GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA
FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2025

THIRD INTERNATIONAL CONFERENCE

24-25 SEPTEMBER, 2025

TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

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GOCE DELCEV UNIVERSITY, STIP
FACULTY OF ELECTRICAL ENGINEERING

ТРЕТА МЕЃУНАРОДНА КОНФЕРЕНЦИЈА
THIRD INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2025

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PREFACE

The Third International Conference "Electrical Engineering, Technology, Informatics, Mechanical Engineering and Automation – Technical Sciences in the Service of the Economy, Education and Industry" (ETIMA'25), organized by the Faculty of Electrical Engineering at the "Goce Delchev" University – Shtip, represents a significant scientific event that enables interdisciplinary exchange of knowledge and experience among researchers, professors, and experts in the field of technical sciences. The conference was held in an online format and brought together 78 authors from five different countries.

The ETIMA conference aims to establish a forum for scientific communication, encouraging multidisciplinary collaboration and promoting technological innovations with direct impact on modern life. Through the presentation of scientific papers, participants shared the results of their research and development activities, contributing to the advancement of knowledge and practice in relevant fields.
The first ETIMA conference was organized four years ago, featuring 40 scientific papers. The second conference took place in 2023 and included over 30 papers. ETIMA'25 continued this scientific tradition, presenting more than 40 papers that reflect the latest achievements in electrical engineering, technology, informatics, mechanical engineering, and automation.

At ETIMA'25, papers were presented that addressed current topics in technical sciences, with particular emphasis on their application in industry, education, and the economy. The conference facilitated fruitful discussions among participants, encouraging new ideas and initiatives for future research and projects.

ETIMA'25 reaffirmed its role as an important platform for scientific exchange and international cooperation. The organizing committee extends sincere gratitude to all participants for their contribution to the successful realization of the conference and its scientific value.

We extend our sincerest gratitude to all colleagues who, through the presentation of their papers, ideas, and active engagement in discussions, contributed to the success and scientific significance of ETIMA'25.

The Organizing Committee of the Conference

ПРЕДГОВОР

Третата меѓународна конференција „Електротехника, Технологија, Информатика, Машинство и Автоматика – технички науки во служба на економијата, образованието и индустријата“ (ЕТИМА’25), организирана од Електротехничкиот факултет при Универзитетот „Гоце Делчев“ – Штип, претставува значаен научен настан кој овозможува интердисциплинарна размена на знаења и искуства меѓу истражувачи, професори и експерти од техничките науки. Конференцијата се одржа во онлајн формат и обедини 78 автори од пет различни земји.

Конференцијата ЕТИМА има за цел да создаде форум за научна комуникација, поттикнувајќи мултидисциплинарна соработка и промовирајќи технолошки иновации со директно влијание врз современото живеење. Преку презентација на научни трудови, учесниците ги споделуваат резултатите од своите истражувања и развојни активности, придонесувајќи кон унапредување на знаењето и практиката во релевантните области.

Првата конференција ЕТИМА беше организирана пред четири години, при што беа презентирани 40 научни трудови. Втората конференција се одржа во 2023 година и вклучи над 30 трудови. ЕТИМА’25 продолжи со истата научна традиција, презентирајќи повеќе од 40 трудови кои ги отсликуваат најновите достигнувања во областа на електротехниката, технологијата, информатиката, машинството и автоматиката.

На ЕТИМА’25 беа презентирани трудови кои обработуваат актуелни теми од техничките науки, со посебен акцент на нивната примена во индустријата, образованието и економијата. Конференцијата овозможи плодна дискусија меѓу учесниците, поттикнувајќи нови идеи и иницијативи за идни истражувања и проекти.

ЕТИМА’25 ја потврди својата улога како значајна платформа за научна размена и интернационална соработка. Организациониот одбор упатува искрена благодарност до сите учесници за нивниот придонес кон успешната реализација на конференцијата и нејзината научна вредност. Конференцијата се одржа онлајн и обедини седумдесет и осум автори од пет различни земји.

Изразуваме голема благодарност до сите колеги кои со презентирање на своите трудови, идеи и активна вклученост во дискусиите придонесоа за успехот на ЕТИМА’25 и нејзината научна вредност.

