

Crosstalk prediction and statistical properties of transmission line

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Abstract: In this paper, for the crosstalk error problem of multi-core stranded wires caused by non-uniform pitch, the Monte Carlo method is used to establish the probability distribution model of non-uniform pitch of stranded wires. For stranded wire crosstalk prediction, a transmission line parameter prediction model is constructed using the BSO-BP neural network algorithm, and the effectiveness of the algorithm in this paper is verified by simulation. The final calculation gives the statistical characteristics of crosstalk on multicore stranded wires.

Keywords: Crosstalk, Neural networks, EMI, Finite time domain difference method

1. Introduction

The existence of distributed capacitance and distributed inductance between cables allows the electromagnetic energy transmitted on the line to couple into neighboring lines, generating electromagnetic interference, which is the essence of crosstalk generation [1, 2]. Therefore, when studying the cable crosstalk problem, the acquisition of distribution parameters is the first step in building the crosstalk model. When the traditional analytical method is applied to the calculation of cable distribution parameters [3-5], the wire spacing needs to meet the spacing condition when calculating the distribution parameters due to the non-uniformity of the insulation layer medium around the cable. Due to the limitations of the analytical method, scholars mostly use numerical calculation methods to obtain the cable distribution parameters. For example, Manfredi uses chaotic polynomial coefficients for the extraction of parameter matrices of random unit lengths of circular conductors [6].

For the calculation of the distribution parameters of non-uniform transmission lines, the numerical method has both accuracy defects and applicability conditions, but modern artificial intelligence algorithms can better deal with the coexistence of computational efficiency and computational accuracy. It is based on this idea that BP neural network is introduced in the literature [7] to construct a nonlinear mapping relationship between the electromagnetic parameter matrix and the axial extension of the stranded wire. To avoid the BP neural network from falling into local optimum [8], C. Huang used the Beetle Antennae Search (BAS) algorithm modified BP neural network to predict the transmission line unit length parameters [9]. However, the BAS algorithm is not ideal for optimization of high-dimensional data, and its iterative results are strongly influenced by the initial positions of the beetles. Therefore, this paper improves the BAS algorithm by extending individual beetles to beetle swarms.

This paper firstly introduces the detailed procedure of Monte Carlo method to build a non-uniform strand model, and analyzes the nonlinear relationship between the rotation angle of the cross-section of the four-core strand and the transmission line distribution parameters. Then, the process of Beetle Swarm Optimization (BSO) algorithm to optimize the neural network is described in detail, and the prediction model of four-core stranded wire distribution parameters is established. Finally, a comparison of the crosstalk results solved by FDTD with the simulation results is given to verify the correctness of the crosstalk prediction algorithm.

2. Multi-core stranded wire model

The principle of stranding can be represented in Figure 1. Its mechanical production requires setting two parameters T_1 and T_2 , which are the rotation periods of spindles A and B, respectively. The stranded wire is achieved by rotating spindles A and B with fixed periods T_1 and T_2 .

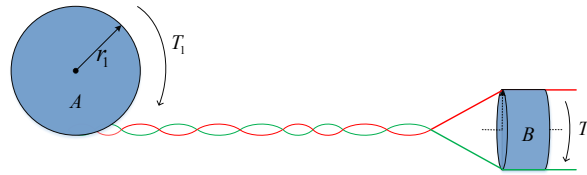


Figure 1: Schematic diagram of the stranded wire production process.

After the production, the radial length of the stranded wire, its pitch number $M=2t/T_2$, where t is the time required for the mechanical production of the stranded wire, t is an integer multiple of $T_2/2$. The pitch p can be expressed as:

$$p = \frac{\pi r_1}{T_1} T_2 = \omega_1 r_1 \frac{\pi}{\omega_2} = F(\omega_1, \omega_2) \quad (1)$$

