Current Status of and Challenges for No-Insulation HTS Winding Technique

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Synopsis: In this paper we summarize what we have learned so far and discuss key technical challenges that face the HTS “NI” magnet wound with the no-insulation (NI) technique, focusing one of its beneficial features, self-protecting. We first describe the basic features of the NI winding technique, including lumped circuit and distributed network models. Next, we present results of a stand-alone NI magnet composed of REBCO double-pancake coils, showing that the magnet is indeed self-protecting. In the last part of this paper, we discuss the technical issues, often called “NI behaviors”, objectionable demerits that still remain, particularly in nested-coil NI magnets. These include charging delay, non-linear magnet constant in time-varying operation, unbalanced forces that can overstrain the conductor. We conclude the paper with our conviction, and optimism, that the NI winding technique is viable for HTS magnets, high-field and large electric power devices.

Keywords: active control, charging delay, no-insulation, overstrain, self-protect

(Some figures in this article may appear in color only in the electronic version)

1. Introduction

Protection of a high temperature superconductor (HTS) coil is a prerequisite to widespread use of HTS technology and has been regarded as one of the most challenging technical issues. Firstly proposed in 2010¹⁾, the no-insulation (NI) HTS winding technique is expected to provide a practical solution on protection of high-current density HTS coils. The key idea is to intentionally eliminate turn-to-turn insulation in a pancake coil, thereby upon a quench, enabling current in the coil to automatically bypass the initial hot spot through turn-to-turn contacts. This “current sharing” philosophy was studied in the 1990s for low-temperature superconductor “short-circuited” coils²⁾. Yet, they experienced premature quench mainly due to the local heating by turn-to-turn leak current and extremely low stability margin of LTS at its nominal operating temperature, 4.2 K or below.

Over the past 7 years, substantial progress has been made in the NI HTS technology: >100 HTS coils and

magnets consisting of REBCO pancake coils have been wound with the NI technique or its variations³⁻⁸⁾; most of them survived multiple quenches, intentional or accidental, without electrical burnout. The “fast” electromagnetic quench propagation was commonly observed in NI magnets that consist of multiple magnetically-coupled coils⁹⁻¹²⁾. Also elimination of soft insulation makes NI windings mechanically robust; a typical Young’s modulus of an NI REBCO winding ranges 140 – 180 GPa, while that of insulated 60 – 100 GPa. These two major benefits, self-protecting and mechanical robustness, enable an NI coil to operate at an extremely high overall current density, e.g., 400 – 1000 A/mm² in liquid helium at 4.2 K, greater than that of conventional insulated counterparts, 100 – 200 A/mm²^{13,14)}. As a result, NI magnets become highly compact to a level that has never been achieved before with the conventional insulated approach.

Several drawbacks in the NI HTS technique have also been identified. Charging delay and non-linear magnet constant are intrinsic demerits of the NI technique that are mainly caused by the turn-to-turn short current path. When a quench occurs in an NI magnet, the turn-to-turn short allows a substantial amount of current induced in each magnetically coupled coil, which may lead to unbalanced forces and overstrains.

In this paper we summarize results to date of studies on the NI technique and discuss its technical issues relevant to actual user magnets. First, we consider two numerical models, lumped circuit and distributed network, which

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Fig. 1 Earlier version of the lumped circuit model for an NI coil firstly proposed in ¹⁾. L_{HTS} , R_θ , and R_R stand for, respectively, self inductance of an NI coil, azimuthal resistance including index loss and matrix resistance, and radial resistance mostly from turn-to-turn contact resistance.

simulate the so-called “NI behaviors”, objectionable demerits. Next, we discuss the self-protecting mechanisms: (1) current sharing in a single-coil, stand-alone magnet; and (2) fast electromagnetic quench propagation among magnetically coupled coils in a nested, multi-coil magnet. Finally, we examine technical challenges: (1) temporal variation of the characteristic resistance; (2) techniques, passive and active, to mitigate the NI behaviors; and (3) overstrain and unbalanced forces.

2. Modeling of NI Coil

2.1 Lumped Circuit Model

Fig. 1 shows a simple lumped circuit model for an NI coil, proposed in 2010 ¹⁾, where L_{HTS} , R_θ , and R_R stand for the NI coil’s, respectively, self inductance, azimuthal resistance including index loss and matrix resistance, and radial resistance mostly from its turn-to-turn contact resistance. Wang, et al., proposed an upgrade version with index and stabilizer resistance components separated ¹⁵⁾. This lumped circuit model has been widely used for simulation of many NI coils ^{12,16,17)}. Hahn, et al., analyzed dynamic response of electromagnetic interactive force between pairs of pancake coils, one insulated and the other NI, under time-varying conditions. The simulated and experimental results agreed well ¹⁸⁾.

