Flywheel energy storage systems for autonomous energy systems with renewable energy sources

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Abstract. One of the main problems of introducing energy systems using renewable energy sources is its dependence on climatic conditions during the year. The instability of incoming energy leads to significant fluctuations in power, voltage and frequency of alternating current in the network. Modern technologies do not yet allow achieving sustainable energy systems, which are driven only by 100% usage of renewable energy. Nowadays production of high-quality electricity is possible with parallel connection of traditional sources and using energy storage systems. This article presents design solutions for application of flywheel energy storage systems (FESS) in autonomous energy systems used by foreign companies. We describe the design of superconducting FESS with magnetic HTS suspension with stored energy of more than 5 MJ, which is the first in Russia.

1. Introduction

In recent times, the share of alternative generation using wind and solar energy has significantly increased worldwide. According to estimates of Bloomberg New Energy Finance (BNEF), in the first half of 2018, the total installed capacity of solar and wind power plants in the world reached 1013 GW, which includes 523 GW of mainland wind power stations (WPS), 19 GW of offshore WPS; small solar power stations (SPS) give 164 GW, industrial SPS give 307 GW [1].

Renewable energy sources (RES) while possessing such advantages as the availability and inexhaustibility of energy source in the conditions of a constant increase in prices for traditional types of energy carriers, as well as environmental safety for the environment, have several disadvantages. The main disadvantage of RES is its dependence on climatic conditions throughout the year, which, in turn, leads to poor predictability of the amount of energy produced by them, as well as high volatility in generation of energy itself. To ensure stable parameters of electrical voltage and frequency in the network, it is necessary to use energy storage systems.

In recent years, flywheel energy storage systems (FESS) are of particular interest among energy storage devices which are proposed to use in autonomous energy systems. Their operation principle is based on conversion of electrical energy into kinetic and vice versa. The main advantages of FESS include high specific power and high specific density of stored energy. In terms of specific accumulated energy per unit mass or volume of accumulating element, FESS significantly exceeds other types of energy storage devices (see Table 1). The FESS lifetime is almost independent on the depth of discharge. Flywheel systems can work equally well for frequent shallow discharges as well as for very deep discharges. This type of load change is usually difficult for rechargeable batteries (RB), since the combination of low and high loads makes their design difficult to optimize. The advantages of FESS also include high cycling ability, scalability and modularity.
Table 1. Comparative characteristics of storages.

| List of Parameters | Battery | Flywheel system |
|--------------------|---------|-----------------|
|                    | GEL     | NiCd | Li-ion |          |
| Specific power, W/kg | 30…90  | 150…300 | 150…315 | 400…1600 |
| Cycle life time    | 100…400 | 1000…2000 | 500…2500 | 10^7 |
| Life time          | 2…10   | 10…15 | 5…10 | >20 |
| Efficiency, %      | 70…85  | 65…80 | 80…95 | 96…98 |

2. Major directions of FESS usage

2.1. Frequency adjusting in power supply
FESS has been used in power systems for a long time [2,3]. 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 from Beacon Power. These are commercially available stationary storages of 6 and 25 kWh accumulated energy, as well as Beacon 400 storages and their modifications (400 Modular and 450 XP). Clusters of these storages are used to control the current frequency of US power grids. These are regulatory plants based on Smart Energy Matrix 0.5 MW (Tyngsboro, MA), 20 MW (Stephentown, NY) and 20 MW (Hazle, PA) [5,6] complexes.

2.2. The use of energy storage devices in power systems with RES
Allows one to: align variable work schedules; reduce power fluctuations; ensure the required quality of electricity; provide uninterrupted power supply to consumers [7]. In 2003, the Japanese company Fuji Electric installed 200 Urenco flywheels with a total capacity of 1,800 kW at Dogo Island in Japan. The use of FESS helped to reduce fluctuations in the system, allowed the diesel generator system to operate with greater efficiency, which led to significant savings of diesel fuel [8].

The M32 super-flywheel developed by Enel and Amber Kinetics should be mentioned while considering FESS used with RES. This steel flywheel weights 2 267 kg, is able to spin up to 10 000 rpm, its energy capacity is 32 kWh (115.2 MJ) and it is capable of delivering 8 kW of power for 4 hours [9]. The design of the super flywheel is based on the 2015 design of Amber Kinetics, i.e. FESS with an energy capacity of 25 kWh [10,11]. In the spring of 2018, Hawaiian Electric, in collaboration with Amber Kinetics and Elemental Excelerator, began testing M32 FESS at the generating station Campbell Industrial Park at the Hawaiian island of Oahu to integrate RES into the network [12].

FESS is successfully used in microgrids (MicroGrid) to stabilize the network with RES. The leading positions in this direction are occupied by ABB, which produces stabilizers of the PowerStore network of three nominal values: 500, 1000 and 1500 kW. Figure 1 shows the design solutions of the ABB MicroGrid Plus system using FESS as a network stabilizer. The PowerStore, which is an element of the MicroGrid Plus system, includes: FESS, inverters and special software (virtual generator). The response time of such a system is less than 150 ms, and the overload capacity is up to 10 nominal powers. The FESS of Piller technology with an energy capacity of 5 kW•h and a flywheel rotation speed of 3600 rpm [13] is used as a PowerStore storage.
2.3. Hybrid energy storage systems with FESS

A promising way to develop energy storage technology is a hybrid energy storage scheme using FESS and a rechargeable battery. This application allows one to get a fully balanced network that is resistant to changes on the generation side and is independent of consumption. Examples of using this technology are the system using Beacon 400 super-flywheels. One of these systems, consisting of two drives of the Beacon 400 Modular series with a power of 160 kW and a lead-acid battery from Hitachi, is installed in Ireland [17]. The next example of a hybrid energy storage system using FESS Beacon 400 is an innovative energy supply project in Anchorage, Alaska; [18,19].