Where ω_1, ω_2 are the angular velocities of the rotating axes A and B, respectively. In this section, it is assumed that ω_1 and ω_2 in equation (1) obey normal distributions of $N_1(2\pi, 0.1)$ and $N_2(100\pi, 1)$, respectively. Set the line length in equation (1) as 1m, the pitch as 50, the average pitch as $p=20$ mm, the radius as $r_1=1/\pi$ m, $t=0.5$ s, $T_1=1$ s and $T_2=0.02$ s. For the normal distribution $N(\mu_p, \delta_p)$, the mean μ_p of this normal distribution can be found to be 20 and the standard deviation δ_p to be 0.325 based on the Monte Carlo method [10]. Setting the confidence level to 99.7%, 99.7% of the pitch falls within the interval of $p = \bar{p} \pm 3 * \delta_p$, which is [19.025mm, 20.975mm].

Figure 2 illustrates the continuous rotation of the cross-section of the four-core stranded wire within a single pitch and the process of axial extension of the wire. The figure shows that the initial cross-section of the four-core stranded wire is rotated by 90° to obtain a cross-section with the same shape as the initial cross-section, and there is only a difference in the artificially defined serial number of the transmission line.

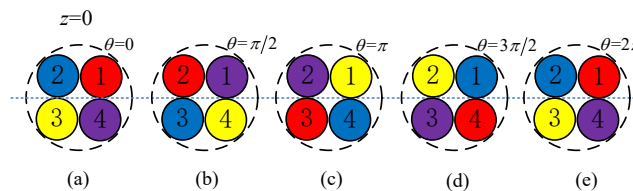


Figure 2: Four-core stranded wire single-pitch transformation model.

With the axial extension of the stranded wire the cross-sectional shape of the stranded wire also changes, which corresponds to the change of the stranded wire distribution parameters, i.e., there is a non-linear mapping relationship between the axial coordinates of the stranded wire and the distribution parameters. Using the functional relationship can be expressed as follows.

$$f(l) = [\mathbf{R}, \mathbf{L}, \mathbf{C}, \mathbf{G}] \quad (2)$$

Where $[\mathbf{R}, \mathbf{L}, \mathbf{C}, \mathbf{G}]$ is the matrix of distribution parameters and l denotes the horizontal distance of any cross section of the stranded wire from the initial cross section. By analyzing the structure of the stranded wire, the coordinates of any point on the stranded wire can be converted into the angle θ of rotation.

$$\begin{cases} \theta = \frac{l}{p} 2\pi, 0 \leq l \leq p \\ \theta = \frac{(l-mp)}{p} 2\pi + 2m\pi, mp \leq l \leq (m+1)p \leq d, m=1, 2, \dots \end{cases} \quad (3)$$

Where d is the total length of the stranded wire.

Equation (2) can be converted as follows

$$f(\theta) = [\mathbf{R}, \mathbf{L}, \mathbf{C}, \mathbf{G}] \quad (4)$$

3. Crosstalk prediction model

3.1 Extraction of distribution parameters

In this paper, a neural network optimized by the BSO algorithm is used to describe the complex mapping relationship in equation (4). For M sets of training samples, the mean square error E between the output values y_j of the neural network and the actual values y'_j extracted by the ANSYS software is

$$f(w) = E(w_i, w_{ij}) = \frac{1}{2M} \sum_{i=1}^M \sum_{j=1}^N (y_j - y'_j)^2 \quad (5)$$

In the BSO algorithm, the position of each beetle represents the BPNN weights, and the objective function of the BSO algorithm to optimize the neural network weights w_{li}^1 and w_{ij}^2 thresholds is $f(w)$, whose optimal value is set to f_{best} , and the specific steps are as follows.

(1) Generate a population with n beetles in a 3D search space: $B = (B_1, B_2, \dots, B_n)$, where the i -th beetle is a vector $B_i = (b_{i1}, b_{i2}, \dots, b_{iS})$. The speed of the i -th beetle is denoted as: $V_i = (V_{i1}, V_{i2}, \dots, V_{iS})$. In order to improve the speed of calculation, the threshold ranges for individual beetle and communities were specified as $U_i = (U_{i1}, U_{i2}, \dots, U_{iS})$ and $U_g = (U_{g1}, U_{g2}, \dots, U_{gS})$.

