JOINT UKRAINE- POLAND R&D PROJECT
FOR THE PERIOD OF 2018 – 2019

Lodz University of Technology
Institute of Electrical Power Engineering

Pryazovskyi State Technical University
Electrical Engineering Department

International Ukraine-Poland Seminar

Power quality in distribution networks with distributed generation

Kiev, July 4-5, 2019

DOI: 10.32073/iepl.2019.15

DISTRIBUTED SOLAR PHOTOVOLTAIC POWER STATION CONVERSION SYSTEM WITH POWER FILTRATION FUNCTION

Dmitry Tugay[*], Yuriy Sayenko[**], Yuri Kolontaevsky[*], Alexandr Shkurpela[*]

[*]O.M. Beketov National University of Urban Economy in Kharkiv,
[**]Pryazovskyi State Technical University

Abstract: This academic work is concerned with the solar photovoltaic station conversion system, which simultaneously with the function of transferring energy from the renewable source to the power network serves as a power active filter. Based on the transformations of the modified *p-q-r* power theory, a method for controlling the specified conversion system is proposed, which in turn allows two independent functions to be implemented in a wide range of changes in load parameters and a renewable energy source while maintaining the standard topology of the power circuit.

1. INTRODUCTION

Significant interest in local power supply systems, consumers of which use renewable energy sources in parallel with the power network, stipulate a list of issues related to the creation of electromagnetically compatible conversion systems adapted to change the operating modes and load parameters [3-7]. Simultaneous use of multiple conversion facilities to implement this functionality, specifically that of the inverter and power active filter (PAF), is not always economically justified. Therefore, the solution of such complex problems should be considered through the creation of new energy-efficient control algorithms for semiconductor converters with standard topological structures.

The operation of solar photovoltaic stations in parallel with the power network is regulated by the quality standards for electrical energy at the point of coupling. In local power supply facilities, this problem is most acute as a result of the impact of solar photovoltaic stations as well as the modes of consumer's work on power quality [5]. Most of the network power inverters, presented on the market of converting equipment for photovoltaic stations, are not designed to solve this complex problem [1]. In our view, this is a significant drawback of underutilization of the converting equipment capacities, since the topology of the power circuit of transistor voltage inverter and power active filter coincides.

The object of this paper is to create an algorithm for controlling the converter of the solar photovoltaic station of standard topology, which simultaneously with the function of generating energy from a renewable source to the power network can maintain the function of the power active filter-compensating device.

2. THE BLOCK-DIAGRAM OF THE DISTRIBUTED POWER SYSTEM WITH A SOLAR PHOTOVOLTAIC STATION

2.1. Research objective

Solar photovoltaic stations are becoming widespread both in the industrial and household sectors. Increasingly, photovoltaic stations whose rated power reaches dozens of hundreds of kilowatts are constructed near or at the territory of industrial enterprises. Among the objects of electricity supply it is possible to distinguish a group of industrial electric consumers of considerable capacity, characterized by stationary mode of operation. These include the frequency-regulated electric drives of oil-extracting enterprises and oil refineries, ventilation of mines and mining plants, industrial refrigeration units, electric furnaces and other equipment. The power system load curve of such consumers is slowly changing over time. Typically, these electrical power supplies cause distortion of the power network. To eliminate their impact on the network and the work of other consumers, passive and active filter-compensating devices are used. On the other hand, the converting equipment of photovoltaic solar power plants is usually selected with a certain margin of current and voltage and is designed for operation in the mode of maximum generation, which corresponds to the maximum solar insolation for the respective climatic zone, where the power plant will be operated. For a moderate climatic zone, the maximum of solar insolation in the course of the year is reached in rare cases, indicating the potential for the additional use of conversion equipment as a filter-compensating device.

