Prediction of Critical Currents in Superconducting Windings using Wire Data and Field Modeling

S. D. Nielsen, and R. R. Taylor

Abstract—This paper reports on the integration of publicly available HTS conductor electromagnetic performance data into a magnetic Finite Element model for determining the critical current distribution along a section of conductor in a spatially fluctuating magnetic field. The simulation results from this model are shown to be in close agreement to experimentally obtained results. Typically monitoring for quench is done by measuring the volt-drop along a section of conductor to be protected and determining when the volt-drop reaches a predetermined level. This work shows that under spatially varying magnetic field conditions, small areas of the voltage monitored section of conductor could have already surpassed the critical current level for that section of conductor and hence stand a high probability of being a site for quench. Under these conditions, it is proposed to use the maximum electric field developed along the conductor as a criterion for determining the critical current. This work points to the need for developing a quench detection technique that can be applied to much smaller sections of conductor, particularly in geometries that are expected to experience the largest variations of magnetic field such as that in a rotating electric machine.

Index Terms— Critical current measurement, Finite element methods, HTS coils, Quench, Modeling

I. INTRODUCTION

FOLLOWING the discovery of high-temperature superconductors (HTS) in 1986, manufacturers and researchers have utilised these materials to produce wires, tapes, thin-film and bulk formulations. This has allowed for the design of a wide range of power systems devices. These HTS technologies offer higher efficiencies and greater power densities over conventional copper conductor-based technologies [1, 2]. In turn, these emerging technologies are potential key enablers for wind farm generators, electric aircraft and naval propulsion, and for providing improved power grid reliability and resilience [3, 4]. Despite the great promise of HTS technologies, commercial adoption has been slow. It is well-recognized that the high cost of HTS materials and cooling technology, as well as the reliability of cooling systems, constitute major barriers to the wide scale adoption of HTS technology [4]. As with the introduction of any new technology, there is a lack of proven design guidelines and/or criteria that can be used to enable the efficient use of the technology with confidence. To address this, there is a need to provide designers with such guidelines and tools that account for the wide variety of characteristics presented across the evolving library of available commercial HTS conductors and the vastly different Electro-Magnetic (EM) environments the conductors can potential be exposed to.

A key design parameter when using HTS materials in an electrical machine design is the electrical current magnitude the conductor can support; in the superconducting state; under the EM operating conditions experienced in the machine. The local critical current \( I_c \) of a section of conductor is an upper limit to the electrical current that section can carry. This local \( I_c \) can vary along a length conductor due to manufacturing defects and process variations. It is well documented that the critical current for a superconductor is a complex function of the externally applied impinging magnetic field density vector \( \mathbf{B} \) on the conductor’s surface and the temperature \( T \) the conductor is operating under [5-7]. For HTS conductors this function varies significantly between different conductors, and even batches of the same conductor, due to their manufacturing quality control, anisotropy, complex engineered pinning landscapes, and the various mechanical stabilizing materials used.

HTS conductor databases are now available detailing static EM test results of short lengths of commercial YBCO and BSCCO wires and tapes over a wide range of operational temperatures \( T \), currents \( I \) and external impinging magnetic fields densities \( \mathbf{B} \) [7]. These results do not give an indication of the variability of the critical current \( I_c \) that can be expected along a much longer length of manufactured tape [5, 8]. There is also uncertainty in the exact EM environment an HTS conductor will be expected to function under when designing an electrical machine. To account for these uncertainties, designers have been obliged to adopt a conservative position and use large safety margins when estimating the maximum current the conductor will be able to sustain. This sub-optimal design approach has led to cost and size increases in designs and has contributes to the hesitance for widespread adoption of HTS technology. This paper will look at a method of incorporating currently available HTS conductor data into EM simulations to improve the prediction of HTS conductor operation in an electrical machine.

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EM characterizations of commercial HTS conductors reveal an often strong and asymmetric dependence of the critical current $I_c$ on the angle $\Phi$ and magnitude of the impinging externally applied magnetic field density vector $\mathbf{B}_e$. This dependence of the critical current on the impinging magnetic field density vector is unique to each conductor. In fact, for some conductors the maximum and minimum critical currents do not occur when the impinging magnetic field density vector is at 0° or 90° from the normal to the conductor’s surface, as is often assumed for numerical models [6, 7]. Several researchers have incorporated available HTS EM performance data into EM simulations with a view to modeling the performance of HTS conductors in EM environments experienced in typical machines [9-12]. The results of this work have demonstrated the validity of this technique via comparison to measured results.

Such models would allow for improved accuracy in predicting the critical current $I_c$ distribution along the length of HTS conductors for specific geometries in various EM environments. It is well accepted that a lack of sufficiently effective detection and control of the critical current and hence quench, contributes significantly to the necessity for conservative safety margins in existing HTS designs [13], and a recent roadmap for superconducting machines identifies quench detection and control as a pertinent area of improvement for HTS technology to fulfil its potential [4].

