Designing a Regenerative Braking and Energy Storage System for the Superconducting Maglev-Cobra Vehicle

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Abstract—This paper presents the first results about energy recovery and storage on the superconducting vehicle MagLev-Cobra project, under the collaboration between DEEC/AC Energia and COPPE-Elétrica (UFRJ). Its aims is the study of the vehicle operation on the 200 m experimental line, which became operational on the fall of 2014. Regarding the operation of the electric vehicle, a scenario is set which takes into account the maximum load and also an estimation on the number of paths made at a rush hour. The results were used to design an energy storage system for an off-grid MagLev-Cobra’s operation.

Keywords—Maglev-Cobra, Energy storage systems, Battery, Supercapacitor, HESS management, Regenerative braking

I. INTRODUCTION

The demand of effective and efficient ways of transportation on a heavily populated city are a challenge that these urban areas will face in the near future, where less consumption of resources, pollution, and the wellbeing of the population will be take into account by the policymakers. Rio de Janeiro and other Brazilian cities are not an exception, where the majority of the population is served by bus services which do not help the city chronic traffic jam problems. The LASUP (Laboratory for Applied Superconductivity) at Coppe/UFRJ has been working on the superconducting Maglev-Cobra as an effective solution of low-speed transportation with 1/3 of the effective constructed cost of the underground. This work is the first result of a collaboration research between LASUP and DEEC/AC Energia for the Maglev-Cobra project. Its aims is the study of technical and economic viability of an energy storage system

II. LINEAR INDUCTION MOTOR (LIM) AND ELECTRIC DRIVE SYSTEM

The Maglev-Cobra module’s propulsion system consists in two linear induction motors with a short primary and a cage type secondary, as shown in figure 1:

![Figure 1 - Linear motor primary and secondary](image)

Table 1 – Linear Induction Motor values

<table>
<thead>
<tr>
<th>MOTOR CHARACTERISTICS</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOMINAL VOLTAGE</td>
<td>420 V</td>
</tr>
<tr>
<td>VELOCITY</td>
<td>7.8 m/s</td>
</tr>
<tr>
<td>TRUST</td>
<td>900 N</td>
</tr>
<tr>
<td>FREQUENCY</td>
<td>25 Hz</td>
</tr>
<tr>
<td>AIR GAP</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

Due to previous work developed by L. Mattos, R. Oliveira, A. Ferreira and R. Stephan [2], it was possible to measure the produced trust and current with both primary and secondary standstill, with different air-gap and infeed frequency values as shown in figure 2.
A. Electric drive

The chosen control technique is the open loop V/F, providing a satisfactory performance for conditions where there is no fast speed variation. The power converter and controller are provided by WEG.

A study [1] has been made on the linear motor and electric drive operation on a ten meter long laboratory track for 10%, 12.5%, and 15% slope angle with different load, acceleration and deceleration values. The evolution of the inverter’s input voltage and current can be seen in figure 4.

III. VEHICLE OPERATION AND ENERGY CONSUMPTION

A. Maglev Operation

The experimental track to be installed in URFJ campus has a length of 200 meters and a slope angle of 0.19°. It was considered that the friction force, due the low-speed and levitation can be described as constant coefficient, μ. Each path on the track will be composed by 3 phases.

A. UNIFORM ACCELERATION

The vehicle accelerates with a constant acceleration coefficient, being the trust force developed by the vehicle for positive (1), negative (2) or null (3) track slope angle given by:

\[ F_{\text{trust}} = M \times a + \mu \times M \times g \times \cos(\alpha) + M \times g \times \sin(\alpha) \]  

(1)

\[ F_{\text{trust}} = \mu \times M \times g \times \cos(\alpha) - M \times g \times \sin(\alpha) + M \times a \]  

(2)

\[ F_{\text{trust}} = M \times a + \mu \times M \times g \]  

(3)