2.2. Description of the block-diagram

The block-diagram of a distributed power supply system using solar photovoltaic stations is shown in Figure 1. The diagram is composed by a modular principle and consists of a certain number of cells (Module 1 – Module N). Each module is created by connecting a power load, for example, a technological industrial installation with a frequency controlled electric drive and a solar photovoltaic station. Nominal load capacity of each unit is greater than the nominal power of the electricity generating station ($P_{Ln}>P_{sbn}$). Let's consider the block-diagram of the first module. The converter of the frequency-regulated electric drive is connected to the secondary winding bus of the network transformer T (10/0.4 kV) by means of the inductance coil L_{s1} and the uncontrolled rectifier $DR1$. The first harmonic of the network load current of each phase is shifted relative to the corresponding phase voltage at the angle φ. In the spectrum of the network current, there are higher harmonics, multiples of the rectifier pulsation $n = 6k \pm 1$, (where $k = 1, 2, 3$ ...) are the number of current harmonics. The aggregate electromagnetic effect of loading units of all modules distorts the sinusoidal shape of the voltage at the input of the transformer T.

The solar photovoltaic station is based on an array of photovoltaic modules $PSP1$, the energy storage $ES1$, the capacitor C, the hybrid inverter and the L-C-L output filter, which is formed by connecting the C_{f1} capacitor banks to the clearance of inductive reactor L_{f1}-L_{f2}. The overall power bus is further connected to the reliable load ($RL1$). The conversion system of the power plant consists of a booster pulse-width converter, which performs the function of monitoring the maximum power point ($MPPT1$), the battery charger converter (DC/DC 1) and the PI/PAF 1 voltage inverter.

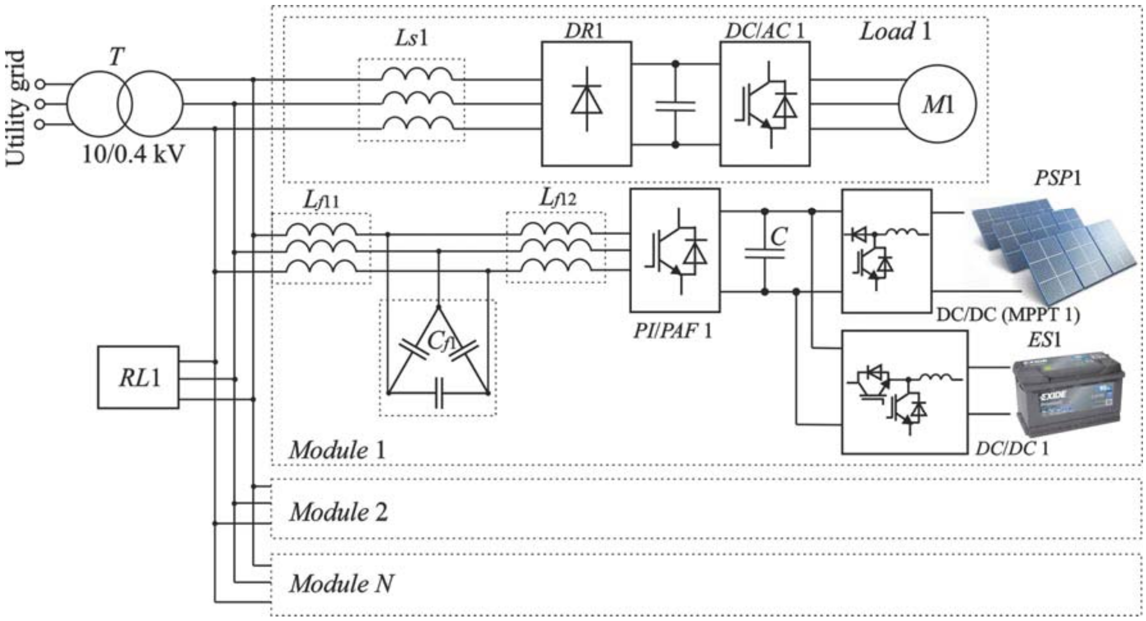

Figure 1.The block-diagram of the power supply system

Part of the power circuit of the converter system from the capacitor bank, in the link of direct current, to the power supply network is structurally consistent with the diagram of parallel PAF.

2.3. Operating modes of the distributed power supply system

The distributed system of power supply coupled with the solar photovoltaic station according to the structural diagram under consideration can implement the following operating modes: 1) generation of energy by a photoelectric station to the power network with stable operation of the power and reliable load; 2) power filtration of the network current with stable operation of the power and reliable load; 3) generation of energy by a photovoltaic station to the power network with simultaneous filtration of the network current with stable operation of the power and responsible load; 4) autonomous power supply of the responsible load from the photovoltaic station; 5) autonomous power supply of the responsible load with a partial power supply of the power load from a photovoltaic station.

