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Conceptual design of a SC HTS linear motor

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Abstract
OSWALD Elektromotoren GmbH, Miltenberg, Germany, is experienced in direct linear motors with high power density. For some special applications the requirements are extremely demanding and almost beyond reach, even for state-of-the-art linear motors operated at room temperature. In order to obtain even higher power density, and hence also increased acceleration, we have to develop a new technology for linear motors. In this paper we propose a round superconducting linear motor. The stator windings will be made of YBCO coated conductors in the shape of double pancake coils. The frequency will be limited to approximately 10 Hz for this application. The actuator will be provided with NdFeB permanent magnets. The special cryogenic design will be discussed. The cooling of the stator will be provided by lN2 at 77 K or lower. The calculated force of this SC linear motor is 10 000 N. The force density will be 2–3 times more than the normal conducting counterpart of the same dimensions.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since about 1970 superconducting motors and generators have been developed, beginning with NbTi wire field windings in the rotor. In recent years several groups have worked on HTS machines, usually developing rotating machines. In most cases these are synchronous machines [1–7], but axial flux, disk type, synchronous [8–10], hysteresis and reluctance type [11–13] motors have also been developed, and with induction motor performance [14]. To our knowledge the concept of a round shaped HTS superconducting motor has not yet been presented so far.

Based on state-of-the-art electric linear motors we provide the design of a superconducting linear motor using HTS tapes. The concept of a cylindrical linear motor is shown in figure 1. This type of motor in a normal resistive version is produced in increasing numbers. These types are described in the literature as polysolenoid motors and they consist of a stack of coils and laminations in the stator to produce a linear moving field comparable to the rotational field in standard rotating motors. The actuator could be asynchronous if equipped with a combination of copper rings and iron laminations, or synchronous if using a corresponding number of permanent magnets or poles in the axial direction. Linear motors of this type are typically short moving amplitude motors for very high acceleration and accurate positioning purposes as required, e.g., in machine tools, textile machines, plastic machinery, etc. A few examples of normal conductive polysolenoid motors are shown in figure 2.

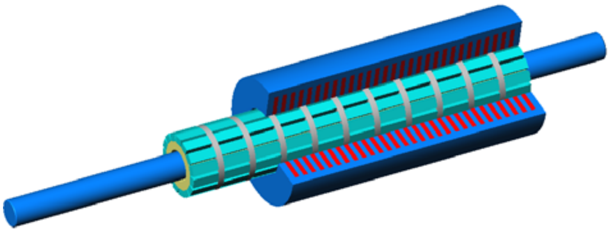
Figure 1. Polysolenoid linear motor, schematic design.

2. Linear motors using superconducting tapes

In order to increase the efficiency, the acceleration and the speed of these motors it would be of great interest to

Figure 2. Normal conductive linear motors for 2000 and 5000 N linear force.

provide superconducting types which could promise improved characteristics (small in volume, low in weight) in this respect [12, 15, 16]. In the case of short motion amplitudes the frequency required for the stator windings is relatively low (below 10 Hz) compared to rotating motors (50 Hz and more), which in fact depends on the pole width of the stator poles and the maximum speed expected. The stator windings consist of double pancake coils which could also be manufactured by using superconducting tapes presently available either as BSCCO tapes or YBCO coated conductors.

Both low frequency and coil geometry could be considered as advantageous for applications of superconducting AC motors. The use of iron lamination is not restricted by excessive iron losses. Since the dominant losses in a synchronous linear motor with rare earth magnets are the ohmic losses in the copper windings of the stator, the use of superconductors promises a significant improvement of the motor characteristics and simultaneously the reduction of the motor size. Small motor size also leads to a high increase of the motor dynamics, which in fact is very important for short movement amplitudes.

To use HTS tapes for AC application is still a demanding task. However, the special coil configuration may be advantageous in this case, as the manufacture of double pancake coils certainly is more appropriate for this material than any other coil configuration. The use of laminated iron will not result in high losses due to the low frequency applied. Furthermore we intend to replace ordinary SiFe by different soft magnetic material in order to reduce the hysteresis losses as well.

3. Design and construction of double pancake coils

The design of a double pancake coil using superconducting tapes is shown in figure 3. Two pancakes are wound in opposite directions, and therefore the conducting ends of the windings are both on the outer circumference. There is no horizontal bending of the tape. Only at the innermost winding do we have to switch over from one plain to the other. This can be done by bending the tape or just by a very low resistive inner copper ring, which in the case of AC application must be slit to avoid high induced eddy currents, and to which the superconductor ends can be soldered.

