Application of Intelligent Water Drops in Transient Analysis of Single Conductor Overhead Lines Terminated to Grid-Grounded Arrester under Direct Lightning Strikes

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Abstract— **In this paper, Intelligent water drop algorithm (IWD) is used to analyze single overhead line connected to grid-grounded arrester. In this approach, at first Norton's equivalent circuit of the overhead line over lossy soil is computed by method of moments (MoM) and then for the problem under consideration, a nonlinear equivalent circuit in the frequency domain is proposed. Finally applying intelligent water drop algorithm (IWD), nonlinear analysis is efficiently analyzed and transient voltage across the arrester is easily computed. Comparison of the achieved voltage with transient solvers shows good agreement as well as fast run-time.**

Index Terms— *IWD, arrester, lossy soil.*

I. INTRODUCTION

As known, to protect power systems against lightning strikes, surge arresters are used. The optimum number and place of them along the overhead line are strictly dependent upon accurate evaluation of transient voltage across them (peak value and rise time of the voltage). To this aim, transient solvers such as **E**lectro-**M**agnetic **T**ransient **P**rogram (EMTP) [1, 2], is used. But in this solver, frequency response of each sub-system is first computed by accurate method for instance applying method of moments (MoM) [3] on the Maxwell's equations, or approximate methods such as transmission line method (TLM) [4]. Then through vector fitting method (VF) [5-7] or matrix pencil method (MPM) [8] each sub-system is converted to equivalent circuit or state space equations. Finally these are imported to transient solvers.

In order to evaluate transient voltage directly, Sheshyekani et al [9], proposed a hybrid model based on combining the TLM and arithmetic operator method (AOM) [10]. Fig. 1(a) shows schematic diagram of an overhead line terminated to the arrester above lossy ground. In this figure, the

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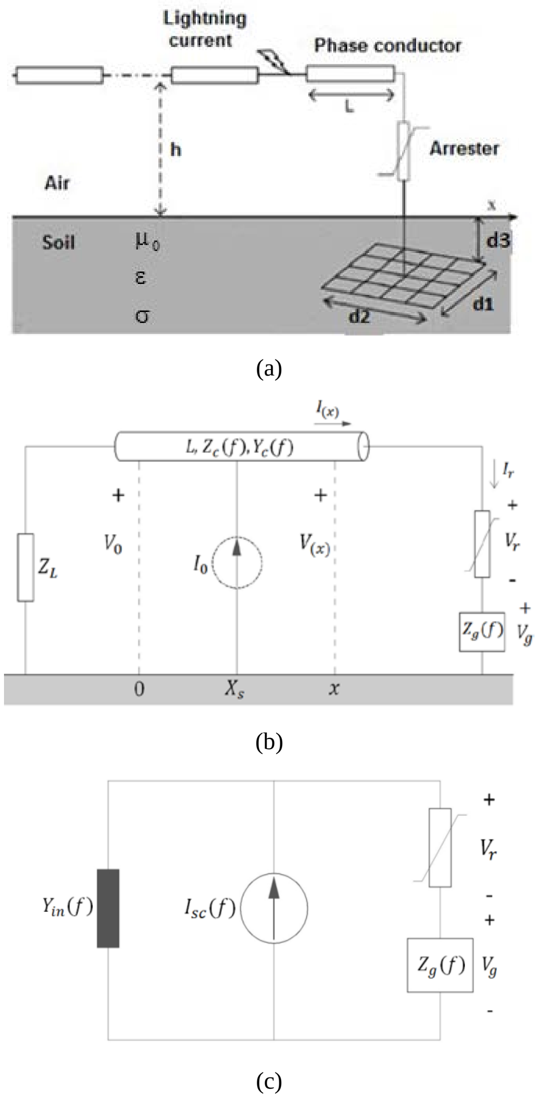

Fig 1. (a). Schematic diagram of an overhead line terminated to grounded arrester. (b), Transmission line representation of 1(a). (c), Nonlinear equivalent circuit of 1(b). Adopted from [11].

grounding system is an equally spaced $d_1 \times d_2$ grounding grid buried in depth of d_3 inside a lossy soil of conductivity σ and dielectric constant ε.

