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RESEARCH OF EFFICIENCY OF THE DIRECT CURRENT ELECTRICAL DRIVES OF THE ALTERNATING CURRENT ELECTRICAL TRAINS

The brief review of promotions work

At support of FEG

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GENERAL CHARACTERISTICS OF THE WORK

ACTUALITY OF THE THEME

Half of extent of railways of the former USSR (now CIS) is electrified on an alternating current of single-phase voltage 25 kV, 50 Hz. On an AC voltage, the truth, other face values and frequencies, railways of many European countries as, for example, Sweden, France, Switzerland, Germany etc., are performed. Therefore perfection of electrical trains of an alternating current is actual in all countries, for both manufacturers and maintenance providers of such trains.

Perfection goes in two directions:

- creation of new trains with the improved parameters;
- reconstruction of maintained trains.

In both directions the main area of perfection is the electrical drive. Creating new trains, it is possible to use different variants of realization of a drive, thus providing search of the optimum decision. At reconstruction it is necessary to replace an out-of-date electric equipment on more perfect new, but practically, thus there is no opportunity to replace the most important element - the traction motor which today in reconstructed AC train systems is the motor of direct current. If reconstruction of electrical train is realized at the existing transmission mechanics it is possible to retain only the same motor of direct current.

Therefore the question of perfection of electrical trains with motors of a direct current is an actual problem.

Creation of new trains of an alternating current is connected with application of a drive of an alternating current. The most widespread is application of the asynchronous traction motor with the converter of a direct current in a variable frequency voltage - the decision which is considered optimum though the converter is very difficult and expensive, it cannot be shunted or excluded from structure of a drive. But weight of AC motor makes only 70 % from those for engine of direct current. The reduced dimensions allow to increase power capacity of motor at restrictions on "inscribing" in inter-wheel space. Asynchronous motor AM is completely the contactless motor with high reliability. However in AC train systems with AC motor and converter the qualitative part of a direct current is also required. This part, as well as in AC trains with DC motors, should well electromagnetic be coordinated with an supply network. Such a coordination can be obtained by realization of transformation of a supply alternating voltage in DC at maintenance of practically sine wave current in an input current circuit of the motor car of an electric train at factor of power equal to unit.

Maintenance of this requirement is the general problem for all electric trains of an alternating current as with AM as also with DC motor. Therefore the researches directed on perfection of this entrance link, are extremely actual. Existing technical decisions do not allow to receive such transformation with high quality of a network current at a simultaneous opportunity of electronic regulation of a level of a DC voltage. Therefore the problem of comparison and optimization here is rather actual.

In its turn the problem of comparison and a choice can not be solved without clear representation of the basic relations in all entrance converters, and, the part from them is investigated completely insufficiently. It also is the main actuality of the offered research directed on studying of processes in entrance circuits, electromagnetic compatibility, converters of an alternating current of a contact network in DC adjustable for motors voltage.

If in trains with AM the non-controllable DC voltage is transformed to an adjustable three-phase variable voltage by inverters with PWM, then in trains with a DC motor actually the single opportunity is application of pulse regulation with the purpose of regulation of voltage of the direct current motors.

Search of answers to the raised questions, and also check of a reliability and expediency of one or other technical decision also defines an actuality of this work. The actuality raises by fact that the Riga electromachine-building factory till now is the main manufacturer and the supplier of electrical drives for trains of an alternating current for the countries of the CIS.

THE PURPOSES OF WORK

1. To investigate opportunities of realization electromagnetic compatible with a power line of an alternating current converters of an alternating current in DC for traction drives with a motors of direct current.
2. To investigate processes in such converters with the purpose of reception of engineering methods of their calculation and comparison.
3. To investigate opportunities of perfection electromagnetic converters of an alternating current compatible to a power line in DC, with realization of regulation of modes of operation of traction engines of a direct current.

SCIENTIFIC NOVELTY OF WORK

Novelty consists that

- it is proved, that electromagnetic influence of rectifier as converter cannot be weakened by introduction of compensation jet capacity as at phase regulation of rectifier the phase between the first harmonic of a current and a voltage varies;
- it is shown, that introduction of filters of harmonics improves electromagnetic compatibility a little, but thus dimensions of the equipment strongly grow;
- it is shown, that in exchange rectifier systems on electric trains of an alternating current pulse regulation devices of a direct current from sources of a constant DC voltage which provide consumption from a contact network a current conterminous on a phase with a voltage or a current of the sine wave form can be used;
- it is shown, that the elementary and simplest decision on reception of a non-controllable source of a direct current is the system the uncontrolled rectifier - passive *LC* filter;
- all necessary dependencies and relations for *LC* filters are received, and also calculations by an estimation of weight and size parameters of reactors are carried out. The decision on application of nonlinear reactors is offered.
- programs of computer modeling of the automated start-up and braking of section of an electric train of an alternating current with different variants of entrance sources of a direct current are developed;
- comparison of integral power factor for various variants of realization of an entrance source of a constant voltage is carried out;
- two circuits of realization of a source of a direct current with a sine wave entrance current are offered and investigated.

PRACTICAL VALUE OF WORK

Results of research can be used by practical development of new circuits of drives of electric trains of an alternating current at Riga electromachine-building factory.

The developed programs of computer research of processes of motion of an electric train can be used for a practical estimation of various variants of realization of circuits of a drive.

The received analytical expressions are given in the form of the engineering expressions, that allows its use at calculation of the equipment.

ON DEFENSE IT IS PUT FORWARD

1. The method of calculation of *LC* entrance filter of an electric train of an alternating current.
2. Results of an estimation of weight-size parameters of *LC* filters.
3. Results of an estimation of electromagnetic compatibility of rectifier drives with compensation and filters.
4. Technical offers on realization of electric trains of an alternating current with entrance link of a non-controllable direct current and an adjustable drive of a direct current.
5. Results of an estimation of parameters of modulated rectifiers for electric trains of an alternating current.
6. Results of" an estimation of integral power parameters of an electric train of an alternating current with different links of a direct current.

STRUCTURE OF WORK AND VOLUME

Promotion work consists of introduction, 4 chapters, the conclusion and the bibliographic list. Volume of work - 111 pages, 88 figures, 9 tables and the literary list which contains 138 names.

APPROBATION OF WORK AND THE PUBLICATIONS

The main results of work are reported and discussed at the international scientific and technical conferences in the following reports:

1. Strāvas kropļojumu kompensācija maiņstrāvas elektrovilciena piedziņa - Rīga: Enerģ. un elektron., sēr. 4, sējums 7. 2002. - 33-41 lpp. Contference at RTU, 2002
2. Maiņstrāvas elektrovilciena reaktīvās jaudas kompensācija. RTU zin. rakstu krāj. "Enerģ. un elektrotehn.", sēr.4, sējums 10, Rīga 2003, 29-34 lpp. Contference at RTU, 2003
3. Maiņstrāvas elektrovilciena impulsveida līdzstrāvas elektropiedziņa. RTU zin. rakstu krāj. "'Enerģ. un elektrotehn.",sēr.4, sējums 10, Rīga 2003, 97-101 lpp. Contference at RTU, 2003
4. Investigation of Filtering Equipment for AC Railway trains// the 9 ' International Conference ELECTRONICS - Kaunas, May 18, 2005.

The main results of work are stated in 9 scientific publications.

THE MAIN CONTENT OF WORK

1. THE REVIEW OF EXISTING CIRCUIT DECISIONS OF THE MAIN DRIVE OF THE ALTERNATING CURRENT ELECTRICAL TRACTION

In the first chapter the classification table is given from which it is visible that all systems of an electrical trains be divided into two large groups: with traction motors of a direct current and rectifiers, and with traction motors of an alternating current with inverters.

Regulation on an primary winding of the transformer is applied seldom. Development on application in an primary winding of the transformer with high frequency converters which would allow to create transformers with small dimensions recently are conducted and also to adjust current flow in two directions through the entrance converter.

Mainly regulation is made on a secondary winding of the transformer, thus there is a big variety of realization of circuits of management. To electric motors of a direct current are applied diodes, thyristors and diode-thyristors rectifiers. To electric motors of an alternating current are applied synchronous and asynchronous ones with inverters.

Thyristors and diodes-thyristors rectifier-inverter converters used in circuits of anchors of traction motors of a pulsating current work in a mode of accelerating drives as rectifiers, and at recuperative braking - as network dependent inverters. Circuits of these converters - single-phase two-half-period bridge - can be symmetric and asymmetrical. In the first case thyristors are applied in all four shoulders of the bridge, in second one use its only in two shoulders, in other two shoulders put diodes.

The symmetric circuit allows to create a contactless power circuit in which there are no switches of steps, contactors and transition reactors and to carry out smooth regulation of a voltage both in traction, and in brake modes, there is an opportunity essentially to simplify the contact switching equipment and even completely to refuse it (at contactless regulation of a voltage). Besides it is easier to carry out inverting of a current and recuperation of energy at electric braking; starting characteristics are improved and most full use of the maximal force of traction on coupling with rail is provided.

To increase factor of power and to reduce negative influence on communication lines, in thyristors rectifier-inverter converters usually is provided four-level regulation of the rectified voltage both in a mode of traction and in a mode of electric braking.

