OPEN ACCESS
IOP Publishing
Superconductor Science and Technology
Supercond. Sci. Technol. **36** (2023) 084001 (5pp)
https://doi.org/10.1088/1361-6668/ace385

Editorial

Artificial intelligence, machine learning, deep learning, and big data techniques for the advancements of superconducting technology: a road to smarter and intelligent superconductivity

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Received 24 June 2023
Accepted for publication 3 July 2023
Published 11 July 2023

Abstract

The last 100 years of experience within the superconducting community have proven that addressing the challenges faced by this technology often requires incorporation of other disruptive techniques or technologies into superconductivity. Artificial intelligence (AI) methods including machine learning, deep learning, and big data techniques have emerged as highly effective tools in resolving challenges across various industries in recent decades. The concept of AI entails the development of computers that resemble human intelligence. The papers published in the focus issue, "Focus on Artificial Intelligence and Big Data for Superconductivity", represent the cutting-edge and forefront research activities in the field of AI for superconductivity.

(Some figures may appear in colour only in the online journal)

1. Introduction

After more than a century since the discovery of the superconducting phenomenon and three decades following a significant breakthrough in finding high-temperature superconductor (HTS) materials, many of us within the superconductivity community had hoped to witness the full commercialization of superconducting technology across various industrial sectors. This expectation stems from the competitive advantages that superconductors and superconducting technology possess over their conventional counterparts, particularly in terms of lower losses, higher current carrying capacity, higher magnetic field strength, increased efficiency, lighter weight, compact size, and greater power density. However, the commercialization of superconducting devices beyond magnetic resonance imaging (MRI) and nuclear magnetic resonance technologies

[1–3] has been impeded by a series of technical challenges. A few of these challenges—the list is not exhaustive—are related to [1–3]:

- low technology and manufacturing readiness levels,
- high initial purchasing cost,
- high levelized cost of energy (at the moment),
- manufacturing and supply chain issues related to fabricating low-cost HTS materials,
- implemented in demonstrator level, and usually not in real sizes, so, there are unknowns about the technological limits in manufacturing of commercial scale devices,
- issues related to reliability of superconducting devices (in sensitive applications) versus conventional systems which were in use for decades already, especially when we may face quench phenomenon by using superconductors,
- concerns related to cryogenic environment and the use of somehow low efficiency cooling system,
- hesitancy of major industries regarding accepting a new technology over well-demonstrated conventional one.

Despite the aforementioned challenges, superconductivity has demonstrated significant potential for integration into various sectors, including healthcare, physics, quantum computing, electronics, communications, power and energy, and transportation applications. A prime example of this is the use of superconductors in MRI technology, which has facilitated substantial advancements in medical and cancer diagnostics by providing detailed, high-resolution scans of the body [4]. Additionally, superconductors have played a vital role in the development of particle accelerators for fundamental physics research, providing invaluable insights into the understanding of our surrounding world.

Recently, new beacons of hope have emerged for the commercialization

of various superconducting devices, particularly in large-scale applications, driven by the new and increasing demand in power and energy, as well as new advancement in transportation sectors. For instance, in the future, advancements in superconductor technology could lead to breakthroughs in offshore and onshore wind power generation, fusion energy, electric and hydrogen-powered transportation, and aerospace applications, playing a pivotal role in the global pursuit of achieving net-zero emissions [1–10]. Through these developments, superconductors would not only contribute to technical advancements in different industrial sectors but also contribute to the development of a better environment and society. This presents a unique opportunity that the power and energy as well as transportation sectors offer. Additionally, the emergence of new technology roadmaps focusing on the utilization of hydrogen, particularly in liquid form, for power and energy and specifically in transportation applications, pave the way for the implementation of both HTS and MgB_2 superconductors. This is because the boiling point of liquid hydrogen is approximately 20 K, which falls well below the critical temperature of commercial HTS and MgB_2 superconductors [10]. However, in order to seize this significant opportunity presented by the power and energy and transportation sectors, the aforementioned challenges must be resolved soon.

2. Artificial intelligence (AI) techniques for superconductivity

AI techniques have emerged as highly effective tools in resolving challenges across various industries in recent decades [1, 2]. The concept of AI entails the development of computers (or machines, as referred to in the computer science community) that resemble human intelligence, enabling them to learn complex processes, identify unknown patterns, and make intricate decisions [1, 2, 11].

