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Analysis on RLCG Parameter Matrix Extraction for Multi-Core Twisted Cable Based on Back Propagation Neural Network Algorithm

CHENGPAN YANG[1], WEI YAN[1], (Member, IEEE), YANG ZHAO[1], YANG CHEN[2], CHONGMING ZHU[3], AND ZHIBO ZHU[1]

[1]Nanjing Normal University, Nanjing 210097, China
[2]Nanjing Research Institute on Simulation Technique, Nanjing 210000, China
[3]State Grid Electric Power Research Institute, Nanjing 210003, China

Corresponding author: Wei Yan (61197@njnu.edu.cn)

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ABSTRACT A new method based on back propagation (BP) neural network for extracting RLCG parameter matrix of multi-core twisted cable is presented. With the properly selected parameter matrix sample, the variation characteristics of the parameter matrix of the multi-core twisted cable can be learned by the Levenberg-Marquardt (L-M) algorithm based on BP neural network. The proposed method is combined with the finite-difference time-domain (FDTD) method to calculate the near end crosstalk (NEXT) and the far end crosstalk (FEXT) of the multi-core twisted cable. To verify the new method, a three-core twisted cable is measured and analyzed in the frequency band of 100 kHz - 1 GHz. The results show that the verification error of the extraction network of the RLCG parameter matrix has good accuracy, which does not exceed 0.8%. Compared with the full wave method, the maximum deviations of FEXT and NEXT solved by the proposed methods are −2.71 dB and 10.56 dB, respectively, which are better than 29.32 dB and 32.45 dB solved by the conventional method.

INDEX TERMS Multi-core twisted cable, crosstalk, finite-difference time-domain (FDTD) method, neural network.

I. INTRODUCTION

Multi-core twisted cable has the advantages on high toughness, good noise immunity and high strength. It is widely used in special environments such as robots, servo systems and drag chain systems. Twisted-wire pair (TWP) is the most widely used stranded wire because of its strong anti-interference ability to conducted noise [1]. The electromagnetic interference of the field coupling to the TWP has been explored in a large amount of literature [2]–[4]. Crosstalk of TWP has been studied by scholars as early as 1960s [5]. However, the research on the internal crosstalk of the multi-core twisted cable is relatively less.

The research method of the non-uniform multi-conductor transmission line (MTL) can be used as a reference for crosstalk research of multi-core twisted cable [6], [7]. According to the cascaded transmission line theory (TLT) proposed by pual and McKnight [8], the non-uniform MTL can be replaced by a cascaded uniform transmission line segments, where the physical characteristics of each segment can be described by the per unit length (p.u.l.) RLCG parameter matrix [9]–[11]. The non-uniform MTL was analyzed by the finite-difference time-domain (FDTD) method using TLT [12]. The result of crosstalk can be solved by the FDTD method if the p.u.l. RLCG parameter matrix of the MTL can be obtained [13].

The extraction of the RLCG parameter matrix is an important step in solving the crosstalk problem of the non-uniform transmission line [14]. The statistical model of the RLCG parameter matrix is also a research hotspot for the field of crosstalk in harness layout [15], [16]. Shishuang Sun used the mathematical method of convolution and probability to process the RLCG parameter matrix of the hand-assembled cable bundle and made a range of predictions on the crosstalk [17].

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Multi-core twisted cable is non-uniform MTL that is different from the random hand-assembled cable bundle. The spatial variation of the multi-core twisted cable is periodic and satisfies a specific functional relationship.

The RLCG parameter matrix is sensitive to the spatial position of the wires and the return plane. The parameter matrix of the transmission line changes with the multi-core twisted cable along the axial direction because the position of the wire is constantly changing. In order to mathematically describe the effect of this continuous change on the RLCG parameter matrix of the cable, a method with strong nonlinear mapping ability, the back propagation (BP) neural network, is introduced in this paper [18], [19]. The neural network is used to obtain the p.u.l. RLCG parameter matrix at any position on the twisted cable. The obtained network for extracting the RLCG parameter matrix can be combined with the FDTD method to predict the near end crosstalk (NEXT) and far end crosstalk (FEXT) of the cable.

The structure of this paper is as follows. A model of multi-core twisted cable is established in Section II. In Section III, the extraction method of the RLCG parameter matrix for the cable is introduced. Section IV uses the three-core twisted cable model to verify the effect of the new method for extracting the RLCG parameter matrix, which then combines FDTD method to analyze the crosstalk. The conclusions are given in Section V.

