Modelling and experimental research of machine with annular HTS winding using equivalent magnetic permeability

K Kovalev¹, N Ivanov¹, V Podguzov¹, S Zanegin¹, S Zhuravlev¹
¹Moscow Aviation Institute, Russia, 125993

E-mail: n.s.ivanov88@gmail.com

Abstract. The paper is devoted to the comparison of the results of finite element modelling and experimental research of the electrical machine with annular high temperature superconducting (HTS) windings. The method of equivalent magnetic permeability is used for determination of magnetic properties of armature HTS coils in the environment of electrical machine. The obtained results are discussed concerning influence of HTS coils properties on output machine parameters and AC losses.

1. Introduction
Development of superconducting (SC) electrical machines is a very important scientific and engineering problem. It is known that superconductors have nonlinear and non-homogeneous electromagnetic and thermal properties[1], [2]. Despite that 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 crucial during the development and manufacturing of the machine. In this case, conventional methods of calculating, modeling, and designing of electrical machines should be modified and take into account the properties of applied superconductor. These new methods need experimental verification.

A machine with HTS stator windings was developed. During the project, several finite element models (FEM) were developed and experimental researches were carried out. It gave us the opportunity to verify approaches of calculating HTS electrical machines. In this paper, results of static and transient modeling of phase current and voltage are compared with experimental data. Besides, results of AC loss measurement are shown.

2. Machine scheme and main parameters
The considered machine is synchronous non-salient pole machine. Its scheme is shown on figure 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. The drawing and a view of a coil are shown on figure 2. One can see that magnetic field produced by permanent magnets is perpendicular to HTS tapes surface.
3. Modelling and experimental research

Nowadays different approaches such as T-formulation, A-formulation and H-formulation are used for determination of HTS coils parameters [3]–[5]. Application of them requires solving of Maxwell equations in the complex area of HTS coils and taking into account non-linear electric resistance of HTS and its temperature and field dependency according to Kim’s model. It corresponds to high computing time cost. According to another approach, HTS coils and bulks could be modelled using the equivalent magnetic permeability ($\mu$) model [6]. It presents a very low computation time when compared with Kim’s model. For example, such approach is used for description of HTS bulks properties [6], [7]. In this case HTS coil could be described as macro-object without determination of internal processes. When we design an electric machine, the main aim is to provide the required characteristics, such as power, voltage, current, and so on. It means that we need to take into account the properties of HTS coils. Unfortunately, calculation of current distribution in HTS coils of armature windings needs a lot of time. Application of equivalent magnetic permeability of HTS coils could decrease calculation time. On the other hand, it will provide an opportunity to obtain the magnetic field distribution in the active part of the machine taking into account HTS coils properties.

Transient simulation was carried out to calculate the EMF of one phase, consisting of 8 coils. As a result (see figure 3), RMS value of EMF and its waveform for different values of the relative magnetic permeability of the HTS coils were obtained for 2500 rpm rotation speed. It could be seen that, as $\mu$ 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 smaller the value of $\mu$, the greater the magnitude of the dip in the EMF curve. This means that the magnetic properties of the HTS coils can be estimated using the shape of the EMF curve obtained experimentally. The effective
value (root mean square) of the EMF decreases with decreasing $\mu$: 78 V at $\mu=1$, 72 V at $\mu=0.5$, 67 V at $\mu=0.2$.

![Figure 3. EMF waveform](image)

It is known that the 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 evolution of the maximum values of the parallel and perpendicular components of the magnetic induction vector in the field of coils (figure 4).

![Figure 4. Maximum values of the parallel and perpendicular components of the magnetic induction vector in the field of coils: a) $\mu=1$, b) $\mu=0.2$](image)

It can be seen from the figure 4 that the perpendicular component is higher than the parallel one in all cases. In addition, one can see that with decreasing $\mu$ of the coil, the magnitude of the induction also decreases and the difference between the maximum of the two components decreases.

Experimental research of the machine includes static and transient modes. A comparison of no-load and underload phase voltage waveforms obtained by the modelling and the experiment is shown in figure 5 and figure 6. One can see that no-load voltage is non-sinusoidal. It is connected with relative
permeability of the HTS coils. The comparison of waveforms in figure 4 with figure 5 and figure 6 allows to determine that $\mu$ of HTS coils is equal to 0.8.

![Phase voltage with no-load waveform](image1.png) ![Phase voltage with underload waveform](image2.png)

**Figure 5.** Phase voltage with no-load waveform. **Figure 6.** Phase voltage with underload waveform.

As mentioned above, the application of equivalent magnetic permeability of the HTS coils does not allow to calculate the current distribution in them, therefore it is impossible to calculate losses in AC HTS coils. Therefore, the corresponding experimental research was provided. The comparison of results of static (the rotor with permanent magnets was installed) and transient (with the rotating rotor) experiments for different frequencies shows the difference between AC losses in HTS coils (see figure 7) [8]. 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 the additional hysteresis losses in the HTS layers of the winding tapes, which occurs in an alternating external magnetic field.

![AC losses dependencies for static and dinamic regimes](image3.png)

**Figure 7.** AC losses dependencies for static and dynamic regimes

4. **Conclusion**

In this paper, we have demonstrated experimental results of determination of equivalent magnetic permeability of HTS coils. According to experimental results its value is 0.8. It gave us the opportunity to determine output characteristics of the machine taking into account properties of HTS coils without calculation of current distribution in them and thus minimize time costs. Finally, AC losses were experimentally determined and compared for static and dynamic regimes.
5. Acknowledgment
This work was supported by Russian Science Foundation (project No. 17-19-01269)

References
[1] Grilli F 2016 IEEE Trans. Appl. Supercond. 26 3 0500408
[2] Kovalev K, Penkin V, Ivanov N, Kosheleva N and Serovaev G 2019 IOP Conf. Ser. Mater. Sci. Eng. 581
[3] Statra Y, Menana H, Belguerras L and Douine B 2019 COMPEL - Int. J. Comput. Math. Electr. Electron. Eng. 38 4
[4] Song W, Fang J, and Jiang Z 2019 IEEE Trans. Appl. Supercond. 29 2 5900405
[5] Benkel T, Lao M, Liu Y, Pardo E et al 2020 IEEE Trans. Appl. Supercond. 30 6 5205807
[6] Fernandes J 2020 Supercond. Sci. Technol. 33 085001
[7] Arish N, Marignetti F and Yazdani-Asrami M 2021 Physica C Supercond. 584 1353854
[8] Zanegin S, Ivanov N, Zubko V, Kovalev K, Shishov I, Shishov D and Podguzov V 2021 Appl. Sci. 11 6 2741