In the proposed method, as shown in the Fig. 1(b), Fig. 1(a) is first substituted by transmission line of length L and characteristic impedance Z_c such that it is matched at left side and terminated to the nonlinear load namely arrester at right side. Also, the grounding grid is represented by the linear impedance $Z_g(f)$ in the frequency domain.

Finally for nonlinear analysis, the Norton's equivalent circuit viewed across arrester and grounding grid is computed by the TLM and then using the nonlinear technique of the AOM, the nonlinear equivalent circuit as shown in Fig. 1(c) is analyzed.

As explained in the previous studies [11, 12], this approach has a few drawbacks. To remove them, the hybrid model based on combining method of fuzzy (MoF) [11] and genetic algorithm (GA) [12] was proposed. Although the GA is mostly efficient, in some cases it is sensitive to initial solutions and the run-time is thus expensive. To improve the proposed method, intelligent water drop algorithm (IWD) is introduced.

The IWD which is based on nature of water drops in rivers is a new and efficient optimization algorithm. It was initially proposed by Shahhosseini et al [13-18] and recently modified as improved IWD [19, 20], modified IWD [21] and adaptive IWD [22]. Up to now, this approach has been used as an optimization technique in engineering applications [23-25].

To the best our knowledge, there is no research by this algorithm in electromagnetic applications. Hence in this article, the IWD algorithm is used in transient analysis of overhead lines terminated to arresters. The achieved results show that firstly good agreement in comparison with EMTP, secondly in comparison with the the previous ones run-time is reduced.

This paper is organized as follows. In the section II, basic principles of the IWD is explained. In the section III, the IWD is used for nonlinear analysis of the problem under consideration and compared to the EMTP and GA. Finally conclusion is given in section IV.

II. BASIC PRINCIPLES OF THE IWD

The basic idea of IWD is based upon the observation of flow of water in rivers. Imagine a water drop is going to move from a point of river (node) to the next point in the front. It is assumed that each water drop flowing in a river can carry an amount of soil. The amount of soil of the water drop increases as it reaches to the right point while the soil of the river bed decreases. In fact, amount of soil of the river bed is removed by the water drop and is added to the soil of the water drop. This property is embedded in the IWDs so that each IWD holds soil in itself and removes soil from its path during movement in the environment.

A water drop has also a velocity and this velocity plays an important role in the removing soil from the beds of rivers. Let two water drops having the same amount of soil move from a point of a river to the next point. When both water drops arrive at the next point on the right, the faster water drop is assumed to gather more soil that the other one. The mentioned property of soil removing which is dependent on the velocity of the water drop is embedded in each water drop of the IWD algorithm.

It was stated above that the velocity of an IWD flowing over a path determines the amount of soil that is removed from the path. In contrast, the velocity of the IWD is also changed by the path such that a path with little amount of soil increases the velocity of the IWD more than a path with a

