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Mathematical Approach to Identification of Load Structure at the Nodes of the Distribution Grids 6–10 kV and 0.4 kV

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Abstract. A significant increasing energy efficiency of the full cycle of production, transmission and distribution of electricity in grids should be based on the management of separate consumers of electricity. The existing energy supply systems based on the concept of «smart things» do not allow to identify the technical structure of the electricity consumption in the load nodes from the grid side. It makes solving the tasks of energy efficiency more difficult. To solve this problem, the use of Wavelet transform to create a mathematical tool for monitoring the load composition in the nodes of the distribution grids of 6–10 kV, 0.4 kV is proposed in this paper. The authors have created a unique wavelet based functions for some consumers, based on their current consumption graphs of these power consumers. Possibility of determination of the characteristics of individual consumers of electricity in total nodal charts of load is shown in the test case. In future, creation of a unified technical and informational model of load control will allow to solve the problem of increasing the economic efficiency of not only certain consumers, but also the entire power supply system as a whole.

1. Introduction

Currently the reduction costs on the production, transmission and distribution of energy resources is an important trend around the world. The increasing importance of energy efficiency is determined by several factors: total increasing needs of industry in electrical energy [1]; limitation, high cost and non-renewable nature of conventional energy resources [2]; ecological requirements toughening to power generation processes [3]. All these factors lead to the necessity of creation of complex management systems that control the process of consumers power supply. One of such systems is the “Internet of Things” system which has been developed for power consumers. The concept of the Internet of things (“smart things”) of consumer interaction algorithm development is aimed to increasing the energy efficiency of individual devices. The concept presents internetwork relationship of physical devices, vehicles, buildings and other elements with inbuilt technologies, sensors and actuating devices [4]. Relationship between devices is carried out by means of software system using internet technologies. The main idea of the “Internet of Things” is to automate various processes through the exchange of information between devices by software without human intervention [5]. Thus, the optimization task of energy resources use is solved locally.

Further development of the “smart things” concept will allow to create a process control system of transmission, distribution and consumption of power energy. The main idea of developing such system should be based on a complex management of the individual electric plant of energy exchange participants. Existing systems based on the concept of “smart things”, have not the technical capacity to identify the consumers composition in the load nodes on the network side. Also the systems have not a function of two-way information exchange between the subjects of electric power industry. These aspects are challenges to determine the load structure, which is necessary to solve the tasks of increasing energy efficiency.

This paper is organized as follows. The applicability of the proposed approach and application area of the developed algorithm are described in Section II. Section III is devoted to the mathematical description of the signal analysis tasks. Conducted experiment and its results are presented in section IV. The conclusions obtained from the study are presented in section V.

2. Application area

The information accessibility on the load composition in the network nodes will allow to solve the problems of increasing the work efficiency for all participants of energy exchange [6]. For example, the electricity grid company can use this information to change the service cost on power transmission from the utility to the consumer. Reducing electricity consumption volumes in the desired time intervals can be achieved through informing the consumer about the change cost. It will allow to increase efficiency of the electric utilities and to reduce losses by load levelling in the grid nodes. The process of full or partial control of the operating mode for each consumer on the network side is called network monitoring. Participant of energy can use network monitoring technology to their advantage, but on the condition that it leads to increasing the efficiency of generation, transmission and distribution of electricity. Energy exchange participant should provide electricity to consumers in contractual relationships. The structure of the proposed organization of the information collection and exchange is presented in Figure 1.

