International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 8, No. 1, March 2017, pp. 176~183
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v8i1.pp176-183

Starting Operating Mode of the Combined Traction Levitation System of the Vehicle Equipped with Magnetic Suspension

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Article Info

Article history:

Received Oct 05, 2016
Revised Dec 11, 2016
Accepted Dec 21, 2016

Keyword:

Linear reluctance motor
Magnetic suspension
Magnetic system
Traction levitation system
Vehicle

ABSTRACT

The article gives the experimental results of the processes occurring in the combined system of traction and magnetic suspension, which was implemented on the basis of the linear switched reluctance motor. The goal of the research is to examine the possibility to combine the levitation and traction functions within one unit. The full- function physical model of the transport system with the magnetic suspension has been produced for experimental verification of the development concept for the combined system of traction and magnetic suspension. The research tests have been performed at the track structure with the limited length in order to study the processes, occurring in the most complicated start-up mode, when the discrete behavior of current in windings has the disturbance effect on the object levitation. The oscillograms of electromechanical transition processes, showing the mutual influence of traction subsystems and a suspension, are provided. The results of researches have illustrated dramatically that the development concept of the combined system of traction and magnetic suspension, based on the linear switched reluctance motor, is absolutely real. Further researches should be aimed at improving the system characteristics by reducing the mutual influence of levitation and traction processes.

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1. INTRODUCTION

The key constrain for the development of high speed transport systems, equipped with the magnetic suspension, is their high cost. At the present time, the applied research is being conducted aimed at seeking for technical solutions, allowing us to reduce the cost for the development of systems due to their simplification. In contrast with the systems presented in [1]-[3], the given system simplification can be achieved by combining the functions of traction, levitation and heading hold within a single power component- the traction levitation module. The simpler traction levitation system is possible to implement based on the linear switched reluctance motor with transverse flux [4]-[6].

The configuration of the magnetic system of the electric machine is a set of U-core ferromagnetic elements mounted in series. The windings are supplied by the simple half -bridge electric converter, which converts DC voltage of power source into unipolar impulses [7],[8]. Ferromagnetic track elements are set discretely at the track, allowing us to develop a passive track structure with reduced materials consumption. Based on the computer modeling results of the processes occurring in the combined system of traction and magnetic suspension ,which was implemented on the basis of the linear switched reluctance motor [1],[3],[5],[6],[9], we have developed the basic technical solutions.

The full- function physical model of the transport platform has been produced for experimental verification of the development concept for the combined traction system and magnetic suspension, based on the linear switched reluctance motor. We have performed the research tests at the track structure with the limited length in order to study the processes, occurring in the most complicated start-up mode, when the discrete behavior of current in windings has the disturbance effect on the object levitation. The article presents the experimental results of the processes occurring in the combined system of traction and magnetic suspension, based on the linear switched reluctance motor.

2. RESEARCH METHOD

The main goal of the research is to examine the possibility to combine the levitation and traction functions within one unit. The task is to ensure the similarity of processes occurring in the physical model to the processes inside the real object under the simplified operating conditions of the studied object. The similarity of processes, occurring in the physical model, is provided by the similarity of the magnetic system configuration of traction levitation model mock, made in scale 1:7, by the identity of scheme topology of power converters of the model, as well as the identity of the control algorithms and control system structure.

The simulation of operating conditions of the combined system of traction and suspension is reached by the simulation of the design scheme of the transport system with magnetic suspension, including the transport platform installed at the track structure. The simplification of operating conditions is connected with the lack of individual secondary suspension of traction levitation modules, installed at the transport platform. It reduces the stability area of the object being in the levitation state. In addition, the track structure has the limited length, so it limits the maximum speed of linear movement. The track elements are made of structural steel which worsens the traction and lifting properties of the system.

The model is equipped with measuring converters, connected with the multilink measuring and computing complex by wireline. The system operating modes are set from the PC via serial communication link. The control is performed by the microprocessor controller according to the program, which executable code is recorded in the internal read only memory (ROM) of the control board. Thus, the test bench equipment makes it possible to study the electromechanical processes, occurring in the traction levitation system of the model, under the starting mode at the track structure section limited by length. The mock basis is the traction levitation modules. The technical data of the module mock is given in Table 1.

