Optimization of Loaded Broadband HF Antenna via Genetic Algorithm

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Abstract

This paper reports on a design technique for broadband high frequency wire antennas. The antennas are loaded with RLC circuit elements to achieve broad impedance bandwidth (for a desired VSWR) and possible high gain, through modifying the current distribution. These loads can be parallel RLC circuits optimized via Genetic Algorithm (GA) for maximum bandwidth. The GA iterative1y guides a population of randomly selected design parameters towards the objectives. Matching network for the loaded antenna is designed to reduce in-band VSWR. The effectiveness of the proposed procedure is demonstrated through design examples with broadband performances.

Index Terms— broadband HF antenna, loaded Parallel RLC circuit, Genetic Algorithm.

1. Introduction

Wire antennas are used extensively in communication systems since the early days of radio transmission. To date, they remain as one of the most popular radiating elements for various systems, especially at high frequency [1].

In general, monopole, dipole and other types of wire antennas offer broader gain and impedance bandwidth as compared to microstrip patches of various shapes [2]. Since the characteristics of an antenna are determined by the current distribution on the structure, their performance can be improved by controlling the current on the antenna. This can be achieved via loading with lumped or distributed circuit elements. For HF to VHF bands, loading with lumped parallel resistor–inductor–capacitor (*RLC*) circuits are adopted [3]. In the analysis of wire antennas with loading, the Method of Moment (MoM) is widely used, with results of good accuracy. Matching network can be designed for the loaded antenna to reduce in-band VSWR.

To optimize the parameters of the lumped circuit elements for a given objective function, such as maximum impedance bandwidth for a desired maximum VSWR, the Genetic Algorithm (GA) is used. This is a stochastic optimization algorithm which repetitively applies three stochastic operators on a population of designs, viz., “reproduction,” “crossover,” and “mutation.” The attractive feature of this algorithm is that it is capable of generating several different designs with good performance, rendering a number of candidates for the final design. The evolution process continues until the set of parameters that meets the design goals is found.

This paper will discuss some cases of broadband HF monopole and folded monopole.

2. Theory

This methodology for the analysis and optimization of loaded wire antennas will be presented in this section.

A. Curved integral equation for wire antenna

An efficient method for solving the current distribution on arbitrarily-curved wire structures is to model the wire by piecewise-straight segments with the integral equation as in the Method of Moment [4]. The integro-differential equation governing the surface electric current density on general three-dimensional curved wires is used. The wire is assumed to be a perfect electric conductor and is electrically thin, i.e. the radius is much smaller than the wavelength and the length of wire. Using the thin-wire condition, the current is taken to be axially directed, circumferentially invariant, and zero at the free ends. The electric field integral equation of the total axial current $I(\vec{r})\hat{t}$ on the thin curved wire is given by

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

where C is the contour along the wire axis, $\vec{r}$ is a field point on the wire surface, $\hat{t}'$ and $\hat{t}$ are the unit tangential vectors of the wire at the source point $\vec{r}'$ and $\vec{r}$, respectively.

The Green’s function $\mathrm{K}(\bar{r},\bar{r}')$ is given by

$$\mathrm{K}(\bar{r},\bar{r}') = \frac{1}{2\pi}\int_{-\pi}^{\pi}\frac{e^{-ik|\bar{r}-\bar{r}'|}}{|\bar{r}-\bar{r}'|}d\phi' \tag{2}$$

In the numerical solution of this integral equation for curved wire structure, the current is expanded into a linear combination of triangular basis functions defined along the straight-wire segments with support over two adjacent segments. The current distribution is approximated by:

$$I(l)\hat{I}(l) \approx \sum_{n=1}^{N} I_n \Lambda_n(l)\hat{I}_n(l) \tag{3}$$

where l is the local coordinate of r in equation (1). The triangle functions Λ_n at the n^{th} node on the segmented wire is defined by:

$$\Lambda_n(l)\hat{I}_n = \begin{cases} \frac{l-l_{n-1}}{\Delta_{n-}}\hat{I}_{n-}, & l \in (l_{n-1,}l_n) \\ \frac{l_{n+1}-l}{\Delta_{n+}}\hat{I}_{n+}, & l \in (l_n, l_{n+1}) \end{cases} \tag{4}$$

where N is the number of basis functions, and I_n are the unknown current coefficients in the finite series approximation (3). Due to the overlapping triangle basis functions, an approximation with N terms will require *(N+1)* segments along the wire.