Bhattarai, et al., expanded the lumped circuit model to a “multi-coil” circuit model ¹⁹⁾ as seen in **Fig. 2**. They reported the first quench simulation on an NI magnet, 7-T/78-mm winding ID having 13 double-pancake coils, constructed at the MIT Francis Bitter Magnet Laboratory ⁷⁾.

Fig. 2 Lumped circuit model applied to a magnet that consists of multiple NI DP coils magnetically coupled ¹⁹⁾.

The magnet survived after multiple over-current quenches in liquid helium at 4.2 K ⁹⁾. The lumped circuit model is a reasonably accurate and time-saving tool to simulate electromagnetic interactions among NI subcoils. However, a distributed network model is required to understand local distributions of current, voltage and temperature within NI winding.

2.2 Distributed Network Model

Unlike the lumped circuit model, a distributed network model segments a winding into multiple sub-sections to simulate local current distribution. **Fig. 3** is an early distributed network model proposed by Yanagisawa, et al. ²⁰⁾. They are the first group to provide numerical explanation on the basic mechanism of self-healing from thermal runaway for NI pancake coils, the so-called “multi-turn-to-single-turn” transition. Wang and Noguchi, et al., proposed another distributed model (**Fig. 4**) using the partial element equivalent circuit (PEEC) approach ²¹⁾. With the PEEC model, they simulated current-sharing and consequent field saturation of an NI coil. Wang, Chan, and Schwartz proposed a coupled model that combines network model, 2D thermal model, and 3D magnetic field model, and successfully simulated electromagnetic and thermal responses of a local hot spot created by a heater in an NI coil ²²⁾.

The early “magnet-level” distributed network analysis was performed by Markiewicz, et al., ²³⁾ where two types of coils were analyzed: (1) a standalone stack of 30

Fig. 3 Distributed network model proposed by Yanagisawa, et al.²⁰⁾, who for the first time provided numerical explanation on the self-protection mechanism, the so-called “multi-turn-to-single-turn transition”.

Fig. 4 Distributed network model based on the partial element equivalent circuit (PEEC) approach proposed by Wang and Noguchi, et al.²¹⁾.

pancake coils; (2) a 15-T insert consisting of a stack of 60 pancake coils in a bore of a 15-T insulated background magnet. With the model, they numerically investigated impact of turn-to-turn contact resistance on charging and post-quench behaviors of the coils. Song, et al., presented another magnet-level simulation using their network model (**Fig. 5**)²⁴⁾. Non-uniform azimuthal and radial current distributions in a stack of 7 NI double-pancake coils were calculated with mutual magnetic coupling among the subcoils incorporated.

3. Self-Protecting Mechanism of NI Coil

Here, we categorize the self-protecting mechanism of the NI technique into two cases: (1) single coil; and (2) a stack of multiple coils magnetically coupled.

Fig. 5 Distributed network model that used by Song, et al., to simulate an NI “magnet” consisting of a stack of 7 double pancake coils²⁴⁾.

3.1 Single NI Coil: Current-Sharing

When a quench occurs in a single coil, an initial hot spot is created and current automatically bypasses it through turn-to-turn contacts. This current-sharing behavior is well explained by the “multi-turn-to-single-turn transition” concept proposed by Yanagisawa, et al. as seen in **Fig. 6**²⁰⁾. To date none of NI single coils were reported damaged after any types of quench (heater induced, over-current, or sudden shut-down of power supply).

3.2 Multi-Coil Magnet: Fast Electromagnetic Quench Propagation

Song, et al., reported the first observation of the electromagnetic quench propagation in a 7-T/78-mm winding ID stand-alone NI magnet that consists of a stack of 13 REBCO double pancake coils⁹⁾. Bhattarai, et al., performed numerical simulation with the lumped multi-coil circuit model in (**Fig. 2**)¹⁹⁾.

The magnet-level quench propagation was also observed with a 26-T/35-mm winding ID NI REBCO magnet⁸⁾, designed by MIT and constructed by SuNAM, Co., Ltd., which consists of a stack of 26 double pancake (DP) coils (**Fig. 7**). A quench test was performed in a bath of liquid helium at 4.2 K at the National High Magnetic Field Laboratory (NHMFL). While the magnet was being charged, a quench occurred at 24 T in DP18, sequentially propagating to the rest of the magnet.

The overall quench propagation was completed within 1 s and the coil survived without electrical burnout. After minor modification by the SuNAM, the magnet is currently installed at the Center for Axion and Precision Physics Research (CAPP) as a user facility magnet for the

Fig. 6 Distributed network simulation results of current distribution within an NI coil: (a) “multi-turn” mode operation at $I_{op} < I_c$; (b) “single-turn” mode operation at $I_{op} >> I_c$ ²⁰.

