

## High-Current Winding for SMES Cable and Its System Configuration for Photovoltaic Power Transmission

Higashikawa, Kohei

Department of Electrical Engineering, Graduate School of Information Science and Electrical Engineering, Kyushu University

Miyazaki, Tomoya

Department of Electrical Engineering, Graduate School of Information Science and Electrical Engineering, Kyushu University

Tabuchi, Tatsuya

Department of Electrical Engineering, Graduate School of Information Science and Electrical Engineering, Kyushu University

Asano, Masaki

Department of Electrical Engineering, Graduate School of Information Science and Electrical Engineering, Kyushu University

他

<https://hdl.handle.net/2324/7432841>

---

出版情報 : IEEE Transactions on Applied Superconductivity. 35 (5), pp.4802305-, 2025-03-17.  
Institute of Electrical and Electronics Engineers (IEEE)

バージョン :

権利関係 : © 2025 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.





# High-current Winding for SMES Cable and Its System Configuration for Photovoltaic Power Transmission

Kohei Higashikawa, Tomoya Miyazaki, Tatsuya Tabuchi, Masaki Asano, Sho Moroi, Takanobu Kiss, Kei Shiohara, Michio Sato, and S. M. Muyeen

**Abstract**— The use of electricity generated from renewable energy sources is essential for a carbon-neutral society, and countermeasures against their severe output power fluctuations are key to this. In our previous studies, we proposed a superconducting cable with energy storage function (SMES cable) as such a countermeasure and successfully demonstrated its function using a small model cable (with a current capacity of the order of 100 A) and a simple circuit model (with photovoltaic assumed by a voltage source) based on a hardware-in-the-loop simulation (HILS). In this study, a kA-class model cable was fabricated by parallel winding of a REBCO coated conductor, and a HILS-based experiment showed that the cable could be regarded just as an inductance with negligible loss. Furthermore, it was found that the application of SMES cable to photovoltaic power transmission could maximize the output power from the photovoltaic while reducing its fluctuation by appropriately combining a DC-DC converter and the current-voltage level of the photovoltaic array.

**Index Terms**— DC power system, energy storage, photovoltaic power generation, superconducting cable.

## I. INTRODUCTION

THE use of electricity generated from renewable energy sources is essential to realize a carbon-neutral society [1], [2] and countermeasures against their severe output power fluctuations are key to achieving this [3]–[6]. Energy storage technology is a strong candidate for such a countermeasure. However, energy storage devices with larger energy capacity (e.g., pumped storage [7], compressed air energy storage [8], hydrogen [9], etc.) tend to have a slower response speed, while those with a faster response (e.g., electric double layer capacitor [10], flywheel [11], superconducting magnetic energy storage (SMES) [12], etc.) tend to have a smaller energy capacity; no energy storage technology exists that combines both the energy capacity and response speed.

Manuscript received September 25, 2024. This work was supported by JSPS KAKENHI Grant Number JP24H00320 and Qatar-Japan Research Collaboration Program Grant Number M-QJRC-2023-317.

K. Higashikawa, T. Miyazaki, T. Tabuchi, M. Asano, S. Moroi, and T. Kiss are with the Department of Electrical Engineering, Graduate School of Information Science and Electrical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan (e-mail: kohei@super.ees.kyushu-u.ac.jp).

K. Shiohara and M. Sato are with the SWCC Corporation, Sagamihara 252-0253, Japan.

S. M. Muyeen is with the College of Engineering, Qatar University, Doha 2713, Qatar.

In our previous studies, we proposed a superconducting cable with energy storage function (SMES cable) as such a candidate [13]. An experiment based on a hardware-in-the-loop simulation (HILS) showed that SMES cables can not only play a role in power transport but also fully compensate for severe output power fluctuation from photovoltaic (PV) generation [14]. However, while full-scale SMES cables requires current capacities of kA or more, the experiment was performed with small-scale model cables wound with a single REBCO coated conductor with current capacities in the range of 100 A. Furthermore, the experiment was also conducted assuming a very simple circuit in which PV was considered just as a variable voltage source. Therefore, for future practical applications of SMES cables, it is still essential to consider higher current capacity and more detailed system configuration.

In this study, a kA-class model cable was fabricated by parallel winding of a REBCO coated conductor. The current capacity of the cable was evaluated by the four-probe transport method, and an experiment based on HILS revealed that the cable could be regarded as a simple inductance. Furthermore, assuming a SMES cable as a large inductance, a system configuration was studied to maximize the output power from PV while suppressing its fluctuation.