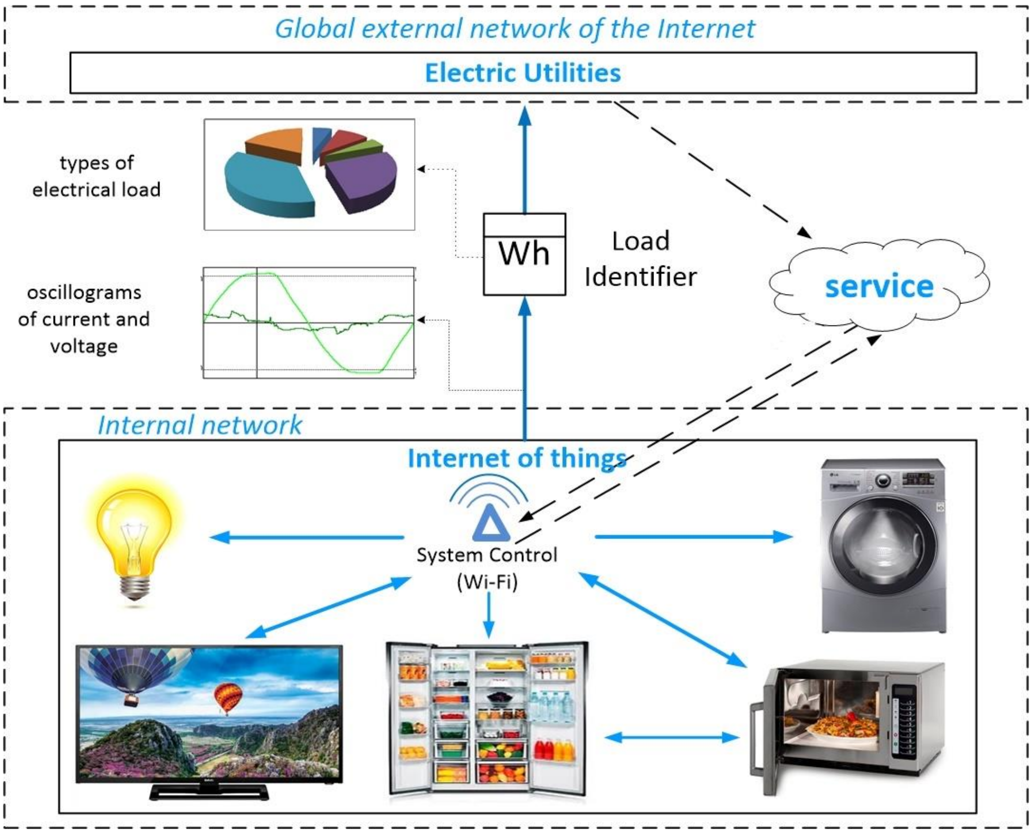

Figure 1. Organization of information collection and exchange

Figure 1 shows that the interaction of the various smart electricity consumers is carried out within a private area of the consumer. The internal system of information exchange is organized through the network of the smart things with required access to the external Internet network. The connection between the internal network of the consumer, which is organized by smart electricity consumers (Internet of things), and the global external network of the Internet is absent at this level. Thus, information on the composition and operating mode of a single consumer can't be accessible to external recipients. The network monitoring technology will be implemented in a device such as an electricity meter. It will allow to partially or completely monitor the work of consumers in each node of the network load without violating the information security of the consumer.

Reverse interaction with energy exchange participants can be carried out through services by transferring control information signals from the network to the consumer. Services provide recommendations for electricity consumers connected to the Internet of things. Signals can be the cost indicators of electricity by means of which the schedule of switching on and off some particularly power-consuming electric consumers is built. It is necessary to develop a mathematical algorithm in digital electricity meters that will allow to determine the composition of energy consumers for the realization of such opportunities.

Therefore, the main goal of the research described in the article is to propose a new approach for solving the problem of distinguishing different types of consumers from the total load signal.

3. Mathematical algorithms

To date, the conventional method of the analysis of electrical signals is the Fourier transform. However, this method has several disadvantages which limit its application in tasks of load composition analysis [6]. Fourier analysis is not capable to give an accurate analysis of the signals in the frequency as well as in the time domain simultaneously. Moreover, signals often include non-periodical components which are imposed on the fundamental frequency signal. This presents a problem for the Fourier transform, because its use requires periodic signals [6, 7]. Therefore, in latter days wavelet transform is widely used for the analysis of digital signals. Mechanisms of signal decomposition by Fourier and wavelet transformations are mathematically similar. Basis, where the original signal is decomposed, is used in both transformations. The strictly deterministic trigonometric basis is used in the Fourier transform, the arbitrary basis is applied in wavelet transform. The basis of wavelet transformation should satisfy certain conditions [7]. Wavelet analysis is a method based on a large-scale transformation, translation of basis (mother) wavelets and comparison of these wavelets with the original signal [8]. Wavelet-coefficients at different scales are obtained as a result of signal comparison with mother wavelet function. Figure 2 shows the principle of Wavelet transform.

