Dynamic Response of No-Insulation and Partial-Insulation Coils for HTS

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October, 2014

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This work was supported by the International Collaborative R&D Program of the KETEP grant funded by the Korean government MKE (20118520020020). Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Dynamic Response of No-Insulation and Partial-Insulation Coils for HTS Wind Power Generator

Jung-Bin Song, Seungyong Hahn, Youngjae Kim, Daisuke Miyagi, John Voccio, Juan Bascuñán, Haigun Lee and Yukikazu Iwasa

Abstract— In this paper, we present results, experimental and numerical, of the electromagnetic interaction forces between pairs of racetrack coils under time-varying conditions. Three turn-to-turn insulation designs were applied to wind three racetrack coils with GdBCO coated conductor: 1) no-insulation (NI); 2) partial-insulation (PI) of a polyimide layer every eight turns; and 3) insulation (INS) of a polyimide layer between each, i.e., NI, PI, and INS racetracks. Two racetrack pairs, NI-INS and PI-INS were tested for their interaction forces, measured with load cell under current-ramping conditions in a bath of liquid nitrogen at 77 K. Good experimental and simulation results validate our equivalent circuit model to compute interaction forces of PI-INS racetrack pair. Over-current test of NI and PI coils, where each racetrack coil was charged above critical current (Ic), was also performed to compare coil stability. This result implies that, although the PI winding technique improves the dynamic response, stability will be somewhat compromised.

Index Terms— Electromagnetic force, equivalent circuit model, no-insulation, partial-insulation, wind power generator.

I. INTRODUCTION

As the power generation capacity of a unit wind turbine continues to escalate, there is an urgent need to reduce the generator size and weight. The smaller and lighter generator reduces its overall system cost. The HTS (high-temperature superconductor) technology enables a “large” wind generator to be compact and lightweight, leading to innovative turbine designs that are not feasible with conventional technology. However, protection of HTS coils in the event of a quench still remains a major technical challenge to the HTS wind generators. Therefore, for practical HTS turbines, these protection and reliability issues need to be fully resolved [1]-[6].

The main feature of the no-insulation (NI) winding technique is complete elimination of turn-to-turn insulation in an HTS winding [7]. In the event of a quench, the NI coil current can "automatically" bypass through the turn-to-turn contacts from its original spiral path and the coil becomes "self-protecting" without any additional protection circuitry. To date, we have demonstrated, with experiment and analysis, the built-in self-protecting feature of the NI coils, absent in their conventional insulated counterparts [7]. Due to this self-protecting feature, NI coils require only a minimal thickness of stabilizer, typically <10 μm, electroplated chiefly for ease of handling and soldering, and thus becoming highly compact. Therefore, many studies for investigating thermal and electrical stabilities of NI magnet have been conducted [7]-[26]. However, for applying the NI technique to large-scale HTS rotating machine such as HTS wind power generator, it is necessary to investigate dynamic responses of the electromagnetic interaction force ($F_z$) between the windings of an NI coil and its insulated (INS) armature.

In 2013, we reported simulation and experimental results of $F_z$ between NI and INS coils under time-varying condition for application of the NI technique to the HTS wind power generator. This earlier study showed that $F_z$ between NI and INS coils lags during current ramping, and increasingly more so at faster ramp rate [27]. Recently, we proposed the partial-insulation (PI) winding technique that can significantly reduce charging delay [28], the source of lagging in $F_z$. As a follow-up study, we have investigated $F_z$ between PI and INS coils under time-varying conditions.

This paper presents results, empirical and numerical, of the $F_z$ between PI and INS pairs of racetrack coils under time-varying conditions. Three turn-to-turn insulation designs were applied to wind three racetrack coils with Cu-electroplated-GdBpco coated conductor: 1) NI; 2) PI of a polyimide layer in every eight turns; and 3) INS of a polyimide layer in turn-to-turn, i.e., NI, PI, and INS racetracks. Two racetrack pairs, NI_{TOP}-{INS}_{BOT} and PI_{TOP}-{INS}_{BOT} were tested for their interaction forces, measured with a load cell under current-ramping conditions in a bath of liquid nitrogen at 77 K. The subscripts TOP and BOT refer to the axial positions of the racetracks. Good agreement between experiment and simulation validates our equivalent circuit model applied to compute interaction forces of the PI-INS racetrack pair. Over-current test of NI and PI coils, where each racetrack coil was charged above critical current ($I_c$), were also performed to compare the stability of the coils. This result implies that, although the PI winding technique improves the dynamic response, stability will be somewhat compromised.

