COMPENSATION METHODS OF INTERFERENCE REDUCTION IN THE RANGE OF ULTRALOW FREQUENCIES

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The problems of using a compensation method for interference reduction in the range of ultralow frequencies (ULF) are considered. The efficiency of the zone-component compensation is analyzed for the cases of atmospheric interference of thunderstorm discharge type and quasiharmonic noise of industrial frequency. The results of experimental verification of the noise compensation effect under natural conditions are presented.

Radio engineering investigations related to geoelectrical prospecting and studies of the terrestrial electromagnetic field require use of ultralow frequencies (ULF) from tens of hertz to a few kilohertz. In this range, there is strong interference by atmospheric and industrial noise. As a rule, the noise in the input units of the receiver exceeds the legitimate signal and the noise is non-Gaussian. The nonlinear transformation for pulsed noise reduction, using amplitude limiters, for example, is ineffective when quasiharmonic noise is added in the input mixture because of the suppression of weak legitimate signals under these conditions. Thus, a compensation method, based on input noise minimization by subtraction of noise from the reception channels, seems to be more effective for noise reduction. Noise compensation is a linear operation, which, in principle, is not connected with structural distortions of the signal processed. In the present paper, we consider the use of a compensator at ULF.

When the radio noise coming to the reception point from fixed directions is limited, the block diagram of the compensator contains \( n \) parallel channels. Each channel turns on a processor operated by the fastest descent method. The input total response of the system is multiplied by each \( i \)th input action \((i = 0, 1, 2, \ldots, n)\) and is subject to integration and amplification. This produces a weight coefficient \( W_i \) in each channel for gain control in the \( i \)th channel in the required direction. A complete set of weight coefficients \( W_i \) minimizes the power of residual voltage at the adder output. The zero channel is a signal channel. It has a separate antenna oriented to the direction of legitimate signal reception. In the signal channel, the processor is absent while the weight coefficient \( W_0 \) is constant and determines the initial gain of the channel. Denoting the signal function at the inputs of the compensator channels by \( \gamma_i, S_i \), where \( S_i \) is the complex envelope of the \( i \)th signal vector of unit length, \( \gamma_i \) is a constant factor, and assuming \( S_i = 1 \), we write the matrix equation of the compensator

\[
\begin{bmatrix}
\gamma_0 \\
\Lambda M
\end{bmatrix}
\begin{bmatrix}
W_0 \\
W
\end{bmatrix}
= 
\begin{bmatrix}
\gamma_0 \\
\Gamma
\end{bmatrix},
\]

where \( p_0 = x_0^2 \) is the power of the received mixture in the signal channel, \( \Lambda \) is the column vector of input voltage correlations between compensation channels (for \( i \geq 1 \)) with voltage in the signal channel, \( M \) is a matrix of size \( n \times n \),

\[
\Lambda = \begin{bmatrix}
x_1 x_0 \\
x_2 x_0 \\
\vdots \\
x_n x_0
\end{bmatrix};
M = \begin{bmatrix}
x_1 x_1 & \ldots & x_1 x_n \\
x_2 x_1 & \ldots & x_2 x_n \\
\vdots & \ddots & \vdots \\
x_n x_1 & \ldots & x_n x_n
\end{bmatrix}.
\]
\( \Lambda^* \) is the conjugate matrix obtained by transposing the column vector \( \Lambda \), \( E \) is a statistical averaging operator, \( \Gamma \) is the vector column of the factors \( \gamma_i \), and \( W \) is the column vector of the weight coefficients \( W_i \) \((i = 1, 2, \ldots)\). Equation (1) is divided into two equations,

\[
p_0 W_0 + \Lambda^* W = \gamma_0 \quad \text{and} \quad \Lambda W_0 + MW = \Gamma.
\]

(3)

The adaptation of the compensator is described by the right-hand equation (3). Hence, we find an expression for the optimum weight coefficients with account of guiding legitimate signals into the compensation channels,

\[
W_{opt} = -M^{-1}(\Gamma + \Lambda W_0),
\]

(4)

where \( M^{-1} \) is the inverse of \( M \). The constant weight coefficient \( W_0 \) is intended to provide for the required gain of the legitimate signal, \( \gamma_0 S_0 \). If the legitimate signal is present only in the signal channel, then \( \Gamma = 0 \) and we have the well-known expression for \( W_{opt} \) [1]

\[
W_{opt} = -M^{-1} \Lambda W_0.
\]

The formation of weight coefficients in the system is the faster the greater is the power of the input action.

