Transient Analysis of the Single-Conductor Overhead Lines Connected to Grid-Grounded Arrester under Direct Lightning by Means of GA

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***Abstract*- In this paper, genetic algorithm-based approach for transient analysis of single transmission line connected to arrester is proposed. In this approach, the lightning channel striking the overhead line is first represented by a current source and this source is truncated by a finite set of frequency harmonies in time domain. Norton equivalent circuit viewed across arrester is then computed by method of Fuzzy (MoF), then applying Kirchhoff's current low to this nonlinear circuit and solving it by genetic algorithm, transient voltage across the arrester is easily computed. Comparison of the achieved voltage with accurate one (EMTP software) shows good agreement as well as fast run-time.**

***Index Terms*-** Arrester, overhead line, genetic algorithm**.**

I. INTRODUCTION

Surge arresters are used along transmission lines to protect power systems against over voltages created by different strikes such as switching, lightning and so on. Suppressing performance of arresters is dependent upon the exact analysis of them, and this accordingly is strictly dependent on exact analyses of the different systems connected to arresters for instance overhead lines and grounding systems. Figure 1 shows two sub-systems connected to arrester, i.e., overhead line and grounding system. Figure 2(a) is frequency-domain representation of th figure 1 in which the overhead line is substituted by a transmission line of length L and characteristic impedance Z_c, and the grounding system is also by linear impedance Z_g. There are different methods for analysis of these two sub- systems such as transmission line model (TLM) [1-7] but most of them are based on quasi static assumptions and thus invalid at high-frequency currents induced along lines.

With reference to [8], evaluation of the overvoltage is carried out through analyzing Norton equivalent viewed across arrester as shown in figure 2(b) by arithmetic operator method (AOM), but the overhead line and the grounding system are analyzed by transmission line model (TLM) [1] and distributed RLC model [2-7] respectively. Therefore the overvoltage is not exactly computed.

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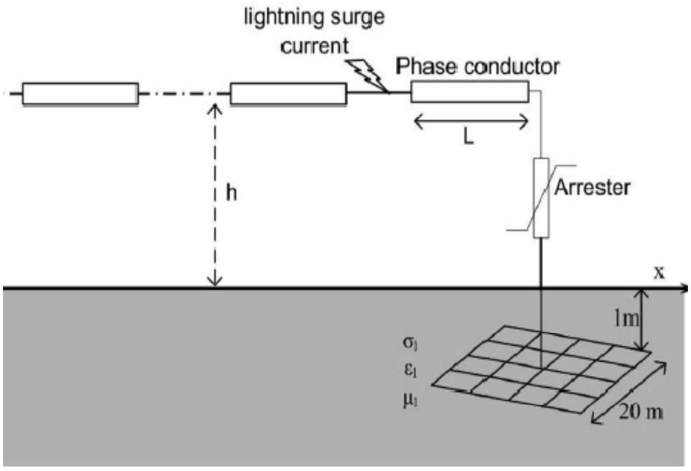
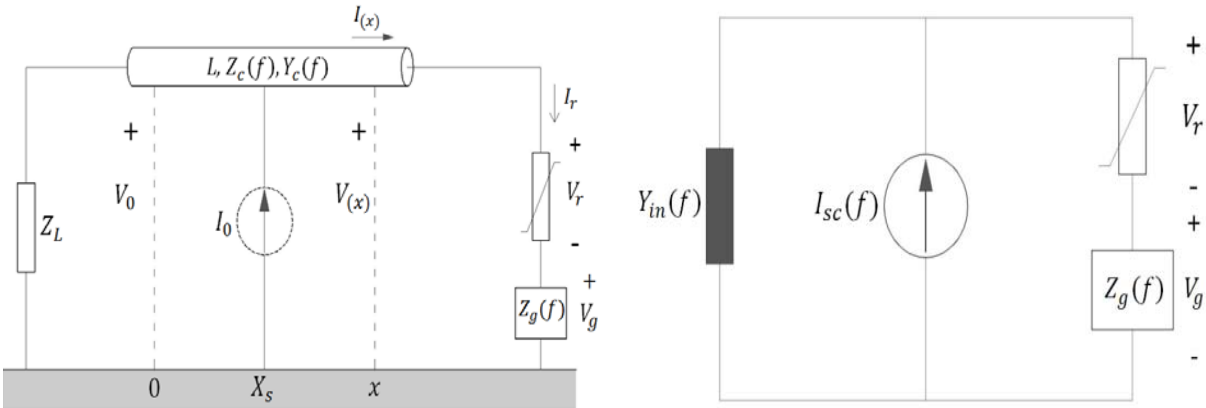


Fig. 1 Overhead line connected to grounded arrester and subjected by direct lightning strike in which grounding system is represented by grid grounding [8].



