# SOLUTION FOR SPEED REGULATION AND RIPPLES LIMITATION IN THE ELECTRIC TRACTION

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*Abstract* – **The paper presents some simulated and experimental results obtained from an electric driving system with chopper of a modernized tram. One makes analysis of the operation during the running regime, at the speed increasing. Also the importance of the input filter is discussed. After the simulation of the system, the results are compared with the experimental recordings of the current and voltage waveforms, during the normal running stage of the tram that use this kind of electrical drive.**

***Keywords***: *electrical drive, pulse width modulation, system simulation, experimental waveforms.*

## 1. INTRODUCTION

Choppers are widely used for traction motor control in electric vehicles, trolley-buses, trams etc. because they provide smooth acceleration control, high efficiency and fast dynamic response. In the same time, the regenerative braking becomes efficient due to the energy that is turned back to the d.c. voltage line [1], [2], [3], [4].

Because of these advantages a solution with choppers was chosen in order to modernize the trams used in Romania and that have been imported from Germany [5], [6]. These vehicles are endowed with traction motors of 600 Vd.c. (two d.c. series motors at rated voltage of 300 V d.c. each), but are supplied from the 825 V d.c. network.

The first solution that had been adopted was the introduction of a resistance in series with the d.c. motors in the rotor circuit. But this technical solution presents a series of drawbacks, the most important of them being the low energetic efficiency.

That was why a solution was adopted in order to modernize the existing vehicles through major changes in the power circuit. These changes focus both on the removing of series resistances and on the substitution of starting rheostats of classic driving by variable voltage regulators (choppers) realized with IGBT, that provide the current control in the regimes "RUNNING" and "BRAKING".

The general block scheme of the electronic equipment with chopper for traction motors' driving is presented in Fig.1. It includes: input filter; recovering diode; filter for intermediate circuit; choppers with IGBTs and electronic control unit with microprocessor.

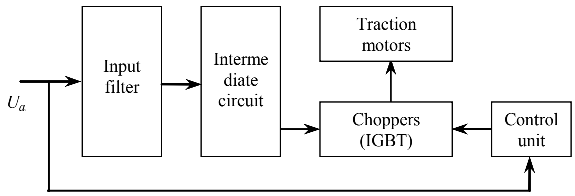


Figure 1: Block scheme of the equipment

The solution that was adopted contains a chopper for the running/braking regimes for each bogie and a chopper for resistive braking. The braking chopper switches into the conduction regime only when the braking voltage is greater then the imposed maximum voltage.

In the same time, one must consider the problems of electromagnetic compatibility that could appear. The active components are the main noise sources in switched mode power systems. The semiconductor devices are utilized as switches where the designer's concern consists in reducing the power losses. Switching operation generates signals with significant $du/dt$ and $di/dt$ and, consequently, wide bandwidths of disturbances. Because the power electronics equipment is usually connected to the supplying lines, those wide-band signals are traveling through them and pollute the electromagnetic environment with unwanted interference. In order to limit them up to an acceptable value (specified in standards) filters must be used. In our solution, an input filter and a line filter in the intermediate circuit were used.

In order to verify cheaply the functionality of the solution that was chosen one performs the simulation of the system during the regimes of interest [7].

In this paper, the variation of the electric quantities at the speed increasing is simulated. Also the influence of the input filter is underlined [8], [9].

The results of the simulations were compared afterwards with the experimental waveforms obtained during the exploitation of the tram endowed with the modernized system.

## 2. THEORETICAL ASPECTS ON THE OPERATING PRINCIPLE OF THE SYSTEM

The traction motors can be considered as a RL load supplied by a d.c. voltage of a variable value. The supply voltage is adjusted using the chopper. For its control, the control by pulse width modulation (PWM) is used.

The mean value of the output voltage is given by the relation [1], [2]:

$$U_m = \frac{1}{T} \cdot \int_0^{t_1} u_0 \, dt = \frac{t_1}{T} \cdot U_a = k \cdot U_a \qquad (1)$$

where $T$ is the period, $k = \frac{t_1}{T}$ is the operating time ratio and $f = T^{-1}$ is the frequency of the chopper. In our case the frequency of 2kHz was chosen for the chopper.

During the running regime, the operating principle of the chopper can be divided as follows [3]:

- the chopper is set ON and the current flows from the source toward the consumer;
- the chopper is set OFF and the current flows through a freewheel diode D.

