Calculation of the efficiency of electrically small MF antenna for mine communications

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Abstract. Today, the developers of electrically small antenna equipment are faced with the problem of reliable modeling of electrically small antennas. The existing methods of computer modeling of electrically small antennas, as experience has shown, are resource-intensive. One of the ways to solve this problem is to use the method of replacing the antenna with an equivalent electrical circuit. This method is based on the assumption that any part of the antenna can be replaced by equivalent values of inductance, capacitance or active resistance, which can be investigated together with the elements of the tuning and matching circuit. The resulting equivalent electrical circuit can be analyzed by the methods of the theory of electrical circuits, and most of the antenna characteristics of interest to the developer can be determined. These include efficiency, quality factor, frequency dependences of impedance and voltage standing wave ratio (VSWR). In this work, a sample of an electrically small resonant medium frequency (MF) antenna and its equivalent circuit are presented, and its characteristics are analyzed using the theory of electrical circuits. The graphs of the dependence of the efficiency on the frequency at the resonant tuning of the antenna are plotted.

1. Introduction

Currently, one of the key directions in antenna technology is to reduce the size of antennas. This area is especially relevant when organizing radio communications in underground mining facilities. For the organization of underground radio communication today, medium-frequency (MF) radio stations Ferra with electric type antennas are produced according to the patent [1]. Figure 1 shows the structural diagram of the antenna, where: 1 is a radiator, 2 is a primary coil, 3 is a secondary coil in a multi-section design, 4 is a movable tuning capacitive element, 5 are power points. Changing the position of the capacitive element allows you to tune the resonant frequency. The antenna is resonant and tunable in the range 950 ÷ 1050 kHz with VSWR <1.2. Figure 2 shows the characteristics of impedance and reflection coefficient |p(f)|. With the correct choice of the equivalent circuit, the simulation results allow us to estimate the efficiency, the direct measurement of which is resource-intensive. One of the ways to determine the characteristics of such antennas is the construction and subsequent analysis of an equivalent electrical circuit [2-5].

The purpose of this work is to reveal the features of the method of equivalent contours as applied to the analysis of antennas of ultra-small wave sizes and the analysis of a sample of an electric antenna by this method.
2. Basic relations of the method of equivalent circuits.

A small-sized resonant antenna is a system with losses, the physical character of which is individual for each design: dissipative losses in current-carrying radiating elements, in dielectric parts of the frame, in tuning elements, radiation losses, etc. The operation of electrically small antennas as elements of radio equipment is associated with the quality of matching, the optimal operating mode is with forced resonance. The relationship of reactive power $P_S = \omega W_S$ ($W_S$ - maximum stored energy) with the total power $P_{TOTAL}$ can be expressed through the power triangle:

$$P_{TOTAL}^2 = P_A^2 + P_S^2 = (P_\Sigma + P_D)^2 + P_S^2$$  \hspace{1cm} (1)

where $P_A$ is the supplied power, $P_\Sigma$ is the radiation power, $P_D$ is the dissipated power.

Efficiency is defined as:

$$K_{eff} = P_\Sigma/P_A = 1/(1 + P_D/P_\Sigma)$$  \hspace{1cm} (2)

The structural components of the linear part of a passive antenna can be represented by inductive, capacitive or resistive elements of the electrical circuit. The construction of an equivalent circuit is made on the basis of these values of capacitances, inductances and resistances of current-carrying conductors and tuning elements of the developed antenna. With known values of the equivalent elements of the obtained electrical circuits, the necessary input characteristics can be calculated: active and reactive resistances, associated reflection coefficients (transmission coefficient, VSWR), active powers on these elements. The elements of the tuning circuits also have their equivalent circuits. Methods for analyzing electronic circuits are described in the circuit theory literature, in particular [6]. The capacitor at low frequencies can be represented by a parallel equivalent circuit, with an $R_C$ resistance, due mainly to the consumption of active power in the capacitor dielectric. The maximum energy is stored in the capacitor during the time when the instantaneous power does not change sign, i.e. for a quarter of the period, and it is determined:
\[ W_{\text{Cmax}} = C U_C^2 = P_{SC} / \omega \]  \hspace{1cm} (3)

where \( U_C \) is the effective range of voltage and \( P_{SC} \) is the capacitor reactive power. The quality factor of a capacitor is found as the ratio of reactive power to active \( P_C \):

\[ Q_C = P_{SC} / P_C = P_{SC} / (U_C^2 / R_C) = \omega C R_C \]  \hspace{1cm} (4)

