Some Issues of Development and Mathematical Modeling of Superconducting Electrokinetic Energy Storage Unit

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Abstract. In this research paper, some results of experimental sample elaboration of the superconducting electrokinetic energy storage unit (SCEESU-1), mathematical modeling and the practical application are given. The inflexibility of the superconducting contactless suspension of rotor-flywheel of the energy storage unit is calculated. The results of computer simulation of suspension stability under the external disturbing effects are presented.

1. Introduction

There is a growing interest in energy systems using renewable energy sources (RES): solar energy, wind, biogas and others. The use of these energy sources meet the social and environmental requirements, thereby reducing costs.

Renewable sources of electricity work on the part of local electric networks (LEN) or intellectual electric SMART GRID [1-6] networks. Local electrical networks include source of electric power, consumers of electrical energy, the electrical energy storage device, intellectual management system modes and power source energy store.

Local electrical networks can be combined into multi-level Enernet network [7,8]. The most important element in such electrical networks are energy storage devices performing the following functions:

– increase the economic efficiency of network;
– align the electrical load during its considerable fluctuations;
– serve as reserve sources of power supply;
– are the switching elements in multi-level LEN;
– serve as a means of energetic commercialization.

Energy storage can be used not only in the local electric networks with alternative energy sources (wind installations, solar panels, etc.), but also in electric transport to improve the energy efficiency of power devices (electric trains, trolley buses, hybrid propulsion systems in motor vehicles, etc.) [9-12].

The analysis of well-known energy storage technical solutions allows the following conclusions [13,14]:

– it is a perspective energy storage device using a passive self-centering suspension-superconducting flywheel rotor. As the motor-generator is reasonable to use the synchronous electrical machine with permanent magnets, and superconducting magnetic suspension as the non-contact prop of the flywheel rotor based on permanent magnets and massive superconductors (high-temperature superconductors (HTSC);

– application this type of suspension eliminates energy costs for maintaining the rotating flywheel rotor in levitating position and use the synchronous electrical machine with permanent magnets and the ferromagnetic stator makes the design of a compact motor-generator. This design reduces the losses in the reversal of energy storage mode and eliminates the energy to create a magnetic excitation field;

– application of contactless HTSC magnetic suspensions in kinetic energy storage in a vacuum significantly reduces the mechanical losses due to friction forces and increases the storage time of stored up kinetic energy;

– superconductors production technology is continuously perfected, which improves their critical parameters, reduce the cost of energy storage, its mass-dimensional characteristics and thus ensure a broad introduction in the energy sector.

The principle of the storage units on high-temperature superconductors (HTSC) based on the effect of the magnetic field expulsion from the superconductor volume, equivalent to diamagnetic "mirror" screen. This physical effect allows creating contactless self-centering suspension of the flywheel kinetic energy accumulator (energy storage unit). Unlike managed electrostatic and magnetic suspension, the given type of suspension does not contain the active control systems, in particular, following-up systems and the magnetic or electric fields regulators.

2. Superconducting electrokinetic storage

Superconducting contactless suspension is characterized by large lifting force, which depends on the magnitude of the critical parameters of the superconductor, self-regulation in the axial and radial directions of the suspension. Besides it superconductive contactless suspension has a good superconductive contactless suspension has good damping properties. A general view of the energy storage device is shown in figure 1.

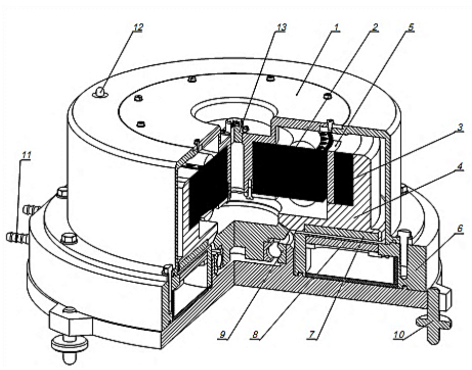

Figure1. Superconducting Electrokinetic Energy Storage Unit (SCEESU-1): 1–synchronous electric machine, 2–stator, 3 – magnetic circuit stator, 4 – flywheel rotor, 5 – excitation (stimulation) magnets, 6 – cryostat, 7 – support suspension magnets, 8 – superconducting plates, 9 – bearing, 10 – supports (props), 11 – fitting liquid nitrogen cooling system, 12 – nipple, 13 – socket.

The energy storage unit is designed to work on the part of local electrical network comprising alternative sources of energy and is used for storage and recovery the electrical energy. It consists of synchronous electrical machine 1 and 6 cryostats filled with liquid nitrogen.

The stator of synchronous machine 2 contains three-phase winding magnetic circuit 3, flywheel rotor 4 with permanent magnets excitation (stimulation) 5 and supporting permanent magnets 7. Superconducting plates are located on the mating surface of cryostat 8, cooled by liquid nitrogen, which is poured through fitting 11.