Expanding the current in (1) using (3) and testing with pulse function yield a system of equations in matrix form:

$$[Z]I = V \tag{5}$$

where $[Z]$ is the $(N \cdot N)$ impedance matrix, N is the number of triangular basis functions, I and V are the current and voltage vectors of length N . Suppose a unit-voltage excitation $v_i = 1$ at node i, I_i will be used to denote the corresponding current vector of length N. Then, the $(\mathrm{N} \cdot \mathrm{N})$ admittance matrix can be written as follows:

$$[Y] = [Z]^{-1} = [I_1 \quad I_2 \quad \ldots \quad I_N] \tag{6}$$

B. Fast analysis for Loaded antenna

In general, stochastic optimization methods incur high computational cost, which is a major concern limiting the widespread use of this class of methods in many engineering design problems. The GA procedure evaluates the objective function for each member of the population at every iteration step. Although the analysis of wire antennas using MoM is relatively simple, a direct application of the conventional MoM (includes matrix-filling and inversion over the desired frequency range) in GA optimization remains very costly.

In our optimization to achieve broad impedance bandwidth, parallel RLC circuits are added to the wire antenna. The GA optimizer then evaluates the performance of arbitrarily loaded antennas at a highly reduced computational cost, based on pre-computed results obtained for the unloaded antenna. Results for the unloaded antenna are computed via MoM at each frequency, and all inverse matrices are stored. This is a one-time computation for the unloaded antenna. For each new set of loads, the solution can be constructed from that of the unloaded antenna.

The wire antenna is sub-divided into linear segments, with lumped loads concentrated at nodes between adjacent segments. The antenna is assumed to have N_L loads located at nodes $n(i), \quad i = 1,\ldots,N_L$, as shown in Fig.1. When the antenna is loaded, the total current distribution as a function of the load voltages $v_n(i)$ is:

$$I = I_s + \sum_{i=1}^{N_L} v_n(i)\ I_n(i) \tag{7}$$

Let I^r and V^r be the reduced vectors of length N_L . These vectors, and the matrices of size $(N_L \cdot N_L)$, are obtained from the non-reduced quantities by sampling them at the load positions (excluding the source), and by the load admittance Y_{Li} at node i. Hence, I^r and V^r are related via the matrix equation: $I^r = -[Y_L^r]V^r$, in which $[Y_L^r]$ is a diagonal matrix whose elements are the load admittances Y_{Li} . The minus sign arises from the fact the load voltage is due to current flowing into the load admittance, while current flows out of the source voltage. On the load positions, V^r is obtained as follows:

$$I^r = -[Y_L^r]V^r = I_r^s + \sum_{i=1}^{N_L} v_n(i)\ I_{n(i)}^r \tag{8}$$

Using $[Y^r] = [I_{n(1)}^r\, I_{n(2)}^r \ldots I_{n(N_L)}^r]$, we obtain the desired equation for the voltages at the loads

$$([Y^r] + [Y_L^r])V^r = -I_s^r \tag{9}$$

From the V^r vector, the current distribution can be computed. The input impedance and other characteristics required in the evaluation of the objective function can be readily obtained via the current vector. For each new optimization, i.e., different set of RLC parameters and frequency, the analysis approach presented here for loaded wire antennas facilitates an efficient combination of the analysis problem and optimization algorithm.

C. Matching network technique

To further improve the bandwidth performance of the antenna, a matching network can be designed and optimized. Typically, the network matches the input impedance of the antenna to the complex conjugate of the generator impedance. Here, the antenna's input impedance is a complex quantity, while the characteristic impedance of the transmission line is real. Hence, we set:

1) Imaginary part equals to conjugate of the imaginary input impedance. Parameters of the lossless network (capacitors, inductors) will be determined by GA optimization.