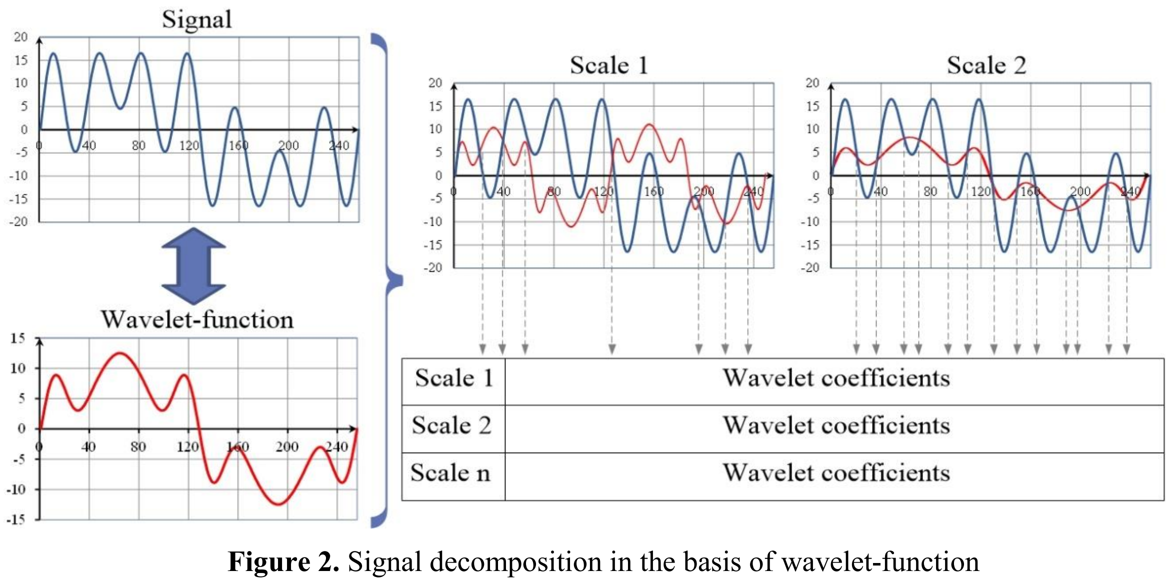

Figure 2. Signal decomposition in the basis of wavelet-function

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In addition wavelet transformation is capable to localize the information in the time-frequency domain with a high quality. These characteristics and advantages of the described method will form the basis of a mathematical algorithm of analysis and identification of electrical load in the network nodes. Direct Wavelet transform is defined as the sum over the entire duration of the signal multiplied by scalable shifted versions of wavelet functions [9]:

$$W(a,b) = C = \int_{-\infty}^{+\infty} s(t) a^{1/2} \psi\left(\frac{t-b}{a}\right) dt \tag{1}$$

where b is scale factor or parameter extension; a is the translation parameter (translation step); the function ψ(t) is transformation function which is called the basis function or mother wavelet; $a^{1/2}$ is the constant, it is necessary for normalization in order to the signal had the same energy at each scale.

It should be noted that the mother wavelet function must satisfy several conditions [9, 10]: it should be short and oscillatory, i.e. it must have zero average and decay quickly at both ends. Several examples of wavelets are shown in Figure 3.

