ELECTRIC RAIL – PROBLEMS OF THE CONTROLLING AND SUPPLYING EQUIPMENT

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Lucrarea tratează probleme ale tracțiunii electrice feroviare moderne: alimentarea cu energie a vehiculelor, utilizând echipamente moderne de alimentare, comandă şi reglare, iar în a doua parte, cele mai noi metode de proiectare şi comandă ale acestor echipamente. După o scurtă prezentare a evoluției tracțiunii electrice, este descrisă modalitatea de proiectare a echipamentelor electronice de alimentare care să aibă în vedere atât consumul redus de energie (valoarea maximă a factorului de putere) cât şi solicitarea minimă a echipamentului. În opinia autorilor, acestea sunt probleme importante în tracțiune.

The paper presents the problem of the modern control, setting and supplying equipment in electric rail, based on the most recent techniques of designing. After a short review of the electric traction development, we present the manner to enhance the supplying and control equipment to get the best efficiency in energy consumption and the traction equipment stability. In authors' opinion this represents an important actual problem in the electric rail transports.

Keywords: traction, control, power factor, converters

1. Introduction

A great number of industrial equipments in energetic or in rail and urban transports need the energy conversion to supply various consumers, such as DC or AC generators. These get the primary energy from various sources (fig. 1–diesel engine). The output voltage has to be constant, no matter the rotation speed - in a set range, or the load changes.

The technology evolution and the development in electronics and mechanics in the last decades, carried on to the important achievements applied in the modern rail vehicles. All these factors lead to the record speeds of over 570 km/h. Greater speeds of the traction vehicles will be possible only using new traction principles, which don't base on the wheel-rail adherence force.[1]

The electrical traction has important advantages compared to the other types of traction: higher speeds, a lower fuel consumption (or null, when electrical

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energy is produced by hydro, nuclear, solar or wind ways), the reduced pollution effect, the increased rail safety, traveler's greater comfort.[2]

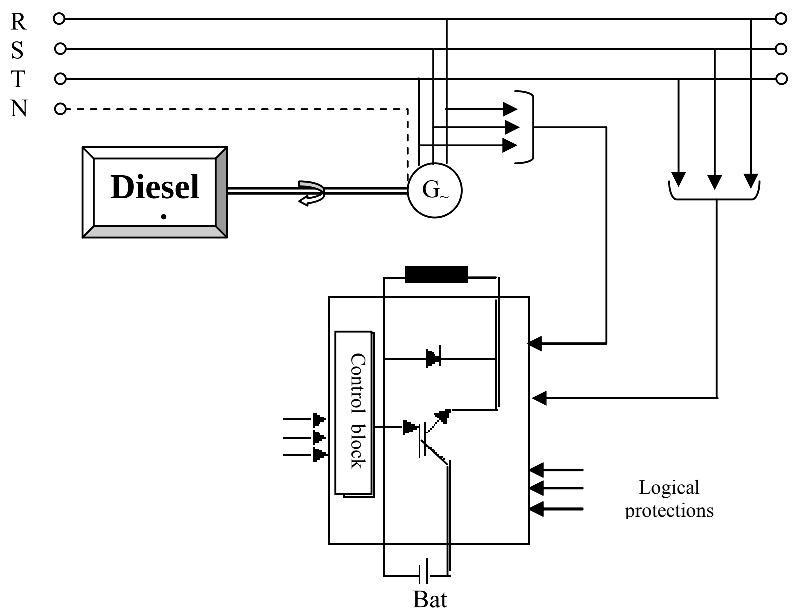

Fig. 1. The control and supply principle of a synchronous generator

The rail traction vehicles are supplied in DC or in AC. The advantages of the latter type imposed it:

-easy transport at great distances using high voltage lines (110 kV)

-small losses due to wire heating

-the electrical machines that are producing the AC energy in the power stations are smaller, more robust and easier to keep up than the DC ones.

One of the most modern methods to efficiently control the traction engines is the field-oriented control. [3].