The additional modes of operation of the distributed power supply system considered are the modes associated with the use of energy-intensive storage devices of photovoltaic solar power plants to equalize the daily load schedule of the transformer station with stable operation of the power and responsible load.

3. SYNTHESIS AND VALIDATION OF THE ENERGY EFFICIENT ALGORITHM FOR SOLAR PHOTOVOLTAIC STATION CONVERSION CONTROL SYSTEM

3.1. Block-diagram of the control system

The multifunctionality of the converting system of the distributed photovoltaic power station is implemented on the basis of a new algorithm based on the conversion of the modified p-q-r power theory [2]. The structural diagram of the control system, which explains the operation of the algorithm, is shown in Figure 2. The block diagram follows the principle of reference formation in accordance with phase currents after the standard conversion of coordinate systems of the *p-q-r* theory and the provisions of the cross-vector theory, except for the addition of a separate node with a feedback in accordance with the DC component of discharge current of the storage device I_{es}. The input of the control system receives signals from voltage sensors installed on low voltage bus transformers u_a, u_b, u_c, and load current sensors i_{La}, i_{Lb}, i_{Lc}. Signals received from voltage sensors are subject to standard Clarke's transformation from Cartesian abc to $\alpha\beta 0$ coordinates [2]:

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}. \tag{1}$$

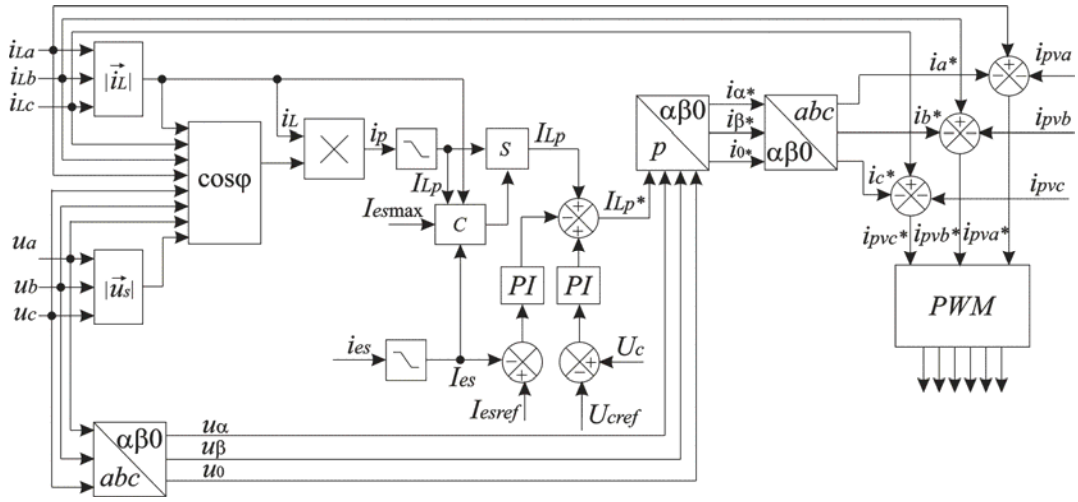

Figure 2. Structural diagram of the control system

Using the provisions of the cross-vector power theory, modules of the spatial voltage vectors of the power supply network and the load current are calculated, as well as the cosine of the displacement angle between the two vectors:

$$u_s = |\vec{u}_s| = \sqrt{u_a^2 + u_b^2 + u_c^2}\,, \tag{2}$$

$$i_L = |\vec{i}_L| = \sqrt{i_{La}^2 + i_{Lb}^2 + i_{Lc}^2}\,, \tag{3}$$

$$\cos\varphi = \frac{u_a}{|\vec{u}_s|} \cdot \frac{i_{La}}{|\vec{i}_L|} + \frac{u_b}{|\vec{u}_s|} \cdot \frac{i_{Lb}}{|\vec{i}_L|} + \frac{u_c}{|\vec{u}_s|} \cdot \frac{i_{Lc}}{|\vec{i}_L|}\,. \tag{4}$$

The multiplication of the load current vector module by the values of the cosine of the displacement angle makes it possible to calculate the value of the module of load current vector along the p axis of the spatial rotary Cartesian p-q-r system

$$i_{Lp} = i_L \cdot \cos\varphi\,. \tag{5}$$

At sinusoidal symmetric voltage of the power supply network, the direction of the vector $\vec{i}_{Lp}$ coincides with the direction of the vector $\vec{u}_s$.

