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

ETIMA 2023

SECOND INTERNATIONAL CONFERENCE

27-29 SEPTEMBER, 2023

TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ,
УНИВЕРЗИТЕТ „ГОЦЕ ДЕЛЧЕВ”, ШТИП, СЕВЕРНА МАКЕДОНИЈА

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

ВТОРА МЕЃУНАРОДНА КОНФЕРЕНЦИЈА
SECOND INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2023

ЗБОРНИК НА ТРУДОВИ
CONFERENCE PROCEEDINGS

27-29 септември 2023 | 27-29 September 2023

ISBN: 978-608-277-040-6

DOI: **https://www.doi.org/10.46763/ETIMA2321**

Главен и одговорен уредник / Editor in Chief
проф. д-р Сашо Гелев
Prof.d-r Saso Gelev

Јазично уредување / Language Editor
Весна Ристова / Vesna Ristova

Техничко уредување / Technical Editing
Дарко Богатинов / Darko Bogatinov

Издавач / Publisher
Електротехнички факултет, Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering, Goce Delcev University, Stip, North Macedonia

Адреса на организационен комитет / Address of the organising committee
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Goce Delcev University, Stip, North Macedonia

Електротехнички факултет / Faculty of Electrical Engineering
Адреса: Крсте Мисирков, 10 А 2000, Штип/ Address: Krste Misirkov, 10A, 2000 Stip
E-mail: conf.etf@ugd.edu.mk

CIP - Каталогизација во публикација Национална и универзитетска библиотека "Св. Климент Охридски", Скопје

62-049.8(062)
004-049.8(062)

МЕЃУНАРОДНА конференција ЕТИМА (2 ; 2023)
Зборник на трудови [Електронски извор] / Втора меѓународна конференција ЕТИМА 2023, 27-29 септември 2023 = Conference proceedings / Second international conference, 27-29 September 2023 ; главен и одговорен уредник Сашо Гелев]. - Штип : Универзитет "Гоце Делчев", Електротехнички факултет ; Stip : "Goce Delcev" University, Faculty of Electrical engineering, 2024

Начин на пристапување (URL): https://www.doi.org/10.46763/ETIMA2321. - Текст во PDF формат, содржи 200 стр.илустр. - Наслов преземен од екранот. - Опис на изворот на ден 25.03.2024. - Трудови на мак. и англ. јазик. - Библиографија кон трудовите. - Содржи и: Appendix

ISBN 978-608-277-040-6

а) Електротехника -- Примена -- Собири б) Машинство -- Примена -- Собири
в) Автоматика -- Примена -- Собири г) Инфоматика -- Примена – Собири

COBISS.MK-ID 63335173

ОРГАНИЗАЦИОНЕН ОДБОР
ORGANIZING COMMITTEE

ПРОГРАМСКИ И НАУЧЕН ОДБОР
SCIENTIFIC COMMITTEE

Божо Крстајиќ / Bozo Krstajic
Електротехнички факултет
Универзитет во Црна Гора, Црна Гора
Faculty of Electrical Engineering,
University in Montenegro, Montenegro

Милован Радуловиќ / Milovan Radulovic
Електротехнички факултет
Универзитет во Црна Гора, Црна Гора
Faculty of Electrical Engineering,
University in Montenegro, Montenegro

Гоце Стефанов / Goce Stefanov
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Мирјана Периќ / Mirjana Peric
Електронски факултет
Универзитет во Ниш, Србија
Faculty of Electronic Engineerig,
University of Nis, Serbia

Ана Вучковиќ / Ana Vuckovic
Електронски факултет
Универзитет во Ниш, Србија
Faculty of Electronic Engineerig,
University of Nis, Serbia

Тодор Чекеровски / Todor Cekerovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Далибор Серафимовски / Dalibor Serafimovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Мирослава Фаркаш Смиткова / Miroslava Farkas Smitková
Факултет за електротехника и информациони технологии
Словачки Технички Универзитет во Братислава, Словачка
Faculty of Electrical Engineering and Information Technology
Slovak Technical University in Bratislava, Slovakia

Петер Јанига / Peter Janiga
Факултет за електротехника и информациони технологии
Словачки Технички Универзитет во Братислава, Словачка
Faculty of Electrical Engineering and Information Technology
Slovak Technical University in Bratislava, Slovakia

