UDC 621.314(045)
DOI:10.18372/1990-5548.62.14390

O. V. Statsenko

REGENERATIVE ELECTRONIC LOAD FOR UNINTERRUPTIBLE POWER SOURCE TESTING

Department of Experimental Research Automation, Faculty of Instrumentation Engineering, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute,", Kyiv, Ukraine
E-mail: o.statsenko@kpi.ua ORCID 0000-0001-8730-2789

Abstract—*The article is devoted to the development of active electronic load for testing uninterruptible power sources with the function of recovering energy to the grid. The requirements for uninterruptible power sources testing have been analyzed, the existing approaches to the construction of electronic loads have been reviewed and their drawbacks have been identified. The electronic load structure and approaches for controlling it are proposed. A virtual model of the proposed electronic load is developed in MATLAB Simulink software environment. Using the developed model, studies of the electronic load operation were carried out when testing a sinusoidal voltage source and recovering energy to the power supply grid. For the main modes of operation, the key parameters of the electronic load have been calculated and shown that its use meets the requirements for testing of uninterruptible power sources.*

Index Terms—Uninterruptible power sources testing; electronic load; energy recovery.

I. INTRODUCTION

Secondary alternating current (AC) power sources are devices that convert the energy of primary power sources or the electricity grid into AC power [1]. Such devices are used in a number of applications, including the following: on-board and stand-alone power systems, laboratory and test equipment, uninterruptible power sources and aggregates, and more.

Uninterruptible power sources (UPS) are designed to provide electricity to connected equipment when the power is turned off. They also perform the function of eliminating the negative impact of grid imperfections on the operation of the equipment. These imperfections include changing the shape or magnitude of the grid voltage, as well as the presence of high-voltage pulses or high-frequency interference. These devices can be combined with various types of electricity generators to ensure long-term operation.

According to the topology UPS can be divided into: UPS with double energy conversion, linear-interactive UPS and backup UPS. But regardless of the type in accordance with international standards IEC 62040 [2], each UPS must be compatible with low-voltage grids providing certain output voltage and frequency characteristics. In addition, the manufacturer must specify the following characteristics: number of phases, rated current, characteristics of starting current, power factor, efficiency and others. To confirm the stated parameters, the manufacturer must carry out a series of tests for which special procedures have been developed. An example of such a procedure could be a procedure developed by the Office of Energy Efficiency and Renewable Energy of US Department of Energy [3].

According to this test procedure for determination of the efficiency UPS input and output power should be measured at load values corresponding to 100%, 75%, 50% and 25% of the declared power. During this procedure the reference test load must be used. This load should provide a power factor greater than 0.99, i.e., act as a resistive load.

II. PROBLEM STATEMENT

The implementation of such a test procedure can be performed by connecting to the tested UPS a set of powerful resistors. However, such a solution is not effective. The fact is that during all the testing procedure, the electrical energy consumed by such a load is converted into thermal energy. Considering the long enough time of the test procedure, it would be appropriate to ensure the return of electricity consumed from the UPS to the power grid. This requires the use of special devices called electronic load units. Herewith, it is desirable to minimize the energy losses in such a load, and, in order to minimize the impact on the power grid, the return of energy should be carried out with a unity power factor.

There are various ways for constructing electronic load units. For UPS testing, the most widely used devices are semiconductor converters consisting of a controlled rectifier, a grid-tie inverter, and an intermediate energy storage device. A considerable amount of works are devoted to solving the issues related to the construction and operation of such devices [4] – [7].

In paper [4], an active electronic load with a three-phase diode rectifier is reviewed, but such construction does not allow controlling the load power.

In paper [5] considered several variants of construction of three-phase programmable AC load, which can operate in regenerative and dissipative modes. Control of these systems is carried out using vector PWM. The disadvantage of the proposed solution is the orientation of the system to work from a source of sinusoidal voltage, which in the case of UPS testing may not be achievable.

In papers [6], [7] the structures of single-phase and three-phase programmable electronic AC loads are presented. For controlling them reference signal generators together with hysteresis relay controllers are used. This allows you to implement loads with different characteristics. However, the availability of these reference generators limits the scope of such load and does not allow it to be used for the case under consideration.

