ELECTROMAGNETIC SUSPENSION OF VERTICAL TURBOMACHINE FOR GT-MHR NUCLEAR POWER PLANT

N.Kodochigov, V.Drumov, S. Belov, N.Delfontsev, V.Chistyakov
I.I.Africantov OKB Mechanical Engineering,
Burnakovsky proezd,15
603074, Nizhny Novgorod, Russia
Tel.: (0 07 83 12) 24 52 88
Tel.: (0 07 83 12) 41 87 72
E-mail: icpokbm@nnov.city.ru

Abstract
The report contains consideration of magnetic bearings for a turbomachine rotor suspension in the GT-MHR nuclear power plant (NPP). Major parameters and overall arrangement of the turbomachine are given. Unique features of the turbomachine rotor characteristics are highlighted. The use of full electromagnetic suspension for the turbomachine rotor is validated. The report identifies problems to be solved for creation of the electromagnetic suspension and ways of their solution. Need for conduction of a whole number of investigations is noted. The concept of rotor scaled model application for development of electromagnetic suspension is described

Introduction

One of the most promising directions of of nuclear power development is associated with creation of power units based on high temperature helium reactors for electric power generation. Such a power unit combines of helium modular reactor capable to generate high temperature heat and a power conversion system, including a turbine, compressors, an electrogenerator, a recuperator, a precooler and an intercooler. The turbine, compressors, electrogenerator are incorporated in a turbomachine. Preliminary design of such NPP [1;2] is developed under support of Minatom (Russia) and US Department of Energy, by a number of Russian enterprises: OKBM, RRC «Kurchatov Institute», VNIINM, NPO «Luch», etc., as well as American firms and laboratories: General Atomics, ORNL. Framatome, ANP and Fuji Electric are interested in this Project.

A prototype NPP includes one power unit with rated of 285 MW. Such power unit is capable of generating electric power with more than 47 % efficiency in direct closed gas-turbine cycle. In near future the designers are planning to develop a prototype of commercial nuclear power plants, competitive in respect to other power sources, including prospective NPPs with PWR-type reactors and fossil fuelled electric power stations.

International GT-MHR Project is based on essential features of GT-MHR modular reactor of up to 600 MW thermal power with gas turbine, developed by General Atomics, as well as on the modern technologies: modular helium reactors with high level of natural safety, inherent to them; highly effective gas turbines developed for aviation and power industry; electromagnetic bearings operating practically without friction and used in different industrial areas; high efficient ultracompact heat exchangers.

Unique parameters of major components require their additional development and testing, this is referred to electromagnetic bearings.

1 Turbomachine

To acquire high efficiency in the GT-MHR design there a direct gas-turbine cycle is used for energy conversion (the Brayton cycle) with high effective recuperation and intermediate cooling of a coolant. Main equipment involved in the gas-turbine cycle are arranged inside a single vertical pressure vessel of power conversion unit (PCU), which is connected to the reactor vessel by gas ducts. Power level and helium pressure in the system and other parameters of the reactor plant (RP) are optimized to acquire a high power conversion efficiency.

The PCU schematic diagram is given in Fig. 1. The turbomachine is located in the central portion of the PCU. The turbomachine is a single machinery consisting of a gas turbine, a generator and low and high pressure compressors. The turbomachine has a single rotor full supported by a electromagnetic suspension. Rotors of the turbine and the compressors are rigidly coupled and formed the turbocompressor rotor, which is connected to the generator rotor by a coupling.

The turbomachine performs the following functions:

– converting thermal power of the working medium (helium) into electric power with high effectiveness of gas-turbine cycle;

– helium circulation through the circuit, including that during the plant NP startup and shutdown and during the reactor cooldown through PCU, including fuel reloading mode.

The main turbomachine indices are given in Table 1.

Turbomachine arrangement is given in [1] and in Fig. 2.