(a) (b)

Fig. 2. (a): Frequency-domain representation of figure 1 in which the overhead line and grounding system are represented by transmission line and linear impedance respectively and surge current by current source $I_0(t)$, (b): Norton equivalent circuit viewed across arrester.

In our previous studies [9, 10], frequency-domain models based on fuzzy inference were proposed for high-frequency analyses of transmission lines and grounding systems, but efficiently nonlinear analysis of the overvoltage was not performed. Conventional electromagnetic transient programs such as EMTP software [11] deal with such nonlinear problems but these solvers substitute transmission lines and grounding systems by time-domain representation. In fact frequency response of each sub-system must be first computed through numerical methods such as method of moments (MoM) [12] and then by vector fitting [13] frequency response is then converted to time domain one and finally imported into EMTP. In contrast with EMTP, the AOM needs to frequency response only, but it suffers from suitable initial guess as well as gradient operation and matrix inversion in the iteration process.

Table I. Parameters related to the nine sinusoidal harmonies.

$\omega_i\,(Mrad/\sec)$	$\omega_1 = 0.11$	$\omega_2 = 0.21$	$\omega_3 = 0.42$	$\omega_4 = 0.63$	$\omega_5 = 0.65$	$\omega_6 = 1.16$	$\omega_7 = 1.26$	$\omega_8 = 1.45$	$\omega_9 = 1.66$
$I_i(A)$	4.67e4	2.05e4	3815	9667	8522	151	185.5	102	62.5
$\phi_i(rad)$	-0.42	0.93	0.43	0.065	3	-2.26	-0.76	-0.57	-0.89

In this contribution, an approach based on genetic algorithm (GA) is proposed. Genetic algorithm has wide spread applications such as in electromagnetic engineering as optimization tool [14-16], but it is here used for analysis of the desired problem. In analyzing with GA, the drawbacks of the AOM are completely removed. Also in despite of the EMTP, for evaluating lightning-induced over voltage, frequency response is only needed, also there is no need to fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT). As a result, transient voltage is efficiently computed by the GA.

This paper is organized as follows. In section II, modeling formulation using the GA is given. In section III, the proposed approach is applied to an overhead line connected to grounded arrester is considered. Finally conclusion is in section VI.

II. Modeling Formulation using Genetic Algorithm

As shown in figure 3, lightning-induced current along overhead line is represented by a current pulse $I_0(t)$ which is expressed as following:

$$i_0(t) = I_m\left(e^{-\alpha t} - e^{-\beta t}\right) \tag{1}$$

Where $I_m = 40KA$, $\alpha = 2(1/ms)$ and $\beta = 400(1/ms)$. At the first of modeling using GA, this current is expressed by a finite number of discrete spectra, i.e., sinusoidal harmonies. Figure 3 shows curve fitting this current by nine harmonies. As it is seen in the figure 3, excellent fitting is achieved. The approximated current is of the following expansion:

$$i_0(t) \approx \sum_{i=1}^{9} \left\{ I_i \sin(\omega_i t + \phi_i) \right\} \tag{2}$$

Where the above parameters are listed in table 1.

To evaluate the lightning-induced voltage, the Norton equivalent circuit in the figure 2(b) is then redrawn as shown in figure 4.

In figure 4, I'_{sc} and Y'_{in} are frequency-domain quantities and computed as following:

$$I'_{sc} = \frac{I_{sc}}{1 + Z_g Y_{in}} \tag{3}$$

$$Y'_{in} = \frac{Y_{in}}{1 + Z_g Y_{in}} \tag{4}$$

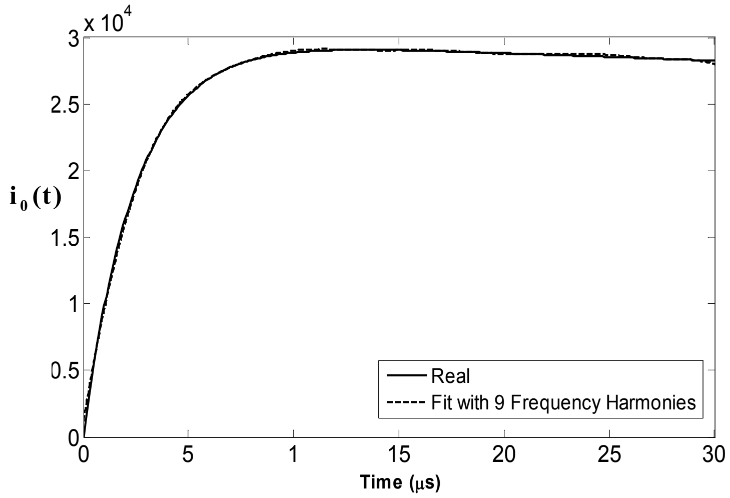


Fig. 3. Approximating the current source $I_0(t)$ by nine frequency harmonies.

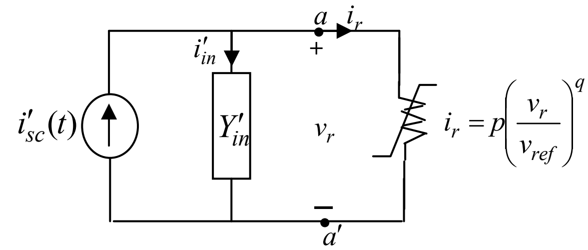


Fig 4. Simplified equivalent circuit of the figure 3.

In the above equations, I_{sc} , Y_{in}, and Z_g were efficiently computed by MoF in [9] and [16] respectively.

According to the (3) and (4) and the figure 2, the amplitude and phase of I_{sc} and I'_{sc} are easily related to individual ones of I_0 in the frequency domain, and therefore computing $i'_{sc}(t)$ in time domain is straightforward.

Now applying KCL to the node (a) in the figure 4 yields:

$$KCL(a) \Rightarrow i'_{sc} - i'_{in} - i_r = 0 \tag{5}$$

where

$$i'_{sc}(t) = \sum_{i=1}^{M} I_{sc,i} \sin(\omega_i t + \phi_{sc,i}) \tag{6}$$

In the equation (6), M is the number of sinusoidal harmonies for fitting the surge current pulse, i.e., 9. It is obvious that in the figure 4, due to nonlinearity of the arrester, the number of frequency harmonies created across the arrester is linear combination of exciting frequency harmonies [17], that is:

$$\omega_j = k_1\omega_1 + k_2\omega_2 + ...k_M\omega_M, \qquad j = 1,2,...N \tag{7}$$

Where integers $k_i, i=1,2,...M$ are chosen in such a way that $|k_i|<q$. Hence the following expression for the voltage is considered:

$$v(t) = V_0 + \sum_{j=1}^{N} V_j \sin(\omega_j t + \phi_j) \tag{8}$$

Where N is the number of created sinusoidal harmonies across arrester and the corresponding arrester current is expressed as following:

$$i_r = p\left(\frac{V_0 + \sum_{j=1}^{N} V_j \cos(\omega_j t + \phi_j)}{v_{ref}}\right)^q \tag{9}$$

Since in the figure 4, Y'_{in} and the arrester are in parallel, the current flowing to Y'_{in} is of the following form:

$$i'_{in}(t) = \sum_{j=1}^{N} G'(\omega_j)V_j \cos(\omega_j t + \phi_j) - \sum_{j=1}^{N} B'(\omega_j)V_j \sin(\omega_j t + \phi_j) \tag{10}$$

Substituting (6), (9) and (10) in (5) yields:

$$\sum_{i=1}^{M} I_{sc,i} \cos(\omega_i t + \phi_i) - \sum_{j=1}^{N} G'(\omega_j)V_j \cos(\omega_j t + \phi_j) + \sum_{j=1}^{N} B'(\omega_j)V_j \sin(\omega_j t + \phi_j)$$
$$- p\left(\frac{V_0 + \sum_{j=1}^{N} V_j \cos(\omega_j t + \phi_j)}{v_{ref}}\right)^q = 0 \tag{11}$$

In the above equation, V_0 , $V_j s$ and $\phi_j s$ are unknown variables and using GA they are computed in such a way that (10) approaches zero, that is:

$$\|\varepsilon(t)\| = \left\| \begin{array}{l} \sum_{i=1}^{M} I_{sc,i} \cos(\omega_i t + \phi_i) - \sum_{j=1}^{N} G'(\omega_j)V_j \cos(\omega_j t + \phi_j) + \sum_{j=1}^{N} B'(\omega_j)V_j \sin(\omega_j t + \phi_j) \\ - p\left(\frac{v_0 + \sum_{j=1}^{N} V_j \cos(\omega_j t + \phi_j)}{v_{ref}}\right)^q \end{array} \right\| \to 0 \tag{12}$$