Institute for Basic Science (IBS) in Korea. The IBS-CAPP reported the first HTS-magnet user experience with this magnet operated at a reduced field of 24 T ²⁵.

4. Key Technical Issues

Here, we discuss key technical issues facing REBCO NI magnets.

4.1 Variation of Characteristic Resistance

Characteristic resistance (R_c in Fig. 2), representing the turn-to-turn contact resistance of each NI coil, is a key parameter to accurately simulate the “NI behaviors” including the charging delay and the non-linear magnet constant ¹⁵. **Fig. 8** presents R_c vs. number of charging cycle data of an NI single pancake coil when in each cycle it was charged to its critical current of 78.8 A in liquid nitrogen at 77 K. In this particular experiment, R_c variation was confined to $\pm 10 \%$. This small variation range in R_c has been commonly observed for other NI coils when operated in liquid nitrogen. However, a substantially larger R_c variation apparently occurs when an NI coil was operated in a bath of liquid helium at 4.2 K, especially after the coil experienced a quench as observed in a 13-T/58-mm winding ID NI magnet composed of a stack of 24 double-pancake coils, built at NHMFL ¹⁰. The magnet experienced a substantial change of R_c , from pre-quench 47 m Ω to post-quench 116 m Ω

Fig. 7 Measured voltages of 26 double pancake (DP) coils of a 26-T/35-mm winding ID NI REBCO magnet ⁸. A quench test was performed in liquid helium at 4.2 K at the NHMFL. The quench occurred in DP18 at 24 T while the magnet was being charged, and then sequentially propagated to the rest of the magnet within 1 s.

(**Fig. 9**). Interestingly, although an increase in R_c has been reported, rarely a decrease. An analytic way to estimate R_c was first proposed by Wang, et al. ¹⁵. Using the same method, Kim, et al., obtained temporal variation results of R_c of an NI coil wound with stainless steel clad REBCO tape during its charging sequences in liquid nitrogen at 77 K ¹⁶.

Lu, et al., reported an experimental study on contact-pressure-dependent R_c for an NI coil under various load cycles ²⁶. They found that the characteristic resistance gradually increased with the number of load cycles and discussed this increase using the Holm’s electrical contact theory. Kim, et al., published an earlier work on dependance of R_c on winding tension. Wang, et al., introduced a concept of “grading” turn-to-turn contact resistance to reduce the non-uniform ramping losses and optimize the temperature gradient with the magnet ²⁷.

4.2 Passive Approach for Mitigating Non-linear NI Behaviors: Increase Average Contact Resistance

To mitigate the charging delay, a few variations of the NI technique have been proposed. The key idea is to

Fig. 8 Variation of characteristic resistance of an NI single pancake coil during multiple charging sequences in a bath of liquid nitrogen at 77 K. Before the test, critical current of the coil was measured at 78.8 A.

Fig. 9 Charging test results of a 13-T/58-mm winding ID NI REBCO magnet consisting of a stack of 24 double-pancake coils (a) before and (b) after a quench in liquid helium at 4.2 K. R_c increased from pre-quench 47 m Ω to post-quench 116 m Ω .

increase the characteristic resistance without sacrificing the self-protecting feature. Song, et al., introduced a partial “insulation” method, where insulation layers were inserted in-between selected turns²⁸⁾. They experimentally demonstrated that the charging time constant of a partial insulation coil was $\sim 1/5^{\text{th}}$ that of its

NI counterpart. Yet, the partial insulation coil survived without damage after an over-current operation in liquid nitrogen at 77 K, while its insulated counterpart was damaged.

The so-called “metal insulation”, a co-winding technique with an electrically resistive metal such as stainless steel, has been studied by a few groups^{3,12-14)}. Lecrevisse reported heater-induced quench results with a stainless-steel co-wound (“metal-as-insulation”) test coil in liquid helium at 4.2 K. The coil survived after multiple consecutive quenches at coil current density up to 830 A/mm²¹³⁾. Choi, et al., published performance test results of a metal insulated HTS racetrack coil, 115-mm radius and 300-mm long, in a conduction cooling operation at 32 K. The coil survived after multiple quenches³⁾.

Recently, SuNAM proposed the so-called “metallic cladding” approach, where a thin (1 – 2 μm thick) layer of stainless steel is coated over REBCO tape to increase R_c . Kim, et al., reported their metal-clad NI coils undamaged after multiple consecutive heater-induced quenches at a coil current density of up to 820 A/mm² in a bath of liquid helium at 4.2 K in a 15-T background field¹⁴⁾. Jang, et al., reported test results of a 3-T/100-mm winding ID magnet of a stack of 32 double-pancake coils wound with stainless steel clad REBCO tape¹²⁾. Although a measured magnet charging time constant was improved to $1/13^{\text{th}}$ that of its NI counterpart, the magnet survived two unexpected sudden full-field discharges caused by the power supply failure.