Table 1 — Turbomachine characteristics

Characteristics	Value
Active electric power, MW	285
Rotor speed, s^{-1}	50
Number of turbine stages	12
Number of low pressure compressor stages	16
Number of high pressure compressor stages	24
Turbomachine rotor mass, t	105
Generator rotor mass, t	68
Turbocompressor rotor mass, t	37
Number of radial bearings	4

The following design options of the turbomachine designs apart from presented one were analyzed during the design development:

– with rotational speed of 100 s^{-1} and a frequency converter;

– with separate rotors of turbocompressor and generator rotating with different speeds and in-line connected turbines;

– with generator located beyond PCU vessel and a shaft seal in PCU vessel.

Presented turbomachine design option is optimized in terms of efficiency and other technical and economic parameters. As result of performed design studies it was determined that the turbomachine of 285 MW electric power would have rotor with f 105 t mass and 29 m length.

Requirements for the turbomachine:

– the turbomachine shall be vertical;

– quantity of auxiliary and service systems shall be minimum;

– turbomachine shall keep its operability at exceeding of nominal rotational speed by 20 %;

– turbomachine shall need minimum actions by service personnel;

– turbomachine shall be seismically resistant;

– damaging to equipment inside PCU vessel and vessel itself in case of accidents associated with fracture of rotating turbomachine parts shall be excluded;
– turbomachine shall not be a source of impurities for helium therefore application of bearings with oil lubricant in the design under consideration is not allowed.

2 Electromagnetic suspension of GT-MHR turbomachine rotor. Main problems

Considering a whole set of the requirements for the turbomachine an electromagnetic suspension has been selected for its rotor, which enables:
– elimination of oil ingress into gas-turbine cycle helium;
– minimization of power losses for bearings operation;
– active influencing actively on a rotor with the aim to reduce bending vibrations amplitude during operation within a of critical speeds range.

Needed number of bearings, their arrangement, load-carrying capacity and other characteristics are a subject of independent analysis, and due to the complexity of evaluation of all significant factors, it is necessary to perform a set of research and testing activities to support a selection.
The turbomachine rotor dynamics analysis shows that the rotor may only be made «flexible» and would have several critical bending vibration frequencies within in the range of potential speeds.

Fig. 2 shows an overall schematic diagram of the bearings. Electromagnets and sensors are made on the basis of well-known solutions and need not to be explained. Each electromagnetic bearing (EMB) is fitted with a closely located catcher bearing. Catcher bearings serve as the rotor supports at planned de-energizing of the EMB and outage, in case of the EMB failure, at dynamic loads exceeding the EMB load-carrying capacity.

A radial catcher bearing consists of an auxiliary planetary-type rolling bearing and back-up bushing bearing. If auxiliary bearings do not ensure carrying of loads caused by seismic and resonance impact, the TM rotor can contact with back-up bearings.

An axial catcher bearing contains a ball bearing supporting on a stack of damping springs, a gas-static relief system with automatic gas supply in case of EMB failure and bushing bearing to take a force acting upward at seismic impact.

A considerable mass and dimensions of the rotor combined with high requirements for its reliability and absence of analogs cause difficulties in development of catcher bearings.

Other design problems are associated with the EMB control system. It is stipulated by the following circumstances:
– presence of several (not less than three) of natural bending rotor vibration frequencies;
– a number of radial electromagnetic bearings may not be less than four;
– high load carrying capacity of the bearings necessitates development of powerful-amplifiers;
– damping of rotor bending vibrations shall be ensured during passing of critical speeds at the turbomachine speedup and slowdown.

To simplify a solution of the problem of electromagnetic suspension creation it is supposed to develop a design option with a flexible coupling between generator rotor and turbocompressor rotor, that practically excludes interaction of the rotors at their radial and axial displacements and allows, with a certain approximation degree, to consider them as independent by bending vibrations. In this case two axial bearings are needed, that increases a total length of the turbomachine rotor.

3 Experimental activities

Complexity and novelty of the task of a full electromagnetic suspension creation for the turbomachine in GT-MHR Project, need for verification of analytical models and software with their certification in regulatory bodies require experimental activities on the rotor dynamics, electromagnetic bearings, catcher bearings, rotor position sensors to be performed.

Activities on the electromagnetic bearings include performance of integral testing of pilot samples of the bearings and their components. Testing results shall confirm that the bearings meet the established requirements and, if necessary, activities to improve the bearings design shall be performed.

