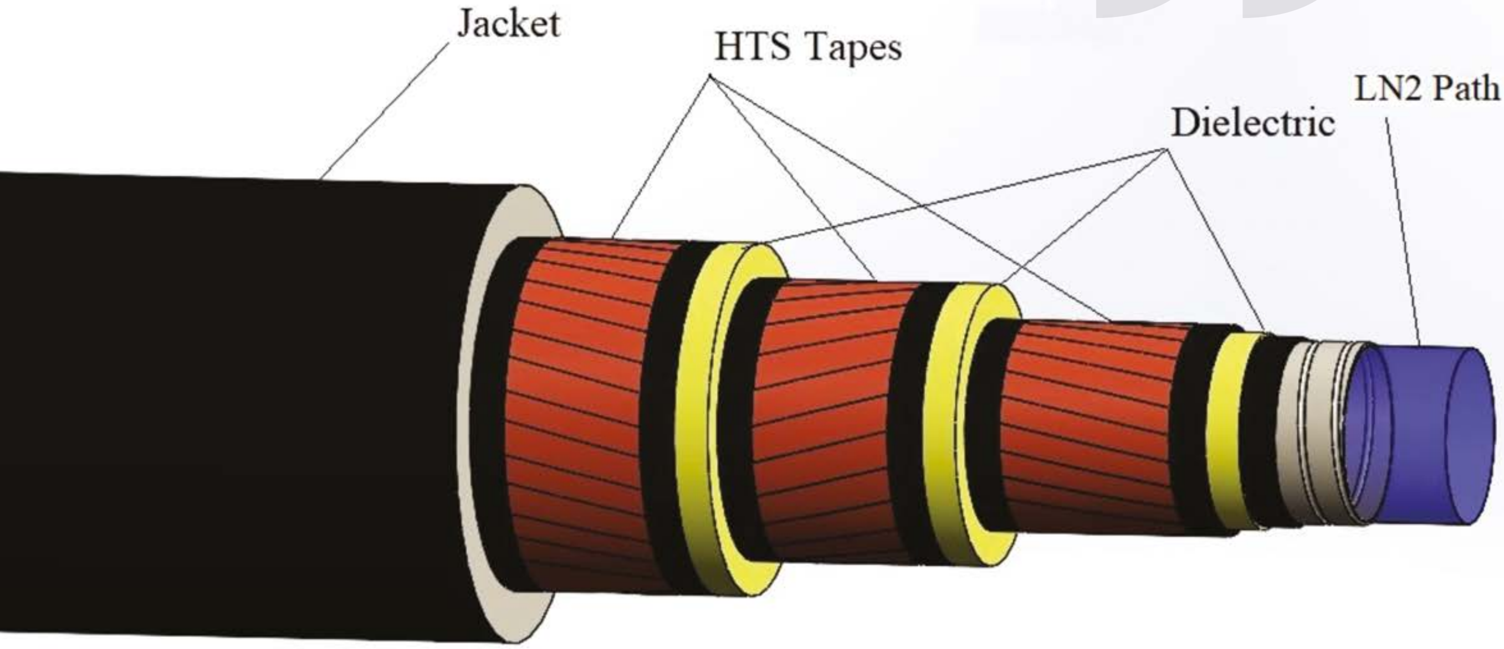
The discovery of HTS materials revived the dream of large-scale application of superconductors in the scientific and industrial world, but it has its challenges



An accurate model of the high-temperature superconducting cable by using stochastic methods

How could an equivalent circuit model of superconducting cable reach a higher accuracy?

ABSTRACT

Modeling of high-temperature superconducting (HTS) cables as key elements of future power grids is a remarkable step at the beginning of projects on superconducting cables. Many projects utilize finite element methods (FEMs) to better understand the cable loss mechanism and its value. These methods are unable to evaluate the behavior of cables while connecting to a real grid. Therefore, equivalent circuit models (ECMs) are introduced as variants to provide a suitable environment for testing capabilities of high-temperature superconducting cables under different contingencies of power grids. This advantage has raised interest in the utilization of ECMs to predict the behavior of HTS cables. The accuracy of modeling by ECMs depends on many factors and considerations, among which twisting effect is a vital factor that is able to highly impress the accuracy of simulations. Thus, the Weibull distribution function (WDF) is utilized in this paper as a stochastic solution to increase the accuracy of the model. By applying WDF and sectionizing tapes, the twisting effect on the critical current of cable is accessible. Investigations on different conditions have shown that an ECM with 100,000 sections has high accuracy and acceptable speed.