(2) Update each beetle speed

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 (U_i^k - B_i^k) + c_2 r_2 (U_g^k - B_g^k) \quad (6)$$

where ω are the iteration weights, c_1 and c_2 are constants, and r_1 and r_2 are two random functions in the range $[0, 1]$.

(3) Calculate the left and right positions of the beetle whiskers and the odor intensity. The position of the i -th beetle left and right whiskers can be expressed by the search behavior as follows, respectively

$$B_{ri}^{k+1} = B_{ri}^k + V_i^k * d / 2 \quad (7)$$

$$B_{li}^{k+1} = B_{li}^k - V_i^k * d / 2 \quad (8)$$

Where d denotes the size of the distance between the left and right whiskers of the beetle. And the odor intensity of the i -th beetle left whisker and right whisker, i.e., the corresponding objective function size can be expressed as

$$f_{ri}^{k+1} = f(B_{ri}^k) \quad (9)$$

$$f_{li}^{k+1} = f(B_{li}^k) \quad (10)$$

(4) To calculate the displacement of the beetle and update the position of the beetle, the increased displacement of the beetle can be expressed as

$$\delta_i^{k+1} = \varepsilon^k * V_i^k * \text{sign}(f(B_{ri}^k) - f(B_{li}^k)) \quad (11)$$

Where ε^k is the beetle step length. The new position of the beetle can be expressed as

$$B_i^{k+1} = B_i^k + \lambda V_i^k + (1 - \lambda) \delta_i^k \quad (12)$$

Where λ is a positive constant, usually taken as 0.5.

(5) Update the relevant parameters in the initialization and perform the optimization of the objective function.

3.2 Transmission line crosstalk calculation

Figure 3 shows the termination conditions at both ends of the four-core stranded wire model and the unit-length equivalent circuit of the multi-core stranded wire.

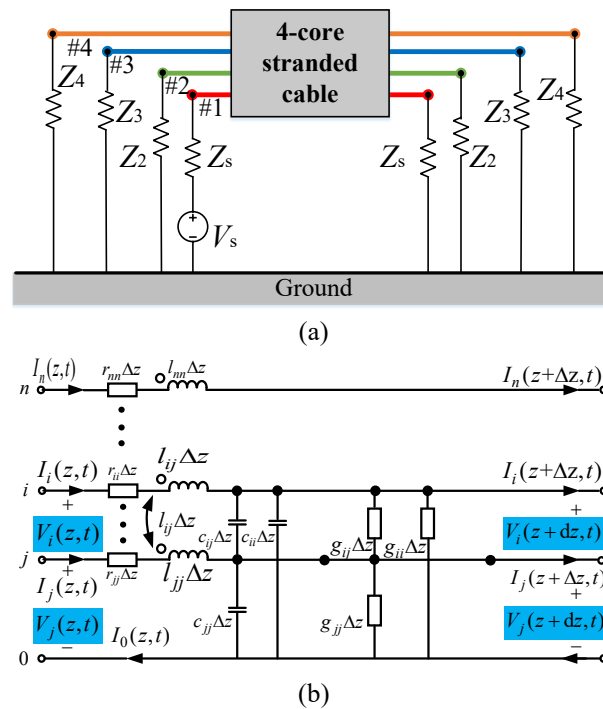


Figure 3: Termination conditions and equivalent circuits (a) termination conditions (b) Unit-length equivalent circuit.

According to Multi-conductor transmission line theory (MTL), this transmission line model satisfies the telegraph equation as

$$\frac{\partial}{\partial z} V(z,t) + R(z)I(z,t) + L(z)\frac{\partial}{\partial t} I(z,t) = 0 \quad (13)$$

$$\frac{\partial}{\partial z} I(z,t) + G(z)I(z,t) + C(z)\frac{\partial}{\partial t} V(z,t) = 0 \quad (14)$$

Where $V(z,t)$ and $I(z,t)$ are the voltage, current vectors in different spaces and times on a multi-conductor transmission line. In this paper, the FDTD algorithm [11] is used to solve this equation, and the near-end crosstalk (NEXT) and far-end crosstalk (FEXT) of the transmission line can be obtained by combining the termination conditions.