B. CONSTANT SPEED

After acceleration, the vehicle reach cruise speed, maintaining it before braking. Trust developed in cases of positive (4), negative (5) and null slip (6) track slope angle are given:

\[ F_{\text{trust}} = \mu \times M \times g \times \cos(\alpha) + M \times g \times \sin(\alpha) \]  

(4)

\[ F_{\text{trust}} = \mu \times M \times g \times \cos(\alpha) - M \times g \times \sin(\alpha) \]  

(5)

\[ F_{\text{trust}} = \mu \times M \times g \]  

(6)

C. UNIFORM DECELERATION

The trust developed in this case for the cases of track slope are:

\[ F_{\text{trust}} = \mu \times M \times g \times \cos(\alpha) + M \times g \times \sin(\alpha) - M \times a \]  

(7)

\[ F_{\text{trust}} = \mu \times M \times g \times \cos(\alpha) - M \times g \times \sin(\alpha) - M \times a \]  

(8)

\[ F_{\text{trust}} = -\mu \times M \times g - M \times a \]  

(9)

The work needed to move the train is calculated by:

\[ W = \int F_{\text{trust}} \times v \, dt \]  

(10)

For the MagLev-Cobra’s energy study, it was considered an operation scenario, related for a plausible peak of use hour, in which the number of users are 20% of COPPE’s population (among 1260) and every path made by the vehicle will be in full capacity (30 users). Table 2 shows other characteristics for the vehicle’s operation.
The design process for the Energy Storage System (ESS), it was decided that due to the light weight of the transportation and low speed profile of the vehicle it is possible to design a technically and economically viable ESS that can guarantee the autonomous operation and the system charge performed on the station.

Following the decision on the ESS proposed, an analysis and decision on the energy storage technology capable of integrating the system was made.

A. Battery

Today’s Lithium based batteries are able to present energy density up to 200 Wh/Kg and power density of 10 kW/Kg [3], making them the first choice for electrical vehicles storage system. For this study three main chemistries were considered.

1. LiFePO$_4$

Lithium iron phosphate batteries are one of the most used types in electric traction. Each cell has a nominal voltage of 3.2 V, lower than normal Li-ion battery which translate in lower energy density (up to 110 Wh/Kg). Due to chemical stability it performs well under a wide temperature range (from -20º to 70º) and it does not ignite or explode under battery fault like other chemistries do. It has a good power density (> 300 W/Kg) meeting the Maglev power demand without increasing excessively the weight.

2. LiMn$_2$O$_4$

Batteries based on lithium magnesium chemistry have an extensive use on EV due to High power and High energy density. It has the same cost per kWh as lithium ion phosphate about 1000 $/kWh. Due to its chemical instability it can ignite or explode if short circuited or over charged, and it has performance downfall with high temperatures.

3. Li$_2$TiO$_3$

Lithium titanate is one of the newest technology to hit the battery market, it has a lower nominal voltage than previous battery types, about 2.4 V representing a lower energy density. Still it has advantages over the previous, due to high power charge capacity, capable withstand charge currents 10 times greater than is capacity, which means 1 to 3 times from previous types. It also has a good performance under a wide temperature range.

Since Maglev will operate in Rio Janeiro, which has a yearly temperature variation of 10º to 45º, regarding safety transportation and also the operation knowledge of battery chemistry, the Lithium iron phosphate battery was chosen.

B. Supercapacitors

Supercapacitors or ultracapacitor can display high power density up to 10 kW/Kg [3], making them a useful choice for high power uses. Despite low energy density up to 5 Wh/Kg [3], they are being integrated in electric vehicles, not as the main storage system, but as a secondary system capable to withstand high current peak from regenerative braking or acceleration event. Therefore a hybrid storage system with Batteries and supercapacitors can be developed.

Supercapacitors still have some disadvantages such as the low nominal voltage, increasing the number of cells in series creating problems with overvoltage and cells monitoring when under sudden high current.