To advantages of thyristor regulation the continuity of process of transition from a level on a level, absence of contacts and the group switch necessary to realize regulations of a voltage changes is facilitated.

To lacks of such regulation it is necessary to relate complication of a design of the transformer, the existence of the harmonics of a current in a traction network and variable, dependent on a adjusted voltage, displacement factor , influence on communication lines , the form of a voltage in a traction network is deformed.

As examples were considered diodes circuits of electric locomotive **VL80^{K}** and electric trains **ER9M** and **ER9E**, thyristor circuits of electric locomotives **VL80^{R}**, **VL85.**

Diodes-thyristors rectifiers apply smooth regulation of a voltage which realizes by smooth interstep valve transition and is contact less. Smooth interstep regulation of voltage is possible both at the circuit with a zero point connection and at the bridge circuit of rectifying of a single-phase current. The bridge circuit in which it is used valve transition (**VL60^{KU}**) was considered.

Pulse-phase regulation (**ER29**) allows to increase factor of power up to 0,95 at the full rectified voltage and to reduce preventing influence of converter on communication lines. In such system jet capacity is reduced due to artificial switching-off of thyristors at the end of each half-cycle. But circuits of artificial switching are very bulky and also occupies a lot of place.

In all cases of application of rectifier circuits a distortion of a current of a power line exists, and in a case of thyristor rectifiers - continuous shift of the first harmonic of a current in way of regulation of opening of thyristors takes place. One of the best circuits should count the circuit of an electric locomotive with the multilevel rectifier where 4 zones of regulation (Fig. 1) are realized. The specified circuit in the given work is investigated on an opportunity of a filtration harmonics of a network current, and also indemnification of jet (reactive) power.

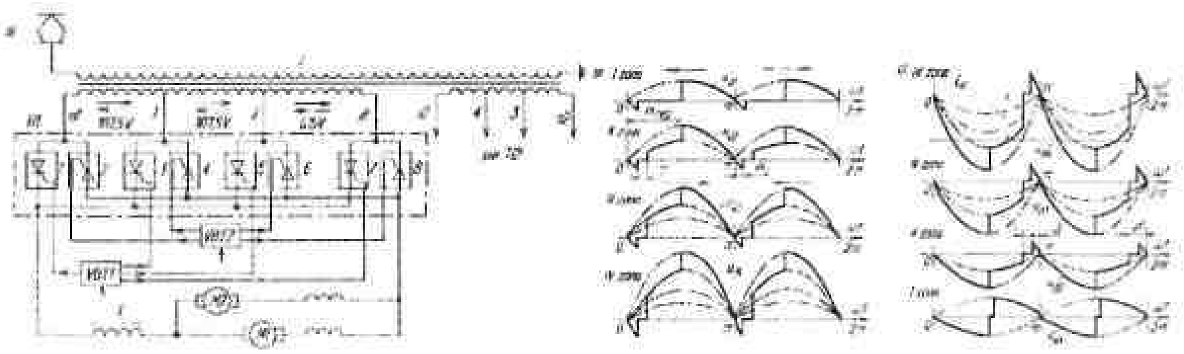


Fig. 1. The simplified circuit of regulation of a voltage **of electric locomotive VL80^{R}** *(a)* and diagrams of a voltage in a traction mode *(b)* and a mode of recuperative braking *(c)*

Since 80th years in an electrical traction of an alternating current asynchronous motors with various types of converters of frequency are applied. Circuits with the asynchronous motors and the inverter of a voltage are developed for electric locomotives **VL80^{A}** , **VL86^{F}** where pulse-width modulation PWM is applied to regulation of a voltage of the power supply.

Systems with application of synchronous motors (**VL80^{V}**) were simultaneously developed. Inverters with natural switching of thyristors here are used, i.e., their work is synchronized with EMF of the motor.

Application of a drive of an alternating current allows to increase power capacity of traction motors, keeping constant as much as possible allowable dimensions of the motors. However converters are very difficult.

To improve harmonics structure of a network current, and also to remove consumption of jet capacity, in an electric train of an alternating current with asynchronous motors in a part of a direct current apply four-quadrant converters, i.e., modulated rectifiers. Most widely such converters apply in systems of multi-level voltage. For example, in train **Re484** of the European railways.

The electric drive of a direct current in an electrical train of an alternating current is simple, widely mastered and convenient in operation. Therefore still in the world development on improvement of system of this drive from a network of an alternating current are conducted. It is possible to count a mainstream introduction of the entrance unit of a direct current accomplished from the point of view of electromagnetic compatibility, and regulation of a voltage of motors of a direct current to fail controlled rectifiers. Actually, here is only one opportunity of realization of regulation of speed - introduction of pulse regulators of a voltage.

Such advanced unit of a direct current can be realized with

- application of the perfect smoothing filter after the uncontrolled rectifier;
- introduction in system with motors of a direct current unit of a direct current with four-quadrant converter.

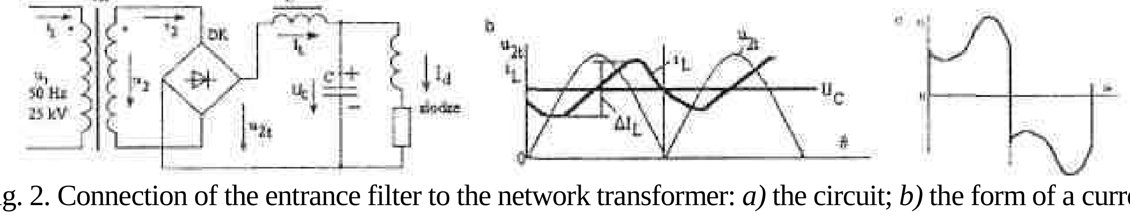


Fig. 2. Connection of the entrance filter to the network transformer: *a)* the circuit; *b)* the form of a current of a reactor of the filter i_L at work with rectified voltage u_{2t} *; c)* the real form of a network current

As the entrance filter is the important part also for trains with asynchronous electric drives, in the first chapter aspects of realization of entrance *LC* the filter (Fig. 2) are considered. Thus one of the greatest lacks of these systems are the big dimensions of the *LC* filter. It is connected with fact that frequency of a voltage of a network is low (50 Hz) and, to receive smoothed voltage of capacitor C_f, is necessary reacto L_f with very big inductance. At the same time, thus dimensions and weight of a reactor strongly grow. As in the literature processes in this filter are poorly described in full to estimate influence of this filter more exact and more full research of the entrance *LC* filter was carried out.

On fig. 2 *(a)* connection of the entrance filter to the network transformer is shown. Work of the filter in this circuit essentially is complicated with the rectified form of a network voltage u_2t. On fig. 2 *(b)* the form of a current of a reactor of the filter i_L. is shown at work of the rectified voltage u_{2t}. Such form of a current of a reactor depends on a difference between a rectified voltage and voltage of capacitor. On fig. 2 (c) the real form of a network current with the filter on an input is represented. Estimating the form of a network current, it is necessary to observe a real operating conditions of a reactor of the filter which deform the form of a network current.

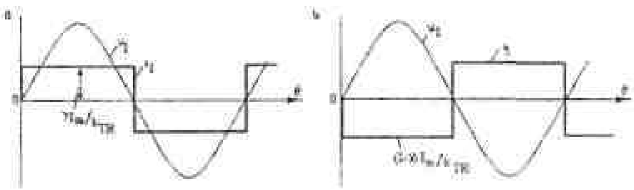


Fig. 3. The idealized form of a network current in traclion *(a)* and brake *(b)* modes

If the current was ideally smoothed, from a network of an alternating current the alternating current of the rectangular form i_L , as shown in Fig. 3, would be consumed. At such form of a current the factor of power is equal 0,9 and shift of the first harmonic is equal to zero. It means, that the network current has constant harmonics structure with constant relation of amplitudes of harmonics:

$$\chi = \frac{P_1}{S_1} = 0,9 \quad . \qquad I_{1(1)} = 0,9 I_1 \qquad \cos\varphi_{(1)} = 1 \tag{1}$$

However it is really difficult to achieve completely smoothed current of a reactor, since a pulsations of the rectified voltage of the single-phase bridge rectifier are very big and their frequency is very small (100 Hz).

In connection with that real processes in the filter differ from idealized, the specified calculation of processes of the filter was carried out. Thus expressions for calculation of a full pulsation of a current of a reactor and a full pulsation of a voltage of the capacitor were received:

$$\Delta I_L = \frac{1,92U}{10^3 L} \qquad . \Delta U_C = \frac{0,304U}{\omega^2 LC}, \tag{2}$$

here *U* - working value of a voltage of a secondary winding of the transformer, and frequency of a network voltage is accepted equal 50 Hz.

For check of the received expressions computer modeling was carried out. Concurrence of results has turned out on an allowable technological level.