Јана Радичова / Jana Raditschová
Факултет за електротехника и информациони технологии
Словачки Технички Универзитет во Братислава, Словачка
Faculty of Electrical Engineering and Information Technology
Slovak Technical University in Bratislava, Slovakia

Драган Миновски / Dragan Minovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Василија Шарац / Vasilija Sarac
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Александар Туџаров / Aleksandar Tudzarov
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Владимир Талевски / Vladimir Talevski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Владо Гичев / Vlado Gicev
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia

Марија Чекеровска / Marija Cekerovska
Машински факултет,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Mechanical Engineering,
Goce Delcev University, Stip, North Macedonia

Мишко Џидров / Misko Dzidrov
Машински факултет,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Mechanical Engineering,
Goce Delcev University, Stip, North Macedonia

Александар Крстев / Aleksandar Krstev
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia

Ванчо Аџиски / Vancho Adziski
Факултет за природни и технички науки,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Natural and Technical Sciences,
Goce Delcev University, Stip, North Macedonia

Томе Димовски / Tome Dimovski
Факултет за информатички и комуникациски технологии,
Универзитет „Св. Климент Охридски “, Северна Македонија
Faculty of Information and Communication Technologies,
University St. Climent Ohridski, North Macedonia

Зоран Котевски / Zoran Kotevski
Факултет за информатички и комуникациски технологии,
Универзитет „Св. Климент Охридски “, Северна Македонија
Faculty of Information and Communication Technologies,
University St. Climent Ohridski, North Macedonia

Никола Рендевски / Nikola Rendevski
Факултет за информатички и комуникациски технологии,
Универзитет „Св. Климент Охридски “, Северна Македонија
Faculty of Information and Communication Technologies,
University St. Climent Ohridski, North Macedonia

Илија Христовски / Ilija Hristovski
Економски факултет,
Универзитет „Св. Климент Охридски “, Северна Македонија
Faculty of Economy,
University St. Climent Ohridski, North Macedonia

Христина Спасовска / Hristina Spasovska
Факултет за електротехника и информациски технологии,
Универзитет „ Св. Кирил и Методиј “, Скопје, Северна Македонија
Faculty of Electrical Engineering and Information Technologies,
Ss. Cyril and Methodius University, North Macedonia

Роман Голубовски / Roman Golubovski
Природно-математички факултет,
Универзитет „ Св. Кирил и Методиј “, Скопје, Северна Македонија
Faculty of Mathematics and Natural Sciences,
Ss. Cyril and Methodius University, North Macedonia

Маре Србиновска / Mare Srbinovska
Факултет за електротехника и информациски технологии,
Универзитет „ Св. Кирил и Методиј “, Скопје, Северна Македонија
Faculty of Electrical Engineering and Information Technologies,
Ss. Cyril and Methodius University, North Macedonia

Билјана Златановска / Biljana Zlatanovska
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia

Александра Стојанова Илиевска / Aleksandra Stojanova Ilievska
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia

Мирјана Коцалева Витанова / Mirjana Kocaleva Vitanova
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia

Ивана Сандева / Ivana Sandeva
Факултет за електротехника и информациски технологии,
Универзитет „ Св. Кирил и Методиј “, Скопје, Северна Македонија
Faculty of Electrical Engineering and Information Technologies,
Ss. Cyril and Methodius University, North Macedonia

Билјана Читкушева Димитровска / Biljana Citkuseva Dimitrovska
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Наташа Стојковиќ / Natasa Stojkovik
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia;

PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the Second International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA*.**
ETIMA has a goal to gather the scientists, professors, experts, and professionals from the field of technical sciences in one place as a forum for exchanging the ideas, strengthening the multidisciplinary research and cooperation, and promoting the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.
Conference ETIMA was held as online conference. More than sixty colleagues contributed to this event, from five different countries with more than thirty papers.
We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA'23 by presenting the results of their current research and by launching the new ideas through many fruitful discussions.
We invite you and your colleague to attend ETIMA Conference in the future as well. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information as well as to involve as much as possible the young researchers into this scientific event.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот „Гоце Делчев“.
ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.
Конференцијата ЕТИМА се одржа online и на неа дадоа свој придонес повеќе од шеесет автори од пет различни земји со повеќе од триесет труда.
Сакаме да ја искажеме нашата благодарност до сите колеги кои придонесоа за успехот на ЕТИМА'23 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Организационен одбор на конференцијата

