Optimization Design Model of a CICC Based on Energy Margin

H. W. Jiang and S. T. Wu

***Abstract*—The design of a cable-in-conduit conductor (CICC) is a very complicated engineering process. In order to simplify the design for CICCs, a simulation design method is presented in this paper with the relationship between the operating current and the critical current, and the extreme case that the Stekly parameter is equal to 1. In addition, a novel optimization model for CICC design is proposed for solving the difference or uncertainty in the subsequent cabling layout of the conductor. This mathematical constraint model, which can maximize the CICC energy (stability) margin, is built to generate a more reasonable conductor structure. For an optimum design of a CICC, although there exists a cabling variety in the fourth stage (level) between the engineering design and the optimization design, the result shows that the optimized conductor structure and the correlated performance conforms reasonably well to the present engineering design that was adopted by the Option II CICC of the International Thermal Nuclear Experimental Reactor experimental fusion reactor project.**

***Index Terms*—Cable-in-conduit conductor (CICC), optimization model, simulation design, stability margin.**

I. Introduction

As THE key configuration for large-scale superconducting magnets, cable-in-conduit conductor (CICC), which was developed from the internally cooled superconductor [1] on the basis of a cable-in-conduit and some experimental investigation, has attracted the attention of researchers since 1975 [2], [3]. Owing to the advantages of supercritical helium cooling, high voltage insulation, and multistage cabling, and so on, CICC has become the favorite conductor for Experimental Advanced Superconducting Tokamak (EAST) [4], Korean Superconducting Tokamak Advanced Research [5], and ITER.

The central solenoid (CS) and toroidal field (TF) superconducting magnets in ITER will operate in a complex environment with high current and transient magnetic field caused by fast excitation, and it will be subjected to more than the 10-T impact. It is obvious that the NbTi-based CICCs do not meet these requirements. In order to overcome limitations in the critical performance of NbTi, Nb_3Sn strand [6]–[8] has been developed for ITER [9]. However, the strain effect resulting from Lorentz forces and warm up and cool down is a key issue that is still being discussed. Some progress has been made in theoretical research on these problems. The main critical parameter, such as critical current density sensitivity to strain is accurately represented in [10], in which the deterioration of the critical current, and the n-index is also analyzed. Muller thought that the performance degradation of wires caused by transverse magnetic load and different coefficients of thermal expansion among their components from heat treatment temperature to operating temperature is the primary factor of strand deformation in CICC [11]. The strain effects on the critical current density, the critical field, the critical temperature, and n-values were described in detail. In the above analysis results, while the deterioration of the critical parameters in CICC could be obtained by some analysis, these experimental analysis results were not applied to the structure design of a conductor through reverse reasoning.

The stability and the ac loss are the major problems for CICCs that need to be solved. In order to simplify the complex design process of CICCs, it is necessary to carry out further research by numerical simulation studies of conductors using optimization theory.

For the optimization design of conductors, Nijhuis and Ilyin presented an optimization model TEMLOP, and reported some helpful methods of computation for conductor design [12], which employed experimental results on the internal tin strand that were used for the Toroidal Field Model Coil. Based on the requirements of strands for the ITER-TF conductor, Zhang *et al.* illustrated an optimized manufacturing process for Nb_3Sn superconducting strand [13] with the filament diameter, heat treatment, and reaction that have been performed in Western Superconducting Technologies Company in China. However, in these optimization methods, the structure design of the conductor has not been fully explained. In addition, cable interactive designer (CID) is a useful software to simulate the cabling process and generate geometric structure of cables [14], which is combined with the technology of the numerical code Gandalf [15]. In CID, the conductor structure (layout) is only formed through the simple and mechanical accumulation of each layer but did not adopt the parameters of the energy margin, current sharing temperature, the given operating conditions, and so on.

An analysis study of strain effects for critical current and other parameters is carried out [16], and a model of structure design to simulate a CICC is built, which is based on stability margin, space current density, and temperature margin. At the same time, the optimization structure for a CICC with

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minimization of ac loss is presented. However, the model is not appropriate for practical application because it is difficult to meet the requirements of engineering design. Furthermore, in the literature [16], the minimized ac losses that include hysteresis losses and coupling losses is found by repetitive computation, that is, the ac loss calculation in every layer is repeated. Then, the relative rational conductor structure for engineering design is acquired. In short, the ac loss calculation in the literature [16] is intricate and unsatisfactory.

In this paper, an improved method is brought forward to avoid the above case. First, a simulation design model of cable (CICC) is proposed according to the relationship between the operating current and the critical current, and the extreme case that the Stekly parameter is equal to 1. Then a novel mathematical programming method maximizing the stability margin is built to generate the optimization design for the conductor structure.

