Operating a MagLev Train Prototype with Supercapacitors and Charge by Opportunity

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Abstract

This work presents an alternative energy supply for urban MagLev vehicles, using supercapacitors. The concept is known as "charge by opportunity". During the necessary stops for passengers′ embarkation and disembarkation, and the few seconds for the completion of this activity, supercapacitors inside the vehicle will be charged. The supplied energy is calculated to ensure the movement until the next station. The low friction of MagLev trains, the short distance between stations for public transportation inside a city, and the flat track given by elevated lines, all contribute to small energy storage requirements. This study not only describes the application, but also maps the market for supercapacitors, describing the main suppliers, prices and characteristics. In this way, an innovative power supply option for urban MagLev vehicles will be offered, which, unlike the existing options, does not visually pollute with overhead cables or extra rails. Experimental results would have been presented with tests on the prototype MagLev-Cobra, from the Federal University of Rio de Janeiro. However, due to a lack of financial support and the coronavirus pandemic the tests were canceled. MagLev-Cobra is a levitating vehicle based on the diamagnetic property of superconductors in the vicinity of rails made up of rare earth magnets. As a prototype system, the ideal test conditions are available. Furthermore, a converter DC-DC is specified to work with the supercapacitors.

Contents

1 Introduction

1.1 Contextualization

The increase in urbanization in large cities and the need to preserve the environment are at the heart of current discussions about the direction of sustainability and technological innovation. Within this scenario, the issue of transport and urban mobility deserves special mention because it interferes daily in the lives of thousands of people, contributing significantly to the emission of pollutants resulting from the use of fossil fuels, as well as noise pollution. In addition, the congestion present in large cities results in both economic losses and losses to the health of the population. In order to provide options for solving these problems, MagLev-Cobra was developed.

This vehicle is an efficient, non-polluting mode of transportation, with competitive implementation and maintenance costs, and is the result of a project started in 2000 by Escola Politécnica (EP) and COPPE/UFRJ using magnetic levitation technology. The vehicle operates from the diamagnetic property presented by high-temperature critical superconductors when interacting with special permanent magnet tracks, also called rare earth magnets due to the presence of the chemical element Neodymium (Nd), used in its construction.

With its physical structure and operating principle, the vehicle uses a traction system by means of a linear induction motor, being formed by small modules that allow the MagLev to be articulated, alluding to a snake. This articulation allows curves with radii of 50 meters to be made and goes over slopes of up to 15%, permitting its implantation with greater freedom in urban environments, being able to be used in elevated magnetic levitation roads, without impacting the traffic of large cities [13].

The MagLev-Cobra travels without mechanical contact between the vehicle parts and rails, which together with the current traction system, makes it a silent vehicle. Levitation also allows the vehicle's mechanical load to be evenly distributed along the track, unlike traditional systems where all the weight is concentrated on the wheels. This feature allows the routes for using the vehicle to be constructed using less material, consequently, making them cheaper when compared to other means of transport on rails, such as the tracks of a monorail.

The project has already gone through three stages: the proof of concept in which a small scale prototype was built; the functional prototype that aimed to demonstrate technical feasibility within a controlled laboratory environment; and the operational prototype that had been operating weekly since October 2015 on the UFRJ campus, meeting the demand of the university community, as well as countless visitors. However, these operations ended with the outbreak of COVID-19. Currently, the project is in the industrialization stage, which consists of the certification of technology and the implementation of an effective transportation line containing five kilometers within the campus of the university. [2].

1.2 MagLev-Cobra Power Supply

The MagLev-Cobra prototype is powered by a DC bus present throughout the entire two-hundred-meter runway. This bus consists of three parallel bars, located on the opposite side of the vehicle entrance, so that visitors do not have access. The external busbar has 550V, the central busbar 0V and the busbar closest to the vehicle is solidly grounded. In addition,

Figure 1: AFW-11 panel.

Figure 2: MPW-100 switch.

the vehicle has two sets of collecting brushes attached to the side, responsible for maintaining contact with the DC bus throughout the operation.