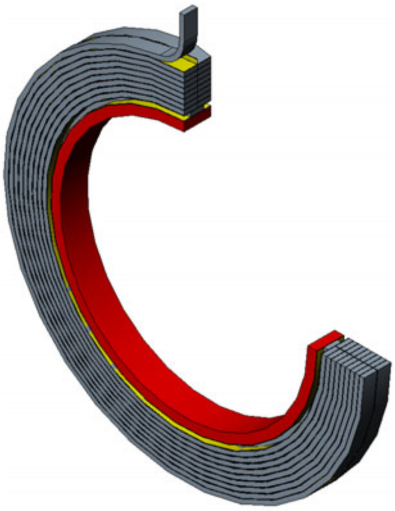

Figure 3. Superconducting double pancake coil.

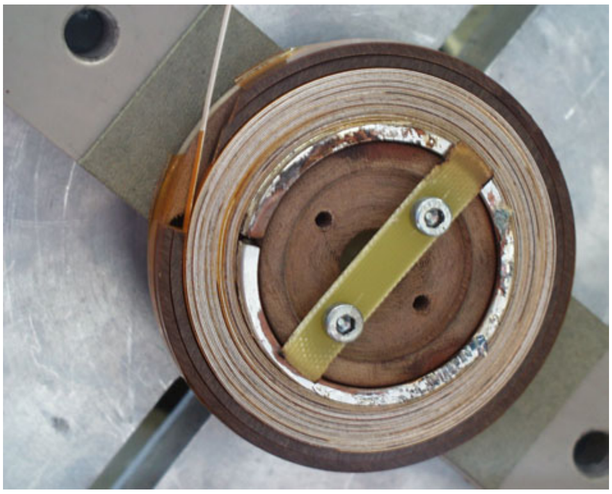

Figure 4. Winding of a double pancake coil using superconducting tapes.

In the case of normal conductive linear motors such coils are produced automatically, whereas superconducting coils have to be wound very carefully by hand in order to keep the bending radius and the strain of the tape within acceptable limits, and to introduce additional insulation consisting of a thin Kapton layer as turn by turn insulation and using thicker mid-plane insulation. The production of superconducting double pancake coils is shown in figure 4. After winding the coils are impregnated under vacuum.

4. Expected characteristics of superconducting coils

Several superconducting coils incorporated in polysolenoid motors will be connected to build a three phase winding which has to produce an axially moving field. To exceed normal conductive coils the superconductors have to carry a sufficiently high overall current density in the range of 30–100 A mm^{-2} and, simultaneously, they have to withstand parallel and perpendicular magnetic fields. The expected high current density offers the possibility of small outside dimensions of the motors. At the same time the magnetic air gap field should exceed 1 T; both a high number of ampere turns and a high field will result in an extremely high force density compared to conventional motor types. In order to keep the transversal fields below a certain limit it is in fact necessary to use iron in parallel to the coils. Nevertheless we have to accept perpendicular fields in the range of 0.1 T or more. The frequency of the fundamental wave is expected to be under 20 Hz. We expect force densities related to the actuator surface exceeding 14 N cm^{-2}.

5. Coil arrangement for testing

It important to test the behaviour of different HTS tapes under nearly the same conditions as expected in polysolenoid motors. Therefore we designed and constructed a stack of coils in combination with iron laminations for testing at various frequencies and temperatures. The expected test results will give information about the performance of HTS tapes of different origin (different wire manufacturers) and of different types (BSCCO or YBCO coated conductors, twisted and non-twisted) for this application. Based on these values a more precise estimate of motor parameters can be made. In this respect the critical current density at magnetic field and the losses are important.

6. Design of the actuator

For the actuator we have different options. First, we could provide a permanent magnet version, where the actuator consists of a number of poles (in the axial direction) out of rare earth magnets which are commercially available in all desirable geometries. Such magnets could be operated at low temperature and also at room temperature without any noticeable difference in behaviour. Second, similar to rotating reluctance motors, we could also provide a reluctance actuator version using bulk superconductors out of a combination of iron laminations and YBCO. In superconducting reluctance motors high T_c superconductors provide enhanced flux concentration in the force producing direction. Third, providing bulk superconductors in the actuator means we also could use them as trapped field magnets in order to get higher fields compared to rare earth magnets. All versions described here are synchronous motor types (with zero losses in the actuator with respect to the basic wave).

