Rare Metal Materials and Engineering
Volume 47, Issue 10, October 2018
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2018, 47(10): 2970-2975.

ARTICLE

Calculation Model of Coupling Loss Time Constant for Nb_3Sn Conductor Under Cyclic Electromagnetic Load

Jiang Huawei[1], **Wu Songtao**[2]

[1] *Henan University of Technology, Zhengzhou 450001, China;* [2] *Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China*

Abstract: On international thermal nuclear experimental reactor (ITER) superconducting fusion device, Nb_3Sn composite strands have been applied to CICC (cable-in-conduit conductor) to undergo the impact of the magnet field above 12 T. The strain of Nb_3Sn-based conductor due to Lorentz forces leads to changes in critical current and coupling loss time constant. Therefore the study on the critical performance degradation of CICC is still inadequate, and the influence of the contact properties with strain on the coupling loss time constant is also insufficient. In order to calculate the coupling loss accurately and quickly, a new calculation model of coupling loss time constant was put forward in this paper. The model is expressed by a linear equation using some parameters such as the cabling sequence ratio, contact resistance and void fraction with strain main from electromagnetic force. In this model, the computation expression of cabling sequence ratio, as well as the contact resistance and the void fraction are obtained under the strain from cyclic electromagnetic load. Compared with numerical calculation using Gandalf and the traditional method, coupling loss calculated by the new model has a small error, and it is close to the engineering measurement.

Key words: coupling loss time constant; cable-in-conduit conductor; cabling sequence ratio; contact resistance; void fraction

With the advantages of supercritical helium cooling, high voltage insulation and multistage cabling[1,2], CICC has been selected as the preferred conductor for magnet system of ITER and CFETR (China fusion engineering testing reactor) that will be built domestically in the next step. CICC in EAST (experimental advanced superconducting tokamak) is NbTi superconducting strands and pure copper strands[3]. However, CICC on ITER will run in the transient magnet field caused by a larger excitation current and suffer the impact of a magnet field above 12 T. In order to overcome the limitation of critical performance, ITER-CS (central solenoid) magnets adopted the Nb_3Sn-based conductor[4]. However, the superconducting property of Nb_3Sn wires is quite sensitive to strain. The strain mainly comes from electromagnetic force, thermal stress as well as deformation in the fabrication process. The above strains will bring a very adverse effect on the application of the Nb_3Sn-base conductor. The change of coupling loss with strain effect in the complex magnet field will particularly affect the steady operation of CICC.

Currently, on the basis of the calculation method of NbTi conductor[5-7], the research on the coupling loss calculation of Nb_3Sn-based CICC has been carried out. For example, Bottura et al [8] put forward a calculation model of coupling loss for CICC in ITER, in which the loss was divided into 3 dimension vectors and introduced a space magnetization shape factor. Egorov[9] gave the coupling loss calculation method of a multistage cabling conductor, in which the induced current in the time-varying magnet field can be simplified as the calculation of coupling current between strands (sub-cables) at every stage. In addition, Lanen et al[10] proposed the parallel algorithm of coupling loss for full size CICC of ITER, which can improve the calculation efficiency of coupling loss by reducing the mutual inductance complexity from $O(N^2)$ to O(N).

In addition, an optimized design model of conductor using multivariate constraint was set up[11,12], and a relatively reasonable conductor structure was obtained. At the same time,

Received date: October 09, 2017
Foundation item: National Natural Science Foundation of China (51677055); Henan Natural Science Foundation (162300410055)
Corresponding author: Jiang Huawei, Ph. D., Professor, College of Information Science and Engineering, Henan University of Technology, Zhengzhou 450001, P. R. China, Tel: 0086-371-67756840, E-mail: lhwcad@126.com

a coupling loss calculation method was established in Ref. [13]. Although the algorithm can simplify the coupling loss calculation, it is assumed that the coupling loss component is linearly increased. Thence, it can lead to a relatively large error for coupling loss calculation.