СОДРЖИНА / TABLE OF CONTENTS:

UDC: 538.945:537.633]:621.039.64
https://www.doi.org/10.46763/ETIMA2321077s

INVESTIGATION OF TURN-TO-TURN CONTACT RESISTANCES OF LARGE-SCALE D-SHAPED NO-INSULATION HIGH-TEMEPERATURE SUPERCONDUCTING MAGNETS TO ACHIEVE SHORT CHARGNING DELAY AND HIGH THERMAL STABILITY

Haru Sato[1] and So Noguchi[2]
[1]Hokkaido University,
email: haru_sato@em.ist.hokudai.ac.jp
[2]Hokkaido University

Abstract

To generate ultra-high magnetic fields, a no-insulation (NI) winding technique was proposed by Hahn on 2011. By removing insulators between turns, the NI winding technique enables a high-temperature superconducting (HTS) magnets to improve the thermal stability while generating ultra-high magnetic fields. The NI winding technique has commonly been applied to circular coils for the targets of magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), air-core cyclotron called as skeleton cyclotron, and so on. Recently, meter-class (large-size) D-shaped NI HTS magnets used for compact fusion reactors are under development applying the NI winding technique. One of critical issues is that large-size D-shaped NI magnets have a long excitation delay. High turn-to-turn contact resistances on NI HTS coils shorten the charging delay times, although high turn-to-turn contact resistances deteriorate the thermal stability. Therefore, the relation between the excitation delay and the thermal stability was investigated on different turn-to-turn contact resistances. Finally, we could find the appreciate resistances with the short charging time and the high thermal stability for two different sizes of D-shaped NI HTS coils.

Key words

High-temperature superconducting magnets, no-insulation winding technique, thermal stability, excitation delay, D-shaped coil

Introduction

A few compact fusion reactors have been under research and development worldwide in recent years [1]. To miniaturize fusion reactors, high magnetic fields are required in small spaces. Since Rare-Earth Barium Copper Oxide (REBCO) superconductors show excellent properties [2]; i.e. a high critical current density under a high magnetic field and a high critical temperature, REBCO coated conductors have a great potential for high field generation [3]-[5]. To suppress a normal-state transition or a quench event derived from a hotspot, a no-insulation (NI) winding technique which is one of the tape-shaped conductor winding techniques is often applied to high-field REBCO coils as a thermal stability improvement method [6]. The NI winding technique allows an operating current to directly flow into adjacent turns through turn-to-turn contact surfaces by removing insulators between turns. The turn-to-turn currents in the coil-radial direction prevent the operating currents from flowing into REBCO superconductors with high resistances at hotspots. It enables the Joule heat reduced drastically comparing with ordinary turn-insulated REBCO coils. The NI winding technique has already been applied to many small-scale circular REBCO coils [7],[8]. The expectations are growing for the introduction of the NI winding technique into large-scale D-shaped REBCO coils for toroidal field (TF) magnets of compact fusion reactors [1],[9]. A critical issue is that as the D-shaped NI REBCO coils are larger, the charging delay times are longer because of large leakage currents in the radial direction. Large turn-to-turn contact resistances on NI

REBCO coils can shorten the charging delay times. Whereas, when a normal-state transition occurs or a hotspot appears on NI REBCO coils, large turn-toturn contact resistances generate large Joule heats, and then a quench would follow. Consequently, it is necessary to investigate the current behaviors of D-shaped NI REBCO coils with a partial element equivalent circuit (PEEC) model depending on different turn-to-turn contact resistances in the terms of the charging delay and the thermal stability.

1. D-shaped coils for tokamak-type fusion reactor

A tokamak-type fusion reactor consists of some large D-shaped TF magnets and some other magnets [10]. In tokamaks, fusion fuel is confined in a plasma state by placing some TF coils in a torus shape which generate high magnetic fields closed in toroidal direction. Several central solenoid (CS) coils are also needed at the center to suppress a charge separation. Due to a spatial constraint on the CS coils, the TF coils are required to be D-shaped instead of circular. In addition, to suppress the hoop stresses of plasma, the tokamak needs several poloidal field (PF) coils which generate a magnetic field penetrating up and down. In common, three different purposes (shapes) of coils are used in tokamak systems. A size of tokamak fusion reactor is not questionable in making fusion fuel in a plasma state. However, to extract enormous energy from reactors, enough space must be made in reactors. Hence, tokamak-type fusion reactors are usually large, comparing with MRI and NMR [4],[7]. Meanwhile, a tokamak-type fusion reactor which is under R&D at the plasma science fusion center, Massachusetts Institute of Technology (PSFC, MIT), well-known as the ARC/SPARC project, is much compacter than the ITER reactor constructed in France [9],[11]. The PSFC succeeded 20-T generation by a demo HTS TF coil [9]. But, the detailed electromagnetic features are not investigated yet. In this study, we have investigated about the relation of the excitation delay and thermal stability on a D-shaped NI REBCO TF coil with different turn-to-turn contact resistances through simulation.

