Optimization of umbrella top-loaded shunt-fed monopole antenna for MF digital radio using WIPL-D Microwave software

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Abstract —**Electrically short ($h/\lambda = 0.17$) medium frequency (MF) monopole antenna was redesigned in order to be used for both analog and digital broadcast. Necessary impedance and bandwidth was achieved by the capacitive umbrella top-loading and a shunt-fed design. In order to achieve desired specifications, antenna dimensions and a simple matching network parameters were simultaneously optimized by a specialized software WIPL-D Microwave.**

Keywords — **Antenna optimization, umbrella loaded antenna, shunt-fed monopole, folded monopole, digital radio, DRM, WIPL-D Microwave.**

I. Introduction

TRADITIONAL medium frequency broadcasting antennas are in the form of vertical monopole masts grounded by a set of (usually 120) buried radial wires, and have heights approximately between 0.25λ and 0.52λ (antifading height) [1], [2]. However, sometimes it is necessary to use lower masts (e.g. lower than 0.2λ). To achieve desired matching, impedance bandwidth and efficiency, these electrically short antennas must be redesigned. Another reason for the redesign of traditional MF antennas is their application for new services, such as hybrid digital transmissions like IBOC[1] [3] and Digital Radio Mondiale (DRM) [4]. These new services could require wider bandwidths, up to two traditional AM channels (2×9 kHz in Europe and 2×10 kHz in US), and VSWR must satisfy specifications in up to 30 kHz bandwidth. The redesign should also be the simplest possible, taking in account large vertical and horizontal dimensions of antenna structures (hundreds of meters). Thus, the use of metallic (steel) ropes only is the most preferable choice in this regard.

In case of electrically short antenna masts, first concerns are to increase radiation resistance and make input impedance flat enough to enable simple matching and efficient performance.

Classical simple method for increasing the radiation resistance is by capacitive top loading of the mast [5]. Most efficient way (in regard of antenna performance improvement) to do this is to use horizontal radial elements — steel guys or rigid steel elements. However, this demands erecting new posts *of the same height* as the original antenna mast for supporting guys, or employing special construction to hold long horizontal rigid elements. These options are usually unaccaptable from economical point of view. More economical design is to use oblique metallic guys, stretched by insulator guys fixed at the ground level, resulting in umbrella top-loaded antennas [6],[7] (Fig.1).

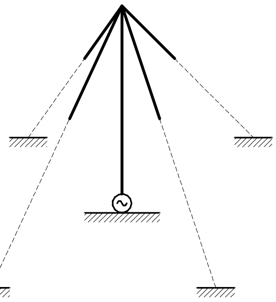

Fig.1. Umbrella top-loaded monopole.

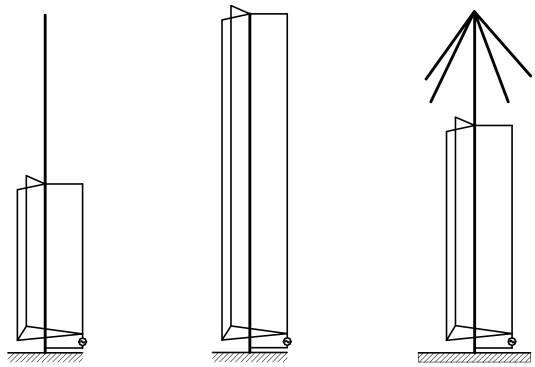

Fig 2. Shunt-fed antennas: (a) with three guys, (b) folded monopole, (c) with top-load.

Increase of radiation resistance can also be obtained by a shunt feeding (Fig.2a). This requires the antenna mast to be grounded, which is even more desirable configuration. Set of steel guys are hanged from some height of a mast, making a characteristic “skirt”. Antenna is now fed

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[1] Simultaneous amplitude modulation and digital transmissions by IBIQUITY

between the bottom of the skirt and the ground [8],[9]. If the guys hang from the antenna top, a folded monopole antenna is obtained (Fig.2b). Sometimes it is beneficial to combine both designs, resulting in top-loaded shunt-fed monopole [10],[11] (Fig.2c).