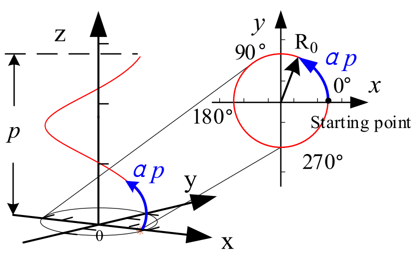

FIGURE 1. Counter-clockwise helix model.

II. MULTI-CORE TWISTED CABLE MODELING

The multi-core twisted cable studied in this paper is a transmission line model with constant cross section shape at any position. Affected by actual production and application environments, the multi-core twisted cable model here is limited to a reasonable number of cores, such as two cores, three cores, and four cores. Helix-based TWP modeling is used as a reference for multi-core twisted cable modeling [20]. The single helix model is shown in Fig. 1, and its function is

$$\begin{cases} x = R_0 \sin(\alpha l) \\ y = R_0 \cos(\alpha l) \\ z = \alpha pl/2\pi \end{cases} \tag{1}$$

$$\alpha = \sqrt{(R_0)^2 + (p/2\pi)^2} \tag{2}$$

where R_0 is the radius of rotation of the helix, l is the arc length of the line, α is the twist factor, p is the pitch, and αp is the angle of rotation of the helix. The initial phase difference of each adjacent helix at the end cross section is $2\pi/n$ for the n-core twisted cable (the actual number of helixes). For example, the starting points of the three-core twisted cable are shown in Fig. 2, and its vector coordinates are

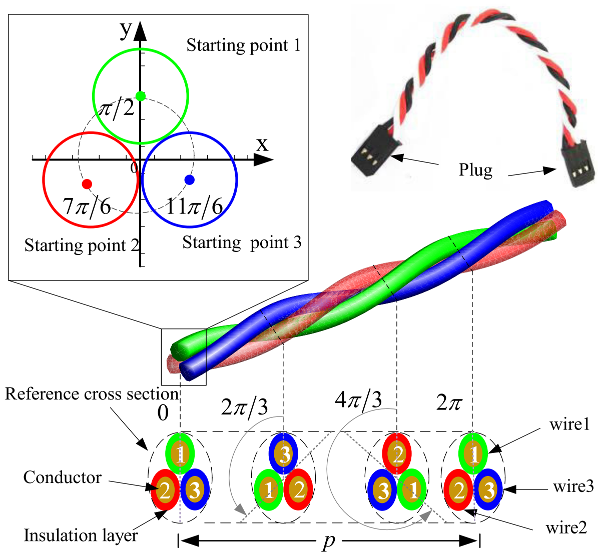

FIGURE 2. The three-core twisted cable (without jackets).

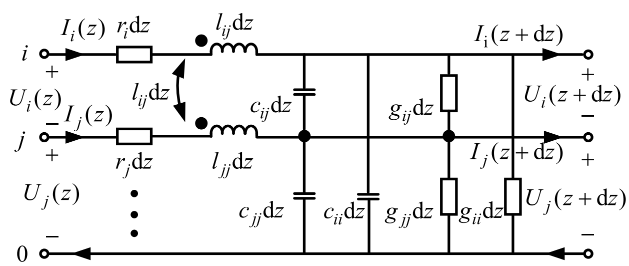

FIGURE 3. The p.u.l. equivalent circuit for MTL.

$$\begin{cases} \vec{r}_1 = (R_0 \sin(\alpha l + \pi/2), R_0 \cos(\alpha l + \pi/2), \alpha pl/2\pi) \\ \vec{r}_2 = (R_0 \sin(\alpha l + 7\pi/6), R_0 \cos(\alpha l + 7\pi/6), \alpha pl/2\pi) \\ \vec{r}_3 = (R_0 \sin(\alpha l + 11\pi/6), R_0 \cos(\alpha l + 11\pi/6), \alpha pl/2\pi) \end{cases} \tag{3}$$

The transposition of the multi-core twisted cable is defined as the position where the geometric shape of the cross section relative to the ground is consistent with the geometric shape of the starting port. And the position of the kp/n point on the cable corresponding to the degree of radial rotation is $2k\pi/n$ (where $k = 1, 2 \ldots n$). Taking the three-core twisted cable as an example, the rotation degree of the transposition is $2\pi/3$, $4\pi/3$ and 2π, as shown in Fig. 2.