2. Effect of turn-to-turn contact resistance on excitation delay and thermal stability

The thermal stability of NI REBCO coils is closely related to the turn-to-turn contact resistances. An HTS coil with the NI winding technique which was proposed by Hahn in 2011 has no insulation between turn-to-turn contact surfaces [6]. Due to mechanical friction, a local normal-state transition occasionally occurs on a REBCO coil. In the case of a conventionally turn-insulated REBCO coil, the enforced current flows through a thin copper stabilizer surrounding the normal-transitioned REBCO layer, emitting extremely large Joule heat. Subsequently, it leads to burning-out, irreversible mechanical damage, critical current degradation, or rarely explosion. In the case of an NI REBCO coil, whereas, the enforced current flows directly into the turns adjacent to the normal-transitioned turn through turn-to-turn contact surfaces, emitting much less Joule heat. Still, the Joule heat on turn-to-turn contact surfaces may lower the thermal stability of REBCO coil. Excessive turn-to-turn contact resistances deteriorates the thermal stability due to large heat generation on turn-to-turn contact surfaces. The excitation delay time is also closely related to the turn-to-turn contact resistance. The operating current on NI REBCO coil can flow into both the radial and azimuthal directions. Therefore, while the operating current of NI REBCO coil increases, some of the operating current goes into the radial direction according to the balance of the coil inductive voltage and the turn-to-turn contact resistive one. In addition, it takes a long time for the radial current to attenuate even after the coil excitation finishes. Consequently, to reach the desired magnetic field is delayed, as opposed to the operating current, which is called an excitation delay problem. Since a meter-class (large-size) HTS coil has a large inductance compared to a low turn-to-turn contact resistance, it may have a long time constant exceeding one hour. The excitation delay (the time constant) can be improved by increasing the turn-to-turn contact resistance. In this paper, we investigate appropriate turn-to-turn contact resistances of large-size D-shaped NI REBCO coils to improve the excitation delay while maintaining the inherent thermal stability of NI REBCO coils by simulation coupled with the PEEC model and the thermal finite element method (FEM).

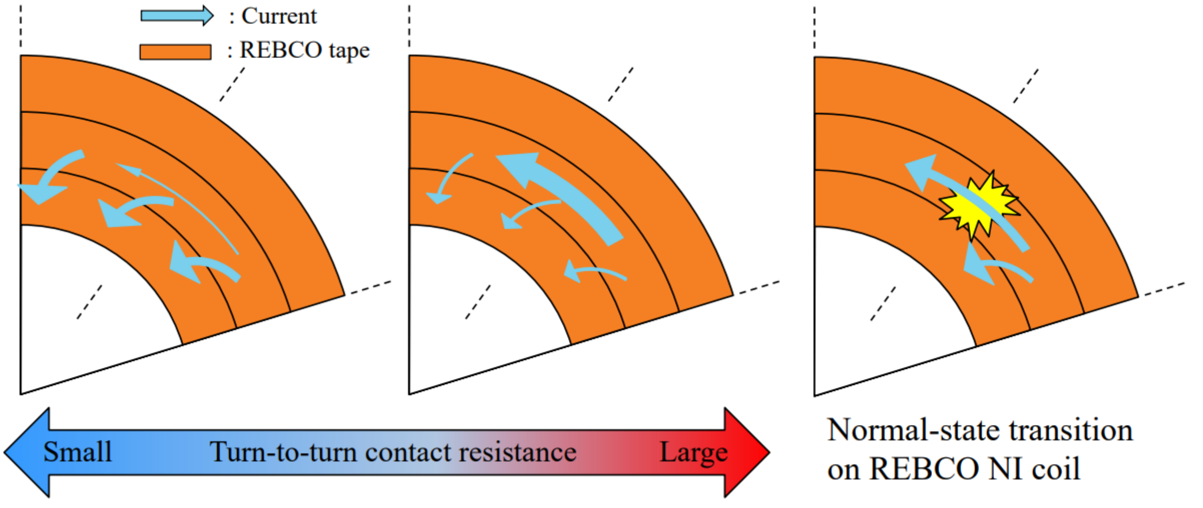

Fig. 1 Schematic views of the excitation delay and the normal-state transition in a part of NI REBCO coil