This 550V DC voltage, responsible for energizing the vehicle's internal circuits, is obtained from the internal electrical network of UFRJ Technological Center, having an AC voltage of 440V and a frequency of 60Hz. The three phases of the network are connected to the high side of a 100kVA Δ-Δ three-phase transformer that has a 440V: 380V transformation ratio. The low voltage side of the transformer is connected to the CFW11-105-RB bidiretional converter bridge, responsible for rectifying the transformer voltage and supplying the DC bus.

The CFW11-105-RB converter bridge is part of the AFW-11 [14] drive panel assembly, from the manufacturer WEG, shown in figure 1, being an induction motor drive panel, equipped with a set of components that allows the regenerative conversion of energy. It is also worth mentioning that there is a breaker MPW-100 [17], shown in figure 2, located in the center of the track, making the connection between the CFW11-105-RB converter bridge and the bus External DC, that is, performing the protection of that bus.

1.3 Motivation

Man has always needed energy sources. Since these sources are not always available, there is a need to store energy for later use. This is true that living beings, by feeding themselves, conserve the energy of food in the form of chemical compounds in the body itself for later use.

Within this context, supercapacitors emerge as energy storage devices, as well as several others existing on the market. Among them, we can mention batteries that store energy in chemical form, magnetic flywheels popularly known as Flywheel Energy Storage (FES), in which energy is stored in mechanical form, and Superconducting Nagnetic Energy Storage (SMES), in which energy is stored in the form of a magnetic field. Consequently, the way in which these technologies store energy makes them completely different.

The fact that supercapacitors already store energy in electrical form means that they are able to transfer energy more quickly when compared to traditional batteries [3], making them useful in applications that require a considerable amount of energy in a short time [12].

Thus, it would be possible to replace the side bus, described in section 1.2, with supercapacitors. With the supply provided by them, there is an improvement in regards to two aspects. The first is economic in nature, there is no longer the need for collecting brushes, shown in figure

Figure 3: Collecting brushes.

Figure 4: Side bus on the track.

3, being the design element that suffers the most wear during the operation of the vehicle. The second related is to safety, since it is no longer necessary to have an energized bus on the road as illustrated in figure 4. In addition, as it is not necessary to use the side bus that represents the vehicle's only point of contact with external surfaces, it makes levitation, the main feature of MagLev, even more impressive [1].

2 Research Methods

2.1 Energy Density and Power Density

To elucidate the main properties of a supercapacitor, it is necessary to introduce two concepts: energy density and power density. The energy density represents the relationship between the stored energy and the mass (J/kg) or volume (J/m^3) of the equipment, that is, a high energy density means that the equipment can store a larger amount of power. Power density, on the other hand, provides the rate at which a certain amount of energy can be transferred by the device per unit of mass (W/kg) or volume (W/m^3).

For a capacitor of parallel flat plates, the capacitance is given by equation 1, where ϵ is the permittivity of the dielectric, A is the area of the plates and d is the distance between them. The energy stored in any capacitor is given by equation 2, where C is the capacitance and V is the terminal voltage of the device, where (V/d) represents the resistance to rupture the dielectric.

$$C = \frac{\epsilon \times A}{d} \tag{1}$$

$$E_c = \frac{1}{2} \times C \times V^2 \tag{2}$$

Using the equations 1 and 2 and considering (V/d) = 200 MV/m and ε= 8.85 x 10^{-11}F/m, we calculate the density of energy of a capacitor by equation 3. Also, it can be seen in equation 4 that the order of magnitude of this measurement for supercapacitors is around 40 times greater [12].

$$\frac{E_c}{V_o} = \frac{1}{2} \times \epsilon \times \frac{V^2}{d^2} = 1.76 \times 10^6 J/m^3 \tag{3}$$

$$\frac{E_c}{V_o} = 0.7 \times 10^8 J/m^3 \tag{4}$$

These two concepts are the main distinction between supercapacitors and batteries. While supercapacitors can provide very high power density with less energy stored, batteries can store more energy, as they have a higher energy density and a lower power density as can be seen in figure 5. These characteristics are related to the way energy is stored in each device.