III. RLCG PARAMETER MATRIX EXTRACTION

A. RLCG PARAMETER MATRIX

The p.u.l. MTL model is shown in Fig. 3, where dz is expressed as an infinitely short transmission line. The p.u.l. resistances of the circuit are represented by the entries

r_i and r_j. The p.u.l. self-inductances and mutual inductances of the circuit are denoted by the entries l_{ii} and l_{ij}. The p.u.l. self-capacitances and mutual capacitances of the circuit are expressed by the entries c_{ii} and c_{ij}. The p.u.l. conductances of the circuit are described by the entries g_{ii} and g_{ij}.

The parameter matrix of the n wires on the infinite conductive metal plane is expressed as

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix} \tag{4}$$

where X represents the R, L, C, and G parameter matrices, and x represents the values of resistance, inductance, capacitance, and conductance. The above matrix constitutes the RLCG parameter matrix of the transmission line. The RLCG parameter matrix of the transmission line is a symmetric matrix [21], $x_{ij} = x_{ji}$. The conductor spacing, ground height, wire radius and its material, insulation thickness and its material are characterized by the RLCG parameter matrix.

The transmission line equation is [21]

$$\begin{cases} \dfrac{\partial}{\partial z}V(z,t) = -R(z)I(z,t) - L(z)\dfrac{\partial}{\partial t}I(z,t) \\ \dfrac{\partial}{\partial z}I(z,t) = -G(z)V(z,t) - C(z)\dfrac{\partial}{\partial t}V(z,t) \end{cases} \tag{5}$$

where $V(z,t)$ and $I(z,t)$ are the voltage and current of the MTL with respect to the spatial position and time, respectively. R(z), L(z), C(z) and G(z) are variables about the spatial position z. Apparently, the crosstalk voltage value of the MTL can be easily solved when the RLCG parameter matrix is obtained.

B. RLCG MATRIX EXTRACTION FOR MULTI-CORE TWISTED CABLE

The external insulation and shielding of the cable are complicated, and the finite element method (FEM), not the only way, can accurately extract the p.u.l. RLCG parameter matrix of the uniform and parallel transmission line. However, the p.u.l. RLCG parameter matrix at any position of the non-parallel MTL cannot be directly and quickly extracted by the conventional method, such as the Ansys Q3D software based on the FEM algorithm.

The extraction of the RLCG parameter matrix of the multi-core twisted cable proposed in this paper can be divided into six steps, and the corresponding flowchart is shown in Fig. 4.

Step 1: The extraction of the RLCG parameter matrix at different rotation degrees based on the FEM algorithm.

From the perspective of axial extension, a multi-core twisted cable can be regarded as an MTL cascaded by infinite conductors with infinite thickness. The cross section at any position has angular variation in the counterclockwise direction with respect to the reference cross section. Taking a three-core twisted cable as an example, the schematic diagram of the cross section rotation of the cable is shown

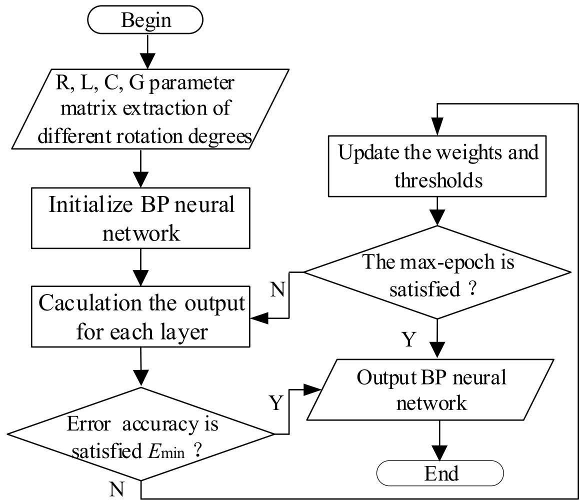

FIGURE 4. Flow chart of the RLCG parameter matrix extraction of the multi-core twisted cable based on BP algorithm.

in Fig. 2. The rotation angle of the cross section at the $p/4$ position relative to the reference cross section is $\pi/2$.

The RLCG parameter matrix of the multi-core twisted cable in (4) is a symmetric matrix, so the actual objects to be studied are upper or lower triangular matrix elements and main diagonal elements. This paper takes the main diagonal element and the lower triangle element as the research object, as shown in (6) and (7).

$$R' = [r_{11}, r_{21}, r_{22}, \ldots, r_{nn}] \quad L' = [l_{11}, l_{21}, l_{22}, \ldots, l_{nn}] \tag{6}$$

$$C' = [c_{11}, c_{21}, c_{22}, \ldots, c_{nn}] \quad G' = [g_{11}, g_{21}, g_{22}, \ldots, g_{nn}] \tag{7}$$

R', L', C' and G' are written in column vector form y:

$$y = \left[R', L', C', G'\right]^T = [y_1, y_2, \ldots, y_m]^T \tag{8}$$

where y stands for the real value of the RLCG parameter matrix samples, in which the total number of elements in y is $m = 2n(1+n)$.

