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Development of a Model Wind and Solar Power Installation Comprising High-Temperature Superconductors

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Abstract

The investigation of main performance properties of the hybrid wind and solar power installation with application superconductive elements was carried out. In the frames of the study, both mathematical simulations and experimental testing were performed. The study shows some difficulties to be solved during mutual operation of the various high-temperature superconductivity (HTSC) devices, especially if they operate with semi-conductive systems.

Key words: Hybrid wind; Solar power installation; High-temperature superconductivity (HTSC); Renewable energy; Simulation; SMES; Fault current limiter; Physical modeling

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INTRODUCTION

Hybrid wind and solar power installations are drawing increasing attention due to high prices of conventional fossil resources and ecological problems of different regions of the world. The main aim of the researches in this field is focused on the improving of the overall efficiency of such installations. The objective can be obtained by: improvement of the solar panels power output, improvement of wind generator efficiency and improvement of control methods and algorithms for entire installation.

Solar and wind are intermittent energy sources as they vary over time and do not usually meet load demands at all periods. Among these two types of renewable energy, wind is a more affective source compared to photovoltaic due to its variability. Similarly, the photovoltaic system also depends on the weather conditions and can operate only at day-time. These two unpredictable energy sources standalone system will produce fluctuated output energy and thus cannot ensure the minimum level of power continuity required by the load.

There exist numerous combined wind and solar power installation developed by different companies, but most of them are based of application of conventional materials. Until the present moment superconductors find only limited application in such types of power installations, for example, American Superconductors (AMSC) offers a design of a similar combined system involving wind generator with HTSC.[1]

One of the ways of increasing wind generators efficiency is to use new types of materials, such as high temperature superconductors (HTSC). Application of HTSC allows increasing the unit rating up to 10 MW and more at the same time reducing the units' mass and dimensions parameters. Superconductors allow setting up of efficient, robust, and compact wind power plants at reduced building, operating, and maintenance costs.

Superconductor based magnetic energy storage units (SMES) can be successfully used in combined wind and solar power installation for storing generated energy and for smoothing load power peaks. Fault current limiters

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[1] http://www.amsc.com/windtec/index. html (AMSC's official site).

protect the load from abnormal modes of operation.

The advantage of application hybrid systems is in the increased reliability of energy supply because it is based on more than one generation source. Moreover, the hybrid system is suitable to use in remote areas with no access to utility grid. However, the disadvantage of these systems lies in the fact, that in most cases they are over-sized because they contain different types of power generation system.

1. GENERAL REMARKS

As a continuation of mutual researches carried out in 2009-2010 by the team uniting specialists of both SUAI (Russia) and Ben-Gurion University (Israel) (Chubraeva, Sokolovsky, & Meerovich, 2010, pp.23-40; Chubraeva, Sokolovsky, & Meerovich, 2010), there is being developed in SUAI a model installation of independent local network comprising photovoltaic batteries and a wind generator. The model is to be equipped as well with power current controllers: SMES and a fault current limiter (FCL). The generator, SMES and FCL utilize high-temperature superconductors, and liquid nitrogen is used as a cooling media. There is also under development a computer based control system intended for the wind power installation, providing complex control on operation of both main and peripheral equipment, including:

- Stabilization of output electrical parameters;
- Alarm and warning indication and emergency protection system;
- Remote and automatic control on all of the processes in a wind power installation during the period of 240 hours (non-attended operation).

The above control system is designed on the base of a programmable logical controller Mitsubishi Electric (FX3U series), that is one of most flexible and cost-effective process control platform for technical systems.

The main aim of the investigation is to evaluate the efficiency and aspects of a synchronous alternator with permanent magnets on the rotor and HTSC armature winding. The design seems to be advantageous as compared to the alternator with HTSC rotor winding. Moreover it is necessary to investigate mutual operation of a complex system with several HTSC devices.

The electrical scheme of the installation is presented in Figure 1.