In our particular case, a $h = 75$ m high monopole of a triangular cross-section (side length $w = 110$ cm) should be redesigned to broadcast analog and digital (DRM) signal on central frequency $f_0 = 684$ kHz (traditional frequency of Radio Belgrade 1), fed by a $125\,\Omega$ line. Thus, the relative height of antenna is $h/\lambda_0 = 0.17$, making it electrically small. Given specifications for VSWR were[2]: VSWR < 1.2 for $f_0 \pm 10$ kHz and VSWR < 1.4 for $f_0 \pm 15$ kHz. In solving this design task, we decided to use only steel guys for antenna reconstruction. For the matching network we adopted the most simple, L-shaped reactive network (to perfectly match antenna on f_0) after antenna reactance is compensated by a single reactive element [1],[2]. For numerical simulations of the antenna we used WIPL-D Electromagnetic Solver [12].

Original antenna had $Z_{\text{in}} = 13.81 - j119.6$ on f_0. With matching network, VSWR at characteristic frequencies ($f_0 - 15, f_0 - 10, f_0 + 10, f_0 + 15$ kHz) was 2.4, 1.8, 1.8 and 2.3, respectively, which is very far from specified.

II. UMBRELLA TOP-LOADED MONOPOLE

This was the first design we have tried (Fig.1). We decided to use $n = 6$ guys, as it was already shown that this practically suffices [8]. We calculated antenna parameters for two angles between guys and the mast: 60° and 45°. Angle of 60° was chosen as the largest angle that can practically be achieved (due to mechanical reasons). Angle of 45° was chosen as somewhat "safer" option. The length of the guys was varied from 0 to 120 m. Dependence of the antenna resistance and reactance on central frequency on umbrella length is shown in Fig.3.

After matching network is applied, the best matching was obtained for $\alpha = 45^\circ, D = 30$ m and $\alpha = 60^\circ$, $D = 40$ m, resulting in characteristic VSWR values of 1.57, 1.36, 1.35 and 1.57. This was better than the original antenna, but still far from specifications.

III. SHUNT-FED MONOPOLE

This was the second design we have analyzed (Fig.2a). We used $N = 3$ vertical guys. The two parameters that we have varied were the hanging height *H* and the distance of the "skirt" guys from the antenna axis, *d*. The larger *d*, the greater influence of the height H on the antenna impedance. However, from construction reasons we decided to limit this distance to $d_{\text{max}} = 200$ cm and to analyze antenna for $d = 160$ cm and $d = 200$ cm. Hanging height was varied from 20 to 75 m. Antenna resistance and reactance on the central frequency is shown in Fig.4. It can be seen that significant increase of antenna resistance is observed for larger hanging heights. However, for these heights the change of antenna reactance against height H (and against frequency too) is very large. This is a very undesirable effect. The best matching was obtained for $d = 200$ cm, $H = 65$ m, resulting in characteristic VSWR values of 3.7, 2.4, 2.2 and 3.0. This is much worse than for the top-loaded antenna. This poor performance of a shunt-fed antenna is due only to a small horizontal distance of the skirt from the antenna mast.

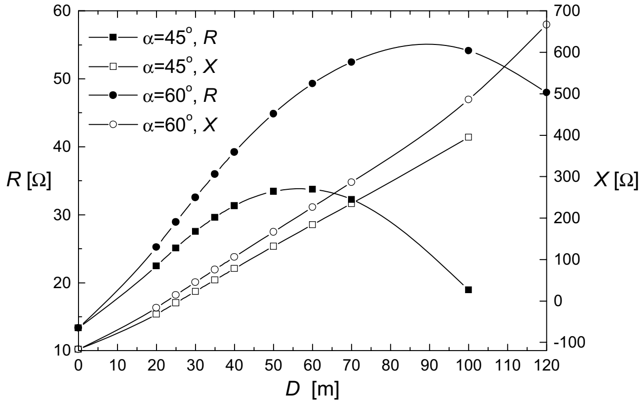

Fig.3. Input resistance and reactance of an umbrella top-loaded antenna as a function of guys' length.

