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# AC loss measurement of a tri-axial superconducting cable based on a digital compensation method

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## 1 INTRODUCTION

Tri-axial high temperature superconducting cable has the advantages of compact structure, low loss, and nearly 2/3 reduction in the consumption of HTS tape. However, due to the different radius of each phase conductor of the tri-axial HTS cable, the symmetry of impedance components of each phase is affected, resulting in the imbalance of the three-phase current, which will reduce the transmission efficiency. We propose a new type of two-section-cable Particle Swarm Optimization to solve the problem of three-phase current imbalance in tri-axial HTS cable. The algorithm divides the cable C-phase conductor and the copper shield into two segments with the same radius but different twist pitches and twist directions, which increases the variable by one-half. By changing the twist pitches and twist directions, considering the thickness of the insulation, optimization of current distribution is realized. Finally, we design a 10 kV/1.5 kA tri-axial HTS cable. The results show that compared with other optimization algorithms, the current imbalance ratio of the superconducting cable is reduced from 10% to 1% after the two- section-cable Particle Swarm Optimization. The correctness of the mathematical model and the imbalance optimization algorithm of tri-axial HTS cable is verified. The optimization results provide important reference for the design and experiment of tri-axial HTS cable.

## 2 STRUCTURE OF TRI-AXIAL HTS CABLE

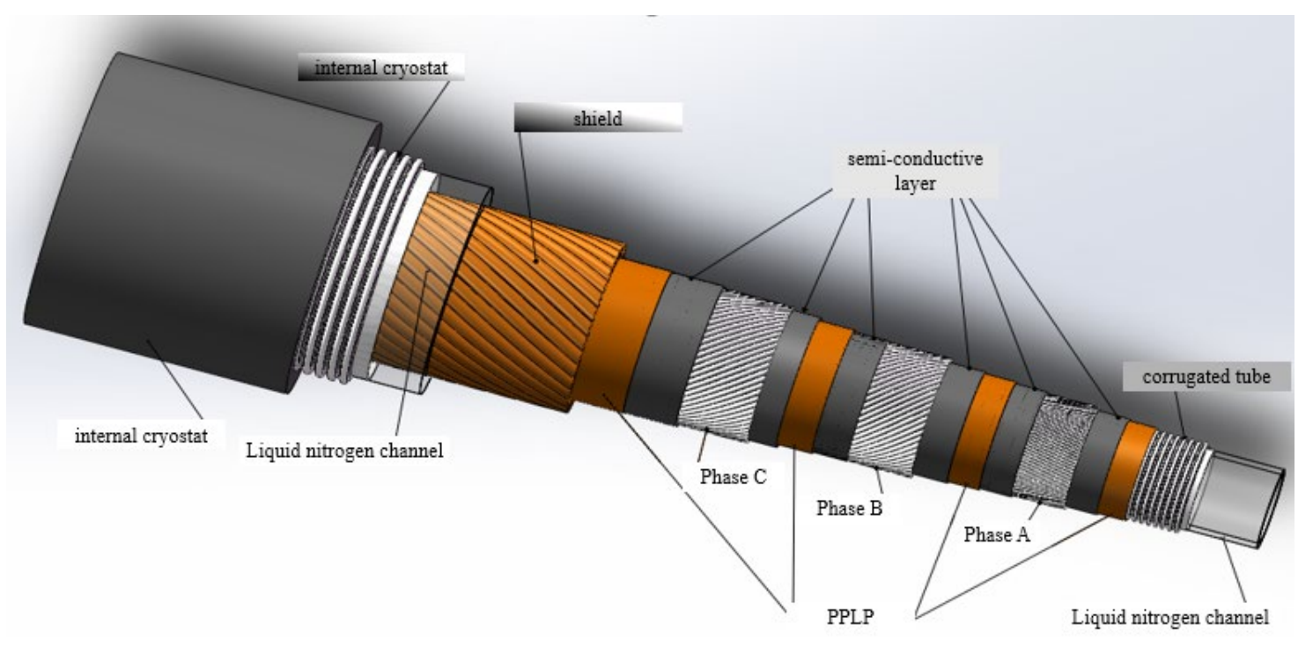

Fig. 1 structure of tri-axial HTS cable

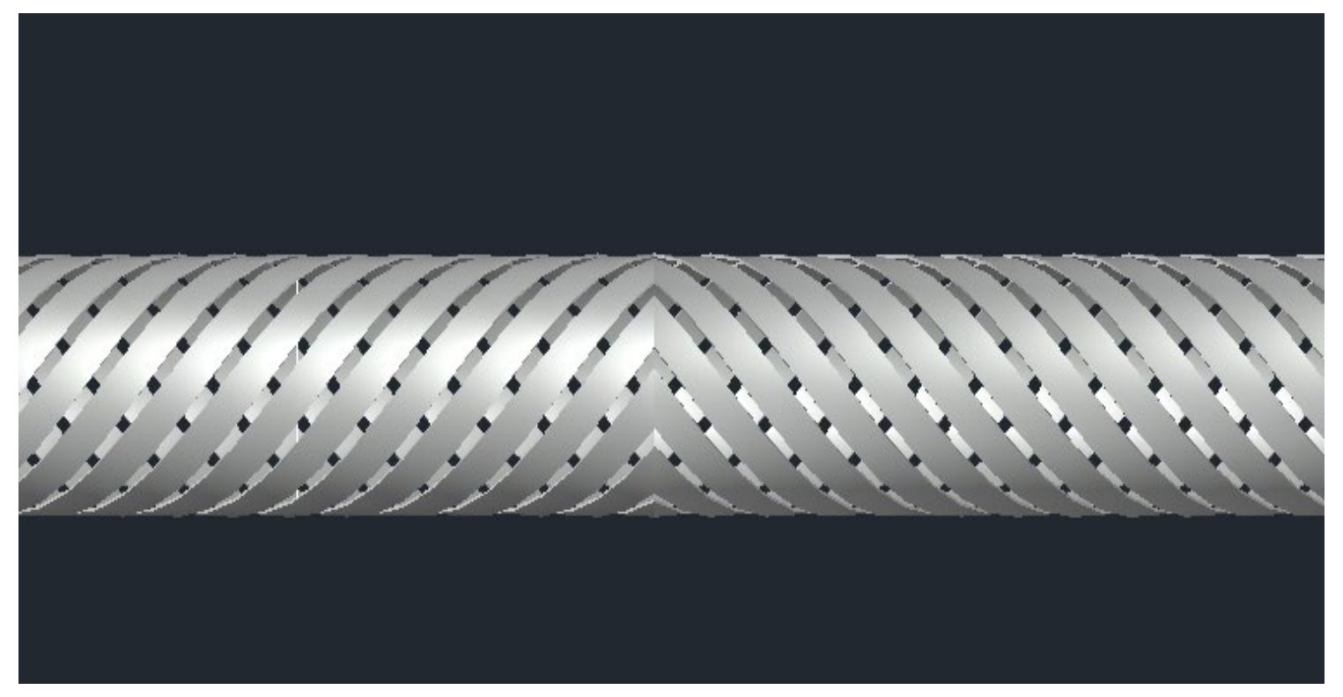

Fig. 2 structure of two-section-cable

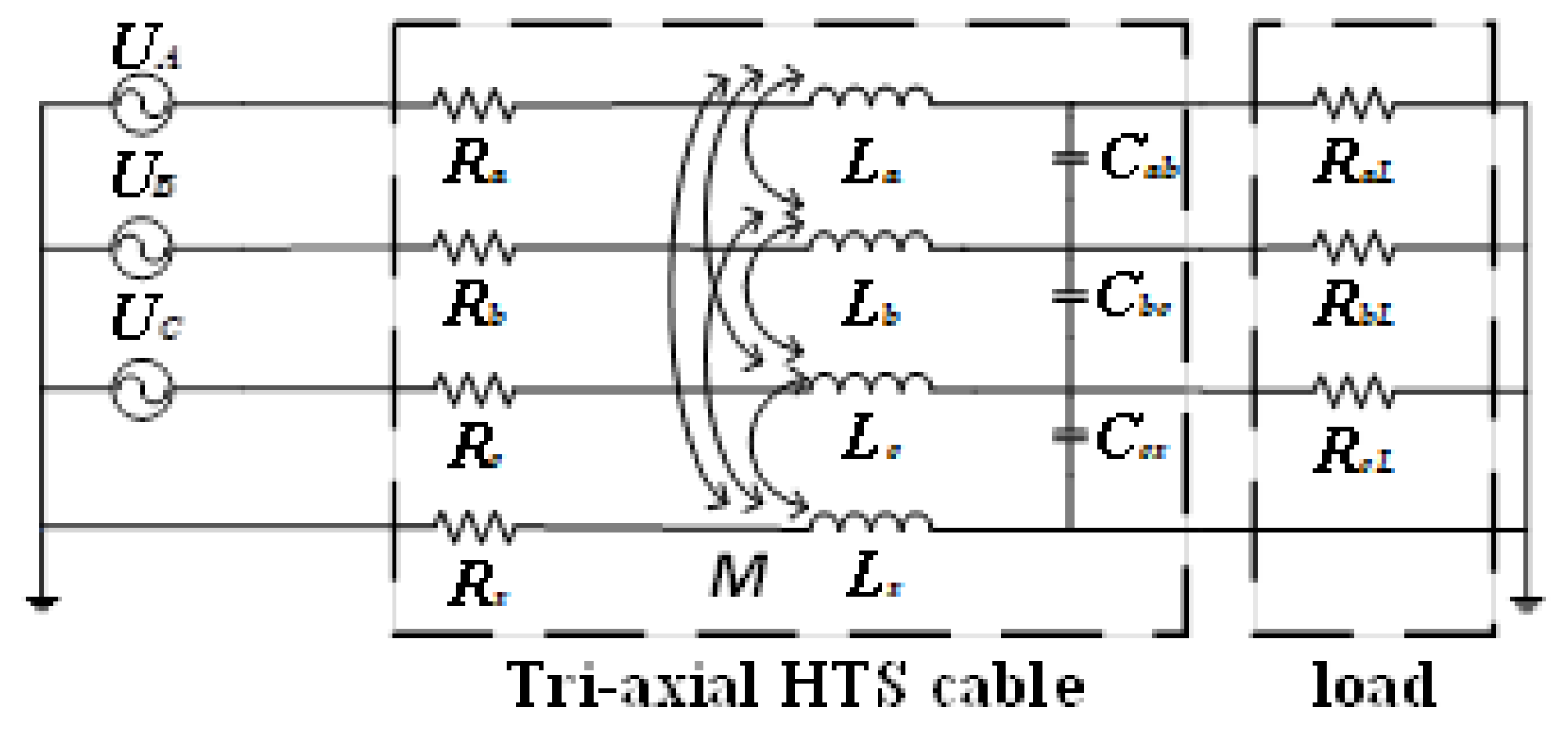

Fig. 3 equivalent circuit model

## 3 CURRENT BALANCE DESIGN

Under the superconducting state, resistance R of the cable is closed to zero, so the balance of three phase current depends on the self-inductance, mutual inductance and capacitance of the cable. The relationship between the voltages and currents are described as follows.