The standard AC rail traction lines in Europe are supplied at 25kV/50 Hz or 15kV/16+2/3 Hz single-phase. The vehicles must be able to use both supplying systems, changing either automatically or manually some units – especially for the main transformer of the vehicle.

2. The constructive and working principle of the electrical locomotives

The structure of the electrical locomotives evolved, as a result of the technological development. The modern working principles could be applied only when progresses in the electronics and in the data processing were implemented.

The first electric locomotives had great power rectifiers, fed from the high voltage line, by the transformer of the locomotive. The DC machines were largely used due to their natural torque-speed characteristic, fitted to the traction effort-speed diagram of a vehicle.[4] The electric principle scheme of such a locomotive is represented in fig. 2.

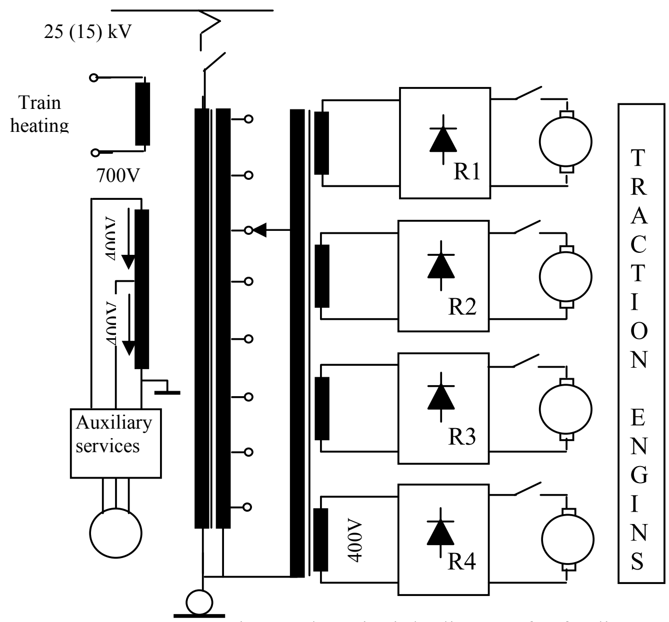

Fig. 2. The principle diagram for feeding the equipments of a locomotive

The efficiency of this scheme made it to be still applied in the locomotives. A step-changer that feeds the rectifiers with an AC step-voltage performed the power control. The designing and the control of the traction equipment have to take into account, besides the main elements, the secondary services equipment, which requires approximately 200 kW of the installed power. The rectifiers R were single-phase, double pulse, so that the power factor was not higher than 0.65 – 0.75. The rectified current had to be filtered with sufficiently great inductance, in order to get a low ripple, which prevents the overheating of the engine or the electromagnetic vibrations and shocks[5]. If the auxiliary services are fed by a synchronous generator (fig. 1), the main task of the control equipment is the speed control, so that the voltage frequency be in a strict given range. It has also to maintain constant the output voltage, but it may provide the protection against overload or short-circuit.

The principle of such an application uses the mechanical and control characteristics of the generator and the current control in the armature of the electric machine, so that the output voltage remain constant. The modern control equipment – the choppers, especially the IGBT-based ones (Insulated-Gate Bipolar Transistor), replaced the inefficient power rheostatic control systems, great energy consumers, and improved the system control capacity and accuracy[6]. The IGBT choppers are able to supply control currents beginning with amperes to hundreds of amperes in the machine's armature, relied to the machine power and parameters (0.5 kW to MW). Such equipments are used in the electrical traction, for the auxiliary services, the traction engines etc (fig. 1,2).

Concerning the equipment in fig. 2, the step-changers were replaced with controlled (or semi-controlled) rectifiers, (fig.3), which allow the continuous control of the power, from zero to the maximum value.