But where did all of this AI development begin? The notion that technology could one day replicate human logical intelligence was introduced by Alan Turing in 1950 when he published the thought-provoking paper titled ‘Can a machine think?’ [2, 12]. It all started with the emergence of computers and intelligent machines, which raised the philosophical and practical question: ‘could a computer ever behave intelligently, exhibiting behaviour similar to a human being?’. The term ‘Artificial Intelligence’ was widely accepted by the scientific community since 1956 [2, 12]. AI was described as the ability of machines to perform certain tasks, which need the intelligence showcased by human [2].

AI methods include multiple techniques, namely machine learning (ML) techniques with specific examples of deep learning (DL) and reinforcement learning; automatic reasoning such as planning, programming, knowledge representation and reasoning, search, and optimisation; and robotics [13].

Since its proposal in the 1950s, AI has been gradually recognised as a powerful tool driving social, technological, and economic advancement and changes. AI techniques have been successfully developed and implemented across various industrial sectors, including but not limited to automotive, aerospace, communication, automation, and medical, some of which have higher reliability requirements and risk concerns compared to existing superconducting applications. In the field of superconductivity, AI approaches offer efficient, fast, and accurate solutions to tackle nonlinear and complex technical and manufacturing problems.

AI techniques can be applied at different stages, such as superconductor tape/wire production, and in design, manufacturing, condition monitoring, operation, and maintenance of superconducting devices. They enable real-time modelling and simulation, design improvement or optimization, hot spot detection, fault detection and discrimination, cost reduction, loss and efficiency improvement, condition monitoring and operation, enhancing manufacturing yield, quality control and assurance, sensor and testing improvement, and the discovery of new superconductors with higher critical temperature or critical current density [1, 2, 11]. Compared to other methods recently implemented in superconductivity, such as finite element (FE), mathematical, and look-up table approaches, AI techniques offer several advantages including faster response time, higher chances of convergence, fewer false outcomes, consideration of interdependencies among inputs, discovery of hidden patterns, and, most importantly, real-time application and implementation. Real-time applications of superconductors often generate large amounts of data, which, once again, require intelligent approaches for handling, storing, and analysing [1, 2, 11].

3. Special focus issue: focus on AI and big data for superconductivity

This focus issue in the 'Superconductor Science and Technology' journal aims to show the utilization of AI, ML, DL, and Big data (BD) techniques for advancements in the design, manufacturing, operation, fault detection, and condition monitoring of superconducting technology (devices or systems). The objective is to generate a momentum within the superconductivity community by accelerating the implementation and application of AI techniques in the near future. By addressing challenges and providing assistance in the commercialization of superconducting technology, this initiative seeks to foster progress and innovation in the field. These goals are fairly achieved as not only we received numerous manuscripts for this focus issue that some of them are accepted and published, but also it triggered new research activities that eventually published in other superconductivity-related journals with other publishers within the superconductivity community. In addition, this focus issue was a driver for two independent special sessions for AI in 2022 Applied Superconductivity Conference (ASC2022) and 16th European Conference on Applied Superconductivity (EUCAS2023).

3.1. Design

One of the key roles that AI techniques can fulfil in the field of superconductivity is providing optimal design solutions for various superconducting devices, including magnets, flux pumps, electric machines, and other large-scale devices. This can be achieved by implementing optimization techniques to a set of sizing or design equations, thereby forming single- or multi-objective cost function that can be essentially solved by different optimizer algorithms. Additionally, AI techniques can be employed to create surrogate models, enabling the application of different optimization methods to identify the optimal solution(s).

The fusion industry stands as a prominent sector for the implementation of superconducting magnets. It is anticipated that, in the reasonably near future, compact nuclear fusion power plants will generate cost-effective energy with no pollution.

Demonstration Power Plants (DEMO), are conceptualized as large, high-field, and steady-state tokamaks intended to be the second generation of fusion power plants, following ITER's implementation [14]. To date, the common practice for designing the most critical components of DEMOs, such as the toroidal field coils winding pack, has relied on a sequential trial and error process using a combination of analytical and FE methods. However, these trial and error methods are time-consuming and computationally expensive. In order to expedite the computation and find optimal design configurations more efficiently, AI methods such as artificial neural networks (ANNs) and swarm-based optimization methods are proposed. These AI techniques are capable of taking into account both real-valued and discrete design variables. They significantly reduce the computational time required for magneto-structural analysis and guarantee convergence to an optimal solution for the winding pack configuration. The proposed methodology has been well demonstrated for the 2019 ENEA DEMO configuration, which consists of 16 toroidal field coils fabricated using 6 Nb_3Sn double layers and a wind-and-react technique in [14].