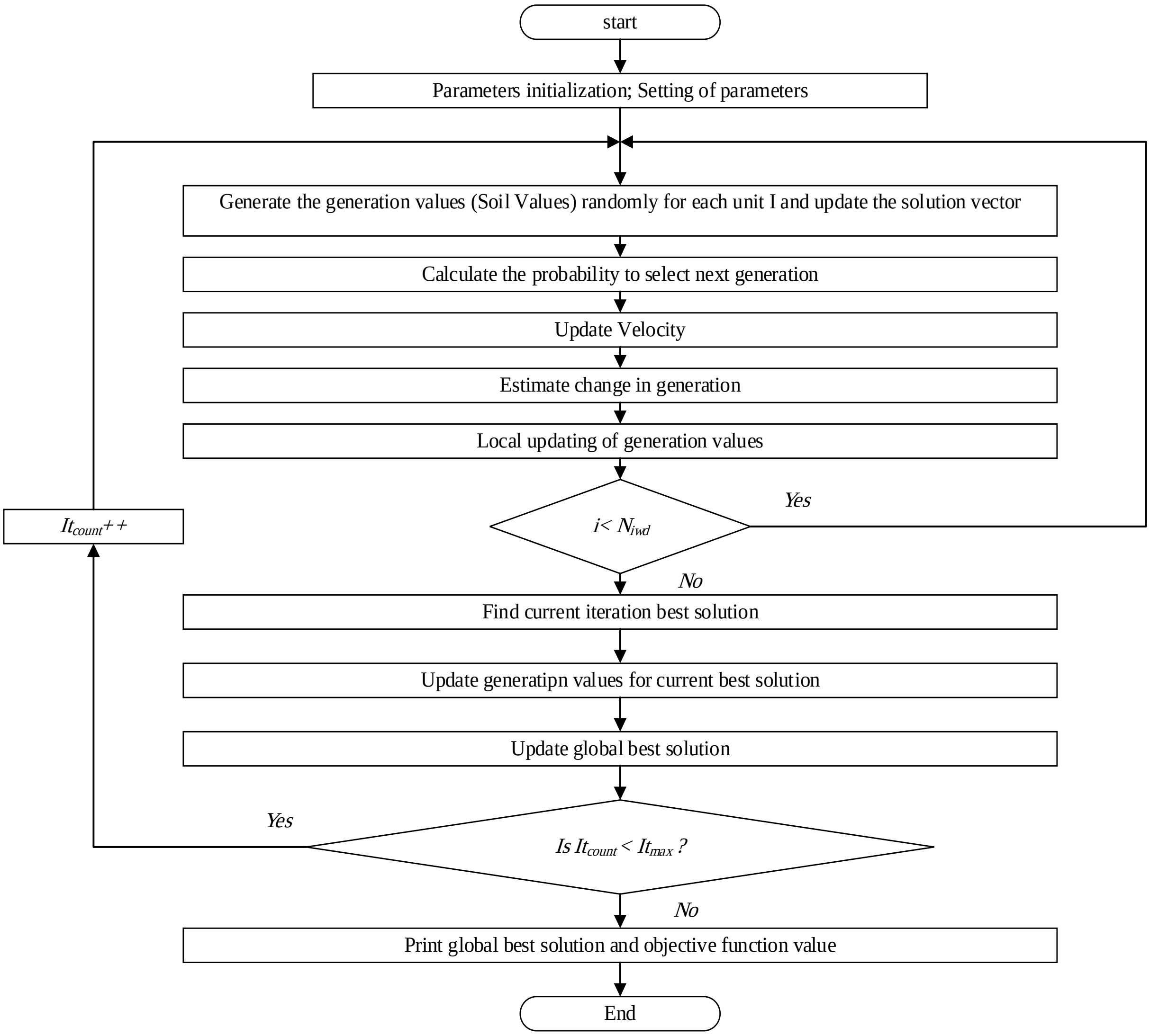

Fig. 2. Flowchart of IWD as step by step.

considerable amount of soil. The path with little soil lets the flowing water drop gather more soil and gain more speed whereas the path with large soil resists more against the flowing water drop such that it lets the flowing water drop gather less soil and gain less speed.

Obviously, a water drop prefers an easier path to a harder one when it has to choose between several branches that exist in the path from the source to the destination. In summury, the algorithm of IWD as step by step is shown in Fig. 2. Further information about this algorothm is found in [14].

III. TRANSIENT ANALYSIS OF OVERHEAD LINES TERMINATED TO ARRESTER BY IWD

In this section, the vertical rod of length $l = 3\mathrm{m}$ and buried in lossy soil with relative dielectric constant $\varepsilon_r = 10$ and conductivity σ is considered. As explained in [12], for the trnsient analysis, at first the Fig. 1c is simplified as shown in Fig. 3.

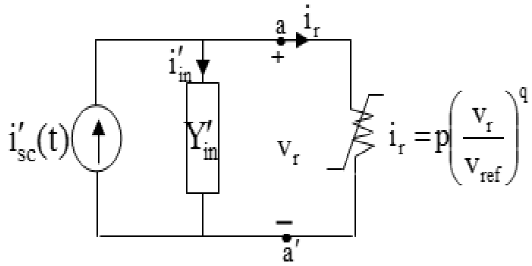

Fig. 3. Simplified model of the Fig. 1c.

