The Electric Energy Waste in Old-Fashioned Traction Systems and the Power Electronics Solutions

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***Abstract* – To eliminate the wasted electric energy of the urban trains in Porto Alegre, a general study of the problem is carried out. A comparison of high voltage DC choppers is presented and the application of GTOs and IGBTs are studied in order to find the best choice for the case. Relevant equations of the chosen topology to drive the traction motors and details of the filter capacitor design are also presented.**

I. INTRODUCTION

Porto Alegre is the capital of Rio Grande do Sul and is situated in Southern Brazil.

The urban trains in Porto Alegre work as most of the old systems, with traditional DC series motors. In the present system, as in many others, it is necessary to make a series connection of several resistors in the main circuit to start and to break the trains.

The amount of wasted energy in these resistors is quite important and can be almost completely recovered (or not wasted) with a chopper circuit. However, due to the large levels of voltage and current of the traction system, the chopper circuit probably will need some kind of association of its switches.

The present traction system deals with a nominal DC voltage line of 3.45kV (the worst case is 4kV) and with an acceleration current of 500A. Present power semiconductor technology allows basically the chopper is made with the use of 4.5kV GTOs or 1.7kV IGBTs. IGCTs and other new power semiconductors are considered too new to this kind of application and, for this reason, they were not analyzed in this work.

The current capacity of the switches does not seem to be a problem, but because of the high voltage level of the DC line and also because of the security coefficient, the chopper circuit needs to have at least two GTOs or four IGBTs in some kind of series connection.

This work starts with an analysis review of the wasted electric energy. The circuits that can fulfill the desired requirements of the high voltage DC chopper are presented and compared, and the chosen topology is then analyzed.

II. THE WASTED ENERGY

Figure 1 shows the simplified equivalent circuits of the acceleration process and a typical acceleration curve of the present traction system.

From Fig. 1, it can be noticed that there are four motors series connected in the first stage of the acceleration process (Fig. 1a) and two branches, each of them with two motors series connected, paralleled connected in the second stage (Fig. 1b). The input voltage Vi is connected to the motors through an equivalent variable resistor $R(\omega)$. Actually, $R(\omega)$ is an association of several resistors that are connected or not in the circuit, determining an almost constant current in the motors during the acceleration time. Note that in the first stage the electrical losses are given by RI^2 and in the second stage by $R(2I)^2$.

The typical acceleration curve shown in Fig. 1(c) is obtained by means of the hypothesis of constant torque and negligible friction losses. The first stage presented in Fig. 1(a) is used while $0 < t < t_1$. The second stage presented in Fig. 1(b) is used while $t_1 < t < t_2$. The duration of each stage are basically determined from the total armature voltages, according to (1).

$$\omega_1 \cong \frac{Vi}{4kI} \quad \text{and} \quad \omega_2 \cong \frac{Vi}{2kI} \tag{1}$$

where ω is the angular speed, Vi is the input voltage, I is the motor current and k is the motor constant.

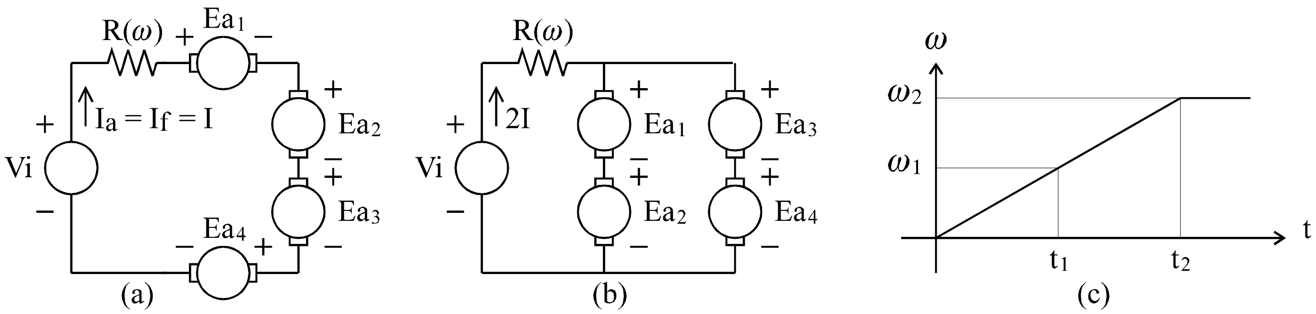

Fig. 1. Simplified acceleration process of the present traction system.
(a) First stage. (b) Second stage. (c) Typical acceleration curve