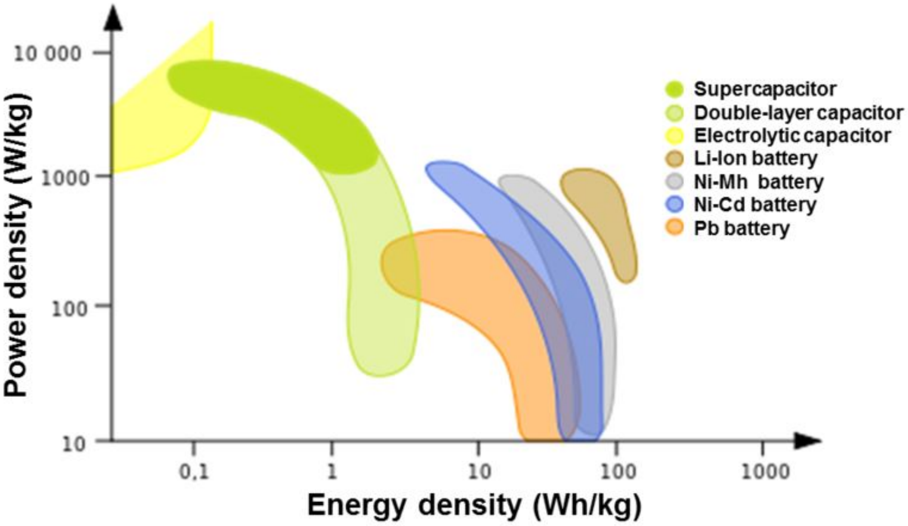


Figure 5: Ragone diagram: energy storage devices.
Source: image authorized by the author [6].

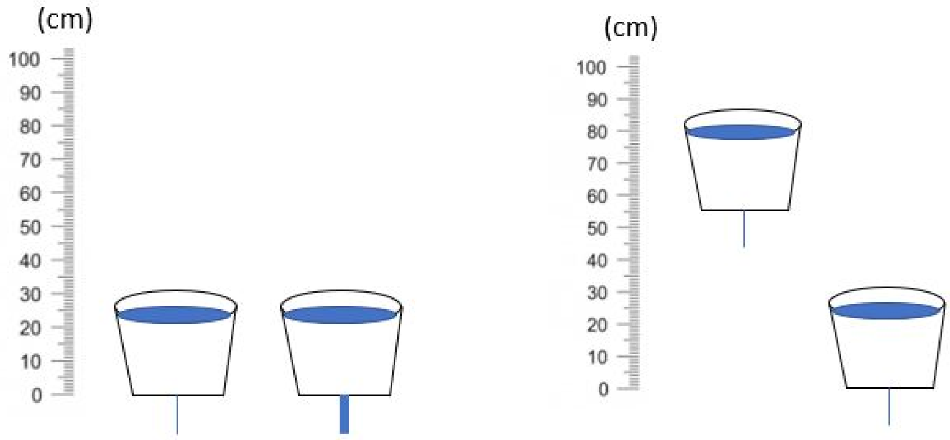
Electrolytic capacitors have a higher power density, but supply peaks in the current for only a few milliseconds. Batteries, on the other hand, have the best cost and energy storage ratio, but end up supplying energy more slowly. In addition, it is possible to notice that the supercapacitors fill the gap that existed between capacitors and batteries.

In figure 5, it can be seen that the lithium batteries also deserve to be highlighted. They differ from other batteries because they have a higher theoretical energy density which is comparable to the energy density of fossil fuels.

Because of these characteristics, supercapacitors and lithium batteries are promising devices for storing energy and will play an important role in the coming years.

It is also possible to verify that supercapacitors are passive energy storage devices with a high power density and a moderate energy density. In addition, they have other features that make their application interesting. They have a long service life (> 1000000 cycles) and an increasingly lower production cost [20].

Through figures 6a and 6b, it is also possible to explain these two concepts through an analogy with a bucket full of water with a hole in its bottom. In figure 6a, the bucket on the right has a higher rate at which a certain amount of energy can be transferred, that is, it has a higher power density when compared to the bucket on the left, this is because it has a hole with a larger diameter in the same position as the bucket on the left. In figure 6b, both buckets have the same power density. However, as the bucket on the left is at a higher height, there is a greater amount of energy stored, even if both buckets have the same size and volume of area.