After averaging the trajectory of the current i_{Lp} in the period of repetition T, we obtain the mean value of the load current along the axis p

$$I_{Lp} = \frac{1}{T}\int_t^{t+T} i_{Lp}\,, \tag{6}$$

which corresponds to a constant power flow from the power source to the load.

An averaged signal of the load current is sent along the axis *p* to the input of commutator *S*, which is switched by the comparator *C*.

In the combined mode of operation of the photovoltaic station and the PAF, the reference signal on the current vector along the *p*-axis is formed by three virtually independent components: the constant current component along the *p* axis I_{lp}, the inconsistency of the voltage signal in the capacitor in the DC link relative the reference (U_c*), and the inconsistency of the discharge current signal of the storage device relative the reference current (I_{es}*). The first two signals are characteristic for the operation of the PAF, and the third signal is characteristic for the inverter operation.

If the power plant operates in the mode close to maximum generation, the input reference block receives the signal by the generation current only from the last regulator, that is, the converter operates as a standard network inverter, recovering the energy of the photoelectric station to the industrial grid. As soon as the given inequality is performed

$$\sqrt{I_{es}^2 + I_c^2} \leq I_{es\max}, \tag{7}$$

where I_{es} is the instant current generation corresponding to the discharge of the storage device; I_{sbmax} is maximum generation current;

$$I_c = \sqrt{\frac{1}{T}\int_t^{t+T}\left(i_L^2 - I_{Lp}^2\right)dt} \; - \tag{8}$$

the current of the compensator, the comparator *C* switches and the reference signal by the compensator current is sent to the reference signal by the generation current. The value of the maximum generation current is limited by the characteristics of the transistor modules of the output inverter.

The calculated components are current references along the *p*-axis in the spatial coordinate system *p*-*q*-*r*. To send them to the PWM-generator input, two inverse coordinate transformations must be performed: $p \rightarrow \alpha\beta 0$

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \\ i_0^* \end{bmatrix} = \frac{I_{Lp}^*}{u_{\alpha\beta 0}} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} \tag{9}$$

and the inverse Clarke transformation $\alpha\beta 0 \rightarrow abc$

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & 0 & -\frac{1}{\sqrt{3}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} i_\alpha^* \\ i_\beta^* \\ i_0^* \end{bmatrix}. \tag{10}$$

After phase subtraction of reference currents from load currents, taking into account the feedback by the power plant currents, we obtain the reference signal by the power plant currents

$$\begin{bmatrix} i_{pva}^* \\ i_{pvb}^* \\ i_{pvc}^* \end{bmatrix} = \begin{bmatrix} i_{La} - i_a^* - i_{pva} \\ i_{Lb} - i_b^* - i_{pvb} \\ i_{Lc} - i_c^* - i_{pvc} \end{bmatrix}. \tag{11}$$

3.2. Matlab model description

To verify the control alg orithm of the solar photovoltaic station conversion system capable of implementing multifunctional modes of operation of the power supply system, the

Matlab-model of the distributed power supply system with specific parameters, as shown in Figure 2, was synthesized. The electrical circuit of the power supply system corresponds to the structural diagram in Figure 1. Its parameters are listed in Table 1. The structure of the solar power plant is based on a detailed mathematical model of the photocell, the totality of which forms a solar photomodule with objective technical parameters [7]. The connection of homogeneous photomodules forms a photovoltaic array.