When the distance between train stations is small, only the first stage is used in the acceleration process. In this case, the electric energy which is wasted in the resistors can be calculated by (2).

$$\begin{aligned} E_{R1} &= \int_0^{t_1} R(\omega) I^2 dt = \int_0^{t_1} \left[Vi - 4Ea(t)\right] I\, dt \\ &= \int_0^{t_1} \left[Vi - 4kI\omega(t)\right] \frac{T}{4kI}\, dt \\ &= J \int_0^{t_1} \left[\omega_1 - \omega(t)\right] \frac{d\omega(t)}{dt}\, dt \\ &= J \int_0^{\omega_1} \left(\omega_1 - \omega\right) d\omega = \frac{J\omega_1^2}{2} = \frac{m v_1^2}{2} = E_{C1} \end{aligned} \tag{2}$$

where E_{R1} is the wasted electric energy; T is the total produced torque in the acceleration process; J is the equivalent inertia; m is the mass of the train; v_1 is the linear speed of the train at the end of the first stage acceleration process; E_{C1} is the kinetic energy of the train at v_1; ω_1, Vi, Ea and $R(\omega)$ were defined in Fig. 1; and k and I were defined in (1).

From (2) it can be concluded that the wasted energy in the first stage of the acceleration process is equal to the kinetic energy stored by the mass of the train.

When both stages are used in the acceleration process, the electric energy which is wasted in the resistors can be calculated by (3).

$$\begin{aligned} E_{R2} &= \int_0^{t_1} R(\omega) I^2 dt + \int_{t_1}^{t_2} R(\omega)(2I)^2 dt \\ &= \frac{J\omega_1^2}{2} + 2\int_{t_1}^{t_2} \left[Vi - 2Ea(t)\right] \frac{T}{4kI}\, dt \\ &= \frac{J\omega_2^2}{4} = \frac{m v_2^2}{4} = \frac{E_{C2}}{2} \end{aligned} \tag{3}$$

From (3) it can be concluded that the wasted energy in the two-stage complete acceleration process is equal to half of the kinetic energy stored by the mass of the train.

In fact, due to mechanical losses, the produced torque must to be slightly increased in order to get the desirable acceleration curve. For this reason, the wasted electric energy is slightly bigger than that given by equations (2) and (3). On the other hand, line and motors resistances losses cannot be recovered. Therefore, electrical and mechanical losses have opposite effects and, in a first approximation, they compensate each other.

Another large amount of energy is wasted in the braking processes. The available energy that can be transformed in electric energy during braking processes is always equal to the kinetic energy stored by the mass of the train. However, considering losses, the brake profile and statistical considerations about the capacity of electric energy absorption of the line, it can be estimated that the recovery energy can be about 70% of the available one.

Computing the number of train stations along the line and the frequency of the trains it is possible to calculate the number of braking and acceleration maneuvers per month and the total wasted energy.

In the present case, the urban trains in Porto Alegre carry out 1495 journeys per week, i.e. 237 on working days, 161 on Saturdays and 149 on Sundays on average. They transport 800000 passengers on average, i.e. 135000 on working days, 75000 on Saturdays and 50000 on Sundays. From that data one can deduce that each train carries an average of 800000/1495 ≅ 500 passengers, i.e. 500*70 = 35 ton.

Considering that the mass of an empty train is 200 ton, the total mass on move is 200 + 35 = 235 ton.

A complete track between Porto Alegre and São Leopoldo comprehends 17 train stations. As a result, the traction motors must perform 17 starts e 17 halts per journey. There are only 3 sections of the line where the maximum speed is 50 km/h. For the rest, the train can reach 70 km/h or even more.