In dealing with the GA, each unknown variable in (12) encoded into $B\!-\!b$ binary code $b_{j_1}b_{j_2}...b_{j_B}$ which is called a gene, and the total number of genes are $(2N+1)B$ as:

$$chromosome = b_{0_1}b_{0_2}.....b_{0_B}...b_{N_1}b_{N_2}.....b_{N_B} \tag{13}$$

The relation between V_j and ϕ_j and their $B\!-\!b$ genes will be characterized as:

$$V_j = V_{j\min} + \frac{V_{j\max} + V_{j\min}}{2^B - 1} \sum_{k=1}^{B} b_{jk}.2^{B-k}, \qquad j = 0,1,2,\ldots N \quad . \tag{14}$$

$$\phi_j = \phi_{j\min} + \frac{\phi_{j\max} + \phi_{j\min}}{2^B - 1} \sum_{k=1}^{B} b_{jk}.2^{B-k}, \qquad j = 0,1,2,\ldots N \tag{15}$$

Where $V_{j(\min),(\max)}$ and $\phi_{j(\min),(\max)}$ are the minimum and maximum range bounds corresponding to the V_j and ϕ_j respectively. Each chromosome of (12) has an associate cost function from (12).

In the next section the achieved formulation above is applied to an overhead line terminated to grounded arrester and the role of the proposed method (MoF-GA) in evaluation of the transient voltage is investigated.

III. TRANSIENT ANALYSIS OF OVERHEAD LINE TERMINATED TO GRID-GROUNDED ARRESTER

In this section, an overhead line of length $L = 600m$ and radius $a = 2.7Cm$ at different heights from earth $h = 10,25m$ is investigated. The grid-grounding system is an equally spaced as $20m \times 20m$ square, and in depth of $1m$ and buried in an earth of electrical parameters of $\varepsilon_r = 10$ and $\sigma = 0.01S/m$.

Without losing generality, for the arrester, $p = 1$, $q = 2$ and $v_{ref} = 10kV$ are chosen as well. The i-v characteristic of the arrester is shown in figure 5. The cost function of (12) in the interval of $[1 - 30]\mu s$ with $\Delta t = 0.1\mu s$ is minimized by GA. Figure 6 and 7 show the mean square error (MSE) by the GA for $h = 10,25m$ respectively.

As it is seen, the MSE is quickly approaching zero (after 20 generation). To observe well the value of the MSE after 20 generation, it is shown inside figure 6 for generation greater than 90.

Finally after converging the MSE, $V_j s$ and $\phi_j s$ are found and transient voltage across the arrester is accordingly evaluated.

To verify the lightning-induced voltage by the GA, it is compared with the one in EMTP. Hence the equivalent circuit of the grid-grounding system should be first extracted by VF [13] and then imported into EMTP.

With refrence to [13], the VF is basically a kind of curve fiiting through which frequency response is approximatted by rational functions, and then these functions are converted to equivalent citcuit. For the chosen grid, the input impedance is first computed by MoM and then modeled by the VF. After then the resulted model is converted to equivalent circuit which is shown in figure 8. The achienved equivalent circuit is time domaine representation of grid in EMTP.

Finally transient overvoltage by the three approaches, i.e., TLM-GA, MoF-GA, and EMTP for two values of height $h = 10,25m$ is computed and shown in figure 9. Note that in these figures, the hybrid approach TLM-GA means that the overhead line is analyzed by the TLM and the transient voltage by GA whereas in the hybrid approach MoF-GA, the overhead line is analyzed by the MoF.

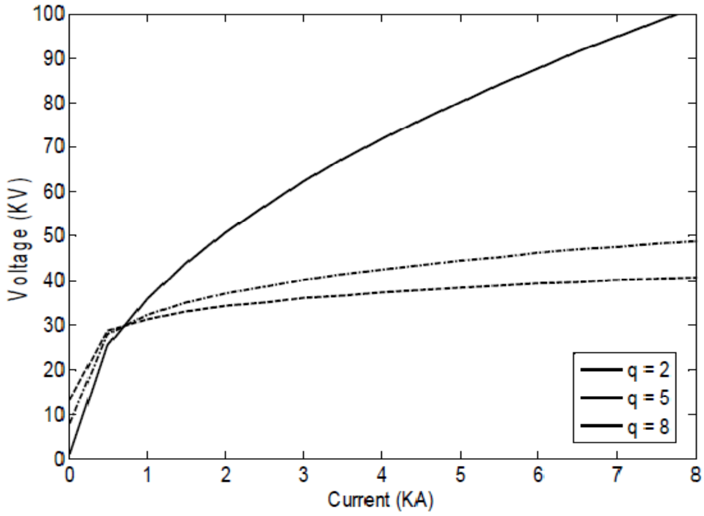


Fig. 5. i-v characteristic of the arrester.