According to the existing research on coupling loss, the loss mechanism of Nb_3Sn-based CICC with strain effect was still not well understood. In turn, it is difficult to quickly and accurately calculate the coupling loss of Nb_3Sn-based CICC and get the actual disturbance produced in the conductor. On superconducting fusion devices, the conductor will be subjected to the impact of the quick excitation current, plasma discharge and burst. In order to prevent the quenching of conductor, the conservative method that amplifies the safe factor (higher stability margin and temperature margin, etc.) was accepted, which will greatly increase the conductor cost for engineering design, manufacture and operation. Thus, it is urgent to study the calculation theory of coupling loss for Nb_3Sn-base conductor with strain effect to solve the engineering design problem of CICC.

For Nb_3Sn conductor, the strain effect not only results in the change in contact conditions (contact resistance and void fraction) of the strands (sub-cables), but also leads to the stiffness change associated with the twist pitch length of each stage in CICC[14,15]. Obviously, the influence of strain on the coupling loss is embodied in the twist pitch length, contact resistance and void fraction. In this paper, the relationship between coupling loss time and twist pitch length, contact resistance and void fraction was studied, and the coupling loss model under strain was obtained. First, the model of coupling loss time constant was formed with the twist pitch length, contact resistance and void fraction by the least squares method. Then, the cabling sequence expressed by the twist pitch of every stage in conductor was established. Finally, the mathematical expression of the contact resistance and the void fraction was constructed under strain from cyclic electromagnetic force.

1 Calculation Model

1.1 Mathematical expression of coupling loss time constant

In the time-varying magnet field with rapid excitation, the coupling loss, which is the main part of AC loss, is the energy dissipation. In the extreme case of coil excitation, plasma discharge and collapse, the traditional calculation of coupling loss time constant in the nth stage was discussed in Ref.[16,17].

Without considering strain effect, the calculation model in Ref. [16] and [17] is not appropriate for practical application because it is difficult to accurately meet the requirements of engineering design. In fact, the Nb_3Sn conductor will bear strain effect, which results in the changes in the void fraction, contact status and coupling loss time constant of superconducting cable. These factors make the calculation of coupling loss time constant very complicated. Therefore, a new method for calculating the coupling loss time constant based on the combination model of cabling sequence ratio, contact resistance and void fraction is proposed to avoid the above case.

Via the analysis of a large amount of test data, the formalization expression of coupling loss time constant in the nth stage of CICC can be written as follows[18].

$$\theta_n \propto L_n^2 / R_{Cn} \tag{1a}$$

$$\theta_n \propto 1 / f_n \tag{1b}$$

where, L_n is the twist pitch at the nth stage, R_{Cn} is the contact resistance between strands (sub-cables) at the nth stage, and f_n is the void fraction at the nth stage.

Although in Ref. [18], Nijhuis et al put forward the qualitative description of coupling loss time constant with Eq.(1a) and (1b), they did not give a rigorous mathematical relationship between the coupling loss time constant and $L_n^2/(R_{Cn}f_n)$. It is not convenient to calculate coupling loss time constant. In this paper, a quantitative research on the relationship is carried out, by which a reliable method can be provided to calculate the coupling loss time constant in engineering design.

According to the experiment analysis, it is found that there is an approximately direct proportional relationship between the coupling loss time constant θ_n and $L_n^2/(R_{Cn}f_n)$. For a precise mathematical description, it is assumed that the relationship is linear, as follow

$$\theta_n = k(L_n^2 / (R_{Cn} f_n)) + b \tag{2}$$

In order to acquire the function of Eq. (2), it is crucial to determine the constant terms k and b. In this paper, the least square method is adopted to dispose the problem. Through analyzing the square sum of the least error between the measurement value of coupling loss time constant and the calculation value by Eq. (2), the constant terms k and b can be obtained. Given that the error between the actual measurement result θ_i and the calculation value x_i is E, there is the following expressions (in a specific calculation process, the analysis calculation value x_i is used to replace $L_n^2/(R_{Cn}f_n)$).