(a) Same energy density, different power density. (b) Same power density, different energy density.

Figure 6: Analogy: energy density and power density.

2.2 Equivalent Circuit

It is practical to represent the supercapacitors by a simplified circuit model. Figure 7 shows the representation of the circuit, where C is the capacitance, ESR is the equivalent series resistance (which represents all ohmic losses, which depending on the application can cause a significant voltage drop, reducing the amount of energy available in the circuit, affecting its functioning, resulting from the materials used), Rp is the parallel resistance (which represents the leakage current caused by losses due to the fact that during the storage of electrical energy in the double layer, the carriers of charge inside the pores are separated by very short distances, thus irregularities can occur, leading to a small change of charge carriers and gradual discharge) and ESL is the equivalent series inductance. Therefore, like Rp $\gg$ ESR, the resistance Rp can be neglected, since it is in parallel, being considered an “opening”. In addition, they behave in an ideal way, due to the porous material used in the formation of the electrodes, and as C $\gg$ ESL, it is common to simplify the circuit to that represented in figure 8 [18].

Therefore, the values of the quantities in figure 8 are the values commonly found in the datasheets of cells and modules.

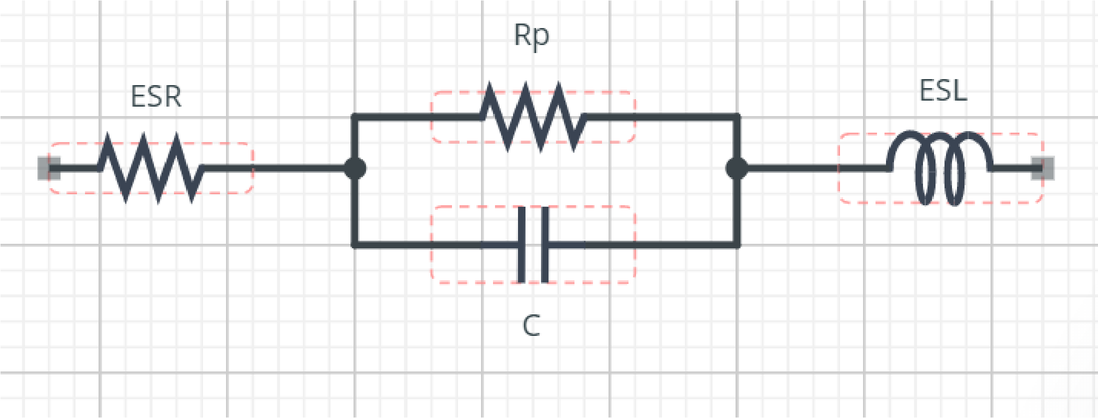


Figure 7: Circuit of a supercapacitor.

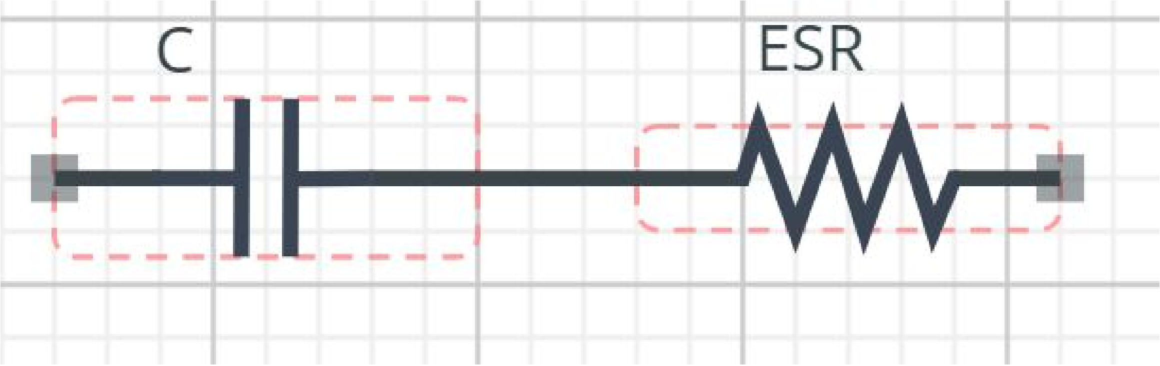


Figure 8: Simplified circuit of a supercapacitor.

