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APPLICATIONS OF SUPERCONDUCTIVITY IN ELECTRIC POWER AND TRANSPORTATION SYSTEM

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Abstract-
The generation, transmission and distribution of electric power over a long distance at low losses are the major challenges today. The application of superconducting materials in cables, generators and motors, transformer, dynamic synchronous condenser, fault current limiter and energy storage devices can accelerate development of electric power system. The rapid operation and high efficiency of these devices using superconductors would play a significant role in improving the system performance which is unattainable using copper windings. It is necessary to improve the current carrying capacity and cryogenics of superconducting devices to meet the power system requirement. This paper aims to present remarkable progress of superconducting materials applications in electric power and transportation sector.

Keywords- HTS cables, Maglev, transformer, SFCL, generator, SMES, ship propulsion

1. INTRODUCTION

Superconductors have the ability to transport large dc current without measurable resistive losses and have large current carrying capacity at high magnetic fields. Practically, Nb-Ti superconductors have upper critical field (H_{c2}) ~9T at 4.2K and 12T at 1.8K. The current carrying capacity of Nb-Ti at 5T, 4.2K is greater than 3700A/mm^2. Similarly current density (J_c) of BSCCO-2212 at 20T, 4.2K is approximately 500A/mm^2 and J_c at 10T is equivalent to 3500A/mm^2. Superconductivity occurs at extremely low temperature i.e. below critical temperature (T_c). To keep the superconductor below critical temperature liquid helium (4K) and liquid nitrogen (77K) are used. Since superconductors are brittle materials so to produce a flexible conductor, the ceramic powder are filled in a tube made of silver, which are then rolled into flexible bands. The production of superconducting compound is still expensive and complex. Power sector includes high capacity transmission line, energy storage unit and power generation setup [1]. In India, about 4% to 10% of the electric power carried by a transmission line is lost due to resistance of copper or aluminum wire cable. The superconducting fault current limiters (SFCL) provide the most promising solution of limiting the fault current in power systems [2, 3]. The power generation systems above the megawatt level require superconducting generators. The superconducting power equipment based on HTS wire has been used for dynamic synchronous condenser supplying reactive compensation in the power grid [4]. Superconductors are enabling a new generation of transport technology including magnetically levitated trains (Maglev), motors and generators for use in ships, aircraft, locomotives and other ground vehicles [5[,[6],[7]. Several superconducting materials with different transition temperature [8] are discovered but few superconducting materials like Nb_3Sn (T_c=18.1K), Nb-Ti (T_c=9K), $Bi_2Sr_2Ca_2Cu_3O_{10}$ (T_c=110K), $YBa_2Cu_3O_7$ (T_c=92K), and MgB_2 (T_c=40K), are used for large scale application in electric power sectors.

2. SUPERCONDUCTING CABLES

Superconducting cables have significant advantages of compactness and larger power transmission capacity that is expected to be installed in a power grid to replace the existing power cables. The first generation wire consists of a composite fine filaments of HTS BSCCO 2223 embedded in a silver matrix. The HTS power cable consisting of YBCO wire with coated conductor [20] is shown in figure 1. An intermediate layer and a superconducting layer are formed on a substrate and a silver layer is formed to protect the superconducting layer. In addition, a copper tape is laminated on the YBCO tape to prevent burnout from over current.YBCO coated conductor is promising material of high temperature

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superconducting cable with higher J_c and better magnetic property. But reduction of ac losses and cost of power cable are important to put it into practical power network [9].

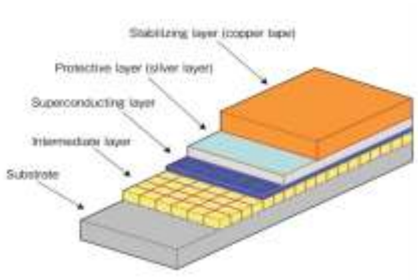

Fig 1 Structure of YBCO tape

A current of 20kA at 24K in an electrical transmission line consisting of two 20 meter long cables with a total outer diameter of only 16 cm made of MgB_2 superconductor is a promising option for the electricity grid of the future. Low cost superconductive cable using the magnesium-diboride [10] powder is very flexible and is able to carry 500 times (3.2 GW) more electricity than copper wires. Single phase coaxial cold dielectric wire consists of concentric layers of high temperature superconducting (HTS) wires and a dielectric material providing electrical insulation compatible with cryogenic temperatures (figure 2).

Fig. 2 Single phase cold dielectric HTS cable developed by Nexans superconductors

It offers non-polluting high current carrying capacity, reduced ac losses, low inductance and complete suppression of stray electromagnetic field outside of the cable assembly. The resistance and inductance of cold dielectric HTS are 0.0001Ω/km and 0.06mH/km respectively which is up to six times lower than that of conventional cable.

The particle accelerator like CERN's large Hadron Collider (LHC) uses coils of superconducting cable to create magnetic fields that are used to accelerate particles to speed approaching the speed of light before they collide with one another or other atoms. The tokamak fusion reactor requires large superconducting coils to create an immense magnetic field to confine plasma in the shape of a torus. Superconducting cable projects for medium and high voltage transportation [12] are shown in table I.

Table I Superconducting cable projects for medium and high voltage transportation

Country	Year	Length (m)	Capacity (MVA)
Albany, NewYork	2006	350	48(34.5kV, 0.8kA)
Long Island, New York	2008	600	574(138kV AC, 2.4kA)
China	2011	360	13(1.3kV DC,10kA)
Essen, Germany	2014	1000	40(10kV AC,2.3kA)
Ishikari, Japan	2014	2000	100(710kV DC,5kA)
Westchester, USA	2014	170	96(13.8kV AC, 4kA)
Jeju Island, Korea	2015	1000	154(154kV AC, 3.74kA)
Yokohama, Japan	2015	250	200(66kV AC,5kA)
St.Petersburg, Russia	2015	2500	50(20kV DC,2.5kA)

3. SUPERCONDUCTING FAULT CURRENT LIMITERS (SFCL)

Superconducting fault current limiters [3] are used to control power flows, especially during short circuit conditions in the electric power system. Superconducting fault current limiters control the current by switching the conductor from non resistive superconducting state to the normal resistive state. Superconductors have zero resistance below critical temperature (T_c) and critical current(I_c). During fault condition, the current start increasing and when it reaches I_c then superconductor quenched (figure 3). During quenching resistance increases exponentially which results in voltage drop across the superconductor. During this period the shunt which is combination of inductor and resistor restrict the voltage increase across the conductor. From figure 3, it is clear that the resistivity at superconducting state just below critical current (Jc) $\approx 10^{-15}\Omega$m and the resistivity shows steep rise of resistivity$\approx 5\times10^{-6}$ Ωm just above J_c. This increase of resistivity during resistive state can be utilized directly to limit the current.

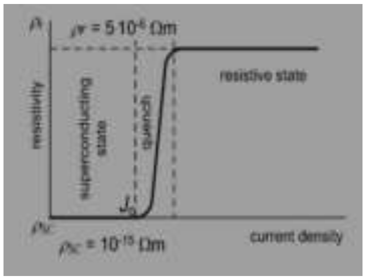

Fig. 3 Resistivity verses current density variation during transition from superconducting state to resistive state.

The superconductor switching times are normally less than 20 milliseconds.

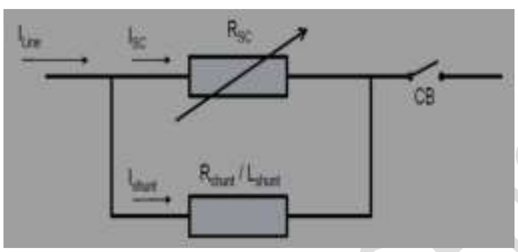

Fig. 4 Resistive superconducting fault current limiter

4. SUPERCONDUCTIVE TRANSFORMER

Superconductive transformer eliminates the need of potentially hazardous cooling oil, thus avoiding the risk of fire and explosion hazard which enhancing ecological compatibility and reducing the environmental impact. Superconducting transformer has the capability of short circuit current limitation under fault conditions and can work continuously in overloaded conditions without insulation damages and any lifetime loss because of the ultra cold operating environment.

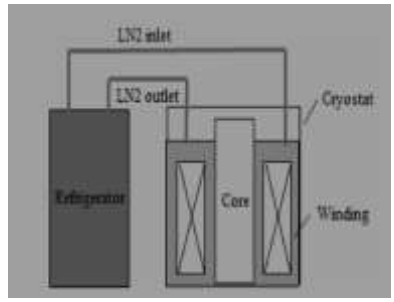

Fig. 5 Structure of HTS transformer

Superconductive transformers [11, 13] have more current carrying capacity (100 times) and less copper losses than conventional one. Superconductive transformers have low impedance. A superconducting transformer is composed of a winding, a magnetic core, a cryostat with liquid nitrogen inlet and outlet and a refrigeration system (figure 5).

HTS wire which is commonly used in high voltage power transformer can be divided into two types: BSCCO (Bi-2212 and Bi-2223) and YBCO wire. The most popular material used in HTS transformer to date has been BSCCO-2223 wires. However, YBCO wire has higher current density and better current magnetic field characteristics than BSCCO wires. A HTS winding of 10kVA transformer containing BSCCO-2223 tape has 37 filament in a silver matrix of outer dimension 3.72x0.24 mm .The nominal current in zero applied field at 78K is 20A giving bulk current density of 22.4A/mm^2. Some of the HTS transformer projects in various countries with specifications are summarized in table II.

Table II. Various HTS transformer projects with specifications

Country	Year	Specification	HTS
Japan	2001	1MVA,22kV/ 6.9kV	Bi-2223
Germany	2001	1MVA,25kV/ 1.4kV	Bi-2223
EU	2003	41kVA,2050 V/410V	P-YBCO ;S-BSCCO
Switzerland	2003	100MVA,225 kV/20kV	Bi-2223
Korea	2004	1MVA,22.9V	Bi-

		/6.6kV	2223
South Korea	2005	60MVA,154kV/23kV	YBCO
China	2005	630kVA,10.5kV/400V	Bi-2223
Japan	2007	2MVA,66kV/6.9kV	YBCO
Japan	2009	2MVA,22kV/6.6kV	YBCO
Newzealand	2011	1MVA,11kV/0.42kV	YBCO
Australia	2013	1MVA,11kV/415V	YBCO
USA	2015	28MVA,69kV/12.47kV	YBCO
Germany	2015	1MVA,20kV/1kV	P-Cu; S-YBCO
Russia	2015	1MVA,10kV/0.4kV	YBCO

The dimensional comparison of conventional transformer with HTS transformer is shown in table III.

Table III. Dimensional comparison of conventional 50MVA transformer with HTS transformer

50MVA HTS transformer	Conventional transformer	HTS transformer
Width	2.29m	1.26m
length	6.40m	3.31m
Height	4.5m	3.26m

The losses in 63MVA conventional transformer are about five times more than the same rated superconducting transformer. A 50MVA HTS transformer has volume 30% less than conventional transformer and its weight is about one third of conventional transformer.

5. SUPERCONDUCTING DYNAMIC SYNCHRONOUS CONDENSER

Here the copper field winding has been replaced with a HTS field winding that always operates at a constant cryogenic temperature. This feature reduces the need for maintenance as compared to a conventional synchronous condenser. As the superconducting wire has dramatically reduced losses, the HTS dynamic synchronous condenser [4] is estimated to be 98.8% efficient than copper based conventional unit. The HTS dynamic synchronous condenser is readily transportable for easy placement in distribution substations due to its compact size and low cost design. A HTS dynamic synchronous condenser machine is stable to transient faults and uses about one half of the energy of a conventional synchronous condenser.

6. SUPERCONDUCTING GENERATOR

A generator converts rotational mechanical energy into electricity. Superconductors have the ability to produce magnetic field of 20-40 tesla required for power generator. This is done by rotating a rotor field, which produces voltages in stationary armature conductors. The current is applied to the superconducting materials through the slip ring. This increases machine efficiency beyond 99% reducing losses by as much as 50% over conventional generators. By using superconducting wire [19] for the field windings, the power losses can be practically eliminated. HTS generators have lower armature reactance and its efficiency could be increased by 0.5%. Superconducting generator is super cooled by a liquid which is contained within the rotor. Superconducting generators offer greater system stability against frequency and load variations in the grid. The 3.6 megawatt superconducting generator has been designed, developed and manufactured by the European Consortium Eco Swing. Since they can operate at high magnetic fields (5 to 6 Tesla), the size can be reduced to 50%, this in turn could reduce capital costs significantly. Superconducting generators offer greater reduction in weight and size in comparison to conventional generators (Table IV). Superconducting generators could be made with a weight of about one tenth that of conventional devices for the same output.

Table IV. Comparison of estimated weight and length of conventional and superconducting generators

Capacity		Conventional generator	HTS generator
1200 MVA	Weight	600 tonne to700 tonne	160 tonne to 300 tonne
	Length	8 to 10 m	4m

26 MVA	Weight	54 tonne	9 to 18 tonne
	Length	3 m	0.8 to1.8m
1.5MVA	Weight	37.5 tonne	9.675 tonne
	Length	4 m	1.8m

7. SUPERCONDUCTING MOTORS

The ability of HTS coils to carry high current density (20000A/cm^2) with little loss, is the key performance characteristics of HTS wire that is used to make the superconducting motor smaller and more efficient than a conventional motor of the same rating[6]. The HTS coils are located on the rotor and are thermally insulated from the rest of the machine components by a vacuum insulation space. The weight of 36.5 MW, 120rpm, 6.6kV conventional copper generator is 180-250 tonnes whereas the weight of same capacity HTS motor is less than 75 tonnes. The cryogenic coolant must be able to remove the total heat generated from field winding due to AC losses in order to keep the HTS coil below T_c even at dynamic conditions. For superconducting motors, the HTS materials are cooled to the 30 to 40K temperature range. For 6000hp motor operating with HTS materials, the input power to the cooling system for the superconducting coil operating at 30K will be about 0.16% of the rated output power of the motor. A superconducting motor provides high efficiency over a wide range. The superconducting motor has a torque of 70Nm, an output of 18 kW and a maximum speed of 70km/h. A 25 MW superconducting motor would weigh between 45 tonne to 63 tonne and its size would be between 2m to3m in diameter.

8. SHIP PROPULSION

Ship propulsion design parameter includes dc current, electrodynamic force and magnetic field created in sea water by superconducting magnet. This current interacts with a field applied by a large magnet, resulting in a backward force on water that propels the ship forward. A magnet of a 10 tesla is needed for commercial system. It is necessary to develop high magnetic field larger size superconducting magnets and improving electric conductivity of sea water from the view point of increasing thrust force. A superconductive electromotive propulsion ship follows the rule: when electric current is sent to sea water at right angles to the magnetic field and Lorentz force acts on sea water in the direction perpendicular to both directions of magnetic field and that of electric current the force gained as are action force of this Lorentz force. A 5 MW, 230rpm, and 6 poles high temperature superconductor ship propulsion motor require an air core armature winding and first generation HTS wire (BSCCO-2223) field winding [14]. A 40MW, 120rpm ship propulsion motor require Bi-2223 (operating at 35K) for field winding and MgB_2 (operating at 20K) for stator winding. The most powerful HTS ship propulsion motor with power rating 36MW, 120 rpm using LTS field coil to create 2.5 T magnetic fields in the air gap of the motor has been successfully tested [15].

9. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

SMES unit stores energy for long period of time in the magnetic field generated by the dc current flowing through a superconducting coil. The electric power is stored in the magnetic field of a large superconducting magnet can be retrieved efficiently at short notice and offers a high efficiency up to 90% in the energy storing and releasing process. Large scale use of SMES in power grids protects sensitive equipment from power failures.

Table V. SMES devices built by different country (source: IIEEE PES ISGT ASIA-2012)

Country	Energy	Superconductor
USA	30MJ	NbTi
USA	1-5MJ	NbTi
Japan	1MJ	Bi2212
Japan	2.4GJ	YBCO
China	10kJ	Bi2223
Korea	600kJ	Bi2223
Germany	150kJ	Bi2223
Poland	34.8kJ	Bi2223
Australia	2.48kJ	Bi2223

Flywheel [16] can be used to store energy for power systems when the flywheel is coupled to an electric machine. The frictionless superconductor bearing is attached to the flywheel. It can transform electrical energy into kinetic energy and in turn the rotational kinetic energy is used to regenerate electricity. Further there is a negligible thermodynamic loss associated while converting one form of energy to another. In these systems, the stored energy is directly proportional to the mass of the object in movement but proportional to the square of their rotational speed [17]. HTS based flywheels operate at <0.1 % loss per hour as compared to 3-5% loss per hours in conventional flywheel.

The best method to store energy is to maintain persistent currents in superconducting coils. Superconducting magnetic storage seems to be the best solution for energy storage [2]. SMES devices built by different country are shown in table V.

X. MAGLEV VEHICLES

The low temperature superconducting technology based transport vehicles such as Maglev trains without wheel can be made to float on strong superconducting magnets virtually eliminating friction between the train and its tracks. The train floats silently on a magnetic field due to diamagnetic behavior of superconductors. A superconducting material may levitate above a magnet and similarly a magnet may levitate above a superconductor. In both cases, levitation is stable. The stability of this type of levitation is due to superconducting property of the magnetic flux quantization. There are two principal levitation (suspension) concepts for Maglev vehicles [5]: attractive-force electromagnetic suspension (EMS) and repulsive force electrodynamic suspension (EDS).

Attractive force electromagnetic suspension (EMS) uses non-superconducting electromagnets mounted on the vehicle which are attracted towards the underside of steel rails [5]. The attractive force Maglev system typically supports the magnets with a spacing of about 1 to 2 cm below the ferromagnetic rail (figure 6).

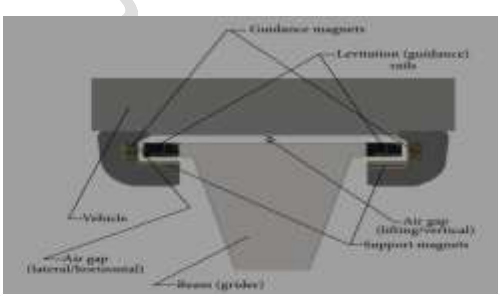

Fig. 6 EMS Maglev System

The air core superconducting magnets produce much higher external fields which generally require a shielding of the passenger compartment and a careful attention is given to the selection of guide way structural materials to avoid excessive electromagnetic drag. There is no possibility of derailment in Maglev system. Since there is no mechanical contact so there are very less noise (60-65dB) of Maglev train.

Repulsive-force force electrodynamic suspension (EDS) uses vehicles levitation by superconducting magnets which induces repulsive currents in a guide way containing aluminum sheets or coils. The repulsive-force maglev suspends the vehicle 1 to10 cm above the guide way (figure 7). This large air gaps allows for additional vertical motion of the vehicle by reducing stresses on the vehicle and guideway and provides substantially greater tolerance for the guide way misalignments. The superconducting magnets are placed on the vehicle so that eddy currents are induced in conducting strips on the guide way when vehicle moves over it.

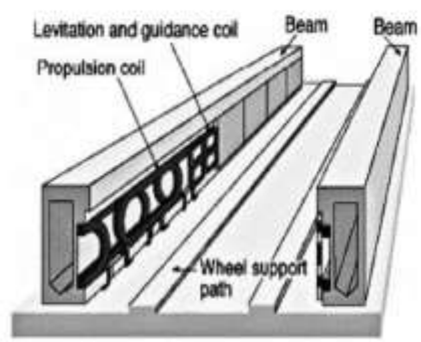

Fig.7 EDS Maglev System

The light weight superconducting magnets can produce intense DC magnetic field over relatively large volumes with far less energy consumption than that of normal magnets. Superconducting magnets operated in the persistence current mode maintain their field strength without energy consumption, except for energy used in refrigeration and the energy losses associated with magnetic field fluctuations. The guideway is the structure on which maglev vehicle move over it and are supported and guided by it [18]. In April 2015, a test vehicle attained an incredible speed of 603 km per hour on Japanese Yamanashi Maglev line (42.8km) called MLX01 (figure 3) and achieved recorded running distance of 4064km in a single day.

Fig. 8 Japanese Maglev train (Yamanashi test line)

11. CONCLUSIONS

The growing demand of energy for the human needs have forced to develop energy efficient technology. The high critical current density and increased electrical efficiency advantages of superconductor wires motivate for highly compact and powerful devices that are more reliable, efficient and environmentally benign. HTS fault current limiters improve system reliability and protect the grid from damage. In future the superconducting propulsion system may bring revolution for transport vehicle system. Application of superconductors in power engineering has still problems of ultra cold operations. Brittleness of superconducting ceramic material is one of the major challenges in making superconducting wires and cable of desired length at reasonable costs.

REFERENCES

[1] H. Thomas, A. Marian, A. Chervyokov, S. Stuckrad, D. Salmieri, C. Rubbia. "Superconducting transmission lines- sustainable electric energy transfer with higher public acceptance?" Renewable and sustainable Energy Review, 55 (2016) 59-72

[2] M. Noe, & M. Steurer, "High-Temperature Superconductor Fault Current Limiters: Concepts, Application and Development Status". Supercond. Sci. Technol, 20 (2007) R15-R-29,

[3] B.V. Vaishnavi, R.S. Angelinsuji, D.P. Trivenishree, Nabi Nidha, G.J. Sowmya. "Superconducting fault current limiter and its application". International Journal of Scientific and Engineering Research, 7, 5 (2016) 126-134

[4] S.S. Kalsi, D. Madura and M. Ross. "Performance of superconductor dynamic synchronous condenser on an electric grid". IEEE/PES Transmission and Distribution Conference& Exhibition: Asia and Pacific, Dalian, China (2005) 1-5

[5] H. Yaghoubi. "The most important Maglev Applications". Journal of Engineering. Hindawi Publishing Corporation (2013) 1-19. http://dx.doi.org/10.1155/2013/537986

[6] J.S. Edmonds, D.K. Sharma, H.E. Jordan, J.D. Edick and R.F. Schiferi., " Application of high temperature superconductivity to electric motor design" IEEE Transaction of Energy Conversion, 7,2 (1992) 322-329

[7] A.M. Wolsky, "The status and prospects for flywheels and SMES that incorporate HTS". Physica C, 372-376 (2002) 1495-1499

[8] Shailaj Kumar Shrivastava, "Search For higher critical temperature (T_c) in superconducting materials" International Journal of Engineering and scientific Research (IJESR), 5, 8 (2017) 40-54,

[9] N. Amemiya, J. Zhenam, M. Yagi, S. Mukoyama, N. Kashima, S. Nagaya, Y. Shiohara, . "Ac loss reduction of superconducting power transmission cables composed of coated conductors". Applied Superconductivity, IEEE transactions, 17, 2 (2007) 1712-1717

[10] R. Flukiger, H.L. Suo, N. Musolino, C. Beneduce, P. Toulemonde, P. Lezza. "Superconducting properties of MgB_2 tapes and wires". Physics C, 385 (2003) 286-305,

[11] T. Bohno, A. Tomioka, M. Imaizumi, Y. Sanuki, T. Yamamoto, Y.Yasukawa, H.Ono, Y. Yagi, K. Iwadate." Development of 66kV/6.9kV, 2MVA prototype HTS power transformer". Physica C: superconductivity, 426-431(2005) 1402-1407

[12] J. F. Maguire, F. Schmidt, F. Hamber and T.E. Welsh. "Development and demonstration of long length HTS cable to operate in the long Island Power Authority grid". IEEE Trans. Appl. Supercond. , 15, 2 (2005) 1787-1792,

[13] Vasant Kumar Upadhye, Utkarsh C Savardekaro. "Superconducting Transformer". Journal of New Innovations in Engineering and Technology, 4, 3 (2016) 67-73

[14] G. Snitcher, B. Gamble, and S.S. Kalsi. "The performance of 5 MW high temperature superconductor ship propulsion". Appl. Superconductivity. IEEE Transaction 15(2005) 2206

[15] B. Gamble, G. Snitcher, T. Mc Donald "Full power test of 36.5 MW HTS propulsion motor". IEEE Transactions on Applied Superconductivity. Vol.21, 3 (2011)

[16] M. Strasik, P.E. Johnson, A.C. Day, J.Mittlender, M.D. Higgins, J. Edwards, J.R. Schinder, K.E. McCaary, C. R. McIver, D. Carlson, J.F. Gonder, J.R. Hull. "Design, fabrication and test of a 5-kWh/100kW flywheel Energy storage utilizing a high-temperature superconducting bearing." IEEE Transactions on Applied Superconductivity, 17, 2 (2007) 2133-2137

[17] H. Ibrahim, A. Ilinca, J. Perron. "Energy storage systems-characteristics and comparisons". Elsevier, Renewable and sustainable Energy Reviews, 12 (2008) 1221-1250

[18] H. Behbahani, H. Yaghoubi, and M.A. Rezvani. "Development of technical and economical models for widespread application of magnetic levitation system in public transport". International Journal of Civil Engineering, 10, 1 (2012) 13-24

[19] P.N. Barnes, M.D. Sumption, G.L. Rhoads." Review of high power density superconducting generators: Present state and Prospects for incorporating YBCO windings". Crygenics, 45, (2005) 670-686

[20] S. Mukoyama, M. Yagi, H. Hirata, M. Suzuki, S. Nagaya, N. Kashima and Y. Shiohara. "Development of YBCO High-Tc superconducting power cables", Furukawa Review, 35(2009)18-22

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