Development of control system of «flexible» multisupport rotor is one of the most difficult problems in creation of the full electromagnetic suspension. To solve this problem it is necessary to perform experimental investigations. Fulfillment of the activities on a full-scale turbomachine model is not economically advisable since it will require considerable expenditures. The most rational approach seems development of electromagnetic suspension with control system on the special scaled (reduced) model of the turbomachine rotor. Results of these activities shall demonstrate a principal possibility of creation of full electromagnetic suspension and confirm analytical techniques. Correctness of selected solution shall be finally confirmed during integral testing of a pilot turbomachine in a special test facility and as part of PCU with a non-nuclear heat source.

Design of the rotor scaled model shall be developed considering identity of the model rotor and actual TM rotor frequency characteristics.

Parameters of the full-scaled rotor are related to appropriate parameters of the scaled rotor by the scaling factors:

$$\lambda_E = \frac{E_H}{E_M}; \quad \lambda_\rho = \frac{\rho_H}{\rho_M}; \quad \lambda_d = \frac{d_H}{d_M}; \quad \lambda_l = \frac{l_H}{l_M}; \quad \lambda_m = \frac{m_H}{m_M} \qquad (1)$$

where λ_E is scaling factor for modulus of elasticity for the rotor material;

λ_ρ - is scaling factor of the rotor material density;

λ_d - is a scaling factor for the rotor diameter;

λ_l - is a scaling factor for the rotor length;

λ_m - is a scaling factor for masses of any rotor sections;

E_H; E_M - is modulus of elasticity for full-scaled and scaled rotor material, respectively;

ρ_H; ρ_M - is density of full-scaled and scaled rotor material, respectively;

d_H; d_M - are diameters of similar sections of full-scaled and scaled rotor, respectively;

l_H; l_M - are lengths of full-scaled and scaled rotor similar sections, respectively;

m_H; m_M - are masses of similar sections of full-scaled and scaled rotor, respectively.

Identity of frequency characteristics of the full-scaled and scaled rotor is ensured at the following relationship of the scaling factors:

$$\frac{\lambda_E \cdot \lambda_d^2}{\lambda_\rho \cdot \lambda_l^4} = 1 \qquad (2)$$

If the same material is used for the full-scaled and scaled rotors a relationship between diameters and lengths of rotor sections may be determined as

$$\lambda_l = \sqrt{\lambda_d} \qquad (3)$$

OKBM is currently working to develop a scaled model of the rotor.

The following scaling factors are preliminary adopted:
as for diameter $\lambda_d = 7.051$; as for length $\lambda_l = 2.655$; as for associated masses $\lambda_m = 132$.
Design diagram of scaled model is depicted in Fig. 3. The rotor model design is simplified however correspondence of rigid characteristics to those of the actual rotor is ensured. The electromagnetic bearings system, forming a full electromagnetic suspension, corresponds to actual turbomachine in quantity, arrangement and range of working speeds and character of force interaction with a rotor. The following investigations are planned to be performed at the scaled rotor model:

– study of rotational speed effect on the rotor and control system operation, including the rotor behavior at passing through critical frequencies and operation at critical speeds;
– study of potentialities for damping of the rotor bending vibrations at critical speeds;
– study of influence of different design changes on the rotor and control system operation, including a number of bearings and their location, design of generator and turbocompressor rotors connection by rigid or flexible coupling, misalignment of various structural elements (bearings, generator stators, turbine and compressors);
– study of influence of different force factors on the rotor and control system operation, including magnetic attraction forces in the generator and the excitor, gas-dynamic forces in the turbine and the compressors.

Conclusion

The use of electromagnetic bearings for the GT-MHR turbomachine is the most preferable compared to other known types of bearings.
Development of electromagnetic bearings for the GT-MHR turbomachine requires performance of a complex of investigation and tests, that is primarily caused by complexity and novelty of problems, stipulated by existence of several critical frequencies of the rotor bending vibrations, considerable mass and large size of the rotor.
A planned scope of the investigation will allow problems associated with creation of the GT-MHR turbomachine bearings to be solved.