In a two-channel compensator \((n = 1)\), under conditions of normal noise in the channels with dispersions \( \sigma_0^2 \) and \( \sigma_1^2 \) and noise correlation coefficient \( \rho_k \), we have \( M = E(x_1 x_1) = \sigma_1^2 \), \( \Lambda = E(x_1 x_0) = \rho_k \sigma_1 \sigma_0 \), whence \( W_{opt} = -(\sigma_0/\sigma_1) \cdot M^{-1} \rho_k W_0 \). The residual dispersion of noise at the compensator output \( \sigma_2^2 = \sigma_0^2(1 - \rho_k^2) \), and the compensation efficiency determining the relative noise reduction has the form [2]

\[
\eta = \sigma_2^2/\sigma_0^2 = 1/(1 - \rho_k^2).
\]

The statistical properties of noise in the ULF range depend on temporal and meteorological conditions under which the receiving equipment is operated. As an example, Fig. 1 shows a density probability curve of the total noise envelope in the region of South Karelia (solid line). The measurements were conducted in a quiet thunderstorm environment in summer and in fall. The receiver was operated at \((30-300) \text{ Hz}\) in the passband \((2-5) \text{ Hz}\). For comparison, the dashed line shows the calculated lognormal incident wave with parameters close to the experimental curve. This figure shows that the noise measured under those conditions can adequately be described by a lognormal distribution.

In the ULF range, it is reasonable to use the different dependence of the electric and magnetic components of the field on distance to the source for noise reduction. This opens up a new horizon for use of noise compensation in one reception zone, keeping the signals from the other spatial zones at an acceptable level. Preliminary discussion of the feasibility of this noise compensation was done in [3]. This method can be defined as the method of zone-component compensation of radio noise.

We now estimate the efficiency of a two-channel nonadaptive zone-component compensation of atmospheric radio noise of lightning discharge type and quasiharmonic noise of industrial frequency. Typically, the pulsed current of a lightning, \( I(t) \), and the heights of the lightning channel, \( h(t) \), are given by

\[
I(t) = Ae^{-at} - Be^{-bt} + Ce^{-\gamma t};
\]

\[
h(t) = \left(\frac{V_0}{ab}\right) \left[ (b-a)-(be^{-at}-ae^{-bt}) \right];
\]

the practical values of the parameters and coefficients are as follows: \( A = 20 \text{ kA}, B = 25 \text{ kA}, C = 5 \text{ kA}, \alpha = 5 \cdot 10^4 \text{ s}^{-1}, \beta = 5 \cdot 10^5 \text{ s}^{-1}, \gamma = 7 \cdot 10^2 \text{ s}^{-1}, a = 6 \cdot 10^4 \text{ s}^{-1}, b = 7 \cdot 10^5 \text{ s}^{-1}, \) and \( V_0 = 3 \cdot 10^8 \text{ m/s}. \) In the near zone, i.e., under condition \( \rho \ll \lambda \), where \( \rho \) is the distance to the noise source and \( \lambda \) is the radiated wavelength, the expressions for the vertical electric field \( E_z \) and horizontal magnetic field \( H_x \) under the assumption of absolute conductivity of the Earth can be written approximately as

\[
E_z(t) = -\frac{1}{2\pi \varepsilon_0} \int \frac{m(t')}{\rho^3} dt; \quad H_x(t) = \frac{1}{2\pi} \frac{m(t')}{\rho^2},
\]

(5)