4.3 Active Approach for Mitigation of the Non-linear NI Behaviors: Active Feedback Control

Since the early days of the NI technique, a lingering question has remained: whether or not the NI coil indeed generates a center field identical to that of its insulated counterpart. Hahn, et al., reported that at steady state the center field from an NI coil was barely discernible “within a Hall sensor accuracy” from that of its insulated counterpart as long as the NI coil⁶⁾. Yet, this issue has not been satisfactorily resolved for magnets requiring a ppm-level field homogeneity such as of NMR and MRI. In addition, temporal instability of an NI magnet until the magnet reaches its “complete” steady-state operation is another crucial drawback as a user magnet.

Kim, et al., reported a method for generating linear current-field characteristics and eliminating charging delay in NI HTS magnets²⁹⁾. A key idea is to control the power supply current (P/S current) with the PI (Proportional-Integral) feedback control for generation of a target center field. An NI magnet consisting of a stack of 13 double-pancake coils was operated to test this method. With this

Fig. 10 Selected variations of the NI technique: (a) partial insulation, where insulation layers are inserted in-between selected turns; (b) metal insulation, where resistive metal is co-wound; (c) metallic cladding, where a thin metal layer, typically stainless steel, is hermetically clad over REBCO tape¹³⁾.

method, the time to reach 99.5% of the target field was reduced to 0.4 s, down from 850 s. This active feedback control is now a common practice in operation of the NI HTS magnets at the NHMFL. **Fig. 11** shows experimental results of the 13 double-pancake NI magnet in a bath of liquid nitrogen at 77 K: (a); (b); and (c) present results of the magnet center fields and P/S current without control, with control, and reference magnetic field, respectively.

4.4 Quench-Induced Forces and Stresses

An NI coil is often operated as an insert of a background magnet. When the background magnet quenches (or trips if it is a resistive magnet), a substantial amount of current may be induced mainly due to flux conservation. Magnetic stress in a magnet may be roughly approximated by the well-known equation, BJR , where as B , J , and R stand for magnetic flux density, conductor

Fig. 11 Operation of an NI REBCO magnet of a stack of 13 double-pancake coils: (a) magnet center field and power supply current ($di/dt=0.09$ A/s) without PI feedback control; (b) magnet center field and reference magnetic field ($dB_{ref}/dt=2.5$ mT/s) with control; (c) P/S current and reference magnetic field with control.

current density, and winding radius, respectively. When the increment rate of the induced current in the NI insert exceeds the decrement rate of the overall magnetic flux density during the quench, it is likely that the overall mechanical strain and unbalanced magnetic forces will exceed design limits.

Painter, et al., reported test results of a 13-T/58-mm

winding ID NI REBCO insert operated in a bore of a 6-T low-temperature superconductor (LTS) background magnet in a bath of liquid helium at 4.2 K¹⁰⁾. With the NI insert initially charged at 13 T, the LTS background magnet quenched at 6 T during its charging sequence to a target field of 7 T. Although all the double pancake coils in the NI insert survived without any damage, a part of the supporting structure was mechanically damaged due to a large unbalanced axial force. The results clearly demonstrate importance of accurate simulation of current distribution within an NI magnet induced during a quench so that we may prevent such and other mechanical failures.

5. Conclusion

Nearly 7 years have passed since the no-insulation (NI) winding technique was proposed in 2010, to make the HTS magnet, specifically composed of DP coils, mechanically robust, compact, and self-protecting. In this article, we have focused on its self-protecting feature. Through experiment and analysis, we now reasonably understand the self-protecting mechanisms of not only single coils but also nested coil NI magnets that rely on fast electromagnetic quench propagation among magnetically coupled coils. We may thus state that the NI technique is a practical solution to quench protection, a critical issue to an HTS magnet. Both lumped circuit and distributed network models have been applied to explain the so-called “NI behaviors” that include charging delay, non-linear magnet constant, unbalanced forces that can lead to mechanical failure, and conductor overstrains. Temporal change of characteristic resistance, for example, worsens the charging delay issue for the NI coil. As a solution to ameliorate the charging delay, methods to increase turn-to-turn contact resistance, e.g., partial insulation, metal-as-insulation, metallic cladding technique, have been investigated and proven quite effective. Additionally, an active feedback control approach has also been demonstrated effective to reduce the charging delay and better control the magnet center field. Unbalancing forces and stresses upon a quench, particularly when an NI coil is operated in the bore of a background magnet, must further be studied to mechanically safeguard the magnet. For this analysis the distributed network model should play an important role. Yet, there still remain issues that require further understanding in the electromagnetic and mechanical behaviors of the NI magnets before their widespread applications, in high field and large electric power devices.

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