Step 2: Initialize BP neural network.

The initial weights and thresholds are defined as the random values generated in the interval $(-2.4/F, 2.4/F)$, where F is the number of weights connected by the input layer.

Step 3: Calculation the output for each layer.

For the RLCG parameter matrix of multi-core twisted cable, the variable is the rotation degree (x) of cross section at any position, and the dependent variable is the p.u.l. RLCG parameter matrix (y). This is a small and middle neural network with only one hidden layer determined by the number of inputs and outputs.

The neural network topology of the multi-core twisted cable is shown in Fig. 5, where the weight of the input layer to the t-th hidden layer is represented by $w_{1,t}$, and the weight of the t-th hidden layer to the m-th output layer is represented by $w_{t,m}$. The number of hidden layer neurons t is the empirical range value affected by the number of RLCG

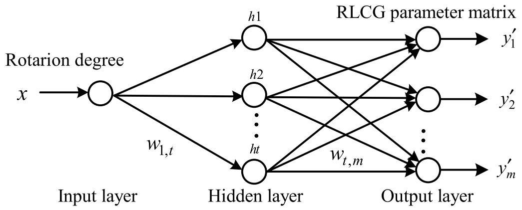

FIGURE 5. **Topological structure of the multi-core twisted cable neural network.**

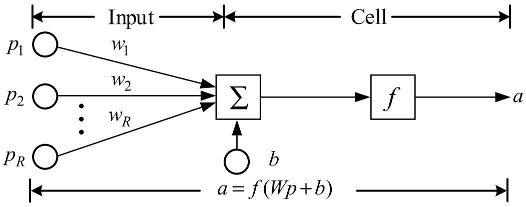

FIGURE 6. **Diagram of BP neuron model.**

parameter matrix elements m. And t can be estimated by the following formula.

$$t = \sqrt{m+1} + n_c \tag{9}$$

where n_c is a constant in the interval [0, 10]. For a single neuron of any hidden layer and output layer, the input and output network structure of the forward propagating signal is shown in Fig. 6.

The hidden layer uses the Sigmoid function as a transfer function, which can better exert the nonlinear mapping ability of the neural network to the angle and parameter matrix. The input of hidden layer is the rotation angle x. The i-th neuron output of the hidden layer is

$$h_i = \frac{1}{e^{-(w_{1,i}x+b_{1i})}+1} \tag{10}$$

The output layer uses the linear function as a transfer function to get a wider range of output results. The value of the i-th element of the RLCG parameter matrix output by the forward propagating signal through the BP neural network is

$$y'_i = \sum_{j=1}^{t} w_{j,i} h_j + b_{2i} \tag{11}$$

The RLCG parameter matrix element values of the forward propagated signal output through the BP neural network are expressed in the form of a column vector matrix as:

$$y' = \left[y'_1, y'_2, \ldots, y'_m\right]^T \tag{12}$$

Step 4: BP neural network error precision analysis.

The training sample data group is n_s. In the training stage, the error index function corresponding to the output y' is:

$$E = \frac{1}{2n_s}\sum_{i=1}^{n_S}\sum_{j=1}^{m}\left(y_{ij} - y'_{ij}\right)^2 \tag{13}$$

where y'_{ij} stands for the value of the j-th neuron output after the i-th training sample passes through the BP neural network. y_{ij} represents the corresponding real value. $E_{\min}$ is the target of training error accuracy. If the error E is greater than the error precision $E_{\min}$ and the iteration number is less than the max-epoch, the weights and thresholds should be updated and adjusted to go to **Step 5**. Otherwise, the neural network stops training to go to **Step 6**. This process reflects the meaning of error back propagation of the BP neural network.

Step 5: Update and adjust **t**he weights and thresholds.

The weights and thresholds update are adjusted by the Levenberg-Marquardt (L-M) algorithm with fast convergence and low storage. The adjustment formula is shown in (14), (15).

$$w_{k+1} = w_k + \Delta w_k \tag{14}$$

$$\Delta w_k = -\left[J^T(w_k)J(w_k) + \mu I\right]^{-1} J^T(w_k)\cdot e \tag{15}$$

where J is the Jacobian matrix of the error e with respect to the weights w. μ is a scalar factor and I is an identity matrix. The error e is the mean square error of each layer corresponding to each training sample.

$$e = \frac{1}{2}\sum_{k=1}^{m}\left(y_k - y'_k\right)^2 \tag{16}$$

Step 6: Output BP neural network.