References

1. Arkal Shenoy. US History of Direct Cycle Gas-Turbine HTGRs. Presented at IAEA Technical Committee Meeting on Gas Turbine Power Conversion Systems Meeting/ November 15, 2000.
2. N.N.Ponomarev-Stepnoy, E.S.Glushakov, V.N.Grebennik, A.I.Kirushin, N.G.Kodochogov, N.G.Kuzavkov: Modular helium reactor GT-MHR application potential for weapon plutonium disposition. ISSN 0869-6772. – Conversion in machine building of Russia. 1999. №3-4.

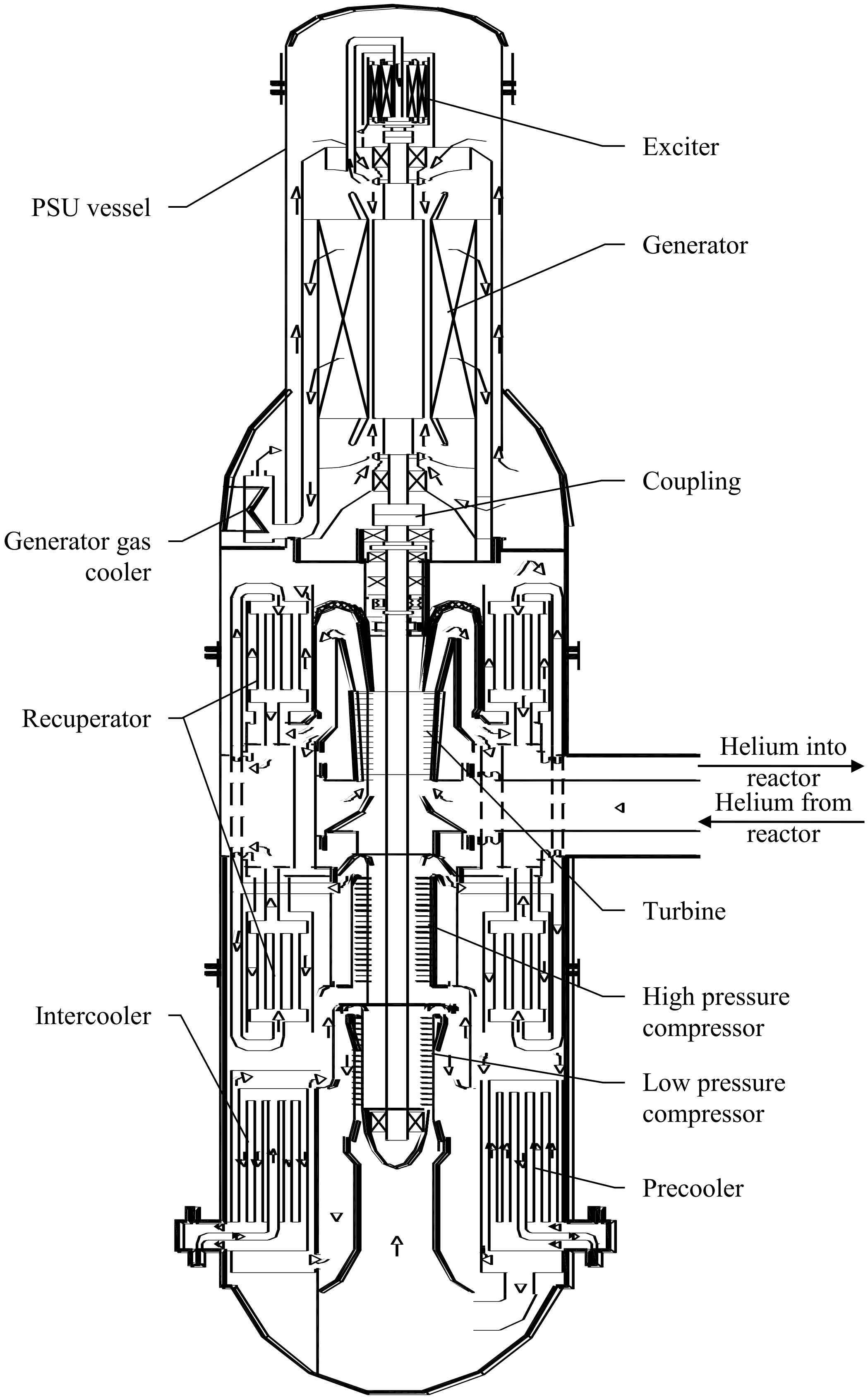

Fig. 1: PSU schematic diagram

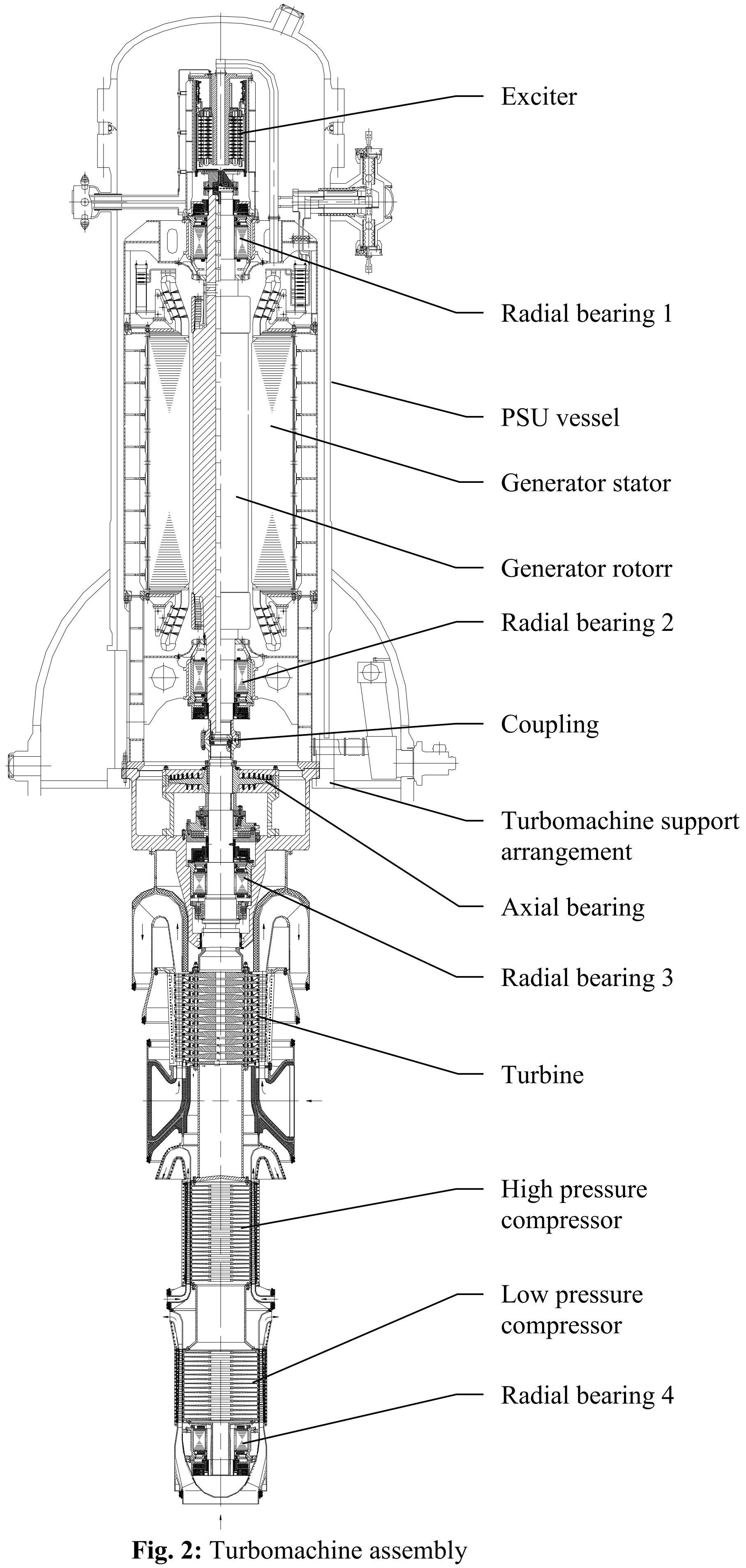

Fig. 2: Turbomachine assembly

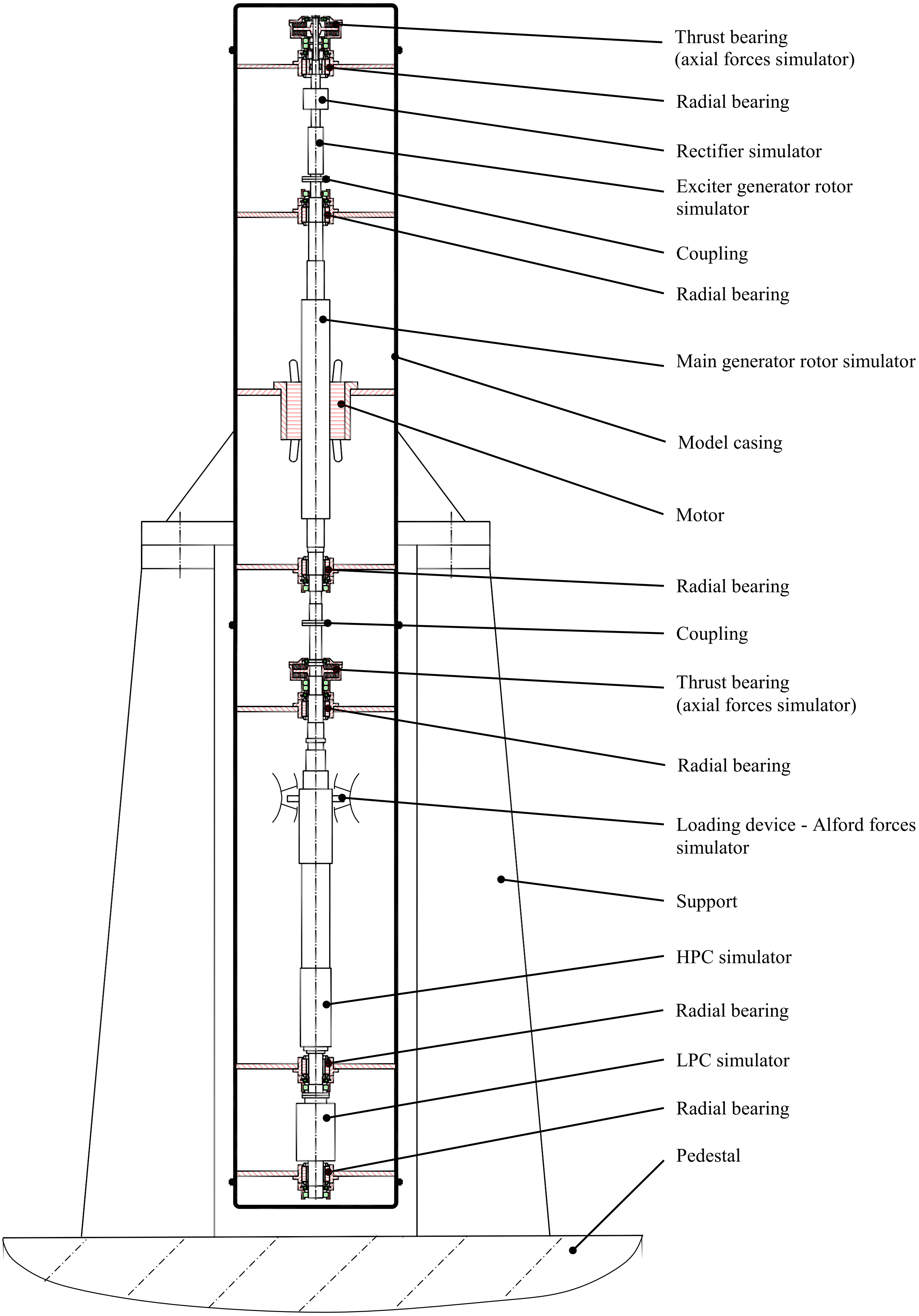

Fig. 3: Rotor scaled model structural diagram