A test rig for thrust force measurements of an all HTS linear synchronous motor

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Abstract. This paper presents the design of a test rig for an all HTS linear synchronous motor. Although this motor showed to have several unattractive characteristics, its design raised a number of problems which must be considered in future HTS machines design. HTS electromagnetic properties led to the development of new paradigms in electrical machines and power systems, as e.g. in some cases iron removal and consequent assembly of lighter devices. This is due to superconductor’s ability to carry high currents with minimum losses and consequent generation in the surrounding air of flux densities much higher than the allowed by ferromagnetic saturation. However, severe restrictions in HTS power devices design that goes further beyond cryogenic considerations must be accounted in. This is usually the case when BSCCO tapes are used as conductors. Its bending limitations and the presence of flux components perpendicular to tape surface, due to the absence of iron, have to be considered for it may turn some possible applications not so attractive or even practically unfeasible. An all HTS linear synchronous motor built by BSCCO tapes as armature conductors and two trapped-flux YBCO bulks in the mover was constructed and thrust force measurements are starting to be performed. Although the device presents severe restrictions due to the exposed and other reasons, it allowed systematising its design. A pulsed-field magnetiser to generate opposite fluxes for both YBCO bulks is also detailed. Thrust force numerical predictions were already derived and presented.

1. Introduction

There is a considerable interest in the application of high temperature superconducting materials (HTS) in power systems, due to its particular magnetic and pinning properties, the ability to carry high currents (tens of kA · cm⁻²) with minimal losses when compared with conventional conductors, and e.g. the resultant generation in the surrounding air of flux densities much higher than the achieved with the best permanent magnets.

In electrical motors one of HTS foreseen advantages is that the consequent increase in power density [1] allows iron removal with resulting decrease in weight and volume. Particularly in linear motors the use of diamagnetism and pinning properties of the materials is expected to allow a stable levitation, minimising mechanical losses. In rotating motors, this may be achieved with contactless
bearings built by HTS and permanent magnets. However, some other properties (e.g., HTS brittleness, critical current degradation with applied fields, cooling requirements) often turns applications unattractive [2] or sometimes even unfeasible.

The all superconducting linear synchronous motor already proposed [2] is built by Bi-2223 (BS SCO from now on) tapes as armature coils, so high current densities are potentially allowed, and two pre-magnetised Y-123 (YBCO from now on) in the mover, so high fields are achieved. These materials are commercially available which was one of this work goals.

In the next section, the motor concept and characteristics are detailed. The numerical determination of the forces developed in the mover is briefly exposed in Section 3, after what the pre-magnetisation system of the mover’s YBCO bulks is exposed. Simulation results are presented in Section 5. Finally conclusions are drawn and future work is suggested in order to improve this motor’s performance.

2. The all HTS linear synchronous motor concept

Ferromagnetic materials are used in electrical machines as magnetic flux conductive means, allowing magnetic linkage between circuits (e.g. transformers) or flux interaction with currents or other fields, thus generating forces and torques (e.g. synchronous motors). Except for airgaps, almost all magnetic flux is confined to ferromagnetic materials, thus minimising leakage. This is due to ferromagnetic materials permeability, usually about three orders higher than air’s. However, these materials impose restrictions in the design of electrical machines: one related with magnetic induction saturation, (typically in the range 1.2 ~ 1.8 T) that impose non-linearities thus turning more complex the machines design; another imposed by the physical characteristics of these materials, namely its high density which, associated with the fact that the output power of an electrical machine is directly related with its active volume [3], makes weight and volume a prevailing factor when designing high specific power machines. In addition, hysteresis and eddy current losses are also generated in iron.

The above reasons are a strong motivation for the design of ironless electrical machines, namely through HTS materials. Another point exploited in this work was the replacement of conventional conductors by BSCO, thus making the device an all HTS machine.

2.1. Armature

The BSCO armature is probably the most sensitive point in the design of the machine due to its brittleness which imposes physical restrictions like minimum bending radius, \( r_b \).