In the starting position, the flywheel rotor is centered with the help of bearing support 9. The internal cavity of the synchronous motor is vacuuming with the help of nipple 12. Hermetically sealed connector 13 connects the three-phase stator winding of the synchronous machine with the mode control unit of its work. Adjustable supports 10 serve for leveling the energy storage on the horizon.

Energy Storage Unit operates as follows. On cooling, superconducting plates up to the liquid nitrogen temperature, the Meissner effect arises as a result of which the non-contact suspension of flywheel rotor carried out.

When connecting the energy storage unit to the three-phase power supplies, the acceleration of flywheel rotor starts up to nominal speed. After that the energy storage unit is disconnected from the power supply and the flywheel rotor rotates by inertia keeping the stored energy.

By switching the stator windings to the current drain, the energy storage unit operates in electric power generation mode providing its supply. The energy storage unit has the following specifications:

– stored energy — 4 MegaJ;
– energy storage time — 5-6 min;
– energy output time — 5-8 min;
– efficiency (coefficient of efficiency) — 95-97%.

The most important characteristic of the energy storage unit is a non-contact stiffness and stability of the superconducting flywheel rotor suspension. The calculation of electromagnetic fields and levitation force in superconducting suspension depends on the choice of the active elements' geometrical configuration of superconducting suspension - superconducting elements and permanent magnets.

The choice of a particular configuration is determined by the requirements for the stiffness of the suspension and energy storage unit operating conditions. For example, in a stationary mode in the substation or in a dynamic mode on a movable base (electro transport, sea vessel, etc.).

The scheme of the active elements arrangement of superconducting suspension in the power unit is shown in figure 2. The configuration of the superconducting suspension and its calculation scheme is shown in figure 3.

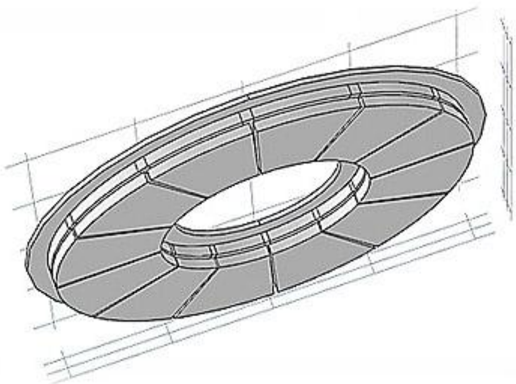

Figure 2. The scheme of arrangement of the active suspension elements in the power unit (modeling of the power block in the COMSOL Multiphysics program).

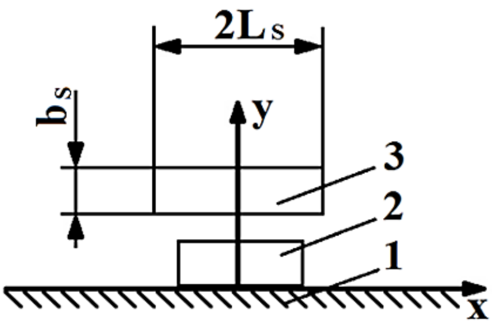

Figure 3. The configuration of the superconducting suspension and its calculation scheme: 1–ferromagnetic basis, 2 – permanent magnet (PM), 3 – superconducting element (HTSC).

The power unit of the superconducting suspension formed 12 sectoral permanent magnets and 12 HTSC sectoral form elements.

From the theoretical point of view, the calculation of the superconducting suspension stiffness reduces to the solution of Dirichlet-Neumann generalized problem under the certain assumptions [15]:

– length of the magnetic suspension base is much larger than its transverse dimensions which allows moving to the two-dimensional formulation of the problem;

– magnetic moment of the permanent magnet (PM) is collinear with the vertical axis of suspension y and is constant in the magnet volume $M\left(M_x, M_y\right) = M(0, M_0)$.

–the structure of the bulk superconducting element (HTSC) is considered to be a single-domain (mono crystalline). In this case, the interaction of PM and HTSC will be determined by the density of critical current J_s;

– it is assumed that the thickness of C.P. Bean's current layers δ is small to compare with the HTSC transverse dimensions element L_s , $\ll$ L_s;

– the center of mass flywheel-rotor displacement in dynamic mode is small compared to its size.

The calculation algorithm reduces to the solution in a two-dimensional formulation of Neumann – Dirichlet's generalized problem relative to the vector potential. Thus the system of magnetostatic equations was reduced to Laplace's two dimensional equations.