KEYWORDS

accuracy, superconducting cable, twisting, Weibull distribution function

Introduction

The discovery of superconductors was the beginning of multiple research directions, efforts, and funding to take the advantages of superconductors in physic, electronic, power engineering, and space programs. However, due to some disadvantages of early superconductors, called low-temperature superconductors (LTS), the application of these materials faced noticeable hindrances. To tackle these restrictions, many efforts have been accomplished. Eventually, a brand-new type of superconductor with a high critical temperature and the critical field was discovered, a high-temperature superconductor (HTS). HTS materials revived the dream of large-scale application of superconductors in the scientific and industrial world [1]. Since the discovery of HTS materials and due to their high current capacity and low loss, many studies and projects have been funded to put these materials in work as an element of power grids or electrifications. Among all available applications of superconductors, HTS cables are the most common and well-researched types. Countless R&D projects have been initiated worldwide not only to utilize HTS cables to the power delivery of loads, namely Albany [2], Yokohama [3], and Ampacity projects [4] but also to employ these cables as components of turbo-electric airplanes, propulsion ships, and electric trains. Generally speaking, the main objective of these projects is reducing AC loss to a minimum possible value and avoiding thermomechanical dissociations during normal and faulty circumstances. To put it differently, by addressing these issues, large-scale utilization of HTS cables could be initiated. It worth noting that regularly the first step in any of these projects is the simulation of HTS cables. This step is conducted to attain a primary evaluation of cable performance under different circumstances and grid congestions.

The simulation phase is conductible through multiple methods, one is able to analyze the characteristics of the cable according to finite element-based methods, while other option is employment of circuit-based techniques. Finite element-based methods (FEM) are normally employed to model electromagnetic devices like synchronous generators, cables, fault current limiters, and many other elements of the power grid. Therefore, one way to model the exact behavior of HTS cables is the employment of FEMs which enable us to perceive the behavior of HTS cables and obtain an acceptable evaluation of AC loss, induced magnetic field, Lorentz force, and thermal behavior. These methods normally utilize the Galerkin approach to solving partial differential equations (PDEs) to predict the magnetic, electric and, thermal behavior of cables. Finite element-based methods can present a spectacular accuracy in modeling HTS cables. These methods have a low speed of solving, limiting the complexities to be connected to a power grid with an actual structure. The second type of modeling that is proposed to tackle these issues, known as the equivalent circuit model (ECM), which uses electrical elements like resistances, inductances, capacitances and is suitable for the real-time coding language, is used to model HTS cable behavior [5]. This method requires the least time and hardware among all other methods, and another important advantage of ECMs is their ability to be connected to the robust and complex power system.

The equivalent circuit model that takes into account electrical elements like resistances, inductances, capacitances and is suitable for the real-time coding language, is used to model HTS cable behavior

Regardless of the type of simulation, the accuracy of the model is a crucial factor that can highly impact our initial outlook of cable behavior in various situations. Consequently, this paper discusses the accuracy in modeling an HTS cable.

Sensitivity of a precise modeling

As mentioned earlier, the first step in HTS cable projects is to simulate the behavior of HTS cable under normal conditions. The accuracy of simulations could be altered with respect to some changes in the model. Depending on the utilization of the HTS cable, the accuracy could be adjusted. Obviously, along with increasing accuracy, simulation time rapidly increases, while lowering the accuracy could lead to a false assessment of HTS cable, which may lead to burning out of cables and tapes. Collapsing of HTS tapes could be catastrophic in some applications of HTS cables, like those used in turbo-electric airplanes or spaceships, and threaten the life of dozens of people. However, in some other applications, like power systems, collapsing is just a matter of economic concerns and does not jeopardize any lives. In order to avoid such consequences, a precise model of superconducting cables could be applied to simulations and, in doing so, reduce the risk of failure in tapes and cable. According to what was stated before, this study could play an important role in the initialization of an HTS cable project and simulations, which are carried out before a cable is tested in a real situation.