Therefore, the purpose of this work is to determine the structure and approaches for controlling active electronic load, which should provide:

– consumption from the tested UPS variable by value current with a power factor greater than 0.99;

– return of consumed energy to the grid with a unity power factor and minimum total harmonic distortion to ensure requirements of electromagnetic compatibility.

An additional task to be solved is to determine the efficiency of the electronic load being developed.

III. Problem Solution

UPSs usually form several output voltages of sinusoidal or quasi-sinusoidal shape depending on the type of UPS. The frequency and magnitude of these voltages should correspond to the parameters of the power supply grid, which for Ukraine are 50 ± 1% Hz and 230 ± 10% V. Accordingly, the developed electronic load must consume the current which form, frequency and phase should coincide to the output voltage of the UPS, and the value should be adjustable.

The structure of this load is shown in Fig. 1.

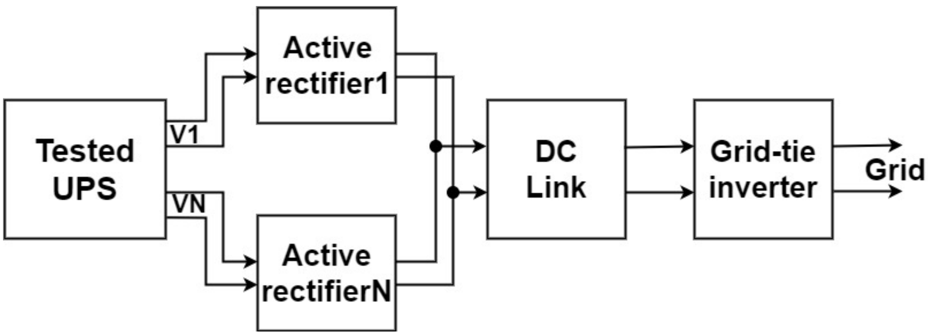


Fig. 1. The structure of electronic AC load

It consists of: one or more (according to the number of tested UPS output voltages) active rectifiers, direct current (DC) link, grid-tie inverter. Each of the active rectifiers and the grid-tie inverter has its own control unit. In order to enable the operation of several active rectifiers on a common DC link, it is advisable to realize them as half-bridge inverters. As a grid-tie inverter it is also advisable to use a half-bridge inverter. With this construction, the ground electrode of the power grid will be common to all components of the electronic load. Thus, generation of the load current will be carried out by active rectifiers, the grid-tie inverter will transmit electricity to the power grid with the required power factor, and the DC link will act as temporary energy storage.

The schematic diagram of the power section of the electronic load is shown in Fig. 2.

The formation of the input current through the inductor L1 is carried out by switching transistors VT1, VT2 turn by turn. Moreover, the switching-on of transistor VT1 leads to a decrease of current, and VT2 – to increase. But this is possible only if the voltage on the DC link U_C is greater than the voltage amplitude of the tested UPS. Otherwise, the diodes VD1, VD2 will act as an uncontrolled rectifier and the possibility of input current generation will be lost.

It is advisable to use a grid-tie inverter to charge the DC capacitors initially and keep the U_C voltages at a predetermined level. This is achieved by adjusting its output current: if the energy consumed from the UPS is greater than the energy supplied to the grid, the DC link voltage will increase, and otherwise it will decrease. Within a short time after connecting to the network, capacitors will charge through the grid-tie inverter, and the test procedure itself should begin after this process is completed the maximum DC link voltage must be less than the maximum allowable transistor voltage. Then, based on the power of the tested UPS, its output voltage and frequency, as well as the selected element base, using the expression (2) it is possible to calculate the value of the DC link capacitance.

