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PRESENT STATE OF POWER ELECTRONICS CIRCUITRY AND PERSPECTIVES OF ITS DEVELOPMENT

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Abstract. This paper is devoted mainly to the circuitry, because element base is a big independent issue.

Let us say a few words about terminology. A modern converter can be rarely represented as a simple device like "rectifier", "inverter" etc. It usually consists of the combination of several units, performing elementary functions. For such multistage units it makes sense to use a definition of converter "technology", keeping in mind some actions with electric current for a certain purpose. It is similar to the step activities in chemistry: to take a substance, to heat it etc. After the formulation of a goal and a number of necessary actions it is possible to present a corresponding structure circuit.

According to described above we tried to mention basic technologies used in modern power electronics. The perspectives of the electronics in the nearest future are connected with the further improvement of basic technologies, because their combination allows for developing new technologies. In our opinion, there are four such technologies.

Keywords: power electronics, technology.

The first place belongs to the AC electric drive with an intermediate DC link. This technology is represented by a structure circuit (Fig.1). Its development leads to two consequences:

1. A regulated DC electric drive with collector electric motors, controlled rectifiers and PWM converters is gradually replaced. An asynchronous electric motor is twice cheaper than the collector one, more serviceable and reliable, and these advantages compensate the additional cost of the more complicated converter (Fig.1).

2. An old structure of the AC electric drive with direct coupling on the asynchronous electric motor to the three-phase mains should be replaced.

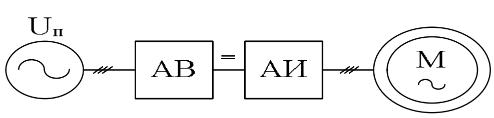


Fig.1. – Structure of AC electric drive with intermediate DC link Uп – three-phase power supply; АВ – autonomous (active) rectifier; АИ – autonomous inverter; М – three-phase mains

Its main disadvantages are:

- the absence of effective techniques of broad-range adjustment of the revolution frequency (according to the estimations available, about 70 % of all drives should be adjusted);
- reactive power comparable with the active one is consumed from the mains;
- start-up currents reach 7-fold values of the rated current.

One of the domestic achievements in this field is the start of commercial production of electric locomotive "ДС-3" with an asynchronous frequency-regulated electric drive at Dnepropetrovsk plant. This is a result of the joint development of the Dnepropetrovsk plant with "Siemens". Many companies in Ukraine deal with industrial drives with the structure as shown in Fig.1. The implementation of results is of high interest for metallurgy and machinery. In the future an electric transmission as in Fig.1 will be used in many means of transport, not only in electric one. The Lugansk plant "Luganskteplovoz" has already completed the development of a diesel train with the electric transmission. Tractors should be switched to electric transmission as well.

Theoretical and applied developments in this field of technology in Ukraine are carried out by East-Ukrainian State University (Lugansk), "Converter" company (Zaporozhie), Research institute of Kharkiv electromechanical plant, "Eos" company, "Energosberezhenie" concern (Kharkov), Kremenchug State Polytechnic University and many other companies.

The second technology is a secondary power supply with an intermediate high-frequency link (represented by structure in Fig.2). This structure shows the possibility of dramatic reducing material consumption and energy losses because of power electromagnetic elements – transformers and filters by using sophisticated semiconductor commutators (compact and inexpensive devices) and by increasing their number. Moreover, the introduction of additional converters significantly improves controllability of the system and, thus, the quality of electric energy.

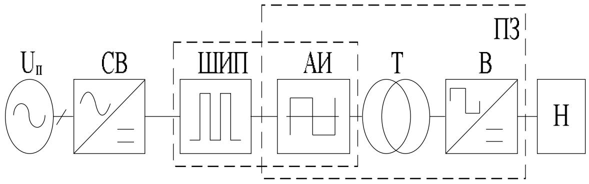


Fig.2. – Structure of secondary power supply with intermediate high-frequency link;
СВ – mains rectifier; ШИП – PWM converter; АИ – autonomous inverter; T – transformer; В – rectifier of intermediate link; Н – load; ПЗ – intermediate AC link

As a result, in medium power range the structure (Fig.2) practically replaced the conventional one and even more simple structure (Fig.3) without the intermediate high- frequency link.

