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Review

The Unique Interaction Behavior Between A Superconductor Coil And A Magnet: A Comprehensive Review

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Abstract: It was found that the interaction between a superconductor coil and a magnet does not comply with one of the primary interpretations of Lenz's law: "the current induced in a circuit due to a change or a motion in a magnetic field is directed so as to exert a mechanical force opposing the motion." There are a number of exclusive features in the interaction between a superconducting coil and a magnet. The discovery of this unique behavioural interaction leads to a principle of developing a new kind of superconducting energy conversion/storage device. With a high-temperature superconducting (HTS) coil and a magnet, this new device is able to complete an energy conversion cycle from mechanical to electromagnetic then to mechanical without need of either a power supply or a motor/generator. Intrinsically, this kind of device has a simple structure, high energy conversion efficiency, high energy storage density, and low operation energy loss. Optimized configuration of the superconductor coil and magnets to enhance the storage capacity and conversion efficiency has been investigated and actualized with theoretical analysis, numerical modelling and experimentation. This article systematically reviews the discovery, the working principle and state of the art of the new energy convertor/storage device as well as its application potentials.

Keywords: superconductivity, Lenz's law, energy storage, energy conversion

1. Introduction

Superconductors has unique properties, i.e., zero resistance and perfect diamagnetism. In 2020, it was discovered that the interaction behavior between a superconductor coil and a permanent magnet was fundamentally different from the interaction behavior between a normal conductor coil and a permanent magnet [1].

In the configuration demonstrated by Figure 1, if the sample coil is a normal conductor coil, the curve of the interaction force on the magnet can be schematically plotted as Figure 2 which is obtained by the experiments with the apparatus and samples described in [1]. When the magnet moves downward from the top non-interacting region to the bottom non-interacting region along the mutual axis of circular coil and the cylinder magnet. The feature of the interaction has been well experimentally tested for a long time and described as "the current induced in a circuit due to a change or a motion in a magnetic field is directed so as to exert a mechanical force opposing the motion." It is even interpreted as the outcome of Lenz's law [2, 3]. If the sample coil is a superconductor coil, the interaction force variation in a same movement process has been experimentally studied in recent year, and can be demonstrated by Figure 3. In this case, the interacting force on the magnet changes its direction from upwards to downwards after the magnet passes the origin (where the geometrical centers of the magnet and the superconductor coil overlap). This means that after passing the origin,

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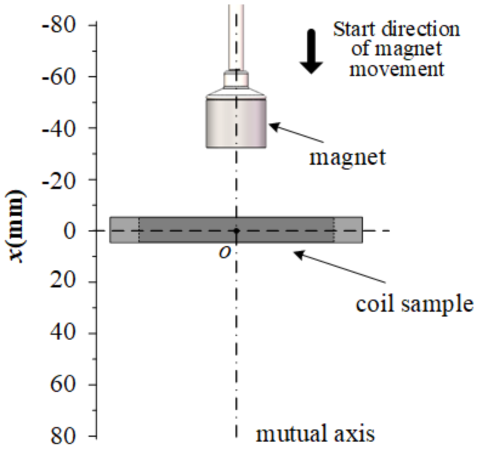
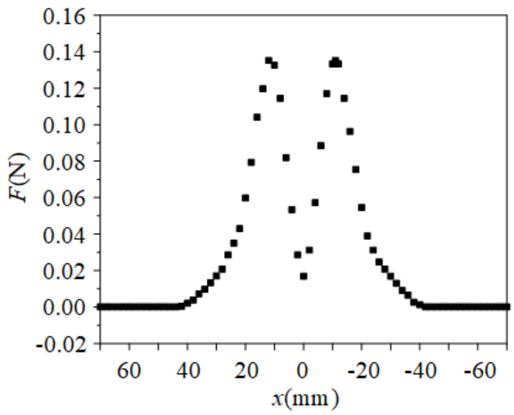
the magnet is subject to a repelling force instead of a resisting one. The interaction behavior between a superconductor coil and a magnet is fundamentally different from that between a normal conductor coil and a magnet.