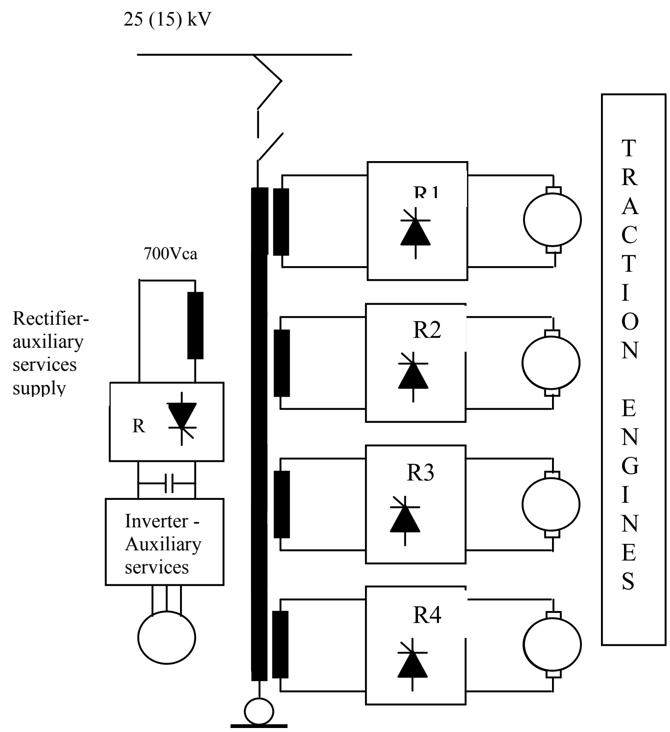

Fig. 3. The principle diagram for driving the traction engines and for supplying the services

In this diagram, the blocks R1, 2, 3, 4 are the controlled rectifiers –for the traction engines and R is the controlled rectifier for the auxiliary services.

A frequently used manner of control and supply consists of a SCR (Semiconductor-Controlled Rectifier) and a PWM (Pulse Width Modulation) three-phase inverter, based on IGBT transistors, as it is presented in fig. 4.

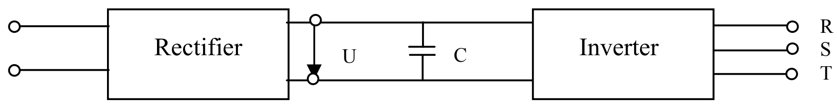

Fig. 4. The block diagram of a converter with PWM inverter

The inverter also supplies the auxiliary services (fig. 5).