HTS cable description

Korean 22.9 kV HTS cable is one of the most commonly investigated, simulated, and utilized HTS cables among all other classes, which has been offered in multiple lengths, from 500-meter to 3-kilometer length. This class of HTS cables is able to provide distribution level loads in a high current carrying capacity, proper thermal performance during faults, and transient and acceptable mechanical behavior. Numerous types, structures, and cooling configurations have been offered for this class of cable. The structure of cable which is employed in this study is a cold dielectric and coaxial cable. This cable was

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first introduced in [6]. Table 1 gives useful information about designated cable with self-designed factors.

Modeling considerations

As mentioned earlier, modeling is a crucial step in any project dealing with superconducting cables. This paper takes the advantages of ECM to model the electromagnetic behavior of the cable. In an equivalent circuit model, parameters like current distribution and resistivity of cable are accessible. AC loss and induced magnetic fields could be calculated. To obtain these values, real-time programming is coupled with the created model in SIMULINK. Firstly, the E-J power law is applied to the model to correlate between temperature and critical current. Secondly, the Kim model is also applied to link the magnetic fields to the critical current. By accomplishing these two steps, the model could express the values of temperature, AC loss, and Lorentz force with respect to the altered values of the critical current with respect to temperature and magnetic field. However, without modeling the twisting effect on the electromagnetic behavior of cable, derived values are inaccurate. It raises a question as to why twisting is such an important factor in the accuracy of a model.

An equivalent model of an HTS cable has n layers in general, in which R_k is the resistivity of layer k, L_k is self-inductance of k^{th} layer, and M_{ki} is mutual inductance between layer k and i

Table 1. Parameters of designated HTS cable

Item	Value and type	Unit
Voltage	22.9	kV
Power	50	MW
Length	1	km
Tape	YBCO	*
Operational temperature	70	K
Material of former layer and thickness	Copper-1	mm
Material of shield layer	Copper	*
Insulation layer	PPLP	*
Number of tapes in each phase [A1 A2 B C]	[22 22 24 28]	*
Pitch length in each phase [A1 A2 B C]	[326 284 221 164]	mm
Pitch angle in each phase [A1 A2 B C]	[18.1 16.3 30.7 45.8]	degree
Former radiuses [A B1 B2 C]	[17 20 21 28]	mm
Coolant	LN2	*
Type of shield layer and thickness	Copper-1	mm
Critical temperature	92	K
Critical current of cable	4.158	kA
Critical current of tapes [A B C]	[189 174 125]	A

Consider Fig. 1 for an equivalent model of an HTS cable with n layers, in which R_k is the resistivity of layer k, L_k is self-inductance of k^{th} layer, and M_{ki} is mutual inductance between layer k and i. Twisting can alter the values of depicted resistances and inductances of this figure. Consequently, the magnetic field, current distribution, and critical current of each layer could undergo changes that lead to AC loss variation with respect to twisting.

The electrothermal performance of a cable could be improved by proper twisting, but mechanical constraints have to be considered