3. Electromagnetic and thermal simulation method

As an electromagnetic simulation method, we have employed the partial element equivalent circuit method (PEEC) model because the finite element method (FEM) well-known as a conventional electromagnetic simulation method is time-consuming for NI REBCO coil simulation. In the PEEC model, an NI REBCO coil is subdivided into partial elements in the REBCO-tape-longitudinal and coil-radial directions. A schematic view of the PEEC model is shown in Fig.2, where i is the index of local winding PEEC elements, k is the number of turns, M is the self-/mutual inductances, R_θ and I_θ are the resistance and current in the REBCO-tapelongitudinal direction, R_r and I_r are the turn-to-turn contact resistance and current in the coilradial direction, respectively. R_θ is the composite resistance of the REBCO superconductor layer and the copper stabilizer. The REBCO superconductor resistance is computed according to the I-V characteristics of REBCO tapes, called the index model. The PEEC method as an electromagnetic analysis can reproduce a local normal-state transition or a quench event derived from a local hotspot, with dramatically reducing a computation time compared to FEM [12],[13]. As the thermal analysis, we employed the FEM method.

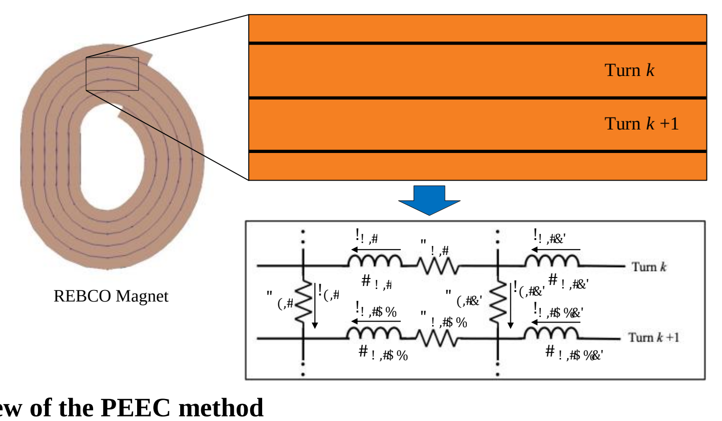

Fig. 2 A schematic view of the PEEC method

In the simulations, two different D-shaped NI REBCO coils were modelled: ~1.12 m (Coil 1) and ~2.24 m (Coil 2) length. A sudden discharging test and a local normal-state transition test were applied for each coil with different turn-to-turn contact resistances.

4. Local normal-state transition tests

On the local normal-state transition tests, one of superconducting-state REBCO elements is enforced into a normal-state one. The temperature rises were investigated for 20 s with the

Table 1: REBCO Tape Condition and Coil Condition

Parameters	Value: Coils 1 / 2
REBCO tape	
Tape width [mm]	4.0
REBCO tape thickness [mm]	0.1
Copper stabilizer thickness [µm]	20.0
REBCO layer thickness [µm]	1.0
Critical current at 77K, self-field [A]	120.0
Pancake coil	
Number of turns	60
Flange width [mm]	1.0
Azimuthal element division	19
D-shaped coil dimensions Arc degree of big circle [°]	120.0
Arc radius of small circle [**m**]	0.3 / 0.6
Arc radius of big circle [**m**]	0.6 / 1.2
Number of pancake coils	1

Table 2: Simulation Condition of Normal-State Transition Test

Parameters	Value
Time step [s]	0.01
Simulation time [s]	20
Operating Temperature [K]	30
Operating current [A]	300

operating current of 300 A. The location of normal-state-transitioned REBCO elements is around the innermost turn of the upper and lower small arcs on the model which has the largest curvature. These elements experience the highest magnetic field perpendicular to the wide surface of REBCO tapes. The simulation conditions are listed in Tables 1 and 2.