Output the actual number of iterations and the weights and thresholds of each layer.

IV. VERIFICATION & ANALYSIS

A. RLCG MATRIX EXTRACTION VERTIFICATION

In this paper, the performance of the new method is illustrated by the three-core twisted cable shown in Fig. 2. The single wire of the cable adopts copper wire with PVC insulation layer, and different core wires are spirally wound counter-clockwise. The height of the cable is 4 *mm* off the ground (close to the reference ground). The specific parameters of the cable are as shown in Tab. 1.

TABLE 1. **Three-core twisted cable.**

parameters	values
pitch	40 *mm*
height	4 *mm*
number of cores	3
conductor radius	0.89 *mm*
conductor conductivity	58000000 *S/m*
conductor insulation thickness	0.8 *mm*
insulation layer relative permittivity	2.7

The cable has axial symmetry, and the RLCG parameter matrix in different transpositions can be transformed into each other through row-column transformation. The training samples only need to process the RLCG parameter matrix of the cable within the 1/3 pitch to obtain the RLCG parameter matrix of the entire pitch. In the 1/3 pitch, from starting at 0° to ending at 115°, the RLCG parameter matrix samples are collected for the cable at intervals of 5°.

In practical applications, the value of R and G are much smaller than the external resistance of the cable (usually dozens Ω), and the effects of R and G on crosstalk can be ignored. Therefore, the BP neural network only needs to train the L and C parameter matrices of cable. The parameter matrix of the cable is a 3×3 order matrix, and the number of neurons in the output layer is 12. The input layer is the degree of rotation x of the cable cross section, and the number of the neuron is 1. In this paper, the training error accuracy of the neural network is set to $E_{\min} = 10^{-5}$. The BP neural network generation process of Fig. 4 was used to train the multi-core twisted cable. After the process, the number of hidden layer neurons in the BP neural network is 10, which can meet the training error accuracy requirements. The training time is about 4s, and the number of iterations is 14.

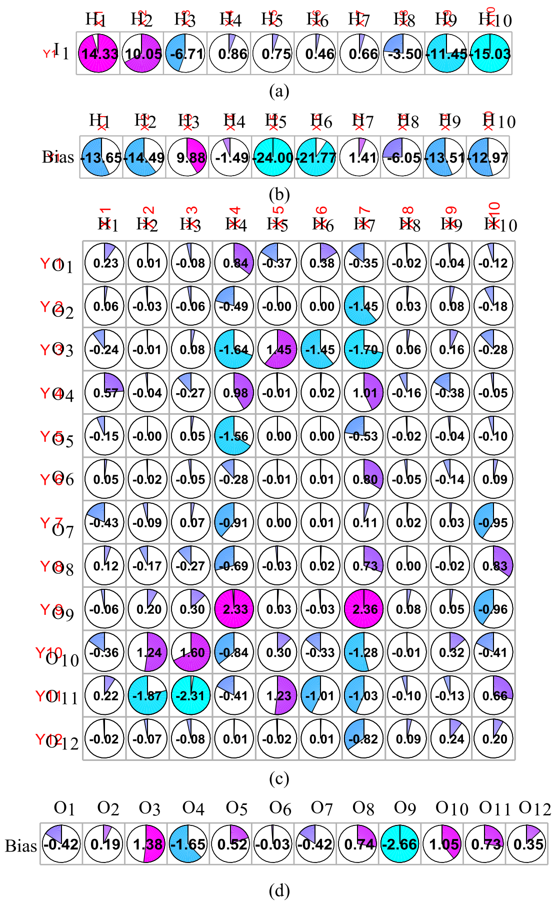

FIGURE 7. **The BP neural network of the three-core twisted cable: (1) weights of the input layer to the hidden layer, (2) thresholds of hidden layer, (3) weights of the hidden layer to the output layer, (4) thresholds of the output layer.**

The weights of the input layer to the hidden layer of the BP neural network of the cable are shown in Fig. 7 (a), the thresholds of the hidden layer are shown in Fig. 7 (b), the weights of the hidden layer to the output layer are shown in Fig. 7 (c), and the output layer thresholds color block diagram are shown in Fig. 7 (d). The i-th neuron of the output layer is represented by O_i. The i-th neuron in the hidden layer is expressed by H_i. The input layer neuron is denoted by I_1.

