Optimal Positions of Loading for a Shortened Resonant Monopole Using Genetic Algorithm

Shifu Zhao, Christophe Fumeaux, Chris Coleman

Abstract— **The size reduction for resonant monopoles is an important issue for HF and VHF antennas. Unfortunately, size reduction results in degradation in both efficiency and bandwidth, as is well known from the fundamental limits on small antennas [1]. This paper firstly introduces a MATLAB-controlled NEC2 simulation tool with genetic algorithm optimization, and uses this to find the optimal position of inductors for a shortened monopole with L-section matching networks. Trade-offs between bandwidth and efficiency are investigated and demonstrated in a systematic fashion for a single inductor case. Various multi-inductor loading schemes are also investigated; including central symmetrically distributed and arbitrarily distributed two-inductor loading schemes. The ultimate goal of the research is to find an optimal distribution of inductors on a reduced-size resonant monopole.**

***Index Terms*— Automation, Genetic Algorithm, NEC2 Simulation, Resonant Monopole.**

I. Introduction

SIZE is one of the critical considerations in HF antenna design. Considering the well-known fact that inductive loading in series with a monopole can shorten its resonance length, an analysis of such monopole has been performed using the NEC antenna simulation software. The miniaturization of the monopole, however, is achieved at the cost of performance, in terms of both lower efficiency and narrower bandwidth. Therefore, locating the inductor on the monopole for optimal performance is a key issue.

This paper introduces an automated NEC2 (Numerical Electromagnetics Code) simulation tool controlled by MATLAB. A genetic algorithm optimization is applied in the automated program so that an optimal solution in terms of inductances and loading positions can be found, optimization of performance being with respect to efficiency and bandwidth. Several other relevant parameters are included in the process, such as the effect of the loading inductor Q-factor in order to describe their loss.

As an example of application, the performance limit of a monopole that is resonant at 300 MHz in its unloaded state is investigated. First, a single inductor load is located at various positions along the monopole and the resulting VSWR, efficiency, and bandwidth simulated. The automated optimization algorithm is employed to search the optimal solutions, and the procedure is validated by comparison to results obtained through a brute force search. The advantage of the automated NEC2 simulation procedure in effectiveness and accuracy can already be observed in this simple case. To probe the optimization of loading further, more complex cases are investigated including two distributed inductors located either symmetrically from the centre of the monopole or arbitrarily along the monopole, as well as arbitrarily distributed three and four inductor configurations.

The generalized MATLAB-controlled NEC2 simulation program, with the assistance of genetic algorithm optimization, provides a powerful tool to conduct investigations towards more complex antenna configurations with various loading schemes.

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II. Automated NEC2 Simulation with MATLAB

The bandwidth and efficiency of a shortened monopole vary significantly with the change of loading along its length. Where to locate one or multiple finely tuned inductors becomes the critical issue in providing the best possible operation of the resonant monopole. To efficiently achieve an optimal solution, electromagnetic simulations are carried out to investigate the monopole performance from various configurations of loading inductances. However, derived quantities such as the resonant frequency and resulting bandwidth, as well as antenna matching, need to be taking into consideration in the simulation. These quantities are computed in Matlab on the basis of the standard NEC2 output. Essentially, NEC2 becomes a fast and efficient electromagnetic solver driven, and controlled, by MATLAB.

A. NEC2 Simulation

NEC2 is a Fortran program for the purpose of numerical electromagnetic computations based on the method of moments [2]. Its input file contains numerical data prepared according to given rules. MATLAB's advanced file I/O capability can perform the task of producing such an input file very effectively. MATLAB then calls NEC2 to execute from this input file. The resulting NEC2 output, containing the information of input impedance and efficiency, is then available to MATLAB for further analysis.

B. MATLAB Control

As the primary control of the simulation and optimization tool, MATLAB carries out many tasks throughout the whole process. Apart from driving the process of NEC2, MATLAB also performs calculation, comparison, and genetic algorithm optimization. It analyzes the simulation results from NEC2, determines if the resonance occurs around the required frequency region, and calculates the matching network as well

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as the associated bandwidth. Using an appropriate fitness evaluation computed on the basis of simulation results, the genetic algorithm is then carried out so that a near-optimal solution can be found.