2) Real part of the input impedance is matched to the characteristic impedance of the transmission line via a transformer. The matching network includes an impedance transformer with turn-ratio *n,* which will be firstly estimated by the average of the real input impedance normalized with respect to 50-Ω at each frequency points:

$$n = \frac{1}{50}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(R_{in}^{i})^{2}} \qquad (10)$$

D. Genetic algorithm for optimization

GA starts with a randomly selected population of potential solutions and gradually evolves towards better solutions through repetitive use of the genetic operators. The resultant optimization process resembles that of natural evolution. The basic binary-coded GA is applied here. Nine bits are allocated for each coded parameter, e.g., the load parameters and matching network parameters.

In applying GA to the antenna design problem, care must be taken in defining the objective function, taking into account all desired performance indices that are to be optimized. In our study, the purpose is to determine the set of load parameters that gives the best performance in bandwidth and gain. The objective function is defined as

$$\mathrm{Aim} = \mathrm{Min}\sum_{i=1}^{N}\left(\left|\mathrm{VSWR}^{i} - \mathrm{VSWR}\right| + \frac{1}{4}\left|G^{i} - G\right|\right) \qquad (11)$$

where VSWR and G are the target values for VSWR and directive gain, respectively. VSWR^{i} and G^{i} are the voltage standing wave ratio and directive gain of the antenna at each frequency point $i = 1, 2, 3, \ldots, N$ across the band of interest.

Upon obtaining the load parameters from the above optimization, the next step determines the parameters of the lossless matching network of a pre-defined topology. This is again done through another optimization, and is subjected to constraints imposed by either the specifications or the realizable component values. The objective function for the matching network is defined as:

$$\mathrm{Aim} = \min\sum_{i=1}^{N}\mathrm{VSWR}^{i}(n, L_p, C_q) \qquad (12)$$

where n is the ratio of transformer, L_p and C_q are the inductors and capacitors used in the matching network. $p = 1, 2, 3, \ldots, P$; $q = 1, 2, 3, \ldots, Q$. i refers to the frequency point in the band during each iterative processing. The above GA procedure is found to be very effective in optimizing for the circuit parameters, due to its robustness and inherent ability to accommodate various constraints.

3. DESIGN AND OPTIMIZATION EXAMPLES

The above methodology is applied to the design of broadband loaded HF antenna, with the following design goals:

1) Maximum in-band VSWR: smaller than 3.0
2) Minimum in-band directive gain: better than -2.0dBi
3) Bandwidth: 2 - 30 MHz

A 15-m straight monopole antenna with radius of 0.02m is considered for optimization, as shown in Fig. 1. From the optimization, it is found that four symmetrically located lumped loads gave the best performance in this case. The parameters of lumped loads are given in Table I.

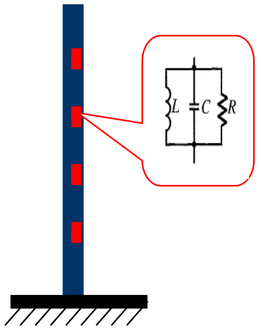

Fig. 1: The loaded monopole antenna

TABLE I. LOAD POSITIONS AND CIRCUIT PARAMETERS

Load No	Position (m)	R (Ω)	L (μH)	C (pF)
Load 1	3.0	122.78	5.07	498.5 pF
Load 2	6.25	115.13	5.01	477.6 pF
Load 3	8.75	131.25	5.03	512.7 pF
Load 4	12	487.56	5.05	29.92 pF

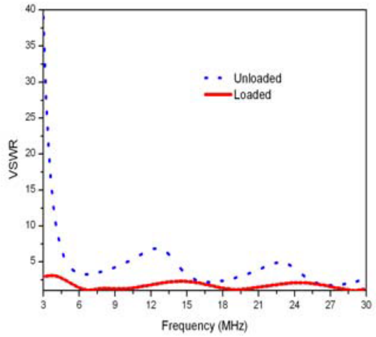

Fig 2: VSWR of the loaded antenna

The matching network for this antenna has the topology and parameters as shown in Fig 3.

