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Parametric estimation study of interstrand conductance in multi-strand superconducting cables ☆

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Abstract

Interstrand conductance is a key parameter to understand the current distribution and stability events in multi-strand superconducting cables. In this paper, a new approach employing the parameter estimation method from system identification theory is applied to estimate the interstrand conductance from existing current distribution model based on experimental data of voltage differences at cable ends. Based on transient voltage measurements at cable ends this method estimates interstrand conductance conveniently and accurately under different conditions (temperature, cable length, cable compaction, etc.). The details of interstrand conductance between all combinations of sub-cables at different cabling stages were obtained. The influence of mechanical load on interstrand conductance was also studied. The experimental data sheds new light on how the mechanics of cable compaction and movement under simulated Lorentz load affects the electrical parameters, namely the interstrand conductance. The data are useful input for cable stability simulations and AC loss estimation, and the experimental method can be used to better characterize cables prior to magnet winding.

Keywords: Interstrand conductance; Multi-strand superconducting cables; Parameter estimation

1. Introduction

Multi-strand superconducting cables are widely used in large-scale magnets to achieve high current carrying capacity. Stability of the superconducting cable is important for continuous and reliable operation. Interstrand conductance is a key parameter to understand the current re-distribution during stability events in multi-strand superconducting cables. Detailed and accurate evaluation of interstrand conductance is also useful for AC loss estimations [1].

The interstrand conductance is determined by the internal resistance of the strand and the surface contact condition, the latter being the dominating factor [2]. Until now the interstrand conductance in cables has been extensively measured by the four-point method [3,4]. However, only a limited number of strand/sub-cables pairs can be measured simultaneously in a single set-up. It takes a lot of experimental work to obtain the full database of the interstrand conductance between all combinations of strand/sub-cable pairs. The four-point method is restrained to steady state electrical conditions.

In our study, we propose an innovative approach to evaluate the interstrand conductance using parametric estimation method from system identification theory [5]. In this paper, this method is refined by developing a sequential least squares estimation method that utilizes extra fresh experimental data to improve accuracy [6]. Based on transient current and voltage measurements at cable ends on a $6 \times 5 \times 6$ NbTi superconducting cable, this method evaluated interstrand conductance conveniently and accurately under different conditions (temperature, cable length, cable compaction, etc.). The details of interstrand conductance

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between all combinations of strand/sub-cables were obtained. The influence of mechanical load on interstrand conductance was also studied.

2. Models

The current distribution in multi-strand superconducting cables can be well described by the distributed parameters circuit model developed by Bottura et al. [7,8] as shown in Fig. 1, which is the elemental length dx in a superconducting cable made by N strands.

Assuming that each strand carries a current uniformly distributed in its cross section, and the current transfer between different strands happens along the length of the cable in a continuous manner, the following equations can be obtained from Kirchhoff's current and voltage laws:

$$\text{Voltage law}: \frac{\partial \mathbf{v}}{\partial x} = \mathbf{ri} - \mathbf{l}\frac{\partial \mathbf{i}}{\partial t} + \mathbf{v}^{\text{ext}} \tag{1}$$

$$\text{Current law}: \frac{\partial \mathbf{i}}{\partial x} = \mathbf{gv} \tag{2}$$

In Eqs. (1) and (2), the vectors $\mathbf{i}$ and $\mathbf{v}$ contain the N-strand currents and voltages, respectively. $\mathbf{l}$, $\mathbf{r}$, and $\mathbf{g}$ are the system inductance, resistance, and conductance matrices of dimension $N \times N$. The vectors and matrices are defined as:

$$\mathbf{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{bmatrix}, \quad \mathbf{i} = \begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ i_N \end{bmatrix}, \quad \mathbf{v}^{\text{ext}} = \begin{bmatrix} v_1^{\text{ext}} \\ v_2^{\text{ext}} \\ \vdots \\ v_N^{\text{ext}} \end{bmatrix}$$

$$\mathbf{r} = \begin{bmatrix} r_1 & 0 & \cdots & 0 \\ 0 & r_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_N \end{bmatrix}, \quad \mathbf{l} = \begin{bmatrix} l_{1,1} & l_{1,2} & \cdots & l_{1,N} \\ l_{2,1} & l_{2,2} & \cdots & l_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ l_{N,1} & l_{N,2} & \cdots & l_{N,N} \end{bmatrix},$$