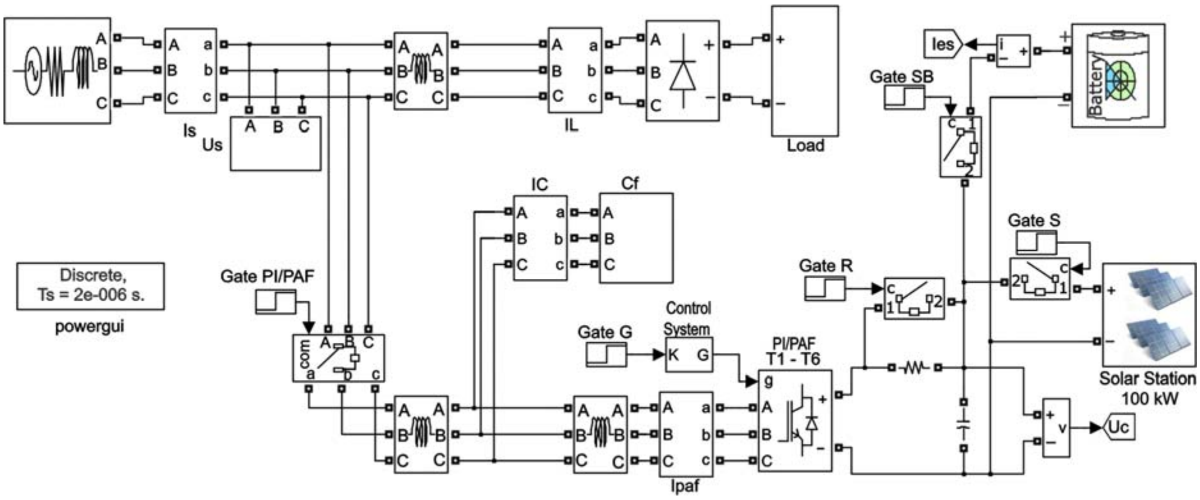

Figure 3. Matlab- model of the distributed power supply system with a solar power plant

The voltage inverter is made according to the bridge circuit using IGBT modules with reverse diodes. A power-consuming Battery and an input filtering condenser are connected to the converter link. On the side of a three-phase power network, an output filter is connected, which is formed by two sections of batteries of inductive reactors, in the gap of which a condenser battery Cf is connected, the phases of the latter are combined into a «triangle».

Table 1. Parameters of the distributed power supply system module

Parameter	Denotation	Value	Parameter	Denotation	Value
Power supply network			***Load***		
Valid value of linear voltage	$U_{л}$	380 V	Rated power	P_{LH}	300 kW
Frequency	f	50 Hz	Inductance of the input reactor	L_d	75 µH
Inductance	L_s	28 µH	***Powerstorage device***		
Active resistance	R_s	0.36 Ω	Type	–	Li-ion
Photovoltaic station and converting system			Rated voltage	U_{esH}	670 V
Rated power	P_{sbH}	100 kW	Rated capacity	C_H	300 Ah
Voltage in DC link	U_c	770 V	Maximum capacity	C_{max}	300 Ah
Capacitance of input capacitor	C	0.594 mF	Full charge voltage	U_{fc}	779 V
Inductance of the output filter	L_{f1} L_{f2}	21 µH 54 µH	Nominal discharge current	I_{ds}	130 A
Capacity of the source filter	C_f	36.8 µF	Inner resistance	R_{es}	0.0223 Ω

3.3. Simulation results

The verification of the proposed algorithm efficiency is carried out by performing a consistent transition from the uncompensated mode of consumer’s operation to the compensated one, and then to the complex mode, which combines the operation of the PAF and the generation of energy from the renewable source. The operational oscillograms obtained in a steady state for each of the three variants of the distributed power supply grid node functioning are shown in Fig. 4. Fig.4 shows that the uncompensated load current possesses a non-sinusoidal shape characteristic of the operation of uncontrolled three-phase rectifier. After the closure of the PAF, the shape of the phase current is almost sinusoidal and coincides with the phase with the corresponding voltage (Fig. 4, b). After closing the solar photovoltaic station, the amplitude of the first harmonic of the network phase current decreases in proportion to the discharge current of the I_{es} storage device (Fig. 4, c), indicating that the power supply load is compatible with the network and the solar power plant.