In the running regime, when the chopper is ON, the load current $i_1$ is given by the expression:

$$i_1(t) = I_1 \cdot e^{-t \cdot R/L} + \frac{U_a - E}{R} \cdot \left(1 - e^{-t \cdot R/L}\right), \qquad (2)$$

where $U_a$ represents the line supplying voltage, $E$ represents the total electromotive force induced by motors, $R$ represents the equivalent resistance of the series motors (mainly due to the stator and rotor resistances), $L$ is the equivalent inductance of series motors (mainly due to the stator and rotor inductances) and $I_1 = i_1\big|_{t=0}$. For the sake of simplicity (to understand better the operating principle), one can assume as constant the values of $L$ and $R$.

When the chopper is OFF, the load current $i_2$ can be determined using the relation:

$$i_2(t) = I_2 \cdot e^{-t \cdot R/L} - \frac{E}{R} \cdot \left(1 - e^{-t \cdot R/L}\right), \qquad (3)$$

where $I_2$ is the value of the current at the end of the operating time ($t = t_1$). At the end of the OFF case, for the steady state conditions, the load current becomes again $I_1$.

The variation of the speed in the running regimes is accomplished through the modification of the supplying voltage and implicitly of the current that is to be prescribed. Thus, for the speed increasing, the operating time ratio k must be modified up to a value $k' > k$. The value of the current through the traction motors will be increased up to a prescribed value. In this case, when the chopper is ON, the load current will be $i_1^{'}$, given by the expression:

$$i_1^{'}(t) = I_1^{'} \cdot e^{-t \cdot R/L} + \frac{U_a - E}{R} \cdot \left(1 - e^{-t \cdot R/L}\right), \qquad (4)$$

where $I_1^{'} = i_1^{'}\big|_{t=0}$, $I_1^{'} > I_1$, and when the chopper is OFF, the load current $i_2^{'}$ can be determined using the relation:

$$i_2^{'}(t) = I_2^{'} \cdot e^{-t \cdot R/L} - \frac{E}{R} \cdot \left(1 - e^{-t \cdot R/L}\right), \qquad (5)$$

where $I_2^{'}$ is the value of the current at the end of the operating time ($t = t_1^{'} = k' \cdot T$).

The peak-to-peak value variation of the current is:

$$\Delta I = I_2 - I_1 \text{, respectively } \Delta I' = I_2^{'} - I_1^{'} \qquad (6)$$

From the relations above one obtains for the first value of the speed, for example:

$$\Delta I = \frac{U_a}{R} \cdot \frac{1 - e^{-k \cdot T \cdot R/L} + e^{T \cdot R/L} - e^{-(1-k) \cdot T \cdot R/L}}{1 - e^{-T \cdot R/L}} \qquad (7)$$

In order to limit these ripples caused by the fast variations of the current, a filter must be used at all costs. This is mainly the role of the input filter. The filter can operate in both directions. If so, it will be effective for the disturbances produced by the chopper that could propagate towards the supply line (figure 2); in the same time, the possible noises from the line will be partially eliminated by it (figure 3).

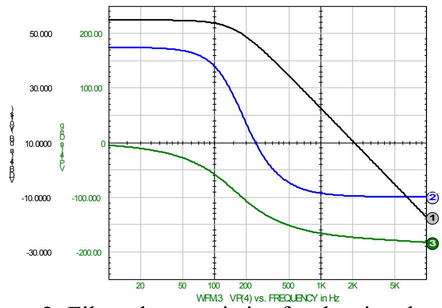


Figure 2: Filter characteristics for the signals coming from the chopper (graphic 1-the attenuation)

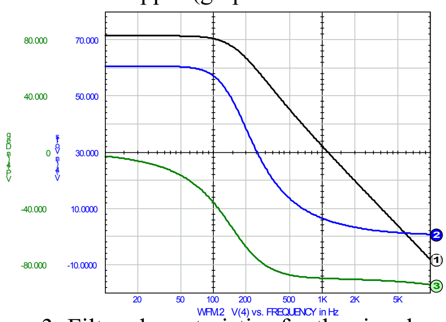


Figure 3: Filter characteristics for the signals coming from the line (graphic 1-the attenuation)