## II. HIGH-CURRENT WINDING FOR SMES CABLE

### A. Fabrication of a Model Cable and Its Current Capacity

A 1-m-long model cable was fabricated by parallel winding of a REBCO coated conductor. Fig. 1 shows the photographs. As a strand, an insulated 4-mm-wide coated conductor with a critical current (at 77 K and self-field) of 196–202 A was wound on a 75-mm-diameter core with 33 turns at a pitch of 37 mm. The number of the strands was eight, and all strands were wound in one layer. Accordingly, the total length of the winding became 1.23 m.

The model cable was immersed in liquid nitrogen and measured by the four-probe method. Fig. 2 shows the results. When the eight strands were connected in parallel, no significant voltage could be detected on any of the strands as shown by the closed symbols even when a current of 1.28 kA, the limit of the power supply (Matsusada Precision PR10-1200), was applied. Therefore, the eight strands were connected in series, and the current capacity of the model cable was estimated as shown by the open symbols.

TABLE I  
EVALUATION RESULTS FOR EACH STRAND OF THE MODEL CABLE

| Strand ID | Self-inductance (μH) | Critical current (A) | <i>n</i> -value |
|-----------|----------------------|----------------------|-----------------|
| 1         | 9.88                 | 207                  | 37.0            |
| 2         | 9.84                 | 203                  | 31.8            |
| 3         | 9.80                 | 197                  | 32.6            |
| 4         | 9.83                 | 186                  | 37.5            |
| 5         | 9.88                 | 191                  | 37.4            |
| 6         | 9.91                 | 191                  | 38.4            |
| 7         | 9.80                 | 193                  | 39.9            |
| 8         | 9.87                 | 195                  | 41.5            |

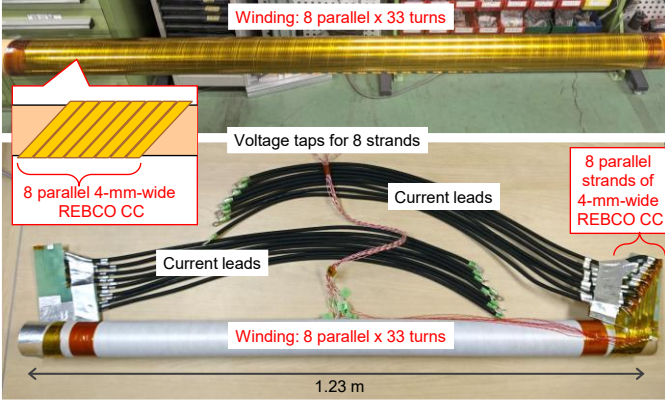


Fig. 1. Photographs of the model cable fabricated with 8 parallel winding of 4-mm-wide REBCO coated conductor (CC).

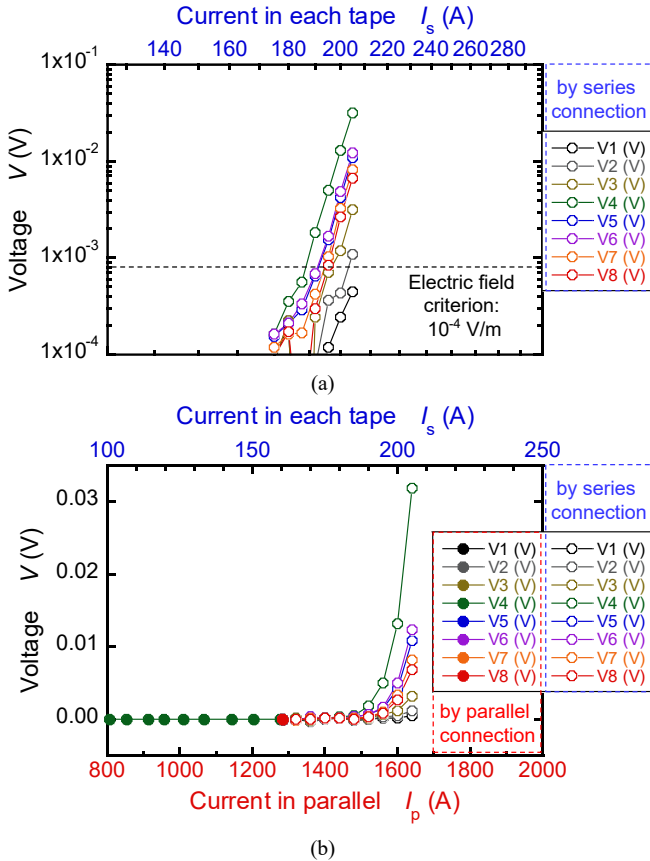


Fig. 2. Current-voltage characteristics of the model cable measured by the four-probe method: (a) double logarithmic plot and (b) linear plot. V1-8 indicates the measured voltage for each strand.