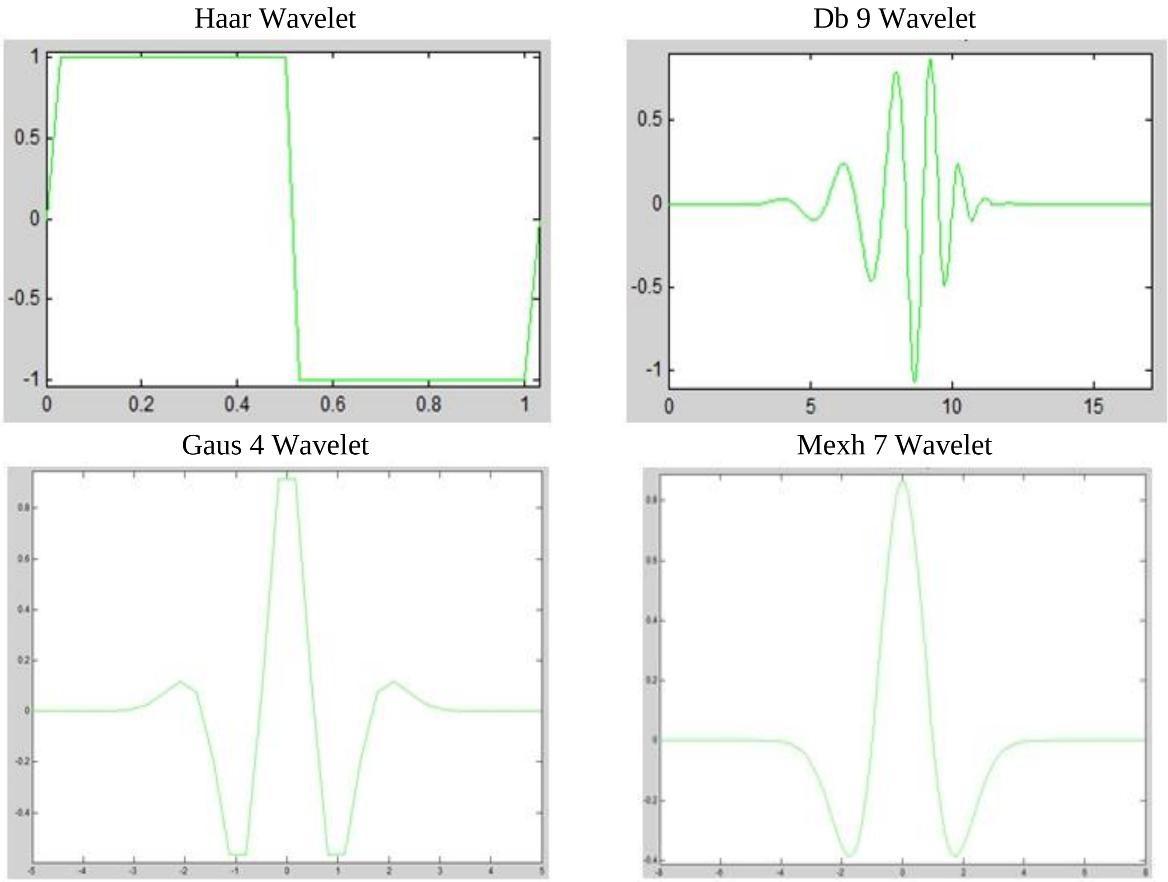

Figure 3. Different types of standard basic wavelet functions

Adequacy of signals analysis is significantly dependent on the chosen mother wavelet [10].This is particularly important to solve the problem of identifying specific types of load from the total load signal. Application of existing wavelets cannot provide a qualitative signal analysis in the context of the load identification, because the total load signals are to be analysed from side of each load.

Therefore, the application of wavelet functions based on an individual load signal is considered in this paper. This will allow to analyze the consumers' composition more accurately and correctly.

4. Experiment and results of analysis

4.1. Experiment description

To prove the possibility of Wavelet transform use for solution of load identification task the experiment has been performed. It has included the follows:

1) Obtaining current and voltage oscillograms of various electric devices by type and power to clearly show the efficiency of Wavelet transform in identifying specific features of particular electricity receivers from the total load signal.
   The following power consumers oscillograms have been considered:
- Light-emitting-diode lamp (P_{nom} = 6 W);
- Laptop (P_{nom} = 28 W);
- Electric kettle (P_{nom} = 1850 W).

2) Obtaining current and voltage oscillograms with different combinations of operating devices:
- LED Lamp and Laptop;
- Lamp and Electric kettle;
- Laptop and Electric kettle.

3) Creation of unique mother wavelet for each type of device under consideration;
4) Obtaining wavelet coefficients of the spectrum for each measured signal;
5) Analysis of coefficients obtained and formulation of criteria for load structure identification in the node of the distribution network by the type of power consumers.

Measurements have been performed by Chauvin Arnoux CA 8335 power quality analyzer. Oscillograms were recorded with one period of industrial frequency 50 Hz. Frequency of measurement was 256 point per period (f = 12.8 kHz).

Figure 4 shows the protocol of the measurements and the experiment scheme.

Figure 4. Scheme of the experiment and measurements report

The analysis of current and voltage oscillograms has shown that current signals are more revealing in solution of load identification task. Figure 5 shows current signals which were measured.