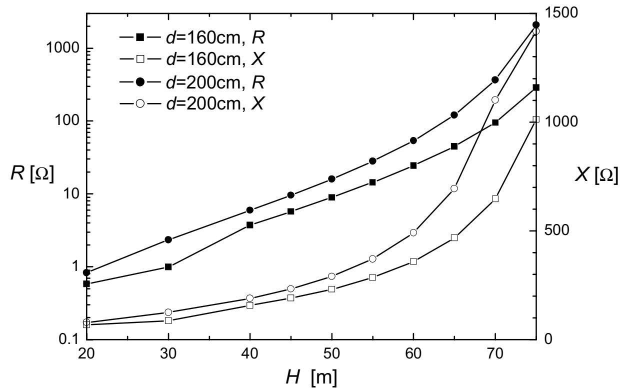

Fig.4. Input resistance and reactance of a shunt-fed monopole as function of hanging height.

IV. UMBRELLA TOP-LOADED SHUNT-FED MONOPOLE

This design is shown in Fig.2c. We again used six umbrella guys and three shunt-feed guys. Now there are four parameters that we varied: umbrella angle and length (α and D) and skirt hanging height and horizontal distance (H and d). Ranges of these parameters were taken to be the same as described in sections II and III.

As the number of parameters (four) was too large for systematic analysis of antenna in complete 4-dimensional space, we decided to use optimization capabilities of the WIPL-D software.

[2] Specifications are dictated by the digital broadcasting DRM standards, these specifications being more severe in all the elements than those of the analog broadcasting.

A. *Successive optimization of antenna and matching network*

The first optimization methodology we used was a successive optimization of the antenna and the matching network. However, it is not very clear what should be the antenna optimization goal. Is it more important to have antenna impedance close to characteristic impedance of a feeding line, $(125+\mathrm{j}0)\,\Omega$, or to obtain impedance that has the smallest deviation in the working frequency range, or those two goals should both be used, and then what should be the appropriate weights? Unable to answer these complicated questions exactly, we decided to use the first goal. As a result of such optimization in WIPL-D Pro [12] we obtained antenna with $Z_{\mathrm{in}}=(126+\mathrm{j}1.56)\,\Omega$ on central frequency, for $\alpha=47.6^{\circ}$, $D=28.4\ \mathrm{m}$, $d=200\ \mathrm{cm}$ and $H=72.4\ \mathrm{m}$. However, the trade-off was in large change of impedance throughout the frequency range: from $Z_1=(155-\mathrm{j}36)\,\Omega$ on $f_0-15\ \mathrm{kHz}$ to $Z_2=(108+\mathrm{j}33)\,\Omega$ on $f_0+15\ \mathrm{kHz}$. Standard matching network was again synthesized, resulting in characteristic VSWR values of 1.40, 1.25, 1.23 and 1.36. The first and the last value now satisfy specifications (VSWR less than 1.40) and the remaining two are very close to the specified VSWR of 1.20.

In the next step we tried to improve the matching network, letting the MWO software [13] optimize its parameters. The result was VSWR values of 1.39, 1.24, 1.24 and 1.36, practically the same as for the initial network. Thus, we concluded that the successive optimization with the optimization goal “antenna impedance as close to Z_{c} as possible” is not the best one.

B. *Simultaneous optimization of antenna and matching network*

WIPL-D Microwave [14] is one of the unique softwares that enable simultaneous optimization of electric circuits and 3D electromagnetic objects (e.g. antennas). Matching network was adopted in the form shown in Fig.5. It is adopted after analysis of all possible reactive Π and T reactive networks (of three elements). However, some other three-element configurations can also be used with similar results.

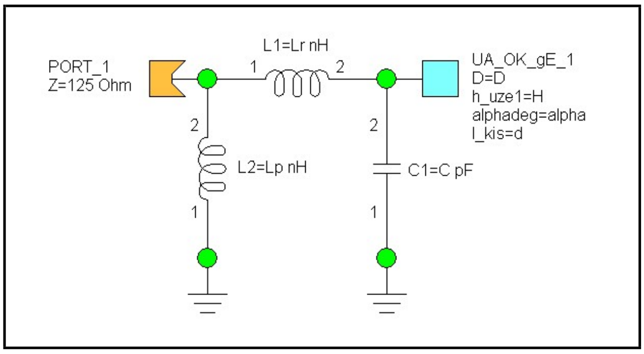

Fig.5. Matching network for simultaneous optimization of antenna and matching network in WIPL-D Microwave.