Table 1 also lists the critical current and  $n$ -value for each strand estimated from the data plotted in Fig. 2 (a). The critical currents of the strands were 186-207 A, which were almost equal to those of the coated conductor at self-field, even though a magnetic field of 50 mT was generated in the model cable then. This would be due to the fact that the magnetic field was applied parallel to the surface of the coated conductor because the winding was almost a solenoid coil. The total critical current is 1.56 kA, which is the maximum potential of the current capacity where the current distribution among the strands is homogeneous. Furthermore, the self-inductance of each strand was also measured with an LRC meter and found to be nearly equal among the strands as listed in Table 1. Therefore, homogeneous current distribution among the strands for a time-varying operation could be expected. In summary, these results showed that the model cable successfully energized 1.28 kA, and its current capacity was estimated to be around 1.5 kA at the maximum.

### B. Evaluation of the Behavior in Discharging Operation

A discharge operation experiment using HILS was also conducted to evaluate the transient characteristics of the model cable. Fig. 3 (a) illustrates the method. Since the concept of the method has already been reported in our previous works [15], it is briefly described here. A full-scale circuit was modeled in the real-time digital simulator (RTDS), and the instantaneous value of the current flowing in a full-scale SMES cable,  $i_{SC}$ , was calculated. Considering the ratio of the current capacity of the model cable to that of the full-scale, downscaled current,  $i_{HW}$ , was applied to the model cable. Then, the voltage induced in the model cable,  $v_{HW}$ , was measured and fed back to RTDS as that of the full-scale cable,  $v_{SC}$ , by scaling up with the ratio of the cable lengths. The procedure was repeated every 50  $\mu$ s.

Fig. 3 (b) shows the results for an extreme situation where the output power from PV,  $p_{PV}$ , suddenly drops from the rated power to zero at  $t = 0.4$  s. Despite such a situation, it can be seen that the load receives power,  $p_{load}$ , without any momentary interruption. This result shows that SMES cables can compensate for high power up to the rating of the power system itself at high speed. The cable supplied such a power by the product of the current and the induced voltage. Here, the relationship between current and voltage of the model cable is given by the following equation:

$$v_{HW} = L \frac{di_{HW}}{dt} + Ri_{HW} \quad (1)$$

where  $L$  and  $R$  are the inductance and resistance of the model cable, respectively. The value of  $L$  was estimated to be 4.99  $\mu$ H theoretically from the diameter, length, and turn number of the winding. If no loss is assumed in the cable, the following equation can be derived from (2) with  $R = 0$ :

$$i_{HW}(t) = \int_0^t \frac{v_{HW}(t')}{L} dt'. \quad (2)$$

Such current waveform estimated from the measured voltage is superposed on the experimental one in Fig. 3 (b); it can be seen that the two curves almost completely overlap. This suggests that SMES cables can be regarded as an inductance with negligible loss.



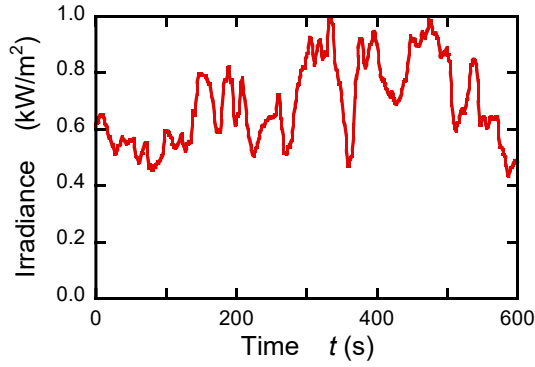


Fig. 6. Time variation of solar irradiance assumed in the simulation.