From the Figure 5 it is clear that current signals of laptop and lamp are significantly distorted by higher harmonic components. This is due to the fact that there are line adapters in these electricity receivers. Also it should be mentioned that laptop has a line adapter of impulse type (dotted line in the Figure 5). The latter explains the “sawtooth” waveform of the signal. The graph of current signal of the kettle is close to the pure sinusoid. This is due to the fact that electric kettle is the pure active load.

From the common load signal it is seen that the more the power of the electric receiver the common graph form looks more like a graph form of powerful electric device. This is well traced for current signals where there is a kettle signal (lamp and electric kettle, laptop and electric kettle).

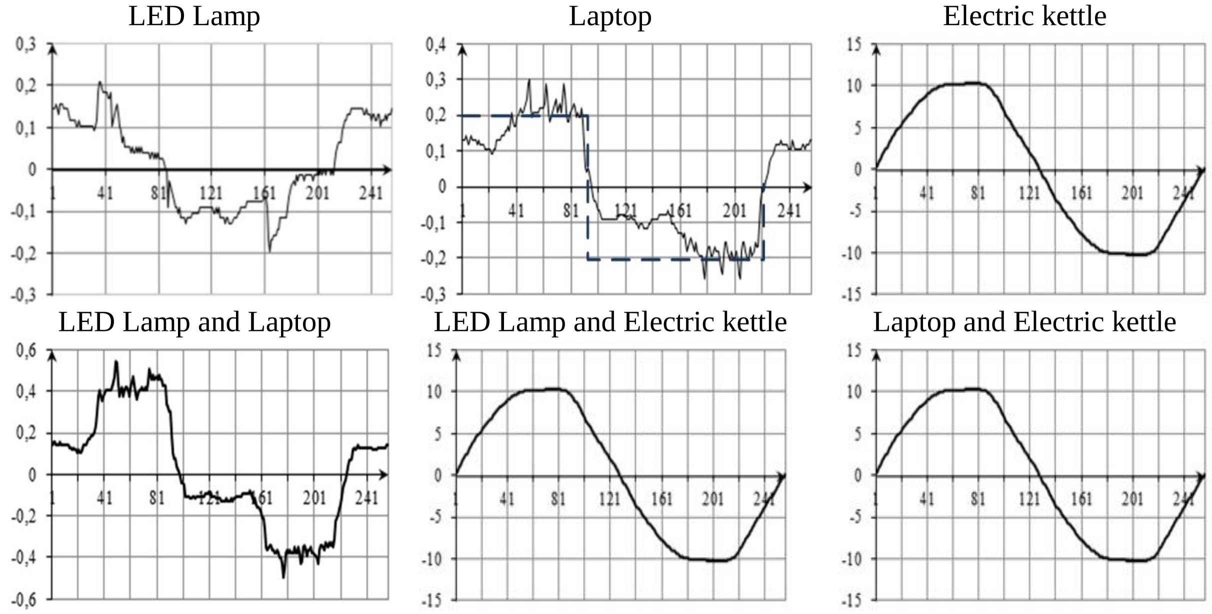

Figure 5. Current Signals
(Current characteristic according to the quantity of measurements)

However, identification of specific features of separate power consumers in the total nodal load schedules is necessary for increasing energy efficiency in electric networks. Therefore, the unique basis wavelet functions were obtained on the basis of the measured load current signals for electric devices under consideration (LED Lamp, Laptop, Electric kettle).

4.2. Creation of unique basic wavelet function

Wavelet Toolbox from Matlab software package was used to create the unique wavelet function adapted to specific load current signal. Matlab software package allows to create wavelet functions for continuous Wavelet transform. Current oscillograms of electricity receivers under consideration (LED lamp, laptop and electric kettle) were used both in named and relative units as original signals to create unique basic wavelet-functions.

It was assumed that significant difference between current signals scales of LED Lamp, Laptop and Electric kettle will strongly influence the values of wavelet-coefficients. Therefore, initially measured oscillograms were considered in relative units. However, it was found by the experimental way that wavelet-functions created on the basis of current signals in named units are more effective for solution of load identification task. For this reason, the unique wavelets created on the basis of current signal in named units were used in these studies.

Unique mother wavelets for LED lamp, laptop and electric kettle are presented in the Figure 6.

Figure 6 shows that graphs of unique basic wavelet functions significantly differ in shape from graphs of current signals of electricity receivers. Graph of lamp’s wavelet function has obvious “noise”. At the same time, kettle’s wavelet function is smoother and more symmetrical. Thus, it can be assumed that unique wavelet function for any active load will be symmetrical and smooth. This feature of Wavelet transform will be useful in identification of electricity receivers and their classification by the type.