Fig. 3 shows the temperature rise on Coils 1 and 2. The temperature on Coil 1 exceeds 77 K at 20 s when the turn-to-turn contact resistance is 2100 $\mu\Omega\cdot cm^2$, whereas it does not exceed 77 K when the turn-to-turn contact resistance is smaller than 1600 $\mu\Omega\cdot cm^2$. Additionally, a rapid temperature rise is observed around 15-20 s. Fig. 4 shows the current distributions obtained with PEEC models. The region of no azimuthal current flow means the occurrence of normalstate-transition of REBCO superconductors, with high resistances. In the cases that the turn-toturn contact resistance is 1600 μΩ·cm^2 and 2100 μΩ·cm^2, a normal-state transition region on Coil 1 expands over time, which means a formation of hotspots occurred and normal-state transition region expands. In the case that the turn-to-turn contact resistance is below 1100 μΩ· cm^2, no expansion of a normal-state transition region appears. Therefore, on Coil 1, the range of turn-to-turn contact resistance below1100 μΩ·cm^2 is suitable for keeping the high thermal stability. Likewise, on Coil 2, the range of turn-to-turn contact resistance smaller than 2100 μΩ·cm^2 is suitable for keeping the high thermal stability.

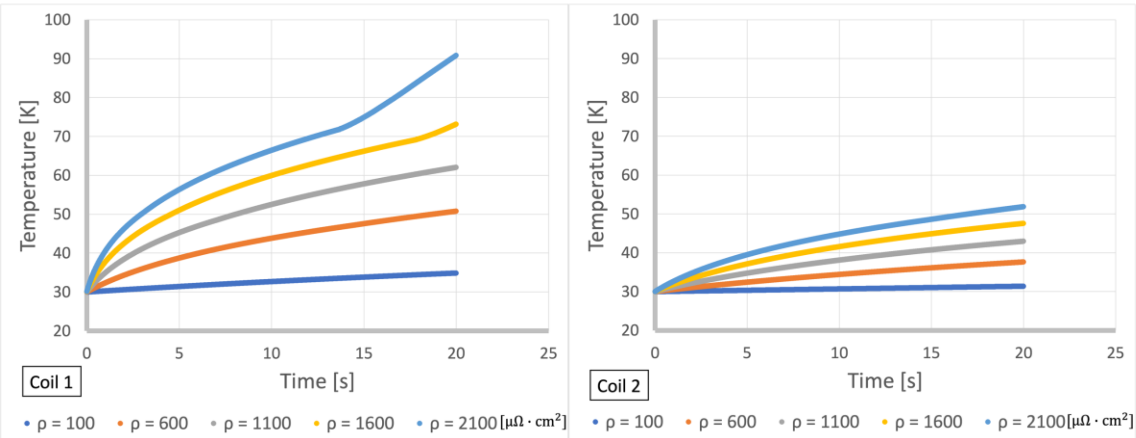

Fig. 3 Temperature rise

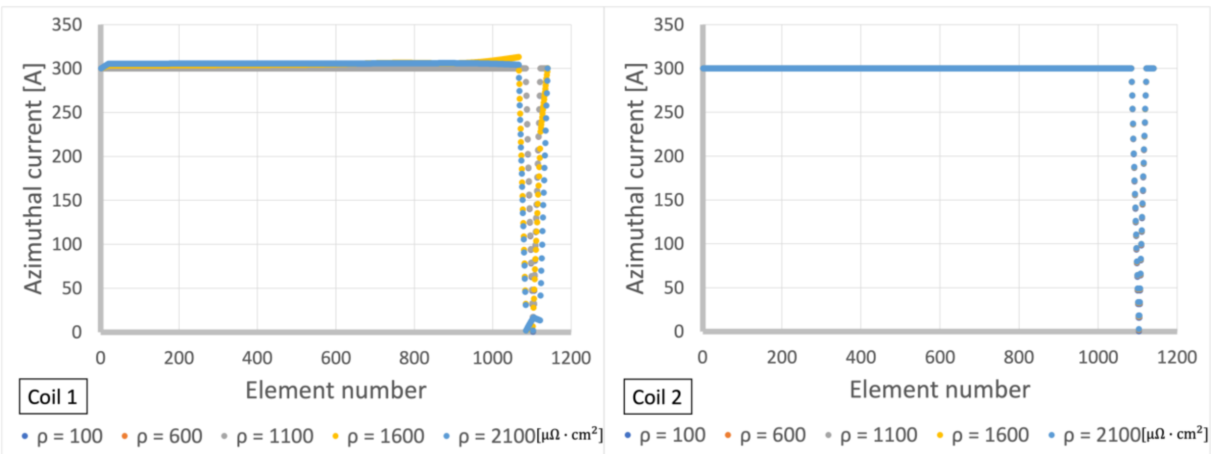

Fig. 4 Azimuthal-current distribution on PEEC elements

5. Sudden discharging tests

On the sudden discharging tests, a steady-state current and a steady-state magnetic field are initially set on the models. Subsequently, after the operating currents are shut down, the time constants are computed from the attenuating magnetic fields. Since the time constant of the excitation delay is identical to the time constant of the sudden discharging test, we indirectly evaluate the time constant of excitation delay in this paper. Tables 1 and 3 list the simulation conditions.

Table 3: Simulation Condition of Sudden Discharging Test

Parameters	Value
Time step [s]	0.2
Simulation time [s]	300-1100
Operating temperature [K]	30
Operating current [A]	50-0

Figs. 5 and 6 show the results of sudden discharging test. Fig. 6(a) shows that the time constants rapidly decreases from minute to second order at 100-1000 μΩ·cm^2. The logarithmic graph of Fig. 6(b) shows that the time constants are inversely proportional to the contact resistivities. Based on the results of the normal-state transition test, the appropriate time constants satisfying the short charging delay while keeping the high thermal stability is 20.0 s or longer on Coil 1 and 44.4 s or longer on Coil 2.

