New Family of AC Regulators with the Switched Quasi-Impedance of Power Supply or Load

Aleksey V. Udovichenko, *Member*, *IEEE*, Gennady S. Zinoviev, *Member*, *IEEE*
Novosibirsk State Technical University, Novosibirsk, Russia

Abstract **– The new family of AC voltage regulators based on the switching quasi-impedance of power supply or load is offered. Such AC-AC converters are intended for construction of conditioners of voltage quality, regulators of a soft start of induction motors, compensators of a reactive power, active filters of harmonics, devices of balancing of three-phase circuits, compensators of voltage sags in electric power distribution systems. Results of mathematical modeling and analytical calculation of RMS values by fundamentals of the currents and voltage are given.**

Index Terms **– Stabilization, quasi-impedance, regulator of alternating voltage.**

I. INTRODUCTION

THE REQUIREMENT for stabilization, regulation of alternating voltage actual for all AC networks and especially for "smart" networks. Traditionally, these problems are solved by use of appropriate power electronic converters based on of voltage or current source inverters. But similar converters require the application of bulky, expensive reactive elements in the form of electrolytic capacitors or reactors respectively. Thus, the presence of the device of internal DC voltage or current link aggravates problems with liquidation of emergency regimes in these links.

Known alternative decisions of specified problems of "smart" networks based on other types of converters namely AC voltage regulators, cycloconverters, matrix converters [1, 2]. And all of these converters are single-stage and, accordingly, do not contain a link of a direct current with large reactive storage elements.

For the successful solution of these problems requires of effective AC voltage regulators. Existing thyristor regulators with phase regulation are not approach for solving of these problems because of deformed forms of the input and output currents and the delay in regulation relating to the properties of the natural commutation. In the mid-nineties of the last century there were offered the transistor AC regulators characterized by practically sinusoidal forms of input and output currents and the good dynamics of their regulation at high frequencies of switching of transistors [3–4].

It is necessary to note here possibility of output voltage increasing respect to the input without using a transformer [3–5]. The family of such AC voltage regulators is obtained by corresponding adaptation of known schemes of up-and-step-down DC-DC regulators for use in AC circuits [3–6].

II. NEW FAMILY BUCK-BOOST AC-AC REGULATORS WITH COMMON SWITCH

The new family of AC voltage regulators based on the switching with high frequency of quasi-impedance of power supply or load is offered in this paper [7–9].

Several types of AC voltage regulators with switching quasi-impedance are considered. The scheme of AC voltage regulator with a switch at zero of the power supply and the load circuit is presented in Fig. 1. The vector diagram explaining the principle of operation of the regulator is shown in Fig. 2. Fig. 3 shows simulation results obtained by the PSIM program for a suggested regulator. The input voltage u_A and current i_A, control signals for the switch of three phase diode bridge at zero of the power supply, the capacitor voltage and current, the reactor voltage and current and the output voltage u_{outA} with current i_{outA} are shown as well.

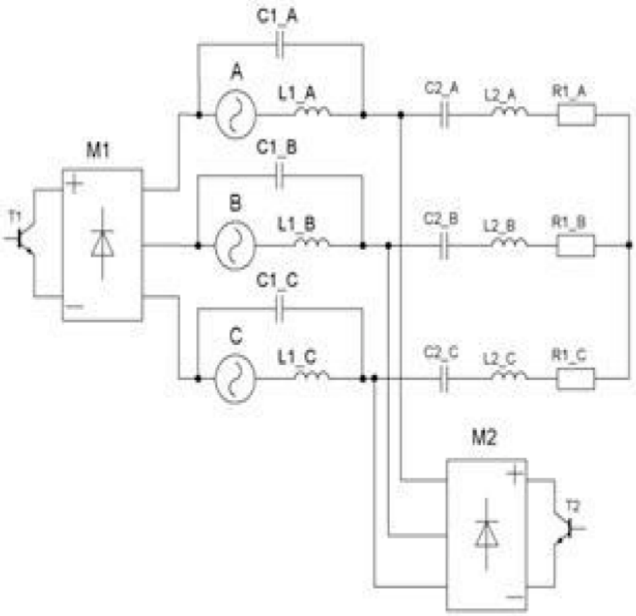

Fig. 1. AC voltage regulator with a switch at zero of the power supply and the load circuit.