The first stage of the acceleration process is used up to $v_1 \cong 50$ km/h, but the current remain constant only up to $v_1 \cong 40$ km/h. In this case, from (2),

$$E_{R1} \cong E_{C1} = \frac{1}{2} m v_1^2 = \frac{235000}{2}\left(\frac{40}{3.6}\right)^2 = 14.5\text{MJ} \cong 4\text{kWh}\cdot$$

However, if the train goes to the end of the second stage and reaches 70 km/h, then, from (3),

$$E_{R2} \cong \frac{E_{C2}}{2} = \frac{m v_2^2}{4} = \frac{235000}{4}\left(\frac{70}{3.6}\right)^2 = 22.2\text{MJ} \cong 6\text{kWh}\cdot$$

On a complete journey, the total wasted energy during departures is $E_R \cong 3*4+14*6 \cong 96$kWh. In a week, this wasted energy totalizes $E_R \cong 1495*96 \cong 143$MWh and in a month, it becomes $E_R = 4.275*143 \cong 0{,}61$GWh.

During stops, one can obtain:

$$E_{F1} \cong 0.7\,E_{C1} = 0.7\frac{235000}{2}\left(\frac{50}{3.6}\right)^2 = 15.9\text{MJ} \cong 4.4\text{kWh},$$

$$E_{F2} \cong 0.7\,E_{C2} = 0.7\frac{235000}{2}\left(\frac{70}{3.6}\right)^2 = 31\text{MJ} \cong 8.6\text{kWh},$$

$E_F \cong 3*4.4+14*8.6 \cong 134$kWh per journey, or

$E_F \cong 1495*4.275*134 \cong 0.85$GWh per month.

Taking into account the wasted energy during the processes of acceleration and deceleration the total wasted energy E_T is about $E_T \cong 0.61 + 0.85 \cong 1.46$GWh per month. This means 18GWh or R$ 2,500,000.00 per year (considering the energy price at R$ 0.14/kWh, which were the prices in March and April 2000), and something like 45% of the total spent traction energy.

III. A COMPARISON AMONG THE POSSIBLE TOPOLOGIES FOR THE CHOPPERS

The first possible solution to the high voltage DC chopper is the use of a direct series connection of two GTOs. However, the direct series connection of any kind of switches has static and dynamic voltage sharing problems and, additionally, GTOs must to be used with snubbers.

Large parallel connected resistors can be used to achieve static voltage balance and the snubber itself helps in the dynamic voltage sharing problem, but snubber losses still remain a problem. One interesting solution for the overall problem is the use of two 4.5kV GTOs (per chopper) and a snubber energy recovery circuit (Fig. 2) [1, 2].

In Fig. 2, Lf and Cf are the input filter; Ea_1, Ea_2, Ea_3 and Ea_4 are the armature voltages; HV is the high voltage line; TC is the traction chopper and BC is the brake chopper; G_1, G_2, D_1 and D_2 are the main switches of TC; G_3, G_4, D_3 and D_4 are the main switches of BC. All the resistors are used to perform static voltage balance. All others components are used to make the snubbers energy recovery circuits

As the capacitor bank is actually a large series/parallel connection of many capacitors and the present traction system has at least two motors always series connected, the chopper can be easily divided in two choppers series connected, one for each motor association (Fig. 3).

In Fig. 3, each current source (I_{01} and I_{02}) represents a parallel connection of two traction motors.

If the switches in Fig. 3 are GTOs, the direct series connection of the switches is not needed and the above mentioned problems are completely avoided. However, the same snubber energy recovery scheme shown in Fig. 2 [1,2] must be used. The major problem of the complete circuit is the large number of used components, but, actually, this is not a prohibitive problem and the circuit in Fig. 3 with GTOs seems to be a better choice than the circuit in Fig. 2.