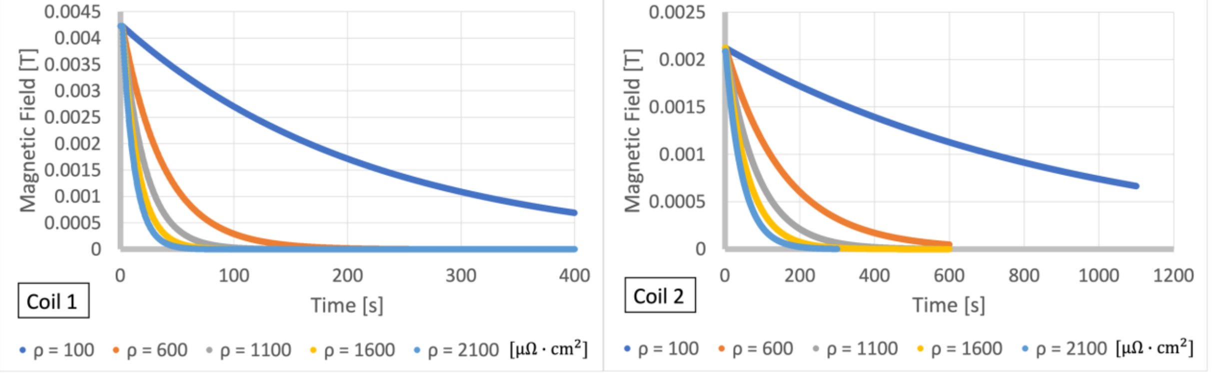

Fig. 5 Magnetic field time-transition

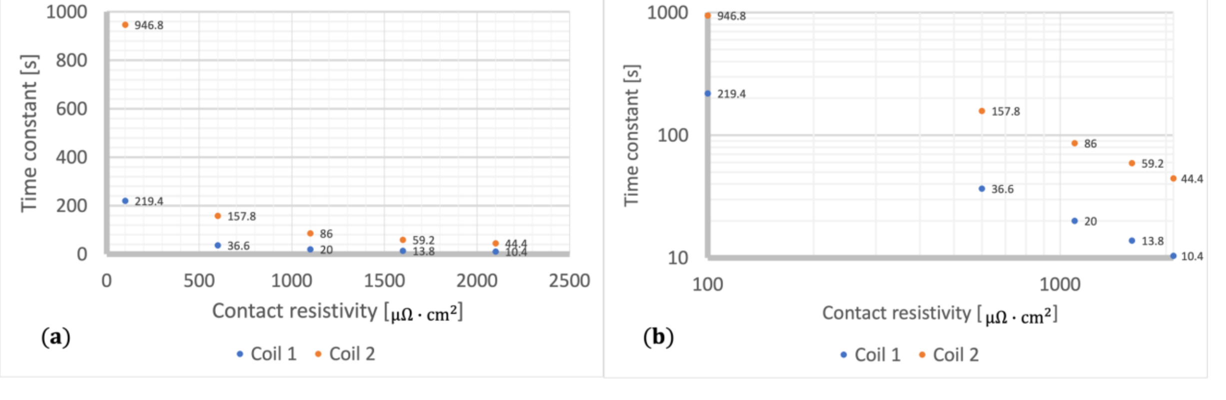

Fig.6 Time constants with (a) linear scale and (b) logarithmic scale

5. Conclusions

In this paper, we have evaluated the charging delay and the thermal stability of the largescale D-shaped NI REBCO coils depending on different turn-to-turn contact resistances. Two PEEC models of D-shaped NI REBCO coils have different sizes: (1) approximately 1.12 m length and 0.75m width and (2) ~2.24 m length and ~1.51 m width. The current behavior was simulated with the PEEC model, the thermal one with FEM. Consequently, The turn-to-turn contact resistances with the short time constant of excitation delay and the high thermal stability are lower than 1100 μΩ·cm^2 for Coil 1 and 2100 μΩ·cm^2 for Coil 2.

In the near future, we will also investigate large-scale D-shaped NI REBCO coils with different types of winding techniques, such as metal insulation and partial insulation.

References

[1] Jacquireid: "MIT-designed project achieves major advance toward fusion energy," Tokamak Energy, accessed at 14 Jul. 2023, available at https://www.tokamakenergy.co.uk/2022/03/10/tokamak-energy-moves-closer-tocommercial-fusion/, 2022.

[2] Wu, Maw Kuen *et al.*: "Superconductivity at 93 K in a new mixed-phase Yb-Ba-Cu-O compound system at ambient pressure," *Phys. Rev. Lett.*, **58**(9), 1987, pp. 908–910.

[3] Maeda, Hideaki / Yanagisawa, Yoshinori: "Recent Developments in HighTemperature Superconducting Magnet Technology (Review)," in IEEE Transactions on Applied Superconductivity, **24**(3), 2014, Art no. 4602412.

[4] Yokoyama, Shoichi *et al*.: "Research and Development of the High Stable Magnetic Field ReBCO Coil System Fundamental Technology for MRI," *IEEE Trans. Appl. Supercond.*, **27**(4), 2017, Art no. 4400604