C. Frequency Error

A wider bandwidth and higher radiation efficiency are the ultimate goals of this investigation. The bandwidth is taken to be the frequency range over which the VSWR is less than 2:1. The target frequency f_{target} should be the center of this band. In our iterated optimization, this might not be strictly the case at some stage so we introduce the frequency error f_{err} defined as:

$$f_{err}^2 = \left| \tfrac{1}{2}(f_1 + f_2) - f_{target} \right|^2 \qquad (1)$$

where f_1 and f_2 are the minimum and maximum frequencies of 2:1 bandwidth (Fig. 1), and f_{err}^2 is a quantity in MHz^2.

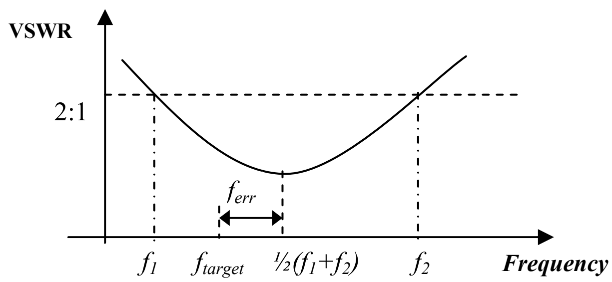

Fig. 1. Central frequency error f_{err} at resonance.

This frequency error is squared in the simulation so that a sharp and differentiable minimum is formed around the target frequency. This quantity should be minimized in the optimization procedure to ensure the monopole resonance occurs as close as possible to the target frequency.

D. Matching Networks and Bandwidth Calculation

An L-section lumped reactive matching network with one inductor and one capacitor is used to conjugately match any Z_G to Z_L, where Z_G is the generator impedance (usually 50 Ohm) and Z_L is the loading impedance (antenna) [3]. The structure of the matching network depends on whether the Z_G is greater or smaller than Z_L. The values for X_1, X_2 for matching at the target frequency can be obtained from standard equations [3]. The schematics of the L-type matching networks are drawn in Fig.2. Matching is applied at the target frequency and bandwidth is then computed using this particular matching network.

E. Q Factor in Inductors

An inductor has an inherent resistive part in reality. Therefore, the Q factor of the inductors loading the monopole is an important parameter in the simulation. Thus, efficiency and bandwidth at each loading position with properly tuned inductances have been investigated with different Q factor values. Q can vary greatly between different forms of loading inductors.

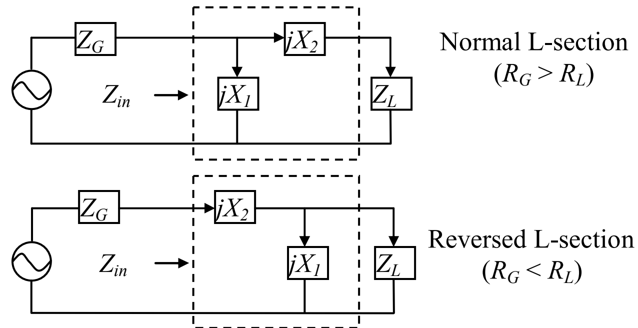

Fig. 2. L-section reactive conjugate matching networks.

III. Genetic Algorithm Optimization

The genetic algorithm is a robust, stochastic search method; it was invented inspired by the natural processes of genetic recombination and evolution [4, 5]. It is particularly effective when the goal is to find the approximate global maxima in a high-dimension, multi-modal function domain in a near-optimal manner [6]. Its advantages come from the facts that it does not require derivatives, unlike calculus-based methods, and constructs a parallel search of the solution space, rather than a point-by-point search [5]; also it manipulates representations of potential solutions, rather than the solutions themselves [5]. Thus, GA is a powerful optimization method in the pursuit of near-optimum solutions in a complex multi-variable environment. In our implementation, the GA is controlled by MATLAB through the following steps. It first represents variables with genes, and then converts binary strings into actual variable values. Based on the simulation results from NEC2, it evaluates the fitness of each gene, and creates new genes by crossover and mutation; the new created genes provide a new generation of antenna configurations for the next round of simulations until certain performance criteria are met. The settings of the optimizations such as crossover and mutation rate techniques should be selected with extra care, as they are the critical issues in guiding the convergence and computation time. The basic settings for the optimization are listed in Table 1.