Created basic wavelet functions adapted to particular load type were used to obtain wavelet coefficients for each measured load signal.

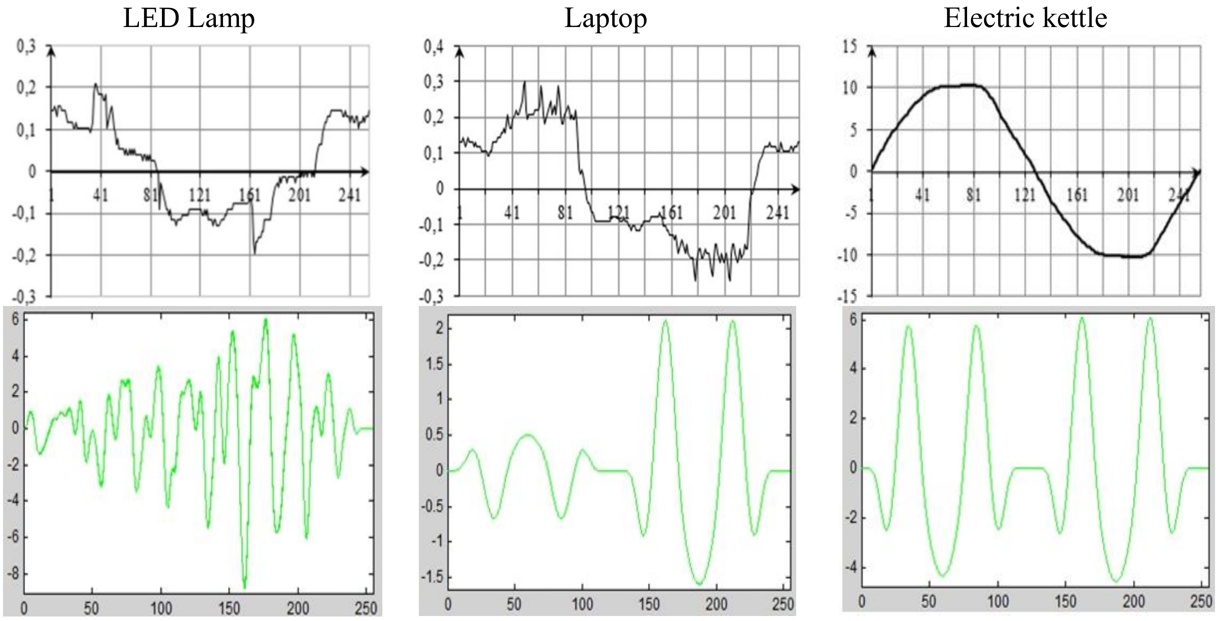

Figure 6. Unique mother wavelets

4.3. Obtaining wavelet-coefficients and results

Wavelet Toolbox in Matlab software package allows to obtain wavelet-coefficients of analyzed signal at different scales. Wavelet-coefficients shows signal features: signal "noise" is traced at small scales and wavelet-coefficients reflects a behavior of measured signal with an increase in scale. It is difficult to visually observe signal of LED lamp and laptop in total measured oscillograms (Figure 5) where there is a signal of electric kettle. Therefore, it has been assumed that we should identify electric devices of small power by wallet-coefficients at small scales.

Values of wavelet-coefficients extremely depend on the type of the chosen wavelet on which basis the analyzed signal is decomposed. The choice of mother wavelet takes a significant part in identification of electric devices. So, wavelet-functions used in the present study were created for their own load type on which basis wavelet coefficients have been created [11].

The algorithm shown in the Figure 7 in the form of block-diagram was used to identify electric devices of total measured signals. It includes the following steps:

- Signals of LED lamp, laptop and electric kettle decomposition in the basis of wavelet-function of the same load and obtaining standard values of wavelet-coefficients;
- Wavelet-transform of total load signal (LED lamp and laptop signal, LED lamp and electric kettle signal, laptop and electric kettle signal) by wavelet-function of lamp, laptop and electric kettle.
- Calculation of deviations of total signal wavelet-coefficients from standard coefficients.