The armature is built by single layer BSCO stacked tape coils, as in [2]. BSCO characteristics are referred in table 1. Phases are denominated \( A \), \( B \) and \( C \) for which phase currents are \( i_a \), \( i_b \) and \( i_c \). The time slot to measure, as referred in the next section, corresponds to \( i_a = +I_s \), \( i_b = 0 \) and \( i_c = -I_s \), for which no coils are needed for phase \( B \). The test armature is shown in figure 1. Since an ideal current inverter is simulated, as explained in next section, with correct electrical connections only one current source is needed to feed phases \( A \) and \( C \). The armature characteristics are presented in table 2.

| Type           | Insulated wire |
|----------------|----------------|
| Critical current, \( I_C \) | 90 A          |
| Average width  | 4.2 mm         |
| Average thickness | 0.23 mm      |
| Minimum bending radius | 30 mm (5% \( I_C \) degradation) |
| Used bending radius, \( r_b \) | 40 mm         |

\(^a\) Acquired to Innova Superconductor Technology Co., Ltd.
Figure 1. Photo of armature with BSCCO windings, wounded in nylon moulds. Black epoxy resin was used to fix tapes to moulds.

Figure 2. Diagram of armature electrical connections. Current in phase $B$ is null. $\tau$ is the pole pitch.

Table 2. Armature characteristics

| Variable | Description                                | Value |
|----------|--------------------------------------------|-------|
| $N$      | Coil’s number of turns                      | 20    |
| $I_s$    | Current amplitude                          | 25 A  |
| $\sigma$ | Medium slot length (with epoxy)            | 10 mm |
| $l_w = 2 \times (\tau + \sigma)$ | Winding length | 100 mm |
| $\tau = 3 \times l_w$ | Magnetic pole pitch                       | 300 mm |
| $w_s$    | Width of armature active part              | 60 mm |

In a classical linear motor there is a magnetic induction travelling wave in the airgap, whose flux lines, when iron is present, are generally perpendicular to armature plane. However, without iron, there is a so-called leakage flux travelling wave, whose flux lines are shown in figure 3, for three-phase sinusoidal currents with the same amplitude. Leakage flux lines generate undesired force components, as latter explained. Airgap loses its meaning as this is the designation used for the air region between iron parts or circuits. Instead, air coupling region should be used.

Figures 4 and 5 shows the tangential and normal components of flux density due to the travelling wave. Ideally, the tangential component should be null, and the normal component should be sinusoidal. This is far from what is accomplished with this motor. The flux density vectors are shown in figure 5. In an iron motor these vectors would be in general perpendicular to armature’s plane.

2.2. Mover

The test mover for this motor is simply built by two YBCO bulks glued to a tufnol piece with epoxy, see figure 7. According to the methodology proposed in [2] the trapped-field components for one piece averaged over one slot height are shown in figures 8 and 9 (components for the other piece are symmetrical as they are polarized in opposite directions). These were calculated according to sand-pile [4] and Bean [5] models..
As is clear from figure 8 the components perpendicular to tape surface could not be neglected, as they affect dramatically BSCCO critical current. For this reason, the current supplied to the coils is far below that value, namely 25 A as referred in table 2.

3. Numerical determination of thrust and lift forces
The methodology to derive thrust and lift forces is described elsewhere [2]. The obtained static forces’ profiles were obtained considering the armature fed by an ideal current inverter (see figure 10 for phases currents). The pre-magnetised mover is then displaced along the armature and Laplace’s law used to calculate forces, considering time slot in the range $\omega t \in [0, \pi/3]$ rad. Forces for other time slots
are just shifts of these ones. According to this methodology, and using the measured values for $J_c$ and current amplitude of $I_a = 25\,\text{A}$, the forces plotted in figure 11 are obtained. One immediate observation that arises from these plots is that lift is comparable with thrust, which may cause undesirable ripple in the air coupling region, especially if this motor is to be driven in contactless levitation, as intended. This may turn into a severe restriction, according to YBCO pinning characteristics, which may not be sufficient to oppose to lift forces variation.