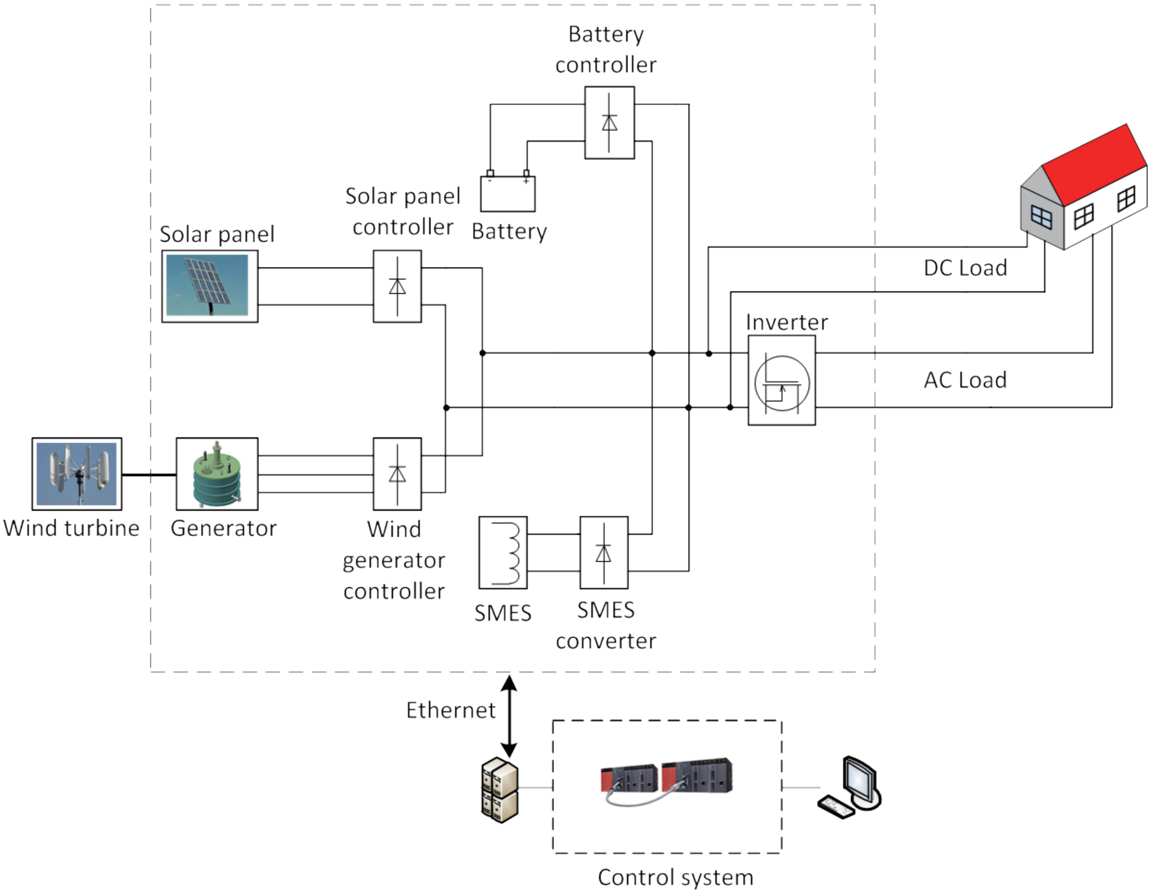


Figure 1
Electrical Scheme of Hybrid Installation

Presented below are results of experimental and theoretical investigations of two HTSC elements: synchronous alternator with permanent magnets on the rotor and HTSC armature winding and SMES with HTSC winding and magnetic cores of amorphous alloy.

2. HTSC MODEL SYNCHRONOUS ALTERNATOR

The wind turbines are generally manufactured in a wide range of vertical and horizontal axis types. Vertical axis turbines have several advantages over the typical horizontal axis turbines, namely:

- They can accept changes of wind direction with no problem;
- The alternator can be fixed on the ground for easier access, rather than up in the air;
- Generally they start rotation at lower velocity;
- They produce less noise.

The general view of HTSC electrical generator with a wind turbine is shown in Figure 2.