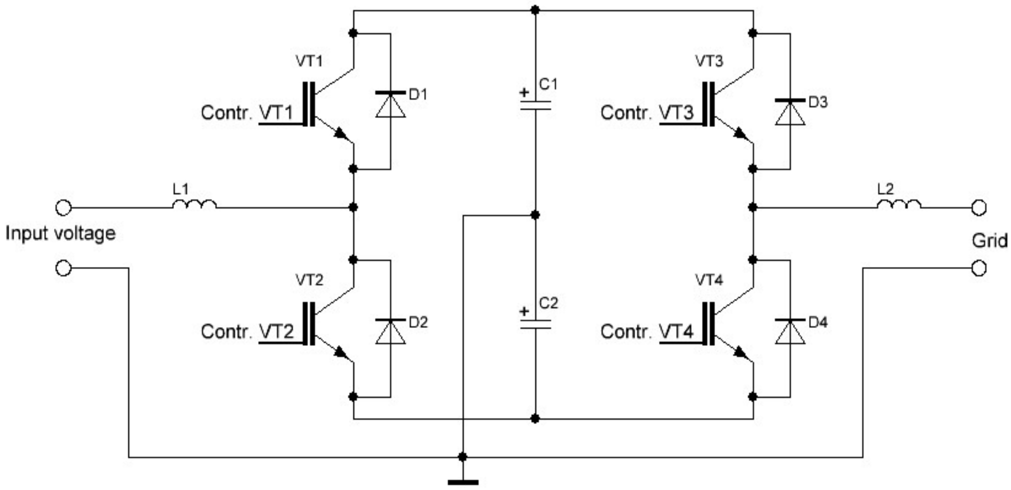


Fig. 2. Scheme of electronic AC load

Based on the operation features of the electronic load parts, approaches for controlling them can be defined. To ensure the resistive nature of the tested UPS load, it is necessary to control the input current of the active rectifier so that its shape corresponds to the UPS voltage shape and the value can be set separately. The transmission of energy to the grid also requires current control, but in this case, the shape of the current must correspond to the grid voltage, and the value must depend on the voltage of the DC link. It is advisable to use relay non-synchronized control to solve both of these tasks. The structure of control unit implementing such approach is shown in Fig. 3.

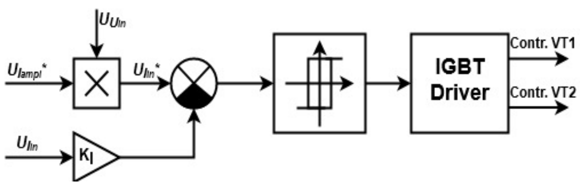


Fig. 3. Electronic load control unit

The transistor control signal is generated by a relay element and driver, with a difference between the current reference $U_{I\text{in}}^*$ and the feedback $U_{I\text{in}}$ signals as an input. In this case, the maximum current deviation from the desired value will be determined by the width of the hysteresis loop and the transmission factor of the current sensor K_I. The $U_{I\text{in}}^*$ reference signal is generated by multiplying the $U_{U\text{in}}$ feedback signal on the current amplitude reference signal, this determines the differences in the control of the active rectifier and the grid-tie inverter. For the active rectifier, this signal must be generated by the control device depending on the particular stage of the testing procedure. For a grid-tie inverter, this signal must be generated depending on the difference between the DC link voltage U_C and the set value U_C^*. In both cases, the amplitude signal must be limited to the maximum permissible level to prevent failure of the electronic load.

With such control approach in quasi-steady-state the capacitance charge current will be equal to the difference between the input and output current, and the DC link voltage will vary according to the expression:

$$U_C(t) = \frac{1}{C}\int (I_{\text{in}}(t) - I_{\text{out}}(t))dt\,. \qquad (1)$$

On condition of sinusoidal form of the input and output voltages, values of the currents will also be almost sinusoidal (with additional high-frequency components due to the switching of the transistors). In this case, the voltage U_C will consist of two components: a constant, due to the initial charge level of the capacitance, and a harmonic, which frequency will be equal to the frequency of currents, and the amplitude will be dependent on the amplitudes of the currents and the phase shift between them. The amplitudes of input and output currents in steady state will be the same. Accordingly, the amplitude of the harmonic component of the voltage U_C at zero phase angle will be the smallest, and at a phase angle equal to 180° – biggest. Considering the worst case, it is possible to find the maximum value of this amplitude:

$$U_{C\sim\text{w. c}} = \frac{2I_{\max}}{\omega C}\,. \qquad (2)$$

As can be seen from expression (2), the amplitude of the voltage harmonic component is directly proportional to the magnitude of the current and inversely proportional to its frequency and capacitance of the DC link. In order to control the input current, the minimum voltage level in the DC link must be greater than the maximum input voltage, and in order to avoid emergency situations, To verify the performance of the proposed system in the MATLAB Simulink software environment [8] virtual model was built. The structure of the model is shown in Fig. 4.

The Simscape library elements were used to model the power section of the electronic load. For power transistors modeling models of IGBT were used, which in their composition have a counter-parallel diode.