II. DESIGN METHOD TO SIMULATE CICC

A. Method of Simulation Design

According to the design requirements of ITER, the ratio between Cu and non-Cu for CICC production and processing is clearly defined. In general, the ratio for a CICC in TF is roughly 1 and 1.5 for CICC in CS. Therefore, as described in the literature [16] and [17], the ratio is known, and it does not need to be varied.

For the first subcable, it contains three strands (including superconducting strands and pure copper strands). Thus, the first subcable has three forms:

1) three superconducting strands;
2) two superconducting strands and one pure copper strand;
3) one superconducting strand and two pure copper strands.

The case of the first subcable with superconducting strands (no copper strands) is discussed in the literature [16] and [17]. In this paper, the strands in the first subcable contain copper strands. Therefore, it is a key problem to solve the strand diameter, the number of strands and the subsequent cabling layout (configuration). According to the manufacturing and cost of the strands, the superconducting strand diameter is equal to the pure copper strand diameter. Hence, three unknowns, namely, the superconducting strand number (N_{sc}), the pure copper strand number (N_{cu}), and the strand diameter (d) are left.

B. Formula for the Simulation Design

In the complex magnetic field environment, with consideration of the strain effects on the critical current density for a Nb_3Sn-based conductor in order to avoid conductor quench, a safety factor of the operating current of the $\mathrm{Nb_3Sn}$-based conductor is selected according to the NbTi-based CICC in EAST [18], [19], and 3 is a much more appropriate one. Hence, the critical current (I_c) is three times the operating current (I_{op}), i.e.,

$$I_c = 3I_{\mathrm{op}}. \tag{1}$$

The value of the critical current density multiplied by the area of superconducting conductor is the critical current, i.e.,

$$I_c = \frac{N_{\mathrm{sc}}\pi d^2}{4} J_c. \tag{2}$$

where J_c stands for the critical current density of $\mathrm{Nb_3Sn}$-based conductor. It can be calculated by the methods in the literature [20] and [21], with fixed conditions of strain (as shown in Table III) and magnetic field (given in II-C).

When (2) is substituted into (1), the following expression can be obtained:

$$N_{\mathrm{sc}} \cdot d^2 = A \tag{3}$$

where

$$A = \frac{12 I_{\mathrm{op}}}{\pi J_c}.$$

For thermal disturbance, if the joule heat generated by the resistance is not greater than the transferring heat with the wetted perimeter, which is formed by the liquid helium and the conductor, the superconductor can come back to the superconducting state from the quench state, i.e., the Stekly parameter is not more than 1. Taking the extreme case that it is equal to 1, it can be expressed in the following:

$$\frac{I_{\mathrm{op}}^2 p_{\mathrm{cu}}}{A_{\mathrm{cu}}} = P_w h (T_c - T_{\mathrm{op}}). \tag{4}$$

The wetted perimeter P_w and the area of the copper A_{cu} of a cable can be expressed as

$$P_w = \pi K_p d (N_{\mathrm{sc}} + N_{\mathrm{cu}}) \tag{5}$$

$$A_{\mathrm{cu}} = \frac{\pi d^2}{8}(N_{\mathrm{sc}} + 2N_{\mathrm{cu}}). \tag{6}$$

where p_{cu} stands for the copper resistivity, and K_p stands for the wet perimeter coefficient. h stands for the coefficient of heat transfer; it seems to be related to the mass flux of the forced flow supercritical helium, the pressure drop (friction), the pressure gradient, and the temperature gradient. The heat transfer coefficient h is highly variable; it is different among strand, helium, and jacket, varying between several 10^2 and 10^3 W/m^{2}K. T_c stands for the critical temperature, and T_{op} stands for the operating temperature.

Considering the number of superconducting strands in the different first subcable, taking into account that Cu/Non-Cu is equal to 1, the mathematical expression can be obtained as follows:

$$\begin{cases} N_{\mathrm{sc}}^2 d^3/3 = B & N_{\mathrm{cu}} = 0 \\ N_{\mathrm{sc}}^2 d^3 = B & N_{\mathrm{sc}} = 2N_{\mathrm{cu}} \\ 5N_{\mathrm{sc}}^2 d^3 = B & N_{\mathrm{cu}} = 2N_{\mathrm{sc}} \end{cases} \tag{7}$$

where

$$B = \frac{8 I_{\mathrm{op}}^2 \rho_{\mathrm{cu}}}{3\pi^2 K_p h (T_c - T_{\mathrm{op}})}.$$