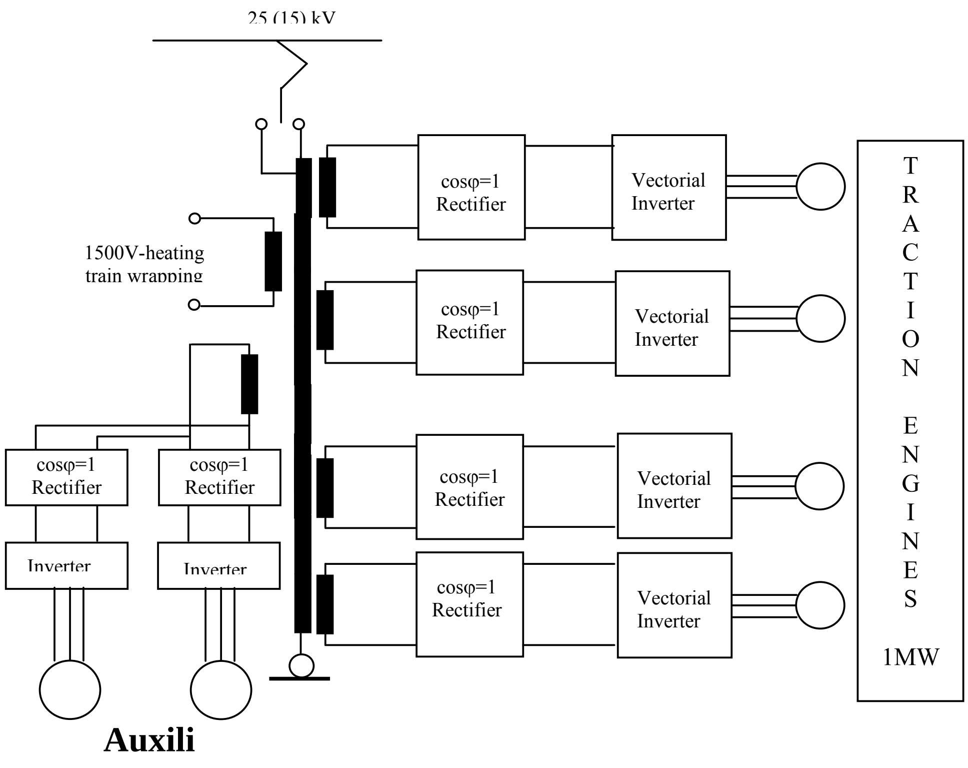

Fig. 5. The block diagram of a locomotive with asynchronous engines, supplied with inverters and with cosφ=1 converters

The frequency converters based on performance electronic devices made possible the simultaneous control of the voltage and frequency, and the wide range speed variation. Even if the converter generates harmonics, the possibility of changing the speed, as the situation requires it, makes the whole system efficient. [7]

3. Four-Quadrant Chopper Rectifiers (FQR)

As it was mentioned before, the electric equipment of the locomotive has to be supplied in DC. The rectifier design implies various problems such as the energy quality, the power factor value, and the efficient control of the parameters.

The power factor must have the value as near to 1 as possible. The value of the power factor is the result of the cosφ and the distorting harmonics. These harmonics have to be compensated, so that the value of the power factor is as much as possible near to the maximum value. From the point of view of the network, a value cosφ=1 means, practically, a resistive load [8].

The usual rectifiers have a quit satisfactory power factor, but an important harmonics content. The correction of this aspect is possible using a rectifier, which can modify the value of cosφ and diminish the harmonics. [9]

The principle scheme of such a rectifier is presented in fig. 6. It must accomplish the following conditions:

- i - sinusoidal shape and in phase with U
- the output voltage U_s –well filtered
- i_s - DC.

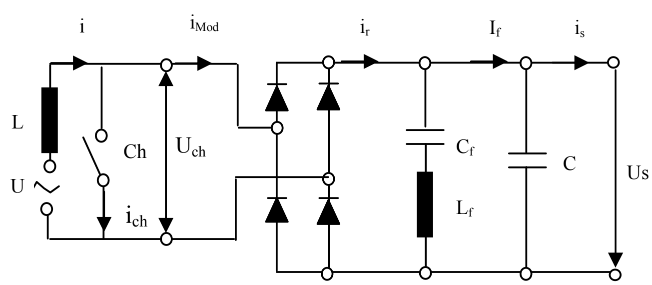

Fig. 6. The diagram of the rectifier

The switch Ch serves to modulate the voltage U_s, so that $U_{ch,}$ and, consequently i, be sinusoidal.

The current will approach to the sinusoidal shape if the commutation frequency of the device Ch will be sufficiently high, and the value of L – sufficiently low.

The shapes of the input, rectified and filtered currents i, i_r and I_f are presented in fig.7.

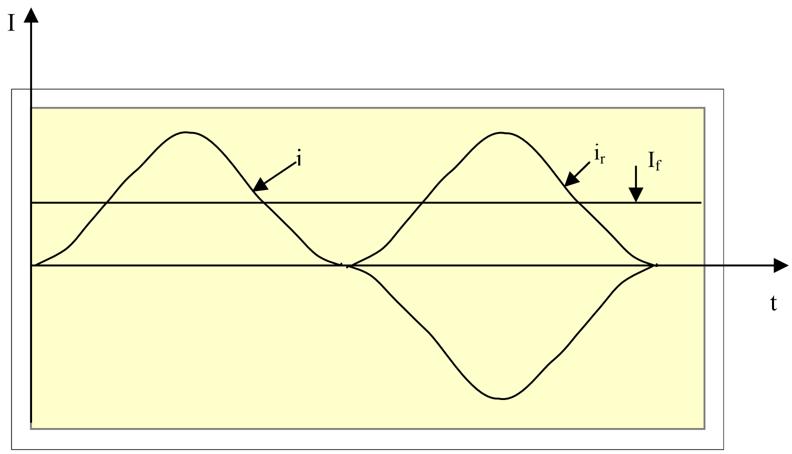

Fig.7. The shapes of the currents

The sinusoidal pulse width modulation, operated by Ch identically in the two semi-periods, changes the current i from the equation 1:

$$i(t) = I_{max} \cdot sin(\omega t) \quad (1)$$

That leads to the current:

$$i_{mod}(t) = I_{max} \cdot sin(\omega t) \cdot |sin(\omega t)| \quad (2)$$

This current is rectified, the result being i_r:

$$i_r(t) = I_{max} \cdot sin^2(\omega t) = I_{max}(1 - cos^2(\omega t)) \quad (3)$$