$$E = \sum_{i=1}^{N} (\theta_i - kx_i - b)^2 \tag{3}$$

Eq. (4) and (5) can be obtained in the following by the first order differentiation and the second order differentiation of the constant terms k and b in Eq. (3), respectively.

$$\begin{cases} \dfrac{\partial E}{\partial k} = -2(\sum_{i=1}^{N} \theta_i x_i - k\sum_{i=1}^{N} x_i^2 - b\sum_{i=1}^{N} x_i) \\ \dfrac{\partial E}{\partial b} = -2(\sum_{i=1}^{N} \theta_i - k\sum_{i=1}^{N} x_i - Nb) \end{cases} \tag{4}$$

$$\begin{cases} \dfrac{\partial^2 E}{\partial k^2} = 2\sum_{i=1}^{N} x_i^2 \\ \dfrac{\partial^2 E}{\partial b^2} = 2N \end{cases} \tag{5}$$

From the above formula, it can be found that Eq. (5)

including the second derivative of the constant terms k and b is positive, which means that the error in Eq. (3) has a minimal value. So, it can be obtained that Eq. (4) is equal to zero. In order to acquire the values of the constant terms k and b, the following matrix Eq. (6) needs to be solved.

$$\begin{bmatrix} \sum_{i=1}^{N} x_i^2 & \sum_{i=1}^{N} x_i \\ \sum_{i=1}^{N} x_i & N \end{bmatrix} \begin{bmatrix} k \\ b \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} \theta_i x_i \\ \sum_{i=1}^{N} \theta_i \end{bmatrix} \tag{6}$$

In Eq. (6), the values of the constant terms k and b can be obtained with N test values (θ_i), and the coupling loss time constant in Eq. (2) can be achieved.

1.2 Calculation model of the twist pitch (cabling sequence ratio)

Once the constant terms k and b in Eq. (2) are determined, the three important variables in Eq. (2): the twist pitch at every stage, the contact resistance and void fraction are required for further study. The specific model with cabling sequence ratio is given in the following.

To describe the cabling sequence of CICC, the cabling sequence ratio (R) can be defined as the twist pitch at the nth stage divided by the twist pitch at the n-1th stage of the conductor.

$$R = L_n / L_{n-1} \tag{7}$$

The computation analysis of CICC conductor with different cabling sequence ratios shows that the coupling loss time constant is not only connected with the cabling sequence ratio of each stage, but also with the average cabling sequence ratio of CICC conductor. To some degree, the coupling loss time constant should be calculated and interpreted by average cabling sequence ratio (R_{avg}).

$$R_{avg} = \frac{\sum_{i=1}^{N-1} \frac{L_{i+1}}{L_i}}{N-1} \tag{8}$$

Therefore, the twist pitch L_n in Eq. (2) can be given by Eq. (7) or (8).

1.3 Calculation model of the contact resistance and void fraction with strain

In general, the contact resistance is estimated by the test result and its value is not accurate. In this paper, the contact resistance is expressed by strain (from electromagnetic force cycle).

In order to get a more accurate description, the model of strain is introduced in the following.

$$\varepsilon = \varepsilon_{th} + \varepsilon_{op} + \varepsilon_{extra} \tag{9}$$

where, ε_{th} is the thermal strain caused by the different coefficients of thermal expansion in the composite, ε_{op} is running strain from the periodic electromagnetic force ($\boldsymbol{I}\times\boldsymbol{B}$), and ε_{extra} is strain stemmed from deformation in the fabrication process. In the Eq.(9), ε_{th} and ε_{op} are the main strains of conductor. In the operating life of conductor, ε_{th} only exists in the cooling process from the room temperature (293 K) to the operating temperature (4.2/4.5 K). However, in the operating period, the conductor will suffer several thousand periodic electromagnetic forces ($\boldsymbol{I}\times\boldsymbol{B}$), which leads to strain ε_{op}, and it determines the performance of the conductor with large operating current (about 49 kA) and the high magnetic field (about 12 T). Apart from the average thermal strain (axial strain) given in Ref. [19], the strain mainly refers to the electromagnetic force in the paper.