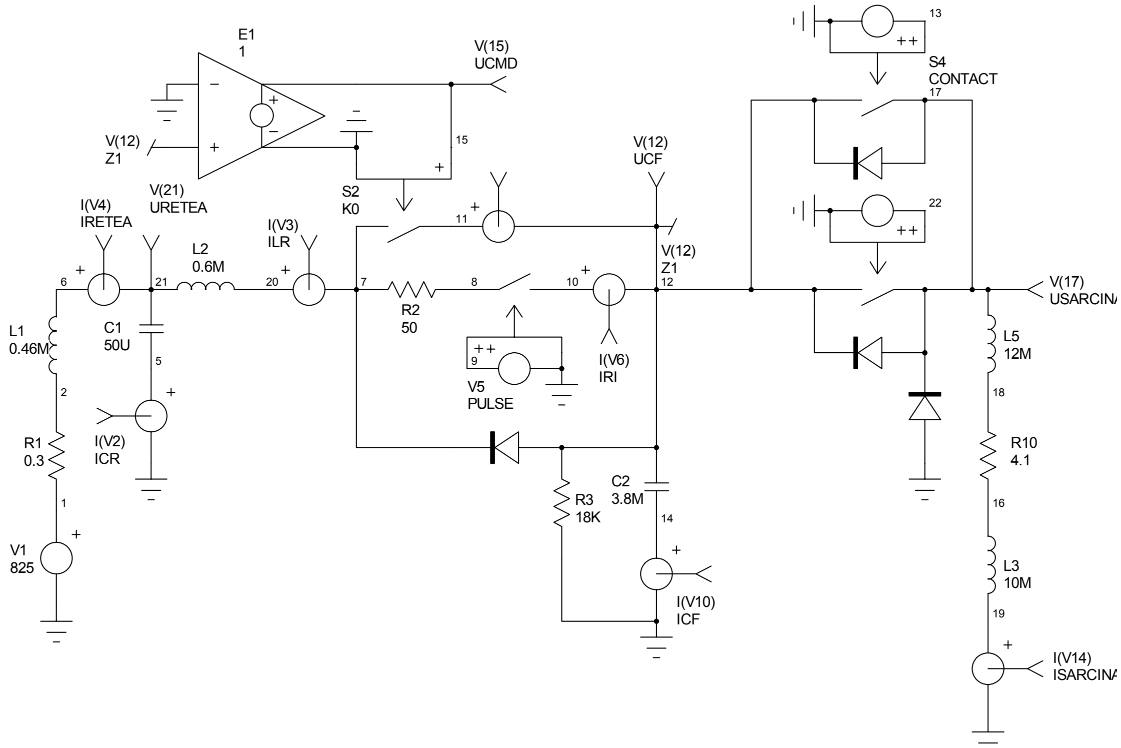


Figure 4: Electric schema considering the filtering circuit (in SPICE)

The resonance frequency of the filter must not fit to any of the values from the frequency spectrum produced by the chopper. It must be inferior to the chopper's operating frequency:

$$f_0 = \frac{1}{2 \cdot \pi \sqrt{L \cdot C}} < f_{chopper} \qquad (8)$$

## 3. SIMULATION OF THE OPERATING REGIMES

Starting from the above analysis, a schematic circuit was conceived and implemented in SPICE (Fig.4).
The values of the RL load's parameters from the right side are the equivalent values of the two series motors of one bogie. On the left side, the supply line parameters are considered; for the sake of simplicity one assumes also that these parameters are constants (in the simulation process).
Firstly one performed the simulation of the entire system, with input filter and intermediate circuit. The possibility to vary the speed in two levels is available.
Figure 5 shows the network voltage (without compensation from the supply station or from other trams that could be connected to the same line) (graphic 1), the current in the supply line (graphic 2) and the current trough the load (traction motors) (graphic 3).

One can notice the current limitation, for each of the speed level, to the prescribed values of 80 A (for the first level) and of 130 A (for the last level). The supply voltage remains almost constant to the value corresponding to the normal functioning. Even if one can notice a small decrease of its value, it is not present in the real operation of the system, in the ideal case.
The simulations show that the supply line current has no jumps and the supply line voltage has no picks due to the switches. Analyzing the load current one can notice the absence of the shocks in the load;

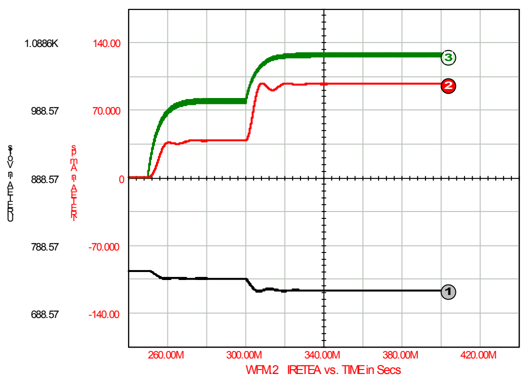


Figure 5: Supply line voltage (graphic 1), current in the supply line (graphic 2) and the current through the load (graphic 3) in schema with filters.

