Modeling and experimental research of machine with annular HTS winding

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***Abstract*—Finite element modeling is an important part of modern development of different devices including HTS electric machines and other superconducting devices. At the same time modern HTS 2G superconductors possess nonlinear magnetic, thermal and mechanical properties. In this case finite element modeling in these devices should be verified with experimental data. The paper is devoted to the comparison of the results of finite element modeling and experimental research of the electrical machine with annular AC HTS windings. The obtained results are discussed concerning AC losses and future applications of these HTS machines in on-land power systems and transport.**

Keywords—superconducting electrical machine, HTS, FEM modeling, modeling of HTS electrical machines.

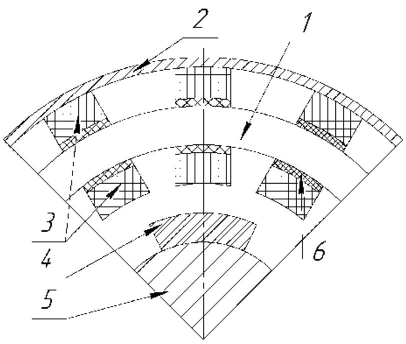
I. Introduction

Development of superconducting (SC) electrical machines is a very important scientific and engineering problem. It is known that superconductors have nonlinear magnetic, mechanical and thermal properties[1], [2]. Even if a lot of work has been done on the characterization of superconducting elements (pellets, tapes, etc.), the transition from the element to the system is not trivial, because the behavior of an isolated element can be quite different when it is integrated into a system [3]. Characterization at the system scale is thus necessary which makes the determination of properties of HTS windings during development and producing machine crucial. In this case conventional methods of calculating, modeling and design of electrical machines should be modified and take into account properties of applied SC. Due to this modeling of superconducting devices is rather complicated and needs experimental verification.

Machine with annular high temperature superconducting (HTS) stator windings was developed. During the project number of finite element (FE) models and experimental researches were produced. It gave us opportunity to verify approaches of calculating HTS electrical machines. In this paper results of static and transient modeling of phase current and voltage and their comparison with experimental research are described. Besides results of AC loss measurement is shown in this paper.

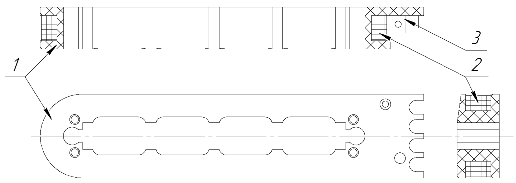
II. Machine scheme and main parameters

Considered machine is synchronous non-salient pole machine. Its scheme is shown on Fig. 1. Permanent magnets are mounted on the rotor with ferromagnetic core. The stator part is an annular magnetic core, on which HTS coils are mounted. Scheme and view of a coil are shown on Fig. 2 and Fig. 3.



1 – ferromagnetic core of stator, 2 – outer shield, 3 – AC HTS coil, 4 – permanent magnets, 5 – ferromagnetic core of rotor

Fig.1. Schematics of the machine



1 – support, 2 – HTS coil, 3 – current lead

Fig. 2. Scheme of the HTS coil

Fig. 3. Outer view of the HTS coil

III. Modeling and experimental research

Experimental research of the machine includes static and transient modes. During the first stage critical current of HTS coils, its AC losses for different regimes were determinate.

Transient simulation was produced to calculate the EMF of one phase, consisting of 8 coils. As a result (see Fig. 4), rms value of EMF and its waveform for different values of the relative magnetic permeability of the HTS coils were obtained. It could be seen that as μ decreases, the waveform of the EMF curve is distorted. Moreover, its appearance is similar to the type of EMF in the presence of a teeth structure of the stator. Thus, we can say that the appearance of "virtual" stator teeth is possible due to diamagnetic properties of HTS coils. Moreover, the magnitude of the dip in the EMF curve is greater, the smaller the value of μ. This means that the magnetic properties of HTS coils can be estimated using the shape of the EMF curve obtained experimentally. The effective value of the EMF decreases with decreasing μ: 78 V at μ=1, 72 V at μ=0.5, 67 V at μ=0.2.

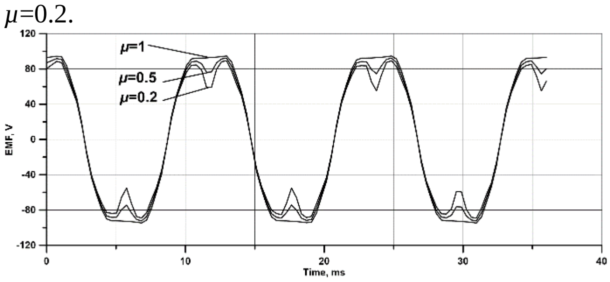
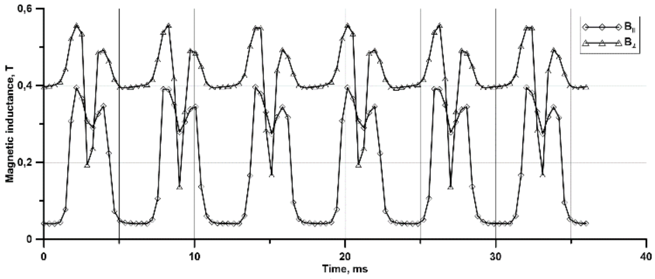
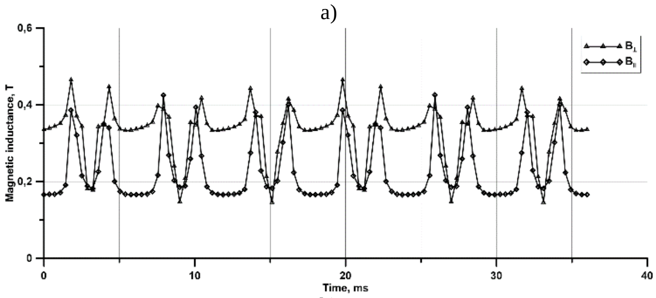