According to Ref. [20], the strain as a function of operating current and magnetic field strength ($\boldsymbol{I}\times\boldsymbol{B}$) in the conductor is plotted in Fig.1.

It can be seen from Fig.1 that strain is approximately linearly dependent on Lorentz force ($\boldsymbol{I}\times\boldsymbol{B}$). In fact, the mathematical model relation between strain and electromagnetic force is expressed by the following Eq. (10) and (11)[15].

$$F = \boldsymbol{I} \times \boldsymbol{B} \times N_S \tag{10}$$

$$\varepsilon = F / A = \boldsymbol{I} \times \boldsymbol{B} \times N_S / d^2 \tag{11}$$

where, $\boldsymbol{I}$ is the operating current in the strand, and N_S is the number of strands. Obviously, $\boldsymbol{I}\times N_S$ is the operating current (I_{op}) in the conductor. B is the magnetic field strength, and the maximum magnetic field strength (B_{max}) will be adopted when calculating the electromagnetic force. d is the diameter of conductor, and d^2 is on behalf of the cross-section area of the conductor. In theory, Eq. (10) and (11) roughly explain the linear relationship between the strain and the electromagnetic force of conductor.

From above description, it can be known that strain is formed by the electromagnetic force and closely related to electromagnetic load cycle. In order to obtain the mathematical model of the contact resistance and the strain, the relationship between the contact resistance and electromagnetic force cycle should be studied. According to a large number of experiment results, the mathematical expression of the contact resistance with strain (simulated by the electromagnetic load cycle) can be summarized as Eq. (12).

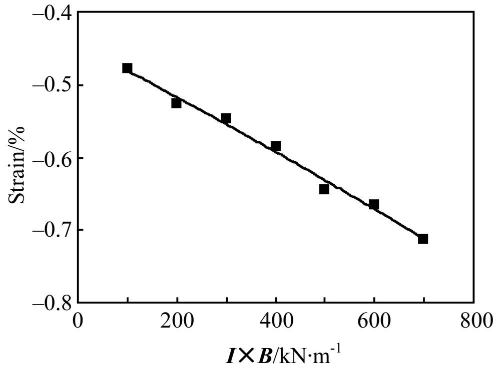

Fig.1 Best fitting curve of the relation between the strain (ε) and the periodic electromagnetic force ($\boldsymbol{I}\times\boldsymbol{B}$)

$$R_{\varepsilon cn} = R_{\varepsilon cn0} + R_{\varepsilon 0}(1 - \exp^{(-\frac{T}{\tau})}) \tag{12}$$

where, $R_{\varepsilon cn0}$ is the initial value of contact resistance without strain, $R_{\varepsilon 0}$ is the deviation of contact resistance, T is the number of electromagnetic force cycle which the conductor will subjected to and τ is the number of cycle, in which the contact resistance is attenuated to 0.632 $R_{\varepsilon cn0}$. $R_{\varepsilon cn0}$ and $R_{\varepsilon 0}$ can be obtained by the interpolation method based on test data of the contact resistance between strands (sub-petals or inter-petals) in different conductor samples[21,22].

Similarly, the mathematical model of void fraction with strain can be obtained based on the experiment data.

$$f_{\varepsilon n} = f_{\varepsilon n0} + f_0 \exp^{(-\frac{T}{\tau})} \tag{13}$$

where, $f_{\varepsilon cn0}$ is the initial value of void fraction without strain, f_0 is deviation of void fraction, τ is the number to cycles, in which the void fraction is attenuated to 0.632 $f_{\varepsilon cn0}$. $f_{\varepsilon cn0}$ and f_0 can also be gotten by the interpolation method according to experiment data of different conductors.