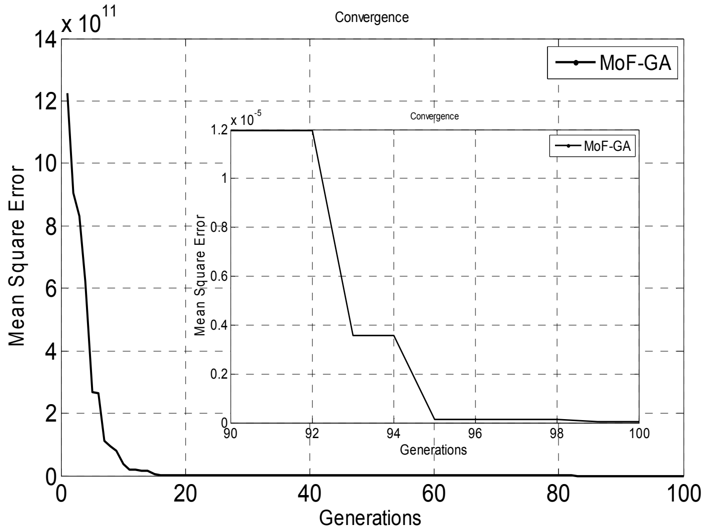


Fig. 6. Mean square error versus generation for h=10m.

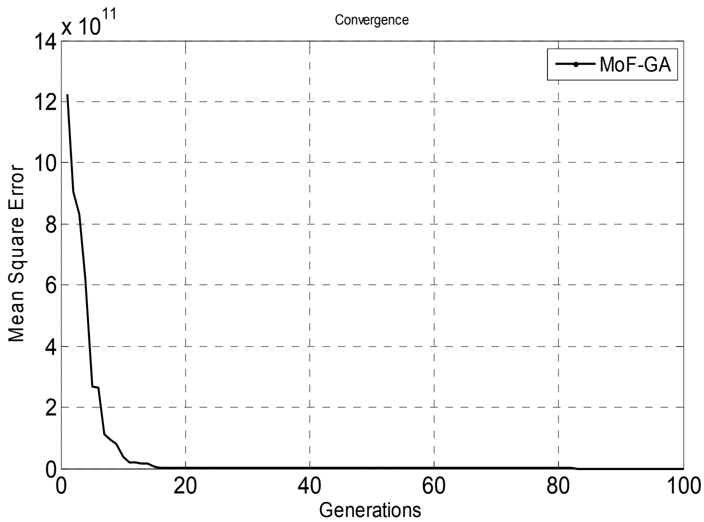


Fig. 7. Mean square error versus generation for h=25m.