The equivalent form of i_r:

$$i_r(t) = I_{max} / 2 - cos(2\omega t) \cdot I_{max} / 2 \quad (4)$$

allows to observe that it consists of a continuous component $I_{max}/2$ and an alternative component, having the amplitude $I_{max}/2$ and the frequency double of the network's one.

After filtering that AC current by L_f and C_f, the result is the DC I_f and the voltage U_s (the amplitude of the current being I/2).

The scheme in fig. 6 is a Two-Quadrant Rectifier (TQR), but it cannot operate as an inverter.

A principle structure that may be used to get both waves commutation is shown in fig. 8, where each diode has a chopper (Ch1, Ch3) in parallel.

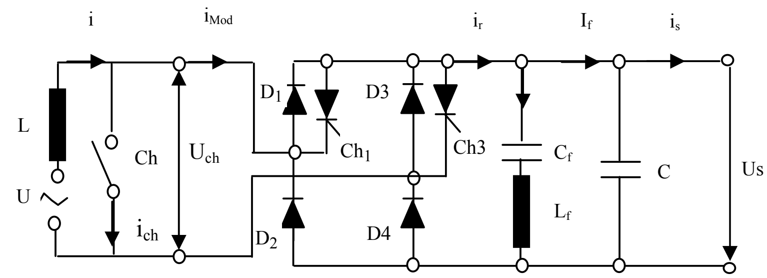

Fig.8. The principle diagram of a rectifier with cosφ=1

The presence of L determines a phase difference between U and U_{ch} as it can be observed in the diagram 9.

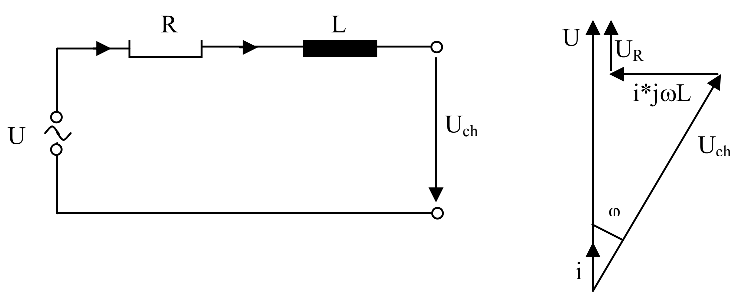

Fig. 9. The phase difference between U and U_{ch}

The switching of Ch has to be operated in a manner that leads to a phase difference φ. Equation 1 becomes:

$$i_{mod}(t) = I_{max} \cdot sin(\omega t) \cdot \left| sin(\omega t - \varphi) \right| \quad (5)$$

After processing the equation 5, the current i_r will be:

$$i_r(t) = (I_{max} / 2) \cdot cos(\varphi) - (I_{max} / 2) \cdot cos(2\omega t - \varphi) \quad (6)$$

The current i_{mod} and the voltage U_{ch} are in phase, and i_r is positive. According to diagram 10, in the d interval occurs a negative component of i_r; it requires filtering the rectified current.