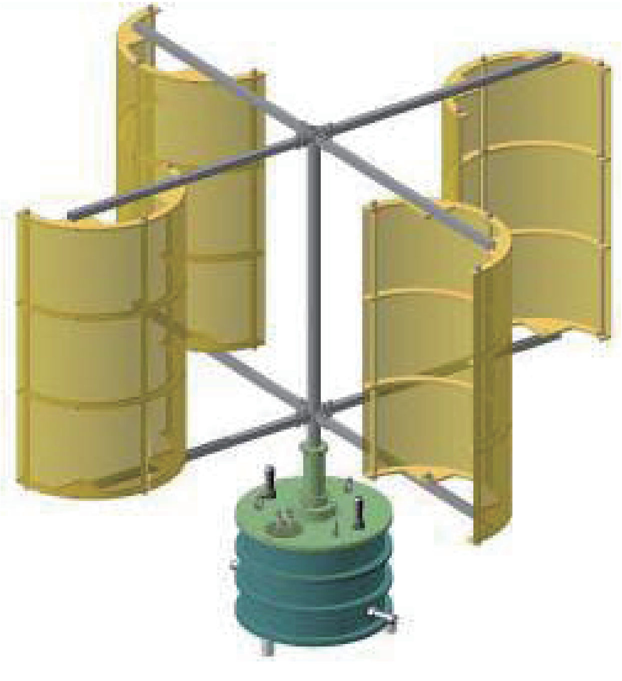


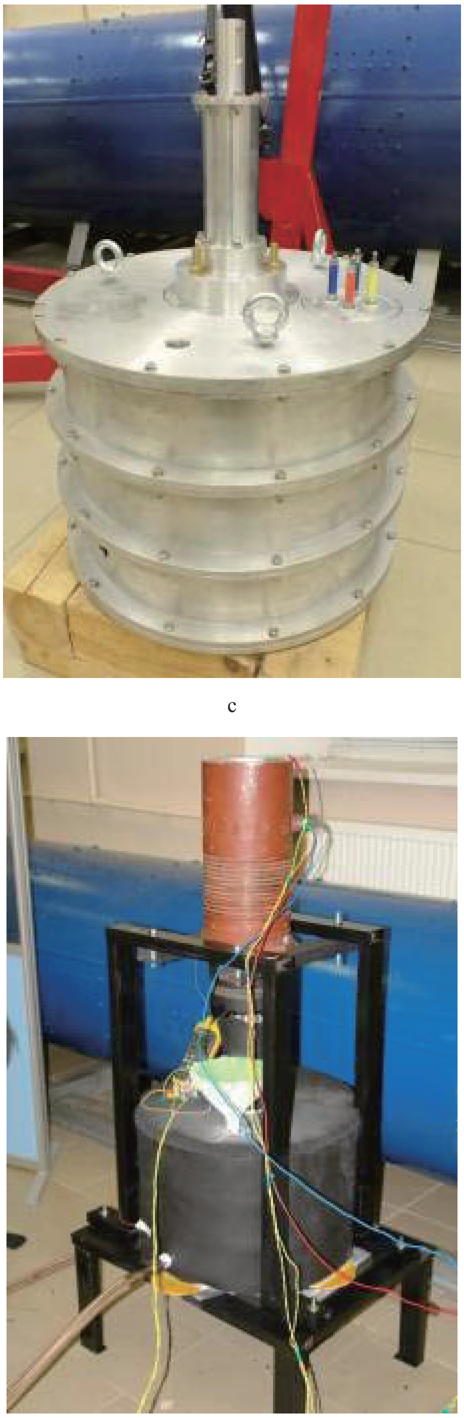
Figure 2
Model Vertical Axis Wind Turbine With the Alternator

Synchronous machines with axial magnetic flux and permanent magnets excitation possess the increased performance characteristics and the lower overall dimensions in comparison with conventional electric machines (Yi, Agelidis, & Shrivastava, 2009). Application of the rare-earth permanent magnets as an excitation element of electric machines allows canceling the excitation losses and permits to exclude the exciter. Axial magnetic flux is perpendicular to narrow edge of HTSC tape, resulting in reduction of losses. Moreover armature coils of a simple circular form may be used. This fact is substantial for HTSC. The coils form one or two layers, providing a reliable, simple and more cost-effective winding (Ahmed, & Miyatake, 2006). The rotor has 8 magnetic poles, each pole comprises two magnets on both rotor sides (Figure 3, b). The magnets are rare-earth Nd-Fe-B. The rotor body is made of aluminum. The alternator rating is 5kW.