[5] Weijers, Hubertus W. *et al.*: "Progress in the Development and Construction of a 32T Superconducting Magnet," *IEEE Trans. Appl. Supercond.*, **26**(4), 2016, Art. no. 4300807.

[6] Hahn, Seungyong *et al*.: "HTS Pancake Coils Without Turn-to-Turn Insulation," *IEEE Trans. Appl. Supercond.*, **21**(3), 2011, pp. 1592-1595.

[7] Iwasa, Yukikazu *et al*.: "A High-Resolution 1.3-GHz/54-mm LTS/HTS NMR Magnet, " *IEEE Trans. Appl. Supercond.*, **25**(3), 2015, Art no. 4301205

[8] Hahn, Seungyong *et al*.: "45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet," *Nature* **570**, 2019, pp. 496–499.

[9] David, Chandler: "MIT-designed project achieves major advance toward fusion energy," MIT news, accessed at 28 Jun. 2023, available at https://news.mit.edu/2021/MIT-CFS-major-advance-toward-fusion-energy-0908, 2021.

[10] Ambrosino, Giuseppe / Albanese, Raffaele: "Magnetic control of plasma current, position, and shape in Tokamaks: a survey or modeling and control approaches," *IEEE Control Systems Magazine*, **25**(5), 2005, pp. 76-92.

[11] Mitchell, Neil *et al*.: "The ITER Magnet System, " *IEEE Trans. Appl. Supercond.*, **18**(2), 2008, pp. 435-440.

[12] Wang, Tao *et al*.: "Analyses of Transient Behaviors of No-Insulation REBCO Pancake Coils During Sudden Discharging and Overcurrent," *IEEE Trans. Appl. Supercond.*, **25**(3), 2015, Art no. 4603409.

[13] Katsumata, Kazuki *et al*.: "Influence of the Turn-to-Turn Contact Electrical Resistance on the Thermal Stability in Meter-Class No-Insulation REBCO Pancake Coils During a Local Normal-State Transition," *IEEE Trans. Appl. Supercond.*, **27**(4), 2017, Art no. 4602005.