4. Simulation and Verification

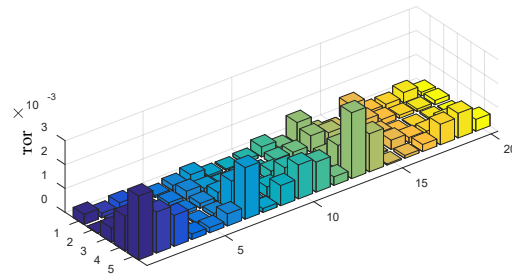
4.1 Neural network error

In this paper, the BP neural network model adopts the topology of single input and single hidden layer. The BP neural network topology is set as 1-10-10, the error accuracy is $1e-6$, and the learning rate is 0.05. The number of iterations of BSO algorithm is set as 200, the number of beetle is 100, the initial step size is 4, and the step size factor is 0.95. The four-core stranded wire model is established in the Ansys Q3D simulation platform, and the extracted parasitic parameters are used as the training samples of the neural network, whose specific parameters are shown in Table 1 shows.

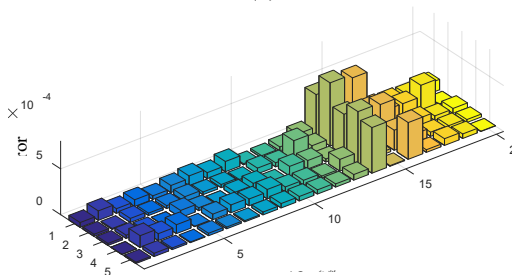
Table 1: Four-core stranded wire parameters.

Parameters	Value
Copper core radius r	1.2mm
Electrical conductivity σ	58000000S/m
Height of stranded wire center to ground h	6mm
Insulation layer thickness t	0.8mm
Relative dielectric constant ϵ_r	2.7F/m
Length of transmission line L	1000mm

The corresponding distribution parameters of angles 78° , 81° , 84° , 87° , and 90° are used as test samples and substituted into the trained neural network to obtain the corresponding predicted output values, and the relative error distribution histograms of the capacitance and inductance parameters are obtained as shown in Figure 4.



(a)



(b)

Figure 4: Relative error distribution histogram (a) BAS-BP (b) BSO-BP.

According to the distribution parameter prediction results, the prediction error of BSO-BP algorithm is less than $5e-4$, where the average relative error of BSO-BP algorithm is $6.06e-5$ and the average relative error of BAS-BP algorithm is $3.58e-4$. Compared with BAS algorithm, BSO algorithm makes the distribution parameter prediction accuracy significantly improved.

4.2 Uniform stranded crosstalk experiment

The electromagnetic simulation software CST Cable Studio Cable Studio enables the time and frequency domain analysis of cable crosstalk, and the transmission line matrix (TLM) algorithm is the core algorithm of CST. In this paper, the crosstalk results solved by the transmission line matrix

method of the CST platform are used as an experimental comparison. A simulation model of a uniformly twisted four-core stranded line is established in the CST environment, as shown in Figure 5.

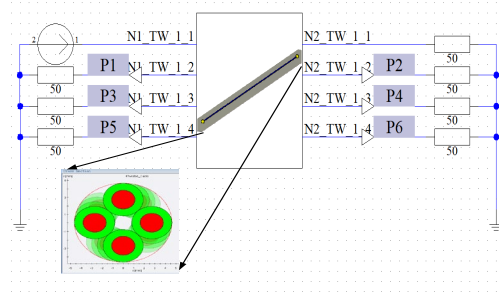


Figure 5: CST simulation circuit diagram.