Table 1. Technical data of the traction levitation module

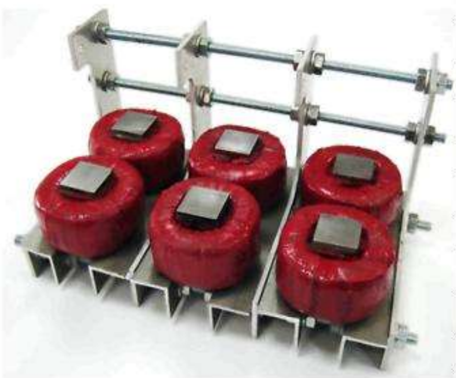
General view of the module	Magnetic system	U-core
	Standard size	PL20X20X40
	Electrical steel	3407
	Number of phases	3
	Passive stator	Iron
	Air gap, mm	2.0
	Overall dimensions, mm	220X120X100
	Weight, kg	2.865
	Active phase resistance at 20°C, Ω	3.622
	Supply voltage, V	24
	Current density, A/mm^2	5
	Rated phase current (RMS), A	2.5
	Type power converter	Half-bridge

Figure 1 presents the frontal view of the left sidewall of the transport trolley model, showing the model design. The model of the transport system consists of the track structure and transport trolley. The track structure is made of the squared beam 1 and installed at the double T-beam 2. The transport trolley of the covering type consists of two sidewalls, each of them has magnet cores 3 with windings 4, mounted between the legs 5 and fixed with threaded fastening, formed by studs, going through the holes of the legs.

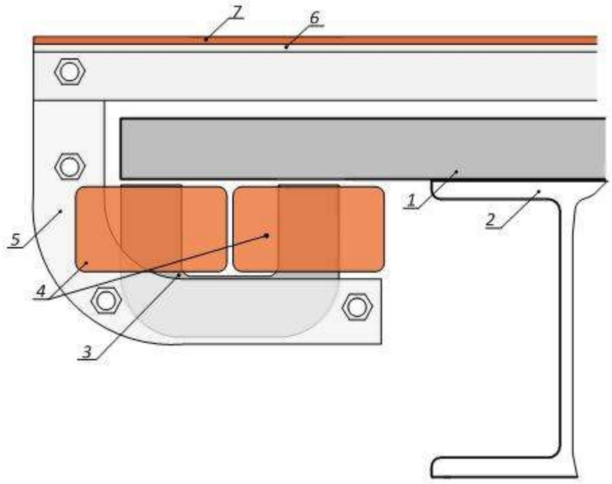


Figure 1. The scheme of the stand

The second sidewall of the trolley mock has the analogous design. Both sidewalls are connected together with cross fastening angels 6 on which the platform 7 with electric equipment is installed. Figure 2 shows the functional scheme of the traction levitation system.