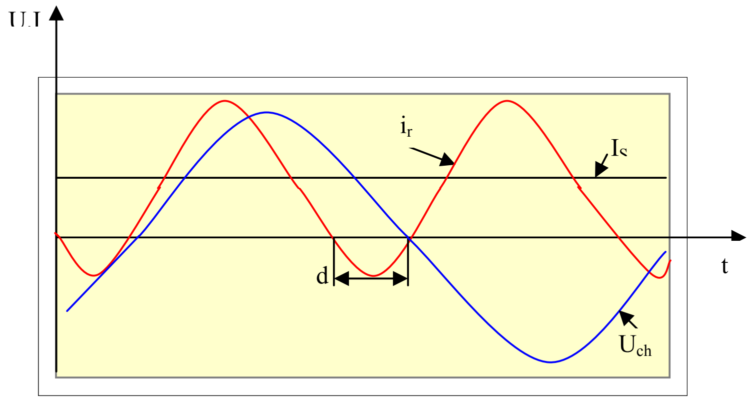

Fig.10 The current-voltage phase difference

The phase difference between U_{ch} and i_r requires the presence of a reactive power. As the rectifier doesn't have elements that accumulate energy, in order to supply the reactive energy, this has to be obtained by its operating manner: recovering the energy from the negative front of the current wave. The result is a FQR rectifier, with a special sequence of controlling the switches Ch1-Ch4 (fig. 11).

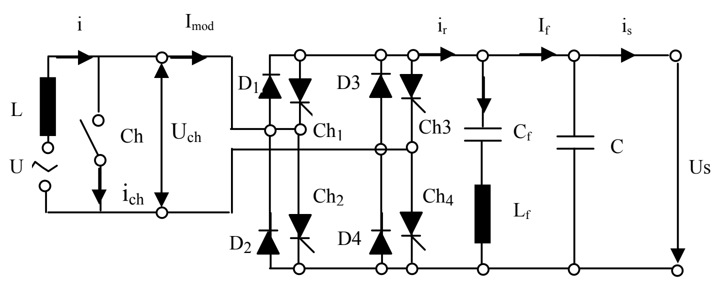

Fig.11. The principle diagram of the FQR module

This switching sequence has to be relied to the polarity of the current. A much simpler method is based on the network's frequency synchronization, without setting the real values of the current. Knowing that the valves of the chopper don't open relied to the value of the current, but to that of the input voltage U_{ch}, no matter the direction of the current in the chopper, it results the opening order of the FQR, identical in each semi-period.

In the positive semi-periods of U_{ch} the voltage pulses are applied on Ch1 and Ch4. The network voltage short-circuiting moments, through L, alternate between the switches Ch1, Ch3 and Ch2, Ch4. It results the switching order:

$$Ch1 - Ch3 : 1-4; 2-4; 1-4; 1-3$$

In the negative semi-period the order is:

$$Ch2 - Ch4 : 2-4; 2-3; 1-3; 2-3; 2-4$$

Before the d area, the current flows through Ch1 and Ch4. If the switches get the firing pulses, then the current will flow through Ch1 and Ch4 (the negative semi-period). The same situation occurs in the d area: the choppers Ch1 and Ch3, respectively Ch2 and Ch4 are switching. The sense of the current must be changed, relied to the situation. That manner of controlling the switches allows the rectifier to work in breaking regime (energy recover), without changing the switching program.

The transfer of the energy can be done in both directions: from the network to the intermediate circuit, when the energy is absorbed by the circuit (the traction conditions), and from the intermediate circuit to the network (the breaking conditions). Both the output and the power factor are great in the breaking and in the traction conditions.

The principle structure of a single-phase FQR is shown in fig. 12, where R_s is any resistive or inductive load, or an inverter supplying the electric machines.

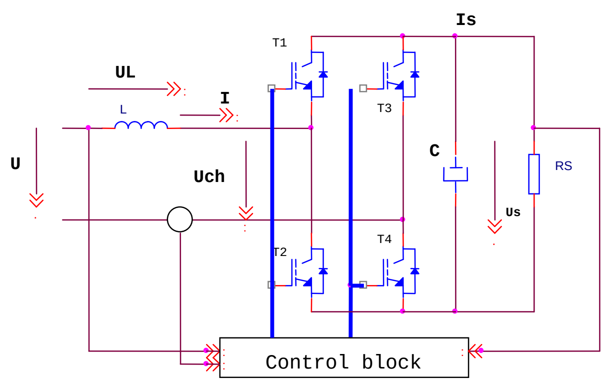

Fig. 12. The diagram of the FQR rectifier with IGBT transistors

The voltage is stabilized, the current I is sinusoidal and in phase with the supplying voltage U.