Организационен одбор на конференцијата

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USE OF MACHINE LEARNING FOR CURRENT DENSITY DISTRIBUTION ESTIMATION OF REBCO COATED CONDUCTORS

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Abstract

Rare-earth barium copper oxide (REBCO) coated conductors (CC) have the following advantages: high current density under high magnetic fields and mechanical strength. The REBCO CCs are expected to be applied for high field applications. However, the REBCO CCs have inhomogeneous critical current density due to local cracks or voids in the REBCO layer. It is known that these local defects might cause the normal-state transition, which can lead to significant damage to the magnet. It is necessary to perform non-destructive measurement of the REBCO conductor properties. A Hall Probe Measurement (HPM) is a non-destructive inspection method for critical current density distribution. In the HPM, a magnetic field is applied to the REBCO CC and the field induced by the shielding current is measured. Subsequently, the current density distribution is estimated from the measured field using inverse analysis, in common, based on the Biot-Savart Law or the Fourier transform. However, the resolution of the current density distribution by these methods is coarse and sometimes insufficient to detect the micro-scale defects. In this research, we have built a method to estimate the critical current distribution using a convolutional neural network (CNN). The CNN model is trained using a set of distributions of the critical current density and the field. The estimation accuracy of the CNN model is investigated, and we compare the estimation results with those using conventional methods.

Key words

REBCO coated conductor, Critical current density distribution, Hall probe measurement, CNN

Introduction

Several useful technologies have been developed that can be realized with superconducting technology. The establishment of technology for superconductivity applications is desired. REBCO ($REBa_2Cu_3O_{7-\delta}$), a cuprate superconductor using rare earths, has excellent superconducting properties. REBCO can maintain high current density even at high temperatures and high magnetic fields. REBCO conductors also have excellent structural mechanical strength. Because of these characteristics, there is a strong demand for REBCO to be used in high-field devices such as fusion reactor magnets and NMR. This is because these devices require high currents and are used in high magnetic fields, and a large mechanical force is applied to the coils.
For applications, REBCO Coated Conductor, which is coated with copper on the outside, is used. However, REBCO CCs often have fine defects in the REBCO layer during the manufacturing process. Defects in the REBCO layer cause a localized decrease in critical current I_c. A localized drop in I_c is directly related to damage to the equipment due to unexpected normal-state transitions and failure of NMR operation [1] - [3]. Therefore, the presence of

defects must be confirmed and removed by non-destructive inspection before and after the magnet operations.

As a non-destructive inspection method, a magnetic field is applied to a conductor and the distribution of defects is determined by computing the current density distribution of the shielding current. The method of obtaining the current density distribution by measuring and analyzing the magnetic field on the conductor created by the shielding current is called Hall Probe Measurements (HPM) [4]. Conventionally, the magnetic field distribution obtained by HPM has been converted into a current density distribution by inverse analysis using a method based on the relationship between magnetization and magnetic field [5] or a two-dimensional fast Fourier transform (FFT) [6]. However, the resolution of the current density distribution obtained by these methods is low and insufficient for inspection of REBCO conductors. The size of defects can lead to fracture, and the shape of defects can have a negative effect on the equipment, such as a normal-state transition. To determine the size and shape of acceptable defects, a higher resolution current density distribution analysis method is required.

In this study, we propose a novel method using a Convolutional Neural Network (CNN) to compute the current density distribution from the measured field. The inversely computed current density is compared with the one using the conventional FFT-based method. The estimation accuracy is also discussed in the paper.

2. Proposed Method

There are two main points where machine learning-based current density distribution estimation has advantages over FFT-based methods in terms of accuracy. The first is that the resolution of the estimation is independent of the spatial variation of the current density distribution. FFT-based methods have the problem that resolution is reduced, especially in areas where the current density distribution changes significantly. FFT-based methods perform electromagnetic field analysis based on the Biot-Savart law on the acquired magnetic field distribution. The estimation results strongly depend on the distance of the source current and the point where the magnetic field is measured. Prediction by machine learning is based on a set of damped magnetic field distributions and the current density distribution that gives the magnetic field distribution. In this way, the output current density distribution is derived from the unattenuated magnetic field distribution. Therefore, machine learning may be used to estimate the current density distribution required from the undamped magnetic field distribution.