To have an opportunity to choose inductance of a reactor depending on allowable pulsation's of a current, on Fig. 4 the curve $L = f(\Delta I_L / I_d)$ is represented. As we can see, the more is allowable pulsation of a current, inductance of a reactor can be lesser. Increasing relation U/I_d , necessary inductance must be increased also. For a practical choice it is necessary to accept value I_d as minimum small and ΔI_L to accept as 2 minimal values of I_d that would provide a continuity of a current in a reactor. As we see from the diagram, if relation of pulsation's is lesser, then greater inductance the reactor needs to be applied. Practically, if minimal I_d makes 0.05 from maximal it is necessary to apply the relation 0,1, and at the relation of a voltage and the maximal current, we allow, as two, it is necessary to apply a reactor with inductance close to 40 mH. It is important to estimate weight of this reactor which needs to be defined on a rated current which makes a part k_{ms}

from the maximal current.

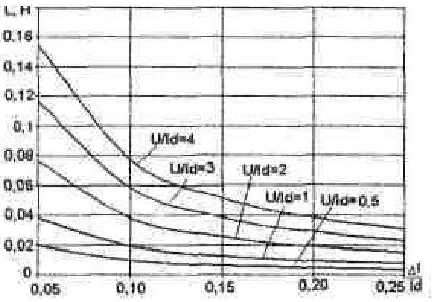


Fig. 4. A curve $L = f(\Delta I_L/ I_d)$ at various values U/I_d

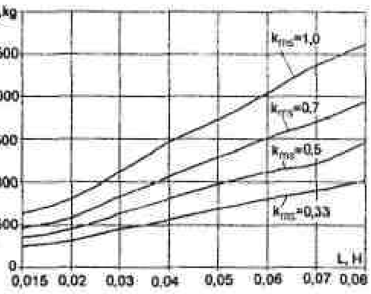


Fig. 5. Curves $G_R = f(L)$ at various values k_{ms} (results of computer modeling), designed at the maximal current 300 A

On Fig. 5 such weights of linear reactors designed in work are represented depending on necessary inductance L at the maximal current 300 A and various relations k_m rated currents to the maximal current.

As we see from Fig. 5, the L is more, the weight of a reactor and accordingly dimensions is more. Thus dimensions and weight grow, if the factor of the relation of currents k_{ms} grows. Be real for the filter this relation should be close to 0,5 and then, for example, at necessary inductance 0,04 H the weight of a reactor can reach 700-1000 kg. As we see, weight of a linear reactor is impressive. Therefore it is proposed to use a non-linear reactor inductance of which is decreasing with current raise.

It is important to investigate harmonics structure of a network current with the passive filter. On Fig. 6 effective values of the maximum harmonics *(nh* = 3, 5, 7, 9, 11) are represented depending on inductance L. Figure is executed according to computer modeling at a current of loading 300 A. According to computer modeling we can define the factor of the general harmonics distortion of current *THD* depending on inductance L and different load currents. On Fig. 7 dependencies *THD* on values L are represented at C=0,01*F* and at various currents of loading I_d. As we see, on the average, it is possible to accept, that *THD* there is at a level 0,4, what is not a bad parameter.

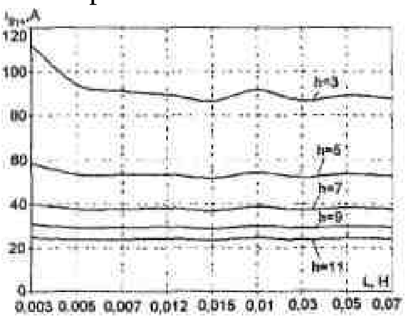


Fig. 6. Change of effective values of the majority harmonics of a current at C = 0.01 F and a loading current 300 A (results of computer modeling)

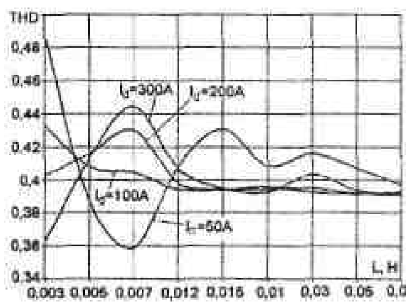


Fig. 7. A curve $THD = f(L)$ at C = 0.01 F (results of computer modeling)

The expressions received in this chapter for a choice of the filter are used further at an estimation of variants of realization of systems of pulse regulation with the entrance filter. In the first chapter the estimation of a situation was carried out. The electric drive of an electrical train developed in two directions: with motors of a direct current and with motors of an alternating current. Each of these directions has the advantages and the lacks. The main advantages of drives of a direct current is well developed drive, the simple converter. The main lacks: restriction of a starting current and the torque because of design features of a collector of the motors, low reliability of operation, the big weight on a power unit. The main advantages of drives of an alternating current: small weight of the motors, reliability of the motor, the large torque in the beginning of start-up. The main lacks: the difficult converter and difficult algorithm of its control management.

In all variants the tendency to achieve is observed:

- the sine wave form of a network current with the displacement factor equal to zero;
- start-up and braking with full regeneration of energy;
- realizations of circuits without switching with electronic management of change of operation modes.

It was offered to improve the electric drive of a direct current introducing of pulse regulation. It will allow to work in a mode of active capacity of a power line and also to increase frequency of pulsations of a current of the electric motor of a direct current and to reduce losses of power of pulsations. Excitation can be independent.

Two variants are here too probable:

- with *LC* the filter after the uncontrolled rectifier;
- with four-quadrant converter on an input.

These circuits allow::

- to apply unified 600 V pulse regulators to one traction motor;
- to apply motors with independent excitation with small losses of pulsations;
- to realize a network current during start-up and braking with zero shift in relation to a voltage of a network and good factor of power.

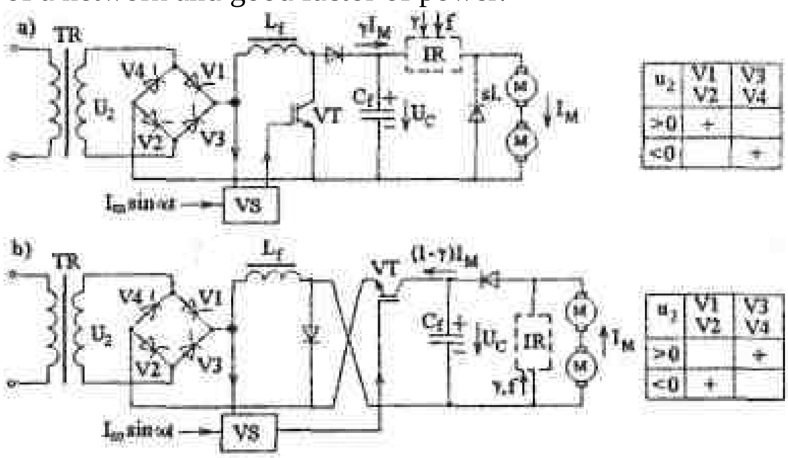


Fig. 8. The probable circuit of a traction drive with active elements in structure of the filter in traction *(a)* and brake *(b)* modes

Is necessary to note, that parameters of passive *LC* filter can be improved essentially if in structure of the filter to enter active elements - keys (Fig. 8). This variant of the circuit can serve as alternative to the four-quadrant converter - with smaller number of switched elements, but with necessity of switching of the circuit at transition to braking.

2. RESEARCH OF EFFICIENCY OF ACTIONS FOR INDEMNIFICATION OF JET POWER AND THE FILTRATION OF DISTORTIONS OF THE CURRENT

In the second chapter one of perspective rectifier circuit of electric trains of an alternating current with a drive of a direct current (Fig. 9, *a)* is in detail investigated. On its basis electric locomotive **VL80^R** is made.

The secondary winding of the transformer is divided into three sections with a voltage 412.5V, 412.5V and 825V. To the outlets of sections there are connected rectifier-inverter converters (RIC) with thyristors *VI - VS.* The traction motor is connected through smoothing reactor. Circuit of RIC can be presented as three in parallel connected single-phase bridge circuits with the combined adjacent shoulders *(VI - V4, V3 - V6, V5 - V8).*

To increase factor of power and to improve the form of a network current, multilevel regulation of voltage - four-zoned - both in traction, and in brake modes (Fig. 9, *b)* is realized. Thus we have a continuity of process of transition from a zone on a zone. This circuit has the following lacks: the deformed current of the network, the deformed form of a voltage, variable, dependent on a angle of regulation, an angular shift of the basic harmonic of a current.

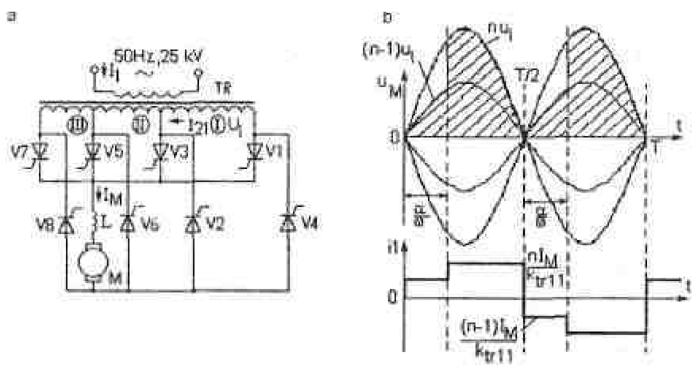


Fig. 9. The circuit of regulation of a voltage of the electric motor *(a)*, diagrams of a voltage of the motor and a current of a network *(b)*

The harmonious structure of a network current was investigated. Effective values for the maximum harmonics in all 4 zones are calculated. They are shown in tab. 1.

