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DESIGN OF FOLDED WIRE LOADED ANTENNAS USING BI-SWARM DIFFERENTIAL EVOLUTION

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Abstract—Folded wire load antennas with matching network are designed by using optimization algorithms. The loads are parallel capacitor/inductor/resistor circuits that are adjusted by means of Differential Evolution (DE) optimizers to maximize bandwidth and the matching networks. The measured voltage standing-wave ratio (VSWR) of the load folded dipoles confirms broadband performance and agrees with data obtained from moment method computations. Antennas having bandwidth ratio of 2.5 : 1, with measured VSWR less than 3.5, meets the requirement.

1. INTRODUCTION

Wire load antennas are widely used for HF\VHF\UHF band communication because of their broad-band performance [1–4]. The bandwidth of the antenna can be increased manifoldly by loading the antenna and designing a suitable matching network. Examples of such a design may be found in [2], which describes three wide bandwidth antennas, viz., a monopole, twin whip, and a folded monopole. A 20 : 1 bandwidth wire load dipole type antenna is report in [3]. The function of the loads is to modify the current distribution on the wires in a manner such that the antenna characteristics are improved in the process. Typically, one tries to find a set of loads that improve both the voltage standing wave ratio (VSWR) and the gain performance by decreasing the variation of the input impedance with frequency and by forcing the antenna to radiate along the desired direction, e.g., near the horizon.

Designing a broad-band antenna to meet certain specifications entails the solution of a nonlinear optimization problem. The solution

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procedure carries out a search for the optimal set of parameters, e.g., load locations, their component values, and the parameters of the matching network.

Differential Evolution (DE) optimization algorithm, proposed by Storn and Price [5], is a very powerful stochastic global optimizer for multi-modal objective function optimization. Like all evolution algorithms (EAs), DE is a population based optimization algorithm. It evolves generation by generation until the termination conditions have been met. Compared with other evolution optimizers, DE algorithm is very simple to understand and implement. It has been applied to various engineering designs [6, 7]. Recently, many researchers have been working on improving the convergence rate of DE [8–10]. An evolutionary algorithm with two groups is introduced in [11].

As a common principle for the EAs, an excessive greediness will weaken the exploration ability and result in the risk of failure search. Consequently, efforts of pursuing the high convergence rate only are not enough, and it is necessary to jointly enhance the convergence rate and the exploration ability of the optimization algorithm. It is an antinomy process to consider the convergence rate and exploration ability simultaneously. It is difficult to make the best tradeoff between convergence rate and exploration ability for a multimodal objective function optimization. A bi-swarm strategy is introduced for overcoming this antinomy problem [12]. It is employed for optimizing antennas successfully [12, 13]. In this paper, a folded wire load antenna is designed by using bi-swarm DE.

2. THEORY

2.1. Electric Field Integral Equation

For a curved thin conducting wire, the electric field integral equation is given by

$$j\frac{\eta}{4\pi k}\left\{\hat{t}\cdot k^2\int_C K\left(\vec{r},\vec{r}'\right)I\left(\vec{r}'\right)\hat{t}'dr'+\frac{d}{dr}\int_C\frac{d}{dr'}K\left(\vec{r},\vec{r}'\right)I\left(\vec{r}'\right)dr'\right\}=\hat{t}\cdot\vec{E}^i(\vec{r}) \tag{1}$$

where $\vec{r}$ is a point on the surface of the wire; C is the contour of the wire axis; $\widehat{t}'$ and $\widehat{t}$ are the unit tangential vectors of the wire at the source point $\vec{r'}$ and field point $\vec{r}$, respectively (Figure 1). The axial current of the curved wire is $I\left(\vec{r}\right)\widehat{t}$, with the Green's function $K\left(\vec{r},\vec{r}'\right)$ given by

$$K\left(\vec{r},\vec{r}'\right)=\frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{e^{-ik|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|}\,d\varphi' \tag{2}$$

The incident electric field is $\vec{E}^i\left(\vec{r}\right)$.

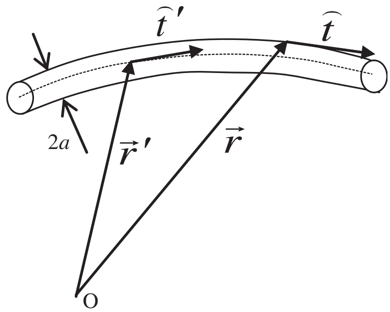

Figure 1. Arbitrary curved wire of radius a.

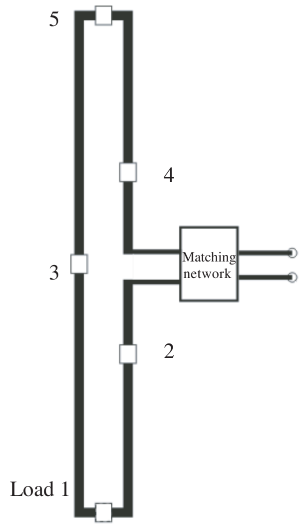

Figure 2. Geometry structure of folded wire load dipole antenna.