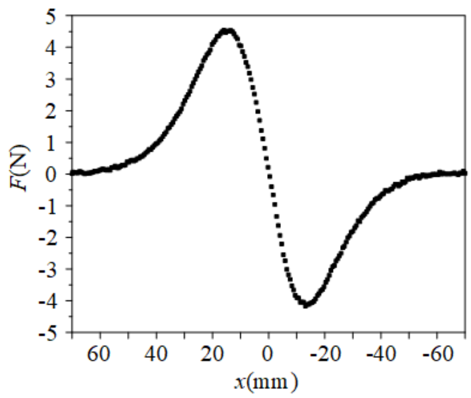
Note: 1. The coordinate origin is defined as the point of the geometric center of the coil sample.
2. x is the displacement of the magnet with respect to the origin.

Figure 1. The configuration of a coil sample and a permanent magnet [1]



Note: x is the displacement of the magnet with respect to the origin, F is the interaction force between the magnet and normal conductor coil.

Figure 2. The interaction force on the magnet as a normal conductor coil is used [1]



Note: x is the displacement of the magnet with respect to the origin, F is the interaction force between the magnet and superconducting coil.

Figure 3. The interaction force on the magnet as a superconductor coil is used [1]

The cause of this difference is the unique property of zero resistance in the superconductor. The magnetic flux in the closed superconducting coil is conserved. The induced current in the coil exhibits an initial increase followed by a subsequent decrease. When the magnet arrives at the origin after the first half of the movement in the experiment mentioned above, the induced current in the superconductor coil reaches maximum. Then, the current decreases from the maximum value to zero in the second half of the movement. It means that the direction of current remains unchanged and has good symmetry. If the magnet stays at the origin, the current will persist due to the coil's zero resistance. In practice, the current is not exactly persistent since there is a nonsuperconducting joint with a resistance of 10^{-8} Ω in the superconductor coil [1]. The current is quasi-persistent with a very slow attenuation. In contrast, the current in a normal conductor coil will be continuously dissipated due to its resistance, and completely exhausted as the coil arrives at the origin.

The interaction force between the magnet and the sample coil is the Ampere force, can be given by $\boldsymbol{F} = \boldsymbol{I} \times \boldsymbol{B}l$, where $\boldsymbol{I}$ represents the total current flowing through the coil, $\boldsymbol{B}$ is the magnetic flux density at position of interaction, and l is the effective circumference of the coil. Obviously, the cross product between $\boldsymbol{I}$ and $\boldsymbol{B}$ is determined not only by their individual magnitudes but also by the spatial configuration between them. In the described process, the radial component of the $\boldsymbol{B}$ reverses as the magnet moves from above and to below the origin. For a normal conductor coil, when the magnet continues to move downwards after passing the origin, an induced current with the opposite direction (compared with when the magnet approaches the coil) appears. The result of these two negative changes is that the direction of the interaction force, $\boldsymbol{F}$, stays unchanged, i.e., always upwards, opposing the movement of the magnet. For a superconductor coil, the direction of current is the same as the magnet moves from above and to below the origin. The changed direction of the $\boldsymbol{B}$ and the unchanged direction of $\boldsymbol{I}$ result in the reversal of the interaction force [4]. Some theoretical analysis and numerical modelling have also been carried out to confirm the physical and mathematical truthiness of the experimentally discovered unique interaction behavior [5].

2. The exclusive features of the interaction behavior

The interaction between a superconductor coil and a magnet has following exclusive and interesting features.

(a) In the above-mentioned interaction, if the magnet stops at the origin and then goes upward back to its starting position, the interaction force acting on it will be in the upward direction. This means that the magnet is subject to a pushing force again. In conclusion, after the magnet is pushed to the origin, it will receive a pushing force as it leaves the origin no matter moving upward or downward. The upward force curve and the downward curve in second half of the movement are symmetric about the line (F=0) [5]. This can be considered as evidence that the current in the superconductor coil is nearly without loss of Joule heating.

(b) As long as the magnet's properties remain unchanged and the superconductor coil operates within its critical current, changing the number of turns of the superconductor coil does not impact the total induced current in the superconductor coil or the interaction force between the coil and the magnet. [6].

(c) When the superconductor coil operates within its critical current, the interaction force and induced current are primarily determined by the properties (maximum energy product and volume) of the permanent magnet [5, 6].

(d) Based on all experimental results so far, it can be concluded that once the magnet and superconductor coil are selected, the speed at which the magnet moves does not influence the interaction force or the induced current behavior. [5-7].

This feature is fundamentally different from the magnetic flux cutting between a normal conductor coil and a magnet in a similar process, it is not immediately accessible to readers. The root mechanism lies in the induced current is directly proportional to the magnetic flux invading the coil during magnet's movement. The change in magnetic flux at a certain position in the process depends only upon the magnet moves from a previous position to this position regardless of the speed of the magnet [7, 8].

(e) If the magnet stays at a certain position in the progress, the current in the superconductor coil is quasi-persistent with a very slow attenuation. The joint resistance is the main cause of the attenuation. If a superconducting joint can be achieved, the current will be very close to a perfectly persistent current.

3. The implication of the interaction behavior

Figure 4 is drawn based on Figure 3 to display the process as an energy storing/releasing cycle. This cycle finishes a complete mechanical to electromagnetic then to mechanical energy conversion. Therefore, the configuration of a superconductor coil and a magnet, described above, can construct a device of energy storing/converting. Energy is charged when the magnet is pushed into the superconductor coil in the form of electromagnetic energy. The amount of energy stored in the configuration reaches maximum when the geometric centers of the magnet and the superconductor coil overlap. Energy is discharged when the magnet leaves the center of the superconductor coil in the form of mechanical force driving the magnet [1, 5, 6, 9]. In perspective of work, the energy charged and discharged are equal to the area of the shaded regions respectively.

Visually, from the Figure 4, the energy charged and the energy released in this cycle is almost the same, demonstrating high energy conversion efficiency and low operation loss for this kind of device.

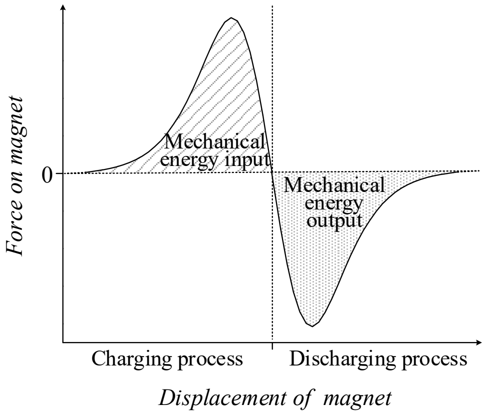
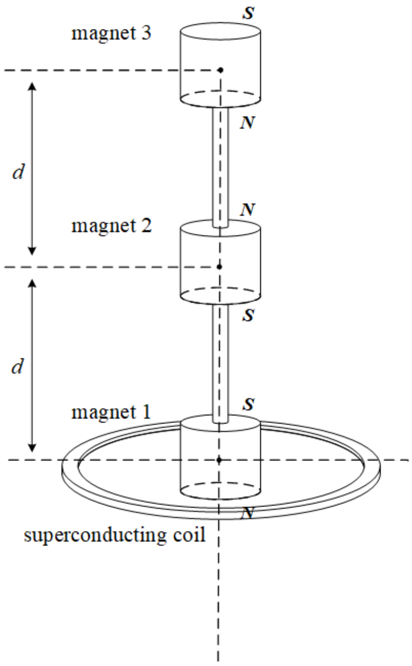


Figure 4. The energy storing/releasing cycle [10]

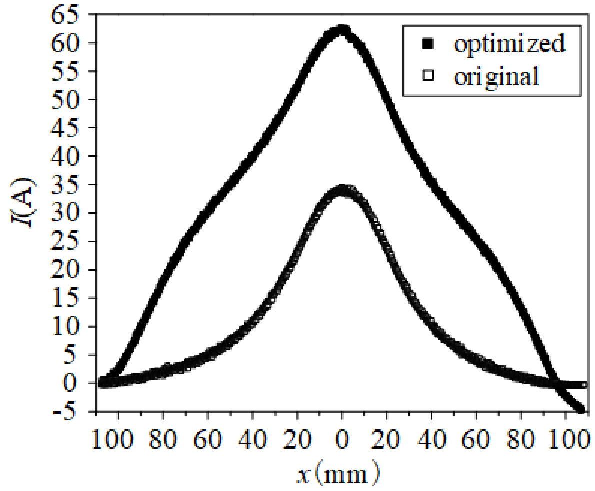
In principle, the operational capacity of the proposed device is primarily governed by the parameters of its two key components and their configuration, i.e. the remanence and geometrical properties of the permanent magnet, the inductance of the superconductor coil and the radial gap between the magnet and the coil. The maximum energy storage capacity is given by $E_{max}=\frac{1}{2}LI_c^2$, where L represents the inductance and I_c is the critical current of the superconductor coil. Clearly, E_{max} is merely determined by the characteristics of the superconductor coil, namely, its inductance and critical current.

For a practical device, as long as the superconductor coil do not quench in operation, the realized capacity E can be given by $E=\frac{1}{2}LI_{max}^2$, where I_{max} is the maximum current obtained in operation, which is determined by both the properties of the magnet and the configuration of the magnet with the superconductor coil. Therefore, optimized selections of magnets and the configuration are crucial for developing a device with high operational capacity, especially once a specific superconductor coil has been chosen. It will increase the E/E_{max}, i.e. increase the utilization of storage capacity of the device.

Some optimization methods have been attempted numerically and experimentally [11]. Figure 5(a) shows the optimized configuration found so far. In the optimized configuration, three magnets are arranged in a group using two non-magnetic rods, as illustrated in the figure. The polarities of the magnets are oriented as shown, the distance between the geometrical centers of two adjacent magnets is d. It's important to note that d should be larger than the interaction distance between the magnet and the superconductor coil. To achieve symmetrical interaction behavior between the magnet group and the superconductor coil, three identical magnets are employed. In this setup, the center of magnet 1 is initially aligned with the center of the superconductor coil by overlapping their geometrical centers. As shown in Figure 5(b), with the optimized configuration, the current in coil will be two times that of a configuration with same single magnet and the same superconductor coil. Consequently, the energy storage capacity improved to four times the original [6].



(a) Diagram of the optimized configuration



(b) The performance improvement

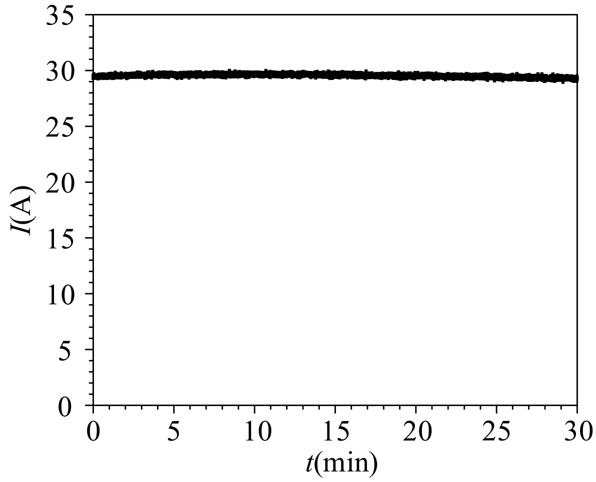
Note: x is the displacement of magnet 2 with respect to the origin.

Figure 5. The optimized configuration and performance improving of the energy conversion/storage device [7, 8]

Study in [11] concluded that the enhance of the energy storage capacity is extremely limited by increasing the number of the superconductor coil. In the other hand, given that superconductor materials are significantly more expensive than permanent magnets, a more effective approach to enhancing the performance-to-cost ratio of such devices is to increase the number of magnets with optimized magnet configuration. It is a more preferable way to raise the commercial merit of this kind of device.

Additionally, it is essential for an energy storage device that the electromagnetic energy held in the superconductor coil decays substantially slowly over time. The experimental result for measuring the current attenuation in the superconductor coil while the magnet remains at the origin for 30 minutes is shown in Figure 6, which is carried out with a specimen consisting of a 90 turn Bi-2223 coil and a N25 NdFeB magnet [10]. In the experiments reported in [10], when the energy storage is completed and the superconducting coil maintain superconducting state, the coil's current attenuated by just 1.5% in 30 minutes. Further speculation based on the feature of an R-L circuit, the current attenuation in the coil with one joint will decrease as the coil scales up due to the increase of inductance. Hence, the current in the coil can be regarded as quasi permanent. This outcome demonstrates that the device is highly suitable for energy storage applications requiring charging and discharging cycles range from several minutes to a few hours.

To validate the concept of the new superconducting energy conversion/storage with the principle derived from the unique interaction between a superconductor coil and a permanent magnet, we performed three sets of experiments on a proof-of-concept prototype, aiming to examine the working principle and its functionality [10]. The experimental findings confirm that the device offers high energy conversion efficiency, low operational losses, and is well-suited for short-term energy conversion and storage applications.



Note: t is the time from the energy storage is completed, I is the current in superconducting coil.

Figure 6. The current in the superconducting coil versus time as the magnet stopped at the origin [10]

This kind of device has a simple structure, so it is able to achieve high energy storage density and compact size. Since no current leads are required for the operation of the device, the operation loss of this kind of device is considerably lower than that of most other high-current superconducting devices. Another advantage is that high temperature superconductor has reasonably low cost of cooling. The HTS coil is fully submerged in liquid nitrogen (LN_2) within a cryostat. Nowadays, LN_2 cryostats can be made with highly reliable thermal insulation and very low thermal loss. Hence, the daily energy loss of the proposed conversion/storage device is practically negligible. Furthermore, no additional energy conversion equipment is needed between the energy conversion of mechanical and electromagnetic. These advantages make the device highly competitive with other short-term energy storages.

4. The application feasibility and potential of the new device

By principle, the operation loss rate of the device can be greatly reduced by increasing the number of turns of the superconductor coil, and further reducing the joint resistance on the superconductor coil. If a superconducting joint is realized, the joule loss can be completely eliminated. Therefore, much lower current decay rate and longer storage duration can be expected with the improvement of the joint technology.

The joule loss on the joint is fixed at a certain current value and each coil needs only one joint. The superconductor coil with larger size and number of turns will have much larger capacity. Then the joule loss will take much smaller weight over the capacity. It is expected that a scaled-up device of such kind will have much smaller relative operation loss and much higher efficiency.

Lately, a new laboratory model with an 800 turn, 185 mm ID, 310 mm OD, REBCO-123 HTS coil and a 120 mm diameter N52 NdFeB magnet has been built and preliminarily tested. The testing results show that the maximum pushing force is great than 1500 N and the storage capacity is about 150 J, the introduction of the new prototype in detail will be reported soon.

Based on the features of direct energy conversion, this kind of device may have great application potential for converting/regenerating mechanical energy and energy storage in practice.

Urban rail transit regenerative braking presents a promising application for this device [12]. Rail transit vehicles start and stop frequently, leading to significant energy loss during these repeated stopping-startings. By integrating the device onto the rail vehicle through an appropriate mechanical coupling and clutch mechanism, it can serve as an energy storage type regenerative braking system, as diagrammed in Figure 7. During braking, the rack connected to the magnet is engaged with the vehicle’s wheels via the clutch and gearbox, converting the vehicle’s kinetic energy into electromagnetic energy, which is then stored in the device. When the vehicle re-starts in any direction, the stored energy is released to boost the vehicle’s acceleration. This function can greatly enhance the energy efficiency of urban rail transit systems and contributes significantly to energy conservation.

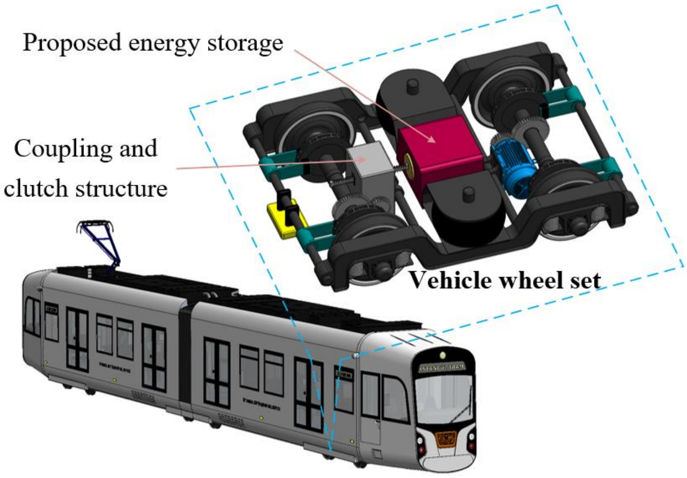


Figure 7. Regenerative braking system with the new energy storing/converting device for urban rail transit [12]

Additionally, the proposed device may be applied to enhance the launch capacity of an Aircraft Launch System without requiring modifications to the ship's existing infrastructure or increasing its power demand [13]. The new energy storing/converting device is equipped together with the main launch system (steam catapult and electromagnetic catapult), and worked as an auxiliary system, as shown in Figure 8(a). The operating process is schematically step-by-step in Figure 8(b). The device can be charged during the intervals between launches when the ship's power load is low. Once charged, the magnet module is held in a balanced position. When a launch is initiated, the propulsion force generated by the device is able to assist in accelerating the aircraft along the launch rail, increase the overall launch capacity of an EMALS.

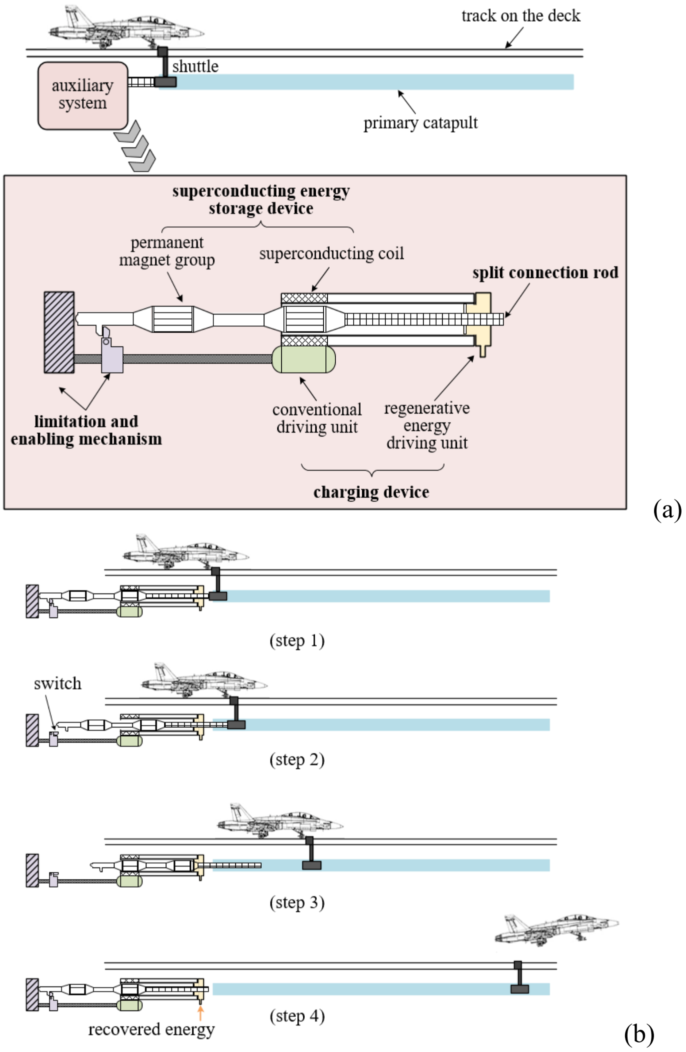


Figure 8. (a) Aircraft launch system equipped with the auxiliary system of the new energy storing/converting device, (b) operating process of the system [13].

When solely utilizing the conversion function of mechanical energy to electromagnetic energy, this device can be regarded as a special generator. Such a generator could be suitable for certain niche applications.

Besides the above applications on the aspects of energy, the interaction feature may be used in measuring the inductance of a closed superconducting coil or the resistivity of a new material [14]. These novel measurement methods may serve as alternatives, when the instrumentation conditions of the conventional methods for such measurements cannot be satisfied.

5. Conclusion

The experimental discovery of the unique interaction behavior between a superconductor coil and a permanent magnet contradicts one of popular interpretations of Lenz's law: "the current induced in a circuit due to a change or a motion in a magnetic field is directed so as to exert a mechanical force opposing the motion". The cause of this behavior has been explained with some theoretical analysis and numerical modelling. A number of exclusive features of the interaction have been revealed.

This discovery brings up a new principle to construct an energy conversion/storage device with a superconductor coil and a permanent magnet. Intrinsically, this kind of device is of a simple structure, high energy conversion efficiency, high energy storage density, and low operation energy loss in an energy conversion and storing processes. It has been found that the performance of the device can be greatly enhanced by optimizing the configuration of superconductor coil and magnets.

The comprehensive advantages of this kind of new superconducting device endow it with some prospective applications. It has the potential to revolutionize the regenerative braking technology and to develop more efficient and sustainable urban rail transportation systems. It may also find a place of application for enhancing the launching capacity of an aircraft launch system with no need to expand the existing electrical power facility on the ship.

Some groups in different fields of study have also quoted the unique interaction behavior in their articles since it was reported in 2020 [15-23].

More and deeper studies on this topic are greatly needed for better understanding the unique interaction behavior between a superconductor coil and a magnet. Further development of the new superconducting energy conversion/storage devices needs to get more attention.

Conflict of Interest

There is no conflict of interest for this study.

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