The second point is that the estimation accuracy does not depend on the number of measurement points of the magnetic field distribution. FFT-based methods cannot obtain detailed magnetic field distribution if the number of measurement points of the magnetic field distribution is small. The accuracy of the estimated current density distribution is highly dependent on that of the measured magnetic field distribution. This is because FFT-based methods are based on electromagnetic field analysis. If the number of magnetic field measurement points is small, the portion that cannot constitute a detailed magnetic field distribution increases. As a consequence, the accuracy of the current density distribution estimation is compromised. On the other hand, machine learning-based methods estimates the current density distribution based on underlying patterns learned from the training data. The accuracy may be improved by devising training data. Combines detailed current density distribution with magnetic field distribution by coarse measurement points. This set is used as training data. Theoretically, this approach could achieve a more accurate estimation of the current density distribution without increasing the number of measurement points. Spatial constraints limit the number of measurement points for magnetic field distribution. For these reasons, machine learning-based methods have the potential to provide accurate estimates that are not possible with FFT-based methods.

Specific uses of machine learning are as follows. First, the user creates current density distributions for J_x and J_y from simulation software or random distributions. The user then calculates the magnetic field distribution B_z corresponding to the sensor height from the created current density distribution. The user performs training of the machine learning model with the current density distribution as output and the magnetic field distribution as input. This operation is performed using a CNN model. The trained CNN solves the inverse problem of finding the current density distribution.

3. Model verification

For verification, the current density distribution is estimated using both the FFT-based, and CNN-based methods applied to the same magnetic field data. The number of measurement points is kept identical for both calculations. The accuracy of using machine learning is compared with that of FFT-based methods. The effectiveness of CNN-based current density estimation is verified.

The input of the CNN-based model is a magnetic field distribution, and the output is the current density distribution. The CNN-based model has five convolutional layers, connected to the fully connected layer, generating the current density map. The hyperparameters are shown in Table 1. The training data is prepared under the assumption that the critical current density J_{ct} has degraded. J_{ct} degradation is assumed to occur extensively on one side of the width direction. Therefore, J_{ct} is different on the left and right in the width direction. The range of J_{ct} is -300~300 A/cm for J_{xt} and -15~15 A/cm for J_{yt}. They are arranged in inverse parallel to satisfy the current conservation law. This is a distribution based on the Bean model. The magnetic field is computed from J_{xt} and J_{yt} based on Biot-Savart's law. They are prepared in 5,000 sets. They are used as training data. The training data is confirmed to be distributed consistently within the given range.

The CNN-based methods are compared to FFT-based methods. Figs. 1-2 shows two distributions (referred to as condition1 and condition2, respectively) which are used as validation data. Condition 1 is a case in the training data. Condition 2 is a simpler case. It is the result of a magnetization simulation of a conductor with no degradation and uniform J_c. The validation data are generated by a finite element simulation. The finite element simulations are performed using COMSOL®. The validation data are modeled by a more complex n-value model. The two methods are compared in terms of error distribution and mean error values.

Table 1 Various hyperparameters in the model of this study

Parameters	Values
Hyperparameters	
Batch Size	256
Epochs	1000
Layers	5
Padding	Zeros
Pooling	Max Pooling
Optimizer	Adam
Loss Function	Mean Squared Error

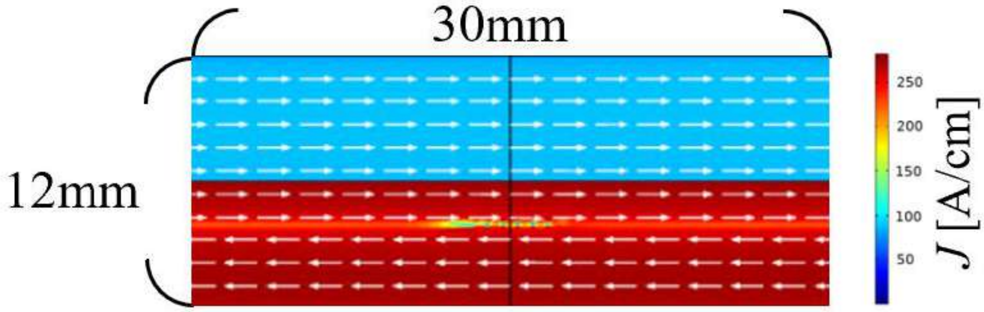

Fig. 1 Data used for verification, Condition 1. This figure is described by the distribution of the magnitude J of the current density.