Some degrees of rotation are randomly selected to verify the prediction accuracy E_{test} of the RLCG parameter matrix of the BP neural network. Combining (8) and (12), the calculation method is:

$$E_{\text{test}} = \left(y' - y\right)/y \times 100\% \tag{17}$$

The specific results of the test are shown in Fig. 8, which includes 28°, 120°, 174°, 232°, 281°, and 345°. The maximum error of the test results has good accuracy, which does not exceed 0.8%.

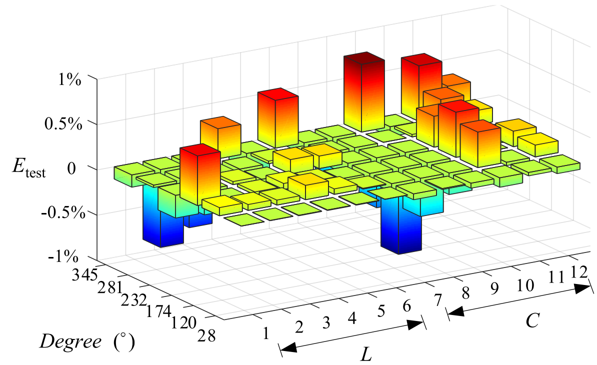

FIGURE 8. **Error histogram of the test sample.**

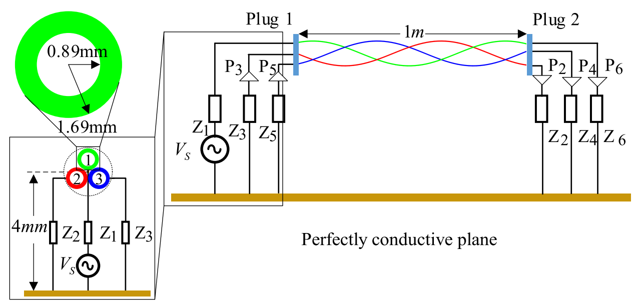

FIGURE 9. **Schematic diagram of crosstalk experiment of the three-core twisted cable.**

B. CROSSTALK ANALYSIS

The schematic diagram of the crosstalk experiment of the three-core twisted cable is shown in Fig. 9. The two ends of each wire are connected to a 50 Ω resistance ($Z_i = 50\ \Omega$, where $i = 1, 2, 3, 4, 5, 6$). The total length of the cable is 1 m, and the excitation conductor is wire 1.

The expressions of NEXT and FEXT are

$$\begin{cases} \text{NEXT} = -20\lg(V_i/V_s) & (i = 3, 5) \\ \text{FEXT} = -20\lg(V_i/V_s) & (i = 2, 4, 6) \end{cases} \tag{18}$$

where V_i stands for the voltage of the probe P_i and V_s represents the excitation voltage of the wire 1, as shown in Fig. 9.

In this paper, the crosstalk calculated by the three methods is compared and analyzed, including the conventional algorithm, the full wave algorithm, and the FDTD method based on the proposed RLCG parameter matrix extraction method. It is worth noting that the spatial segment of the FDTD method is 1000. The conventional algorithm is an FDTD method based on the geometric mean of training samples

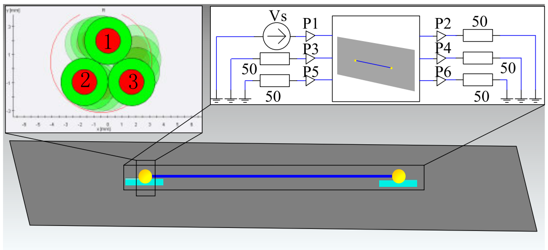

FIGURE 10. CST simulation model of the three-core twisted cable and its schematic diagram.