Effective RMS values of harmonics of a current in a primary winding of the transformer

Table 1

Zone	h=1	h=3	h=5	h=7
I	$\frac{2I_M\sqrt{1+\cos\alpha}}{\pi k_{TR11}}$	$\frac{2I_M\sqrt{1+\cos 3\alpha}}{3\pi k_{TR11}}$	$\frac{2I_M\sqrt{1+\cos 5\alpha}}{5\pi k_{TR11}}$	$\frac{2I_M\sqrt{1+\cos 7\alpha}}{7\pi k_{TR11}}$
II	$\frac{2I_M\sqrt{5+3\cos\alpha}}{\pi k_{TR11}}$	$\frac{2I_M\sqrt{5+3\cos 3\alpha}}{3\pi k_{TR11}}$	$\frac{2I_M\sqrt{5+3\cos 5\alpha}}{5\pi k_{TR11}}$	$\frac{2I_M\sqrt{5+3\cos 7\alpha}}{7\pi k_{TR11}}$
III	$\frac{2I_M\sqrt{13+5\cos\alpha}}{\pi k_{TR11}}$	$\frac{2I_M\sqrt{13+5\cos 3\alpha}}{3\pi k_{TR11}}$	$\frac{2I_M\sqrt{13+5\cos 5\alpha}}{5\pi k_{TR11}}$	$\frac{2I_M\sqrt{13+5\cos 7\alpha}}{7\pi k_{TR11}}$
IV	$\frac{2I_M\sqrt{25+7\cos\alpha}}{\pi k_{TR11}}$	$\frac{2I_M\sqrt{25+7\cos 3\alpha}}{3\pi k_{TR11}}$	$\frac{2I_M\sqrt{25+7\cos 5\alpha}}{5\pi k_{TR11}}$	$\frac{2I_M\sqrt{25+7\cos 7\alpha}}{7\pi k_{TR11}}$

And also the formula of definition of effective value of harmonics of a network current for the common case was extracted:

$$I_{1(h)ef} = \frac{2I_M}{\pi k_{TR11}\cdot h}\sqrt{2n^2-2n+1)+(2n-1)\cos(h\cdot\alpha} \qquad (3)$$

Where h - number of a harmonic, n =1, 2, 3, 4 - number of a zone. kT_{TR11} = 62,5 - factor of transformation for the first zone, $\alpha = arccros\left(\frac{8t}{t_p} - 1\right)$ - an angle of regulation, $0 < t < t_p$ - current time in each zone.

Researches of harmonics of a network current show, that, except for the basic harmonic, the big sizes have harmonics 3, 5, 7 order. Effective values of these harmonics are shown on Fig. 10. On figure it is visible, that average size of effective value of 3-rd harmonics during start-up is 0.608 from a base current (I_M/k_{TR11}), 5-th harmonic - 0.377, and 7-th - 0.269. As we see character of change theoretically designed curve and received as a result of computer modeling in common coincides.

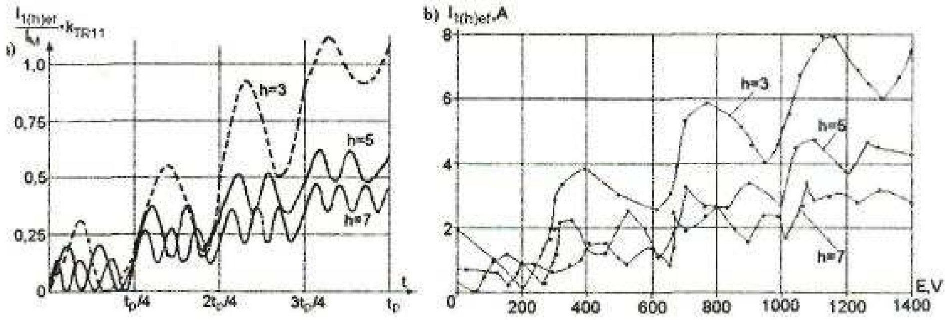


Fig. 10. Change of effective values of the maximum harmonics of a network current during start-up without indemnification: *a)* - theoretically designed in relation to a base primary current of the first zone of regulation; *b)* - results of computer modeling at a current of motor 300 A

Electromagnetic processes in the circuit with the controlled rectifier were investigated. The voltage of the motor in each zone is determined as

$$U_{Mn} = \frac{\sqrt{2}U_1}{\pi}[(2n-1) + \cos\alpha], \tag{4}$$

Effective value of a current for each zone - as

$$I_{1n} = \frac{I_M}{k_{TR11}}\sqrt{n^2 - \frac{(2n-1)\alpha}{\pi}}, \tag{5}$$

In that case consumed general apparent power is defined as

$$S_n(t) = \frac{U_1 I_M}{k_{TR11}}\sqrt{n^2 - \frac{(2n-1)}{\pi}\arccos\left(\frac{8t}{t_p} - 1\right)}, \tag{6}$$

and active power as

$$P_n(t) = I_{M\max}U_{M\max}\left[\frac{n-1}{4} + \frac{t}{t_p}\right], \tag{7}$$

Where $U_{M\,max}$ - the maximal voltage of the motor.

Jet power is defined as

$$Q_n(t) = \sqrt{S_n^2(t) - P_n^2(t)}, \tag{8}$$

Analytically it is difficult to calculate Q, the graphic method therefore is used. On Fig. 11, a theoretically designed curves $S_n*(t) = f(t)$, $P_n*(t) = f(t)$ and $Q_n*(t) = f(t)$ for each zone are represented. As we see jet power is big enough.

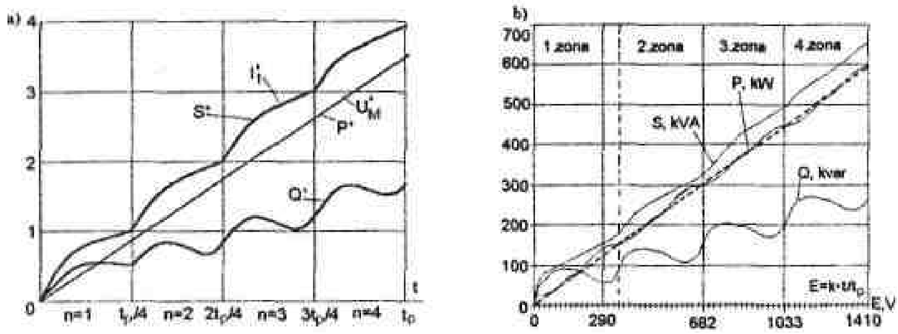


Fig. 11. *a)* changes of jet power, a network current and a voltage of the motor during start-up in relation to base power of the first zone, *b)* changes of common *(S)*, active *(P)* and jet *(Q)* power during start-up according to computer modeling;—the approximate calculation of active power

For check of results computer modeling was carried out at the following parameters: a current of engine I_M = 400 A, R = 0.21 Ω, $k_{TR11}=62.5$, U_{Mmax} = 1490.7 V. The angle of regulation varies from a =180 ° up to a =0. On Fig. 11, *b* curves $S_n * (t) =f(t)$, $P_n * (t) =f(t)$ and $Q_n * (t) =f(t)$ by results of computer modeling for each zone are constructed. As we see, results coincide.

According to computer modeling curve of *THD* (Fig. 12) is constructed. On the average it is possible to accept *THD* = 0,47. Thus it is visible, that in the first zone this parameter is very bad.

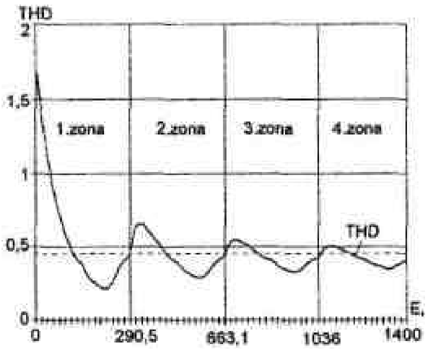


Fig. 12. Curve *THD =f(E)* during start-up (computer modeling)

In the second chapter actions for indemnification and a filtration were carried out and evaluated. On Fig. 13 connection of the compensation capacitor C and harmonics resonant filters *(L-C-R)* for the maximum harmonics (3, 5, 7) on the primary side of the transformer is shown.

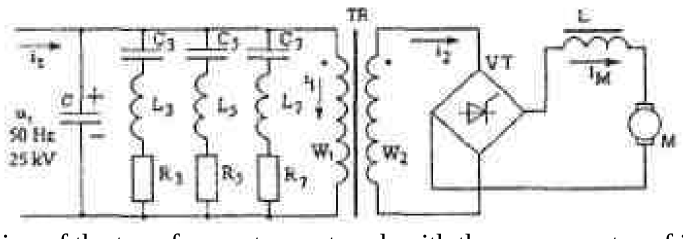


Fig. 13. Connection of the transformer to a network with the compensator of jet capacity and the harmonics resonant filter

To reduce common capacity consumed from a network, it is rational in general to lead indemnification of jet power. As one of variants can be connection of the capacitor to the transformer on the side of a voltage of a network. As confirm researches, this decision can be effective only in the first zone when there is a real shift of the first harmonic of a current. As can be seen from Fig. 14, in the first zone it is really possible to reduce jet power. Besides, the best variant is, established at capacity 0,2μF when in the first zone jet power decreases on the average on 40 %. However, the jet power consumed in the first zone is a small part from those all in starting process, and connection of the capacitor practically does not influence consumption of reactive power in other zones.