The other version of AC voltage regulator with switching quasi-impedance is shown in Fig. 4, this regulator with a switch at the load circuit. The same waveforms of currents and voltages are shown in Fig. 5.

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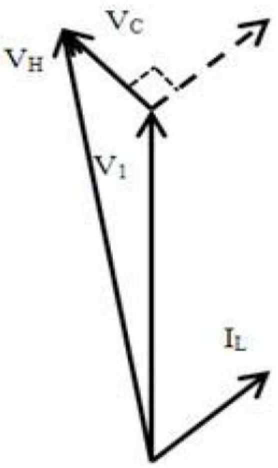

Fig. 2. Phasor diagram.

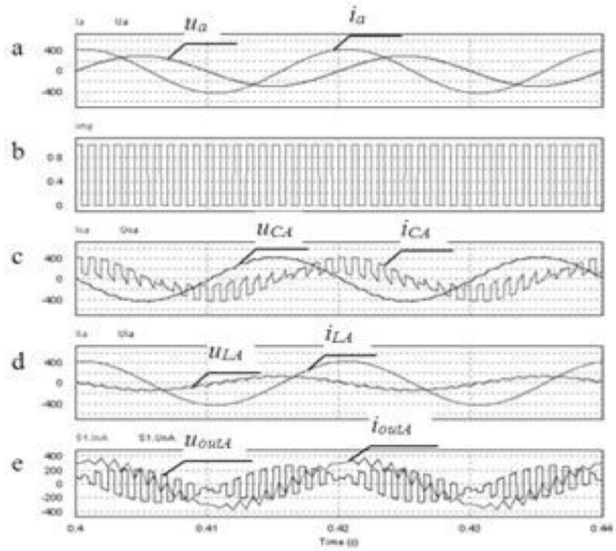

Fig. 3. Waveforms of the currents and voltages of AC voltage regulator with a switch at zero of the power supply and the load circuit.

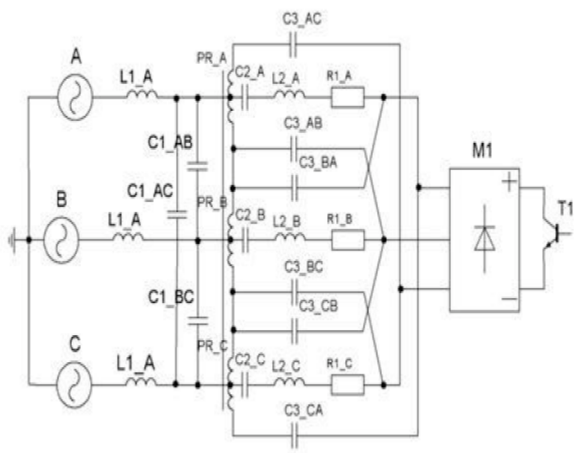

Fig. 4. AC voltage regulator with a switch at the load circuit. (PR – paralleling reactor).

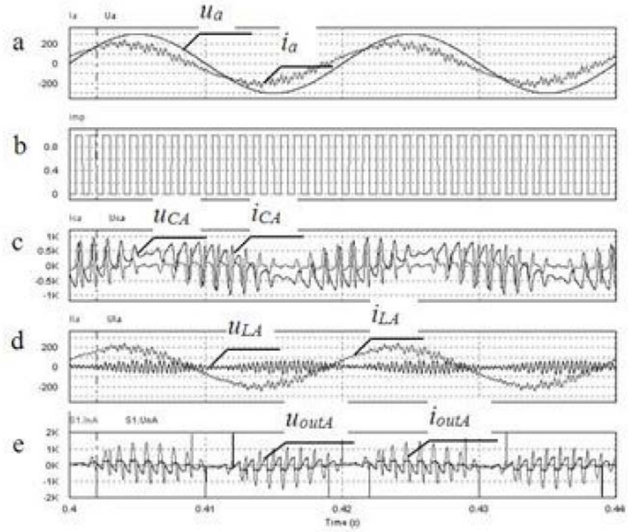

Fig. 5. Diagrams of currents and voltages for the AC voltage regulator with a switch at the load circuit.