### A. Method

Fig. 1 presents a flow chart of the developed modelling methodology. A 2D magnetostatics plane-parallel Finite Element Method (FEM) simulation is used to determine the magnetic field vector along the tape due to an external magnetic field source (step 1). This 2D geometry is derived from the experimental setup shown in Fig. 2. A 240mm long section of HTS tape is modeled as a 2D curve in space, placed in the external magnetic field produced by a 50x50x25mm N42 permanent magnet, that is positioned 0.1mm from the surface of the tape. The curve representing the tape is divided into eight 30mm voltage measurement segments, labelled $dv_0$ to $dv_7$. The resultant magnetic field vector $\mathbf{B}_e$ relative to the tape’s surface is calculated at 24000 points evenly spaced along the curve representing the tape. The magnitude of the magnetic field density at the $n$th point along the tape $B_n$ and the angle $\Phi_n$ between $\mathbf{B}_n$ and the normal to the tape is extracted from the FEM simulation. Using these simulation results and the publicly available tape characterization data for Amperium 8502 HTS tape at 77.5K [7] shown in Fig. 3, the values of $I_c$ and the $n$-power at the $n$th point along the tape are estimated (step 2). Using the minimum value of $I_c$ along the length of the tape, an upper limit to the operational current of the machine can be estimated under the modeled EM operational conditions.
However, to evaluate the model against an experimental setup, further steps in the modeling are necessary. In an experimental setup the volt drop along defined length of the HTS conductor is typically measured as a function of the current flowing through the conductor. From these measurements, it is possible to then calculate the effective \( I_c \) and the effective \( n \)-power for these segments of HTS conductor. This is done by fitting the measured volt-drop versus current magnitude to the E-J power law (1). This relates the volt drop \( V \) along a tape segment of length \( d \) to the current \( I \) flow in the segment. \( E_0 \) is the electric field at the critical current \( I_c \) and is typically taken as \( 1 \mu \text{V/cm} \). In the experimental setup detailed here, these volts drop measurement segments are each 30mm long and are labeled as dv0 to dv7 in Fig. 2.

\[
V = E_0 d \left( \frac{I}{I_c} \right)^n
\]  

(1)

Step 3 in Fig. 1 is used to calculate the volt-drop \( V_n \) along any small segment on the tape with a length of \( \Delta d = 240 \text{mm} / 24000 \) at a particular current \( I_m \). These volt-drops can then be summed over the measurement tape segment length \( d = 30 \text{mm} \) to obtain the simulated measured voltage for that tape segment at the current \( I_m \) (step 4). By sweeping through a range of \( I_m \), the current-voltage (I-V) characteristic for each tape measurement segment is determined. The E-J power law may then be fitted to each tape segment’s I-V curve to attain an effective \( I_c \) and the effective \( n \)-power values for each 30mm tape measurement segment (step 5). Using step 3, the electric field \( E \) over the distance \( \Delta d \) at a particular current \( I_m \) can be calculated at any point \( n \) along the tape. This can be used to determine if any small section of tape exceeds the limit of \( E_0 \) before the segment reaches the effective \( I_c \) for its 30mm voltage measurement segment.

Fig. 4 shows the magnitude of the calculated magnetic field density \( B \) and its angle from the normal to the tapes surface \( \Phi \), along the path of the HTS tape for the geometry in Fig. 2. Fig. 5 shows the calculated critical current \( I_c \) and the \( n \)-power along the path of the HTS tape. The calculated \( n \)-power values are seen to be noisy; this is due to the noisy \( n \)-power input characteristic data shown in Fig. 3. By sweeping the applied current to the tape from 0A to 180A, the volt-drop along each of the eight 30mm long measurement tape segments dv0 to dv7 is calculated. The results of this are shown in Fig. 6. The effective critical current \( I_c \) and the \( n \)-power values for each of the eight measurement sections of tape is calculated using curve fitting to (1), the results of this are shown in Table I.

### III. EXPERIMENTAL WORK

The physical setup of the experimental verification of the modelling is shown in Fig. 2. This was constructed using a 240mm long piece of 4.8mm wide Amperium 8501 tape wound around a wooden “horse-shoe” former. The setup was immersed in LN2 at atmospheric pressure. The ends of the tape are clamped in two heavy copper connections so current can be injected into the tape using a precision DC power supply operating in the constant current mode. Thin insulated copper wires for voltage measurements are soldered directly onto the tape, dividing it into eight 30mm voltage measurement segments. The effective \( I_c \) and \( n \)-power values for each of the eight 30mm tape segments is calculated using curve fitting to (1), the results of this are shown in Table I.