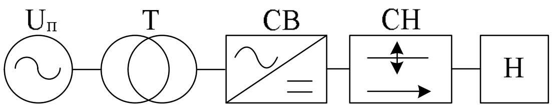


Fig.3. – Conventional structure of secondary power supply: СН –voltage stabilizer

Many companies in Ukraine and in Kharkov produce secondary power supplies. Further perspectives of the secondary power supply technology, in our opinion, are connected with its application in the system of electric energy transmission. The motives are as follows.

If the use of an old structure of the drive with direct coupling on the motor to the mains with its already mentioned disadvantages is declined, the obvious question arises: is it expedient in the modern energy system to have the monopolistic use of three-phase sinusoidal low-frequency current as a carrier of transferred energy or basic signal. At the beginning of introducting the AC Energy Transmission System (ETS) the application of such a signal was explained by a necessity of providing direct coupling on the motors to the mains (Fig. 4).

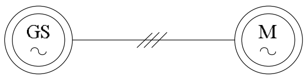


Fig.4. – Structure of the three-phase AC low-frequency energy transmission system

At that time the structure (Fig.4) had no alternative, because there were no semiconductor converters. However, upon the switch to feeding a motor by a converter there are no power components in the load which need three-phase sinusoidal voltage. Thus, in ETS there is possible to use alternative basic signals. In our opinion, the signal used in the technology of the secondary power supply can be chosen, namely: single-phase high-frequency current with a rectangular waveform (Fig.5, б).

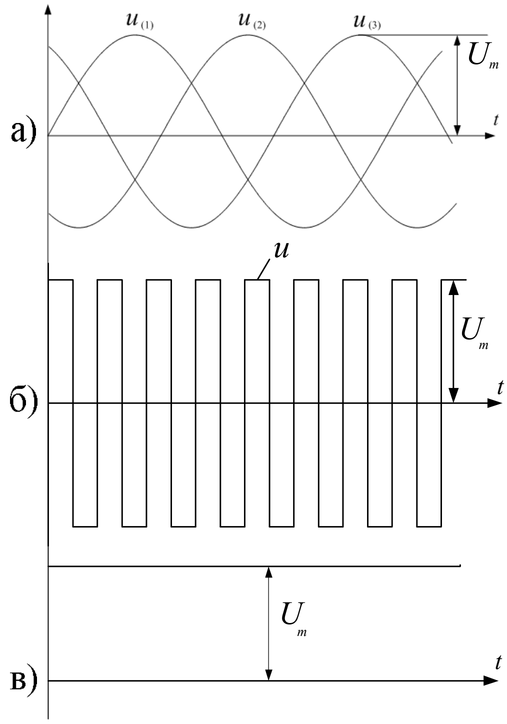


Fig.5. – Basic signals of ETS:
а – three-phase low-frequency sinusoid; б – single-phase high-frequency meander; в – time-constant signal

This signal keeps leadership as a carrier of energy in the intermediate AC link and that is why this system of secondary power supply is so effective.

We don't suggest replacing the existing ETS for the aim of using that signal. We only propose connecting additional parts to the structure, some of which are shown in Fig. 6 – Fig.9.

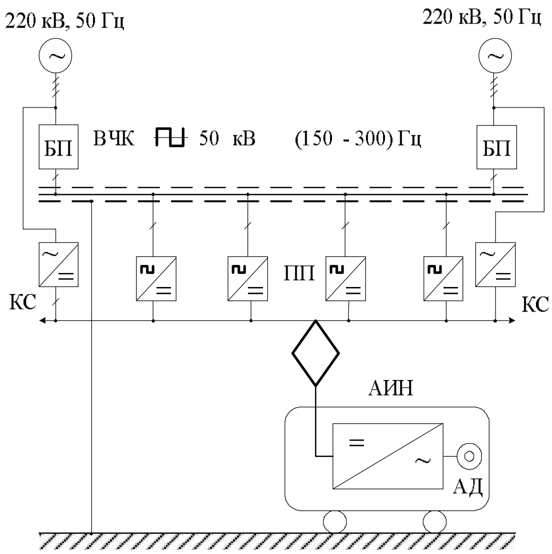


Fig. 6 – System of distributed power supply of the railroad contact grid: БП – basic converter, ВЧК – high-voltage high-frequency cable, ПП – sub-supply point, КС – DC contact grid