V. ENERGY STORAGE SYSTEM

The design process for the energy storage system has taken into account the following factors:

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### Table 2 - Operation conditions

| NOMINAL VELOCITY | 5.6 m/s |
| ACCELERATION     | 0.368 m/s$^2$ |
| MAX LOAD         | 6000 kg |
| NUMBER OF PATHS  | 42 |

The results are shown in table 3.

### Table 3 - Peak hour scenario results

| WORK CONSUMED | 1428.9 Wh |
| BRAKING WORK  | 351.45 Wh |
| TIME OF A PATH| 51.1 s |

### Table 4 - Auxiliary electric system's energy consumption

<table>
<thead>
<tr>
<th>POWER [W]</th>
<th>ENERGY [WH]</th>
<th>UTILIZATION FACTOR [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGHT</td>
<td>19.2</td>
<td>19.2</td>
</tr>
<tr>
<td>SCREEN</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>MOTOR DOOR</td>
<td>184</td>
<td>6.336</td>
</tr>
<tr>
<td>HYDRAULIC SYSTEM</td>
<td>30</td>
<td>0.99</td>
</tr>
<tr>
<td>TOTAL ENERGY [WH]</td>
<td></td>
<td>76.53</td>
</tr>
</tbody>
</table>

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- **Weight** – The system must store the energy needed for the peak hour of use with least weight possible;
- **Performance** – Under vehicle operation the system has to deliver the power needed, and work under the inverter input voltage interval, 610 – 530 V;
- **Cost** – The cost of the designed system needs to be reduced as much as possible

The first system taking into account was a battery storage system. In order to respect the working input voltage of the inverter, it was defined that the battery system should work on the linear region of battery discharge curve, for maximize the use of the energy stored. Therefore, it was chosen the maximum and minimum voltage of each cell should be 3.25 V and 2.82 V.

### Table 5 - Battery system characteristics

<table>
<thead>
<tr>
<th>MAXIMUM VOLTAGE</th>
<th>610 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINIMUM VOLTAGE</td>
<td>530 V</td>
</tr>
<tr>
<td>CELLS IN SERIES</td>
<td>188</td>
</tr>
<tr>
<td>CAPACITY</td>
<td>6 Ah</td>
</tr>
</tbody>
</table>

Due the power demand from the vehicle, the battery system will be face current values over 13 C-rate, this value can accelerate the battery degradation process and the system security, therefore an oversize capacity should be considered, in order that charge currents does not reach values over 2 C-rate. Considering that the maximum value of the current form uphill’s acceleration is about 80 A, the oversize capacity of the battery is 10 Ah.

An oversize capacity means more weight and cost of the battery storage system. Addressing this issue, it was analyzed various typologies of hybrid energy storage system (HESS) based on batteries and supercapacitors.

#### i. Passive hybrid typology

Passive typology is simplest hybrid typology, it consists in the connection in parallel the supercapacitor and battery unit. The supercapacitor acts when there are power variation, like power peaks regarding the vehicle acceleration and deceleration. The sharing of power between the two units, results in less suddenly power variation on battery side, which benefits its lifecycle.

#### ii. Semi active hybrid typology

The semi active typology consists in isolating one of the units with a power converter, making possible the implementation of power management techniques. There are two types of semi active typologies, shown the figure 7.

![Figure 7 - Semi active hybrid typologies](image)

In the case a) the DC-DC converter can manage the power deliver from or to the supercapacitor unit, which can be fully used, compared to the passive hybrid typology. In case b) battery is managed by the DC-DC converter, the supercapacitor is connected to the inverter and must guarantee the voltage between the interval 530-610 V, which have the same issue of the passive typology on the amount of...
energy possible to be used from the supercapacitor unit. The simulation on this typology shows also that in order to hold the input voltage interval during vehicle’s operation, the supercapacitor capacity need to be oversized to 9 F.

iii. Active hybrid typology

This typology uses two or a multi-input DC-DC converter isolating both units from the traction system which guarantees a full power management on the hybrid energy storage system.