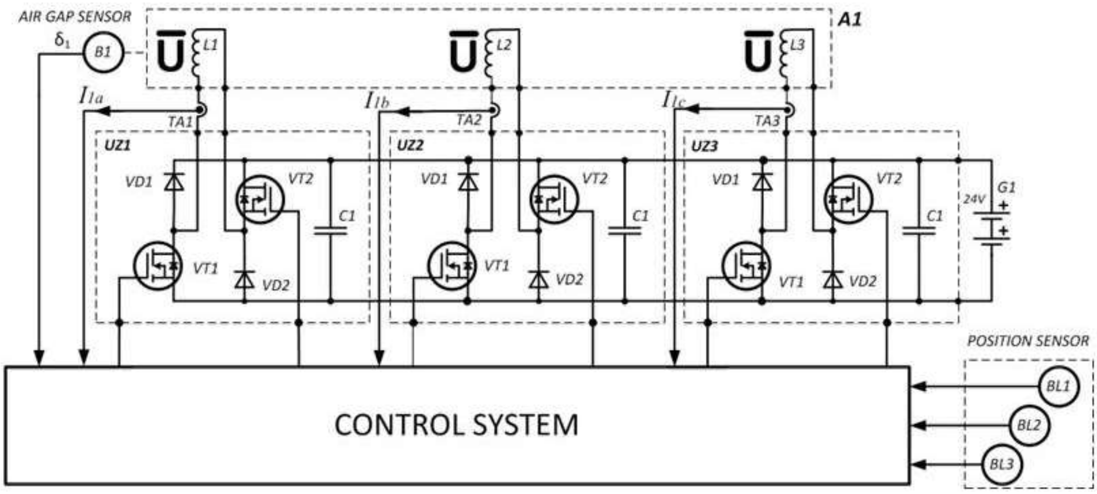


Figure 2. Functional scheme of the combined traction levitation system

Windings *L1, L2, L3* of *A1* module are included into the power scheme of half-bridge converters *UZ1–UZ3* ,supplying by accumulator battery *G1.* The control system generates the switching algorithm of power keys *VT1, VT2,* converters *UZ1–UZ3,* ensuring the object levitation and its linear movement along the track structure. The control system input gets the signals, which are proportional to the current in windings I_1a, I_1b, I_1c ,coming from current sensors *TA1–TA3,* air gap δ1, coming from air gap sensor *B1* ,as well as logic signals recording the poles position of the magnetic system module relative to the track elements, coming from block position sensor *BL1–BL3.*

The combined traction levitation system is absolutely independent and can be adapted to the different design structures of the transport platform. Figure 3 presents the general view of the scaled model of the traction levitation vehicle system with magnetic suspension.

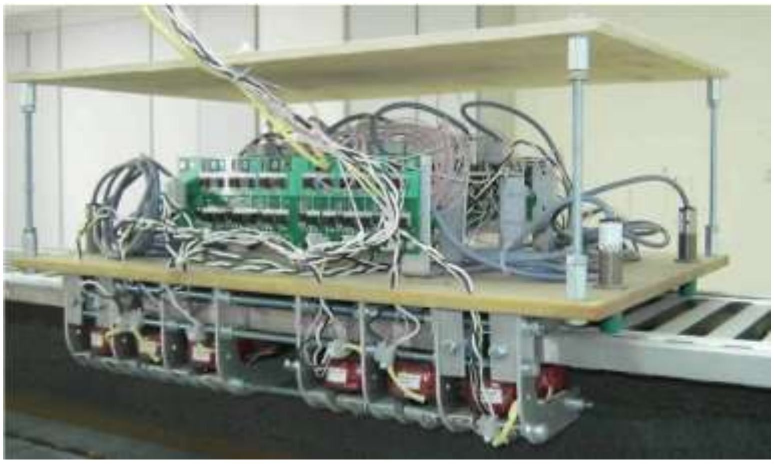
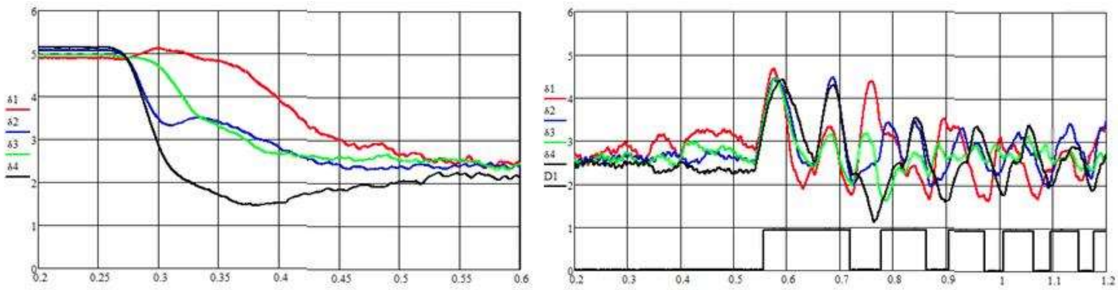


Figure 3. The model of traction levitation vehicle system with magnetic suspension

The model includes four traction levitation modules installed at the transport trolley; the platform with mounted electrical equipment; the additional technological platform, where the loads are fixed during the tests. During the experiments, the module was transferred to the levitating state. For this purpose, the windings of traction levitation module were fed by DC, regulated by the value in the function of the air gap value between module poles and track elements. After that, the drive system was started and the currents in the phase windings were switched according to the signals, coming from the position sensors. At the same time, this non-contact transport platform moves along the track structure.

3. RESULTS AND ANALYSIS

Figure 4 shows transition processes of the air gap changes δ1- δ4 during the transition of the transport platform to the levitation (Figure 4a) and start-up modes (Figure 4b).