On Fig. 15 curves of *THD* are represented during start-up in all 4 zones with various values of compensating capacitor. If to compare *THD* of the compensated system with not compensated we see, that in the first zone in compensated case *THD* even has worsened. In other zones *THD* practically is identical, i.e., indemnification of jet power with connection of the capacitor does not give appreciable effect.

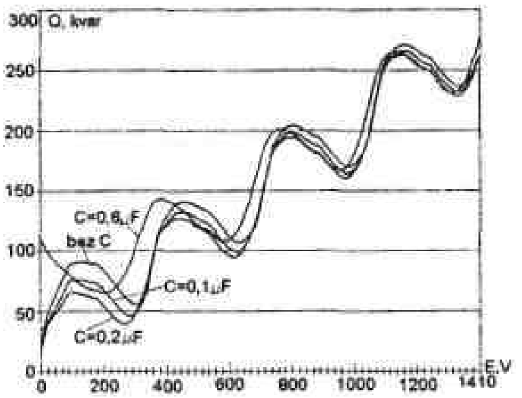


Fig. 14. Dependence of jet power from *E* of the motor (start-up) with connection of capacitors of various capacities

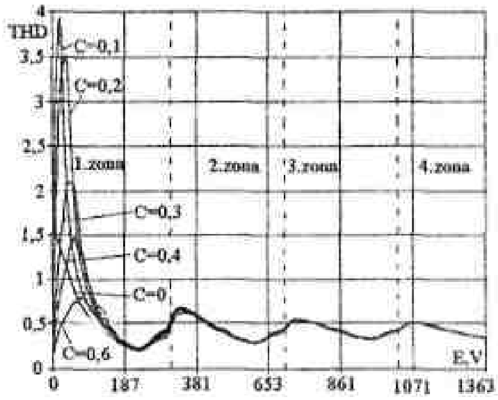


Fig. 15. Curve *THD =f(E)* during slart-up in four zones at various values of capacities C (computer modeling)

To improve the form of a network current, it is necessary to apply three *L-C-R* the filter which are adjusted accordingly:

$$L_{(3)}C_{(3)} = \frac{1}{4\pi^2 \cdot 9 f^2}; L_{(5)}C_{(5)} = \frac{1}{4\pi^2 \cdot 25 f^2}; L_{(7)}C_{(7)} = \frac{1}{4\pi^2 \cdot 49 f^2} \qquad (9)$$

Thus that the filter worked effectively, good quality should be with value $Q = \sqrt{\frac{L_h}{C_h}} / R_h = 30...50$. Taking into account an equivalent circuit of the generator of a harmonious current resistance of the resistor of the filter is determined as

$$R_{(h)} = \frac{h.k.X}{\sqrt{1-k^2}},$$

where *k* - desirable factor of weakening of a harmonious current in supply line with inductive resistance *X* which depends on remoteness from substation. Taking into account these ratio, at *k=0.*1 and X=12 *SI* the chain for 3-rd harmonic has *R*3=3.6 Ω, *L*3=0.114 H, *C*3=9.83 μF.

On Fig. 16 curve of *THD* designed according to computer modeling with the connected filter of 3-rd harmonics is represented. As we see, the curve is much better, than with compensating capacitor and without it. Especially it regards to 1-st zone. In other zones influence is minimal. (Average value of *THD* with the filter of 3-rd harmonics is 0,49).

However it is necessary to note, that on network frequency the chain of the filter represents practically a capacitance and a current, for example, through a chain of 3rd harmonics of the filter at network frequency makes near 70 A, i.e., the power supply system is overcompensated. Thus dimensions of the filter are significant for the limited conditions of accommodation on an electric train. Therefore it is possible to conclude, that not indemnification, not the filtration does allow to improve power parameters of controlled rectifier drive.

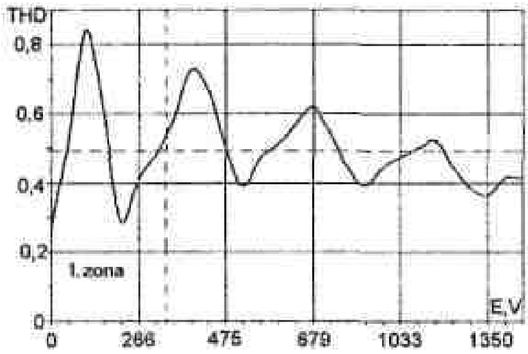


Fig. 16. Curve *THD =f(E)* during start-up with the connected filter of the third harmonic (computer modeling)

To estimate the received data, computer modeling of starting process of an electric train of an alternating current with 4 zoned controlled rectifier without additional actions for a filtration and indemnification (Fig. 17) was carried out. In figure speed of rotation of an anchor of the engine, change of effective values of the consumed active and common power are shown during start-up of motors of section of an electric train (from 0 up to 1455 rev/min). Transitions from a zone to a zone are very well visible. Thus the integrated parameter of the relation of powers *P/S* was determined, i.e., the integrated factor of power here is equal **0,78.**

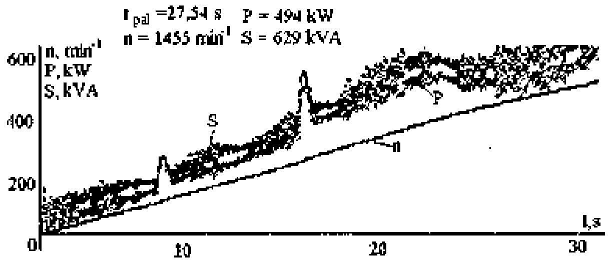


Fig. 17. The diagram of computer modeling of starting process; *P* - active power, *S* - common power, *n* - speed

3. SYNTHESIS AND ANALYSIS OF ELECTRICAL TRAIN OF THE ALTERNATING CURRENT WITH SYSTEM OF DIRECT CURRENT ELECTRIC DRIVE WITH PULSE REGULATION

Substantial improvement of a drive of a direct current can be achieved with introduction of a pulse regulator. It will allow to use the entrance unit of a direct current accomplished on power parameters and also to increase frequency of a pulsation of a current of traction motors. Thus the unit of a direct current can be executed both with the filter and the switched rectifier, and with four-quadrant the modulated rectifier.

In a traction mode the pulse regulator is connected consistently to the electric motor, and a voltage of loading is changed adjusting relative time of switching on *y* a pulse key during switching cycle *T = I/f.* In practice apply as thyristors pulse regulators which are well investigated, rather reliable in work, and, working with frequency *f* = 400 Hz, provide change *y* in limits from 0,07 up to 1, and transistor pulse regulators with wider range of regulation. In a traction mode is possible bypassing of a pulse regulator with contactor *ŠK.* In a brake mode the pulse regulator is connected in parallel to the electric motor which works in a generating mode.

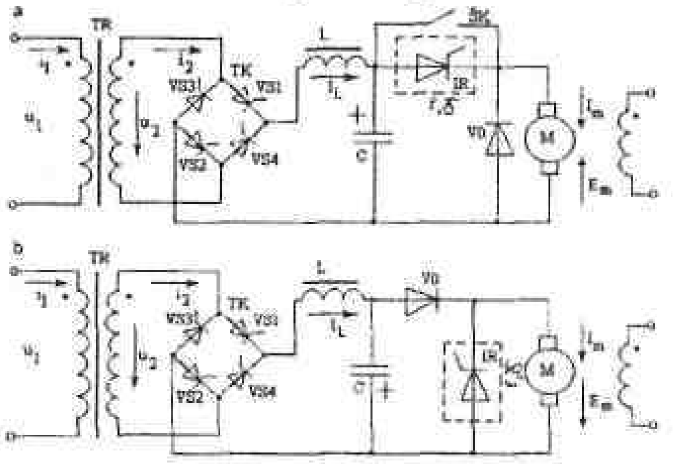


Fig. 18. The electric drive of a direct current of an electric train of an alternating current with a pulse regulator in a traction mode *(a)* and a mode of recuperative braking *(b)*

In the first variant with the entrance filter to realize traction and brake modes it is necessary to enter switched thyristors bridge unit which works on algorithm represented on tig. 19.

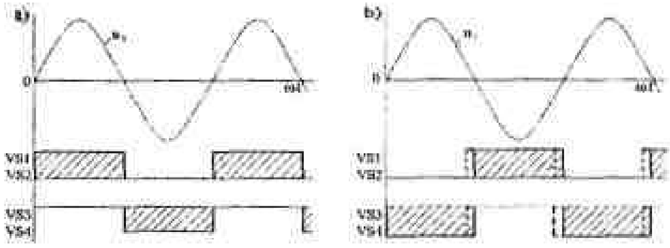


Fig. 19. Diagrams of management of the entrance switched rectifier in a traction mode *(a)* and a mode of recuperative braking *(b)*

If thyristors bridge works as the switched then in the beginning of a positive half-cycle of mains voltage thyristors *VS1* and *VS2* (in a mode of braking *VS3* and *VS4)*, and negative - thyristors *VS3* and *VS4* (braking, accordingly, *VS1* and *VS2)* are turned on, then the voltage of the capacitor of the filter practically does not change and is equal $U_C = 0.9U_2 = 0.9U_1 /k_{TR}$, and a voltage of the motor in a traction mode $U_{MV} = \gamma U_C$, in a brake mode $U_{MB} = (1-\gamma)U_C$, however a voltage of the capacitor of the filter in both modes of operation is with opposite sign. In its turn the current of a reactor of the filter in both modes is with constant polarity and accordingly $I_{LV}=\gamma I_m$, and $I_{LB} = (1 - \gamma)I_m$, where I_m is average value of a current of the motor. In a brake mode it is necessary to enter some advancing of switching so that at the moment of switching off working before thyristors to create a reverse voltage across them. Basically, the switch-bridge also can be a transistor mode.