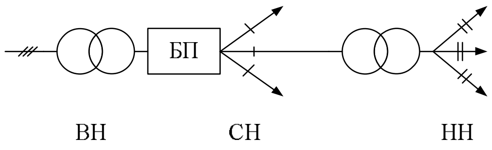


Fig.7 – District electric energy supply scheme: ВН, СН and НН – high-, medium- and low voltage levels

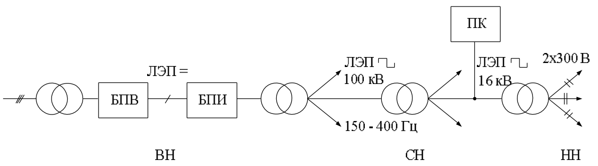


Fig.8 – Structure "DC" – "Single-phase meander": ПК – converter-corrector (active filter)

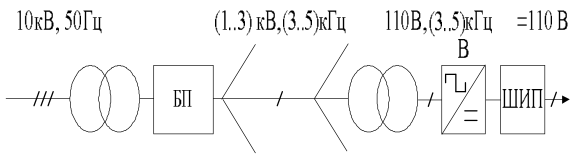


Fig.9 – Alternative solution of low-voltage distribution mains 220/380 V, 50 Hz.

Let us comment on the situation. When M. Dolivo-Dobrovolsky developed his structure of AC energy transmission, his main objective was to get rid of low voltages of the DC energy transmission. At assigned power the low voltage leads to high currents and, thus, to high material consumption and low efficiency. M.Dolivo-Dobrovolsky has mainly handled that, but there was impossible to remove low-voltage distribution mains 220/380 V from his system, because many consumers, mainly utility ones, require low level of voltage. Thus, energy losses in the distribution mains 220/380 V are about 10 % or more, and that energy is wasted heating cables of low-voltage power transmission lines, which can't have a small cross-section.

A possible alternative (Figc.9) is the use of single-phase voltage 1-3 kV with frequencies of 3-5 kHz and reducing it at consumer's by an insulating transformer $T_л$, and then transforming it into a stabilized 110 V voltage for using the lowest voltage distribution mains. Such technology is represented by conversion units in the initial structure of the secondary power supply (Fig.2), but it is recommended to rearrange them and to merge. The advantages of the application of secondary power supply technology in ETS are clearly shown by this example.

A basic converter (Fig.10) is a series of output connections of 2-4 sections with three-level rectifiers and inverters.

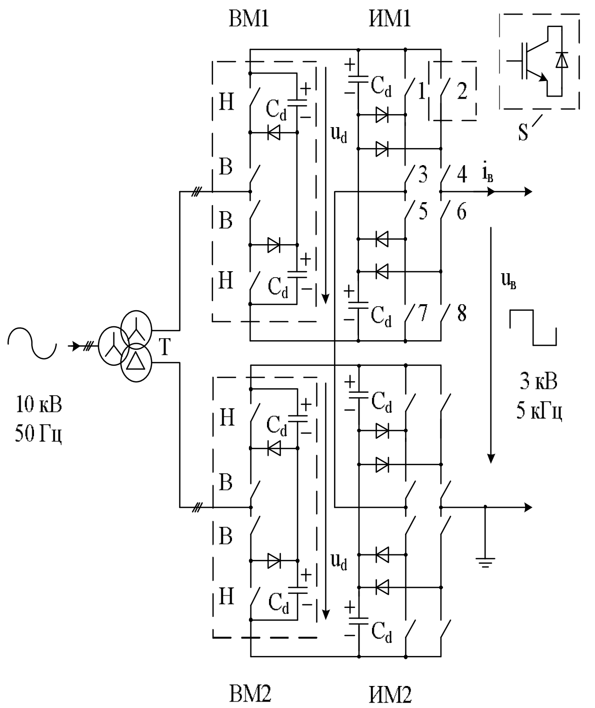


Fig.10 – Scheme of the converter: BM1-BM2-rectifier modules; ИМ1, ИМ2 – inverter modules; S - power switch; T - power transformer

They allow to form quasi-rectangular output voltage (Fig.11) with stepped processing of edges without switching at the top of the meander. That provides the switching frequency of semiconductor devices coincident to the main frequency and a possibility of applying power IGBTs available now.