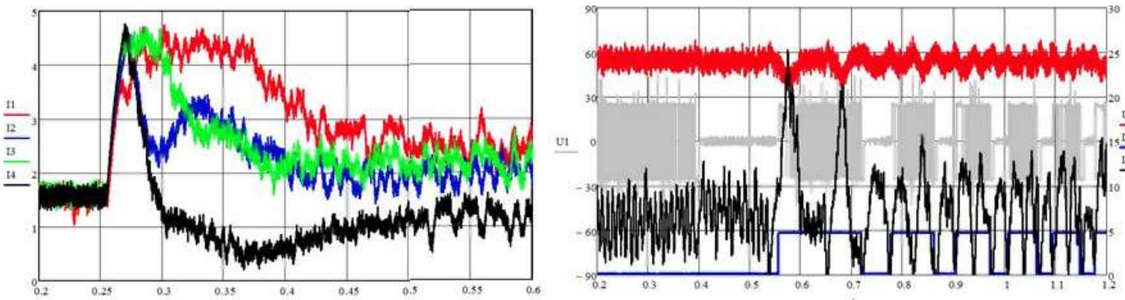
a b

Figure 4. Transition process in the levitation mode a), in the start-up mode b)

In an initial state the platform leans against support rollers. The air gap is δ=5mm. During the current supply to the phase windings of traction levitation modules, the air gaps δ_1- δ_4 of each suspension point decrease and stabilize at the value δ≈2.3 mm. It proves that the platform is in the levitating state. At the start–up under *t*≈0.56 s (Figure 4b), the currents in the phase windings are switched by the signal of position sensors *D1*. The platform starts the rapid traverse along the track. The discrete behavior of phase currents has the disturbance effect on the levitation system. The wave behavior of the gaps of suspension points in the range of 1–4.5 mm is observed. However, the levitation system keeps stability and with increasing of the traverse speed of the platform, the amplitude of oscillation decreases.

Figure 5a gives the oscillograms of the average values changes of phase currents *I1–I4* of the modules in the suspension points during the transition of the transport platform into the levitation mode. As it follows from the oscillograms, at the beginning of gaps δ_1- δ_4 changes, there is a sharp increase of the currents followed by decreasing and stabilization of their values at the level determined by the air gap value.

Figure 5b shows the oscillograms of current *Id* changes, absorbed from the power source, the voltage of power source *Ud*, phase voltage *U1*, the signal of position sensor *D1* during the transition to the start-up mode. At the time of start under $t \approx 0.56$ s, there is a sharp increase of current *Id* and its pulsing behavior with the tripled frequency relative to the signal frequency of the position sensor *D1* during the platform moving. The phase voltage *U1* is a package of two polar impulses operating on the signal interval of the position sensor *D1*. The power supply flutter *Ud* is inconsiderable.



a b

Figure 5. Transients in electrical circuits: in the levitation mode a), in the start-up mode b)

The peculiarity of the traction levitation system is the mutual influence of traction subsystems and suspension. Figure 6 shows the oscillograms of electromechanical processes occurring during the transition of the traction levitation system from the levitation mode to the levitating traversal mode along the track structure. The oscillogram presents the phase currents of the modules (I_{1a}… I_{4c}), signals of gap sensors δ_1–δ_4, signals of position sensors D_a, D_b, D_c.