**TABLE I**

| Dv | Simulated Amperium 8502 | Measured Amperium 8501 |
|---|---|---|
| | \( I_c \) | \( n \) | \( I_c \) | \( n \) | \( I_c \) \( \mu \text{V/cm max} \) | \( n \) | \( I_c \) | \( n \) |
| dv0 | 168.3 | 33.6 | 168.2 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
| dv1 | 165.8 | 33.5 | 164.2 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
| dv2 | 167.7 | 33.5 | 167.1 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
| dv3 | 168.3 | 33.6 | 168.2 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
| dv4 | 166.2 | 33.7 | 168.1 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
| dv5 | 167.7 | 33.5 | 167.1 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
| dv6 | 166.2 | 33.7 | 168.1 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
| dv7 | 167.7 | 33.5 | 167.1 | 33.9 | 36.8 | 18.2 | 27.1 | 171 | 33.9 |
IV. DISCUSSION

The resultant effective $I_c$ and the effective $n - \text{power}$ from the measured and the simulated results over the eight 30mm tape segments with and without the magnet are presented in Table. I. The Amperium 8501 used in the measurements, and the Amperium 8502 used in the simulations, have different critical currents $I_c$ and $n - \text{power}$ values for the same external conditions. It is however assumed that the tapes would have been constructed using the same formulation and processing parameters. Therefore, the results from the two tapes can be compared by normalizing the results using the maximum effective critical current and maximum effective $n - \text{power}$ values obtained for all eight of the 30mm segments. The results of this normalization are shown in Table. II. From these results, it is evident that the critical effective current as well as the effective $n - \text{power}$ values of the eight-tape segment for the simulation and the measurements are in good agreement.

Fig. 7 presents a comparison of the measured I-V curve using Amperium 8501 tape and the simulated results for Amperium 8502 tape at 77K for segments $dv_0$, $dv_2$ and $dv_7$ with the magnet present. The I-V curves of the simulated data have been scaled in the current axis such that the critical current $I_c$ of the measured results line up with that of the simulated results. This figure shows that the simulation results closely match those of the measured results, even when the tapes are different widths.

The criteria for determining when the critical current is reached for a particular section of tape is determined by the average electric field along that section of tape. This criterion is often used as $1\mu$V/cm. This holds true if the section of tape experiences a uniform magnetic field or the length of the section is so short that this criterion of uniform magnetic field as can be assumed to be true as is shown in Fig. 8 for tape section $dv_7$. However, if the section of tape experiences a changing magnetic field distribution of over its length, this criterion does not hold true as can be assumed to be true as is shown in Fig. 8 for tape section $dv_0$ to $dv_2$. From the modelling it is seen that for some 30mm measurement sections of tape experiencing large changes of magnetic field, such as $dv_0$ to $dv_2$, when the effective critical current listed in Table. I is applied to the tape, small areas of the tape have electric field values that exceeded $1\mu$V/cm as is shown in Fig. 8 for tape section $dv_0$ to $dv_2$. These small areas of tape therefore have a high probability of developing or are already in quench. Therefore, when the magnetic field is spatially varying along the length of the tape, it is better to use the maximum electric field over that section as a criterion for determining critical current. Using this criterion of determining the critical currents for the eight measurement sections of modelled tape is shown in Table. I. This would suggest that it is necessary to develop a monitoring method that is able to monitor much smaller segments of tape $\approx 10\mu$m particularly for conditions where the spatial magnetic field changes over the tape’s length. This would provide a more effective quench detection method in power equipment such as rotating machines where the spatial magnetic field is complex and changes rapidly.

V. CONCLUSION

An algorithm has been developed to simulate the I-V performance of an HTS tape in a non-uniform magnetic field environment. The modelled effective $I_e$ and the effective $n$-power values obtained from the I-V characteristics determined across 30mm tape segments are compared to experimentally measured data by normalizing the results. The simulation results are shown to be in close agreement to the experimental results at 77K. Monitoring the voltage across a segment of tape to determine the effective $I_e$ or even quench, is high risk, particularly in a non-uniform magnetic field distribution such as that found in a rotating machine. Voltage monitoring across much smaller segments of tape, ideally in regions subjected to high non-uniformity of the impinging magnetic field, would provide a lower risk method of monitoring/measuring the critical current $I_e$ or quench in complex magnetic field environments.

| Div | Measured Amperium 8501 $I_e$ | No Magnet $I_e$ | Simulated Amperium 8502 $I_e$ | No Magnet $I_e$ |
|-----|----------------------------|----------------|----------------------------|----------------|
| $dv_0$ | 0.28 | 0.38 | 0.97 | 0.83 | 0.22 | 0.54 | 1.00 | 1.00 |
| $dv_1$ | 0.36 | 0.60 | 0.99 | 0.88 | 0.37 | 0.62 | 1.00 | 1.00 |
| $dv_2$ | 0.76 | 0.65 | 1.00 | 0.91 | 0.59 | 0.77 | 1.00 | 1.00 |
| $dv_3$ | 0.96 | 0.88 | 0.97 | 0.83 | 0.95 | 0.98 | 1.00 | 1.00 |
| $dv_4$ | 1.00 | 0.96 | 0.99 | 0.90 | 0.98 | 0.99 | 1.00 | 1.00 |
| $dv_5$ | 0.97 | 0.85 | 0.97 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 |
| $dv_6$ | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $dv_7$ | 0.99 | 1.00 | 0.97 | 0.87 | 1.00 | 1.00 | 1.00 | 1.00 |
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