![Active hybrid typologies](image)

**Figure 8 - Active hybrid typologies**

iv. Proposed hybrid energy storage system

In order to design a simple hybrid energy storage system capable of optimize the use of the supercapacitor unit and prevent high charge and discharge currents that could accelerate the degradation process of the battery, it is proposed a semi active typology, based on figure 7 a). The power in or out the supercapacitor unit can be controlled by a Bi-directional DC/DC buck-boost converter, represented in figure 9.

![Bi-directional DC/DC buck-boost converter](image)

**Figure 9 – Bi-directional DC/DC buck-boost converter**

For the battery system it was selected a battery model A123 Systems AMP20M1HD-A, with 20 Ah, discharge rate up to 16 C-rate and charge rate of 2 C-rate. Aiming to have the desirable capacity and voltage, the battery pack should be consisted by a group of 188 cells connected in series.

For the case of the supercapacitor it was chosen a maximum voltage the same as the battery unit, 610 V.

The capacitor model chosen for these application was the Maxwell BCAP0350, capable of discharge currents up to 170 A and a capacity of 350 F.

**Table 6 - Battery unit characteristics**

<table>
<thead>
<tr>
<th>MAXIMUM VOLTAGE</th>
<th>MINIMUM VOLTAGE</th>
<th>CELLS IN SERIES</th>
<th>ARRAY IN PARALEL</th>
<th>CAPACITY</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>610 V</td>
<td>530 V</td>
<td>188</td>
<td>0</td>
<td>20 Ah</td>
<td>93,300 Kg</td>
</tr>
</tbody>
</table>

**Table 7 - Supercapacitor unit characteristics**

<table>
<thead>
<tr>
<th>MAXIMUM VOLTAGE</th>
<th>MINIMUM VOLTAGE</th>
<th>CELLS IN SERIES</th>
<th>CAPACITY</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>610 V</td>
<td>150 V</td>
<td>222</td>
<td>1,58 F</td>
<td>13,320 Kg</td>
</tr>
</tbody>
</table>

VI. POWER FLOW CONTROL

The power converter have two operation modes:

A. Buck Mode

When a current is injected by the load, for example in braking, the buck mode can be used for charge the SC.

S1 ON & S2 OFF – When $0 < t < T$ ;

S1 OFF & S2 ON – When $T < t < 2T$;

$$U_{bat} = \delta U_{SC}$$

![Buck operation](image)

**Figure 4 - Buck operation [5]**

B. Boost Mode

When load requires power, the SC bank can provide it when the converter work as boost.
S2 ON & S1 OFF – When $0 < t < \delta T$;

S2 OFF & S1 ON – When $\delta T < t < T$;

\[
U_{bat} = \frac{U_{sc}}{1 - \delta}
\]

Figure 5 - Boost operation [5]

C. Control algorithm

Taking advantage from converter functionality, a control was developed taking account the vehicle specifications. In order to the discharge current of the battery system do not be higher than the 2 C (40 A) and the charge currents higher than 1 C (20 A), these values were established as the current limits for the converter operation, as shown by the figure 17.

Figure 6 - Powerflow control diagram

The power converter is controlled by a current control technique, using a PI compensator for a RLE load, as presented [5] and [11].

Figure 7 - Current control diagram for a RLE load

The supercapacitor current reference calculation takes into account the battery current limits (11).

\[
I_{ref} = \frac{(V_{bat}[I_{load} - I_{lim}])}{V_{SC}} \tag{11}
\]

In order to prevent overcharge or undercharge of the supercapacitor unit, a security factor was established, as shown below.

\[
f_{security} = \begin{cases} 
0, & I_{carga} < 0 \text{ e } SOC_{SC} > 95 \\ 
1, & 25 \% < SOC_{SC} < 95 \\ 
0, & I_{carga} > 0 \text{ e } SOC_{SC} < 25 
\end{cases}
\]

Therefore the final reference current is given by (12)

\[
I_{ref}' = I_{ref} \times f_{security} \tag{12}
\]

D. Simulation

Based on the semi active hybrid typology analysis, it was developed a model for simulate the system performance under the proposed MagLev-Cobra operation on chapter III.