Fig. 4. EMF waveform

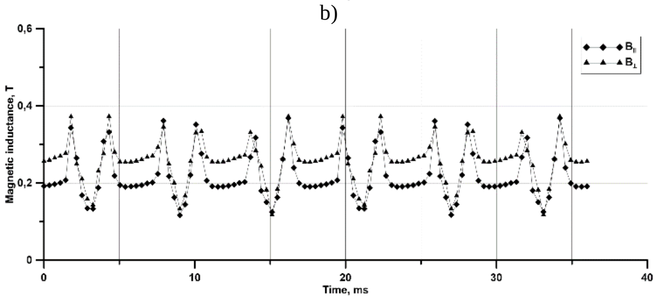
It is known that magnitude and direction of the magnetic flux density of the external field affects the magnitude of AC losses in the HTS winding. In this regard, we determined the maximum values of the parallel and perpendicular components of the magnetic induction vector in the field of coils intime change (Fig 5). It can be seen from the figures that the perpendicular component is in all cases higher than the parallel one. In addition, it is seen that with decreasing μ of the coil, the magnitude of induction decreases and the difference between the maxima of the two components decreases.



a)



b)

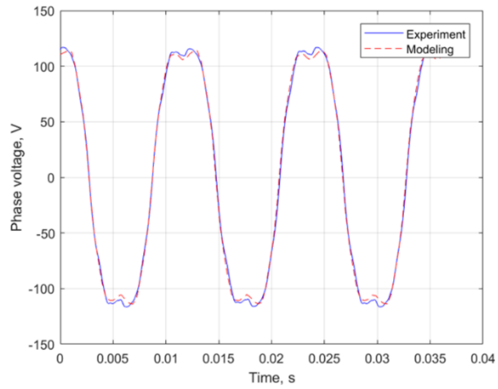


c)

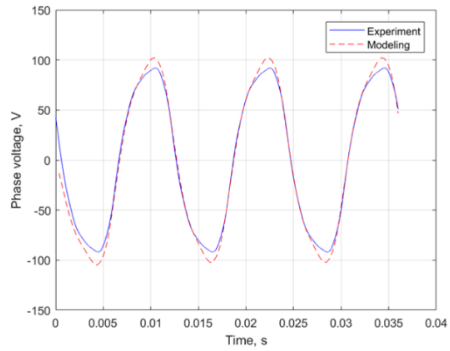
a) – μ=1, b) – μ=0.5, c) – μ=0.2

Fig. 5. Maximum values of the parallel and perpendicular components of the magnetic induction vector in the field of coils in-time change

Comparision of no-load and underload phase voltage waveforms obtained by modeling and experiment is shown on Fig. 6. The one can see that no-load voltage is non-sinusoidal. It is connected with relaitive permeability of HTS coils. Comparision of waveforms on Fig 4 and Fig. 6 allow to determine that μ of HTS coils is equal to 0.8.



a)



b)

a) – no-load, b) – underload

Fig. 6. Phase voltage waveform

Comparision of results of static (rotor with permanent magnets was installed) and transient (with rotated rotor) experiments for different frequencies shows difference between AC losses in HTS coils (see Fig 7). We can see a good coincidence of the curves at different frequencies for the generator mode, therefore, the nature of the losses is hysteresis, since it does not depend on the frequency. The level of losses with a movable rotor is much higher. The increase in losses is associated with additional hysteresis losses in the HTS layers of the winding tapes, which occur in an alternating external magnetic field.

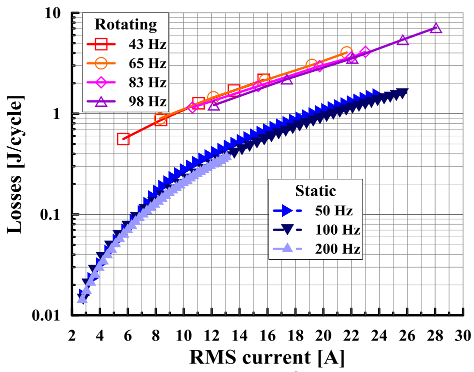


Fig. 7. AC losses dependencies for static and dinamic regimes

IV. References

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