Neumann's task was solved using the Green formula. After appropriate transformations the following analytical dependence of distribution field intensity of the magnetic suspension system component has been obtained [15]:

$$Hx\ (x,\mathrm{y}) = -\frac{M_0}{4\pi}\ \{\ln[(x-L)^2+(\mathrm{y}-b)^2] - \ln[(x-L)^2+(\mathrm{y}+b)^2] - \ln[(x+L)^2+(\mathrm{y}-b)^2] + \ln[(x+L)^2+(\mathrm{y}+b)^2]\}; \quad (1)$$

$$H\mathrm{y}\ (x,\mathrm{y}) = -\frac{M_0}{4\pi}\ 2[arctg[\frac{x-L}{\mathrm{y}-b}] - arctg[\frac{x-L}{\mathrm{y}+b}] - arctg[\frac{x+L}{\mathrm{y}-b}] + arctg[\frac{x+L}{\mathrm{y}+b}]]; \quad (2)$$

$$B_x = \mu_0 H_x\ ; \quad B_\mathrm{y} = \mu_0(H_x + M). \quad (3)$$

The magnetic field formed by two or more systems of permanent magnets (PM) are calculated by the superposition of the solutions (1), (2) shifted along the axis «X» in the appropriate distance "c" PM geometric centers of suspension axis according to the calculation scheme which is shown in figure 3:

$$H_\Sigma(x,\mathrm{y}) = H(x+c,\mathrm{y}) + H(x-c,\mathrm{y})\ , \quad (4)$$

$$H_\Sigma(x,\mathrm{y}) = H(x,\mathrm{y}) + H(x+c,\mathrm{y}) + H(x-c,\mathrm{y})\ . \quad (5)$$

By activating the HTSC magnetic suspension mode «fc-process», magnetic field lines are "frozen" in the superconducting element of suspension. In this case the absence of superconducting suspension movement and therein permanent magnet electric currents are zero and the mechanical interaction is absent.

Magnetic field inside the superconductor in Bean's model framework does not change when moving the suspension element along the "Y" axis. The magnetic field on the surface of the element will result in electrical currents occurrence in the superconductor surface layer and the magnetic field disturbance's appearance. Magnetic fields interaction leads to the Meissner's effect of levitation force occurrence.

The average values of tension and the magnetic field induction will be equal.

$$B_{xav} = \mu_0 H_{xav}. \quad (6)$$

Then the specific and the total forces acting on the HTSC element will be determined by the following formulas

$$f_\mathrm{y} = B_{xav};\ F_\mathrm{y} = L_w \int_{-Ls}^{L_s} f_x dx, \quad (7)$$

where I_s and L_w are the half-width and the length of HTSC element.

3. Modeling SCEESU-1

Similarly, it is possible to calculate the disturbance of magnetic field intensity H_{zB}, the specific and full force with lateral displacement along the axis «Z». For the rotationally symmetric design of the power unit this force will fit the radial component. The calculation results of vertical F_y and radial F_r components of levitation force for the power unit parameters values: b = 0.01 m, L = 0.038 m, M0 = 1.4 T, the nominal value of the gap between PM and HTSC 0.003 m, PM amount – 12, shown in figure 4.

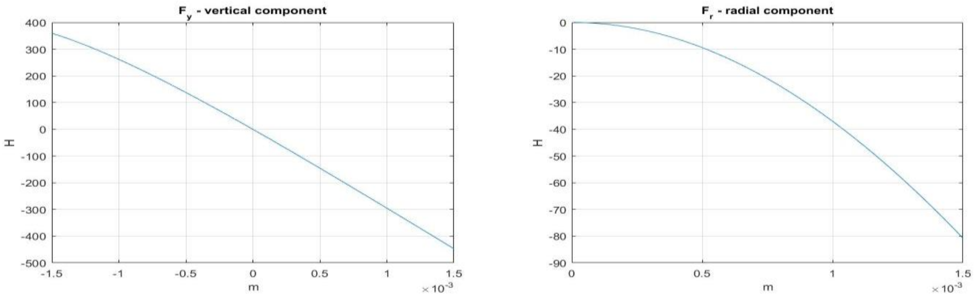

Figure 4. Vertical and radial flywheel rotor levitation force depending on magnitude of displacement from equilibrium position.

From these calculation dependences, both vertical and radial component levitation force determined the average stiffness coefficient and C_{yr} contactless suspension flywheel rotor in the working gap:

$$C_{rc} = \frac{1}{N}\sum_{i=1}^{N}\frac{\Delta F_{ri}}{\Delta z_i} = -\frac{3{,}75x10^2\text{H}}{m^2}, \tag{8}$$

where ΔF_{yi}, ΔF_{ri}, Δyi, Δz_i – changes in the components of levitation force and displacements in the gap between the stator and the flywheel rotor, N is the number of averaging intervals.