Inductance can be represented by a parallel equivalent circuit with series resistance \( R_L \) due to dissipative losses in the conductor, insulation losses, radiation losses and parallel interturn capacitance \( C_L \). For inductance, similarly to (3)-(4):

\[ W_{\text{Lmax}} = L I_L^2 = P_{SL} / \omega \]  \hspace{1cm} (5)
\[ Q_L = P_{SL} / P_L = P_{SL} / (U_L^2 / R_L) = \omega L / R_L \]  \hspace{1cm} (6)

where \( I_L \) is the effective value of the current, and \( P_{SL} \) is the reactive power on the inductor.

The antenna under consideration operates in the forced parallel resonance mode, and in the general case at the frequency of the minimum VSWR: \( X_A \neq 0, W_{LS} \neq W_{CS} \) and \( P_S = |P_{SL}| - |P_{SC}| \).

Thus, from the measured frequency characteristics of the impedance, it is possible, using the methods of circuit theory, to estimate the efficiency.

3. Simulation results

Figure 2 shows the equivalent antenna circuit: \( C_1 \) - lumped capacitor, \( L_1 \) - primary coil, \( R_1 \) - equivalent losses in \( L_1, L_2, L_3, L_4, \ldots \) - inductors corresponding to the sections of the secondary coil, \( R_{2,1} \ldots R_{2,7} \) - resistors equivalent to losses in sections, \( C_{2,1} \ldots C_{2,7} \) - capacitors equivalent to the turn-to-turn capacitance of the sections, \( C_{\text{VAR}} \) - variable capacitor equivalent to a movable capacitive element, \( C_3 \) - capacitor corresponding to the capacitance of the radiating vibrator, \( R_3 \) - resistance to dissipative losses of the vibrator, \( R_S \) - radiation resistance.

![Figure 3. Equivalent antenna circuit.](image)

The model parameters are set by calculation and experimental method. Losses in the sections of the secondary coil can be determined from the formulas for multi-turn coils presented in the literature, in particular for a litz-wire coil [7], the use of which is optimal at 1 MHz frequency. \( C_{\text{VAR}} \) is an integral characteristic that includes the cylinder's own capacity and the capacity distributed in space, depending on the surrounding objects (position of the radio station, user, etc.). The lower limit of the possible \( C_{\text{VAR}} \) values can be determined by the capacity formula for a cylindrical tube of finite length [8]:

\[ C = 4\pi^2 \varepsilon_0 a [\ln(16a/l)]^{-1} \]  \hspace{1cm} (7)

where \( a \) and \( l \) are the radius and length of the cylindrical tube, respectively.

AWR Microwave Office & MATLAB were used to carry out the calculations. The calculated frequency dependences of the antenna input impedance are shown in Figure 4. Comparison of the
impedance graphs in Figure 2 and Figure 4 shows that the resulting model is equivalent to the antenna under study. Figure 4 shows the efficiency graph. According to the results obtained, the efficiency is about 1% at the resonance frequency and drops rapidly when operating at frequencies above or below the resonance frequency. The resulting value should be considered high enough.

![Graph](image)

**Figure 4.** Input impedance and efficiency in the range 950–1050 kHz obtained as a result of simulation.

4. Discussion

At the moment, in the MF range, the dimensions of the antennas exceed the dimensions of the antenna studied in this work, while the authors often do not aim to measure the efficiency, limiting themselves to measuring the radiation pattern and impedance characteristics. According to the known works, the efficiency of antennas with dimensions less than 0.01λ is several percent even for stationary structures [9-12]. Several firms in the international market offer devices with low efficiency loop or ferrite antennas. The characteristics (in particular, the efficiency) of these antennas are not given. At the moment, the authors are not aware of similar MF devices that allow providing underground communications without metal guide lines at a distance of more than 1000 m at a power of 5 W. This means that competitive antennas are even less efficient.

5. Conclusion

An equivalent circuit of a small-sized resonant antenna according to [1] has been obtained. The simulation of the equivalent circuit in the resonant operating mode is carried out. The reliability of the selected equivalent circuit is shown by comparing the measured and calculated dependences of the input resistance.

It was found that the efficiency of the antenna under study is about 1% with dimensions of about 0.0016λ, which is a high indicator for a portable MF antenna.
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