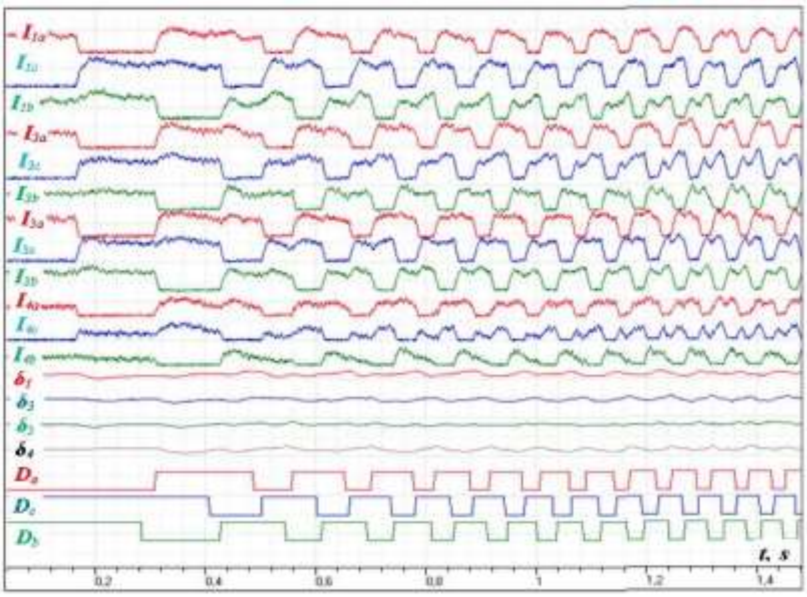


Figure 6. Oscillograms of phase current *I*, air gap δ, and logic signal *D* of position sensors

The phase currents are sent to the windings at the intervals of positive values of position sensors signals. In this case, the current waveform changes from period to period, since the gap controller continuously adjusts the current in order to keep the required value of the air gap. Figure 7 shows the detailed processes.

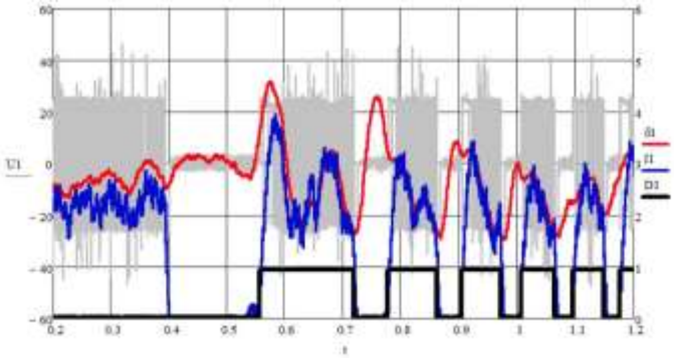


Figure 7. Oscillograms of phase voltage *U1*, phase current *I1*, air gap δ1, and logic signal *D1* of position sensors

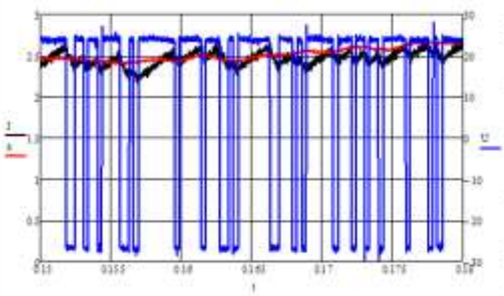
At the time interval t < 0.4 s, the platform is in the levitating stall position. DC is sent to the phase winding. At the time interval 0.4< t<0.56 s, the operation mode is changed – the current in the phase is switched off. At the time t = 0.56 s, the system is switched to the start-up mode. The phase winding is applied the voltage *U1* by the signal of the position sensor *D1*. The amplitude of the unipolar pulse is regulated in the way to keep the given value of the air gap. With increasing of the traverse speed of the platform, the amplitude of the gap oscillation decreases.

To compare the performance of the magnetic suspension systems, designed as separate and combined levitation and traction schemes in the start mode, the parameters of the power element in the levitation mode were estimated. When implementing the separate levitation and traction scheme, the poles of the middle power element were installed in line with the track element. Converter *UZ2* fed winding *L2* with direct current, the value of which was specified by the air gap controller. During the experiment we were estimating the system operation mode with the actual current value 2.5A. This was done by varying the gap value in the range from 2 mm to 3 mm, and load weight in the range from 90 N to 130 N. The stable operation mode of the traction levitation system was ensured by adjustment of the air gap controller. Table 2 shows the technical data of the power element in the levitation mode.

Further options trailer levitation module, combined the functions of levitation and traction, have been identified. Subsequently, we determined the parameters of the traction levitation module, combining the functions of levitation and traction. For this purpose, windings *L1, L2, L3* of module *A1* were fed from converters *UZ1–UZ3* by currents I_1a, I_1b, I_1c, the values of which were set by the air gap controller. During experiment the load was selected to ensure the stable levitation mode under the same gap and current values, indicated in the previous experiment.