ABB in its MicroGrid Plus systems also uses a hybrid energy storage scheme (PowerStore stabilizer + RB). An example is the Chugach Hybrid Accumulation System (Chugach, Alaska, USA), commissioned in 2017. Two PowerStore FESS operating in parallel reduce the peak load and reduce the load on the existing RB-based energy storage system [20].

3. Superconducting FESS

Due to the progress and availability of superconducting passive magnetic bearing technology, a number of FESS has been recently created using magnetic HTS bearings. In Japan, in 2015, Railway Technical Research Institute jointly with Furukawa Electric Co., Ltd. and Kubotek Corporation created the world’s largest-class superconducting FESS with a superconducting magnetic bearing. It has 100 kWh (360 MJ) storage capacity and 300 kW output capability, and contains a carbon-fiber-reinforced-plastic flywheel. This flywheel rotor is weighs 4 tons and 2 m diameter, and is suspended by a superconducting magnetic bearing composed of superconducting coil (HTS-2 tape) and superconducting bulks (YBa2Cu3Oy). This FESS is planned to be used as a power stabilizer for the megawatt-class solar power plant at Komekurayama in Yamanashi Prefecture [21].

In Russia, in 2015, a FESS prototype with a magnetic HTS suspension with stored energy of more than 5 MJ was created and tested in the framework of implementation of the Rosatom atomic energy state corporation Innovative Energy / Superconducting Industry project (2011-2015) [22,23]. FESS with a magnetic HTS suspension and its main technical characteristics are presented in Figure 2.
The main structural elements of FESS (Figure 3) are: flywheel 1, motor generator 2, upper 4 and lower 6 magnetic HTS suspension, magnetic bearing on permanent magnets (PM) 5 and mobile lower bearing 7.

The flywheel rotor of the 5 MJ FESS 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. In order to debug design methods and flywheel manufacturing technology for a FESS prototype, a flywheel layout on a 1:2 scale was designed, manufactured and tested. Figure 4 shows a photo of the flywheel during FESS assembly. The layout of the flywheel and the flywheel of the FESS prototype were manufactured at JSC “VPO Tochmash”. Flywheel bandage is manufactured at “Centrotech-SPb”.

### List of Parameters

| Parameter                        | 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  |

**Figure 2.** 5 MJ FESS with magnetic HTS suspension and its main technical characteristics.

**Figure 3.** Scheme of the superconducting FESS.

**Figure 4.** Assembly of FESS with magnetic HTS suspension.
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 support is made on the basis of counter-magnetized conical ring permanent magnets (PM) of trapezoidal section made from NdFeB.

The main elements of HTS suspensions are stator and rotor. Figures 5 and 6 show the scheme of magnetic HTS suspension and its main components. The magnetic suspension stator (Figure 6c) contains a block with HTS elements based on yttrium ceramics (YBCO), which were made at the Bauman Moscow State Technical University. Maintaining the temperature of the HTS stator elements in the range from 65 to 75 K is provided by a closed-loop cryogenic system. At the stage of debugging of the FESS prototype, the charge cryopreservation system was used.

The rotor of the magnetic HTS suspension (Figure 6 b) 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. HTS suspension of the FESS prototype was designed and manufactured at MBDB “Horizont”.

![Figure 5. Scheme of a magnetic HTS suspension.](image-url)

![Figure 6. Assembly of magnetic HTS suspension: a - the lower suspension on the support adapter; b - rotor; c - stator of lower HTS suspension without outer casing with HTS unit.](image-url)

A developed synchronous six-pole electric machine with PM made of NdFeB with radial-tangential magnetization and iron-free stator is used as a FESS motor-generator. The parameters of the motor-generator are shown in Table 2.

### Table 2. Parameters of the motor-generator.

| List of Parameters       | Value         |
|--------------------------|---------------|
| Rated power, kW          | 100           |
| Phase voltage, V         | 230 – 380     |
| Nominal current, A       | 156 – 96      |
| Operating speed range, rpm | 5000– 8000   |
| Number of poles, 2p      | 6             |
| Number of phases         | 3             |
| Stator outer diameter, mm | 428           |
| Stator inner diameter, mm | 220           |
| Stator length, mm        | 120           |
Work on creation of 5 MJ FESS prototype with a magnetic HTS suspension has been successfully completed. It was experimentally studied.

4. Conclusions

The use of flywheel energy storage systems in autonomous electric power systems with RES contributes to integration of RES into the network with an increase in their share in energy generation system, an increase in reliability and stability of the energy system, as well as an increase in quality of electricity for supplying consumers. Usage of new composite materials for fabrication of flywheels makes such devices quite reliable and safe, allowing one to significantly increase the speed of rotation of the flywheel, and accordingly, the energy intensity of the accumulation system. The use of magnetic HTS bearings in FESS design increases the working life (more than 20 years) of the drive, thus creating environmentally friendly energy storage systems with long shelf life of stored energy. Taking into account such FESS advantages as scalability and modularity, “matrix” energy storage systems can be built on the basis of a single FESS. These “matrix” FESS are intended for large levels of stored energy and power, and can be both mobile (containers) and stationary.

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