The armature of the generator is of a slotless design with a stator core made of amorphous alloy tape. The stator winding consist of 12 pancake single-layer HTSC coils divided into two layers (upper and lower), each stator layer is mounted on a separate stator disk (Figure 3, a). It is worth nothing that the alternator may be of a multi-disc design with a multiphase armature winding. The entire alternator is emerged in liquid nitrogen.

a

b



c

d

Figure 3
HTSC Generator: a) Armature Disc With Installed Coils; b) Rotor and Stator Assembly; c) Assembled Generator Without Thermal Insulation; d) Generator With Thermal Insulation Layer in a Test Bed (a Drive Motor in the Upper Part)

The armature and the rotor are mounted in a hermetically sealed vessel, which acts as a cryostat (Figure 3, c), the outer surface of the vessel is covered with a layer of a thermal insulation made of cellular rubber substance (Figure 3, d). The generator was tested at liquid nitrogen temperature, it took 2 hours to cool down the generator to the temperature of 77K. The cooling process was controlled manually and the dynamics of the process is shown in Figure 4.

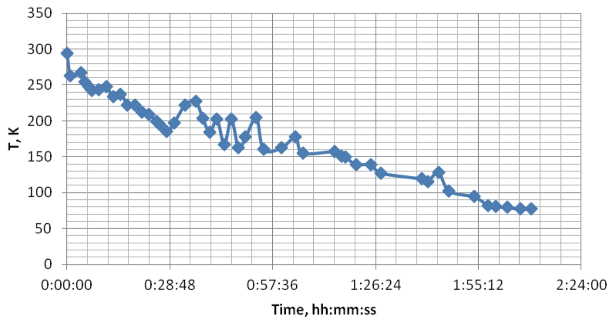


Figure 4
Cooling Dynamics of the Generator

The obtained no-load characteristics and wave forms of output voltages are presented in Figure 5. It is worth mentioning the highly sinusoidal voltage curves, although the magnetic flux in the air-gap contains relatively big amount of high harmonics.

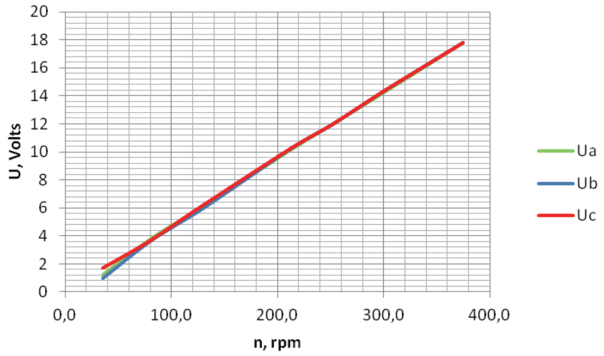
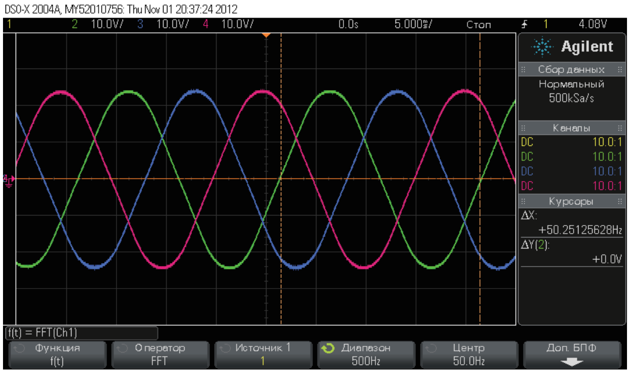


Figure 5
No-Load Characteristics



DSO-X 2004A, MY52010756: Thu Nov 01 20:37:24 2012

1 2 10.0V/ 3 10.0V/ 4 10.0V/ 0.0s 5.000ms/ Стоп 1 4.08V

Сбор данных: Нормальный 500kSa/s

Каналы: DC 10.0:1; DC 10.0:1; DC 10.0:1; DC 10.0:1

Курсоры: ΔX: +50.25125628Hz; ΔY(2): +0.0V

f(t) = FFT(Ch1)

Функция f(t); Оператор FFT; Источник 1 1; Диапазон 500Hz; Центр 50.0Hz; Доп. БПФ

Figure 6
Output Voltage Waveform

At nominal speed the output voltage (Figure 6) was 25 V, it agrees with design parameters, asymmetry between phases is not present. To evaluate the friction losses of the rotor in LN_2 medium, there were carried out experiments on a special model (De S. Ribeiro, Saavedra, De Matos, Bonan, & Martins, 2009).