Comparing these different versions, we favour the actuator equipped with NdFeB as this seems to be the most economic solution.

7. Cryogenic cooling

There are different possible solutions for an efficient cooling circuit for the motor. First, the total motor including stator and actuator are working in a cryogenic coolant like liquid nitrogen or other media. This solution is advantageous for short motion amplitude. Then bellows could be used in order to separate the bearings from the low temperature region. In the case of long motion amplitude however, the bearings are immersed into the cooling liquid, and the force must be transferred through the cryostat. Second, only the superconducting stator is cooled. In this case we need a cryostat for the stator only and a temperature insulation inside the air gap with some reduction of force as a consequence of this. One significant advantage in this case would be that within the actuator there would be no axial temperature gradient from the outside to the inside of the motor. Furthermore the possibility of obtaining reduced temperature (below 77 K) within the stator would be rising. Third, since the losses are very low, the motor also could be cooled by a cryocooler that allows working temperatures below 77 K. In this case we shall expect improved values for superconducting currents. In the case of the entire motor being cooled to low temperatures, the axial force must be transferred to the outside room temperature. In order to limit the heat transfer along the shaft it will be provided with a low heat conductive material like stainless steel, titanium or composite materials like coal fibre.

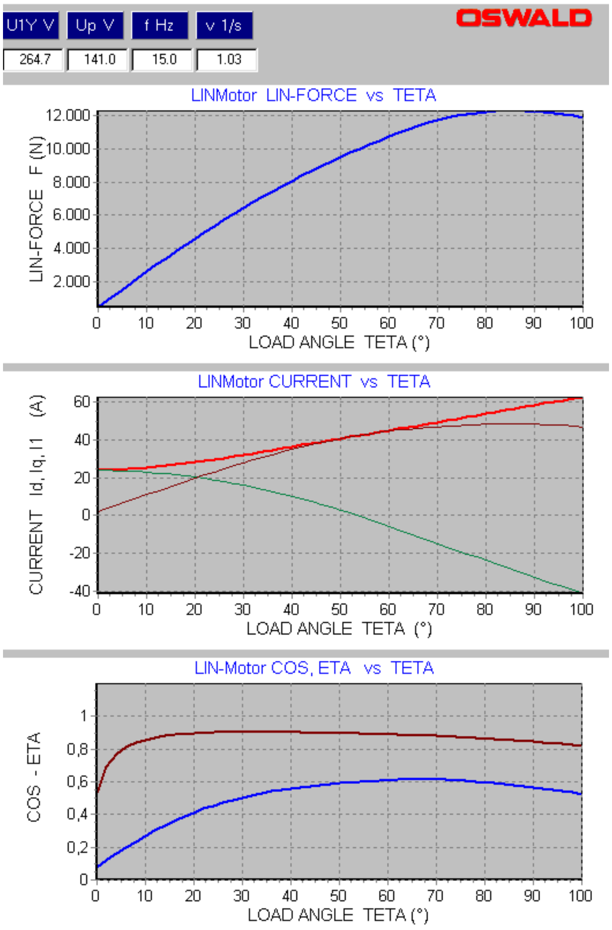

Figure 5. Results of the calculation program for a superconducting linear motor with 10 000 N force.

Which technical solution we shall develop first is not yet decided. The decisions depend upon the kind of application we shall be aiming at as a first example.

8. Calculation program

In order to get an optimal motor design we developed an analytic computer program which gives us a sufficient approach for the expected load characteristics. The procedures