In the ideal multi-core stranded wire model, the results of calculating the magnitude-frequency characteristics of the crosstalk of conductors No. 2, No. 3 and No. 4 in comparison with the simulation results are shown in Figure 6 using the method of this paper with a voltage source applied to conductor No. 1 and a power supply in the frequency range from 1 MHz to 1 GHz. Among them, the NEXT and FEXT amplitude-frequency characteristic curves of conductor No. 2 and No. 4 are very close, which is due to the fact that the magnitudes are so close when the power source is applied to conductor No. 1, while the disturbed conductors No. 2 and No. 4 are symmetrically distributed to each other.

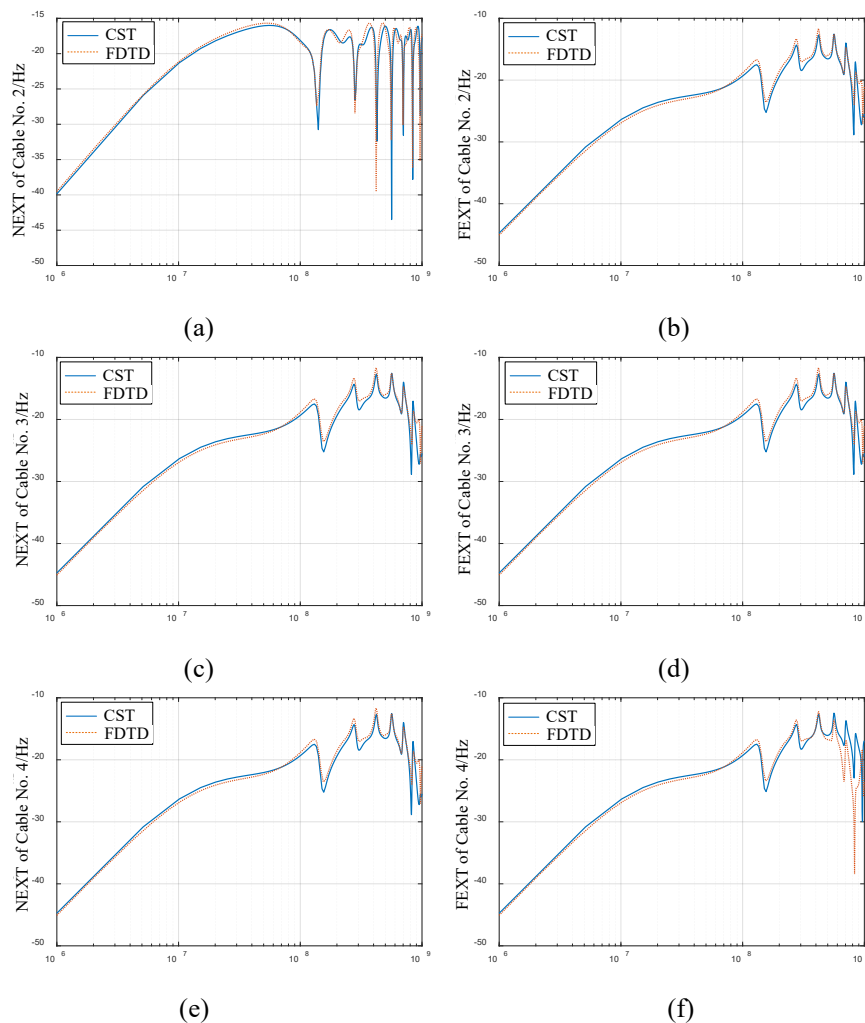


Figure 6: Comparison of crosstalk prediction and simulation results.

Table 2 and Table 3 represent the average values of NEXT and FEXT amplitudes in different frequency ranges, respectively. Due to the symmetry of the strand structure, for the crosstalk values

on lines 2 and 4, between 100 MHz and 500 MHz, the predicted results show a mean value of -18.74 dB for near-end crosstalk and -19.07 dB for simulated near-end crosstalk, with an error within 1 dB. Between 500MHz and 1000MHz, the two algorithms result in the same trend of near-end crosstalk and stabilize at about -19dB.

Table 2: Average crosstalk in different frequency ranges of Line 2 (-1dB).