Therefore, the voltage profile has resistive and capacitive components. Several models have been proposed and studied to represent the non-idealities of the device. However, the complexity of the model to be adopted depends on the specific application and the admissible error in the analysis [7].

3 Obtained Results

With the theoretical basis formed in the previous chapter, it is possible to understand and execute the project presented.

The power supply of the external 550V DC bus, which will be replaced by supercapacitors, feeds the vehicle's linear induction motor, being previously connected to the frequency inverter WEG CFW11-88A [16], whose function is to generate the three-phase voltage alternating supply of primary circuits, in addition to establishing motor speed control. It is worth mentioning that it is not part of the present work to modify this internal configuration of the vehicle, since there would be no economic or visual gain with this change, that is, it is only necessary to know the energy consumption of the load in relation to the induction motor. while traveling between stations.

3.1 Energy Consumption

According to [4], the data that will be presented in table 1 were acquired considering a constant mass of 2565kg.

Weight (kg)	Time of travel (seconds)	Energy (kWh)
2565	235	0.111

Table 1: Energy consumed in a complete trip of 2x200 = 400 meters.

3.2 Commercially Available Modules

As shown in table 1, the module must deliver at least 111Wh, as well as having a voltage that allows a boost-type DC-DC converter to be used to raise this voltage to 550V that the existing DC bus in the track provides.

Manufacturers with a sales catalog about modules were: Maxwell, Skeleton and Yunasko, the latter of which had not yet started production.

Item	Product	Voltage (V)	Capacitance (F)	Quantity	Brand
(1)	BMOD0063 P125 B08	125	63	1	Maxwell
(2)	BMOD0165 P048 C01	48	165	3	Maxwell
(3)	SMA170V53FAF	170	53	1	Skeleton
(4)	SMA51V177FAF	51	177	3	Skeleton
(5)	48V / 165F Module	48	165	3	Yunasko

Table 2: Modules analyzed for acquisition.

The data sheets required in table 2 can be found respectively on the reference sites [9], [8], [10], [11] and [19].

In addition, it was necessary to understand the situation of each company in the current scenario. Maxwell Technologies was purchased by Tesla, Inc. in 2019, an American electric vehicle and clean energy company. Since then, Maxwell's share of supercapacitors has been reduced more and more. Thus, negotiations with this supplier were interrupted, since, for future acquisitions or possible maintenance, there would be no offers. In fact, the module consulted for the first configuration had already been discontinued.

In contrast, Skeleton Technologies, founded in 2009, appears as the main supplier of modules in the current scenario, even offering technical support for any project, being the safest option. Yunasko, founded in 2010, appears as a good alternative, as it is looking for new partners in the market, however it only has a plant located in Ukraine and, therefore, is unable to expand its production.

The idea would be to use only a single module in which its voltage is raised to 550 V by means of a boost converter to be used to energize the vehicle. With all aspects considered, the configuration (3), made up of a single SMA170V53FAF module from the Skeleton manufacturer, becomes the best option for application in the MagLev-Cobra vehicle, considering it recharges after each complete trip.

However, due to its dimensions and mass, it was not possible to allocate the module inside the vehicle. Thus, it became necessary to carry out new market research and, in that time, four more manufacturers appeared with modules above 100V, they are: Eaton, SPSCAP, SECH and GTCAP.

After a new filtering, the XVM-315R9515-R [5] module from the manufacturer Eaton was chosen, which is ideal because it is more compact. The properties are described in table 3.

Product	XVM-315R9515-R
Voltage	315 V
Capacitance	5.13 F
Energy	71.1 Wh
Weight	13.5 kg
Length	0.44 m
Width	0.38 m
Height	0.10 m

Table 3: XVM-315R9515-R module features.

To meet the vehicle's energy demand, it will be necessary to use two XVM-315R9515-R modules in a series circuit. However, it will be necessary to recharge each trip, because with this arrangement we have the following stored energy.

$$E_c = \frac{1}{2} \times 2.565 \times 630^2 = 509024J = 141.40Wh \tag{5}$$

However, the maximum DC voltage on the road is 550V, so the maximum energy obtained with this arrangement would be:

$$E_c = \frac{1}{2} \times 2.565 \times 550^2 = 387956J = 107.70Wh \tag{6}$$

That would make it impossible to carry out a recharge for each complete trip.