$$\mathbf{g} = \begin{bmatrix} -\sum\limits_{\substack{k=2 \\ k\neq 1}}^{6} g_{1,k} & g_{1,2} & \cdots & g_{1,6} \\ g_{2,1} & -\sum\limits_{\substack{k=1 \\ k\neq 2}}^{6} g_{2,k} & \cdots & g_{2,6} \\ \vdots & \vdots & \ddots & \vdots \\ g_{6,1} & g_{6,2} & \cdots & -\sum\limits_{\substack{k=1 \\ k\neq 6}}^{6} g_{6,k} \end{bmatrix} \tag{3}$$

Also, the total operating current i_{op} in the cable cross section is conserved at any point in time and space:

$$\sum_{h=1}^{N} i_h = i_{\text{op}} \tag{4}$$

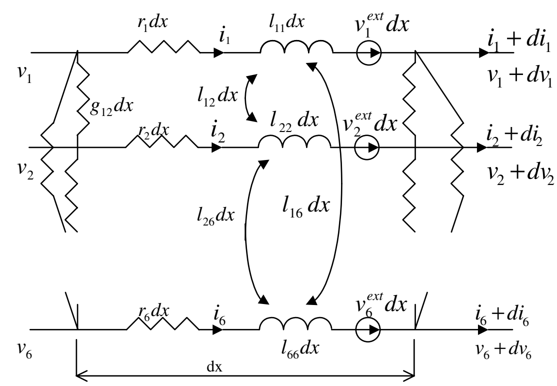

Fig. 1. Distributed parameters circuit model of multi-strand superconducting cables. v and i are voltage and current, respectively. v^{ext} is external excited voltage per unit length of cable, r is longitudinal resistance per unit length of cable, l is self and mutual inductance per unit length of cable, and g is interstrand conductance per unit length of cable. In this case $N = 6$.

Assuming that the interstrand conductance is uniform along the cable axis, the spatial derivative of the interstrand conductance matrix $\mathbf{g}$ is nil. Taking the spatial derivative of Eq. (2), a single system of partial differential equations for the currents in the strands is obtained:

$$\mathbf{gl}\frac{\partial \mathbf{i}}{\partial t} + \frac{\partial^2 \mathbf{i}}{\partial x^2} + \mathbf{gri} - \mathbf{gv}^{\text{ext}} = 0 \tag{5}$$

In the above equation, the longitudinal resistance $\mathbf{r}$ is known from the properties of the superconducting/copper matrix material. The inductance $\mathbf{l}$ can be found analytically from the cable geometry (e.g., cable length, sub-cable radius and distance between the sub-cables) [9]. Using the initial approximate value of interstrand conductance obtained from four-point method measurement, we can have the numerical solution of $\mathbf{i}(x, I)$.

Eq. (2) can be rearranged as

$$\Delta\mathbf{v} = \frac{\partial \mathbf{i}}{\partial x}(\breve{\mathbf{g}}^{-1})^{\text{T}} \tag{6}$$

in which the Nth strand is removed and taken as voltage reference, $\Delta\mathbf{v}$ is the voltage differences with respect to the Nth strand, which can be measured by experiments. $\partial\mathbf{i}/\partial x$ can be obtained numerically by solving the system Eq. (5). $\breve{\mathbf{g}}$ is unknown $(N-1)\times(N-1)$ conductance matrix obtained by removing the Nth row and Nth column of $\mathbf{g}$ defined in Eq. (3). Since the interstrand conductance is non-zero, the matrix $\breve{\mathbf{g}}$ is nonsingular and has its unique inverse.

In Eq. (6), consider the spatial derivative of current $\partial\mathbf{i}/\partial x$ as input, and the voltage differences ($\Delta\mathbf{v}$) as output. If at the cable terminal ($x = L$), we can measure the output ($\Delta\mathbf{v}$) from experiments and the input $\partial\mathbf{i}/\partial x$ from simulation, then we can estimate the parameter $\mathbf{g}$ (interstrand conductance) in the expression by using least squares method to minimize the "error" between the observed and calculated voltage differences.

Suppose we have m sets of measurements. Eq. (6) can be arranged in the following form: