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Superconducting technologies for renewable energy

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Abstract. The main trends in the development of modern wind-mills are increasing of the output power and efficiency which leds to the increasing of their weight and sizes. The application of high temperature superconducting (HTS) technologies can solve these problems. The article describes of the designs 1 MVA superconducting synchronous generator and 5MJ flywheel energy storage systems (FESS) with HTS magnetic suspension for autonomous wind power engineering.

1 Introduction

One of the key strategic directions of the world development of electric power industry is to increase its energy efficiency through the introduction of new innovative technologies, including the development of superconducting equipment and its use in power systems. Superconducting materials make it possible to create high-performance devices with a new level of maintenance parameters that can not be achieved using traditional electrical materials.

In recent years leading foreign and Russian scientific centers are working on the creation of wind power plants based on the effect of superconductivity. High-temperature superconducting (HTS) generators are characterized by higher specific output power, high efficiency, more compact and have an increased resource (see Figure 1). Currently, there are two concepts for designing a superconducting wind turbine generator: fully superconducting machines and partially superconducting machines. In the first case, the rotor and stator windings are superconducting. In the second case, using superconducting wire for the field excitation winding.

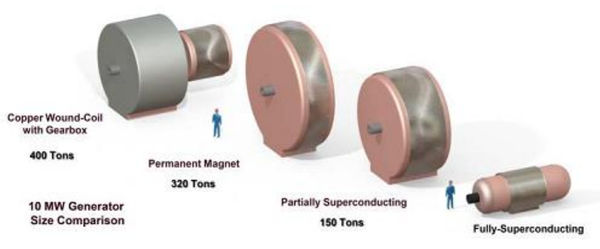

Fig. 1. Comparison designs of 10 MW wind turbine generators [1].

For the manufacture of superconducting windings using the following HTS tapes:

- 1st generation (1G HTS) - compounds based on magnesium diboride MgB2 and bismuth ceramics in a silver matrix BSCCO, operating at temperatures of liquid hydrogen (20 K) and neon (27 K);

- 2nd generation (2G HTS) - compounds based on yttrium ceramics YBCO, operating at a temperature of liquid nitrogen (77 K).

The main advantage of 2G HTS tapes is very high magnetic fields and high critical current at liquid nitrogen temperature. The limiting of the critical current in a magnetic field for BSCCO has fundamental reasons (high anisotropy of the electrophysical properties and the associated pinning force of magnetic flux vortices). MgB2 superconductor is characterized by weak anisotropy of superconducting properties and low cost in comparison with both BSCCO and YBCO, but their use is limited by temperature the hydrogen level (20 K). The choice of 2G HTS tapes could lead into a simpler and less costly cooling system compared to 1G HTS. Table 1 presents a list of projects already created or developed superconducting wind turbine generators.

The main problem of introducing wind power stations (WPS) is the irregularity of their output power. First of all, this is due to the uneven wind speed, which leads to significant fluctuations in power, voltage and frequency of the alternating current of WPS. To ensure stable parameters of electrical voltage and frequency in the network, it is necessary to apply energy storage systems (ESS) using rechargeable batteries (lead-acid, lithium-ion and lithium-polymer) or flywheel energy storage systems (FESS). The main advantages of FESS also include high specific power and high specific density of stored energy, high cycling ability, scalability and modularity. Flywheel systems can work equally well for frequent shallow discharges as well as for very deep discharges.

FESS has been used in power systems for a long time [15]. Primarily they are used in grid companies, and this allows one to smooth the consumption and load peaks, adjust frequency and voltage, and reduce losses at transmission and regulation of reactive power. The most famous developments are that from Beacon Power. These are regulatory plants based on Smart Energy

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Table 1. Superconducting wind turbine generators.

Year to reach	Power (MW)	Speed (rpm)	Conductor type	Cryogenic cooling	Company/Project
2010	0.5	30	BSCCO		Converteam
2012	1	500	BSCCO	LN_2	Wuhan Institute of Marine Electric Propulsion [2]
2009-2013	1.79	214	BSCCO	GHe	Converteam (Hydro-Genie) [3]
2011-2015	1	600	YBCO	LN_2	MAI [4]
2015	3.6	15	YBCO		Envision (EcoSwing) [5]
2009-2016	0.5		MgB_2	GHe	Technalia [6]
	10	8	MgB_2	GHe	Technalia [6]
	10	10	(RE)BCO	GHe	AIST/Furukawa Electric [7]
	8	11	YBCO	LN_2	AMSC/TECO [8]
	12	10	YBCO	GHe	Changwon National Univ. [9]
	10	10	YBCO		GE [10]
	8	12	YBCO	GHe	GE/ Converteam [11]
	10	8	YBCO	GHe	Converteam [12]
	10	10	MgB_2	GHe	Kalsi Green power system [13]
	10	10	YBCO		Tokyo Univ. of Marine Sci.& Tech. [14]

Matrix 0.5 MW (Tyngsboro, MA), 20 MW (Stephentown, NY) and 20 MW (Hazle, PA) complexes [16]. FESS is successfully used in MicroGrid to stabilize the network with renewable energy sources (RES). The leading positions in this direction are occupied by ABB [17-19].

The latest achievements in the field of technology of superconducting passive magnetic bearings and their application in the design of the FESS can increase the working life (more than 15 years) of the drive, creating environmentally friendly energy storage systems with a long shelf life of stored energy.

2 Superconducting generator for wind turbines

In 2015 MAI jointly with the leading Russian research centers (JSC «NIIEM», NRC «Kurchatov Institute» – IHEP, Protvino) created and tested first of Russia 1 MVA high-temperature superconducting synchronous generator (HTSSG-1000) with HTS 2G field windings cooled with liquid nitrogen [6]. This work was carried in the framework of implementation of the Rosatom atomic energy state corporation Innovative Energy/Superconducting Industry project (2011-2015). Photo of the prototype HTS wind generator during the bench tests is shown in Figure 2. Table 2 lists main parameters of 1 MVA HTS generator.

Fig. 2. 1 MVA prototype HTS wind generator (left) with drive motor (right) on the test bench.

Table 2. Main parameters of 1 MVA synchronous 2G HTS generator

List of parameters, units	Value
Nominal output power, kVA	1000
Phase voltage, V	690
Nominal speed, rpm	600
Rated electrical frequency, Hz	50
Nominal torque, Nm	16 000
Nominal current, A	500
Number of poles	10
Number of phases	3
Inner diameter of the stator, mm	800
Active light, mm	400
Field winding type	HTS 2G tape
Coil shape	Racetrack
Cryogenic cooling	LN_2
Armature winding type	Cu
Stator coolant	Water
Weight, t	4.2
Full load efficiency (without the cryocooler), %	98.6

Stator HTSSG-1000 is made according to the classical scheme with copper windings. The stator with 120 slots made of the electrotechnical steel sheets with the thickness of 0.35mm. The thermal calculation of the geometric model HTSSG showed the need for forced cooling of the stator. As a result, the stator is water cooled through cooling channels in the housing.

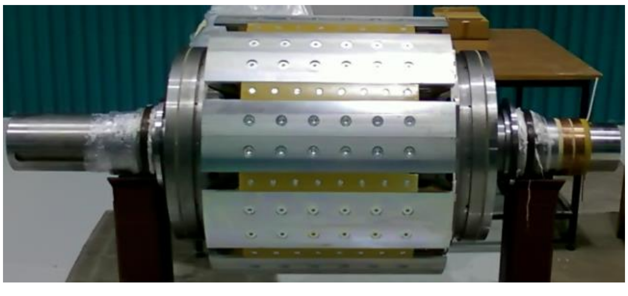

Fig. 3. Rotor HTSSG-1000 assembly (without cryostat).

The HTS rotor is an explicit pole structure. Salient pole ferromagnetic rotor with HTS field excitation winding consist 10 poles (see Figure 3). The rotor poles are manufactured separately and then installed on the magnetic core. Between the poles there are wedges made of fiberglass (see Figure 4), which together with the pole tips form a cylindrical surface.

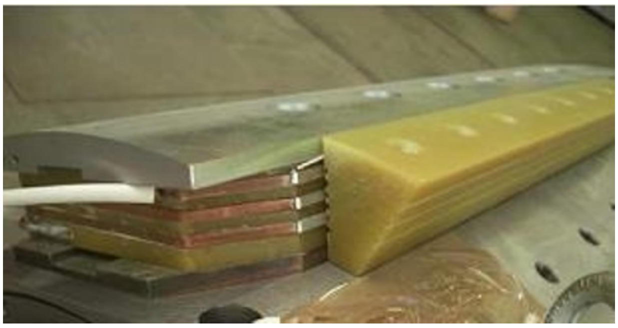

Fig. 4. YBCO coil and ferromagnetic pole shoe installed on the ferromagnetic rotor yoke.

When choosing the type of HTS coils were taken into account features of HTS 2G tape. These are limitation of the bending radius of the tape, no possibility of bending on the edge, low mechanical strength. To create a superconducting excitation winding HTSSG-1000, the racetrack type coil was selected (Figure 5). This design is modular and each individual module is mounted on the magnetic core.

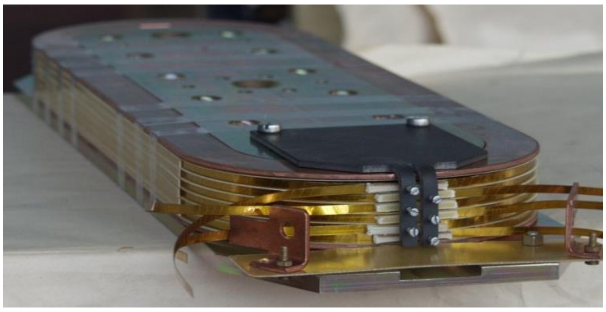

Fig. 5. YBCO coil.

The rotor HTSSG is a rotating cryostat carrying an HTS winding consisting of racetrack modules. The HTS coils are cooled with liquid nitrogen, which circulates through channels in the pole and wedges. The total length of HTS tape (AMSC – Amperium™, dimensions are 4.93×(0.32-0.40) mm^2.) for field coils that has been used is about 5.2 km [4].

The operating temperature of the superconducting excitation winding of the rotor at the level of 65-75 K for 10,000 hours (the life of the continuous operation of the HTSSG-1000 in the windmill) is provided by an autonomous system of cryogenic support using the Turbo-Brighton cycle with a cooling power of 2.5 kW (see Figure 6). This cryogenic system was specially designed and manufactured at MAI. This type of cryogenic systems provides a large overhaul interval (over 30000 hours) with high efficiency.

Fig. 6. General view of cryogenics cooling system.

3 Flywheel energy storage systems with magnetic HTS suspension for autonomous wind power stations

In 2015 MAI jointly with the Bauman Moscow State Technical University, MBDB "Horizont", JSC "VPO Tochmash", "Centrotech-SPb and JSC "NIIEM" created and tested 5 MJ FESS prototype with magnetic HTS suspension. This work have been similarly carried in the framework of implementation of the Rosatom atomic energy state corporation Innovative Energy/Superconducting Industry project (2011-2015) [20, 21]. Table 3 lists main parameters of the 5 MJ FESS.

Table 3. Main parameters of the prototype FESS

List of parameters, units	Value
Stored energy, MJ	5
Output power, kW	100
Supply voltage frequency, Hz	300-400
Output voltage range, V	150-350
Frequency using the inverter, Hz	50
Nominal charging time, sec	300
Minimum discharge time, sec	50
Maximum rotation speed, rpm	8000

The main structural elements of FESS are: flywheel, motor generator, upper and lower magnetic HTS suspension, magnetic bearing on permanent magnets (PM) and mobile lower bearing. Photo of the prototype FESS with a magnetic HTS suspension during the bench tests is shown in Figure 7. The flywheel rotor of the 5 MJ FESS (Figure 8) has a multi-layer construction (D16 aluminum alloy disc, stainless steel pipe and carbon fiber bandage). Such flywheels are more reliable and safer in operation than solid metal flywheels.