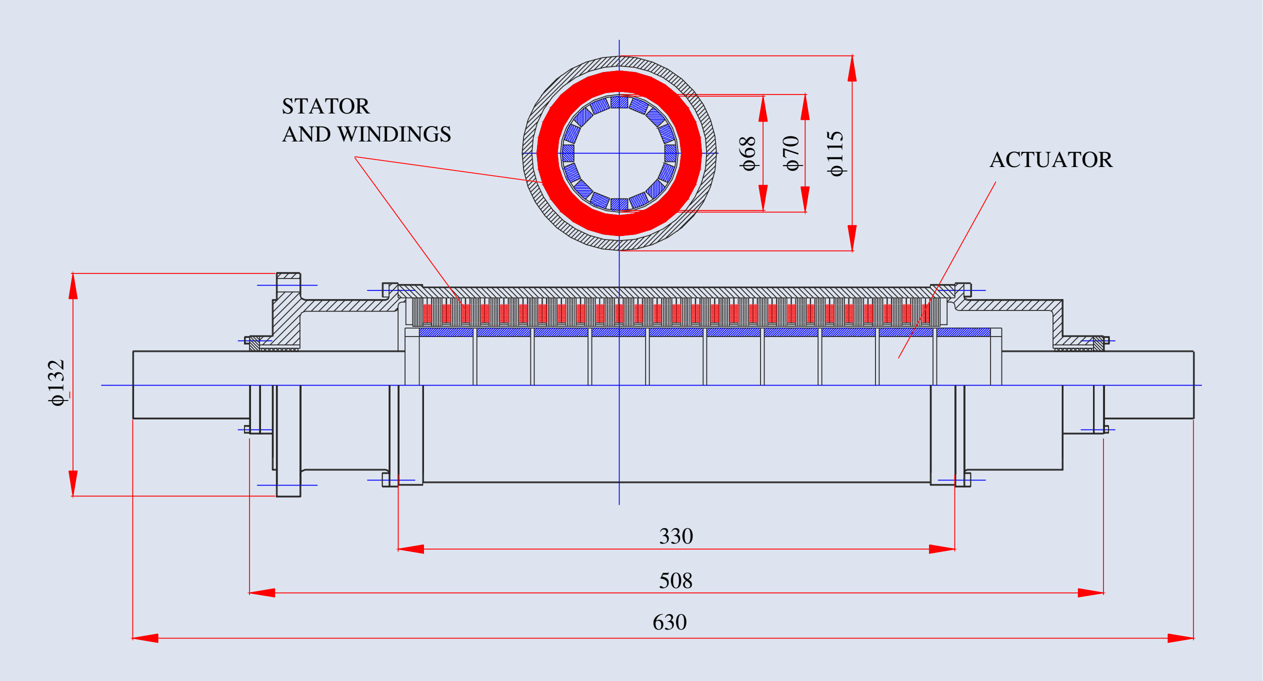

Figure 6. Design of a superconducting linear motor for 10 000 N.

of the Delphi simulation program include the magnetization curves of the iron provided for the stator yoke, the laminations (teeth) and the actuator yoke. The NdFeB permanent magnets are characterized by the corresponding magnetic energy (remanence and coercive force). Different dimensions of the magnets can be introduced. The primary winding (stator winding) is expected to have an engineering current density between 20 and 40 A mm^{-2}, therefore much higher values compared to copper windings at room temperature. The AC losses are taken into account by an estimated ohmic resistance of the tape. Actually we expect mainly hysteresis losses, and only a small amount of eddy current losses, related to the relatively low frequencies applied.

The advantage of this program compared to FEM calculation is the easy and fast change of all input parameters and hence an easy way to optimize the motor design. The accuracy of the analytic results was repeatedly checked by FEM calculations. some results of the calculation program for a superconducting linear motor for 10 000 N linear force are shown in figure 5.

The first diagram (upper curve) shows the linear force F versus the load angle TETA which corresponds to the load angle of rotating synchronous motors. The second diagram (centre) shows the current in the stator windings consisting of two components (lower curves) id and iq, where iq is the force producing current. The nominal current (usually determined by $id = 0$ in order to minimize I1) in this case is 45 A and the optimal load angle 55°. The third diagram (lower curve) (efficiency ETA and power factor COS versus load angle) shows the corresponding curves for efficiency (assuming AC hysteresis losses in the superconducting windings) and power factor.

9. Design of a superconducting linear motor

We propose the design of the synchronous HTS linear motor shown in figure 6 with the following features:

- stator windings made of HTS tape alternating BSCCO at 65 K and YBCO coated conductors at 77 K;
- double pancake winding technique;
- one order increase of engineering current density compared to Cu at RT;
- rotor equipped with NdFeB magnets;
- reduction of motor volume by a factor of 2, cryostat included;
- considerable enhancement of the motor dynamics expected.

The active length of the motor consisting of a stack of double pancake coils (cross section shown on top) and iron laminations is 330 mm. On the actuator, ten permanent magnets (NdFeB) are assembled. The total motion amplitude of the motor (in the axial direction) is 70 mm. The speed and acceleration depend on the mass of the actuator in addition to the external load. The calculated nominal force of the motor is 10 000 N.