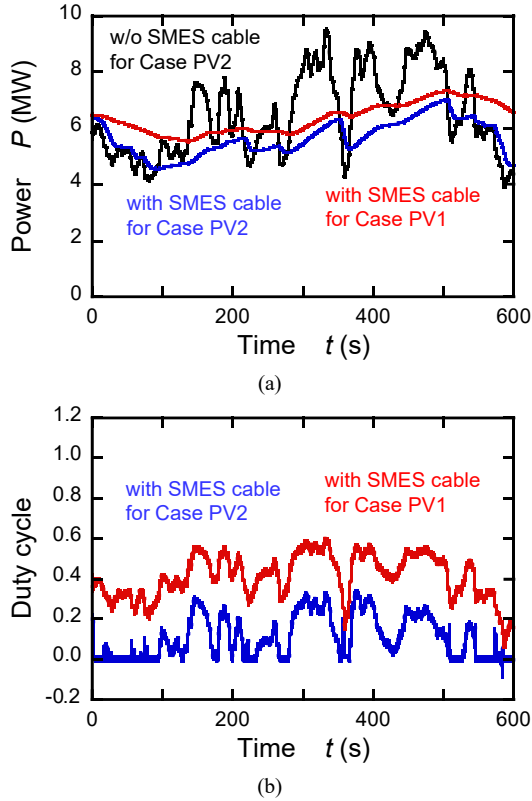


Fig. 7. Simulation results obtained with a boost converter: (a) power received at the terminal and (b) duty cycle for MPPT. Explanation of Cases PV1-2 are given in Fig. 4.

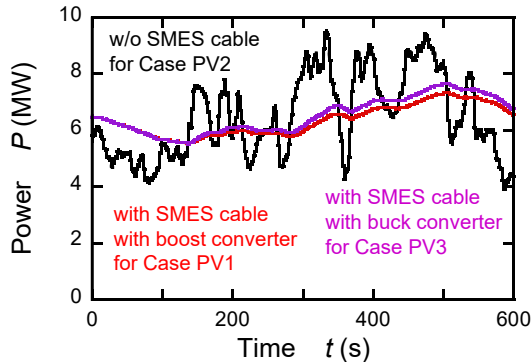


Fig. 8. Simulation results of the received power at the terminal obtained with a buck converter compared with those with the boost converter. Explanations of Cases PV1-3 are given in Fig. 4.

## B. Results and Discussion

Fig. 7 shows the results obtained with a boost converter. Fig. 7 (a) also includes the results for the case without SMES cable; the fact that the received power at the terminal is corresponding to the time variation of the solar irradiance shown in Fig. 6 suggests that the MPPT works for Case PV2 without problems. On the other hand, the fluctuation is greatly suppressed with the SMES cable. However, for Case PV2, the energy received at the terminal with the SMES cable (3.39 GJ) became smaller than that without it (3.90 GJ). To investigate the reason, the duty cycle was checked, and it was found that the duty cycle reached its lower limit as shown in Fig. 7 (b) when solar irradiance was low. Then, the current from the PV array became smaller than the current in the SMES cable; the boost converter cannot deal with such situation. To prevent such a situation, the series-parallel connection of the PV array was changed to Case PV1 where the current from the PV array became higher. As a result, the power received at the terminal increased; accordingly, also the energy increased to a similar value (3.82 GJ) to that without the SMES cable (3.90 GJ). Furthermore, Fig. 8 shows the results obtained with a buck converter. By selecting an appropriate series-parallel connection for the PV array, the buck converter was successfully operated for Case PV3. Not only the output fluctuation from the PV array was significantly suppressed, but also the energy received at the terminal became almost same value (3.92 GJ) as that without the SMES cable (3.90 GJ). From these results, it can be concluded that SMES cables can provide significant compensation function for output power fluctuation from PV with extracting energy from it as much as possible.

## IV. CONCLUSION

A kA-class model cable of SMES cable was fabricated and successfully demonstrated a current capacity of 1.28 kA. A discharge operation experiment based on HILS showed that the cable could be regarded just as an inductance with negligible loss. By a numerical simulation using such a finding, it was confirmed that the application of SMES cable to photovoltaic power transmission could maximize the output power from the photovoltaic while reducing its fluctuation by appropriately combining a DC-DC converter and the current-voltage level of the photovoltaic array. These results will be an important step toward the practical application of SMES cables for the use of renewable energies as a main power source for a carbon-neutral society.

## ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number JP24H00320 and Qatar-Japan Research Collaboration Program Grant Number M-QJRC-2023-317.

## REFERENCES

- [1] D. Infield and L. Freris, "Renewable Energy in Power Systems," John Wiley & Sons, Ltd, 2020.
- [2] A. Qazi, F. Hussain, N. ABD. Rahim, G. Hardaker, D. Alghazzawi, and K. Shaban, "Towards Sustainable Energy: A Systematic Review of

- Renewable Energy Sources, Technologies, and Public Opinions,” *IEEE Access*, vol. 7, pp. 63837-63851, May 2019.
- [3] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, “Battery Energy Storage to Mitigate Rapid Voltage/Power Fluctuations in Power Grids Due to Fast Variations of Solar/Wind Outputs,” *IEEE Access*, vol. 9, pp. 12191-12202, January 2021.
  - [4] Yushu Sun, Zhenxing Zhao, Min Yang, Dongqiang Jia, Wei Pei, and Bin Xu, “Overview of energy storage in renewable energy power fluctuation mitigation,” vol. 6, pp. 160-173, March 2020.
  - [5] S. Shivashankar, Saad Mekhilef, Hazlie Mokhlis, and M. Karimi, “Mitigating methods of power fluctuation of photovoltaic (PV) sources – A review,” *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 1170-1184, June 2016.
  - [6] Abdul Motin Howlader, Naomitsu Urasaki, Atsushi Yona, Tomonobu Senjyu, and Ahmed Yousuf Saber, “A review of output power smoothing methods for wind energy conversion systems,” *Renewable and Sustainable Energy Reviews*, vol. 26, pp. 135-146, October 2013.
  - [7] Shafiqur Rehman, Luai M. Al-Hadhrani, and Md. Mahbub Alam, “Pumped hydro energy storage system: A technological review,” *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 586-598, April 2015.
  - [8] Henrik Lund and Georges Salgi, “The role of compressed air energy storage (CAES) in future sustainable energy systems,” *Energy Conversion and Management*, vol. 50, pp. 1172-1179, May 2009.
  - [9] Meiling Yue, Hugo Lambert, Elodie Pahon, Robin Roche, Samir Jemei, and Daniel Hissel, “Hydrogen energy systems: A critical review of technologies, applications, trends and challenges,” *Renewable and Sustainable Energy Reviews*, vol. 146, ArtID. 111180, August 2021.
  - [10] Pawan Sharma and T.S. Bhatti, “A review on electrochemical double-layer capacitors,” vol. 51, pp. 2901-2912, December 2010.
  - [11] Mustafa E. Amiryar and Keith R. Pullen, “A Review of Flywheel Energy Storage System Technologies and Their Applications,” *Applied Science*, vol. 7, ArtID. 286, March 2017.
  - [12] Bukola Babatunde Adetokun, Oghenewvogaga Oghorada, and Sufyan Ja'afar Abubakar, “Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications,” vol. 55, ArtID. 105663, November 2022.
  - [13] Kohei Higashikawa, Takanobu Kiss, Hitoshi Kitaguchi, Naoki Hirano, Kazuhiko Hayashi, and S. M. Muyeen, “Superconducting cable with energy storage function and its potential for next-generation power system compatible with large-scale renewable energy installation,” *Superconductor Science and Technology*, in press.
  - [14] K. Higashikawa et al., “Development of Superconducting Cable with Energy Storage Function and Evaluation of its Functionality in DC Microgrid With Renewable Energy Sources,” *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, ArtID. 5400405, August 2023.
  - [15] K. Higashikawa and T. Kiss, “Novel Power System with Superconducting Cable with Energy Storage Function for Large-Scale Introduction of Renewable Energies,” *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, ArtID. 5402204, August 2019.
  - [16] S. Morozumi, “Micro-grid demonstration projects in Japan,” *Proc. IEEE Power Conversion Conf.*, Nagoya, Japan, Apr. 2007, pp. 635–642.
  - [17] Siva Malla, “Perturb and Observe (P&O) Algorithm for PV MPPT,” *MATLAB Central File Exchange*, Available: <https://www.mathworks.com/matlabcentral/fileexchange/39641-perturb-and-observe-p-o-algorithm-for-pv-mppt> Accessed on September 25, 2024.
  - [18] Robert W. Erickson and Dragan Maksimovic, “Fundamentals of Power Electronics,” Springer, 2020.