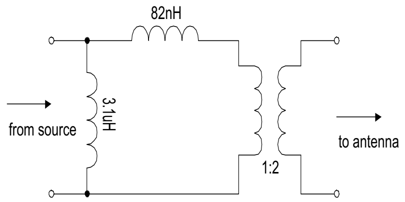

Fig. 3: Matching network for the loaded antenna

The optimization achieved an in-band VSWR of better than 2:1 across the HF band, as shown in Fig 2 and Fig 4.

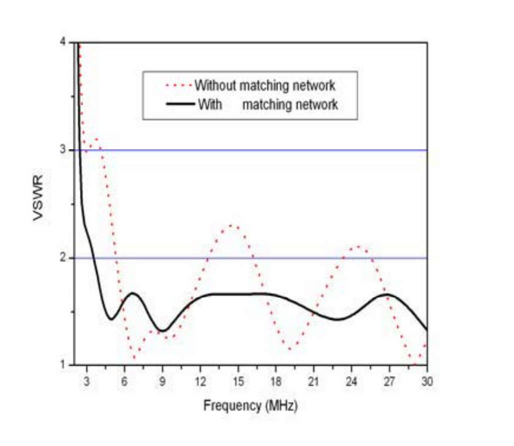

Fig. 4: VSWR of loaded antenna with matching network

The second case is a folded monopole antenna with three segments (L3=10m, L2=3.4m, L1=9.9m) and radius 0.02m, as shown in Fig. 5.

TABLE II. LOAD POSITIONS AND CIRCUIT PARAMETERS

Load No		Position (m)	R (Ω)	L (μH)	C (pF)
Line 3	Load 1	4	103.5	7.33	754.6
	Load 2	6	256.13	0.68	103.6
	Load 3	8	131.25	2.03	152.6
Line 1	Load 4	6	589.29	9.08	8.36
	Load 5	8	315.21	5.98	356.25

Five RLC lumped loads are added in series to the antenna. It is found that the best performance is obtained with two loads on L1 and three loads on L3. Table II shows the optimized parameters for the loads. The matching network for this antenna has the topology and parameters as shown in Fig. 6.

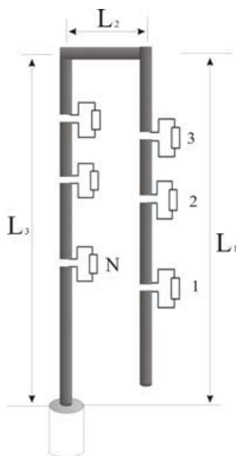

Fig. 5: Folded monopole antenna with loaded circuits

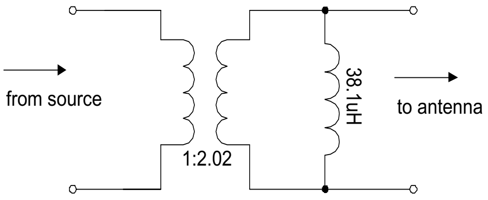

Fig. 6: Matching network for the loaded folded monopole antenna

The optimized design has an in-band VSWR of better than 2.5:1 across the HF band, as shown in Fig. 7.

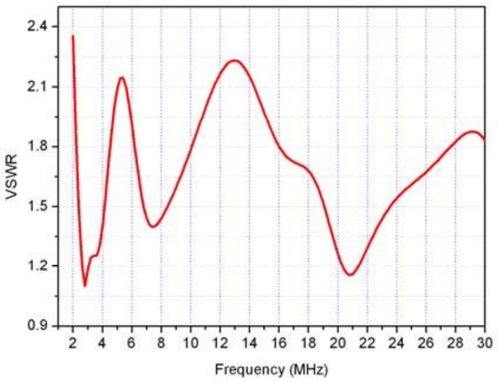

Fig. 7: VSWR for the loaded folded antenna with Matching network

4. CONCLUSIONS

Loaded wire antennas optimized by GA have been investigated for broad bandwidth. The impedance bandwidth for VSWR of better than 2.5:1 is able to cover the entire HF band from 2 – 30 MHz, i.e. 15:1. The combination of lumped loading on the antenna and optimization of the load and matching network parameters via GA is found to be a very effective and efficient approach to improve the bandwidth performance for this class of wire antennas.

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