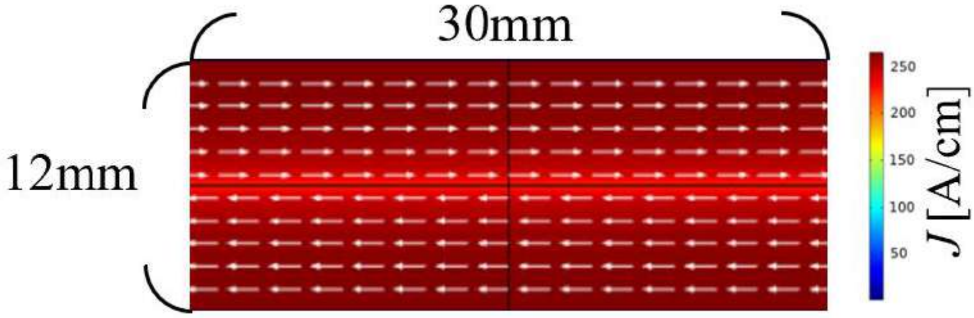

Fig. 2 Data used for verification, Condition 2. This figure is also described by the distribution of the magnitude J of the current density.

For condition 1, which is close to the trend of the training data, the error distribution was as shown in Fig. 3. In the case of condition 2, which differed from the trend of the training data, the error distribution was as shown in Fig. 4. For these results, shown in Figs. 3-4 are the magnitudes J of the current density, calculated from J_x and J_y obtained in the analysis.

Figs. 3-4 show that the estimation by the CNN-based method is particularly accurate in the axial direction, which in this case has fewer measurement points along the y-axis than the FFT-based method. The method using CNN does not directly perform electromagnetic field analysis but rather relies on training data for estimation. This is because the estimation results from the CNN-based method well reflect the trends in the training data. The accuracy of FFT estimation strongly depends on the number of sampling points. Therefore, as long as there is a physical limit to the number of sampling points in terms of the installation of the Hall sensor, it can be said that machine learning can provide more accurate estimates than FFT.

The CNN-based method also accurately estimates the current density distributions that are not explicitly included in the training data. This suggests that the CNN-based method has the potential to flexibly estimate the current density distribution of conductors with defects, which is a complex condition.

The average error for the two test conditions is shown in Fig. 5. The error of the CNN-based model is much less than FTT-based model in both cases. These results show that a single CNN can be used to analyze more complex conditions while maintaining accuracy for simpler conditions, depending on the training data.

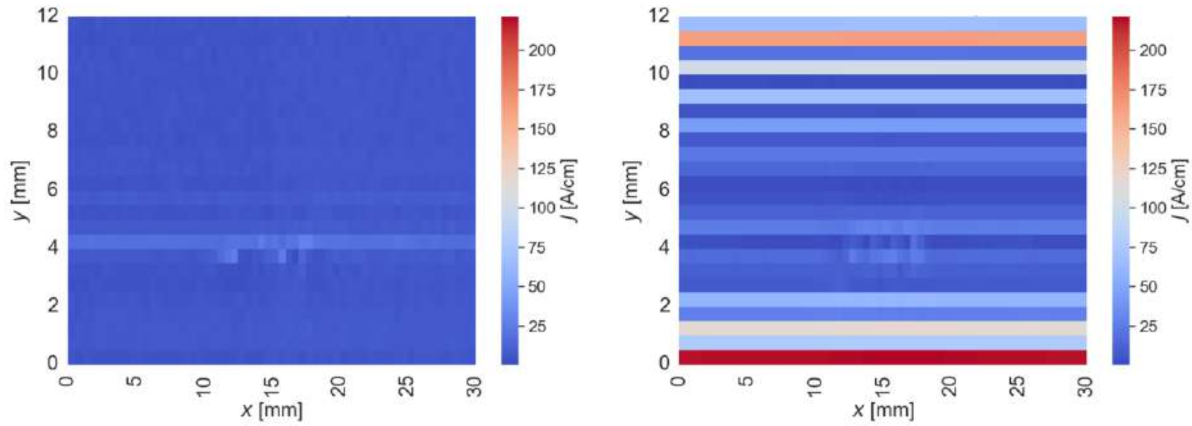

Fig. 3 Error distribution of estimated current density for condition 1 with using (left) CNN-based, (right) FFT-based.