Table 2. Technical data of the power element in the levitation mode

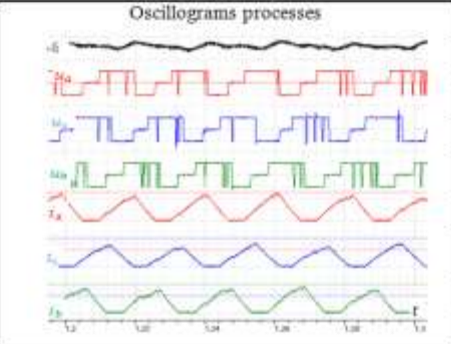
Oscillograms processes



Parameter name	Value
Supply voltage, V	24.125
The coil current (RMS), A	2.398
Air gap average value, mm	2.434
Deviation of air gap from the average value, %	+9.2 -9.8
The active winding resistance, Ω	4.342
Power consumed by the power element, W	25.354
Active power losses in winding, W	24.959
Consumption current, A	1.051
Lift force, N	129
The coefficient voltage forcing	2.305
Energy levitation quality factor	0.984
Coefficient levitation quality	15.2

Table 3 presents the parameters of the module in the system stable operation mode under the switching frequency of phase currents equal to f = 50 Hz.

Table 3. Technical data of the traction levitation module in the levitation mode

Oscillograms processes	Parameter name	Value
	Supply voltage, V	24
	The coil current (RMS), A	2.48
	The coil current (amplitude), A	4.45
	The active winding resistance, Ω	4.342
	Air gap average value, mm	2.43
	Lift force, N	220
	Current frequency, Hz	50
	Coefficient levitation quality	8.64

The comparison shows, that at the equal gap and current values in the windings, the levitation quality coefficient (the ratio of the lift force to the electromagnetic module weight) of the combined traction levitation system decreases 1.76 times due to periodic changes of phase currents, in comparison with the conventional electromagnetic suspension system. In order to estimate the energy efficiency of the electromagnetic suspension systems, the Energy levitation quality factor k_L is used, which is equaled to the ratio of the active loss power in the windings P_Ω to the power P_d consumed from the power source. For the combined traction levitation system, the Energy levitation quality factor is defined by the following equation:

$$k_L = \frac{P_\Omega}{I_d \cdot U_d - F_x \cdot V_x} \quad (1)$$

where P_Ω – active loss power in the windings of traction levitation modules;
U_d – power supply voltage;
I_d – current consumed by traction levitation system;
F_x – force realised by traction levitation module in toward moving ;
V_x – linear speed.

Using the equation (1), we calculated the dependency of value k_L from the time t in the running mode at the different weight of the transport platform (Figure 8).

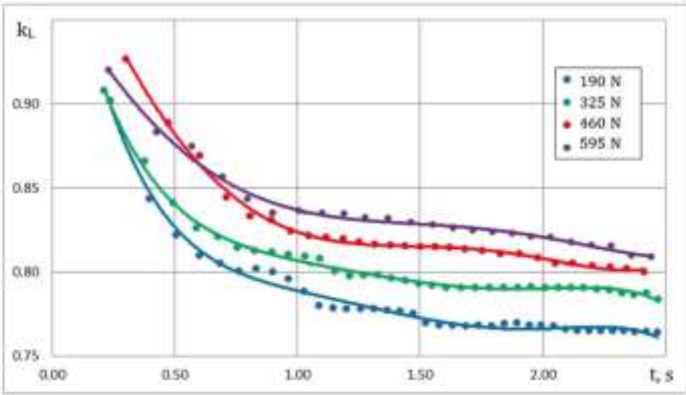


Figure 8. Energy levitation quality factor

The given dependencies prove that at the start-up mode the value k_L increases with increasing of the platform weight.

4. CONCLUSION

The results of researches have illustrated dramatically that the development concept of a vehicle equipped with the combined system of traction and magnetic suspension, based on the linear switched reluctance motor, is absolutely real. The further research should be aimed at improving the system performance parameters by reducing the mutual influence of levitation and traction processes.

ACKNOWLEDGEMENTS

The presented research has been developed with support of Russian Ministry of Education, grant RFMEFI57614X0040.

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Alexander Vladimirovich Kireev was born in 1974. He finished -Russian State Technical University (NPI), Novocherkassk on "Power supply of industrial enterprises" specialty in 1999. He received PhD degree in Technical Sciences in 2004. Since 2006 he has worked as associated professor in South-Russian State Technical University (NPI). His main scientific interests are related to control of electrical drive, switched reluctance motors, simulation.

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