In order to reduce the number of optimization parameters, we fixed the umbrella angle, and performed automatic optimization of the remaining six parameters. First, we let $\alpha=60^{\circ}$, as a more promising variant. Optimization was performed and the resulting optimal parameters were rounded to two digits in order to carry out an elementary check of the solution sensitivity. Optimal (rounded) antenna parameters are $\alpha=60^{\circ}$, $D=26\ \mathrm{m}$, $d=190\ \mathrm{cm}$ and $H=62\ \mathrm{m}$, resulting in antenna impedance of $Z_{\mathrm{in}}=(97.2+\mathrm{j}65.4)\,\Omega$ on f_0. This is quite different from $(125+\mathrm{j}0)\,\Omega$, proving that the optimization goal used in successive optimization was not the best one. Optimal (rounded) values of the matching network parameters (see Fig.5) are $L_1=2.4\ \mu\mathrm{H}$, $L_2=27\ \mu\mathrm{H}$ and $C=3.0\ \mathrm{nF}$. Fig. 6 shows the resulting VSWR (1.28, 1.18, 1.18 and 1.28 for optimal and 1.27, 1.18, 1.18 and 1.27 for sub-optimal antenna). Specifications are now completely met.

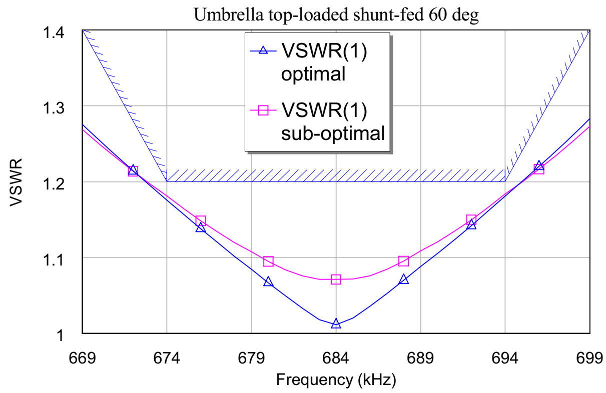

Fig. 6. VSWR of the optimal and sub-optimal (rounded optimal parameters) antenna for $\alpha=60^{\circ}$.

Next we let $\alpha=45^{\circ}$ and repeated the same procedure in order to check if the solution is possible for this “safe” umbrella angle too. Optimization resulted in (rounded) parameters of $\alpha=45^{\circ}$, $D=30\ \mathrm{m}$, $d=200\ \mathrm{cm}$ and $H=75\ \mathrm{m}$, $Z_{\mathrm{in}}=(104+\mathrm{j}47.8)\,\Omega$ (on f_0), $L_1=100\ \mathrm{nH}$, $L_2=22\ \mu\mathrm{H}$ and $C=3.3\ \mathrm{nF}$. Fig. 7 shows the resulting VSWR (1.30, 1.19, 1.19 and 1.29 for optimal and 1.30, 1.19, 1.19 and 1.31 for sub-optimal antenna). Specifications are again completely met. Resulting VSWR is only slightly higher than for $\alpha=60^{\circ}$.

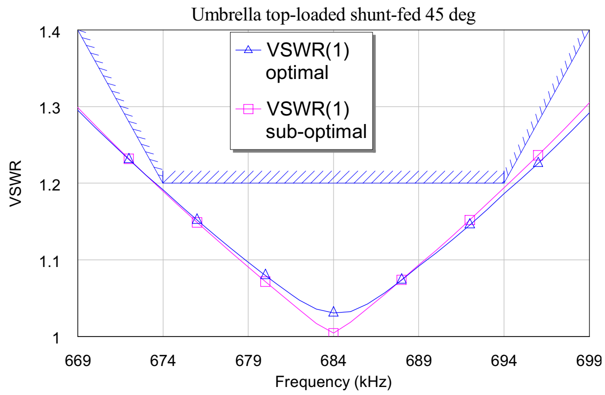

Fig. 7. VSWR of the optimal and sub-optimal (rounded optimal parameters) antenna for $\alpha = 45^{\circ}$.

V. Conclusions

From the presented analysis two important conclusions can be formulated:

- Electrically short MF antennas can be successfully reconstructed by modest means, by applying umbrella top-loading and/or shunt feeding of the antenna mast.
- Synthesis of antennas with stringent constrains can be efficiently achieved only by systematic simultaneous numerical optimization of both antenna and the matching network.

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