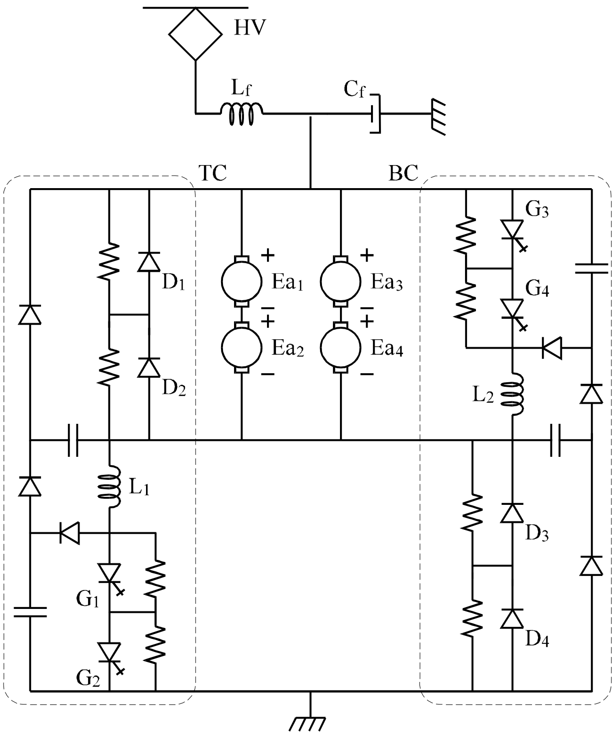

Fig. 2. Series connected GTO chopper with snubber energy recovery circuits.

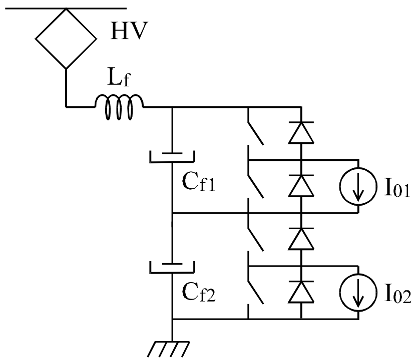

Fig. 3. Two choppers series connected.

The use of 1.7kV IGBTs in the circuit in Fig. 3 is not possible unless they are series connected. However the direct series connection of IGBTs are not recommended, because the IGBTs will need some kind of snubber in order to solve dynamic voltage sharing problems.

Fortunately, multi-level topologies can solve the problem in a better way, without any kind of snubber. As the blocking voltage of the switches of 3-level choppers is half of the input voltage, they are specially indicated to be used with IGBTs, replacing the 2-level choppers in Fig. 3.

Conventional multi-level inverter topologies using diodes (Fig. 4) [3] are not possible in chopper applications, because capacitor voltage balance cannot be achieved without an auxiliary power circuit. As an example, consider that the circuit in Fig. 4 is working in the traction mode and the output voltage is equal to half of the input voltage or zero. There are only two modes of operation: 1) All switches are opened: The output voltage is zero and the load current flows through the freewheeling diodes. 2) Only the switch S_2 is closed: The output voltage is equal to half of the input voltage and the load current flows through D_1 and S_2.

As the other clamping diode D_2 never conducts, the current Ix has always the same direction and the capacitor voltage balance is not possible.

Another interesting circuit is the floating capacitor multi-level inverter [4]. This topology is well adapted to chopper applications and can have an arbitrary number N of output voltage levels, but uses $(N-2)$ additional capacitors. Fig. 4 shows a 3-level chopper, where the additional capacitor Cx is the floating one.

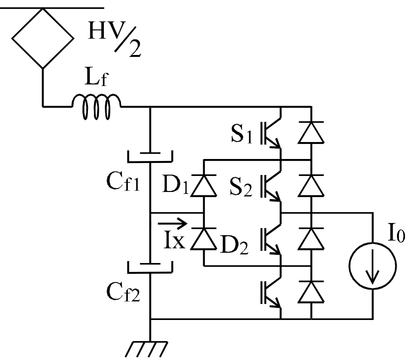

Fig. 4. Conventional diode multi-level inverter.

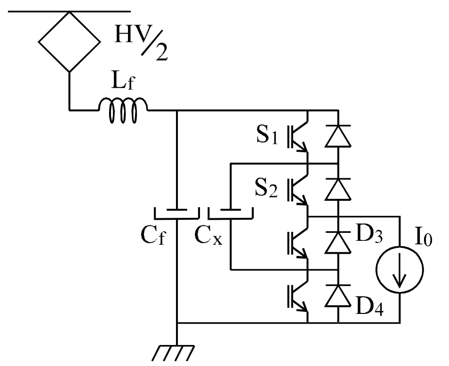

Fig. 5. Floating capacitor multi-level chopper.