In- systems of the Riga electromachine-building factory two types of the motors of a pulsating current 1DT.004 and 1DT.8 with rated voltage U_N =825 V are applied.

There are two variants of realization:

- two parallel branches on two motors each consistently; in a circuit of each branch the pulse regulator; one common filler on an input;
- separate pulse regulator for each motor; then it is necessary to have a two filters.

Using ratings of motors, were calculated inductance and weight of reactor of the filter for both cases. Dimensions of reactors have turned out impressive.

Dimensions of a reactor can be reduced, having applied a reactor without an air gap. This reactor has the maximal inductance at the minimal current and with increase of a current of loading inductance decreases (Fig. 20). It means, that the range of pulsation's of a current of a reactor in a range of regulation will not be a constant, and grows at increase of a current of a reactor (Fig. 21). Pulsation's are designed at $2I_{Lmin}$.

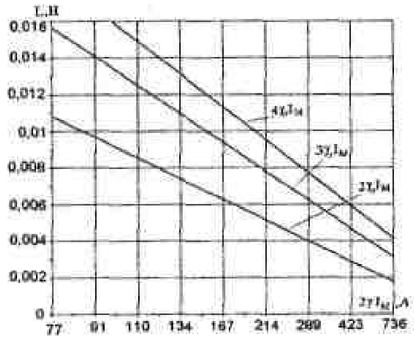


Fig. 20. Change of inductance of a nonlinear reactor in a range of regulation of the motors

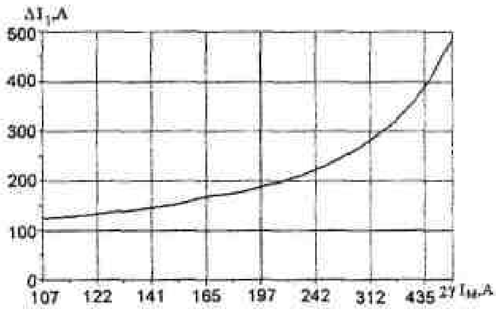


Fig. 21. A range of pulsation's of a current of a reactor of the filter in a range of regulation of the motors with change of inductance of a nonlinear reactor

Curves for changes of *THD* for a linear reactor (Fig. 22, *a)* and for nonlinear (Fig. 22, *b)* were constructed. In both cases *THD* is within the limits of 0,48 and 0,42, that is a rather good parameter. Thus, in case of a nonlinear reactor the weight of a reactor in 5 times is lesser than at linear.

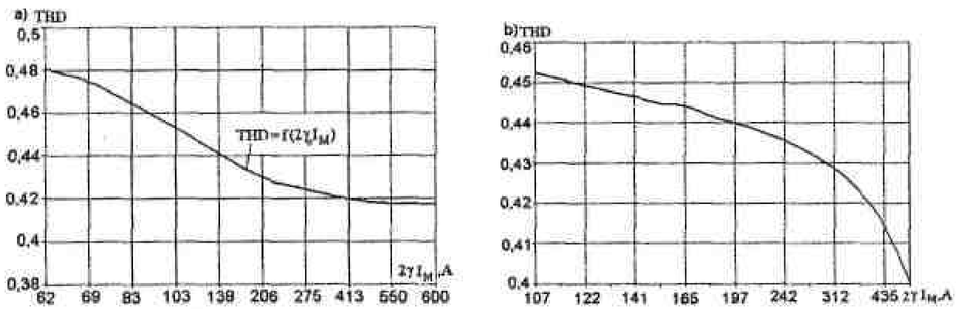


Fig. 22. Change *THD* of a network current in a range of regulation of the motor with a linear reactor *(d)* and with not a linear reactor *(b)*

The formula for calculation of the relation of factor of power x *=P/S* was extracted. We see, that this parameter depends on a full pulsation of a current of a reactor. If $Al_L=0$, *x* = 0.9, and generally

$$\chi = \frac{P}{S} = \frac{2\sqrt{2}}{\pi\sqrt{1+0,25\left(\frac{\Delta I_L}{I_L}\right)^2}} \qquad (10)$$

Curve for dependence of the relation of powers on a current of a reactor are designed at various values $A1_L$ for a linear reactor (Fig. 23, *a)*, and also for nonlinear (Fig. 23, *b)*. On Fig. 23, *b* the curve corresponds approximately to a case of a linear reactor with $\Delta I_L = I00A$, i.e. *P/S* ≈ 0,8. To check up the real integrated in transient processes time relation between *P/S*, computer modeling of start-up and braking of section of an electric train with 4 traction motors, everyone on

825 V which are connected in two parallel circuits with two consistently connected motors, is carried out. The common starting current of motors - 600A, working frequency of a pulse regulator 400 Hz.

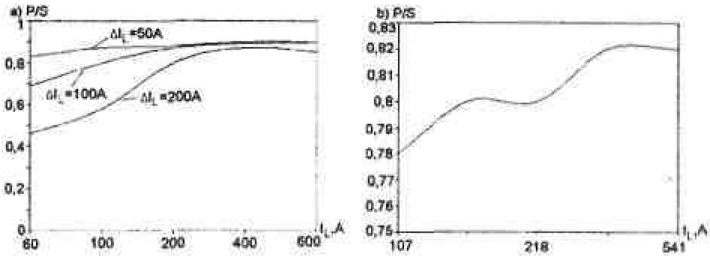


Fig. 23. Curves *P/S* with constant values ΔI_L *(a)* and with the pulsation's, corresponding to Fig. 21 for a nonlinear reactor *(b)*

On Fig. 24, *a* process of start-up with a pulse regulator with a linear reactor is presented, thus value of an integrated ratio of powers approximately equal to a parameter for multilevel controlled rectifier variant is received, i.e., *P/S=0,793.* On Fig. 24, *b* the result of computer modeling of brake process of the same electric train is shown, thus integrated *P/S=0,72* since the most part of brake process is busy with process of introducing in a generating mode.

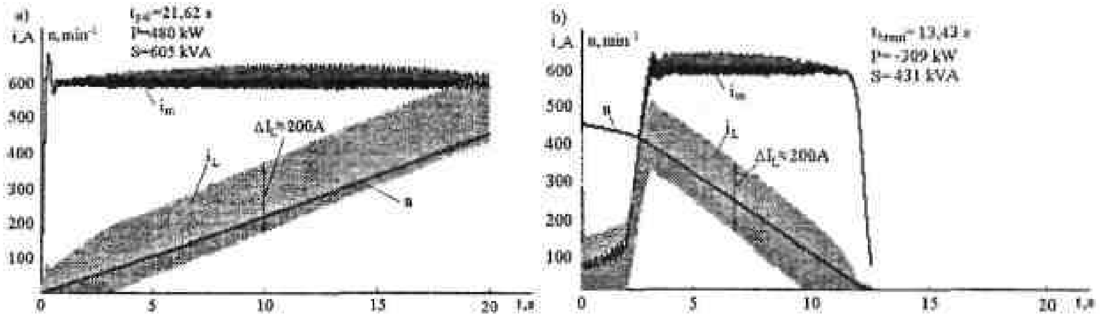


Fig. 24. *a)* the starting diagram of an electric train of an alternating current with final speed of the motor 1300 rev/min (57 km / h); *b)* brake diagrams of an electric train of an alternating current with initial speed of the motor 1300 rev/min (57 km / h)

The system of an electric train of an alternating current with a input filter and inverter can be used also for a drive with the asynchronous electric motor. To check up power characteristics of this drive, computer modeling of start-up of the asynchronous motor with inverter was carried out. In this case the integrated in duration of start-up relation of powers in respect to the inverter turned out as *P/S=0,59,* i.e., it is worse than in system of an electric train with an entrance filter, pulse regulator and a drive of a direct current in respect to network. It speaks that the asynchronous motor consumes both active, and jet powers, i.e. the drive with the asynchronous motor has advantages only in reliability of the motor and in reduction of weight. In relation to a power supply line the integrated parameter of powers corresponds to those with motor of a direct current and the filter.

The second variant of improvement of an electric train of an alternating current with the electric drive of a direct current was connected with introduction a four-quadrant modulated converter of a voltage source SAMT (Fig. 25). The system consists of the transformer, reactor *LI* and single-phase modulated transistors-diodes rectifier (i.e., four-quadrant converter). To an output of a bridge a capacitor *CI* is connected but to the latter a filter *LC* and a pulse regulator for motors are inserted.If inductance of windings of the transformer is big enough it is possible to do design without an entrance reactor, and at sufficient capacity of the condenser - without the *LC* filter.