3.3 Determination of the Cyclic Ratio of the Converter

As already mentioned, the voltage of the supercapacitors decreases with their discharge. Thus, it is necessary to have a converter that has a control in order to maintain the constant voltage required in the 550V load, that is, it varies the value of the duty cycle D with the unloading of the module.

As the required voltage on the load is equal to the value on which the supercapacitor module will be loaded, the initial value of the duty cycle D is equal to 1. When analyzing a DC converter that can raise the voltage from 180V to 550V, we have the following scenario: an amount of energy will not be used, as the module cannot be completely discharged, to keep the use of the DC-DC converter viable. This unused energy can be quantified by the following equation:

$$E_c = \frac{1}{2} \times 2.565 \times 180^2 = 41553J = 11.54Wh \tag{7}$$

In this way, it is possible to obtain the total energy during the discharge, subtracting the energy obtained with the maximum voltage from the energy obtained with the lowest voltage, calculated by equations 6 and 7.

$$E_c = 107.7 - 11.54 = 96.16Wh \tag{8}$$

In addition, using the equation of a boost converter, it is possible to determine the minimum value of the cyclic ratio D.

$$550 = \frac{1}{1-D} \times 180 \tag{9}$$

$$D = 0.67 \tag{10}$$

Therefore, the control of the boost converter should vary the cyclic ratio D between 0 ≤ D ≤ 0.67.

3.4 Allocation of Technologies in MagLev-Cobra

With the modules defined, it was possible to allocate them in the vehicle. In order not to affect the operation of the MagLev-Cobra, which is already well adapted to the track and not to hinder the comfort of passengers inside, both modules were placed under the floor in such a way that they do not interfere during the operation. The converter will be in the first module of the vehicle so that it can be connected to the supercapacitors by cables that will also travel under the floor. The modules and the converter can be better viewed through figures 9 and 10, where the modules are highlighted in yellow and the converter is highlighted in red.

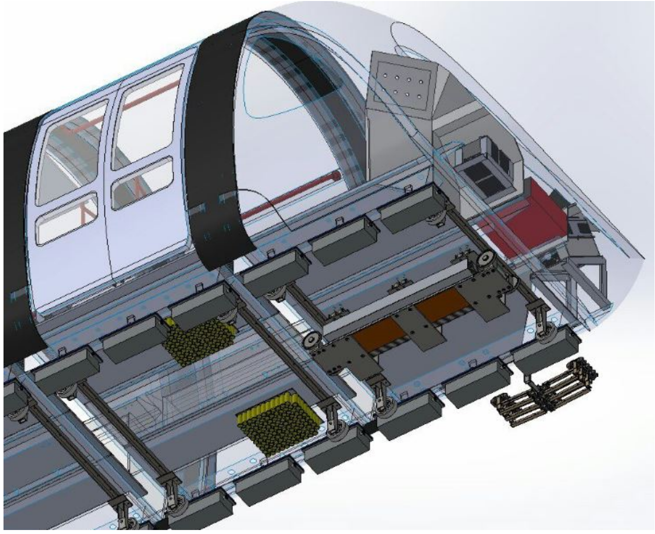


Figure 9: Bottom view of the vehicle: the modules are highlighted in yellow and the converter is highlighted in red.

3.5 Charge of Supercapacitors

We chose to use WEG CFW11-105-RB [15] converter. This converter will be responsible for rectifying the voltage of the internal electrical network of the UFRJ Technological Center, generating a voltage of 550V for the supercapacitors. It is worth mentioning that this converter has a rated output current, that is, a current limiter, solving the peak load problem.