II. EXPERIMENTAL SETUP

Fig. 1 shows pictures of the NI, PI and INS single-pancake (SP) racetrack coils. Each test coil was wound onto a phenolic bobbin with GdBpco coated conductor (CC) manufactured by SuNAM, with a winding tension of 20 N. Although the 25-mm inner diameter end sections and the 80-mm long straight section were the same for the three racetrack test coils, the outer diameters were 32.2, 29.3, and 29.8 mm, respectively, indicating a larger outer diameter for the INS than...
TABLE I

SPECIFICATION OF THREE RACETRACK SP TEST COILS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>NI_TOP</th>
<th>INS_BOT</th>
<th>PI_TOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor (ReBCO, SuNAM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width/Thickness [mm]</td>
<td>0.41; 0.085</td>
<td>0.41; 0.085</td>
<td>0.41; 0.085</td>
</tr>
<tr>
<td>Insulation method</td>
<td>No insulation</td>
<td>No insulation</td>
<td>No insulation</td>
</tr>
<tr>
<td>Coil constant (k) [mT/A]</td>
<td>0.811</td>
<td>0.786</td>
<td>0.806</td>
</tr>
<tr>
<td>Self inductance [mH]</td>
<td>0.534</td>
<td>0.501</td>
<td>0.528</td>
</tr>
<tr>
<td>Mutual inductance [mH]</td>
<td>0.145</td>
<td>0.146</td>
<td>0.146</td>
</tr>
<tr>
<td>Magnetic force constant ($F_c$) [N/A]</td>
<td>-0.25</td>
<td>-0.25</td>
<td>-0.25</td>
</tr>
<tr>
<td>$I_c$, @ 77 K, self-field [A]</td>
<td>71</td>
<td>69</td>
<td>72</td>
</tr>
</tbody>
</table>

The load cell constant was 0.5 mV/N, and its measurement uncertainty, due primarily to temperature change during measurement, was about 10%. To prevent damaging the load cell by thermal shock, it was always placed above the LN2.

Over-current test was also performed to investigate stability of NI and PI racetrack coils. For the test, the NI and PI racetrack coils were tested by following three sequential steps: 1) charge to 1.25 $I_c$ at a current-ramping rate of 10 A/min, 2) maintain at 1.25 $I_c$ for 300 s, and 3) discharge at the rate numerically equal to the ramping up rate.

III. EQUIVALENT CIRCUIT MODEL

Fig. 3 shows an equivalent circuit model for the NI-INS and PI-INS pairs. The current flows toward the radial direction through the turn-to-turn contacts as well as through the superconducting spiral direction. This circuit model can be formulated as following equation by applying Kirchhoff’s laws:

\[ I_{\theta} + I_R = I_{TOP} \]  \[ (1) \]

\[ \frac{dl}{dt} + M \frac{dl_{BOT}}{dt} + I_{\theta} R_{\theta} = I_R R_e \]  \[ (2) \]

where $I_{TOP}$, $I_{BOT}$, $I_\theta$, $I_R$, $R_\theta$, $L_{NI}$, and $M$ are, respectively, power supply currents to the top and bottom coils, the currents through the spiral and radial directions of the NI or PI coil, azimuthal resistances, self and mutual inductances. $R_e$ is the characteristic resistance of a NI pancake coil, NI or PI, representing the total sum of resistances.

Here, $R_\theta$ generated by the index and AC losses, may be neglected under nominal operating conditions, and $R_e$ is mostly from the turn-to-turn contacts. In addition, $dl_{BOT}/dt=0$, because $I_{BOT}$ was maintained constant at 40 A in this test.

IV. RESULT AND DISCUSSION

A. Characteristic Resistance $R_e$ of NI and PI Racetrack Coils

To determine $R_e$ of NI and PI racetrack coils, experiment and calculation were conducted on each coil in the following four steps: 1) charge a racetrack coil to 10 A at a current-ramping
current was ramped at rates of 1, 5, 10, and 20 A/s to the top coil, from −40 to 40 A without pause. This test was repeated 4 times with the power supply controlled manually.