External capacitance impedance is added to own inductive impedance of the actually power supply. It is known that the voltage phase on capacitor in the series circuit is opposite to the voltage phase on reactor, i.e. voltage on the capacitor is added to the voltage of the power supply. It is possible to raise, lower and stabilize load voltage, if to regulate with high frequency of the relative duration of the load connection to circuits with specified various impedances.

The control, load characteristics of the regulators and the dependence of input power factor of the modulation index are plotted Fig. 6, Fig. 7, Fig. 8, by the data obtained in the simulation in PSIM for both types of schemes. The quality of the output voltage and input current, which is represented as a dependency of the output voltage total harmonic distortion of the modulation index, Fig. 9, and the input current total harmonic distortion of the modulation index, Fig. 10 are evaluated.

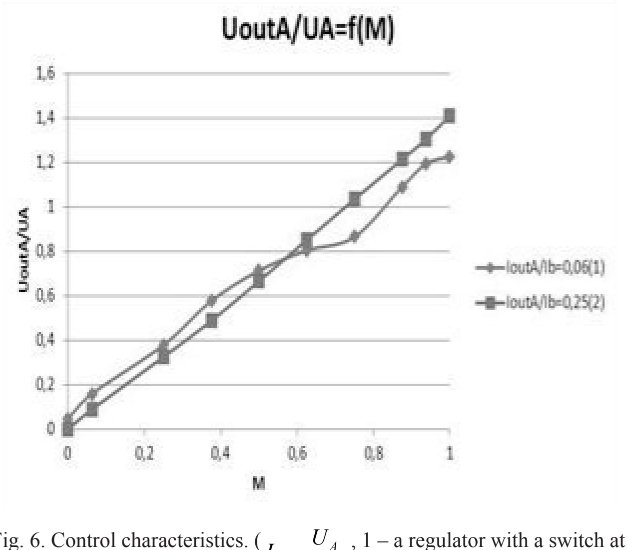

Fig. 6. Control characteristics. ($I_b = \frac{U_A}{\omega L_A}$, 1 – a regulator with a switch at zero of the power supply and the load circuit, 2 – a regulator with a switch at the load circuit).

From the control characteristics should be that scheme 1, 2 have full range of adjustment to zero voltage. The scheme 1 provides the greatest increase in the output voltage to a level of 1.4…1.5.

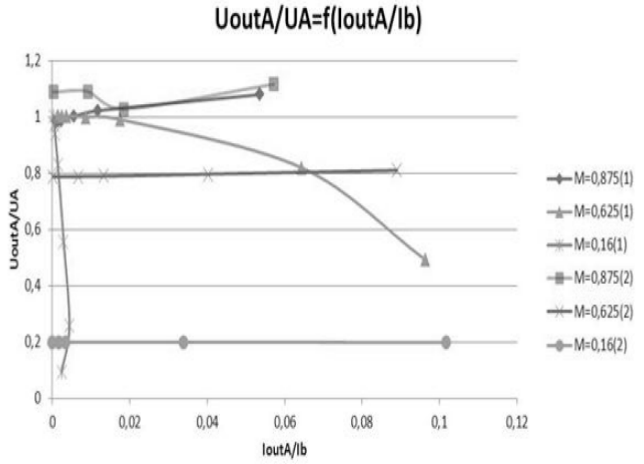

Fig. 7. Load characteristics.

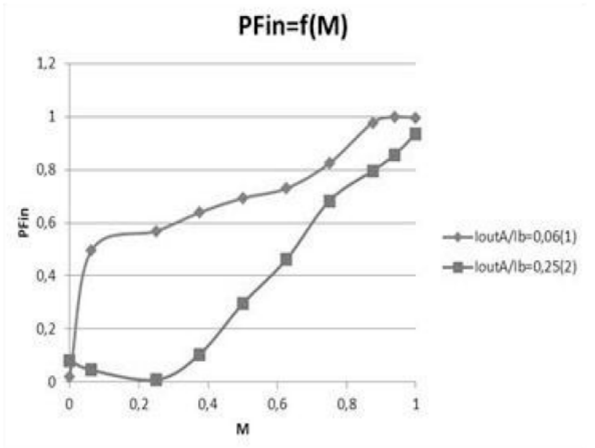

Fig. 8. The dependencies of input power factor of the modulation index.

