Numerical evaluation of a novel high-temperature superconductor-based quasi-diamagnetic motor

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Abstract. An investigation is being pursued at the Budapest University of Technology and Economics, Department of Electric Power Engineering for the application of high-temperature superconductors (HTS) in electrical power systems. In this paper we are going to propose a novel electrical machine construction based on the quasi-diamagnetic behaviour of the HTS materials. The basic operation principle of this machine will be introduced with detailed numerical simulations. Also a possible geometric outline will be presented.

1. Introduction
Most of the electrical machines are using the magnetic field to convert the electrical energy into mechanic energy. This conversion basically relies on the attraction of the opposite magnetic poles. The discovery of high-temperature Type II superconductor opened the possibility of using the superconducting materials in electrical power systems. These materials maintain their superconducting state in case of high current densities and high external fields. Also, if we consider the first magnetization curve of these materials with lower external fields, such as 1...2 T, we can see that the penetration of the field is very low. (Fig. 1.) This magnitude of field is already high enough for technical applications. At this interval we are going to consider the material as an almost ideal diamagnetic (quasi-diamagnetic) material. Based on this behavior it is possible to design a novel type electrical machine where we can utilize this quasi-diamagnetic effect. The operation principle of this new machine is different from any currently used or proposed machine.

2. Application of superconductors in electrical machines
The most common application of HTS material in electrical machines is the use of HTS wires for winding. This solution also gives the possibility to create homopolar machine [1][2]. These solutions use the HTS in the stator. There are also several applications where they used it in the rotor. With the application in the rotor it is possible to create hysteresis motor or it can be used to replace permanent magnet in synchronous machines (with Field Cooling). [3] Special application of HTS is to concentrate the magnetic flux in the rotor of synchronous reluctance machines or switched reluctance machines. [1][3]

The only application of pure HTS rotor is the Meissner-motor. This motor utilizes the Meissner-effect and the transition between superconducting and normal state. This solution is basically a thermodynamic motor. [4] The stator consists of a single permanent magnet. The torque and the possible application of this motor are very limited. The construction is known for more 20 years and no practical application came forward so far.
3. Operation principle of the HTS quasi-diamagnetic motor (QDM)

For the proposed quasi-diamagnetic motor we are going to use the following properties of the high-temperature superconducting materials. The typical level of magnetic induction (the magnitude of 1T) used in an electrical machine is below the total penetration field of an advanced HTS Type II material. Based on this we expect a quasi-diamagnetic behavior of these material as long as we remain below this total penetration field level. Our proposal is to utilize this quasi-diamagnetic effect to create a repulsive force between the stator and the rotor. This effect was already used in the Meissner-motor. In our case it is not necessary to change between the superconducting and non-superconducting state in order to create rotation. Instead of that one should use a suitable geometric configuration and switching of the poles’ current to create rotation without state-change.

The idea of the geometric setup comes from the switched reluctance machines (SRM). The machines have salient poles on the stator as well as on the rotor, (Fig. 2.) The rotor consists of ferromagnetic material only. To create the rotation the poles are energized one after another with pulses. One pair of the salient poles of the rotor align with the nearest energized poles. As the next pole is being energized the rotor again aligns and the rotation is created. This is basically an attractive force. The SRM has many configuration usually indicated by the following convention: number of poles on the stator slash number of poles on the rotor. We are going to use this convention for our setups as well.

The idea is to change the rotor material of an SRM with a diamagnetic material. In this way the attractive force acting on the rotor becomes a repulsive force, which is quite unique among the electrical motors. The only occurrence is the Meissner-motor mentioned earlier. The operation Meissner-motor requires state-change in the superconducting material. For this reason it is not so interesting for practical application. In the following sections we are going to show that it is possible to create a motor without state-change and the expected torque of this machine is at the same magnitude as a similar SRM.

For the analysis of the proposed machine we used a software called Finite Element Method Magnetics. The simulation was performed in 2D. The parameters of the machine are: the length of active part 150 mm, outer diameter of the stator is 300 mm, outer diameter of the rotor is 200 mm, airgap between the stator and rotor is minimum 1 mm. The excitation current for poles is 20 A/mm$^2$ which is higher than normally, but it makes easier to see the effect. For modeling the superconducting material, relative permeability value of $10^{-6}$ was set.