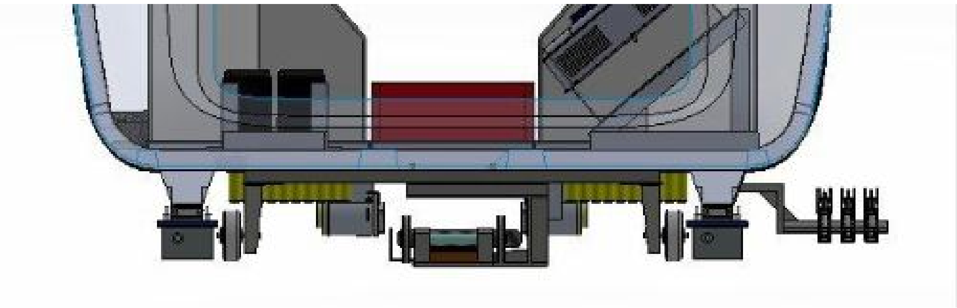


Figure 10: Front view of the vehicle: the modules are highlighted in yellow and the converter is highlighted in red.

3.6 Final System

With the necessary technologies for the application defined and properly arranged in the vehicle, the energy supply and storage system is presented as follows: two XVM-315R9515-R modules from the manufacturer Eaton in series loaded at 550V, being connected to the DC converter of boost topology that is connected to the supercapacitor bank and the WEG CFW11-88A frequency inverter. This converter has the function of keeping the voltage constant at the load, in this case, the linear induction motor, even with the unloading of the module. The final system of operation can be seen in figure 11.

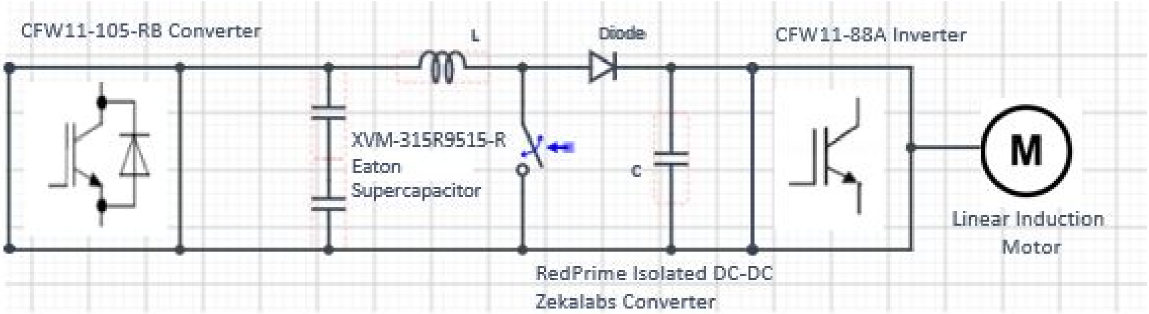


Figure 11: Electrical application diagram.

4 Concluding Summary

With this project, it was initially possible to better understand characteristics of supercapacitors, as well as some electrical models used for their representation. The complexity of the model to be adopted depends on the specific application and the admissible error in the analysis. With the mapping of the market, it was discovered that there are modules that deliver a quantity of energy capable of setting heavy vehicles in motion, such as trains and trucks. Another point highlighted was the characterization of the main suppliers of these modules in the current scenario.

In addition, the low energy consumption of the MagLev-Cobra vehicle was confirmed, which ends up allowing for other possibilities for powering the vehicle, one of which being the use of supercapacitors. Regarding the DC-DC converters, it was possible to choose the most suitable equipment to work with the module previously determined. Although, there is no specialized national manufacturer, there is international equipment with wide voltage gain as well as bidirectional and high power. With the supercapacitors module and the DC-DC converter defined, they were allocated in such a way that they did not affect the vehicle's operation or the passengers' comfort.

5 Future Work

Another project that may come from this application of supercapacitors in the vehicle is the automation of the charging process. For example, on buses that use this technology, the modules are coupled to the top of the vehicle so that when the bus arrives at a particular station for boarding and disembarking passengers, the terminals of the modules are lifted automatically , allowing contact with an external bus present at the top of the station for automatic charging of the modules.

In addition, with the creation of a longer track [2], it will be possible to use a hybrid system, that is, using batteries and supercapacitors together. Thus, a more in-depth study of this combination will be necessary.

Finally, there is also the possibility of harnessing the energy generated by decelerating the vehicle. It would be possible to absorb kinetic energy during braking in supercapacitors and release that energy during acceleration.

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