Load characteristics of the regulators are also different. Scheme 1, 2 have increasing behavior (for $M = 0.875$), circuits 1, 2 are decreasing characteristics (for $M = 0.16$), also scheme 1 have a «hard» load characteristics (for $M = 0.16$).

Input power factor of circuit 1 is high (> 0.6…1) in the range $0.3 < M < 1$.

The quality of the output voltage and input current is high in the operating range, while it deteriorates with increasing load current.

The quality of the input current deteriorates at low load currents, the quality of output voltage remains high in the range $M > 0.5$.

III. ANALYTICAL CALCULATION AND RESULTS

The direct method of calculation (ADE2) [2] is used for the construction of the regulator mathematical model on a smooth component (fundamental). The equivalent circuit of one phase of regulator is shown in Fig. 11.

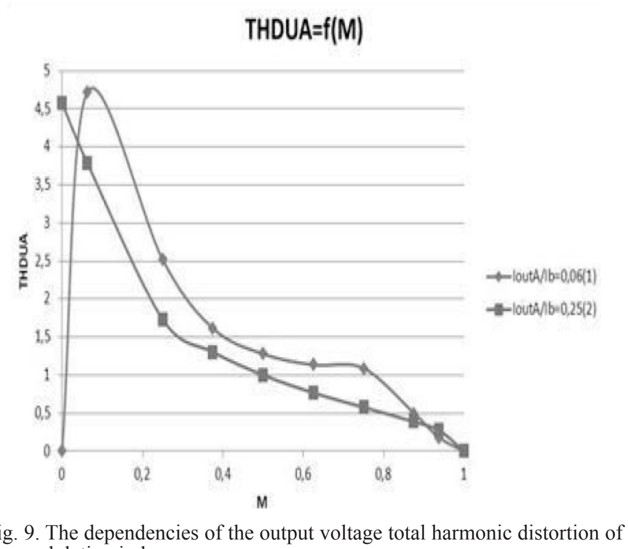

Fig. 9. The dependencies of the output voltage total harmonic distortion of the modulation index.

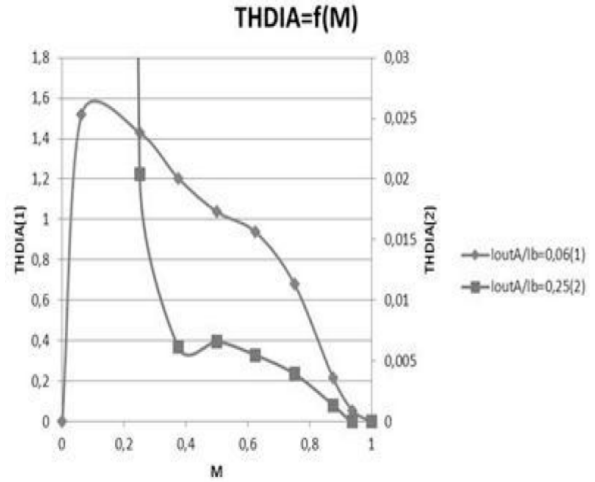

Fig. 10. The dependencies of the input current total harmonic distortion of the modulation index.

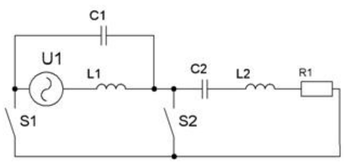

Рис. 11. Equivalent circuit of one phase of AC voltage regulator with a switch at zero of the power supply and the load circuit.

Differential equations of the circuit for both its states can be written as:

$$L_1(1-\psi)\frac{di_1}{dt} + u_{C2} + R_1 i_2 + L_2\frac{di_2}{dt} = u_1(1-\psi) \tag{1}$$

$$u_{C1} - L_1\frac{di_1}{dt} = -u_1 \tag{2}$$

$$-C_1\frac{du_{C1}}{dt} - i_1 + C_2(1-\psi)\frac{du_{C2}}{dt} = 0 \tag{3}$$

$$C_1\frac{du_{C1}}{dt} + i_1 - i_2 = 0 \tag{4}$$

where ψ – is the switching function, equal to unity when the switch *S1* is switched on and equal to zero when the switch *S2* is switched on.