The FESS rotating assembly is supported by a levitation system consisting of a magnetic support and two cylindrical magnetic HTS suspensions located in the upper and lower parts of the flywheel shaft. Magnetic support keeps the flywheel axially, and magnetic HTS suspensions provide radial stability and partial compensation of the flywheel's weight. The magnetic

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support is made on the basis of counter-magnetized conical ring permanent magnets (PM) of trapezoidal section made from NdFeB.

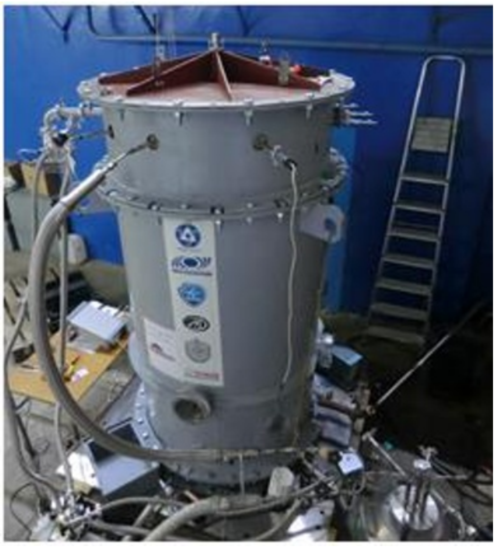

Fig. 7. 5MJ FESS with magnetic HTS suspension during the bench tests.

Fig. 8. The flywheel rotor with rotors (upper and lower) of magnetic HTS suspensions.

The main elements of HTS suspensions are stator and rotor (Figure 9). The magnetic suspension stator (Figure 9b) contains a block with HTS elements based on yttrium ceramics (YBCO). The rotor of the magnetic HTS suspension (Figure 9c) consists of magnetic rings made of NdFeB, which are arranged along the axis and connected by a liner. Spacers made of magnetically soft material are located between the magnets, which provide formation of the necessary structure of magnetic field in the gap between the rotor and the stator.

Fig. 9. Assembly of magnetic HTS suspension: a - the lower HTS suspension; b - stator of lower HTS suspension with HTS unit; c - rotor.

This 5 MJ FESS employed a motor/generator with a rated power of 100 kW. Structurally, it is a three-phase six-pole electric machine with PM made of NdFeB with radial-tangential magnetization and an ironless stator. The motor/generator was designed by MAI. The stator of the motor/generator is shown in Figure 10.

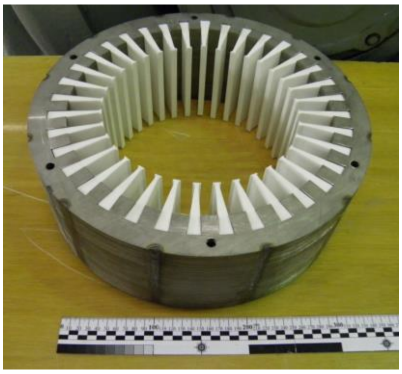

Fig. 10. The stator of the motor/generator.

4 Conclusions

Works on creation of prototypes 1 MVA synchronous 2G HTS generator and 5 MJ FESS with a magnetic HTS suspension are been successfully completed.

Technical and economic effect of the use of superconducting analogues of existing generators of wind turbines at the same electrical power is expressed in a significant reduction in size and weight, which reduces costs and reduces the time of manufacture and installation of wind turbines.

The economic effect of the introduction of superconducting FESS in autonomous wind power system (AWPS) is achieved by increasing the reliability and stability of the energy system, improving the quality of electricity to supply consumers. The use of magnetic HTS bearings allows to increase the working life (more than 15 years) of the drive, creating environmentally friendly energy storage systems with a long shelf life of stored energy. Recent advances in the technology of production of composite materials and their use for the manufacture of flywheels makes such a flywheel quite reliable and safe, allowing to significantly increase the speed of rotation of the flywheel, and consequently the energy consumption of the accumulation system.

Thus, the use of superconducting electrical equipment as part of AWPS will reduce capital costs, improve overall efficiency by reducing losses in the generation, conversion and distribution of energy, as well as increase the level of fire and environmental safety.

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