10. Conclusions

The presented calculation and design of a superconducting linear motor of the polysolenoid type and for small movement amplitudes for a linear force of 10 000 N can be considered as a first step to introduce superconducting tapes in AC application. The theoretical results let us expect a significant improvement of the load characteristic of such a superconducting motor compared to conventional linear motors [17, 18]. Both the size and dynamics of a superconducting version are of remarkable interest for future industrial applications.

References

[1] Sato K, Hayashi K, Ohmatsu K, Fujikami J, Saga N and Isojima S 1997 *IEEE Trans. Appl. Supercond.* **7** 345–50

[2] Nick W, Nerowski G, Neumüller H-W, Frank M, van Hasselt P, Frauenhofer J and Steinmeyer F 2002 380 kW synchronous machine with HTS rotor windings—development at SIEMENS and first test results *Physica* C **372–376** 1506–12

[3] Muta I, Jung H, Nakamura T and Hoshino T 2002 Performance of axial-type motor with Bi-2223 HTS bulk rotor *Physica* C **372–376** 1531–4

[4] Jo Y-S, Kwon Y-K, Sohn M-H, Ryu K-S, Hong J-P and Lee J 2002 Temperature characteristic of rotor of HTS synchronous rotating machine cooled by solid nitrogen *Physica* C **372–376** 1535–8

[5] Al-Mosawi M K, Beduz C, Goddard K, Sykulski J K, Yang Y, Xu B, Ship K S, Stoll R and Stephen N G 2002 Design of a 100 kVA high temperature superconducting demonstration synchronous generator *Physica* C **372–376** 1539–42

[6] Maki N, Oso H, Asada M and Takahashi R 2003 *EUCAS 2003: Study on a Design Method and Results of Small-Scale to Large-Scale Superconducting Generators (Sorrento, Sept. 2003)*

[7] Caserza Magro M, Sfetsos A and Ventim Neves M 2003 *EUCAS 2003: Multipole Superconducting Synchronous Generator (Sorrento, Sept. 2003)*

[8] Marquez I *et al* 1999 *IEEE Trans. Appl. Supercond.* **9** 1249–52

[9] Alvarez A, Suarez P, Caceres D, Granados X, Obradors X, Bosch R, Cordero E, Perez B, Caballero A and Blanco J A 2002 Superconducting armature for induction motor of axial flux based on YBCO bulks *Physica* C **372–376** 1517–9

[10] Granados X, Pallares J, Sena S, Blanco J A, Lopez J, Bosch R and Obradors X 2002 Ironless armature for high speed HTS disk shaped rotor in self levitating configuration *Physica* C **372–376** 1520–3

[11] Kovalev L K, Ilushin K V, Koneev S M A, Kovalev K L, Penkin V T, Poltavets V N, Oswald B, Gawalek W, Habisreuther T and Best K-J 1999 Hysteresis and reluctance electric machines with the bulk HTS rotor elements *IEEE Trans. Appl. Supercond.* **9** 1261

[12] Oswald B, Krone M, Straßer T, Best K-J, Soell M, Gawalek W, Gutt H-J, Kovalev L, Fisher L, Fuchs G, Krabbes G and Freyhardt H C 2002 Design of HTS reluctance motors up to several hundred kW *Physica* C **372–376** 1513–6

[13] Kovalev L K, Ilushin K V, Penkin V T, Kovalev K L, Koneev S M-A, Modestov K A, Larionoff S A, Gawalek W and Oswald B 2001 HTS electrical machines with YBCO bulk and Ag-BSCCO plate-shape HTS elements: recent results and future development *Physica* C **354** 34–9

[14] Kovalev L K, Ilushin K V, Penkin V T, Kovalev K L, Koneev S-A, Modestov K A, Larionoff S A, Akimov I I and Dew-Hughes D 2002 HTS electrical machines with BSCCO/Ag composite plate-shaped rotor elements *Physica* C **372–376** 1524–7

[15] Oswald B, Krone M, Soell M, Strasser T, Oswald J, Best K-J, Gawalek W and Kovalev L 1998 *ASC 1998: Superconducting Reluctance Motors with YBCO Bulk Material*

[16] Oswald B, Krone M, Soell M, Strasser T, Oswald J and Best K-J 1999 *IEC/ICMC 1999: Optimization of Superconducting Motors with YBCO Bulk Material*

[17] Linear motor *Patent Right* DE 42 17 357 A1

[18] Synchronous motor *Patent Right* DE 195 42 551 A1