Spectrum of switching function looks like:

$$\psi = M_1 + \sum_{n=1}^{\infty}\left(\frac{1}{\pi n}\sin\left(2\pi n M_1\right)\cdot\cos\left(2\pi n f t\right) - -\frac{1}{\pi n}\left(\cos\left(2\pi n M_1\right)-1\right)\cdot\sin\left(2\pi n f t\right)\right) \tag{5}$$

where f – switching frequency of the keys, $M_1 = 1 - M$, M – modulation depth. For $n = 1$ calculation was carried out on the first harmonic. Thus:

$$\psi_{(1)} = M_1 + \frac{1}{\pi}\sin\left(2\pi M_1\right)\cdot\cos\left(2\pi f t\right) - -\frac{1}{\pi}\left(\cos\left(2\pi M_1\right)-1\right)\cdot\sin\left(2\pi f t\right) \tag{6}$$

The following system of equations for the sine and cosine components of the fundamentals of the variables prepared to write in the matrix form is obtained as a result of this system of equations algebraization by the ADE2 approach:

$$\left|\begin{array}{cccccccc} 0 & R_1 & 0 & 1 & \omega L_1\psi_{\sin} & \omega L_2 & 0 & 0 \\ 0 & 0 & 1 & 0 & -\omega L_1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & -\omega C_1 & \omega C_2\psi_{\sin} \\ 1 & -1 & 0 & 0 & 0 & 0 & \omega C_1 & 0 \\ \omega L_1\psi_{\cos} & \omega L_2 & 0 & 0 & 0 & -R_1 & 0 & -1 \\ -\omega L_1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & -\omega C_1 & \omega C_2\psi_{\cos} & 1 & 0 & 0 & 0 \\ 0 & 0 & \omega C_1 & 0 & -1 & 1 & 0 & 0 \end{array}\right| \cdot \left|\begin{array}{c} I_{1(1)a} \\ I_{2(1)a} \\ U_{C1(1)a} \\ U_{C2(1)a} \\ I_{1(1)r} \\ I_{2(1)r} \\ U_{C1(1)r} \\ U_{C2(1)r} \end{array}\right| = \left|\begin{array}{c} U_{1(1)a}\psi_{\sin} \\ -U_{1(1)a} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{array}\right| \tag{7}$$

where

$$\psi_{\sin} = 1 - \frac{1-M}{2} - \frac{\sin\left[2\pi(1-M)\right]\cdot 8\pi^2\cdot\sin\left[T\omega_1\right]}{\pi T\omega_1\cdot\left(16\pi^2 - T^2\omega_1^2\right)} + +\frac{\left[\cos\left[2\pi(1-M)\right]-1\right]\cdot 16\pi^2\cdot\left[\cos\left[\frac{T\omega_1}{2}\right]^2-1\right]}{\pi T\cdot\left(T^2\omega_1^3 - 16\pi^2\omega_1\right)} \tag{8}$$

for $T = \frac{1}{f}$, $\omega_1 = 2\pi f$

$$\psi_{\cos} = 1 - \frac{1-M}{2} - \frac{\sin\left[2\pi(1-M)\right]\cdot\sin\left[T\omega_1\right]\cdot\left(8\pi^2 - T^2\omega_1^2\right)}{\pi T\omega_1\cdot\left(16\pi^2 - T^2\omega_1^2\right)} + +\frac{\left[\cos\left[2\pi(1-M)\right]-1\right]\cdot 2\cdot\sin\left[\frac{T\omega_1}{2}\right]^2\cdot\left(8\pi^2 - T^2\omega_1^2\right)}{\pi T\omega_1\cdot\left(16\pi^2 - T^2\omega_1^2\right)} \tag{9}$$

The control, load characteristics of the regulator and the dependence of input power factor of the modulation index are plotted, Fig. 12, Fig. 13, Fig. 14 by the solutions of these equations, which presented simultaneously with the corresponding characteristics obtained in the model of the PSIM program.