One method of charging superconducting magnets in fusion and electric machine applications is through the use of HTS flux pumps, which enable wireless charging of the magnets [15]. This approach eliminates the need for current leads, making the system more compact and remove current lead losses. HTS flux pumps, e.g. rotary types, generate non-zero time-averaged DC voltage and charge the rest of the circuit when a closed loop is formed. Over the last decade, the characteristics of rotary flux pumps have been studied using an equivalent circuit model, FE method, and experimental investigations. However, AI techniques can be utilized in future to develop a surrogate model that aids in the design optimization of flux pumps. In [16], a ML model was developed to examine the impact of various design parameters (such as frequency, air gap length, width of HTS tape, and remnant flux density) on the output voltage through parameter sweeping and analysis of variance. The results demonstrated that the output voltage of a rotary flux pump can be promptly obtained with satisfactory accuracy using Gaussian process regression.

3.2. Modelling

One of the most useful applications of AI techniques in applied superconductivity is for intelligent modelling of superconductors and superconducting systems. There are a few main modelling techniques currently used and well-demonstrated within superconductivity community, including analytical, equivalent circuit-based models, and FE techniques. These models all have their advantages and disadvantages. Some of these methods are computationally expensive and are not applicable in real time. However, AI techniques offer same high accuracy with much faster computation speed, and in most cases, much lower computational burden. In addition, in some problems, because of the complexity of geometry, unknown materials, real-time application, the AI techniques are the only viable solution.

Electric transportation applications are recently the centre of attentions for integrating superconducting technology. One of the promising candidates is high speed bullet trains developed as HTS maglev. They offer high self-stability and low energy consumption compared with conventional trains. Guiding force which has strong non-linearity is a key index to guarantee the lateral self-stability of HTS maglev, and is usually determined by numerous interdependent parameters. AI techniques could be used to predict guiding force more accurately and with less computational burden in real-time manner compared with traditional FE and polynomial fitting methods [17, 18].

In [17], five different AI-based models utilizing ANN were developed to predict HTS maglev guiding force. The prediction efficiency of these models was compared based on thousands of collected data. The models were radial basis function, deep neural network (DNN), convolutional neural network, recurrent neural network, and long short-term memory (LSTM) neural network. These models effectively reduced computational time and unnecessary iterations. The study demonstrated that AI-based DL algorithms can effectively deliver highly accurate predictions of HTS maglev guiding force, taking into account factors such as field cooling height, real-time magnetic flux density, liquid nitrogen temperature, and motion direction of the bulk. Among the models, the DNN model exhibited the best fitting goodness, while the LSTM model displayed the smoothest fitting curve for guiding force prediction. Furthermore, in [18], the highly nonlinear levitation force between the superconductor and the magnet was predicted using a back-propagation (BP) perceptron ANN. The data set consisted of thousands of experimental data points, considering nine input factors and force as the only output. The prediction results accurately illustrated the features of the force, including nonlinearity, hysteresis, external field dependence, and differences between the bulk and stack. This study confirmed the feasibility of using a BP neural network to predict the levitation force.

3.3. Condition monitoring

Superconducting devices such as transformers, cables, and fault current limiters often offer quite competitive solutions against conventional technology in terms of technical aspects such as AC loss, size and weight. However, one must note that full commercialization of superconducting power devices needs much more than the technical superiority in design aspects but fairly comparable performance during operation and life-span. To guarantee safe operation and high reliability of the superconducting devices, specific condition monitoring techniques for them must be developed over the next decade. On the other hand, in some applications such as in fusion industry, condition monitoring is not only a commercialization measure to show competitiveness against conventional technology, but a real safety measure against magnet quenches which can release high amount of energy if it occurs without proper protection. AI techniques can assist development of intelligent techniques for fast and reliable condition monitoring of superconducting devices.

The development of new high-quality HTS tapes has opened up opportunities for device manufacturers to explore novel structural designs for HTS cables, including the spiral geometry, which has gained popularity as a compact HTS cable structure. However, one of the main challenges in manufacturing spiral HTS cables lies in the instability of the winding quality due to various winding methods, such as manual winding, device-assisted winding, or automatic winding [19]. In [19], an AI-based model is developed to monitor the winding quality and prevent errors during automatic winding. The model encompasses image data preparation, AI detection, and post-processing, ultimately providing the final results in the form of a binary image that shows the winding intervals. The identification of these winding intervals helps determine the monitoring strategy for the fabrication of spiral HTS cables. DL techniques were successfully employed in [19] to achieve effective real-time interval detection results.