3. MODEL FOR FRICTION LOSS INVESTIGATION

To evaluate the friction losses of the rotor body in liquid nitrogen a special model was developed (Figure 7). The model comprises rotor and armature disks, support elements, cryostat, LN_2 level pick-ups, DC drive motor. The design of the model permits to change the size of the air-gap between the rotor and the stators. The rotor diameter is 560 mm, its thickness is 22 mm.

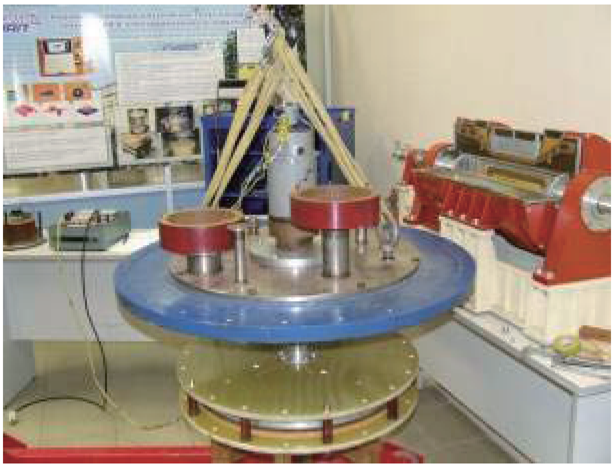


Figure 7
General View of the Model Prepared for the Installation in Cryostat

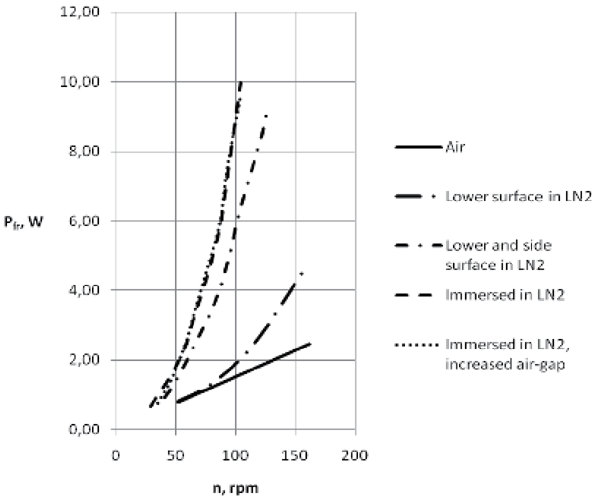


Figure 8
Dependence of Friction Losses on the Rotor Velocity

The experimental test-bed comprised several units controlled via PC: unit of LN_2 level control for evaluation of heat losses; unit of the drive motor frequency regulation; unit, indicating parameters of the drive motor: unit, measuring the torque of the drive motor. The frequency of rotation was limited by the drive motor rating. The size of the air-gap practically does not influence the friction losses (Weiss & Xiao, 2003). Experimental results are presented in fig 8. These results refer mainly to the no-load mode, when the alternator will operate with armature current, the friction losses will decrease due to N_2 temperature increase.

4. MODEL HTSC SMES

The model SMES comprises three concentric elements: inner magnetic core, HTSC coil, outer magnetic core. The HTSC Bi-2223 tape has maximum current around 100 A. Amorphous alloy tape is characterized by low loss level at LN_2 temperature. During the winding of the coil the absence of short-circuits was controlled. The outer surface of the inner core was covered by a glass tape, the outer surface of the coil was covered with glass tape as well. The outer magnetic core serves a bandage cylinder for the HTSC winding and it improves the inductance value as well. The process of SMES manufacturing and testing is presented in Figure 9 a, b, c, & d.

The model SMES has undergone preliminary tests with inductance measurements and evaluation of operating current at LN_2. The results of inductance measurements are presented as follows: HTSC coil with inner magnetic core, 30.16 mH; HTSC coil with inner and outer magnetic cores, 33.65 mH). The inductance measurements under 100 Hz AC introduce a certain error due to electromagnetic screening effect of electrically conducting elements, but it may be neglected in comparison with magnetic screening effect.

a

b

c

d

Figure 9
a) Model SMES Insulated Inner Magnetic Core; b) Final Stage of HTSC Winding Laying out; c) Assembled Model SMES; d) Model SMES Prepared for Cryogenic Tests at LN2

During the low temperature experiments SMES was installed in a cryostat and cooled by liquid nitrogen. The operating DC current was 100 A. No transition to normal state was witnessed at this current value.