For the checking of the principle we choose a 6/2 configuration as shown in Fig. 3. This is a very simple setup just to demonstrate the base effect. One can see that the electro-magnetic force is created as the field “pushes” away the quasi-diamagnetic material. During the simulations a torque-angular position was calculated in order to check the behavior and to prove the appropriate level of torque for technical application. For reference an SRM motor with the same parameters was calculated. The peak torque of QDM is around 4 Nm compared to the SRM which has around 60 Nm. The difference is around one order of magnitude, which indicates that with further improvements the QDM can be a valid alternative to other motors.
4. Geometric optimization

During our examination we found two ways to improve the torque of this QDM. First solution is to make the rotor wider than the original construction, and the second is to energize two pole pairs at the same time. Figure 4. shows the solutions applied together.

The peak torque of the reference SRM doesn’t change significantly (from 59.15 Nm to 63.47 Nm). Meanwhile the peak torque of the QDM increased five times (from 4.16 to 20.93 Nm). This means that with appropriate changes in the geometric outline and in the control strategy it is possible to optimize the QDM.

5. Geometric outline

We already showed that it is possible to create electromagnetic torque based on the quasi-diamagnetic behavior of the Type II superconductors. In this section we are going to propose a possible geometric outline of the machine. Based on torque curve of the 6/2 QDM one see that the peak torque is created when rotor pole is slightly misaligned with stator pole. One effective way to decrease the torque ripple is to increase the number of poles. This will result in more peaks in the torque during one full turn.

When we make the concept of rotor we have to take into account the followings:
- increasing the number of the poles it is not necessary for them to be wide,
- the length of the salient poles on rotor affects the torque of the machine,
- the distance between two poles should be wide enough in order to allow the magnetic flux to act on the side of the pole.

Based on these requirements one possible geometric outline is shown in Figure 5. This rotor is like a wheel of a water mill (part (a) in Fig. 5.). One can imagine that the flow of the magnetic flux is pushing this wheel. Figure 6. shows the torque characteristics of this machine. The figure shows the electromagnetic torque dependence on the angular position when different poles are energized. One can notice that only energizing one pair of stator poles we can produce almost the same torque as the best result with the 6/2 setup. With this solution the control strategy will be simpler as well.

6. Design considerations

One can notice that for the ease of the simulation we used pure HTS material for the rotor. When we are going to realize this machine it is not necessary to do it this way. It is enough to have thin superconducting layer over inner core of the rotor. The thickness of the layer is depending on the critical current/field of the HTS material.

One can also notice that the current density at the stator coil is higher than the normally allowed current density of copper conductors. Partly this is not a problem since the stator pole is only operating with short pulses. Other solution to this issue can be the application of HTS wires at the stator coils. Since it is necessary to cool the rotor we will have cryogenic system anyway.
Also the question of cooling can arise. For cooling the rotor we can think about two possible solutions. One is the encapsulation of the rotor and the other is to flood the airgap with liquid nitrogen. The second solution certainly has the advantage of smaller airgap which increases the peak torque of the machine. With this solution it is also quite evident to use HTS coil windings at the stator. This gives the possibility to increase current of the stator coils. As a first approximation we can say that the torque has quadratic dependence on the current. Even if we increase the current of one order of magnitude the steel components will not saturate. This can compensate the difference between this concept and the currently used machines.

7. Summary
In this paper we presented a novel electrical machine concept based on the quasi-diamagnetic behavior of the Type II high-temperature superconductors. Our suggestion is to name it as “quasi-diamagnetic machine”, and QDM in a short form. We showed the results of detailed finite-element method simulations of different configurations of this machine. The results indicate that this machine can be a real alternative to the currently used electrical machines.

We also presented a possible geometric outline of the new machine which can enhance the dynamic behavior of the machine. It also gives relatively high torque and simpler control strategy.

Finally we presented design considerations which should be taken into account during further design of this new QDM.

We would like to emphasize that this paper is the first publishing of this idea. Everything in it should be considered as a preliminary conceptual design.

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