It was considered that traction system would have a unitary power factor and the demand DC current would be taken from the MagLev-Cobra’s power curve.

The simulation results show that the requirements on the power management on the supercapacitor and battery side are fulfill. The figure 20, 21 and 22 represent the current inverter’s input, supercapacitor and battery on the downhill path after an uphill path with a full charged system.

Figure 19 - Inverter input DC Current curve

Figure 20 - Supercapacitor Current

Figure 21 - Battery Current

During the operation the voltage levels in both units, are within the acceptable interval, but the voltage level of the supercapacitor unit is 380 V at the end of the downhill path, since from the uphill simulation, the minimum SC unit
charge needed is about 63%, the HESS need to be charged on the station.

VII. ECONOMIC EVALUATION

The hybrid energy storage system proposed on this work was designed for the autonomous operation of the MagLev-Cobra on the 200 long experimental track intended for the replacement of the power lines.

For the economic evaluation, it was analyzed the possible investment and lifetime saving generated by adopting an autonomous operation. The estimated HESS cost are presented in table 8.

<table>
<thead>
<tr>
<th>Table 8 - HESS expectable cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BATTERY UNIT COST</strong></td>
</tr>
<tr>
<td><strong>SC UNIT COST</strong></td>
</tr>
<tr>
<td><strong>CONVERTER COST</strong></td>
</tr>
<tr>
<td><strong>BMS$ COST</strong></td>
</tr>
<tr>
<td><strong>TOTAL COST</strong></td>
</tr>
</tbody>
</table>

According to [13] the cost of electrifying a railroad line is about 40% of all cost related to the electrical infrastructure. Since the work [14] expected that the MagLev-Cobra cost are 1/3 of the cost for the underground line costs per km, it was made an approximation for electrifying 200 meter line, which is about 106.6 k$.

The table 9 shows the cost analyses in a 10 year period, considering a 0% inflation rate and taking into account that the battery unit need to me switch every 3 years, the SC unit every 10 year, and yearly electric and HESS maintenance cost is equal to 1% and 5%, respectability, of initial investment cost.

<table>
<thead>
<tr>
<th>Table 9 - Cost comparison of HESS and electric line</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>YEAR</strong></td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>9</td>
</tr>
</tbody>
</table>

The analysis based on the estimated cost of both systems shows that the HESS can generate saving of 96 k$ in a 10 year timeline for the 200 long experimental track.

It is expected that these saving could be much higher for longer tasks, therefore the autonomous operation of the vehicle could prove economical viable.

VIII. CONCLUSION

In this work, an analyses of MagLev operation was made taking into account a scenario expectable in a peak hour of utilization. The results shows that the energy that could be regenerated by braking is around 24.5% of the total consumed by the vehicle.

Due the lightweight characteristics of the vehicle it is possible to design an energy storage system capable of power the whole vehicle operation, becoming an electric autonomous vehicle.

For that propose, various energy storage system typologies were analyzed, which the chosen typology were the semi active HESS with the supercapacitor unit isolated from the battery/traction system by a bi-directional dc/dc buck-boost converter. The simulation performed of the HESS during vehicle operation, allows o point out the system works under the control principles expected from the design phase, guaranteeing that the battery does not work under high discharge or charge currents.

The cost analyes estimation shows that a vehicle autonomous operation can generate savings, which can be decrease even more the cost of implementation of these urban vehicle.

For future works it is suggested the control algorithm optimization in order to avoid the current and voltage peak on battery, also the study of the HESS charge process, and the build and testing of the system’s prototype.

IX. REFERENCES


interfacing battery and ultra-capacitor units’, IEEE Transportation Electrification Conference and Expo (ITEC), June 2013