To study the dynamic stability of the flywheel rotor under the influence of random external disturbances and an imbalance presence of flywheel rotor center-mass is carried out a computer simulation in the MATLAB/Simulink/Multibody program. Simulation parameters: imbalance of flywheel rotor center-mass d= $8.25x10^{-3}$ m, frequency of external influences f = 5Hz, the amplitude of external influences 2 N / m, flywheel rotor angular velocity $\Omega = 12000$ rev / min and 20000 rev / min, rotor weight(mass) m=40 kg, the nominal gap between the PM and HTSC h=3 mm. The computer model is shown in figure 5.

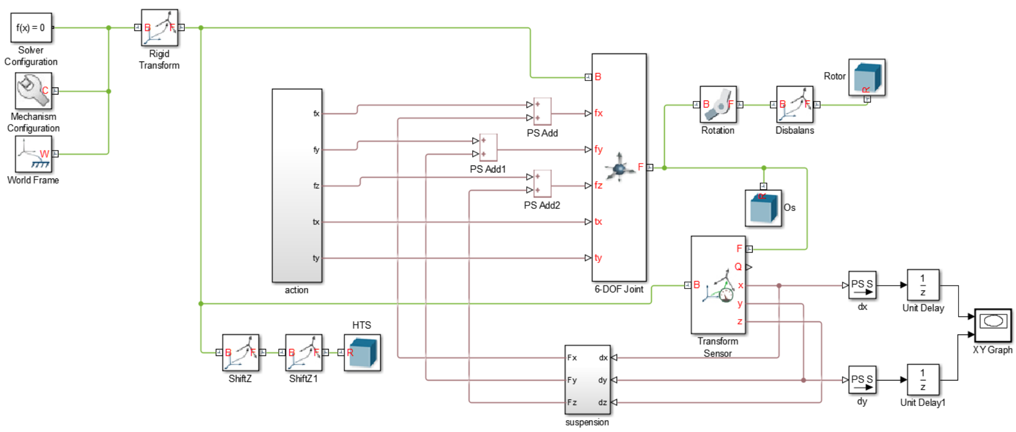

Figure 5. Computer dynamic model SCEESU-1.

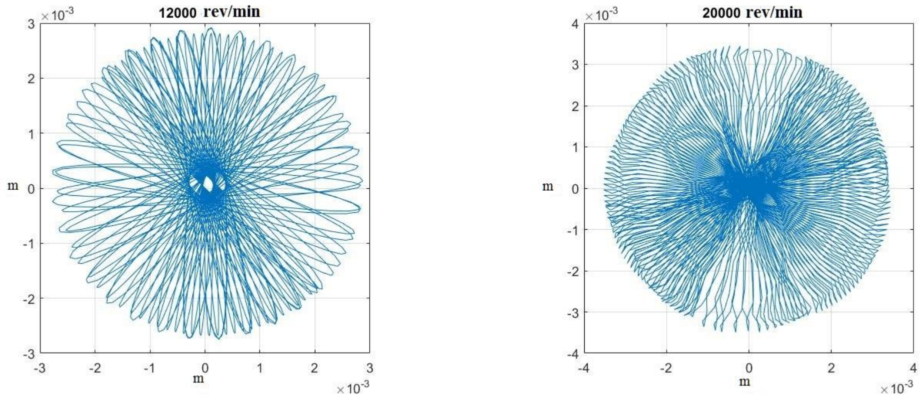

Figure 6. Flywheel rotor fluctuations in a radial plane under the external impacts and the rotor imbalance presence.

External influences and the flywheel rotor imbalance lead to fluctuations in its axis and to a change in nominal operating gaps between the power unit components. The simulation (modeling) results are shown in figure 6. Main contribution to the amplitude fluctuations introduces rotor center mass imbalance. The external influences impact is much less important. The maximum fluctuation amplitude for given imbalance of flywheel rotor mass center is 1.5 - 3 mm in a radial plane and less than 1 mm in the vertical one.

Thus, to ensure the energy storage unit normal operation, flywheel rotor balancing and working gap optimization between the stator and the flywheel rotor is necessary along with the force and dynamic characteristics.

4. Conclusion

Electrokinetic energy storage design with flywheel rotor contactless suspension are proposed and substantiated. The energy storage application is considered, particularly in local electric networks.

The power characteristics of non-contact superconducting suspension calculation is carried out, and its coefficients of stiffness, the flywheel rotor suspension in the vertical and radial axes are identified.

Computer modeling of the flywheel-rotor in the dynamic mode, considering the center of mass imbalance and random external disturbances, has been done. Due to the modeling results, the running clearances between the stator and the flywheel rotor, the magnitude of flywheel rotor center-mass imbalance should be optimized for the power and dynamic characteristics, which ensures the energy storage unit’s stable operation.

These obtained results allow clarifying and optimizing the design and technological documentation, creating calculation base for the development and designing various devices by a superconducting contactless suspension of the active element, for example, gyroscopes and electric machines with contactless suspension in a movable part of a machine.

Acnowlegments

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