Based on the above model, the contact resistance and void fraction in Eq. (2) can be given by Eq. (12) and (13), respectively.

2 Results and Discussion

2.1 Analysis of the contact resistance and void fraction

In order to analyze the effect of strain on the contact resistance and void fraction, different electromagnetic load cycles (1~4000 cycle which conductors will suffer in their operating life) are applied to simulate the corresponding strain effect. According to operating current and the maximum magnetic field strength, the electromagnetic load of about 600 kN/m is adopted to calculate the contact resistance and the void fraction of conductor.

For the computation of the contact resistance and the void fraction, the CICC pattern of CSMC (central solenoid model coil) on CFETR is shown in Table 1. The conductor will exist in a severe environment with a maximum magnet field of about 12 T (B_{max}) and a maximum operating current of about 49 kA (I_{op}), and the Lorentz force is about 600 kN/m. The contact resistance between strands (sub-petals or inter-petals) can be calculated by Eq. (12). The result of contact resistance versus cycle is shown in Fig.2, in which the test value is from Ref. [23].

Table 1 CICC pattern of CSMC on CFETR

Conductor structure		(2SC+1Cu)×3×4×4×6
Strand diameter/mm		0.83
Number of superconducting strand		576
Number of copper strand		288
Operating current, I_{op}/kA		49
Maximum magnet field strength, B_{max}/T		12
Twist pitch	L_1/mm	25
	L_2/mm	49
	L_3/mm	89
	L_4/mm	160
	L_5/mm	462
Void fraction/%		32.5

Fig.2 indicates that the contact resistance increases with the load cycle. The change of contact resistance between strands (inter-petals) is small, and the change in contact resistance between sub-petals (2nd, 3rd, 4th stage) is big. The difference of contact resistance may be related to strand contact conditions (indentation), sub-cable deformation and filament fracture under the corresponding strain (by different electromagnetic load cycle).

It can also be found from Fig.2 that the contact resistance calculated by the method in this paper is close to the test value. In some degree, the model can be used for engineering calculations.

At the same time, the value of void fraction computed using Eq. (13) is shown in Fig.3, which reveals that the void fraction decreases slightly with the load cycle. Although the trend between the calculation value and test value is slightly different, the error between them is acceptable.

2.2 Analysis of coupling loss time constant

Coupling loss time constant as a function of electromagnetic

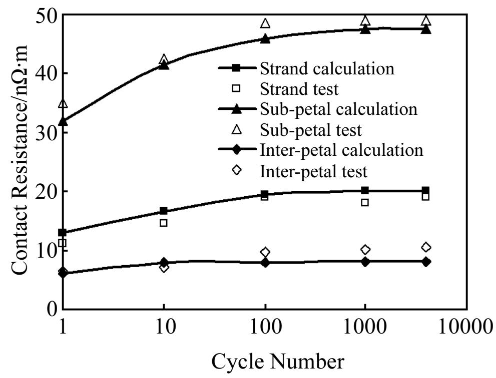

Fig.2 Contact resistance of strands (sub-petals or inter-petals) as a function of electromagnetic load cycle

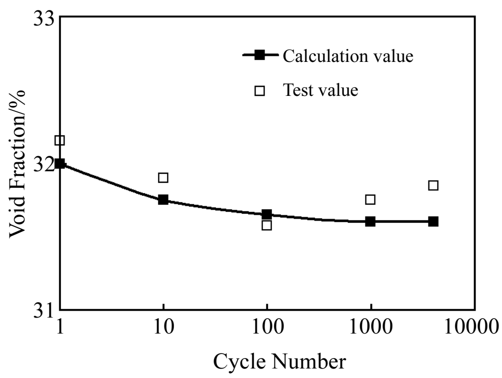

Fig.3 Void fraction as a function of load cycle calculated by Eq.(13) and test value

load cycle, which is calculated by Eq. (2), is shown in Fig.4.