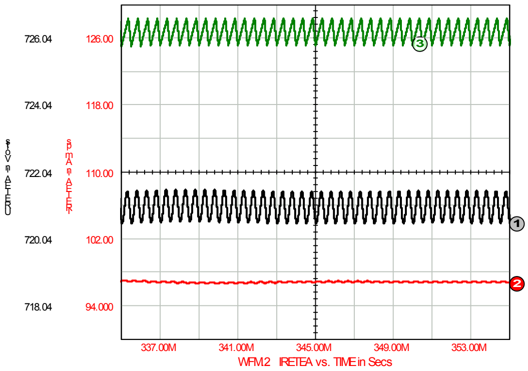


Figure 6: Line voltage (graphic 1), supply line current (graphic 2) and load current (graphic 3) for the second speed value

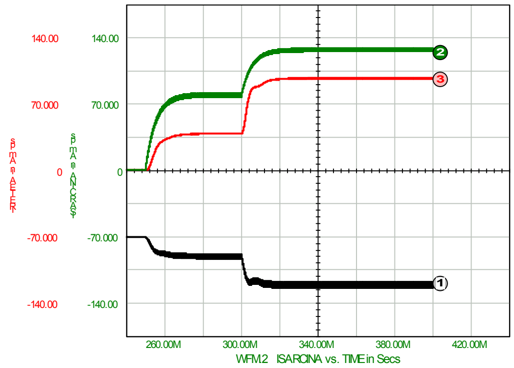


Figure 8: Supply line voltage (graphic 1), current through the load (graphic 2) and the current in the supply line (graphic 3) in schema without input filter.

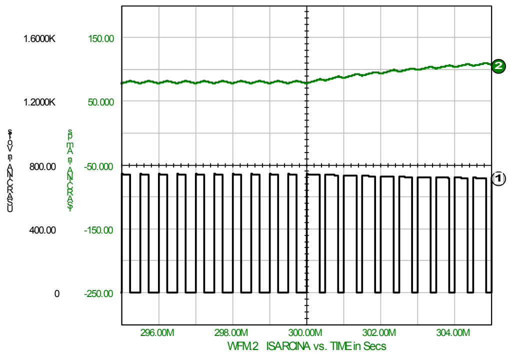


Figure 7: Load voltage (graphic 1) and load current (graphic 2) during the change of the speed

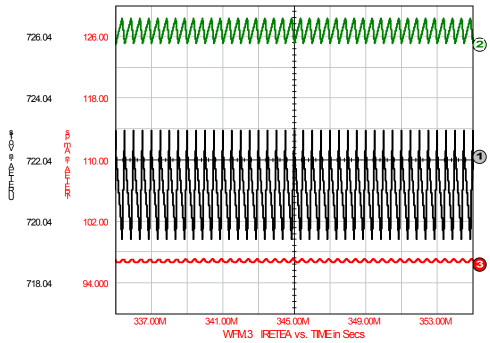


Figure 9: Supply line voltage (graphic 1), motors current (graphic 2) and the supply line current (graphic 3) in schema without input filter, for the second speed value

this means that the traction motors are spared and the probability of fault is low. Also the travelers' comfort is improved.

Figure 6 presents the electrical quantities in the same case, during the running at constant speed, corresponding to the second value of the prescribed current.

Thus one can see how the ripples are minimized up to acceptable levels; the peak-to-peak value variation of the supply voltage is of around 1V and the current ripples in the supply line are below 0.4 A.

Figure 7 depicts the equivalent consumer voltage (graphic 1) and the current through the motors (graphic 2) during the modification of the speed; it corresponds to the modification of the current during the running stage, from the first prescribed value of 80 A to the second one of 130 A. The voltage waveform shows the increasing of the operating time ratio in this case.