Gene Selection Strategy	Ranking & Elitism
NO. of Bits for Loading Position	4-6
NO. of Bits for Loading Inductance	10
Mutation Rate	20%
Population Size	1024
NO. of Iterations	20
Simulation Frequency Range	95 – 105 MHz
Simulated Frequency Resolution	0.25 MHz

Table 1: Settings in simulation & optimization

A. Genes Representation

One variable in the optimization is the value of loading inductor(s) on the monopole. Due to the fact that the possible inductance may vary over several orders of magnitude in practice, and a greater number of genes being a significant burden, a logarithmical scale is applied to represent this variable with a limited number of genes. If the variable is represented by a binary string of x bits and the variable's magnitude ranges from n_1 to n_2, a number of 2^x genes generate logarithmically spaced inductances between 10^{n1} and 10^{n2}.

B. Fitness Function and Weighting Factors

The fitness evaluation is a key step because it determines the goodness of a gene, and decides which better-fit genes should be kept in the population while less-fit are removed. Therefore, an appropriately chosen fitness function is critical. One multi-objective function that combines efficiency, bandwidth and frequency error is employed in the optimization.

$$fitness = w_1 \cdot \eta + w_2 \cdot B - w_3 \cdot f_{err}^2 \qquad (3)$$

where η is the efficiency in percent, B is the bandwidth in MHz, and f_{err}^2 is defined in (1) and needs to be minimized (as indicated by the minus sign) to achieve a bandwidth centered on the target frequency. The weighting factors w_1, w_2, and w_3 are empirically chosen to be 2, 1, and 2.5 respectively to achieve a good balance between the different criteria when maximizing the fitness function.

C. Flow Chart

The MATLAB controlled NEC2 simulation with GA optimization is most effectively designed by the flow chart of Fig. 3.

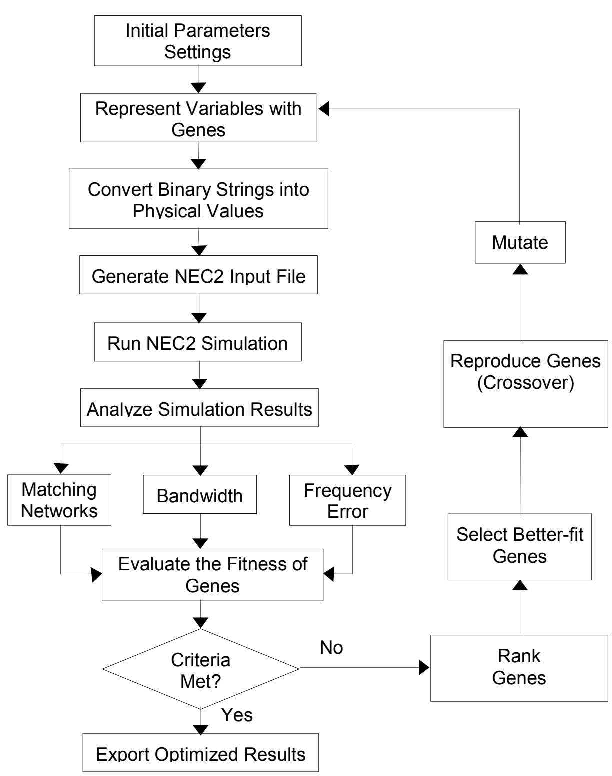

Fig. 3. Flow chart of MATLAB-controlled NEC2 simulation and GA optimization.