In Fig. (3), I'_{sc} and Y'_{in} are computed as following

$$I'_{sc} = \frac{I_{sc}}{1 + Z_g Y_{in}} \tag{15}$$

$$Y'_{in} = \frac{Y_{in}}{1 + Z_g Y_{in}} \tag{16}$$

Also in this Fig., the arrester is represented as a nonlinear load as shown in Fig. 3. Assuming the arrester voltage as following

$$v_r(t) = V_0 + \sum_{j=1}^{N} V_j \sin(\omega_j t + \phi_j) \tag{17}$$

Where N is the number of frequencies in spectral content of the arrester voltage. Since the arrester and Y'_{in} are in parallel, the current following into Y'_{in} is expressed as:

$$\begin{aligned} i'_{in}(t) = &\sum_{j=1}^{N} G'_{in}(\omega_j) V_j \sin(\omega_j t + \phi_j) \\ &+ \sum_{j=1}^{N} B'_{in}(\omega_j) V_j \cos(\omega_j t + \phi_j) \end{aligned} \tag{18}$$

Where G'_{in} and B'_{in} are real and imaginary parts of Y'_{in}. Through applying Kirchhoff's current low (KCL) at node (a) yields a cost function as following:

$$\left\| \overline{\varepsilon(t)} \right\| = \left\| \begin{array}{l} \sum_{i=1}^{M} I_{sc,i} \cos(\omega_i t + \phi_i) \\ - \sum_{j=1}^{N} G'_{in}(\omega_j) V_j \cos(\omega_j t + \phi_j) \\ + \sum_{j=1}^{N} B'_{in}(\omega_j) V_j \sin(\omega_j t + \phi_j) \\ - p\left(\dfrac{v_0 + \sum_{j=1}^{N} V_j \cos(\omega_j t + \phi_j)}{v_{ref}} \right)^q \end{array} \right\| \to \bar{0} \tag{19}$$

In (5), there are $2N + 1$ unknown variables. To find them, the cost function in (19) is discretized at

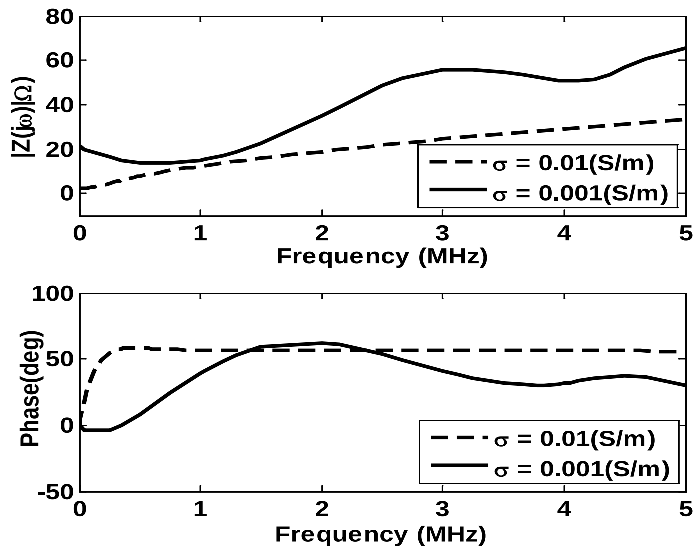

Fig. 4. Input impedance of grounding grid computed by MoM for two values of soil conductivity.

$t = k\Delta t,\ \ k = 0,1,..2N$ and $\Delta t = 1\mu s$ and finally the achieved equations are solved by the proposed optimization algorithm, i.e., IWD. Note that Δt=1μs is chosen to cover at least one period of the signal with sampling interval Δt satisfying the Nyquist criterion for the highest harmonic frequency of lightning current (see table I in [12]).

This algorithm is run for two values of soil conductivity, i.e. $\sigma = 0.01, 0.001 S/m$. The input impedance of the grounding grid for these cases are computed and shown in Fig. 4. The line height is $h = 10m$ and the lightning current in the Fig. 1(b) is the same as previous study [12].

The mean square error (MSE) for the problem under consideration is shown in Fig. 5. Also for comparison, the mean square error by the GA is shown in the same figure. As seen, the IWD is faster converged than the GA which is in agreement with [13-25]. Finally after converging the two algorithms, the voltage across arrester for two values of conductivities are computed via (١٧).

In this study, all results achieved by the proposed approach, are compared with well-known software (EMTP). Hence, in this software, the overhead line is substituted by frequency dependent line (FD line), and the grounding grid is imported into EMTP by an equivalent circuit extracted by the VF. In extracting equivalent circuits by VF, at first the frequency responses in Fig. 4 are converted to rational functions and then each of functions are easily represented as parallel braches of lumped elements as shown in Figs. 6 and 7. In these figures, all resistors, inductors, capacitances are in Ω, H and F respectively.