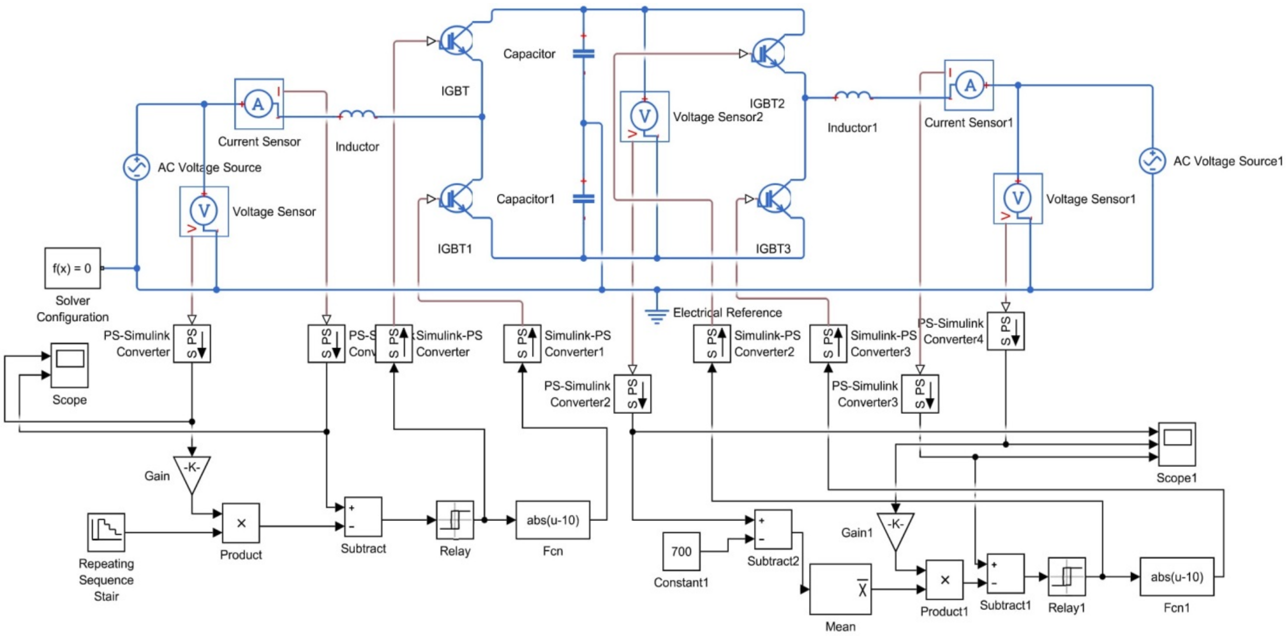


Fig. 4. Virtual model of the electronic load

Let's consider the UPS testing process, which generates one alternating sinusoidal voltage (220 V, 50 Hz) with a power of 1 kW. This power level corresponds to a current with a RMS value of 4.54 A or an amplitude value of 6.4 A. For testing, it is necessary to provide input current formation at the levels of 25%, 50%, 75% and 100% of the specified value. The inductances of the input and output inductors are 20 mHn with an active resistance of 0.1 Ohms, and the capacitors of the DC link capacitors are equal to 5 mF. The calculation is carried out under the condition of a full charge of the DC link capacitance to the value $U_C = 700$ V.

The simulation results are shown in Fig. 5a and b.

The input current amplitude is set by the Repeating Sequence Stair unit, at the output of which a step signal of magnitudes 0, 6.4, 4.8, 3.2, 1.6 A is formed within time intervals of 0.1 s. The transmission factor of the voltage sensor is $1/U_{U\text{in.max}}$, respectively the current reference signal repeats the shape of the input voltage with a step-by-step variable amplitude. The deviation of the input current are determined by the Relay unit and is equal to ± 0.1 A. Thus, relatively to the tested power source, the proposed converter has the properties of resistive load.