IV. Sample Case Results

In the present investigation, a monopole resonant at 300 MHz at its unloaded state is used as the base model to investigate the performance with various loadings schemes. For the simulation, this monopole is divided into 25 equal-length segments, and labeled 1 to 25 from the base excitation to the top free end. The characteristics of the monopole are shown in the Table 2. We will investigate a target frequency of 100 MHz.

Self-Resonant Frequency	300 MHz
Length	0.25 m
Ground Condition	Perfect Ground
Number of segments	25
Excitation Segment Number	#1
Excitation Voltage	1 V

Table 2: Specifications of resonant monopole

1) Single Inductor Monopole

When single inductor is located on the monopole, the optimized loading inductance varies with position and the corresponding efficiency and bandwidth change as well. Nevertheless, the fitness at one or several loading positions may outperform significantly that of other loading possibilities. By repeating the GA optimization on this model, it is observed that the optimal solutions converge to loading positions at a height between 25% and 50% of the total height from the base. Besides, the effect of inductor Q-factor is also investigated and shown in Fig. 4. It will be noted that when the Q factor increases, 1) the radiation efficiency is increased, and 2) the bandwidth decreases; tradeoffs between the two parameters exist. It can be seen that a realistic Q factor of 100 leads to some, but not dramatic, changes in both efficiency and bandwidth. Therefore, the Q factor is taken to be 100 in this investigation. An optimal solution is found when a single inductor of 1.14 μH is loaded at position #9 and results in an efficiency of 37.8% and a bandwidth of 1.012 MHz.

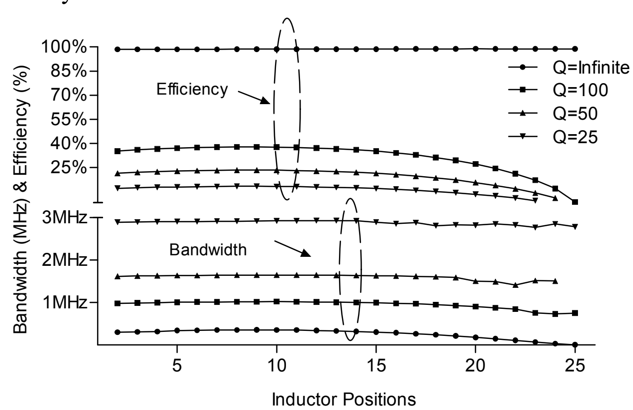

Fig. 4. Bandwidth & efficiency of a monopole resonant at 100 MHz with an optimized single inductor of various Q factor at different positions.

2) Two Arbitrarily Distributed Inductors Monopole

To further probe the effectiveness and accuracy of the MATLAB-controlled NEC2 simulation and optimization, two distributed inductors loading schemes are considered. First, a special case of two equal inductors located symmetrically about the centre of the monopole is investigated. Fig. 5 shows the bandwidth and efficiency of all possible loading position sets at their resonances. The monopole exhibits the best performance when it is loaded at positions #17&#9, #18&#8, or #19&#7. In those cases, the bandwidth is greater than 1 MHz and the efficiency is greater than 39%. The optimal solution is found for two inductors of 0.849 μH located at segment #17 and #9, with a resulting bandwidth of 1.05 MHz and an efficiency of 39.4%.

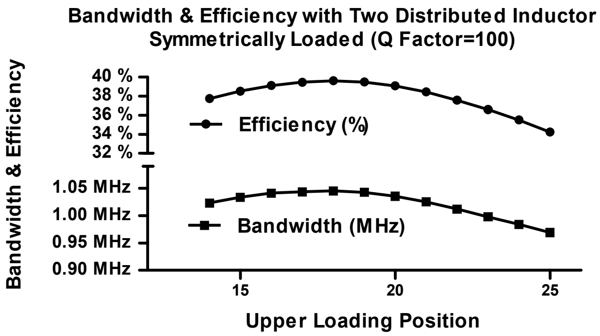

Fig. 5. Efficiency and bandwidth at resonance for all possible symmetrically distributed loading sets with properly tuned inductance. The loading position describes the position of the top inductance. The bottom inductance is identical and located symmetrically from the center of the monopole.