As known, in desighning arresters, the maximum (V_{max})and rise time (t_r) of the transient voltage across them are of importance [26]. Comparion of the two parameters computed by three approaches

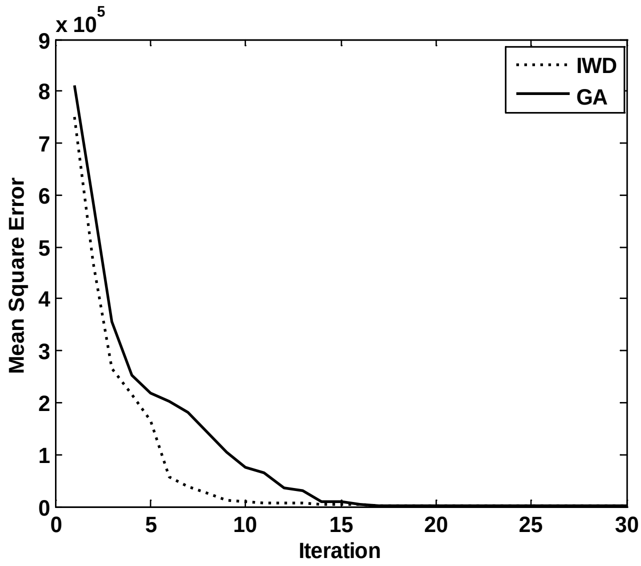

Fig. 5. Mean square error versus iteration for IWD and GA.

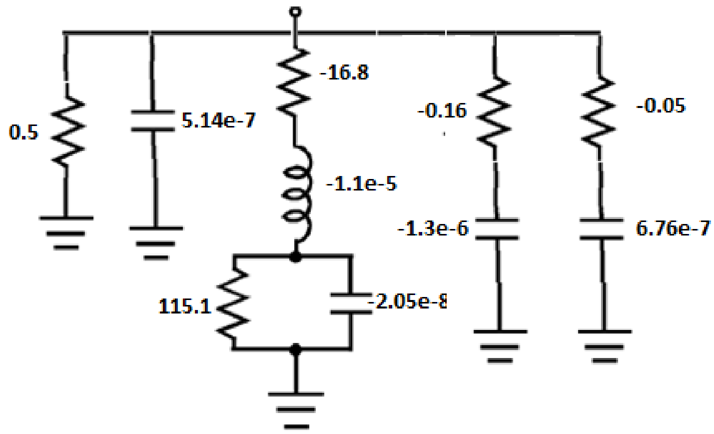

Fig. 6. equivalent circuit of grounding grid extracted by VF for $\sigma = 0.01\mathrm{S/m}$.

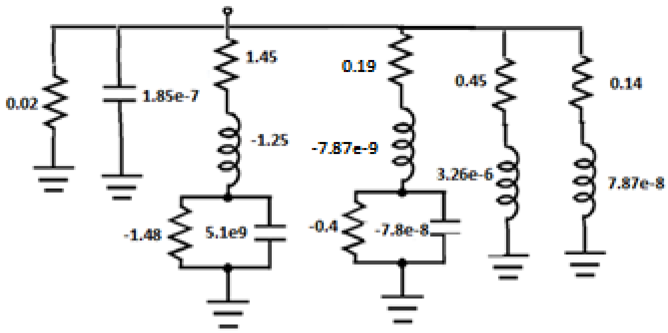

Fig. 7. equivalent circuit of grounding grid extracted by VF for $\sigma = 0.001\mathrm{S/m}$.