The Galerkin method is employed for solving the current on the surface of the wire [14].

2.2. Load Wire Antenna

A loaded wire antenna is shown in Figure 2. Based on the MoM, the currents of the loaded wire antenna may be acquired. The matrix equation is:

$$[Z + Z_{load}]\,[I] = [V]$$

where Z is impedance matrix, and Z_{load} is a diagonal matrix in which the nonzero element corresponds to a load value.

Then, we may get the input impedance Z_{in} of the antenna. The reflect coefficient Γ and VSWR are:

$$|\Gamma| = \left|\frac{Z_{in} - Z_o}{Z_{in} + Z_o}\right| \tag{3}$$

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{4}$$

2.3. Fitness Functions

The purpose of the optimization is to find the value of load's parameters. Fitness functions are defined:

$$F(f_{\mathrm{i}}) = \sum_{\mathrm{i}} \begin{matrix} |D_{\mathrm{i}} - G_0| & \text{if } VSWR_{\mathrm{i}} \leq VSWR_0 \\ w \cdot (VSWR_{\mathrm{i}} - VSWR_0) + |D_{\mathrm{i}} - G_0| & \text{if } VSWR_{\mathrm{i}} \geq VSWR_0 \end{matrix} \tag{5}$$

where, $VSWR_0$ and G_0 are the target value of VSWR and Gain, respectively. $VSWR_{\mathrm{i}}$ and D_{i} are VSWR and directivity coefficient of the folded wire load antenna at frequency f_{i}. Some frequencies are sampled for balancing the VSWR at the entire band. w is factor for adjusting the fitness function.

3. BI-SWARM DIFFERENTIAL EVOLUSTION

DE is a population based optimization algorithm. It evolves generation by generation until the termination conditions have been met. It is a parallel direct search method which utilizes NP M-dimensional parameter vectors:

$$\bar{X}_{jG} \quad \text{where, } j = 1, 2, \ldots, N_P \tag{6}$$

$\bar{X}_{j,G}$ is an M-dimensional vector. G expresses the generation, for each iteration of the optimization.

The initial population is chosen randomly and tries to cover the entire parameter space uniformly. To produce the next generation offspring parameter vectors, DE firstly introduces a perturbed vector $\bar{V}_j$ by adding the weighted weighted difference between two population vectors to a third vector. The detailed description is in [5].

Bi-Swarm Differential Evolution (BiS-DE) divides the population (N_{P} vectors) into two swarms. Let $\{\bar{X}_{j,G}, j = 1, 2, \ldots, N_M\}$ denote the member set of the assimilative swarm, Swarm 1 (S_1). The evolution swarm, Swarm 2 (S_2), consists of the rest members $\{\bar{X}_{j,G}, j = N_M + 1, N_M + 2, \ldots, N_P\}$.

The operations to produce the offspring vectors, $\bar{V}_j$, are different in S_1 and S_2. The assimilation speed is emphasized in S_1. In S_2, the operation should be with large randomicity. To produce new offspring parameter vectors, same as DE, it firstly introduces a perturbed vector $\bar{V}_j$ by adding the weighted difference between two individual vectors to the third vector. From Gth generation vector $\bar{X}_{j,G}$ ($j = 1, 2, \ldots, N_P$), $\bar{V}_j$ is generated by following operations. In S_1, ($j = 1, 2, \ldots, N_M$),

$$\bar{V}_j = \bar{X}_{obt,G} + F \cdot \left(\bar{X}_{i1,G} - \bar{X}_{i2,G}\right) \tag{7}$$

where, i_1 and $i_2 \in (1, \ldots, \mathrm{N_M})$ are randomly chosen integers, and $i_1 \neq i_2$.

In S_2, $(j = N_M + 1, N_M + 2, \ldots, N_P)$,

$$\bar{V}_j = \bar{X}_{i5,\,G} + F \cdot \left(\bar{X}_{i1,\,G} - \bar{X}_{i2,\,G} + \bar{X}_{i3,\,G} - \bar{X}_{i4,\,G}\right) \tag{8}$$

where, i_1, i_2, i_3, i_4 and $i_5 \in (1, \ldots, N_P)$ are randomly chosen integers, and $i_1 \neq i_2 \neq i_3 \neq i_4 \neq i_5$. Here, the order j is replaced by i_5 in the right side of (8) for increasing randomicity of $\bar{V}_\mathrm{j}$ and avoiding early convergence at a local optimum.

F is the real scale factor, and $F \in (0, 2)$.

The crossover operation is similar to that in conventional DE. Regarding to the criterion, let $\bar{X}_{worst,\,\mathrm{S1}}$ be the worst vector of S_1 and $\bar{X}_{best,\,\mathrm{S2}}$ be the best vector of S_2. If the performance of $\bar{X}_{best,\,\mathrm{S2}}$ is better than that of $\bar{X}_{worst,\,\mathrm{S1}}$, $\bar{X}_{best,\,\mathrm{S2}}$ will be exalted into S_1 to replace $\bar{X}_{worst,\,S1}$.