Figure 8. Result of flux density longitudinal component averaged over one slot height.

Figure 9. Result of flux density normal component averaged over one slot height.

Figure 10. Evolution of currents in phases A, B and C, namely, $i_a$, $i_b$ and $i_c$.

Figure 11. Numerically determined thrust and lift forces in the mover as a function of armature mechanical angle.

4. Magnetisation system

The YBCO bulks are pre-magnetised in the beginning of motor’s operation, thus behaving as trapped-field magnets. A pulsed-field magnetiser, built by two split air core coils, $L_a$ and $L_b$, with total inductance of $645\,\mu\text{H}$ each is used. Energy is first charged in a bank of 20 capacitors in parallel, see figure 12. Each element in the bank has a capacity of $2.2\,\text{mF}$, which results in an equivalent capacity $C_{\text{bank}} = 44\,\text{mF}$. The bank is charged up to $U_{\text{DC}} = 450\,\text{V}$, so the total stored energy is $E_p = 4455\,\text{J}$. The electrical block diagram of the overall pulsed-field magnetiser is represented in Fig. 6.

By simple circuit analysis, considering no magnetic linkage between $L_a$ and $L_b$ (which is not true), the peak current is

$$I_p \approx \sqrt{\frac{C_{\text{bank}}}{L_{\text{eq}}}} \cdot U_{\text{DC}} \cdot \exp \left( -\frac{R}{2} \left( \sqrt{\frac{C_{\text{bank}}}{L_{\text{eq}}}} \tan^{-1} \left( \frac{2}{R} \sqrt{\frac{L_{\text{eq}}}{C_{\text{bank}}}} \right) \right) \right) \cdot \sin \left( \frac{2}{R} \sqrt{\frac{L_{\text{eq}}}{C_{\text{bank}}}} \right)$$

(1)

where $L_{\text{eq}} = 645/2 = 322.5\,\mu\text{H}$. For the used electrical elements, a peak current of about $8\,\text{kA}$ is expected. The term $R$ in (1) is mainly the resistance of the copper wire in the coils. An oscillatory voltage regime should be avoided, since the used capacitors are electrolytic. The thyristor that triggers
the discharge through the coils prevents this fact, while freewheel diodes guarantees current continuity in the coils. After the initial peak current, this one dissipates through coils and diodes resistance.

![Figure 12. Bank of capacitors with a total capacity of 44 mF.](image)

![Figure 13. Diagram of the pulsed-field magnetiser (La is built by La1 and La2, and Lb by Lb1 and Lb2).](image)

Each air core coil is built by two elements. Each element (see figure 14) is made by nylon, and the windings are in copper tape, with a rectangular cross section. The copper is wrapped up in a first layer of epoxy resin than embedded in a layer of glass fibre. These reinforcements are used to absorb the high mechanical stresses during pulse discharge.

![Figure 14. Coil element before assembly. Two of these elements build one air core coil. Both coils generate opposite fields that are trapped in YBCO bulks.](image)

5. Simulation results
Due to magnetiser air core coils, the field generated by each affects the other, which means that they are magnetically coupled, opposing the assumption made before. This will affect the experimental
results, as the field trapped in YBCO has different components, see figure 15, where it is visible the misalignment between magnetic axis in YBCO bulk.

![Figure 15. Trapped-field process during magnetisation of an YBCO bulk.](image)

### 6. Discussion of results and conclusions

A test rig for an all HTS linear motor is presented in this paper as some details its design.

One first conclusion, which is related to the available materials when designing the motor, is that the relation between YBCO width and BSCCO bending radius is too low. One solution is to use wider bulks, e.g., by welding elements. However, the best solution (which can also be implemented simultaneously) seems to be the replacement of BSCCO by YBCO coated conductors, since these are less field dependant, avoiding the degradation on critical current by perpendicular field components.

The future work consists in starting experimental measurements. Unfortunately these were not ready for the conference due to problems with the air core coils assembly. Other calculations will involve the evaluation of an identical motor with iron so both performances are realistically compared.

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