$$\mathbf{I} = \left[[\mathbf{R} + \mathrm{jw}\mathbf{L}]^{-1} + jw\mathbf{C}\right]\mathbf{U} \tag{1}$$

$$\mathbf{I} = \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_s \end{bmatrix} \mathbf{U} = \begin{bmatrix} U_a \\ U_b \\ U_c \\ U_s \end{bmatrix} \mathbf{R} = \begin{bmatrix} R_a & 0 & 0 & 0 \\ 0 & R_b & 0 & 0 \\ 0 & 0 & R_c & 0 \\ 0 & 0 & 0 & R_s \end{bmatrix}$$

$$\mathbf{L} = \begin{bmatrix} L_a & M_{ab} & M_{ac} & M_{as} \\ M_{ba} & L_b & M_{bc} & M_{bs} \\ M_{ca} & M_{ca} & L_c & M_{cs} \\ M_{sa} & M_{sb} & M_{sc} & L_s \end{bmatrix}$$

$$\boldsymbol{C} = \begin{bmatrix} C_{ab} & -C_{ab} & 0 & 0 \\ -C_{ab} & C_{ab} + C_{bc} & -C_{bc} & 0 \\ 0 & -C_{bc} & C_{bc} + C_{cs} & -C_{cs} \\ 0 & 0 & -C_{cs} & C_{cs} \end{bmatrix}$$

imbalance ratio $k_e$ is:

$$\varepsilon_n = I_n / I_1 \tag{2}$$

$$k_e = (\varepsilon_0 + \varepsilon_2 + \varepsilon_s) \times 100\% \tag{3}$$

where $I$ is the sequence current, and the subscripts 0, 1, 2, and S represent zero sequence, positive sequence, negative sequence and shield.