According to the values of calculation and test in Fig.4, coupling loss time constant calculated by the method in this paper decreases by 7 ms in the range between 1 to 4000 electromagnetic load cycles, which is in good agreement with the test value. However, Gandalf and traditional methods[16,17] in Fig.4 hardly take into account the strain effect from electromagnetic load cycle, and they only give the coupling loss time constant of the no-load cycle, which is shown as the initial value in Fig.4.

In order to calculate the coupling loss of CICC shown in Table 1, the change rate of external magnetic field is set to 0.8 T/s based on the practical engineering operation requirements of CS in CFETR. The coupling loss of calculation and test result are shown in Fig.5.

From Fig.5, it can be seen that coupling loss decreases with load cycle. In the range between 1 and 100 cycles, it decreases rapidly with the cycle, and then, it presents a relatively flat trend. Compared with the calculations of Gandalf and traditional method[16,17], the coupling loss calculated by the model in this paper confirms the test value.

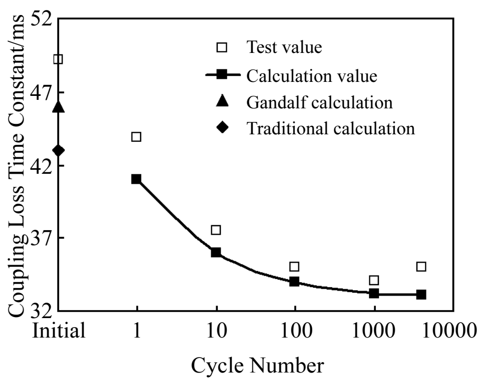

Fig.4 Coupling loss time constant as a function of cycle calculated by Eq.(2), Gandalf and traditional method and test value

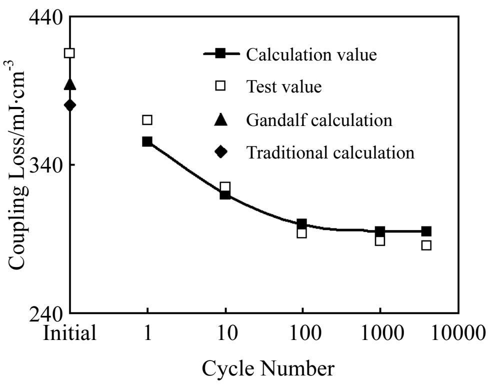

Fig.5 Coupling loss as a function of cycle calculated by the method in this paper, Gandalf and traditional method and test value

3 Conclusions

1) Considering the strain effect on the coupling loss time constant of the Nb_3Sn-base conductor, an analysis method of coupling loss time constant is proposed by combining the cabling sequence ratio, contact resistance and void fraction. On the basis of mathematical expression of the contact resistance and the void fraction, the coupling loss time constant can be calculated.

2) Different electromagnetic load cycles result in discrepant coupling loss time constants. The electromagnetic load cycle can reduce the coupling loss time constant, which indicates that strain (led by electromagnetic load cycle) can cause the strands slippage and local deformation in CICC.

3) Compared with Gandalf and the traditional method, the calculation error using the combination of the cabling sequence ratio, the contact resistance and the void fraction with strain is smaller, and close to the measured results.