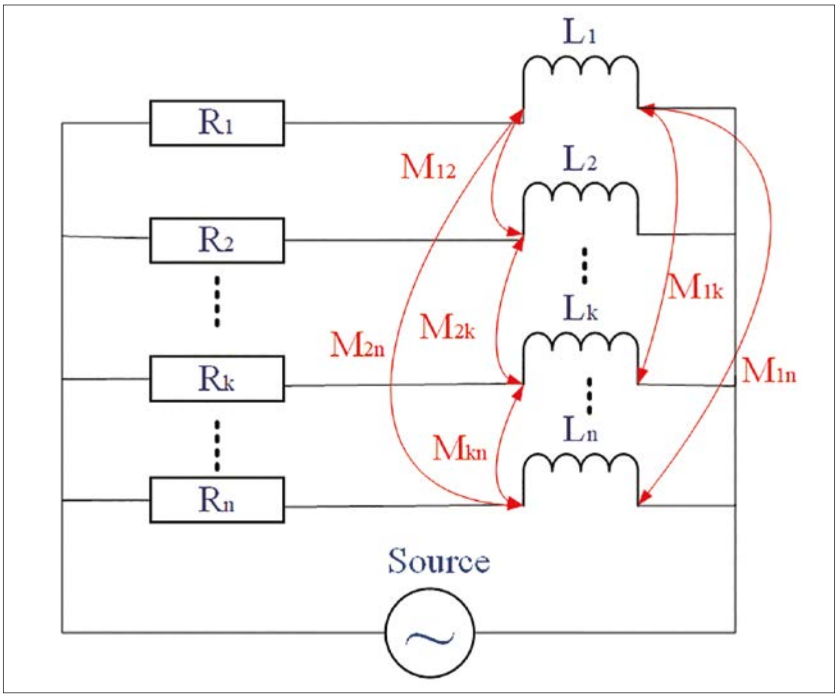

Figure 1. ECM of an HTS cable with n layer

Importance of twisting an exact model

Twisting can highly impact the efficiency of a cable. In other words, the electrothermal performance of a cable could be improved by proper twisting while mechanical constraints are considered. Without twisting, AC loss of cables could be extremely high, and this leads to the requirement of a cooling system with a higher capacity to cool down HTS cable, which might be assessed as an uneconomical circumstance. Accordingly, twisting is a necessary step in the manufacturing of HTS cables. As a matter of fact, superconducting tapes are wound on former layers of cables to reduce the magnetic field and, therefore, AC loss of the cable. By wounding tapes around the former, thermomechanical considerations lead to the downgrading of critical current at some points on tapes. Therefore, a method is required to model twisting in ECMs, in order to enable achieving critical current distribution in the whole length of tapes. Finite element-based methods linked with ECMs and analytical approaches are two common ways to conduct such simulations. However, twisting effects are also modellable with respect to stochastic processes which are known as Monte Carlo methods. Stochastic distribution has the advantage of easy and simple linking to ECMs and outstanding simulation speed.

Weibull probability function

Stochastic methods typically utilize a Weibull cumulative distribution function (WCDF) to model twisting. This distribution function was first introduced in 1951 by Swedish scientist Waloddi Weibull, and it is normally employed to model contingencies of the natural world or natural behavior of an object. In power systems, lighting, system reliability, and so many other intrinsic behaviors and concepts are modellable through this function [7].

According to [8], WCDF could also be applied to model the twisting effect on the critical current of tapes. WCDF uses a shape parameter and a scale parameter to model the downgrading of critical current values of tapes and whole cable.

To do this, every tape needs to be divided into sections. Section length is a crucial parameter to increase the accuracy of the model. Normally, the length of each section should be 1 cm. However, in this paper, for a cable with 1 km length, multiple section lengths are tested to analyze the accuracy of the model during the twisting of tapes. After dividing tapes into sections, a random Weibull number is dedicated to each section. Afterward, (1) is solved for $I_{n-c}(i)$ in each section [9]. By accomplishing this procedure, the twisting effect on tape and cable failure is modeled in an ECM, while the twisting effect on AC loss and the magnetic field is reachable according to [10].

$$R_w(i) = \exp\left(-\left[\frac{I_{nc}(i) - I_{c,min}}{I_0}\right]^m\right) \quad (1)$$

In this equation, $R_w(i)$ is a generated random Weibull number for each section of the tape, I_0 is the scale parameter, m is the shape parameter, and $I_{c,min}$ is the lower limit of critical current.

The twisting of the HTS cables and tapes has stochastical properties, and it typically utilizes a Weibull cumulative distribution function to model twisting