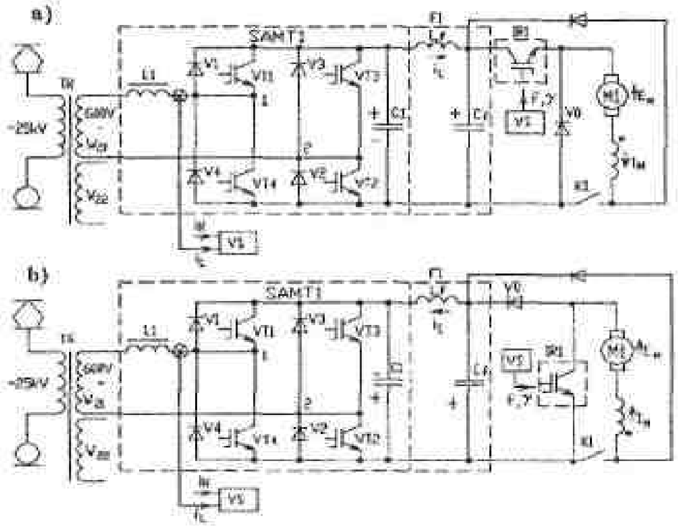


Fig. 25. The electric drive of a direct current of an electric train of an alternating current with a pulse regulator in a traction mode (a) and a mode of recuperative braking *(b)* and with entrance four-quadrant converter SAMT

On Fig. 26, *a* circuit of the SAMT is given. This circuit was in detail investigated in dissertation work. In a traction mode the current of an entrance reactor coincides on phase with a voltage of a network H_l, and in a brake mode is in an antiphase (Fig. 26, c, *d).* In a traction mode in a positive half-cycle of voltage transistors *VT4, VT3* and diodes *V1, V2* (in a brake mode - *VT1, VT2, V4, V3)* are activated, in a negative half-cycle on the contrary - *VT1, VT2, V4, V3* (in brake mode *VT4, VT3, VI, V2)* work.

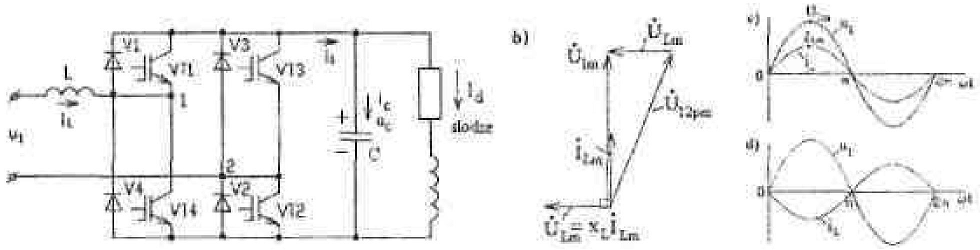


Fig. 26. Circuit of SAMT *(a);* the vector diagram *(b);*
the form of network current in traction *(c)* and brake *(d)* modes

For the circuit on Fig. 26, *a* the following expressions were suggested: - relative time of connection of capacitor to points 1 and 2

$$\frac{t_A}{T} = \frac{\sin \omega t - U_L^* coa\,\omega t + \sqrt{1+U_L^{*2}}}{2\sqrt{1+U_L^{*2}}} \qquad (11)$$

- the formula for calculation of the fundamental harmonic of current of the capacitor

$$i_{Cp} = -I_d(\cos 2\omega t + U_L^* \sin 2\omega t); \qquad (12)$$

- the formula for calculation of the law of change of an instantaneous voltage of the capacitor

$$u_{Cp} = U_{Co} - \frac{I_d}{2\omega C}\cos 2\omega t - 0{,}5\Delta U_C + \frac{I_d}{2\omega C}; \qquad (13)$$

- expression for calculation of change of switching frequency . Frequency is inversely proportional ΔI_L and an inductance of an entrance reactor:

$$f = \frac{[\sin \omega t - U_L^* \cos \omega t + \sqrt{1+U_L^{*2}} \cdot |U_{\text{Im}} \sin \omega t - U_{C0}|}{2\sqrt{1+U_L^{*2}} \cdot L\Delta I_L}, \qquad (14)$$

here $U_L^* = \omega L I_{Lm} > U_I$,U_{1m} , I_{Lm} is magnitude value of reactor's current.

On Fig. 27 change of a variable component of a current of the capacitor concerning a current of loading is shown during the period of a voltage of a network. As we see, the current varies with double frequency of a voltage of a network and the amplitude is equal to amplitude of a current of loading.

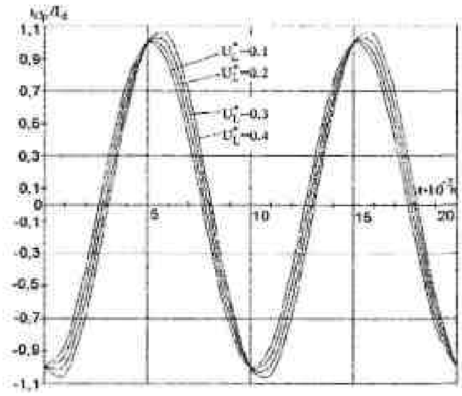


Fig. 27. Change of a variable component of a current $i_{Cp}/I_d = f(t)$ at various U^*_L

On Fig. 28, *a* the diagram of electromagnetic process is represented during start-up. Computer modeling is carried out providing that the amplitude of a network current twice surpasses a current of loading which is accepted equal to a starting current of the motor. As we see, the current and a voltage of network coincide on a phase, average value of a voltage of the capacitor approximately is equal to rated voltage of the traction engine (825V). The range of pulsation's of a voltage of the capacitor (in the case 320V) also depends on capacity of the capacitor.

On Fig. 28, *b* it is represented diagrams of computer modeling of electromagnetic process in a mode of recuperative braking. The current and a voltage of the network are in an antiphase.

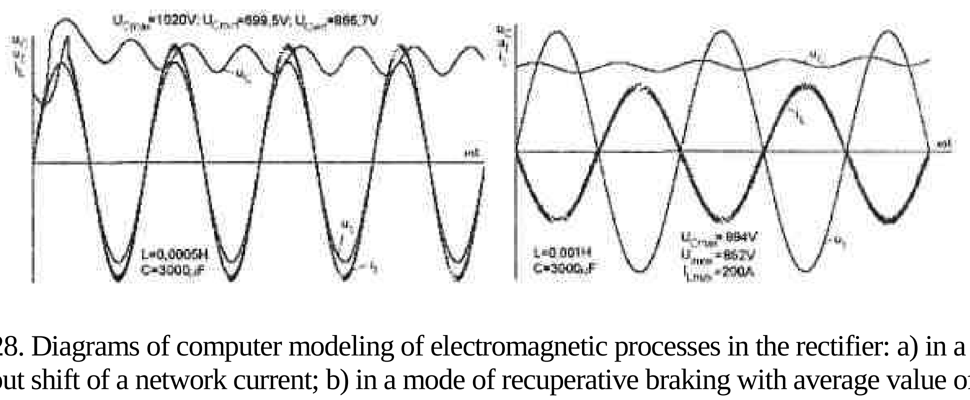


Fig. 28. Diagrams of computer modeling of electromagnetic processes in the rectifier: a) in a traction mode without shift of a network current; b) in a mode of recuperative braking with average value of an entrance current of the capacitor 100 A

On Fig. 29 the result of computer modeling of starting process with four-quadrant entrance converter is shown. We see, that i_L pulses and grows according of management I_{lm}=2I_d. Pulsation's of U_C - also grow (since the current of loading grows too). Here integrated in duration of start-up parameter ***P/S* =0,904**, i.e., it is the best variant because four-quadrant converter consumes from a network almost sine wave current which has no a phase lag of a voltage. However a current is not completely sinus shaped since there is a compelled modulation to fluctuation of a current.