The optimization variables are:

$$X = [r_a, r_b, r_c, r_s, \beta_a, \dots, \beta_{s2}, \gamma_a, \dots, \gamma_{s2}] \tag{4}$$

r is the radius of the conductor layer, β is the winding direction angle, and γ is the winding direction.

optimal target function is:

$$F(X) = minf(X) = \min k_e\,(X) \tag{5}$$

Constraint condition is:

$$\beta_{min} < \beta_i < \beta_{max} \tag{6}$$

βmin and βmax is related to tape parameters.

## 4 COMPARISON

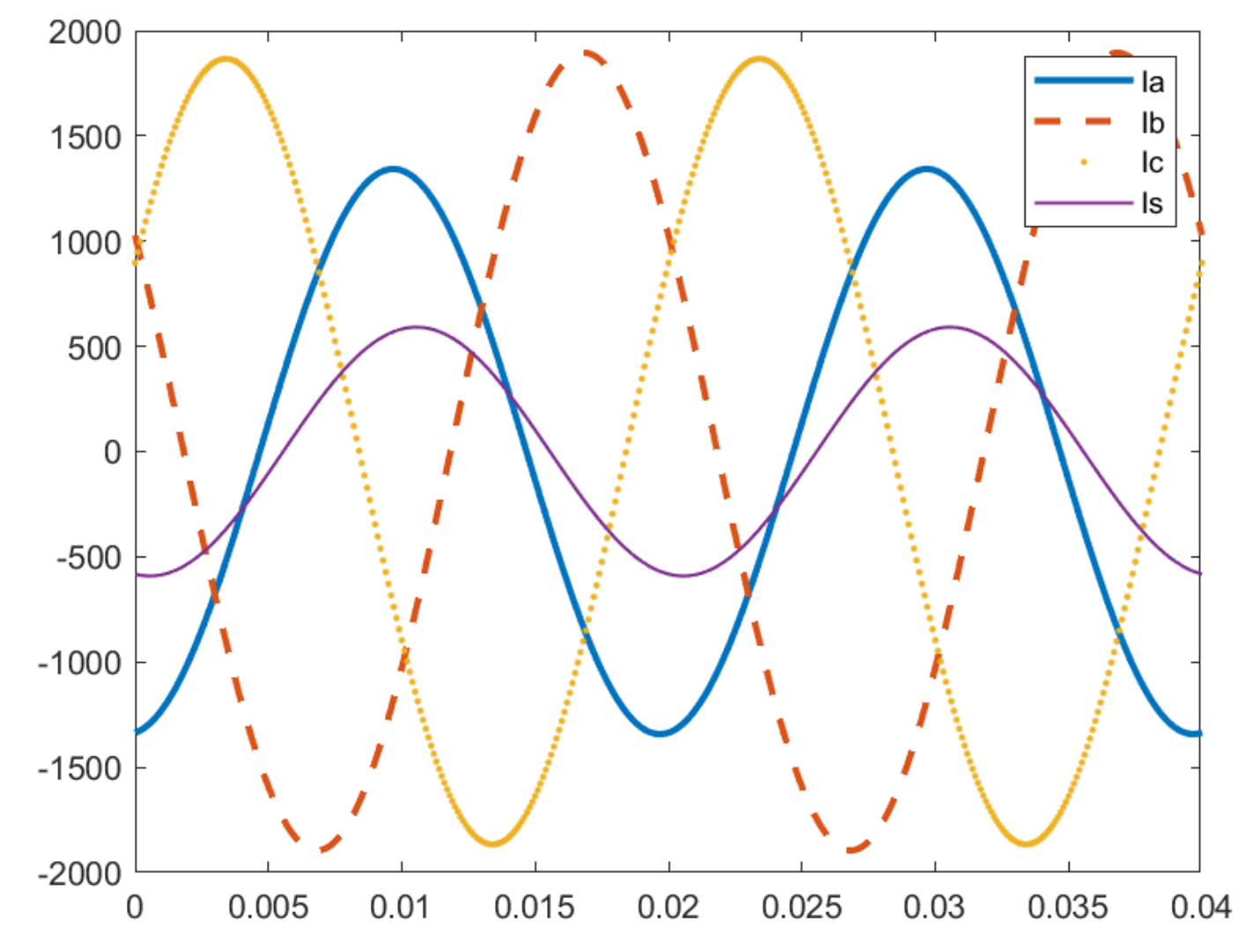

Fig. 4 current waveform before optimization

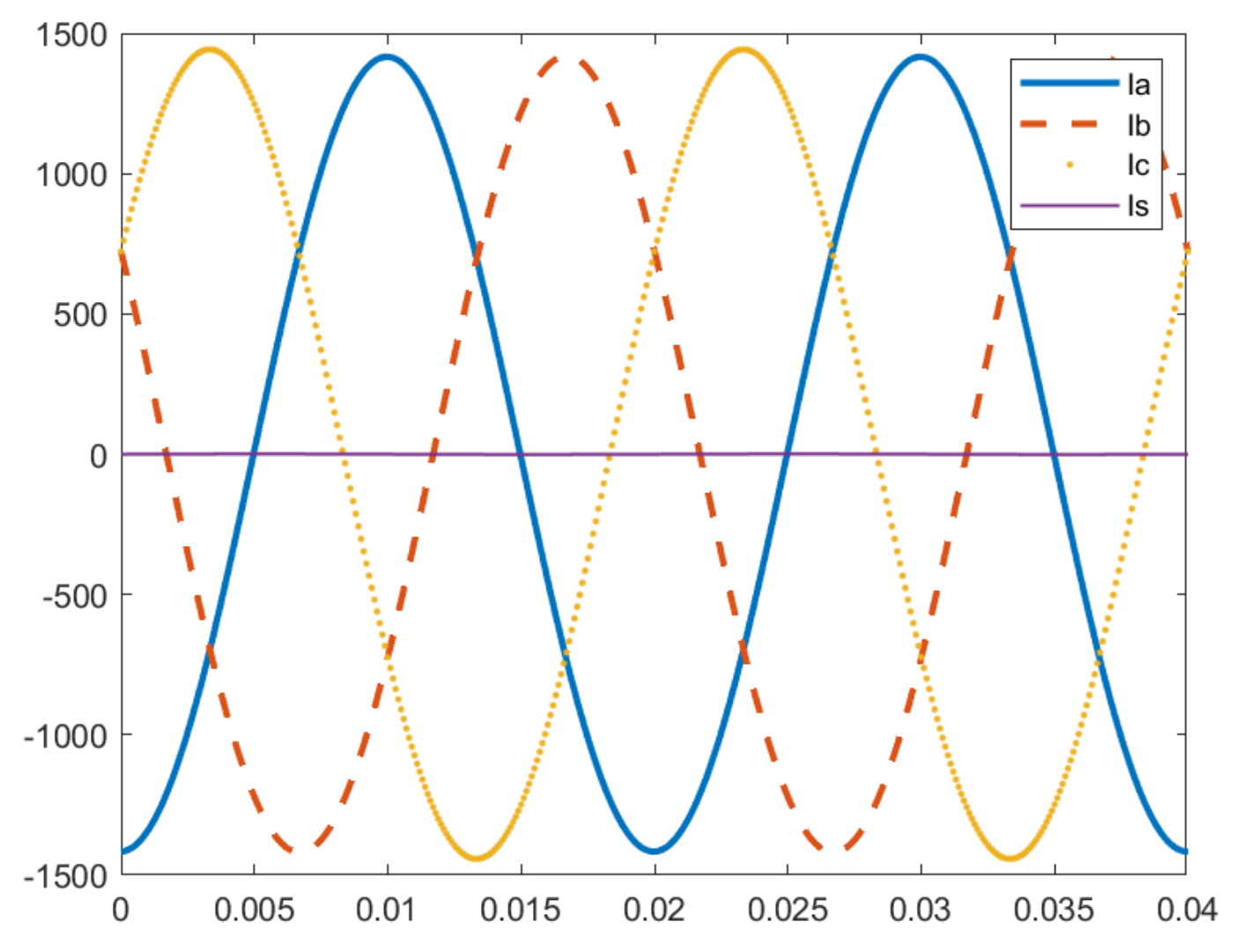

Fig. 5 current waveform after optimization

Table 1. Comparison of simulation results

| | | |
|---|---|---|
| **Before optimization** | Imbalance ratio | 10.4% |
| | A phase current | 1000Arms |
| | B phase current | 1230Arms |
| | C phase current | 1214Arms |
| | AC loss | 0.5908W/m |
| | Shield current | 347A |
| **After optimization** | Imbalance ratio | 1.2% |
| | A phase current | 1000Arms |
| | B phase current | 1004Arms |
| | C phase current | 1020Arms |
| | AC loss | 0.3768W/m |
| | Shield current | 0.6A |

After the optimization, the shield current amplitude decreased from 500A to 1A and the three-phase imbalance ratio was significantly reduced, which proved the correctness of the optimization algorithm.