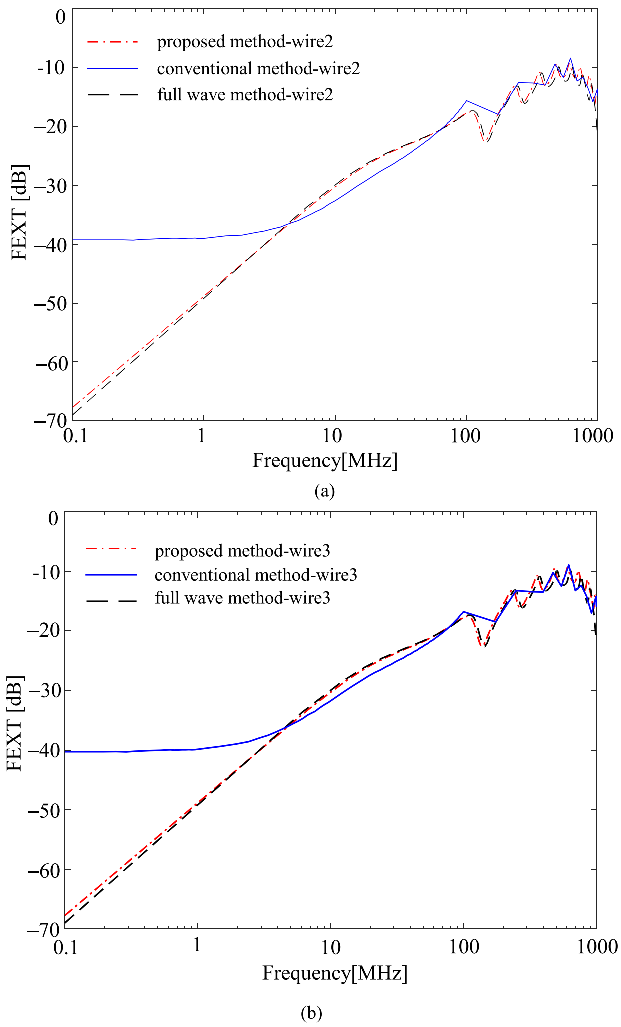

FIGURE 11. Far end crosstalk of multi-core twisted cable: (a) wire 2, (b) wire 3.

of the 24 RLCG parameter matrix extracted in the previous section [21]. The full wave algorithm is an exact solution [22]. The full wave simulation of the CST Cable Studio® commercial software - the transmission line matrix (TLM) method, an electromagnetic field numerical method based on the Huygens wave propagation model, is used to solve the crosstalk results as a reference standard in this paper.

According to the parameters in Fig. 7 and Tab. 1, the three-core twisted cable crosstalk is solved by three methods in the

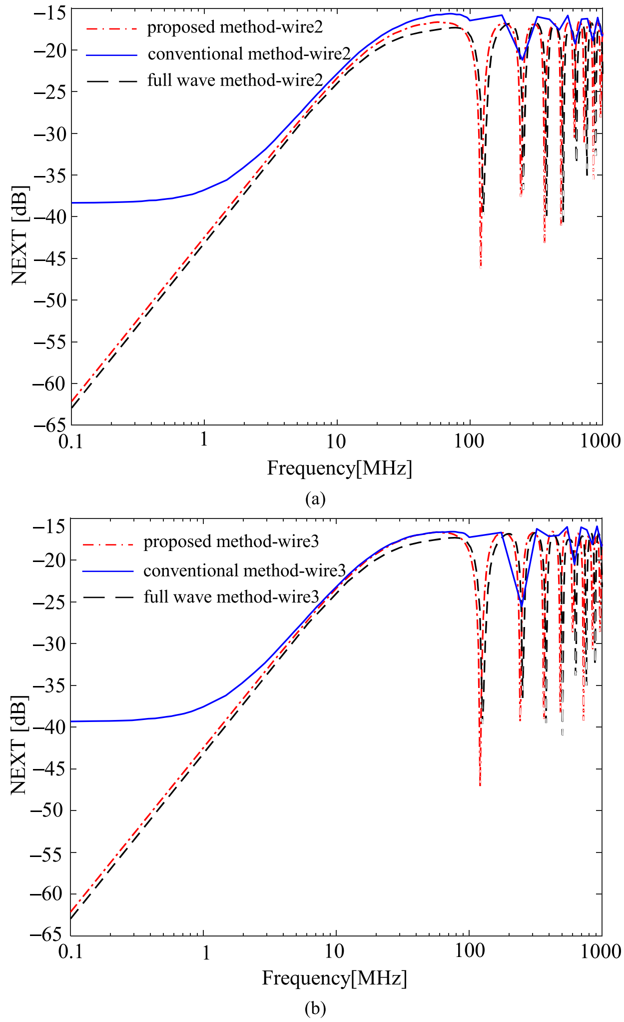

FIGURE 12. Near end crosstalk of multi-core twisted cable: (a) wire 2, (b) wire 3.

frequency band 100 kHz – 1 GHz. The p.u.l R, L, C, and G parameter matrices of MTL are also related to frequency. However, the small variation of the parameter matrix caused by the frequency can be ignored when comparing with different method solving strategies [21]. The RLCG parameters of the proposed method and the conventional method both use the values extracted at 500 MHz. The full wave simulation model and schematic of CST are shown in Fig. 10.