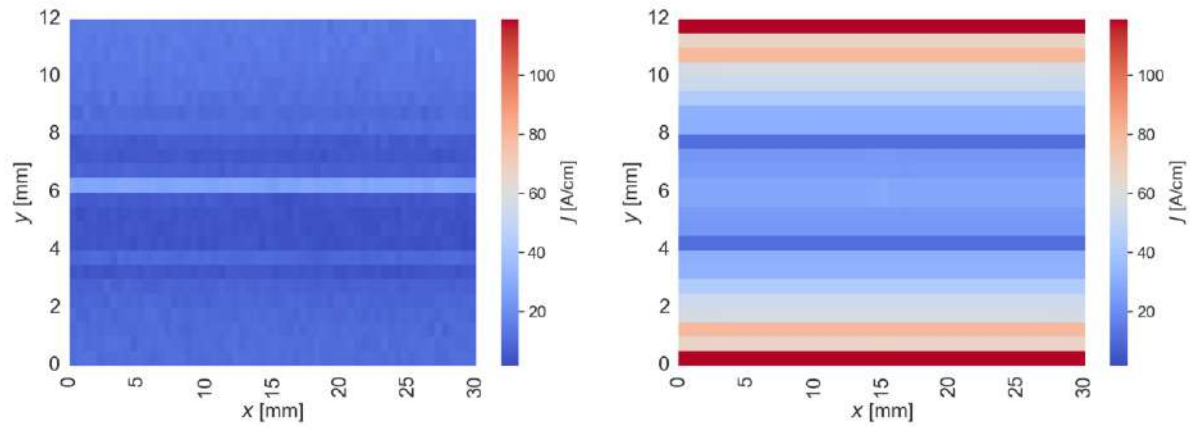

Fig. 4 Error distribution of estimated current density for condition 2 with using (left) CNN-based, (right) FFT-based.

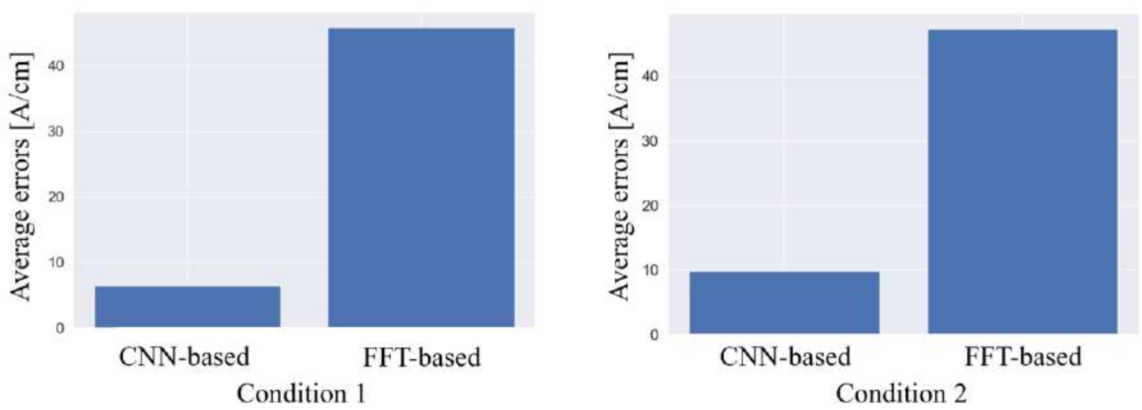

Fig. 5 Comparison of the average errors in each validation for Condition 1 (left) and Condition 2 (right).

4. Conclusion

In this study, we proposed the CNN-based model to inversely compute the current density distribution from the measured magnetic fields. The estimated current density is compared with the one using the conventional FFT-based method. As a result, the CNN-based method is found to be more accurate than the FFT-based method. The difference is particularly large when the number of sampling points of the magnetic field is small. This result shows the expected accuracy beyond the conventional limitation of the number of magnetic field measurement points. The CNN-based method can analyze simple and complex conditions simultaneously and with high accuracy. This has the potential to create more versatile models for defects of various geometries. Given this, the use of machine learning is one of the possible approaches to achieve higher resolution in current density distribution estimation.

For future prospects, we plan to apply the CNN-based model to compute the current density in the REBCO CC with defects. This is more complex than the conditions verified in this study. The experimental validation is also required because the experimental data includes several uncertainties, such as the noise voltage from instruments and the assembly errors. In addition, to check the reliability of the results is important when the number of magnetic field measurement points is reduced.

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