4. OPTIMIZATION RESULTS BY USING BIS-DE

The objective function is presented as formula (5). Only the gain and VSWR are considered. The structure of the objective antenna is assumed to be located in free space (Figure 2). The radius of the wire and the length of folded antenna are fixed when BiS-DE is used for optimizing. There are five loads. The loads R_i, C_i and L_i $(i = 1, 2, 3)$ are left as the design variables for random manipulation by the BiS-DE. Load 4 and load 5 are the same as load 2 and load 1, respectively. The locations of load 1 and load 3 are fixed. But the location of load 2 is a variable for optimizing. The loaded wire antenna is analyzed by using the method of moment, and the δ-voltage is used as a source at the feed point. After the matrix equation is solved, the currents on the surface of the antenna is obtained. Then the impedance and VSWR of the antenna are acquired. The fitness function (5) is employed for DE processing. The loads (R_i, C_i, L_i) and matching network (La, Ca, n) are optimized variables of the fitness function.

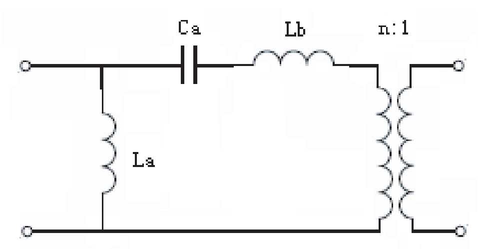

Figure 3. Matching network of folded dipole antenna.

The matching network is shown in Figure 3. La, Lb, Ca and n in the matching network are also variables to be optimized. Then there are fourteen variables altogether. The matching network to the wire dipole antenna includes the passive matching circuit elements and transmission line transformer. The matching circuit is considered for lowering the antenna's operational frequency. The passive matching network can also give an additional miniaturization and broad bandwidth compared with the normal antenna design.

The folded dipole antenna with lumped RLC loads has a total height of 0.9 meter and width of 5 cm. VSWR is requested lower than 3. The optimized parameters of the antenna are shown in Table 1. And $La = 0.39\,\mu\text{H}$, $Lb = 0.15\,\mu\text{H}$, $Lc = 10\,\text{pF}$, and $n = 4$ for matching with $50\,\Omega$ feed line. For fabricating the antenna more easily, the locations of load 1, load 3, and load 5 are fixed. The locations of load 2 and load 4 are optimized. Load 2 and load 4 are symmetry. Based on the optimized results, a folded dipole is fabricated and measured. The photograph of the fabricated wire loaded antenna is presented in Figure 4. Figure 5 shows the frequency response of the compared simulated and measured VSWR results of the folded wire dipole antenna. The fabrication result achieves a VSWR of better than 3 over 52 MHz to 117 MHz.

Table 1. Data of folded dipole antenna.

R_1	$175.1773\,\Omega$	R_2	$4000\,\Omega$
L_1	$3.8256\,\mu\text{H}$	L_2	$0.0022\,\mu\text{H}$
C_1	3.0469 pF	C_2	3.2494 pF
R_3	$1403.0495\,\Omega$	Load 1 position	0 meter, 0.9 meter
L_3	$0.4571\,\mu\text{H}$	Load 2 position	0.18 meter, 0.72 meter
C_3	0.0001 pF	Load 3 position	0.45 meter
Total height	0.9 meter	Width of fold	5 cm

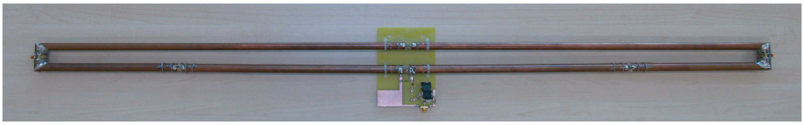

Figure 4. Photograph of designed folded dipole antenna.

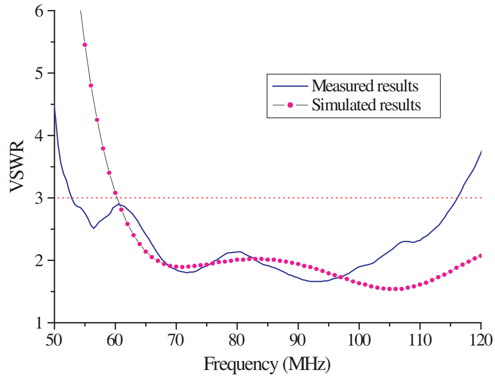

Figure 5. VSWR of folded dipole antenna.

5. CONCLUSION

The BiS-DE is employed for optimizing the loaded folded wire antenna. The Galerkin method is used for analyzing the antenna. Loads (Rs, Ls, Cs), matching network, and locations of loads are optimization variable parameters. The loading of the antenna enables us to achieve important improvements in Gain and VSWR of the antenna over the frequency band. The results show that the design tools and process are successful.

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