The shapes of U_{ch} and i are presented in the diagrams 13 and 14.

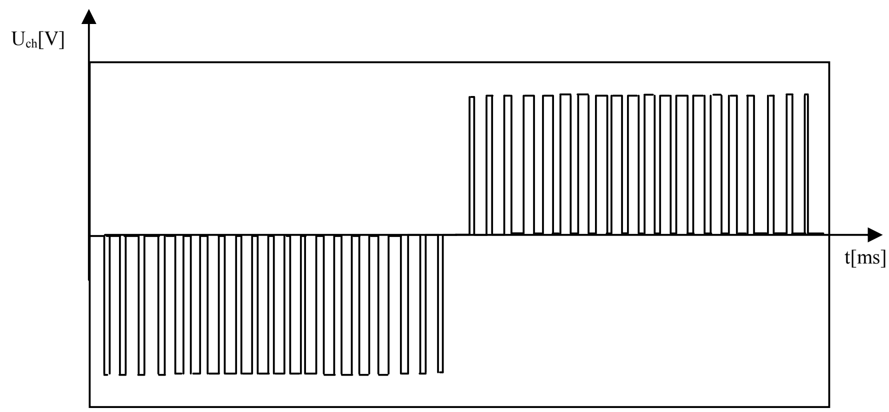

Fig. 13. Time variation of the voltage U_{ch}

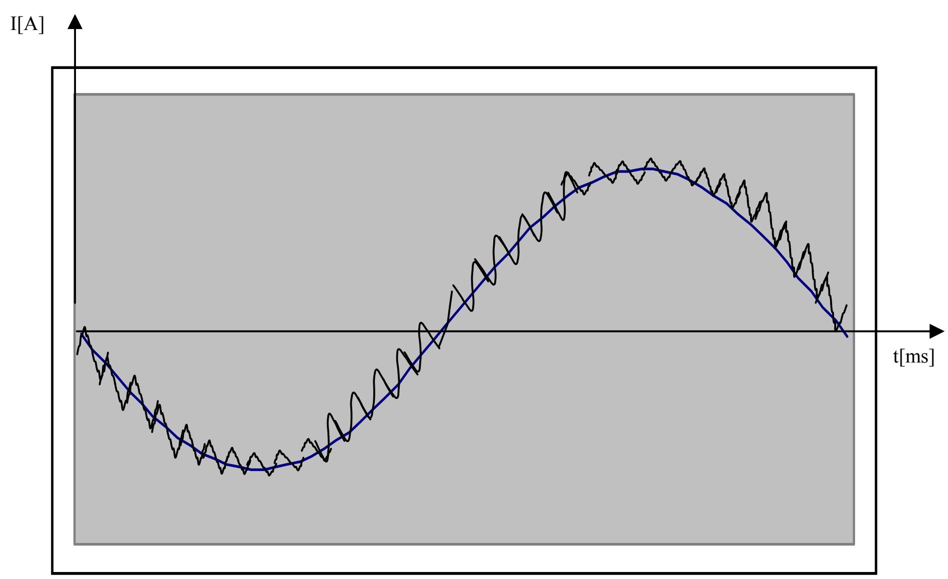

Fig. 14. The variation of the current i

U_{ch} is PWM modulated and its average value is sinusoidal; the voltage pulse amplitude is U_s. U_{ch} is 0 when two of the rectifier's switches are short-circuiting the supply voltage by L. The voltage rectangular shape is PWM integrated, thus resulting a sinusoidal shape – fig. 14, where the ripple is as lower as greater the switching frequency is. The U_{ch} phase is controlled in order to lead to a zero phase difference between i and U. As a consequence of the high switching frequency, if, for example, f is equal to 1 kHz, the network harmonic spectrum has the shape presented in fig. 15.