Fig. 5 shows the electromagnetic interaction force \( F_z \) as a function of \( I_{\text{top}} \) with ramp rates of 1, 5, 10 and 20 A/s and at \( I_{\text{bot}} = 40 \) A. For the NI_{\text{top}}-INS_{\text{bot}} pair (Fig 6a), as the ramp rate was increased from 1 A/s, the major axis slope of the \( F_z \) loop abruptly decreased at 5 A/s, decreased further with ramp rate, reaching almost flat at 20A/s. In addition, a measured \( F_z \) value of 2.8 N of this pair at a ramp rate of 20A/s greatly differs from a calculated figure of 10 N for \( I_{\text{top}} = 40 \) A. This disparity indicates that the dynamic response of the NI_{\text{top}}-INS_{\text{bot}} pair under time-varying conditions is very slow. For the PI_{\text{top}}-INS_{\text{bot}} pair (Fig. 6b), the major axis slope of the \( F_z \) loop decreased only slightly with increasing ramp rate. At \( I_{\text{top}} = 40 \) A, a measured \( F_z \) of 7.6 N at a ramp rate of 20A/s demonstrates that the PI technique can eliminate an abrupt change in the major axis slop of the \( F_z \) loop.

B. Dynamic Responses of NI and PI Racetrack coils

Two pairs, NI_{\text{top}}-INS_{\text{bot}} and PI_{\text{top}}-INS_{\text{bot}}, were each tested in a bath of LN2 at 77 K. In each pair, the coils were axially separated by 17.2 mm, and the calculated interaction force constant \( (f) \) was −0.25 N/A, repulsive.

For measuring dynamic responses of each pair, while the INS_{\text{bot}} racetrack coil carried a constant current of 40 A, a
are in good agreement, demonstrating clearly observed that the experimental result in reduced $F_z$, which is increased by partial insulation, which in turn results in reduced $F_z$ lag [see equation (2)]. Furthermore, it may be clearly observed that the experimental and calculated results are in good agreement, demonstrating that our equivalent circuit model is valid for computing the interaction force of PI$^\text{TOP}$-INS$^\text{BOT}$ racetrack pair.

\[ F_z = F_c I_\theta \]  \hspace{1cm} (3)

Fig. 6 shows measured and numerically calculated values of $F_z$ and current as a function of time at ramp rate of 20 A/s, corresponding to Fig. 5 (square data). As shown in Figs. 6 (a) and (b), the maximum $I_\theta$ value of the PI$^\text{TOP}$-INS$^\text{BOT}$ pair (33.5 A) was ~22 A higher than that of the NI$^\text{TOP}$-INS$^\text{BOT}$ pair (11.2 A). The PI racetrack coil has a significantly faster dynamic response $I_\theta$ than the NI coil, because $I_\theta$ decreases with $R_c$, which is increased by partial insulation, which in turn results in reduced $F_z$ lag [see equation (2)]. Furthermore, it may be clearly observed that the experimental and calculated results are in good agreement, demonstrating that our equivalent circuit model is valid for computing the interaction force of PI$^\text{TOP}$-INS$^\text{BOT}$ racetrack pair.

C. Over-Current Test of NI and PI Racetrack Coils

To estimate the thermal stability of NI and PI racetrack coils, the coils were charged up to 1.25$I_f$ and discharged to zero at a current-ramp rates, respectively, of ±10 A/min (Fig. 7). As shown in Fig. 7, the voltage (13.3 mV) of the PI racetrack coil (closed circle) was much higher than that (3.5 mV) of the NI racetrack (closed circle). In addition, when an over-current was maintained, the voltage of the PI racetrack coil dropped a little and reached a plateau, which indicates that the coil shows automatic turn-to-turn bypassing characteristics of an NI coil. This result implies that, although the PI winding technique improves the dynamic response, stability will be somewhat compromised. Therefore, optimization of dynamic response vs. stability is required when the PI technique is applied to the superconducting coils in the wind generator.

V. CONCLUSION

Charging-discharging tests and numerical analyses were performed on two racetrack pairs, NI-INS and PI-INS, in order to investigate the dynamic response of each pair. Over-current test was also performed to determine the degree of stability in NI and PI racetrack coils. Based on the test results, we may conclude that:

· The PI$^\text{TOP}$-INS$^\text{BOT}$ pair shows significantly faster dynamic response force than that of NI$^\text{TOP}$-INS$^\text{BOT}$ pair, because current ($I_\theta$) flowing through radial directions decreases as the characteristic resistance ($R_c$) is increased by partial insulation.

· The numerical results based on an equivalent circuit model agreed well with experimental results. The agreement validates our equivalent circuit model to compute the interaction force of PI-INS racetrack pair.

· For fast dynamic response, the PI technique is superior to the NI technique; however, the coil stability is somewhat compromised. Therefore, it is necessary to optimize dynamic response vs. stability when applying the PI technique to the superconducting coils in the wind generator.

In sum, the PNI technique is suitable to the field coil of a wind generator if it’s optimized in terms of dynamic response vs. stability.
REFERENCES