When it comes to two inductors arbitrarily located on the monopole, the value of the optimized inductance may vary in a greater scale, which will increase the load of the computation dramatically. For a Q factor of 100, an optimal solution achieves maximum efficiency and widest bandwidth with two inductors of 0.709 µH and 0.819 µH loaded at positions #8 and #15 respectively. The resulting optimized VSWR in Fig. 6 shows that the monopole is resonant 0.25 MHz away from the target frequency, but with maximized efficiency and bandwidth.

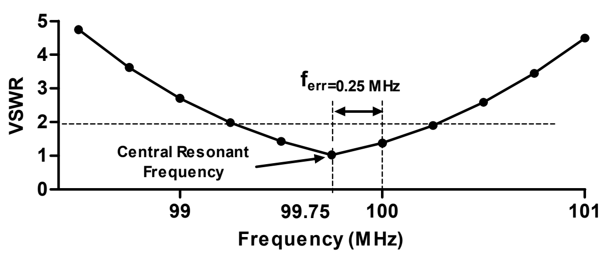

Fig. 6. An optimized VSWR plot from a shortened monopole loaded with two arbitrarily distributed inductors.

3) Three or Four Arbitrarily Distributed Inductors Monopole

A further step in complexity is achieved by increasing the number of loading elements to three and four arbitrarily located inductors. Near-optimal solutions are obtained when three inductors of 0.548 µH, 0.539 µH, and 0.579 µH are located at segments # 4, #13, and #18 on the three-inductor monopole; and 0.426 µH, 0.319 µH, 0.383 µH, 0.568 µH inductors loaded at segments #3, #10, #14, and #18 respectively on the four-inductor monopole. The efficiency and bandwidth are slightly improved in both cases.

4) Loading Schemes Comparisons

The optimal solutions corresponding to the four different loading schemes are compared in Table 3 and plotted in Fig.7. It can be observed that a larger number of distributed inductors lead to a greater efficiency and a wider bandwidth. Nevertheless, the slope of the increase is becoming smaller when more inductors are added, indicating diminishing returns in both efficiency and bandwidth.

	Single Inductor	*Two Arbitrary*	*Three Arbitrary*	*Four Arbitrary*
Efficiency	37.8 %	39.6%	40.4%	40.7%
Bandwidth	1.012MHz	1.050 MHz	1.058 MHz	1.063 MHz
Loading Positions	#9	#8, #15	#4, #10, #16	#3, #10, #14, #18
Inductance (µH)	1.142	0.709, 0.819	0.548, 0.539, 0.579	0.426, 0.319, 0.383, 0.568

Table 3: Best solution of different loading schemes

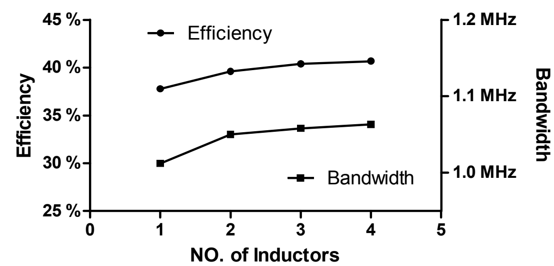

Fig. 7. Optimized efficiency and bandwidth as a function of the number of loading inductors.

V. Conclusion

This paper has described an optimization tool for HF antenna loadings implemented by combining MATLAB computations and NEC2 simulations. The optimization has been performed using a genetic algorithm. Different loading schemes are applied to a shortened monopole to verify the effectiveness and accuracy of the procedure. The achieved optimized solution can effectively reduce the size of a resonant monopole while optimizing efficiency and bandwidth. These, however, show diminishing return when a large number of inductors is used. On the basis of this tool, the level of complexity of the antennas can be increased to investigate advanced performance in future work. Solutions for optimized, complex antennas might be found that intuition and experience, based on traditional antenna designs, might not have suggested. The ultimate goals of this investigation are to first identify the trade-offs between smaller size, wider bandwidth, and higher efficiency, and to pursue corresponding near-optimal solutions in accordance with physical requirements.

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