance of buried rod is computed by MoM and shown in polar plane in figure 15(a).

To model the figure 16, three sets of starting points around $L/\lambda = 0.2, 0.35, 0.53$ are chosen for defining three fitted circles as shown in figure 15(b). Modelling the input impedance of buried rod is the same as $Y_{in}(f), I_{sc}(f)$ hence only optimized membership function for modelling partial locus and partial phase are shown in figure 16.

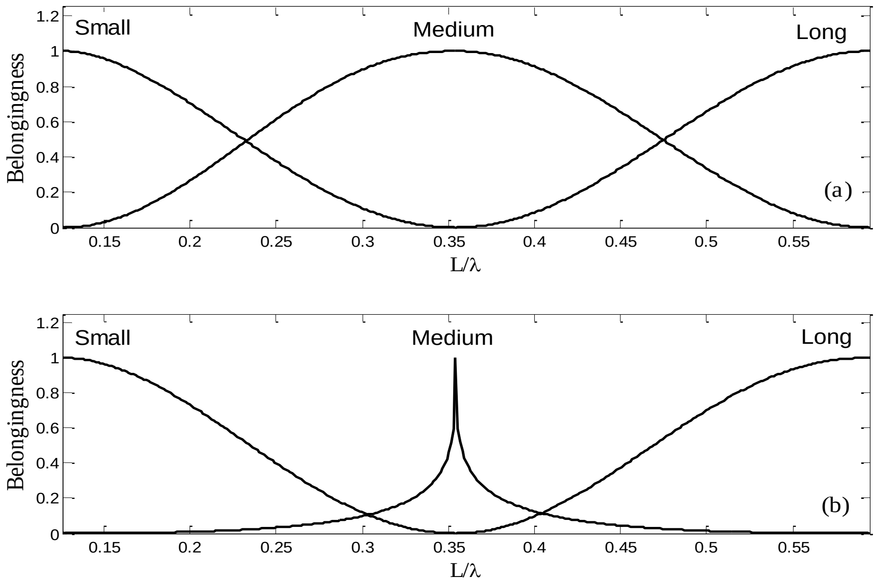


Fig. 16. The optimized membership functions for modelling (a) partial locus, (b) partial phase.

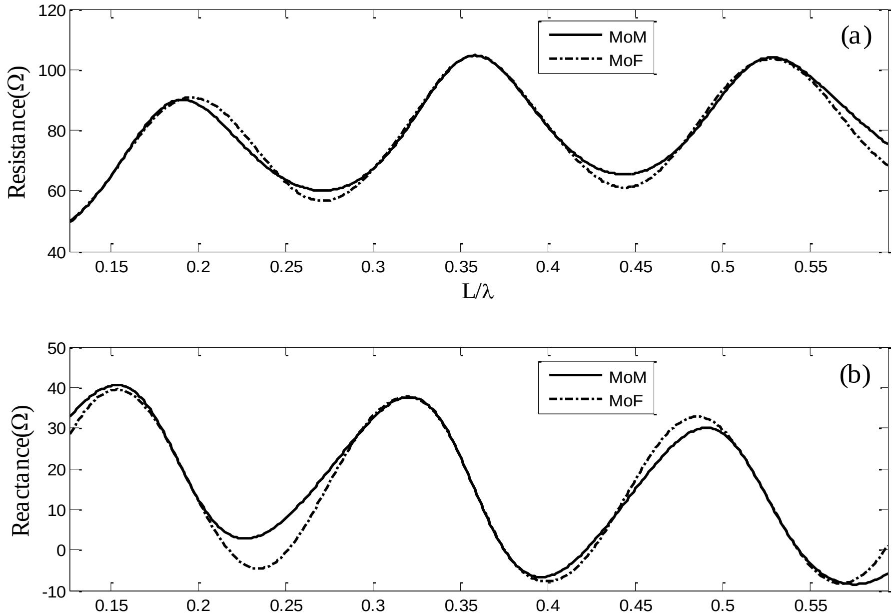


Fig. 17. Comparing the modelled input impedance by MoM and MoF.

To know how accurate the modelled input impedance of buried rod is, predictions of two methods of MoM and MoF are compared and shown in figure 17.

From now on, the three quantities which were efficiently modelled can be substituted in figure 3 so that the overvoltage across the arrester is correctly computed by arithmetic operator method (AOM) technique [24].

V. CONCLUSION

In this paper, a combined MoF-AOM approach was proposed to compute the overvoltage correctly in single overhead line. In the MoF, the transmission line is analyzed intelligently in which the behavior of the problem is considered as simple membership functions. Then in despite of TLM, the input admittance, short circuit current and also the input impedance of grounding system at high frequencies are efficiently computed. Analysis of this problem considering frequency dependence of the electrical parameters of soil is another study that is underway.

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