If one eliminates the input filter from figure 4 in order to show its influence, some important perturbations can be noticed. They are observed in the graphics depicted by figures 8 and 9.

One can see that in the absence of the filter, the current through the motor presents variations between 112 and 117 A (of 5 A), while in the circuit with filtering system the variations of the current do not reach the value of 3 A, value that is accepted by the standards.

This means that the current superior harmonics are reduced and consequently the motor's supplementary stress is reduced.

As for the supply voltage, it presents significant ripples, four time higher than in the case when the input filter is used.

These facts result into the reduced exploitation costs, an increased period between two repairs, a longer lifetime for the entire system, etc.

## 4. EXPERIMENTAL RESULTS

The system that was presented previously was implemented on a KT4D tram. After its installation on the tram, experimental determinations were made. During the experimental tests one performed recordings using the scope of the load current and voltage waveforms for various operating regimes (running, regenerative braking and mechanical brake). The oscillograms were recorded choosing the scope time basis for an optimum visualization, namely 1 s/div. The current waveform was recorded using the first scope channel (waveform CH I) and

the voltage waveform was recorded using the second channel (waveform CH II).
They proved that the system was design properly and its functioning is in accordance with the expectations.
In order to compare the theoretical with the practical results, the waveforms of the current and of the voltage corresponding to one of the running/breaking chopper during the first and the second running stages are presented further (figure 10).

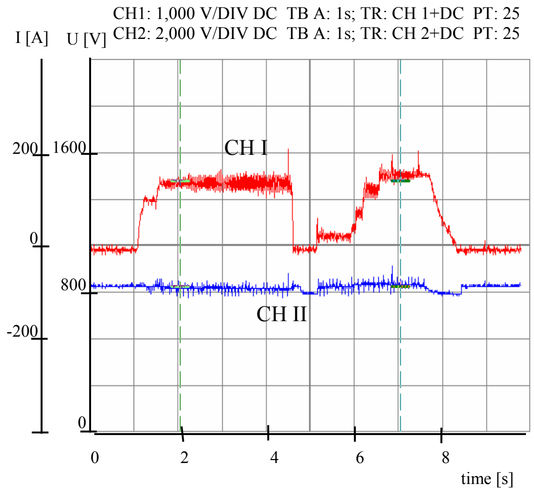


Figure 10: Current and voltage corresponding to the chopper during the first and the second running stages

The pressing level of the running treadle determines each stage of the current. Thus, for example, when the driver presses the acceleration pedal on first stage (with lower intensity) the current raises with a slope of 150 A/sec, followed by its stabilisation to a value of 100 A for 0.5 sec., value that corresponds practically to the first running stage. Afterwards, pressing on the running pedal, one passes to the second stage and the current remains constant to a value of 130 A. After 6 sec., the driver releases the running pedal and consequently the current falls to 0 A. Afterward the breaking regime is installed.
On the voltage oscillogram one can notice that the voltage from the supplying line has an initial value of 820 V and afterward the acceleration process begins, when the voltage drops to 812 V. The voltage rises when the running pedal is released up to a value of 832 V and then falls to 800 V during the resistive braking regime (no other consumer is connected to the same line).
One can notice both on the voltage and on the current oscillograms that some noises appear; they are caused mainly by the mechanical chocks of tram in running regimes or of the switches when they are submitted to state changes. During the measurements one must also consider the possible disturbances from the supplying line due to other trams in running regimes or faults on line.

One can notice the low level of voltage ripples. Even if sometimes the voltage value can grow (for example at regenerative braking), its value falls within the operational range admitted by the beneficiary.

## 5. CONCLUSIONS

By analyzing the simulated and the experimental results, one can notice than they are similar, with small differences caused by the exploitation conditions that could not be simulated in their total amount. In the same time, at the initial design stage level all the parameters and the limitations are not totally finalized; some of them could be modified during the subsequent stages of the design, even during the practical determination. So, if the parameters could be a little different, the operating modality and the behavior of the system remain the same.
One could observe also that the input filter and the line filter for the intermediate circuit significantly reduced the electromagnetic interferences. This means an important improvement in the electromagnetic compatibility.
The new equipment has the advantages that it eliminates the shocks corresponding to start, stop and speed regulation regimes, directly influencing the travelers' comfort.
Now the modernized vehicle is under exploitation. Its monitoring continues in order to define exactly the reliability indicators and the maintenance program.

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