References

1 Dresener L. *Journal of Fusion Energy*[J], 1995, 14(1): 3

2 Seeber B. *Hand Book of Applied Superconductivity*[M]. London: Institute of Physics Publication, 1998: 265

3 Yan L G, *IEEE Transactions on Applied Superconductivity*[J], 2010, 20(3): 123

4 Ciazynski D. *Fusion Engineering Design*[J], 2007, 82(5-14): 488

5 Bruzzone P. *Physica C*[J], 1998, 310(1-4): 240

6 Fang J, Weng P , Chen Z M *et al. Plasma Science Technology*[J], 2003, 14: 76

7 Marinucci C, Bottura L, Calvi A. *Cryogenics*[J], 2010, 50(3): 187

8 Bottura L, Bruzzone P, Lister J B *et al. IEEE Transactions on Applied Superconductivity*[J], 2007, 17(2) : 2438

9 Egorov S. *Physica C*[J], 1998, 310(1-4): 272

10 Lanen E P A V, Nugteren J V, Nijhuis A. *Superconductivity Science Technology*[J], 2013, 26(1) : 138

11 Jiang H W, Wu S T. *Chinese Science Bulletin*[J], 2011, 56(27): 2978

12 Jiang H W, Wu S T. *IEEE Transactions on Applied Superconductivity*[J], 2014, 24(2): 4 800 105

13 Jiang H W, Wu S T, Zhang D X *et al. Science China Technological Sciences*[J], 2012, 55(5): 1132

14 Zhu J Y, Lou W, Zhou Y H *et al. Superconductivity Science Technology*[J], 2013, 26(12): 125 011

15 Nijhuis A, Ilyin Y. *Superconductivity Science Technology*[J], 2006, 19(9): 45

16 Wang Q L. *High Magnetic Field Superconducting Magnet Science*[M]. Beijing: Science Press, 2008: 248 (in Chinese)

17 Fang J. *The Theoretical and Experimental Research on HT-7U CICC Stability*[D]. Hefei: Institute of Plasma Physics, CAS, 2002: 58 (in Chinese)

18 Nijhuis A, Lanen E P A V, Rolando G. *Superconductivity Science Technology*[J], 2012, 25(1): 15 007

19 Torre A, Bajas H, Ciazynski D. *IEEE Transactions on Applied Superconductivity*[J], 2014, 24(3): 8 401 105
20 Zanino R, Ciazynski D, Mitchell N *et al*. *Superconductivity Science Technology*[J], 2005, 18: 376
21 Nijhuis A, Ilyin Yu, Abbas W *et al*. *IEEE Transactions on Applied Superconductivity*[J], 2005, 15(2): 1633
22 Dong O K, Sangjun O H, Hyoung C K *et al*. *IEEE Transactions on Applied Superconductivity*[J], 2010, 20 (3): 495
23 Ilyin Y A, Nijhuis A, Abbas W *et al*. *IEEE Transactions on Applied Superconductivity*[J], 2005, 15(2): 1359

周期电磁载荷下 Nb_3Sn 导体耦合损耗计算模型

蒋华伟[1]，武松涛[2]
(1. 河南工业大学，河南 郑州 450001)
(2. 中国科学院等离子体物理研究所，安徽 合肥 230031)

摘　要：在国际热核试验反应堆（ITER）上，已采用铌三锡(Nb_3Sn)复合股线来满足导体遭受 12 T 以上的磁场冲击，但 Nb_3Sn 运行时的洛伦兹力会导致临界电流和耦合损耗时间常数的变化，因此 Nb_3Sn 基 CICC (cable-in-conduit conductor)性能退化研究还有待加强，而且应变下接触特性对耦合损耗时间常数的影响也仍在探索中。为了快速精确计算耦合损耗，本文提出新的最小二乘法计算耦合损耗时间常数的方法，它采用电缆序列比、电磁载荷应变作用下的接触电阻和空隙率等参数的线性关系来表示。在该模型中，不仅给出绞缆序列比的计算表达，也给出电磁载荷周期应变下接触电阻和空隙率的经验计算方法。与 Gandalf 及传统的数值计算相比，本文采用电缆序列比、接触电阻和空隙率组合计算耦合损耗误差较小，非常接近工程测试值。

关键词：耦合损耗；CICC；电缆序列比；接触电阻；空隙率

作者简介：蒋华伟，男，1972 年生，博士，教授，河南工业大学信息科学与工程学院，河南 郑州 450001，电话：0371-67756840，E-mail: lhwcad@126.com