TABLE I
CICC STRUCTURES WITH FOUR-STAGE CABLING

2nd Sub-Cables	3rd Sub-Cables	4th Sub-Cables
5	9	10
5	10	9
9	5	10
9	10	5
10	5	9
10	9	5

TABLE II
CICC STRUCTURES WITH FIVE-STAGE CABLING

2nd Sub-Cables	3rd Sub-Cables	4th Sub-Cables	5th Sub-Cable
3	5	5	6
3	5	6	5
3	6	5	5
5	3	5	6
5	3	6	5
5	5	3	6
5	5	6	3
5	6	3	5
5	6	5	3
6	3	5	5
6	5	3	5
6	5	5	3

C. Result of the Simulation Design

As a representative situation to solve (3) and (7), in this paper, the case that the number of superconducting strands is two times that of the pure copper strands is used.

According to the operating conditions of ITER-TF, namely, $B_{\max} = 12$ T, $T_{\text{op}} = 4.2$ K, $I_{\text{op}} = 68$ kA, the temperature margin $\Delta T_{\text{cs}} = 1$ K, $d_B/d_t = 11$ T/s, and the stability margin $\Delta E = 580$ mJ/cm^3, the superconducting strand number is 900, the pure copper strand number is 450, and the diameter is about 0.82 mm. The structure of the CICC includes two cases. From Table I, it is found that there exist six cabling modes for the structure of CICC with four-stage cabling. At the same time, from Table II, it can be also seen that there are 12 cabling modes for the CICC structure with five-stage cabling.

III. OPTIMIZATION DESIGN OF CICC

A. Optimization Design of CICC

It can be seen that there exists various structures for the latter stage (as shown in Section II-C) based on permutation and combination. Apparently, the conductor structure is not unique, it will appear that the structures, such as (2SC + 1Cu) × 10 × 9 × 5 and (2SC + 1Cu) × 6 × 5 × 5 × 3, which does not meet the requirements of conductor mechanical (structure) stability.

Hence, it is necessary to determine a relative reasonable conductor structure with restricted parameters. In this paper, the structure stability and maximal stability margin method is adopted to optimize the conductor structure. Hence, it needs to meet the following mathematical programming conditions:

$$\begin{cases} \text{Min}(-\Delta E) = \text{Min}\left(f(n_i)\right) \\ \text{s.t.} \qquad n_i \le n_j \quad (i < j) \end{cases} \tag{8}$$

where $\text{Min}(-\Delta E)$ is the maximum value of the stability margin defined by (9), $f(\ldots)$ stands for the negative stability margin function of component coefficient, and s.t. is the abbreviation of the words *subject to*. n_i stands for the structure of the ith subcable, which is the subcable (strand) number.

According to requirements of the structural stability, the number of the latter subcable strands is not less than that of the former stage subcable strands. There are many unreasonable structures that can be excluded. Only (2SC + 1Cu) × 5 × 9 × 10 and (2SC + 1Cu) × 3 × 5 × 5 × 6 can meet this requirement.

For the selection from the two conductor structures above, it is necessary to optimize the stability (energy) margin and get a relatively reasonable conductor with the maximum stability margin. The stability margin is an important parameter that affects the steady operation of the conductor. As we know, liquid helium flows in the gap between the strand and the subcable, and the heat exchange between them is a complex process. If the generating disturbance is large enough, it will exceed the energy margin that the conductor can withstand, and it will lead to quenching. The stability of the CICC is the ability to keep its superconductivity when it undergoes interference. Hence, the stability (energy) margin of a CICC is that the conductor can bear the maximal unit volume disturbance without quench. It is obvious that the conductor can more safely operate with the maximal stability margin.

Taking into account the component coefficient of the CICC, the stability margin ΔE of a CICC in the transition regime is expressed as follows [19], [22]:

$$\Delta E = (1 - f_{\text{cu}} - f_{\text{nc}}) p_{\text{he}} C_{\text{he}} (1 - a) \left(\frac{T_{\text{cs}} - T_{\text{op}}}{f_{\text{cu}} + f_{\text{nc}}} \right) \tag{9}$$

where p_{he} is the helium density, C_{he} is the helium heat capacity, a is the Stekly parameter, and T_{cs} stands for the current sharing temperature. f_{cu} and f_{nc} are the copper and noncopper fractions of materials in the composite wire, respectively. As we know, a CICC is made of several petals (the final stage subcable wrapped with ribbon), which contain the compressed subcables/strands. Hence, in a sense, the f_{cu} and f_{nc} can be known as the copper and noncopper fractions of materials in the CICC.