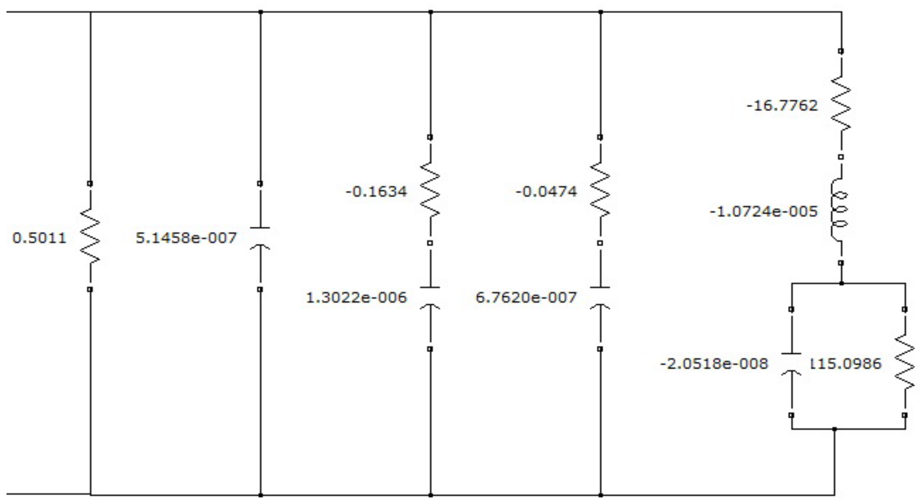
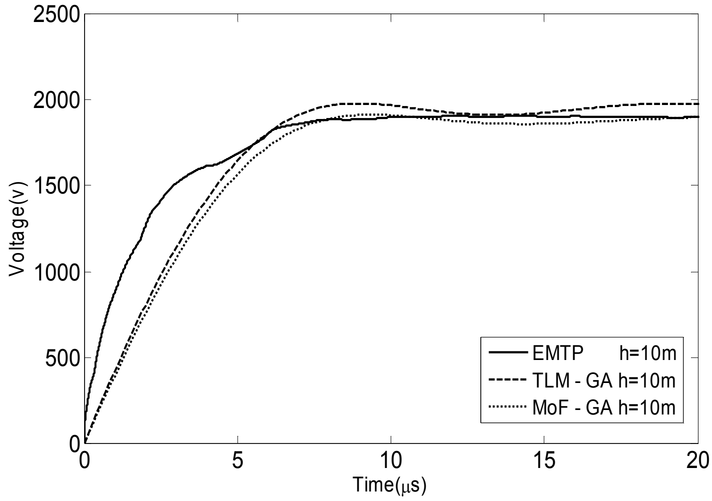
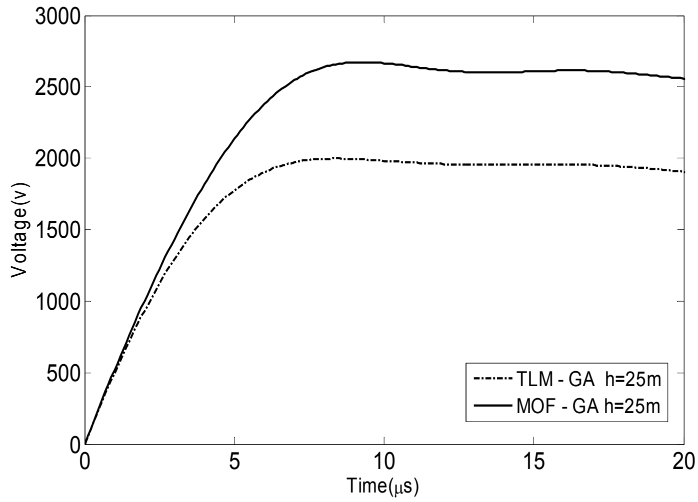


Fig. 8. Equivalent circuit of grid grounding system by VF for conductivity=0.01S/m. Resistors, inductors and capacitances are in, Ω , H and F respectively.



(a)



(b)

Fig. 9. Transient voltage across the grid-grounded arrester for (a): h=10m, and (b): h=25m.

As it is seen in figures 9 (a) and (b), when height of the overhead line is increasing, the performance of the TLM is failing since the condition $kh << 1$ starts being invalid. This makes the proposed hybrid method (MoF-GA) efficient in computing transient voltage. It is well known that exact computation of this parameter is so important in insulation coordination study of power system and the selection of lightning arresters.

Recant researches [18-21] show that the electrical parameters of soil are frequency dependence. It is evident that considering this effect and the one investigated in this study, effect the transient voltage across arrester simultaneously that similarly should be involved.

IV. CONCLUSION

In this study, frequency domain approach based on genetic algorithm was used for analysis of single overhead line terminated to grid-grounded arrester. In dealing with this problem, the overhead line was first analyzed by the our previous method (MoF) [9], and the transient voltage across the arrester was then computed by GA. Comparison of the hybrid approach with EMTP software and the AOM, the following key findings are achieved:

I. In despite of EMTP, fast Fourier transforms (FFT) and inverse Fourier transform (IFFT) are not needed.

II. In despite of AOM, transformation matrix from time domain to frequency domain is not needed, and it is not sensitive to initial guess and gradient operation in the iteration process.

III. Analysis of the overhead line by the MoF is valid at any frequency where as TLM is restricted to low frequencies.

IV. Run-time by proposed hybrid model is reduced.

It is evident that there are lots of optimization techniques. The number of generetations of the GA can be more reduced if novel optimizations techniques instead of GA are used.

Analyzing multi-conductor overhead lines terminated to grounded arrester by MoF-GA approach is another study that is in progress.

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