## 5 EXPERIMENTAL RESULTS

Fig. 6 experiment photo of tri-axial HTS cable

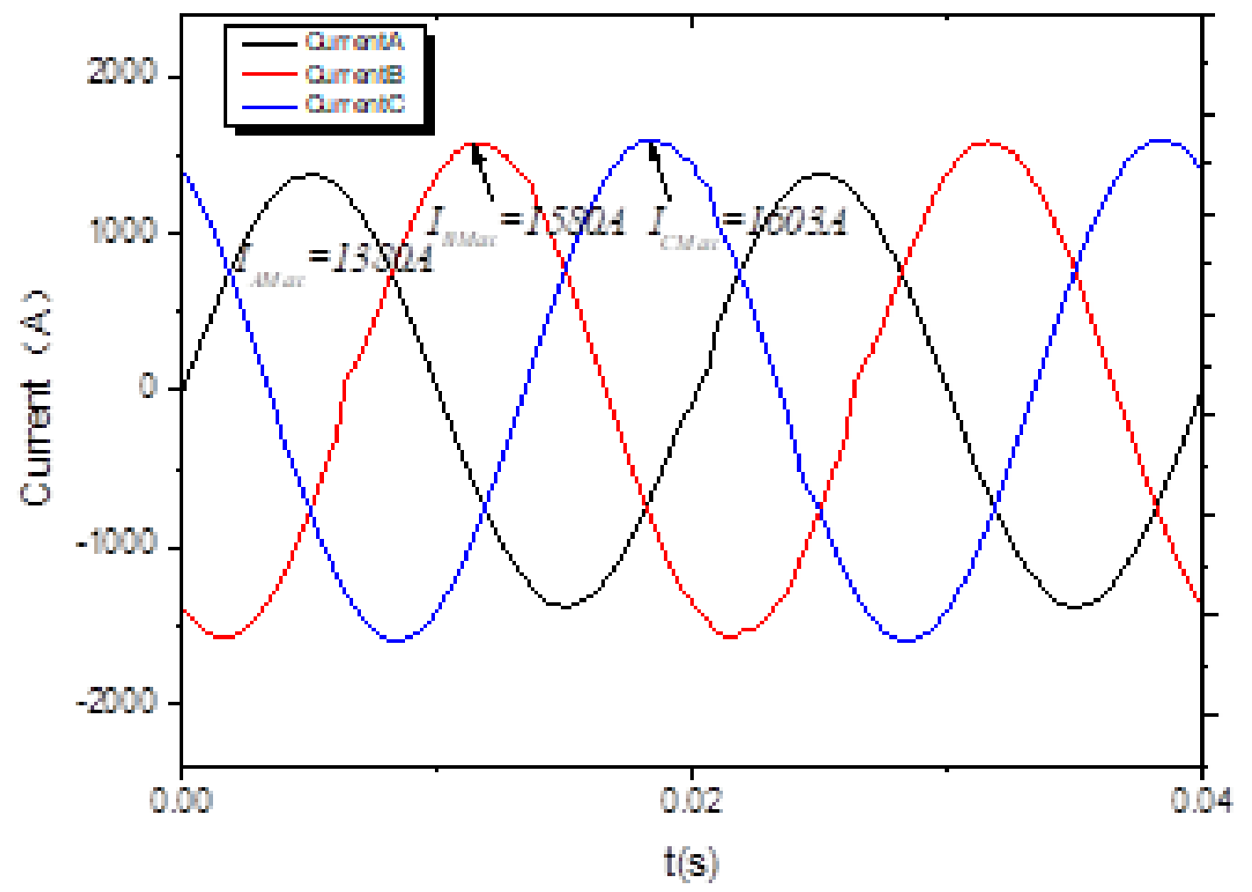

Fig. 7 three-phase current waveforms of test

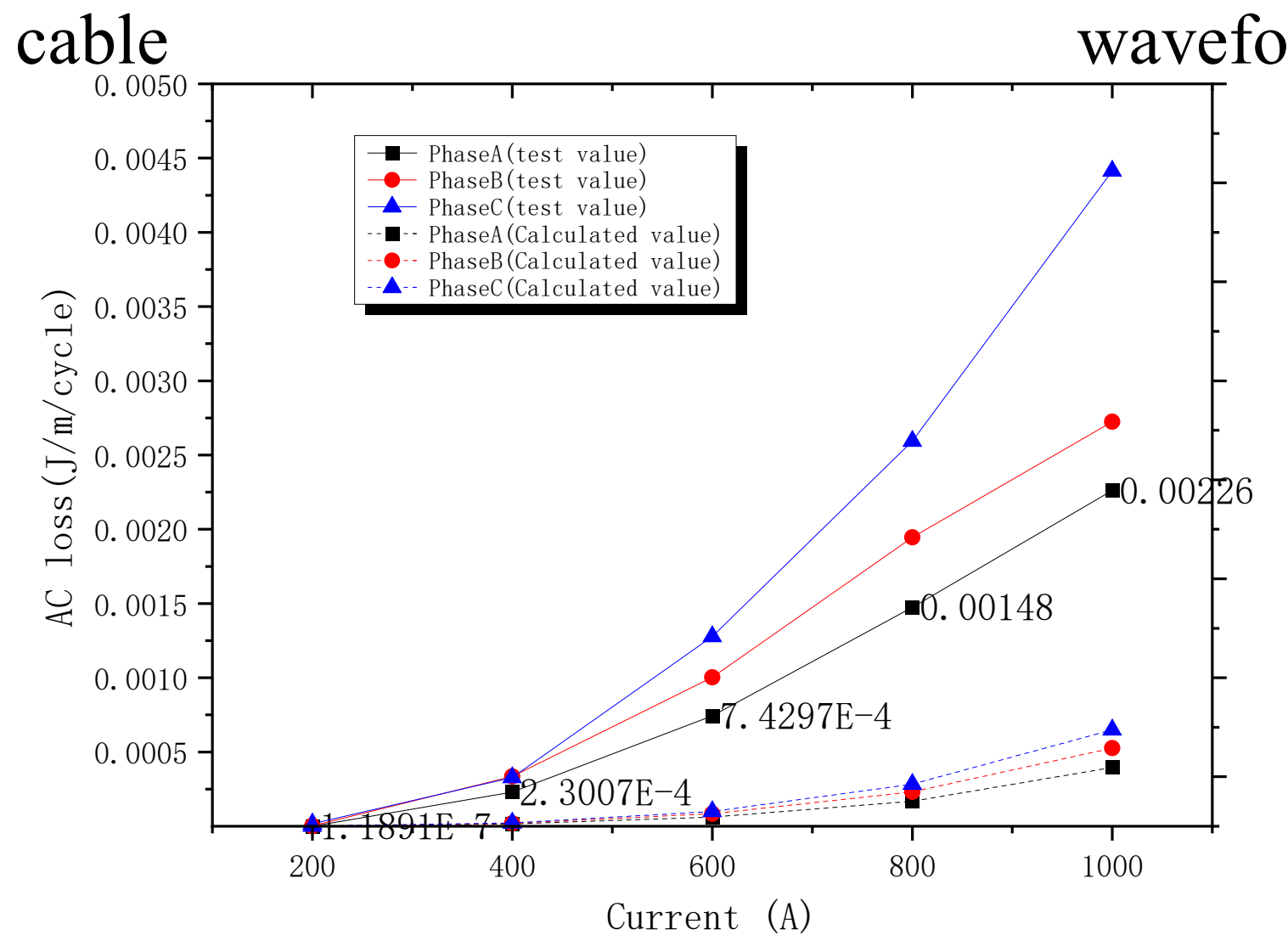

Fig. 8 comparison of AC loss test value and simulation calculated value

## 6 CONCLUSION

After optimization, the three-phase current imbalance ratio of the cable drops from 10% to 1%, and the shield current amplitude drops from 30% of the phase current to less than 1%, and the transmission loss reduce 36%. The current distribution test verified the correctness of the mathematical model and the optimization algorithm of current distribution.