The capacitor Cx can be charged (when only S_1 is closed and the load current flows through S_1, Cx and D_3) and discharged (when only S_2 is closed and the load current flows through D_4, Cx and S_2) and, for this reason, its voltage can remain stable. However, to guarantee this voltage stability, a specific control circuit is required.

This circuit has an additional problem at the power-up, because at this moment, the floating capacitor Cx is not charged, the load current is zero and the voltage across switch S_1 can be equal to the line voltage, that is the double of its nominal value. The solution of this problem is possible, but, once again, requires an additional auxiliary circuit.

As a matter of fact, the complete traction chopper can use two series connected 3-level choppers (Fig. 6) or just one 5-level chopper (Fig. 7). As the 5-level chopper has more capacitors, bigger problems at the power up and bigger problems of capacitor voltage unbalance, the circuit in Fig. 6 seems to be a better choice for the case than the one in Fig. 7.

The circuit in Fig. 8 is similar to the one in Fig. 6, as it also has two 3-level choppers series connected and also has capacitors to make the N-level function. Moreover, it has all the advantages of the one in Fig. 6 and none of those main disadvantages. It does not use additional capacitors, it does not present problems at the power up and it has a much simpler control circuit of the capacitors voltages.

IV. THE CHOSEN TOPOLOGY

Although each of the previously mentioned circuits (Figs. 2 – 8) has its advantages and disadvantages, it seems that the best choice for the present traction system is the circuit in Fig. 8. The reasons for the choice are that the circuit does not use the direct series connection of the switches, neither a large number of snubber components, nor extra capacitors, and has a simple control.

For simplicity, only numbers are naming the components in the circuit in Fig. 8. As an example, the number "1" points out to the output current source I_{01}, to the IGBT S_1, to the diode D_1 and to the capacitor C_1; and so on. It can be noticed that each current source of the circuit in Fig. 8 is, actually, a parallel connection of two traction motors.

The upper 3-level chopper is made with the components named with the numbers 1 – 4. The lower 3-level chopper is made with the components named with the numbers 5 – 8. The upper and the lower choppers are completely independent and their switches can have any modulation strategy. However, as they have identical loads, the same modulation strategy must be used for both of them.

The modes of operation of the upper 3-level chopper working in the traction mode are shown in Fig. 9. In the brake mode there are an analogous situation.

From Fig. 9, it can be concluded that the output voltage is equal to the input voltage in mode I, it is equal to half of the input voltage in modes III and IV, and it is zero in mode II. For this reason, this is a 3-level chopper.

Additionally, it must be noticed that the input voltage of the 3-level chopper in Fig. 9 is only half of the line voltage, because, actually, there are two of them series connected in the complete circuit (Fig. 8).

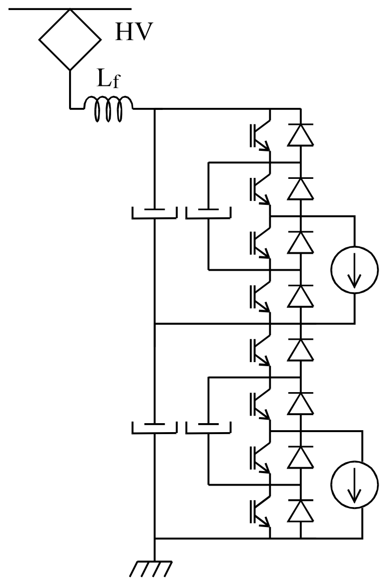

Fig. 6. Two 3-level choppers series connected.

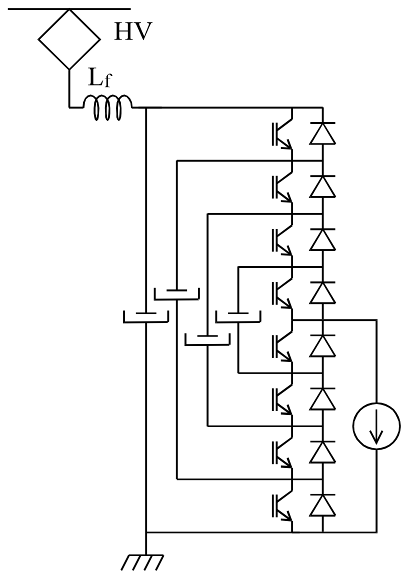

Fig. 7. The 5-level chopper.