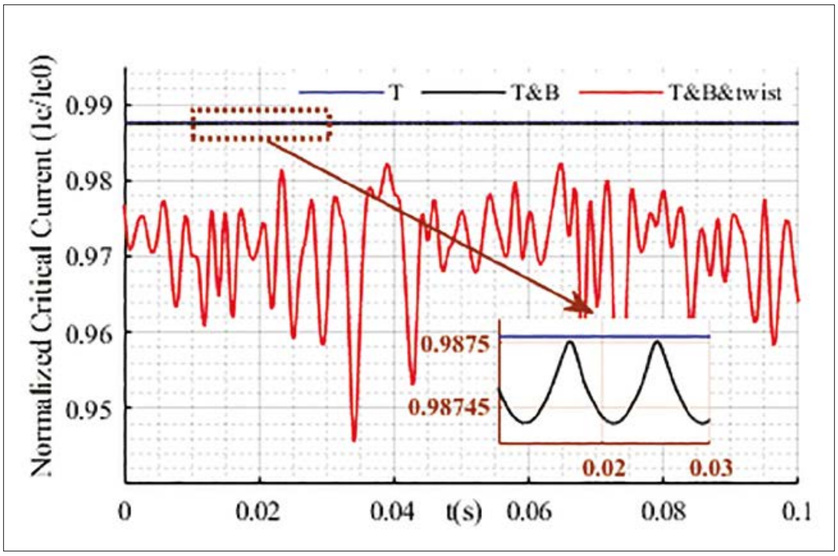

Figure 2. Twisting effect on critical current

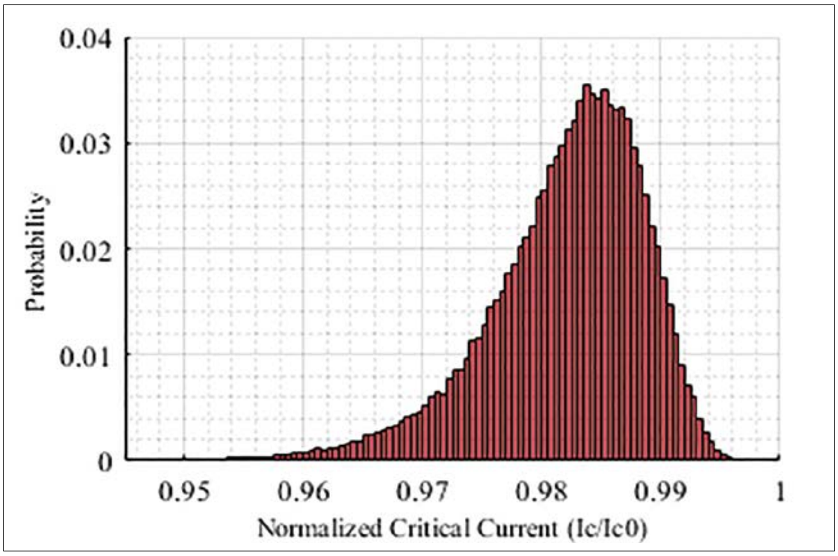

Figure 3. The probability distribution function of the normalized critical current of HTS tapes

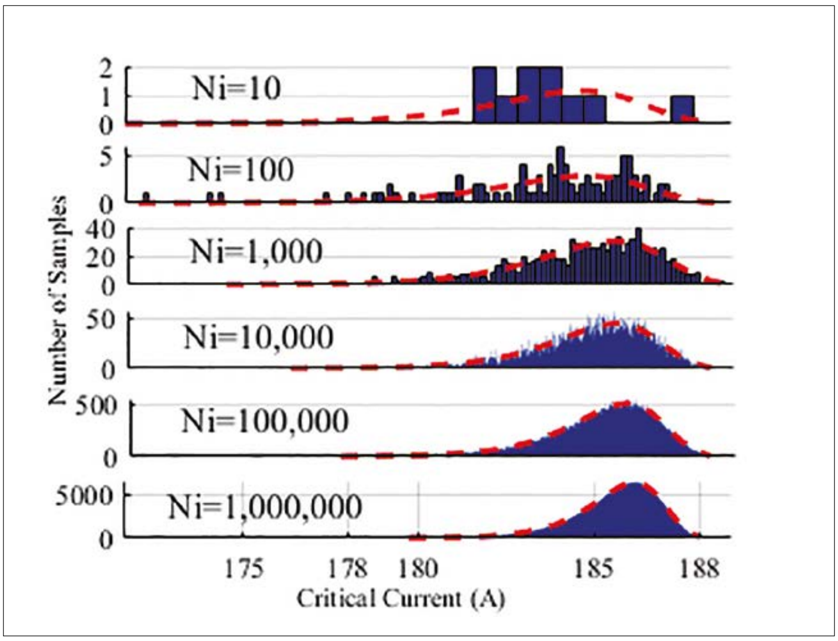

Figure 4. The critical current of phase A distribution with respect to the number of sections

Normalized critical current distribution in the HTS cable is governed by the Weibull probability density function

Fig. 2 represents the impact of twisting consideration on critical current degradation. In this figure, T is a critical current variation, while just temperature impresses this parameter. Variation of critical current with respect to temperature is a small value, while T&B is dedicated to effects of temperature and magnetic field. Considering these values, the critical current drops about 98.745 % in comparison to just modeling temperature. At last, in T&B, twisting is also considered. As a matter of fact, twisting leads to a maximum of 91.5 % drop in critical current and a minimum of 98.2 %. This figure displays the importance of modeling the twisting effect on the behavior of the cable.