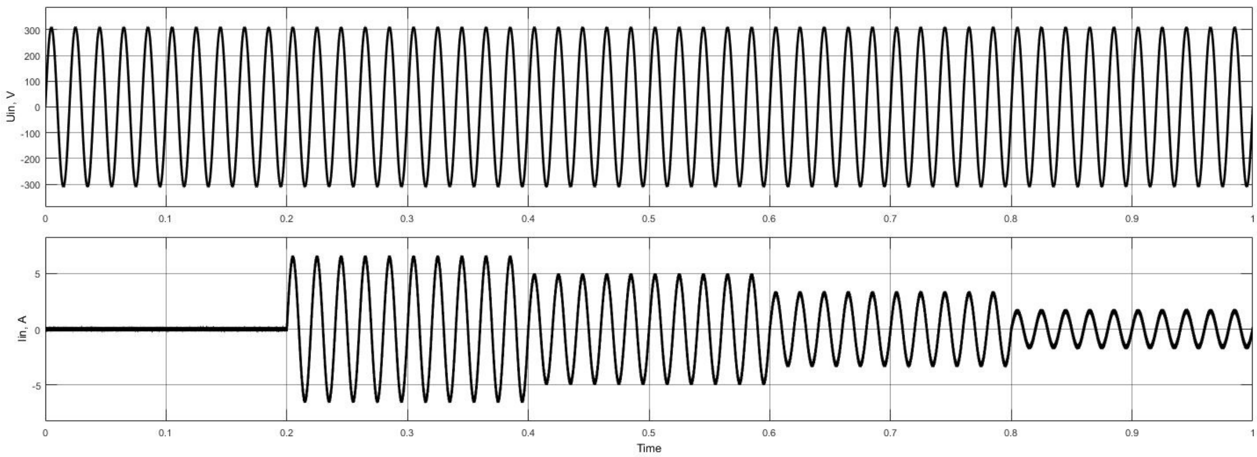
The amplitude of the output current is given by the Subtract2 unit, which calculates the difference between the set value of the DC link voltage U_C^* and the true U_C value. The instantaneous value of the current reference signal is formed by the Product1 unit as the product of the amplitude reference signal and the signal proportional to the grid voltage. In this case, this signal is generated in counter-phase with the output voltage, which provides energy transmission to the grid. The deviation of the output current from the reference value, as well as for the input current, is determined by the block Relay1 and is equal to ± 0.1 A.

Analyzing the work of electronic load as a whole, it can be seen that as the input current increases, the DC link capacitors are charging and the voltage on them increases. This, in turn, leads to increase of the output current amplitude. When the equilibrium is reached between the energy consumed from the tested UPS and the energy supplied to the grid, a quasi-steady regime comes. The voltage U_C in this mode differs from the set value, which is caused by the implementation of proportional control of the output current, and this difference increases as the input current increases.

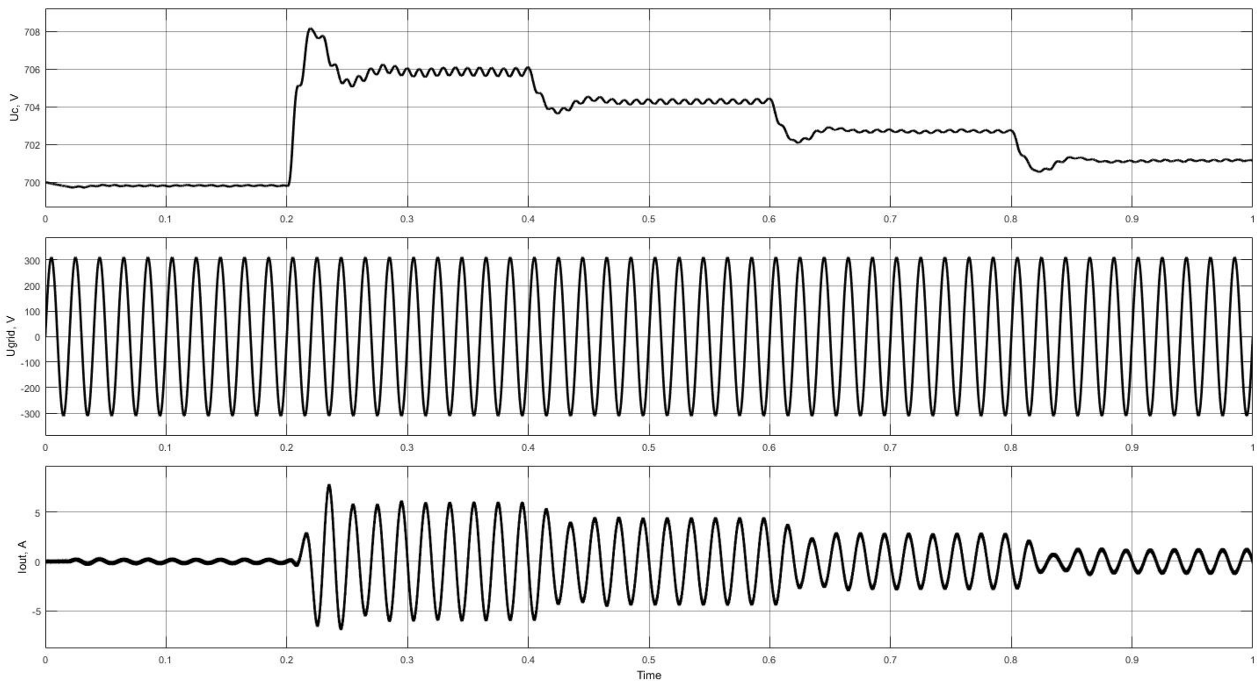
To quantify the quality of electronic load operation, the following parameters will be calculated: total harmonic distortion (THD) of input and output current, efficiency, power factor (PF), which has an electronic load relative to the tested UPS. The power factor for linear loads is defined as the ratio of active power to full power. In the case of non-linear current distortions, the power factor must be calculated according to the expression:

$$\mathrm{PF} = \cos\varphi \frac{1}{\sqrt{1+\mathrm{THD}^2}}. \quad (3)$$

The results of calculations for steady-state modes of operation at loads corresponding to 25%, 50%, 75% and 100% of the nominal, are given in Table I.



(a)



(b)

Fig. 5. Modeling results: (a) are graphs of input voltage and current; (b) are graphs DC link voltage, grid voltage and output current

TABLE I. ELECTRONIC LOAD MAIN PARAMETERS IN STEADY STATE

Parameter	I_{IN} / I_{NOM}, %			
	25	*50*	*75*	*100*
THD_{IN}	0.1348	0.0702	0.0465	0.0367
THD_{OUT}	0.1322	0.0608	0.0407	0.0306
PF	0.991	0.997	0.998	0.999
Efficiency	0.787	0.882	0.92	0.939

As it can be seen from the given data, the THD increase as the input current of the electronic load decreases. This is due to the fact that with the decrease of the current main harmonic component, the harmonic components of the higher frequencies hardly change, and accordingly their ratio increases. The power factor decreases due to the increase of the THD, but for all load values its value exceeds 0.99.

The efficiency at low loads also decreases. This is due to the fact that the energy losses in such a device are mainly determined by the losses on the switching elements, which consist of static and switching. Static losses are proportional to the product of the current to the voltage of the transistor, and the switching depends on the switching voltage and switching frequency. Therefore, as the current decreases, the static losses are reduced proportionally, and the switching losses increases slightly through increasing the switching frequency, which in turn leads to a decrease in the efficiency. But this reduction is not significant because the overall level of energy losses while reducing current is also reduced.

IV. Conclusions

The article proposes an approach to the construction of electronic load for UPS testing, which involves the use of an electric converter consisting of an active rectifier, a DC link and a grid-tie inverter. It is appropriate to use relay non-synchronized control to regulate the currents of this converter. Using the developed model, studies were conducted of the proposed device operation and it was shown that it meets all the requirements for testing uninterruptible power sources.

References

[1] E. N. Haytenko, *Sources of secondary electricity supply. Scheme and calculation.* Moscow: SOLON-PRESS, 2008, 448 p.

[2] *IEC 62040-3:2.0. Unterruptible power systems (UPS) – Method of specifying the performance and test requirements.* International Electrotechnical Committee, 2011, 220 p.

[3] *Energy Conservation Program: Test Procedure for Uninterruptible Power Supplies.* DEPARTMENT OF ENERGY, Office of Energy Efficiency and Renewable Energy, 2016, 61 p. Web address: https://www.energy.gov/sites/prod/files/2016/04/f31/Uninterruptible%20Power%20Supply%20Test%20Procedure%20NOPR_0.pdf

[4] N. Chen and H.-H. Chung, *Energy-recyclable burn-in technology for electronic ballasts.* IEEE Transactions on Power Electronics, 2011, vol. 26, no. 9, pp. 2550–2562. https://doi.org/10.1109/TPEL.2011.2111386

[5] *Programmable alternating current (AC) load having regenerative and dissipative modes:* Pat. US 2019/10184990B2: MPK G01R 31/42. Appl. No.: 14/528,474; Date of Patent: Jan. 22, 2019.