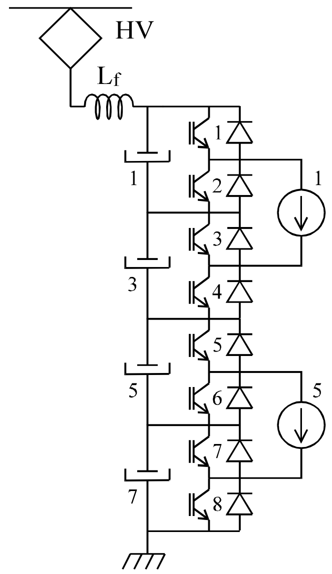

Fig. 8. The chosen topology.

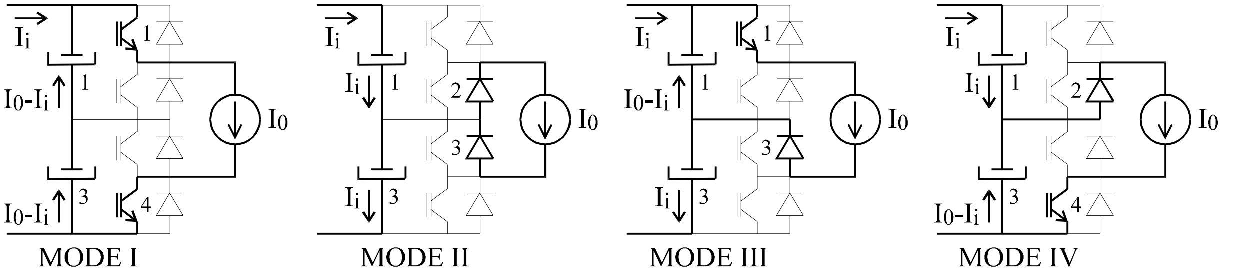

Fig. 9. Modes of operation of the traction 3-level chopper.

When the speed of the train is low, the chopper output voltage is also low and modes II, III and IV are used. When the speed is high, the chopper output voltage is also high and modes I, III and IV are used. A typical sequence of modes of operation is shown in Fig. 10.

From Fig. 10, one can realize that the reference voltage V_{ref} is compared with two high frequency triangular waves displaced from one another by 180^{o} (V_{t1} and V_{t4}) in order to generate the IGBTs gate signals V_{G1} and V_{G4}. As a result, the output voltage V_0 has only two possible sequences of modes of operation: II III II IV or I III I IV, as shown in Fig. 10.

Again from Fig. 9, it can be concluded that, considering mode I is used during time t_I, mode II during time t_{II}, mode III during time t_{III} and mode IV during time t_{IV}, the capacitor voltage balance is obtained only if $t_{III} = t_{IV}$. In a theoretical point of view, this equality is quite easy to implement. However, slight differences at the commutation times of the IGBTs cause an unbalance problem. These non-idealities force the use of control circuits that control the voltages of the capacitors. The main idea of these voltage control circuits is to make a slight shift of the gate signal at the appropriate IGBT, just in order to compensate the corresponding non-ideality.

V. DESIGN CONSIDERATIONS

The transfer function of the adopted chopper circuit is given by (4) and (5).

$$\overline{V_0} = d\,Vi \tag{4}$$

$$\overline{Ii} = d\,I_0 \tag{5}$$

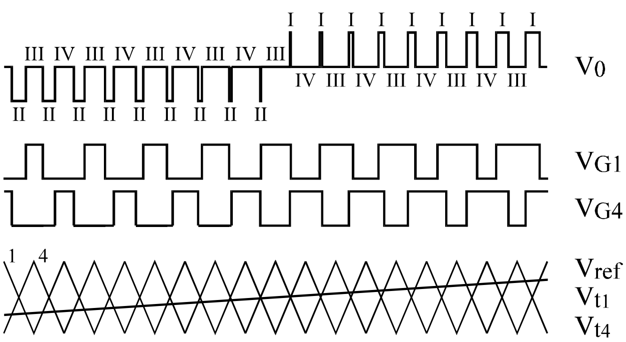

Fig. 10. The 3-level chopper modulation strategy.

where $\overline{V_0}$ is the mean value of the output voltage, $\overline{Ii}$ is the mean value of the input current, d is the duty cycle of the IGBTs, Vi is the input voltage and I_0 is the output current.