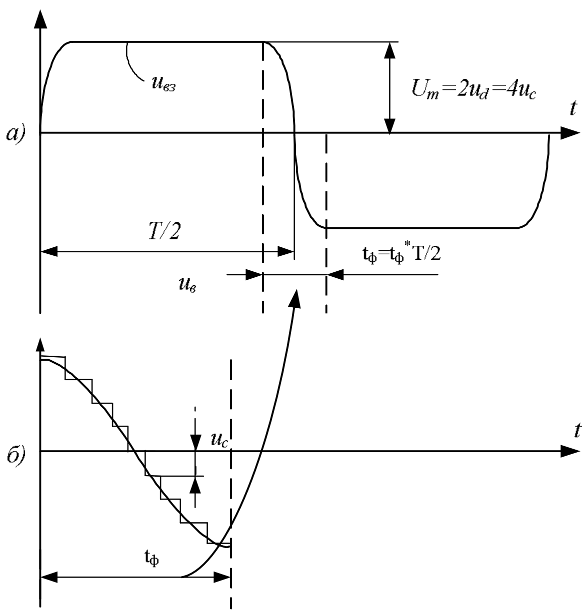


Fig.11 - Meander with limited spectrum (a) and stepped formation of its edge (б)

The formation of sinusoidal voltage would require 2-3 times more switchings (Fig.12).

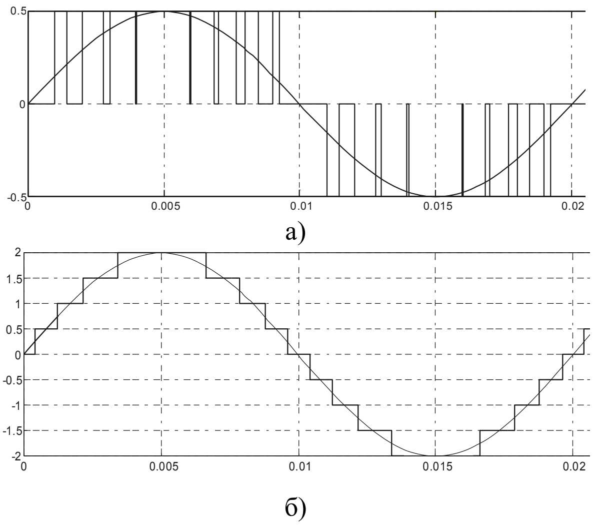


Fig.12 – Methods of formation of sinusoidal voltage: а – PWM; б – inverter

Another advantage of the meander in comparison with a sinusoid is that its effective values of voltage and current are comparable to the amplitude ones (for a sinusoid they are $\sqrt{2}$ times smaller), which allows to obtain the efficiency of basic converter about 99 %, and almost twice reduce rated power of semiconductor switches.

Increasing the main frequency (3-5 kHz) allows to reduce the dimensions of insulating transformers, which are mounted on distribution boards of each consumer (in a single apartment or in a small group of them). Their ferrite cores can be made in the "Ferrokeram" plant, located in Belaya Tserkov. At power about kilowatts such a transformer weighs 3-4 kg and its efficiency is about 99%. In technologies using the frequency equal to 50 Hz the weight of the transformer and losses in the system would be ten times higher. The insulating transformer provides a possibility of voltage selection for the consumer. It can be decreased to 110 V or less, with increase in electric safety.

Obviously, certain measures should be taken for prevention of the consumer access to the high-voltage input of the transformer, similar to those made to prevent the consumer access to an watt-hour meter for stealing electrical energy.

Introduction of PWM converter, installed together with load rectifier on the same board, allows to improve the quality of electric energy at the consumer's end at the expense of voltage stabilization and the limitation of current overloads. Energy consumption takes place with DC voltage that removes vibration at sound frequencies. If to add up losses, they will make about 4 % instead of 10 % in theconventional mains with 220 / 380 V. Material consumption is decreased in the same degree with the increase of electric safety and the improvement of energy quality at consumer's.

However, a lot of work should be done to neutralize the disadvantages of the alternative signal; the list of those considering object features (the presence of power transmission lines as distributed parameters objects and high power) becomes quite long.