As shown by simulation results, simultaneous operation of two regulators, namely the voltage regulator of the capacitor and the regulator of the discharge current of storage device does not practically affect their stability due to the fact that the value of the voltage on the condenser is maintained by the unchanged additional charge controller by the energy of the renewable source. If the generation mode performs inequality (7), the switching of the comparator occurs, and the load current compensation mode is added to the generation mode (Fig. 4, d).

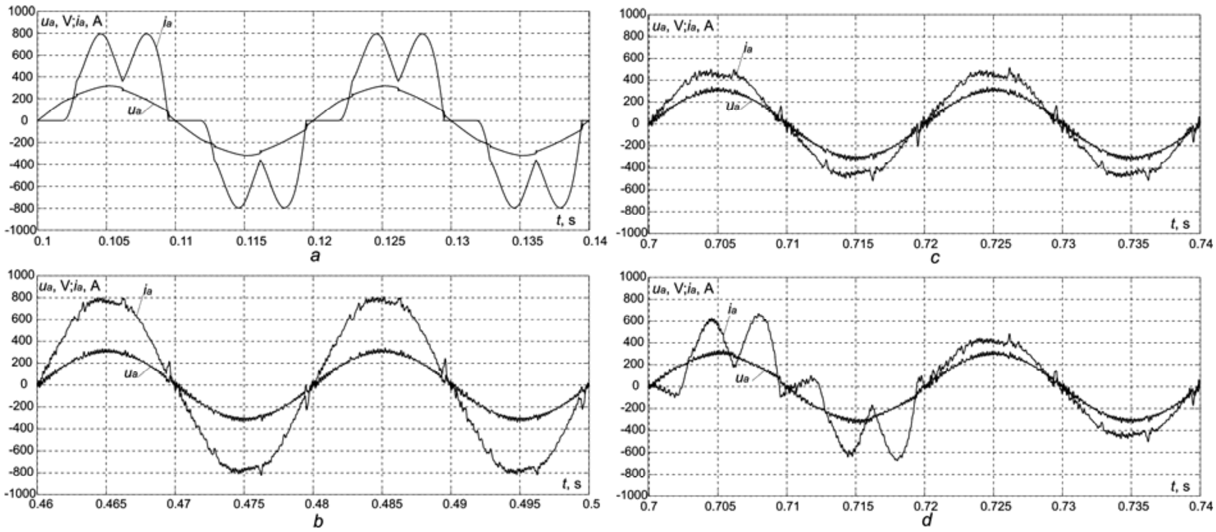

Figure 4. Oscillograms of network voltage and current in phase A

4. CONCLUSIONS

The new algorithm of the converting system of the solar photovoltaic station is developed and implemented in the software environment of Matlab/Simulink, which makes it possible by means of standard topology of the power part to simultaneously implement two operational modes, namely the generation of power of the renewable source to the power supply network and the correction of the network current shape. While implementing the algorithm, the use of the modified *p-q-r* power theory has been proposed, this made it possible to significantly reduce the number of calculations of the microcontroller autoregulation system.

The verification of the algorithm using the synthesized simulated model of the grid node of distributed power supply system confirmed its correctness in a wide range of changes in load parameters and current generation of a renewable source.

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Ass. prof., D.Sc., Dmitry Tugay
O.M. Beketov National University of Urban Economy in Kharkiv, Department of Alternative Power Engineering and Electrical Engineering
Marshal Bazhanov 19, 61002 Kharkiv, Ukraine
e-mail: tugaydmytro@gmail.com

Prof., D.Sc., Yuri Sayenko
Pryazovskyi State Technical University, Electrical Engineering Department
Universytets'ka 7, 87555 Mariupol, Ukraine
e-mail: yls62@i.ua

Ass. prof., Ph.D., Yuri Kolontaevsky
O.M. Beketov National University of Urban Economy in Kharkiv, Department of Alternative Power Engineering and Electrical Engineering
Marshal Bazhanov 19, 61002 Kharkiv, Ukraine
e-mail: yuri_kolontaevsky@kname.edu.ua

P.G., Alexandr Shkurpela
O.M. Beketov National University of Urban Economy in Kharkiv, Department of Alternative Power Engineering and Electrical Engineering
Marshal Bazhanov 19, 61002 Kharkiv, Ukraine
e-mail: 447Alexashka@gmail.com