The design of the components of the circuit can be obtained from (6), (7) and (8).

$$\overline{I_S} = d\,I_0 \tag{6}$$

$$I_{CRMS} = I_0\sqrt{d-d^2} \tag{7}$$

$$\Delta Vc = I_0\,\frac{d-d^2}{C\,fs} \tag{8}$$

where $\overline{I_S}$ is the mean current of the IGBTs, I_{CRMS} is the RMS current of the capacitors, ΔVc is the voltage ripple of the capacitor, C is the capacitance of the capacitors and fs is switching frequency.

Maximum values of (7) and (8) occur when d = 0.5 and the corresponding figures are given by (9) and (10).

$$\left(I_{CRMS}\right)\max = \frac{I_0}{2} \tag{9}$$

$$\left(\Delta Vc\right)\max = \frac{I_0}{4\,C\,fs} \tag{10}$$

Considering the typical speed versus time profile of the present traction system (Fig. 11) and its influence over the design of the components, then, from (6) and (7), $\overline{I_S} \cong 150A$ and $I_{CRMS} \cong 120A$.

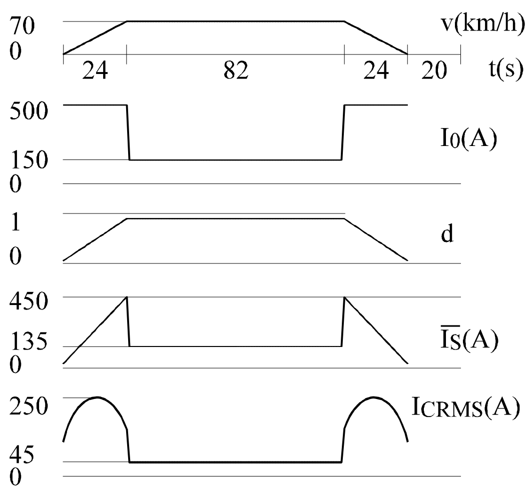

Fig. 11. Typical speed versus time profile of the present traction system.

Considering $I_0 = 500A$, $fs = 1kHz$ and $(\Delta Vc)max = (10\% \text{ of } Vc) = 86V$, then, from (10), $C \cong 1{,}500\mu F$.

With the present capacitor technology is not possible to find a capacitor that handles a current ripple $I_{CRMS} = 120A$ with a capacitance of only $1{,}500\mu F$, even with the new types that allow the use of heatsinks. Therefore, as usually happens in this kind of application, the capacitor must to be current-ripple designed, instead of voltage-ripple designed.

As a result, each capacitor in Fig. 8 is, actually, a large association of capacitors. In the present case, three 470V, 12mF capacitors are parallel connected (to handle the current ripple) and 3 of these associations are series connected (to handle the 1kV voltage), performing a total of 9 used capacitors and an equivalent capacitance of 12mF. As the circuit has 4 capacitances, each of them with an association of 9 capacitors, 36 capacitors of 12mF, 470V are needed and a total volume of $0.1m^3$ is occupied.

These numbers shown in a better way that topologies with many capacitances as the ones in Figs. 6 and 7 have, at least, one big disadvantage: the number of needed capacitors.

VI. CONCLUSIONS

In this work, the wasted electric energy in traction systems with DC motors not driven by power electronics is studied. The urban trains in Porto Alegre are used as a specific example and it was shown that the amount of wasted energy is quite important, meaning approximately 18GWh per year and 43% of the total spent traction energy.

The most appropriate topologies of high voltage choppers for the present traction system using GTOs and IGBTs are compared. It was shown that choppers with GTOs need to use many components in the snubber circuits and choppers with IGBTs need to use some scheme of voltage multi-levels.

The chosen topology is presented in Fig. 8 and the most important design equations are also presented. It was specifically shown that the capacitor bank has a big volume and its design must to be current-ripple based, instead of voltage-ripple based.

VII. REFERENCES

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