Results and discussion

Firstly, the critical current behavior of superconducting tapes should be analyzed. Fig. 3 depicts the probability distribution function of calculated values of critical current. Obviously, this figure, which is derived according to 100,000 sections, shows a close behavior to the Weibull distribution function. It raises a question as to how many sections in each tape could give us an exact model of the tapes' behavior.

To answer this question, multiple section lengths are considered in this study. A section length in each tape could highly impact the accuracy of the model. Fig. 4 represents generated Weibull distribution frequency according to section length variations. In this figure, the horizontal axis is dedicated to the critical current of tapes in phase A, and the vertical axis is the frequency, and N_i is the number of sections. In addition, we have assumed that tapes are integrated, and the joints of tapes are neglected. This assumption is due to the fact that joints are just connection points of tapes, and twisting has no remarkable effect on them. According to Fig. 4, by the increasing of section length, accuracy also increases. With respect to the results of this section length, it can be observed that the critical current of tapes starts to behave closely to an ideal WCDF after 1,000 sections. For some applications of tapes, this accuracy is acceptable. Though, for some other applications, accuracy needs to be improved. Again, a decrease in the section length is conducted, and this value is changed to 10 cm (0.1 m). By doing this, the critical current of tapes shows a remarkable behavior closely to an ideal WCDF. In the two last steps, while section lengths are 1 cm (0.01 m) and 0.1 cm (1 mm), a very small change in behavior of calculated data is observable.

Fig. 5 illustrates the minimum calculated critical current with respect to the increment in the section number. Obviously, the minimum of the critical current drops while section numbers are increased to 1,000,000. The calculated minimum is a crucial factor in the assessment of the total critical current of a cable. Making a false assessment of cable critical current increases the risk of failure of a cable during operation.

To increase the accuracy of the presented model and gain a closer behavior of tapes to WCDF, section lengths are increased to the last possible value. However, this leads to a significant simulation time. Table 2 shows the relation between time and the number of sections. According to this table, section number 1,000,000 requires the highest simulation time. It should be noted that resulted simulation time is related to the hardware properties of the utilized computer, and these values are acquired by a computer with 16 GB RAM and AMD Ryzen 7 1700 eight-core processor unit (CPU).

Selecting the number of sections is now discussable with respect to Fig 6. In Fig 6 some statistical indices are shown which enable us to designate a proper section length for simulations. Mean, median and variance are approximately stable after the number of sections 100,000, while the mode of data is hardly stable after 800,000 sections. This behavior of a mode refers to the definition of mode, which is the most repeated data in distribution. According to this definition and with respect to the stochastic procedure of the proposed method, repeated data could not be the same as before, and this leads to instability of the mode. This means that the proper number of sections is between 10,000 and 100,000 with respect to Fig. 6.

According to Fig. 6, Weibull cumulative distribution function is able to present a model with high accuracy. Relying on demanded accuracy of the model, WCDF could be adjusted to present an optimum level of accuracy. This adaptivity of the WCDF method for modeling the twisting effect is transcending to other methods that utilize direct mechanical formulations with respect to their simulation time and complexity.