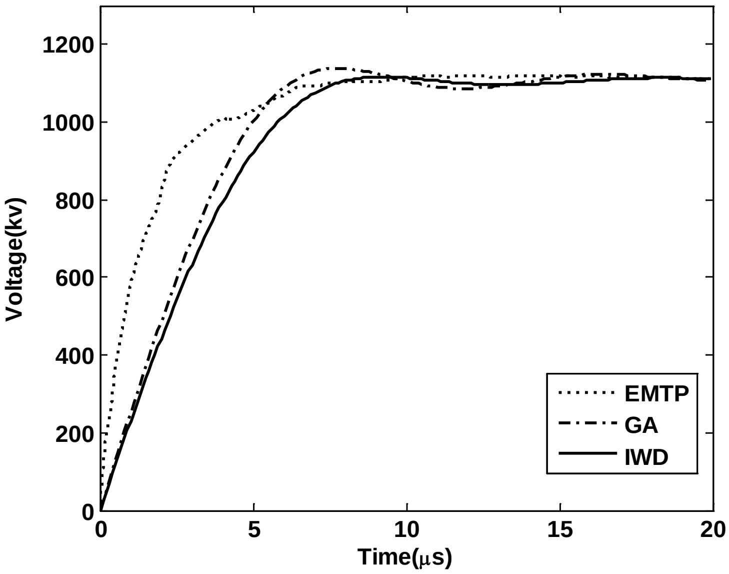

Fig. 8. Transient voltage across the arrester computed by the three approaches for $\sigma = 0.01\mathrm{S/m}$.

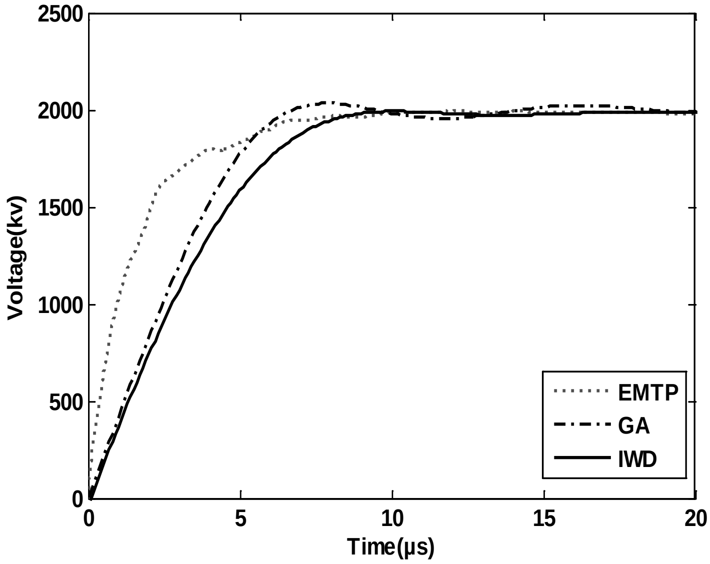

Fig. 9. Transient voltage across the arrester computed by the three approaches for $\sigma = 0.001\mathrm{S/m}$.

in Figs. 8 and 9 shows that the IWD approach is in excellent agreement with EMTP whereas the ones computed by GA are different. This makes the IWD efficient in transient analysis of power systems.

Meanwhile according to IWD indespite of EMTP based on only frequency response, transient voltage is easily computed. As a result, the run time for the IWD is reduced. It should be noted that as seen in Figs. 8 and 9, in the interval of $[0-5]\mu s$ difference between the IWD and EMTP is observed. This may be owing to the EMTP solves transmission line equations which are based on quasi-static assumptions [4] whereas frequency content of the lightning current is from dc to 10MHz. Table 1 and 2 compare the rise time and maximum of transient voltage computed by the three approaches.

Table 1. Comparison of computed early parameters of transient voltage by the three approaches for $\sigma = 0.01 S/m$.

Method / Parameter	GA	EMTP	IWD
$t_r (\mu s)$	≈ 7	≈ 8	≈ 8
$V_{max(kV)}$	1100	1050	≈ 1050

Table 2. Comparison of computed early parameters of transient voltage by the three approaches for $\sigma = 0.001 S/m$.

Method / Parameter	GA	EMTP	IWD
$t_r (\mu s)$	≈ 7	≈ 8	≈ 8
$V_{max(kV)}$	2050	1950	≈ 1950

IV. CONCLUSION

In this paper, an intelligent method namely IWD was used in transient analysis of single conductor overhead line terminated to grid-grounded arrester. In this approach which is based upon behavior of water drops in rivers in despite of conventional optimization techniques such as GA is more efficient in finding nearly global minimum. Comprehensive analysis of multi-conductor overhead line terminated to grounded arresters over lossy soil is another study that is in progress.

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