[6] K. Benjanarasut, J. Benjanarasut, B. Neammanee, *Single phase AC electronic load with energy recovery.* 5th International Electrical Engineering Congress, Pattaya, Thailand, 8-10 March 2017. https://doi.org/10.1109/IEECON.2017.8075777

[7] R. L. Klein, A. Paiva, M. Mezaroba, *Emulation of nonlinear loads with energy regeneration.* COBEP 2011 - 11th Brazilian Power Electronics Conference, September 2011. https://doi.org/10.1109/COBEP.2011.6085270

[8] S. G. German-Galkin, *Computer modeling of semiconductor systems in Matlab 6.0: Proc. allowance*. SPb.: KORONA print, 2001, 320 p.

Received September 19, 2019.

Statsenko Oleksiy. orcid.org/0000-0001-8730-2789
Candidate of Engineering Science. Associate Professor.
Department of Experimental Research Automation, Faculty of Instrumentation Engineering, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine.
Education: Kyiv National University of Technologies and Design, Kyiv, Ukraine, (2003).
Research interests: digital control systems, electrical energy converters, electric drive systems with induction motors.
Publications: 55.
E-mail: o.statsenko@kpi.ua

О. В. Стаценко. Регенеративне електронне навантаження для тестування джерел безперебійного живлення

Стаття присвячена розробці активного електронного навантаження для тестування джерел безперебійного живлення з функцією рекуперації енергії до мережі. В роботі проаналізовані вимоги до тестування джерел безперебійного живлення, виконаний огляд існуючих підходів до побудови електронних навантажень та визначені їх недоліки. Запропонована структура електронного навантаження та визначені підходи до керування ним. В програмному середовищі MATLAB Simulink розроблена віртуальна модель запропонованого електронного навантаження. З використанням розробленої моделі проведені дослідження роботи електронного навантаження при тестуванні джерела синусоїдальної напруги та рекуперацією енергії до мережі живлення.

Для основних режимів роботи виконаний розрахунок ключових параметрів електронного навантаження та показано, що його використання задовольняє вимоги до тестування джерел безперебійного живлення.
Ключові слова: тестування джерел безперебійного живлення; електронне навантаження; рекуперація енергії.

Стаценко Олексій Володимирович. orcid.org/0000-0001-8730-2789.
Кандидат технічних наук. Доцент.
Кафедра автоматизації експериментальних досліджень, Приладобудівний факультет, Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна.
Освіта: Київський національний університет технологій та дизайну, Київ, Україна, (2003).
Наукові інтереси: цифрові системи керування, перетворювачі електричної енергії, системи електроприводу з асинхронними двигунами.
Публікації: 55.
E-mail: o.statsenko@kpi.ua

А. В. Стаценко. Регенеративная электронная нагрузка для тестирования источников бесперебойного питания

Статья посвящена разработке активной электронной нагрузки для тестирования источников бесперебойного питания с функцией рекуперации энергии в сеть. В работе проанализированы требования к тестированию источников бесперебойного питания, выполнен обзор существующих подходов к построению электронных нагрузок и определены их недостатки. Предложена структура электронной нагрузки и определены подходы к управлению ей. В программной среде MATLAB Simulink разработана виртуальная модель предложенной электронной нагрузки. С использованием разработанной модели проведены исследования работы электронной нагрузки при тестировании источника синусоидального напряжения и рекуперацией энергии в сеть. Для основных режимов работы выполнен расчет ключевых параметров электронной нагрузки и показано, что ее использование удовлетворяет требованиям к тестированию источников бесперебойного питания.
Ключевые слова: тестирование источников бесперебойного питания; электронная нагрузка; рекуперация энергии.

Стаценко Алексей Владимирович. orcid.org/0000-0001-8730-2789
Кандидат технических наук. Доцент.
Кафедра автоматизации экспериментальных исследований, Приборостроительный факультет, Национальный технический университет Украины «Киевский политехнический институт имени Игоря Сикорского», Киев, Украина.
Образование: Киевский национальный университет технологий и дизайна, Киев, Украина, (2003).
Научные интересы: цифровые системы управления, преобразователи электрической энергии, системы электропривода с асинхронными двигателями.
Публикации: 55.
E-mail: o.statsenko@kpi.ua