Difficulties associated with that can be overcome because of the following:

- the limitation of relative edge duration on a level of 1/3 - 1/7 (Fig.11);
- the application of frequencies lower than in the system of the secondary power supply (150-400 Hz in the range of medium voltages (tens of kV) and 5 kHz at voltage lower than 10 kV);
- the use of the alternative signal in co-axial cable power transmission lines, which has much lower inductance and higher capacitance in comparison with the aerial ones and can play a role of electromagnetic screen;
- the application of special techniques of converters control, preventing the appearance of resonant phenomena in power transmission lines.

The third technology of power electronics can be named "technology of active filtering" (Fig.13).

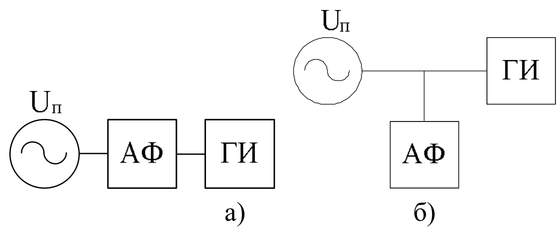
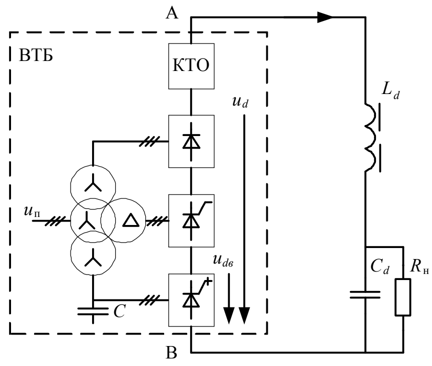
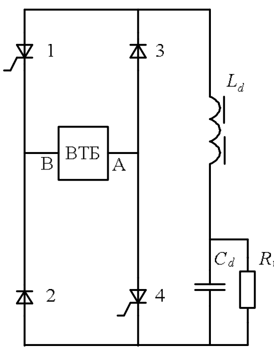


Fig.13. Structures, realizing active filtering.
ГИ – distortion generator; АФ – active filter; $u_П$ – filtered source (load of АФ)

There are several directions there, some conventional and some perspective ones. Reactive power compensators which have a quite wide application in the modern ETS, belong to the conventional group. However, their drawback is that we try to eliminate inactive power components instead of their source. More than 50 years ago the founder of Industrial electronics department of Kharkov polytechnic institute Prof. O. Mayevsky in his scientific works proved that it is better to eliminate or to minimize reactive power at the point of its appearance. Thus, there is no need for compensation. The devices of the perspective group implementing this approach consist of power factor correctors used separatly for realizing this function and in combination (for example, with rectifiers). High capacities of active filtering technology are proved by the fact that the majority of converter manufacturers deal with it. In Ukraine those are Institute of Electrodynamics of NAS of Ukraine, Kiev polytechnic institute, Dnepropetrovsk national university of railroad transport and others. Several proposals in this field were made at Industrial electronics department of NTU "KhPI". They were presented at the conference by professors Zhemerov, Domnin and others. One of them, which has not been presented at "Power electronics and energy efficiency" conferences yet, introduces the application of the correction of power factors based on a booster principle. It can be explained by the example of the power supply of the electrified railroad, which is developed by NTU "KhPI" together with Scientific center of "Ukrainian railroads" and Dnepropetrovsk national university of railroad transport (Fig.14).



a)



б)

Fig.14 – Scheme of a booster converter
a) – nonreversible; б) – reversible
(ВТБ – switch-transformer block; КТО – short-term current limiting unit; Ld, Cd – output filter; Rн – equivalent resistance for load consideration; C – capacitors of input booster filter)

The main rectifier can be built with the use of diodes or SCRs operating in a steady-state mode with a firing angle $\alpha=0$ or α, close to 180^0. It is equipped with the reversible booster converter with the regulation range ±20% with GTOs. Using the booster controlled by PWM technique makes it possible to compensate the reactive component of the current on the mains side, because of inductances of the feeding transformers, and upper low-frequency harmonics generated by the main rectifier. On the load side it is possible to compensate non-canonical and canonical harmonics of the main rectifier. Obviously, we can't compensate both input and output harmonics in one unit. To realize such combined function it is necessary to use a low-power series active filter at the output. The expensive part of the structure consisting of GTOs is low-power and doesn't significantly reduce the efficiency of the system.