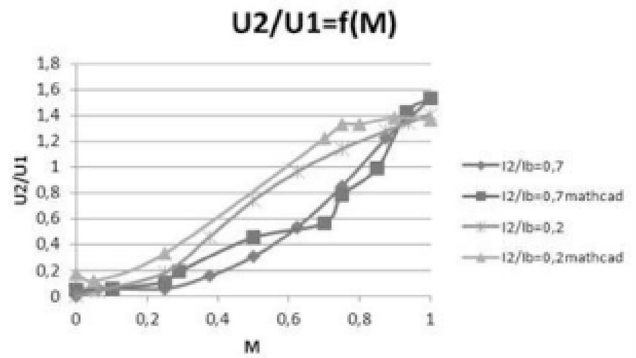

Fig. 12. Control characteristics.

As seen from the characteristics, operation range of voltage increase is within the range $0.5 < M < 1$, at the maximum value of the output voltage up to 1.6 times higher than the input at a sufficiently high quality.

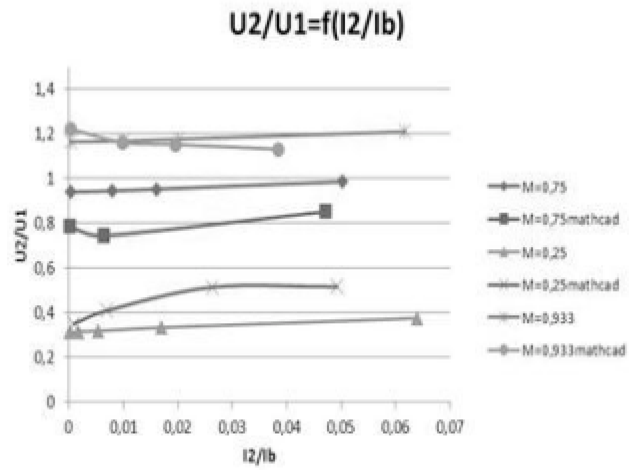

Fig. 13. Load characteristics.

The increased output voltage is achieved in the range of the depth of modulation $0.8 < M < 1$, at all levels of the modulation depth is available stabilized voltage.

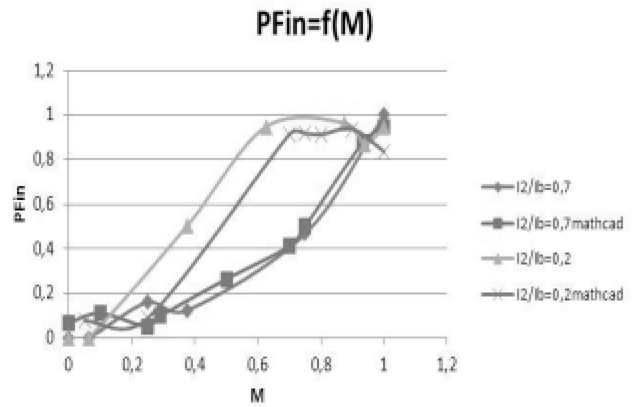

Fig. 14. The dependencies of input power factor of the modulation index.

Input power factor is high ($> 0.8\ldots1$) in the range $0.6 < M < 1$ at low load currents.

IV. CONCLUSION

1. The new family of buck-boost AC-AC converters with practically sinusoidal forms of input and output currents is offered.
2. Control, load and power characteristics of AC voltage regulator with a switch at zero of the power supply and the load circuit, and AC voltage regulator with a switch at the load circuit are defined.
3. AC-AC converters are intended for construction of conditioners of voltage quality, regulators of a soft start of induction motors, compensators of a reactive power, active filters of harmonics, devices of balancing of three-phase circuits, compensators of voltage sags in electric power distribution systems.
4. The expansion of the calculation direct method of the energy quality performance based on the model with variable parameters leading to differential equations with the periodical discontinuous coefficients is constructed. The accounting of first terms in the expansion of variable coefficients in a Fourier series allowed obtaining the analytical expressions in a closed form for all state variables and output variables fundamentals. This in turn led to the analytical expressions for all regulator general characteristics: external, adjusting and energy.

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Aleksey V. Udovichenko born in Novosibirsk in 1987 year. Third year postgraduate student of Novosibirsk State Technical University.

Gennady S. Zinoviev – Doctor of Science professor of the Industrial Electronics Department of the Novosibirsk State Technical University (NSTU), research supervisor of the Research Laboratory "Optimization of Energy in Converting Systems". Author of the textbook on power electronics, two monographies devoted to electromagnetic compatibility of gated converters, 90 patents and over 200 publications.