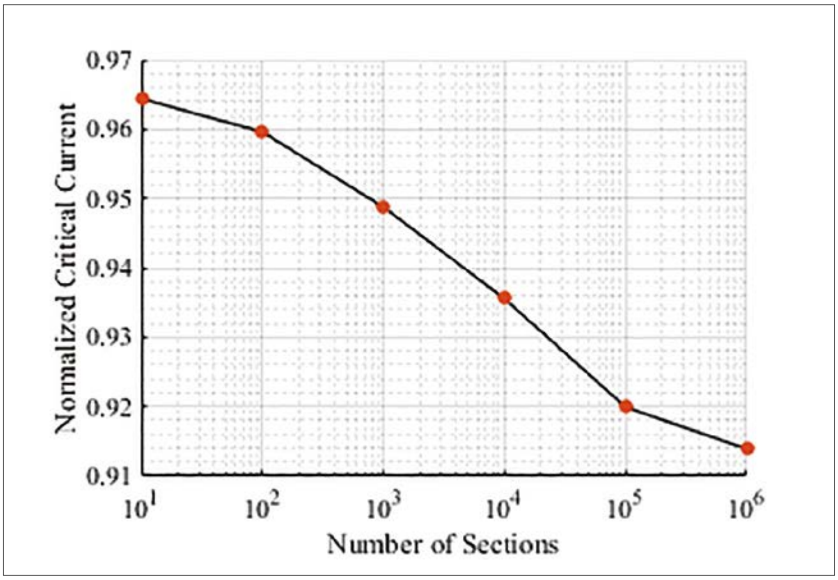

Figure 5. Minimum calculated critical current in tapes of phase A while the number of sections increases

The question is how many sections are needed to model the HTS tape's behavior accurately but to keep the simulation levels acceptable

Conclusion

This paper clarifies the procedure of modeling the twisting effect in an equivalent circuit model that is conductible through sectionizing tapes and applying the Weibull distribution function. By utilization such a method, an accurate model of a high-temperature superconducting cable is accessible. By increasing the number of sections, the model gains higher accuracy, and the minimum critical current of tapes is predicted precisely. For 100 sections, the minimum calculated critical current of tapes is 96 % of critical current without

Table 2. Simulation time for a different number of sections

Number of sections	Simulation time (s)
10	210
100	2,078
1,000	3,154 s
10,000	28,000 (7 hours)
100,000	325,000 (90.27 hours - 4 days)
1,000,000	2,975,200 (826 hours - 34 days)

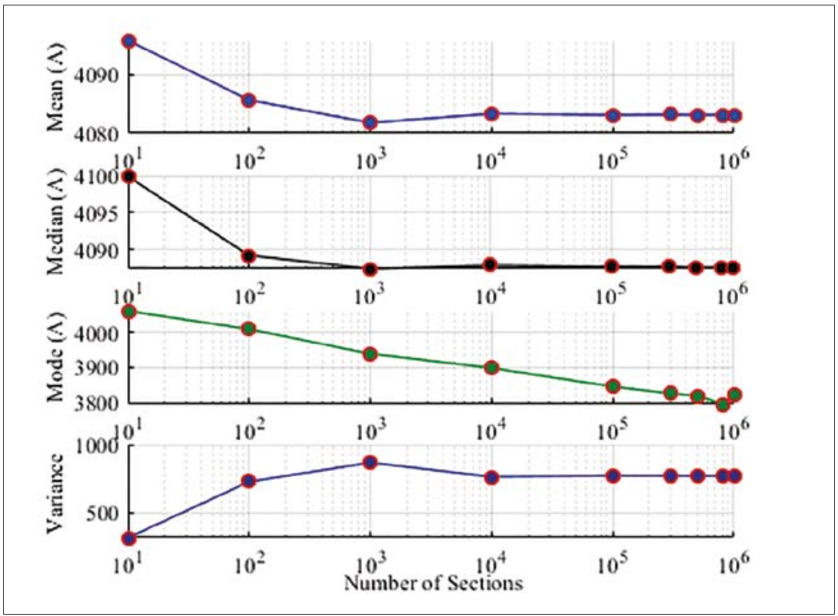

Figure 6. Mean, median, mode, and variance of the critical current of the whole cable with respect to the number of sections

Conducted analyses show that the proper number of sections should be selected between 10,000 and 100,000 to get the optimal tradeoff between accuracy and simulation time

considering twisting, while for 1,000,000 sections, this value is reduced to 91.5 % of the real value. Obviously, along with the increase in the number of sections in the stochastic method and shortening the length of sections, the accuracy of the model could be increased. However, section numbers greater than 10^4 may cause a negligible increase in the accuracy, while the simulation times rise significantly. Thus, the number of 10^4 sections could be assessed as an optimal point, in which the accuracy and simulation time are at the optimum state.

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