There were carried out theoretical investigation of the model SMES with a Simulink-model of mutual operation HTSC SMES and a regulated power supply with active load, using combination of the structural schemes of individual operation modes (Figure 10). The simulation is carried out using the following specifications:

• Superconductive winding inductance	0.034 Henry;
• Winding active resistance at 770K	10-6 Ohm;
• Power supply voltage	5 V;
• Current controller active resistance	0.05 Ohm;
• Load resistance	0.6 Ohm.

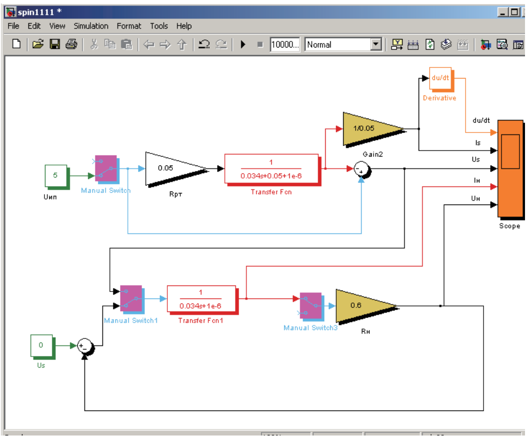


Figure 10
Linear Simulink-Model of HTSC SMES Operation Modes

At Figure 11 there are presented are the simulation results with time dependencies of HTSC SMES current variation, its derivative and voltage under the variable operation modes, as well as dependences of current and voltage variation under load conditions during discharge period of the stored energy.

Mathematical simulation results are confirmed by the experimental trials of the model HTSC SMES.

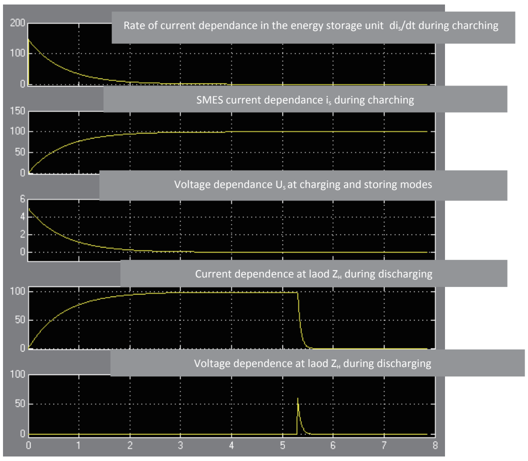


Figure 11
Simulation Results
Model Fault Current Limiter

The fault current limiter is intended for protection of a load from occasional abnormal modes in the independent grid. For the model installation it was chosen a resistive type of FCL with a meander winding of HTSC tape fixed between two non-metallic cylinders (Figure 12). The FCL model is under manufacturing process at present.

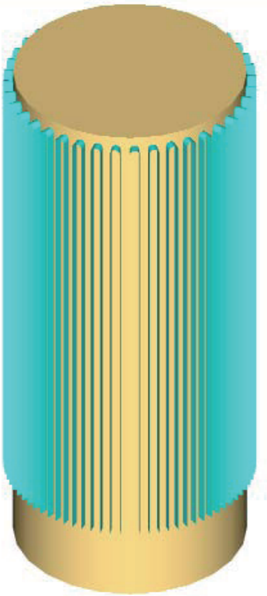


Figure 12
Meander Winding of HTSC Tape

If there is a need to protect DC circuits against abnormal currents, the FCL comprises two concentric elements, otherwise in case of a 3-phase AC network, there are three concentric cylinders housed in a cryostat.

Our previous experience shows that the major difficulties appear during mutual operation of several HTSC devices in the circuits containing semiconductive elements (Andreev, et al., 2007). Therefore, our next step is the development of control systems for electrical and cryogenic parts of the model.

CONCLUSION

a. Experimental investigation carried out on the model alternator show advantages of the proposed design due to simple geometry relatively low losses and possibility to develop of the alternator. In the first case the rating increases, in the second—the mutual operation with a DC/AC link is simplified.

b. Magnetic energy storage is unable to cover all the possible needs of the consumer, but it solves the problems of peak loads, which may happen in the morning and in the evening (if the hybrid system supplies energy to the individual building).

c. Control circuit for the hybrid system operation is a complicated one and is to be responsible for both electrical and cryogenic equipment reliable functioning.

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