Frequency/MHz	1~100		100~500		500~1000	
Type	NEXT	FEXT	NEXT	FEXT	NEXT	FEXT
FDTD	17.6	22.8	18.7	16.6	19.4	18.5
Simulation	17.6	24.7	19.1	17.8	19.1	18.4

Table 3: Average crosstalk in different frequency ranges of Line 3 (-1dB).

Frequency/MHz	1~100		100~500		500~1000	
Type	NEXT	FEXT	NEXT	FEXT	NEXT	FEXT
FDTD	17.7	22.8	18.7	16.8	18.8	21.0
Simulation	17.6	22.4	19.0	17.4	19.0	19.7

The analysis of the crosstalk results verifies the high accuracy and efficiency of the proposed BSO-BP algorithm combined with the FDTD algorithm for strand crosstalk prediction. In general, the crosstalk prediction results of the algorithm in this paper show good agreement with the simulation experimental results in terms of crosstalk variation trend, and also show good accuracy in terms of numerical magnitude.

4.3 Statistical properties of stranded wires crosstalk

To characterize the crosstalk variation caused by random non-uniform twisting of stranded wires, this paper extracts the distribution parameter matrix of 500 groups of non-uniform stranded wire models at each segment location by BSO-BP neural network algorithm and calculates the transmission line crosstalk, and the results are shown in Figure 7. The solid blue line indicates the upper and lower envelope values of crosstalk, which is the crosstalk amplitude boundary, and the non-uniform stranded crosstalk waveforms of different models should be included in the upper and lower envelope values.

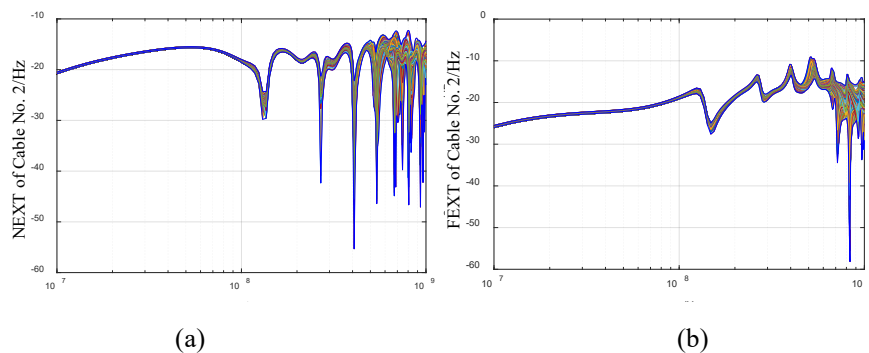


Figure 7: Random non-uniform strand crosstalk.

Table 4: Average width of envelope value (dB).

Crosstalk	10-100MHz	0.1-0.5GHz	0.5-1GHz	Maximum value
NEXT	0.52	3.28	13.22	34.32
FEXT	0.30	1.95	9.66	43.24

From Table 4, it can be concluded that the maximum upper and lower envelope width of the near-end crosstalk is 34.32 dB, and the maximum upper and lower envelope width of the far-end crosstalk is 43.24 dB, and the maximum width corresponds to the frequency in the high frequency range. At the same time, the mean crosstalk value in the higher frequency band shows a greater difference. This shows that the stranded wires crosstalk is more susceptible to the effect of non-uniform twisting of the stranded wires under the action of high frequency signals.

5. Conclusion

Aiming at the crosstalk error problem caused by stranded non-uniform pitch, this paper adopts the probability distribution model of stranded non-uniform pitch established by Monte Carlo method to realize the distribution of actual stranded pitch in engineering to a certain extent. The crosstalk prediction is completed by using BSO-BP neural network algorithm and FDTD algorithm, and the effectiveness and applicability of the algorithm are verified by simulation experiments. In this paper, a complete set of transmission line modeling and crosstalk prediction model is established, and the statistical characteristics of stranded wire crosstalk are effectively analyzed. In engineering applications, the results of NEXT and FEXT prediction can directly provide theoretical references for line layout and selection.

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