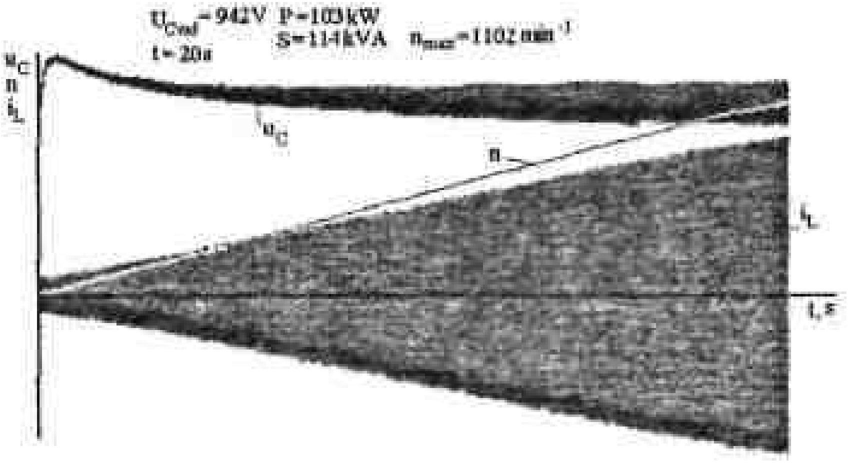
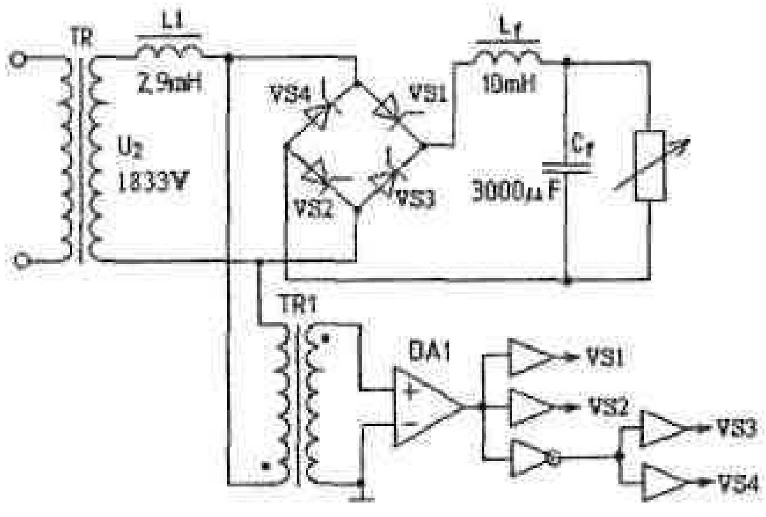


Fig. 29. The starting diagram of an electric train with four-quadrant converter on input

4. REALIZATION PRINCIPLES AND EXPERIMENTAL RESEARCHES

To prove suggested schemes of realization and to evaluate a real parameters of it operation computer simulation using programme packet PSIM6.0 have been conducted creating a full schemes of control at given schemes of presentation of power system. On Fig.30. is presented system of modelling with LC input filter for traction and braking regime respectively. In this schemes is introduced an inductance L1, presenting leakage inductance of the secondary winding of transformer, which is presented twice bigger than a rated one because modelling is provided for only one branch of pulse regulator with sequential connected motors. This latter in model is presented by loads resistor in traction mode and source of current in braking case. Nevertheless modelling a pulse regulator on 1 kHz frequency and motor circuit with appropriate parameters have been applied on mean value of start and brake current 300 A.



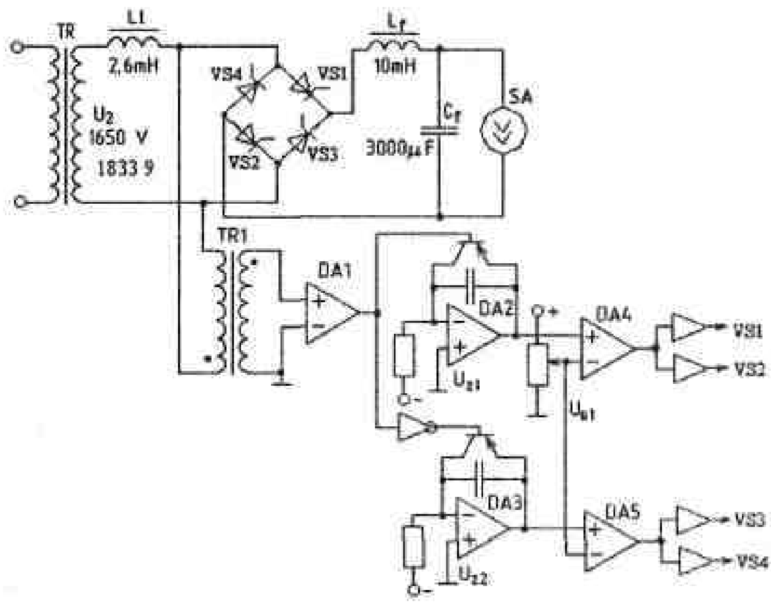
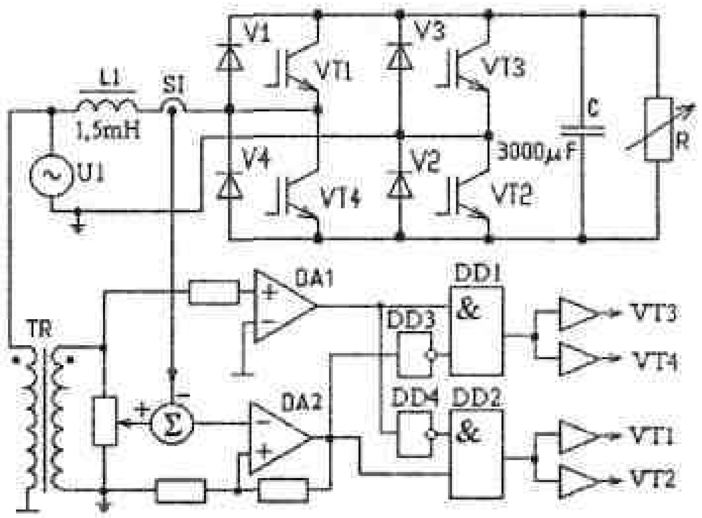


Fig.30. Schemes of modelling with LC input filter in traction case (upper) and brake case

Investigating this scheme it became clear that crucial factor is value of input inductance L1, which was not considered in theoretical investigations. Inductance arises a commutation (overlap) regime of input current which in its order creates phase shift between input voltage and fundamental harmonic of current. Especially important it is in brake regime because for thyristors of the bridge must be introduced leading angle of switching bigger than largest possible overlap angle. In this case it is close to 40º.

What about a values of pulsations of current of the choke and voltage of the filter's capacitor then experimental values are very close to the theoretical calculated in the traction case. In brake case distinctions are bigger and rise up to 30% because introducing leading angle of switching. It means that obtained equations must be specified taking into account this leading angle.

System with modulated input rectifier (four quadrant one) have been investigated using principle schemes presented on Fig. 31. Also in these schemes pulse regulator with motor load is substituted by loading resistor in traction case and current source - in brake regime. Nevertheless at modelling those substitutes have been presented by pulse regulator and motor load. Such a regime practically not influenced an action regime of device.



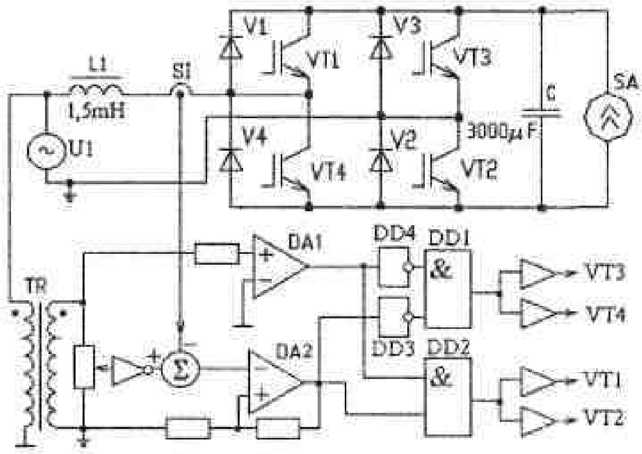


Fig. 31. Scheme for modelation using four quadrant converter in traction (upper) and brake cases

As regards to the accuracy of mathematical descriptions of the schemes provided in theoretical part all equations but equation for calculation of switching frequency showed a very good coincidence with experimental results. Equation for calculation of switching frequency gives bigger frequency than experimental obtained because theoretical calculations was done in simplified circuits.

CONCLUSIONS

1. Controlled rectifier's electric drive of a direct current for electrical train of an alternating current rises distortion of network current which is difficultly filtrated and consumption of reactive power which is difficultly compensated because of variable delay angle.
2. Introduction in the electric drive of a direct current of an electrical train of an alternating current unit of a constant DC voltage with the improved power parameters and pulse regulation of traction motors is perspective.
3. The unit of a direct current of system of pulse regulation can be realized

   - with passive entrance *LC* filter;
   - with introduction of four-quadrant modulated converter of a voltage source **SAMT** on an input.

4. Researches of realization entrance *LC* filter have shown, that filter with a linear reactor is too heavy. Weight of the filter can be reduced introducing in the filter a nonlinear reactor (the weight of a reactor decreases approximately in 5 times), thus power parameters are a little worsened.
5. For an estimation of power efficiency of the electric drive during start-up transient of a drive the integrated parameter of the relation of powers *P/S* is introduced.
6. Comparing integrated power parameter *P/S* during start-up of the circuit with the controlled rectifier and circuits with a pulse regulator with the entrance filter, we see. that this parameter is approximately equal for both systems and is close to 0,78. Precisely same this parameter will be also for an asynchronous drive with the inverter of a voltage.
7. Integrated power parameter *P/S* can be improved up to 0.9, having entered on an input converter SAMT. All necessary performance data for realization of SAMT on the electric drive of an electrical train are investigated

8. The ralional algorithm of management of SAMT with double value of amplitude of a sine wave current of an entrance reactor concerning average value of a current of loading is received.
9. Modern parameters of transistors IGBT answer to parameters of the traction electric motor (U_N = 25 V, I_{st}=300 A). Therefore is real to create the electric drive of a direct current with pulse regulation with transistor converter SAMT on an input of each traction motor with a separate pulse regulator.
10. Realized and proposed algorithms for control of schemes prove very good properties and provided very good action of systems.

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