Recently the Ukrainian companies mentioned above, as well as companies in Russia and some other countries, has developed a theory of active filtering. It isn't possible to mention here all done in this subject and we can only voice our opinion on that issue.

Particularly, attempts to search for integral material criteria for inactive components of full power together with non-sinusoidal voltages and currents, that is, the criteria, which are correct regardless application purposes, will not lead to the positive result. It is proved, first of all, by our experience: there are dozens of such criteria and none of them is universal.

The second issue deals with the basic algorithm of operating the power factor correction devices in load circuits. This algorithm should provide an equivalent active load relatively to the power supply, which is the proportional link between current values of voltage and current waveforms. With the sinusoidal internal EMF of the mains it provides a sinusoidal waveform, and with non-sinusoidal (for example, a meander) it produces all harmonics presented into the internal EMF to do useful work.

At active filtering of the harmonics with frequencies of converter modulation one of the key problems is their measurement. Unfortunately, a filter with the ideal rectangular waveform of the frequency characteristic, that passes harmonics of a certain continuous range without phase distortions and doesn't pass any other harmonics, can't be practically realized. It should forecast the future and its response to the current value of the input signal must start earlier than the signal is applied. Such filter can be realized for steady-state mode because the future value for a periodic signal is connected to the previous ones. As our joint study with Dnepropetrovsk national university of railroad transport has shown, it is not necessary to calculate band-pass harmonics for the realization of such filter, because the number of those can be quite large, and it is enough to use an integral digital filter with certain properties. In our opinion, the development of effective distortion sensors should be continued.

Finally, **the fourth** technology is a controlled energy exchange between the parts of the electric system. It can be used, for example, for connection of more and more popular energy storages, described by Prof. S.A. Kharitonov at one of the previous conferences (Fig.15).

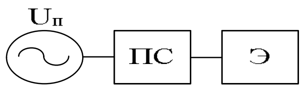


Fig.15. - Structure, realizing controlled energy exchange: $u_П$ – main energy system; Э – energy storage; ПС – connection converter.

Another direction contains the structures with distributed power supplies. They are considered to be the distinctive feature of the new type of energy system, which is called "Intellectual energetic system" (Smart System) in Ukraine. Power electronic devices in the "Intellectual energetic system" perform the functions of final control elements making this system intellectual. Converters can do that and it is proved by an example of energetic system in miniature, that is, the secondary power supply. Besides conventional control functions, they can realize the new ones. For example, the control of resonant properties of the system, caused by power transmission lines as distributed parameter objects. We presented the possible solution of this problem at one of the previous conferences. The existing means of energy system control don't have sufficient speed for it.

The possibilities of the realization of those and many other quite sophisticated control techniques, described above, has dramatically expanded due to the development of a new generation of microprocessor control systems. The perspective methods are: the prognosis control and a principle of indirect determination of the parameters of an electric system allowing for minimizing the number of current state sensors of the system and the number of information control points.

Considering the features of converter circuitry as a whole, we can admit the increase of the number of units in converter structures and the use of more complicated commutators with the purpose of weight reduction of power electromagnetic elements and broadening functional capabilities.

It is expected that in the future the semiconductor converters will tend to switches ("electronic contacts"), coupling on one part of electric system to another practically without any filters. The difference from mechanical contacts is that those couplings take place with a certain frequency, which can be different in the different parts of the system. Secondary power supplies and drives have already realized that ideology on 50 % and will complete it on 100 %, if we feed them not with the sinusoidal voltage, but with the meander. We can see the results of such a metamorphose on information electronics devices where it has already taken place. Electromagnetic elements are eliminated in electronic circuits, and the units themselves turn to a group of semiconductor devices, quite sophisticated but compact and with wide functional capabilities.

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Анотація.

Стаття присвячена проблемам схемотехніки у сучасній енергетиці. Розглянуто декілька напрямків розробок електроприводів, відмічено їхні переваги та недоліки. Описано сучасні схемотехнічні можливості та перспективні напрямки їхнього подальшого розвитку в Україні

Sokol Yevhen was born in 1952. Dsc., full professor, vice-rector on scientific and pedagogical activity, the head of the department of industrial and biomedical electronics of National university "Kharkiv Politechnical Institut", the author of more then 250 scientific and methodological works. A specialist in electronic systems and power electronics.