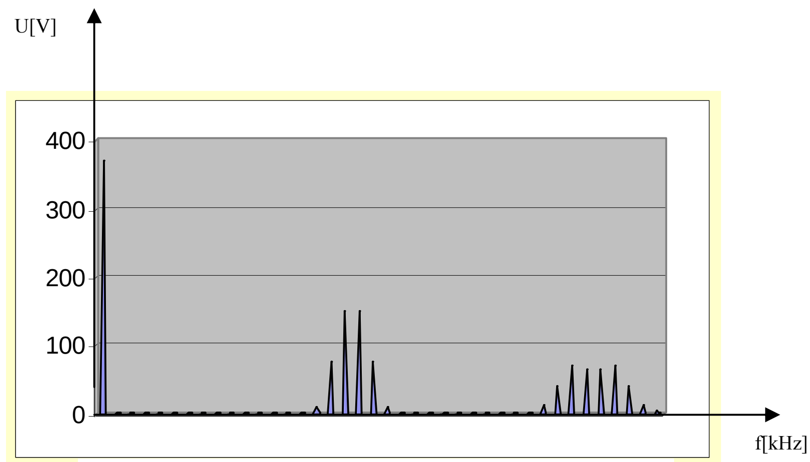

Fig. 15. The spectrum of the harmonics in the network

The first harmonics that appear in the network around the switching frequency are grouped centered on the switching frequency multiples.

The control-setting structure of the FQR rectifier is presented in the block diagram (fig. 16).

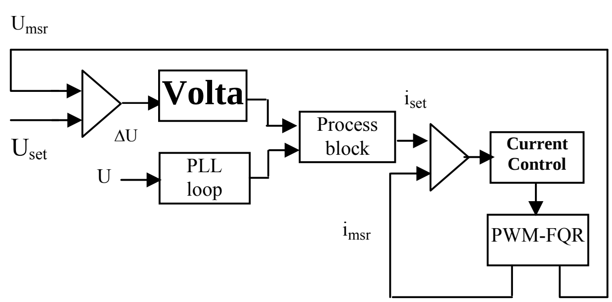

Fig. 16. The control block diagram of the four quadrant rectifier

The finite commutation frequency of the chopper generates a large spectrum of high frequencies in the input voltage U_{ch}. The result is the presence of high harmonics in the network current. The current through L is the result of the integration of the rectangular chopped voltage pulses of U_{ch}, their average value being a sinusoid (fig. 14).

The current ripple through the inductance is proportional with the period of the applied voltage pulse (sPWM):

$$T = \frac{1}{2} \cdot f \tag{7}$$

Taking into account the supplied power, it is not possible to increase the value of L over certain limits, or to increase the commutation frequency f, in order to reduce the current pulses and the harmonics in the network.

For greater powers, they may be used 2 or more (n) FQR in parallel. With a proper triggering of the rectifiers, it is possible to decrease the high oscillations in the network. The effective total value of the high oscillations in the network current diminishes in 1/n ratio, compared to the corresponding value of a single FQR.

4. Conclusions

The electric AC driving is an important part of the electric rail. Due to its characteristics, the AC traction replaced, almost totally, the other rail traction alternatives.

The development of the electronic devices and of the data automatic processing made possible to use the asynchronous engine – much more simple and robust than the former used engines.

Power systems based on modern power electronic devices, like the IGBT and GTO, proven higher efficiency and operational characteristics.

These devices improved the efficiency of the electric rail traction. Using modern equipment such as the inverters, it became possible to get the maximum power factor. That led to lower energetic consumption and to better performance of the electric rail vehicles.

The authors present in that paper the main designing principles for one of the most competitive control equipment, dedicated to supply the electric rail vehicles and their auxiliary equipment. The control equipment dedicated to supply the auxiliary services generator was designed and tested, the relied conclusions being presented in the doctoral thesis of the author. They are also presented problems that, in authors' opinion, have to be taken into account in designing the equipment, so that its outcome is the best one. Some of these are:

- continuous power control and the synchronous control of frequency and voltage, employing modern control techniques and electronic devices.
- efficient compensation of the harmonics;
- the improvement of the power factor and, consequently, the reduced energetic expenditure.

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