The HTS tapes has been recently considered a promising option for ultra-high field magnet windings in fusion reactors. However, the main challenge with use of HTS material is fast detection of a hot spot which could lead to a quench. A fast, and reliable hot spot detection system is extremely important for the safe operation of a superconducting magnet which was show possible using optical fibre sensors as an alternative to the voltage-based quench detection method. In [20], an AI-based hot spot detection algorithm has been developed for ultra-long fibre Bragg gratings (FBGs) at cryogenic temperatures. The method can detect of a hotspot, for example, for quench detection in HTS materials but not its precise location. This type of intelligent hot spot detection techniques is vital for magnets with HTS tapes, where quench propagation is much slower than low temperature superconductors [1]. The developed system provides the advantages of cost reduction and faster response time compared to conventional FBGs with wavelength-division multiplexing and continuous FBGs with time-division multiplexing, respectively. It was shown that the proposed technique can detect a hot spot as small as 1 K temperature rise. It is proven that AI-based technique can detect a small hot spot more rapidly from the big spectral data in real-time.

3.4. Estimation

Data-driven models can predict, estimate, and monitor any highly nonlinear and multi-variable behaviour of HTS materials, and superconducting devices to analyse their characteristics with a very high accuracy in an almost real-time procedure, which is a significant figure of merit as compared with traditional numerical approaches [21–23]. This task is essentially an estimation or regression task for AI techniques.

For modelling HTS materials, analytical equations and interpolations are commonly used to consider the relationship between the critical current density, $J_c(B,\theta,T)$, index-value, $n(B,\theta,T)$, and other electromagnetic and physical quantities. However, look-up tables are not available in all modelling and coding environments, and interpolation methods must be manually implemented. Moreover, analytical formulas only roughly approximate real physics of superconductors and, in many cases, lack a high level of accuracy demanded for many sensitive superconducting applications. On the other hand, FE models are usually computationally costly due to the high aspect ratio and the strong nonlinearity of the E–J characteristic of HTS tapes. AI-based methods including ANN, eXtreme Gradient Boosting, and kernel ridge regressor were used to estimate and predict the critical current and n-value surfaces of HTS tapes in [24] and [25].

The critical current and the n-value of HTS conductors vary for different manufacturers and even for the same manufacturer but different production batches. That is where usually conventional techniques face with problem in predicting the values. However, AI techniques can easily understand and consider interdependencies of inputs. The ANN model was proven as the most accurate in predicting the critical current and n-value surfaces of HTS materials, performing goodness of fit very close to 1 and extremely low root mean squared error. Therefore, the proposed AI techniques has the potential to be applied to the optimization and analysis of the superconducting related equipment in modelling stage as a plug-and-play code [24, 25].

The electromechanical behaviour of twisted HTS tapes under different strains, magnetic fields, and temperatures is a complicated problem to be solved using conventional approaches, including FE-based methods, otherwise, experimental testing is needed to characterise it, accurately. In [26], an AI-based data-driven model using an adaptive neuro-fuzzy inference system (ANFIS) was designed to predict the electromechanical behaviour of HTS tapes operating under various thermomagnetic conditions when twisting. The normalised critical current value and stress of twisted tapes were predicted under different temperatures and magnetic flux densities using experimental data as model input. To achieve the best performance of the prediction system, multiple clustering methods were used, such as the grid partitioning method, fuzzy c-means clustering method, and sub-clustering method. Sensitivity analyses were conducted to find the best hyperparameters and architecture of ANFIS to predict and model electromechanical behaviour of twisted tapes with high accuracy. The model developed in [26], can be easily adjusted for other materials and other similar applications.

4. Concluding remarks

The papers published in this special focus issue, i.e. ‘Focus on Artificial Intelligence and Big Data for Superconductivity’, represent the cutting-edge and forefront research activities in the field of AI for superconductivity, ranging from the use of AI in design to the development of new condition monitoring methods for superconductors and superconducting devices and systems. It is my hope that this focus issue serves as an inspiration for researchers across various fields within the superconductivity community, encouraging them to recognize and harness the potential of AI and big data techniques to unlock new opportunities in superconducting materials and technologies. A scientific wish that I already see it as partly fulfilled.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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