The expression above can be also transformed into the following:

$$\Delta E = C \left(\frac{1}{f_{\text{cu}} + f_{\text{nc}}} - 1 \right) \tag{10}$$

TABLE III
VALUE OF SOME PARAMETERS

ε (%)	h ($\mathrm{Wm^{-2}K^{-1}}$)	f_{cu} (%)	f_{nc} (%)	f_v (%)
-0.35~-0.55	500~800	45~50	15~25	25~30

TABLE IV
CALCULATION OF STABILITY MARGIN

Parameter	3SC×3×4×5×6	3SC×5×8×9
$f_{cu}+f_{nc}$ (%)	70	67
f_v (%)	30	33
ΔE ($\mathrm{mJ/cm^3}$)	645.27	623.36

TABLE V
OPTIMIZED DESIGN CONDUCTOR AND ITER TF CONDUCTOR

Design Model	Configuration	
Engineering design	(2SC+1Cu)×3×5×5+1Core)×6	1Core=3×4Cu
Optimized design	(2SC+1Cu)×3×5×5×6	

where $C = pC_{\mathrm{he}}(1-a)(T_{\mathrm{cs}}-T_{\mathrm{op}})$

$$\mathrm{Min}(-\Delta E) = C\left(1 - \frac{1}{f_{\mathrm{cu}}+f_{\mathrm{nc}}}\right). \tag{11}$$

Parameters f_{cu} and f_{nc} are related to the cabling pattern and the structure of the CICC (for the "Option II" cable design for ITER, a longer twist pitch and a lower void fraction was used). The range of f_{cu}, f_{nc}, and other parameters are gathered in Table III for the optimization calculation.

The stability margin of two CICC structures can be obtained through optimization calculation according to Table III (the calculation result is shown in Table IV), i.e., 645.27 and 623.3 6 mJ/cm^3. Taking the greater of the stability margins, the structure (2SC + 1Cu) × 3 × 5 × 5 × 6 is a more acceptable one.

B. Analysis of the Optimization Design

To validate the optimization result for a conductor, a numerical simulation design and optimization calculation was carried out. We focused on the main parameter differences between the optimization design results and the engineering design of ITER. In comparison with that of "Option2 (II)" for ITER, the result that originated from the optimized structure of a conductor is shown in Tables V and VI.

As Table V shows, the optimized structure agrees reasonably well with the present ITER design, which is the optimal design result according to the energy margin. However, there is a difference between the optimized structure and the engineering structure, which is in the fourth stage (level), where there is 1 core (3 × 4Cu) in the engineering design.

In Table VI, it would appear that the stability margin of the optimized conductor is more than that of the engineering design's, obviously the performance of the optimized CICC is better. Meanwhile, the ac loss of the optimized conductor is much less than that of the engineering design, which implies that the disturbance from the optimized conductor is lower than that of the engineering calculation. All these results show that the conductor with the optimization design could operate well under the same operating situations.

TABLE VI
RESULTS OF OPTIMIZED DESIGN AND ITER STRUCTURE

Result	Engineering design result	Optimized design result
Acu ($\mathrm{mm^2}$)	342.2	341.2
Ast ($\mathrm{mm^2}$)	228.1	227.3
Tc (K)	12	12.56
Tcs (K)	<10.2K	7.62
Ic (A)	68000	73128
dsc (mm)	0.82	0.82
ΔE ($\mathrm{mJ/cm^3}$)	580	645.27
AC Loss ($\mathrm{mJ/cm^3}$)	≤350	132.67

In addition, it can be seen that there are some differences between the optimization calculation and the engineering design, as shown in Table VI. For example, the cross-sectional discrepancy of the copper strands is caused by different compression ratios and cabling coefficients in every stage. Furthermore, there exists the critical current difference between the optimized design and the engineering design, which results from the numerical calculation. Moreover, the distinction of the energy margin is generated from A_{cu}. In order to eliminate these differences, an improvement measure with the proper wetting perimeter coefficient is taken to remedy the optimization calculation errors.

IV. CONCLUSION

In this paper, the fundamental principle of a numerical simulation design for a conductor has been proposed, which employs the ratio between the operating current and the critical current, and the utmost Stekly parameter value (equal to 1).

Furthermore, in this paper, a mathematical programming method with the maximized stability margin of CICC is established. Hereby, a reasonable structure for a CICC is provided by the optimization calculation. As the design result and calculation show, the energy margin of the optimization conductor is larger than that of the engineering design, and its ac loss is smaller. Thus, the optimized conductor can be safer. At the same time, the errors are analyzed, and the improvement measure is given.

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