Fig. 11 and Fig. 12 show the FEXT and NEXT of multi-core twisted cable solved by the proposed method, the conventional method, and the full wave method. The cable has axial symmetry, and NEXT or FEXT on the wire 2 and wire 3 have similar characteristics. In each frequency band, the maximum FEXT and NEXT deviations of the proposed method and the conventional method relative to the full wave method are shown in Tab. 2. Compared with full wave method, the maximum deviation of the FEXT of wire 2 and wire 3 (Fig. 11a and Fig. 11b, respectively) solved by the proposed method is 1.98 dB, and the maximum deviation of the NEXT of wire 2 and wire3 (Fig. 12a and Fig. 12b,

TABLE 2. Maximum deviation of FEXT and NEXT.

frequency	conventional method		proposed method	
(MHz)	FEXT(dB)	NEXT(dB)	FEXT(dB)	NEXT(dB)
LF ~ HF (0.1~30)	29.32	-24.62	1.32	0.85
VHF (30~300)	5.81	23.49	-2.71	-6.42
UHF (300~1000)	4.62	32.45	1.98	10.56

respectively) solved by the proposed method is 10.56 dB. The accuracy of the proposed method is higher than that of the conventional method in solving FEXT and NEXT, especially in the LF $\sim$ HF band. The deviation values calculated by the conventional methods are 29.32 dB and -24.62 dB, respectively. And the deviation values calculated by the proposed method are 1.32 dB and 0.849 dB, respectively.

V. CONCLUSION

In this paper, an extraction method based on the BP algorithm for the p.u.l. RLCG parameter matrix of multi-core twisted cable is proposed. We first establish a model of the multi-core twisted cable and analyzed its spatial characteristics from axial direction and radial direction. Then, we use Ansys Q3D software based on the FEM algorithm to sample the RLCG parameter matrix of the cable at different positions and use the L-M learning algorithm based on the BP neural network to learn the samples. Finally, the extracted network and FDTD method are combined to solve the crosstalk of the cable. Compared with the conventional method, the proposed method not only exhibits good solving performance in the crosstalk of multi-core twisted cable but also provides a p.u.l. RLCG parameter with a smaller error at any position. In the case of three-core twisted cable, the BP neural network has a high precision for its parameter matrix extraction, which does not exceed 0.8%. The new method has excellent predictive effects on NEXT and FEXT in the frequency band of 100 kHz and 1 GHz, especially in the LF$\sim$HF band.

In fact, the extraction method is not confined to the multi-core twisted cable model. Any spatial wiring model that satisfies or approximates a certain mathematical relationship can obtain a good RLCG parameter matrix by this method.

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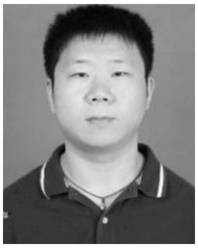
CHENGPAN YANG was born in Sichaun, China. He received the B.S degree in automation and information engineering from the Sichuan University of Science and Engineering, Zigong, China, in 2017. He is currently pursuing the master's degree in electrical engineering with Nanjing Normal University, Nanjing, China. His research interest includes new technology of electrical engineering.



WEI YAN received the Ph.D. degree in physics and electronics and the M.S. degree in electrical engineering from Nanjing Normal University, in 2014 and 2011, respectively, where he is currently a Doctor and an Associate Professor. He is the Senior Member of the China Electrical Technology Association and the evaluation expert of the Electromagnetic Compatibility Calibration Specification of China.

YANG ZHAO received the B.E., M.E., and Ph.D. degrees in power electronic technology from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 1989, 1992, and 1995, respectively. He is currently a Professor with Nanjing Normal University. His research interests include electromagnetic compatibility, power electronics, and automotive electronics.

YANG CHEN received the M.S. degree from Nanjing Normal University, Nanjing, China. He is currently with the Nanjing Research Institute on Simulation Technique. His research interest includes electromagnetic compatibility.

CHONGMING ZHU received the M.S. degree from Southeast University, Nanjing, China. He is currently pursuing the Ph.D. degree with the Chinese Academy of Sciences. He is also with the Electromagnetic Compatibility Laboratory, State Grid Electric Power Research Institute. His research interest includes electromagnetic compatibility.

ZHIBO ZHU was born in Jiangsu, China. He received the B.S degree from the Automation College, Nanjing University of Information Science and Technology, in 2017. He is currently pursuing the master's degree in electrical engineering with Nanjing Normal University. His research interest includes new technology of electrical theory.