Deviations are calculated by the formula [12]:

$$\sigma = \sqrt{\frac{\sum_{1}^{n}\left(k_{\mathrm{W}}^{STANDART} - k_{\mathrm{W}}\right)}{n}} \tag{2}$$

where $k_W^{STANDART}$ – value of standard wavelet-coefficient, k_{W} – value of total signal wavelet-coefficient in each measured signal, n – frequency of measurements per period (in the present study it is equal to 256 point per period).

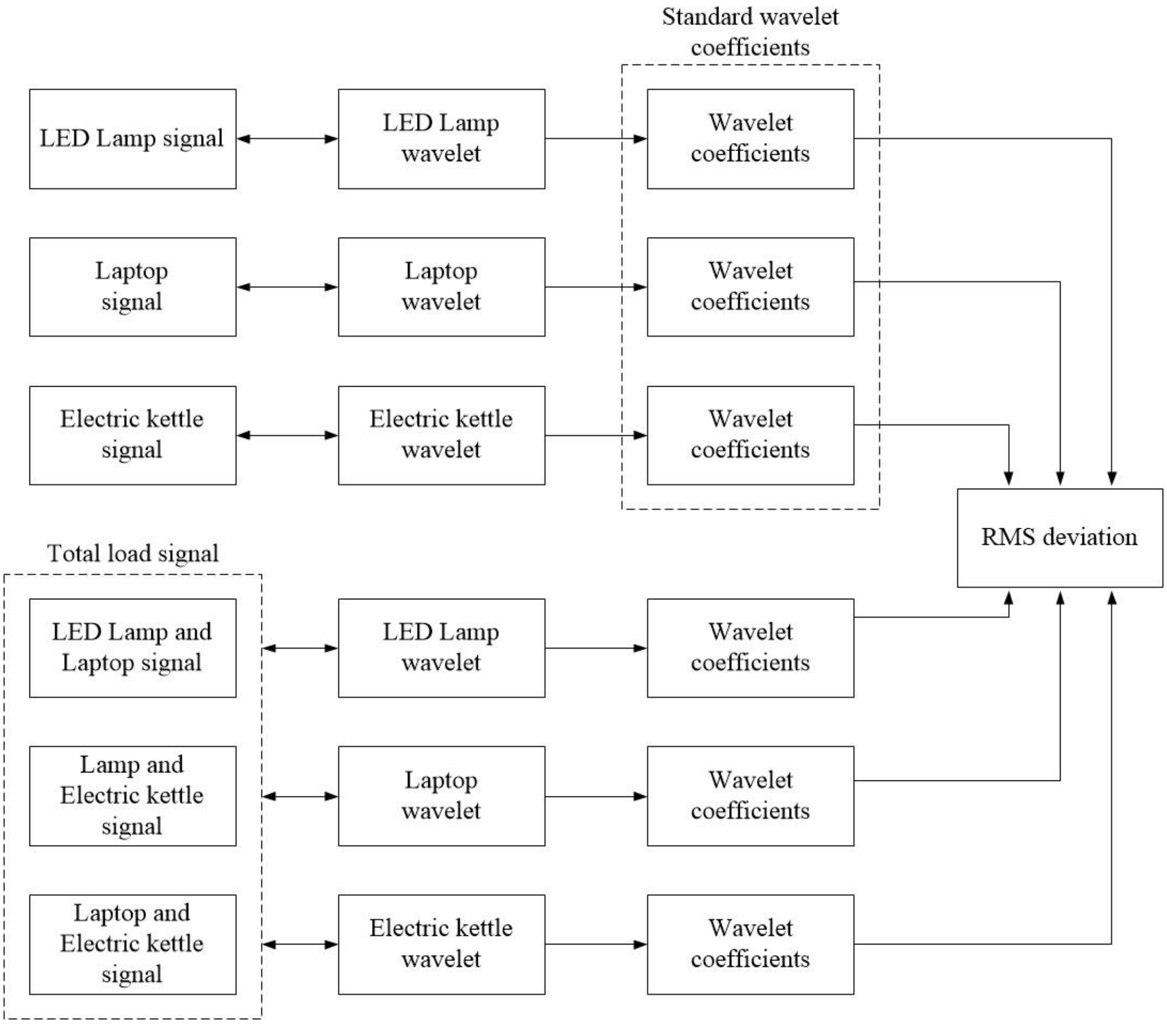

Figure 7. Block-diagram describing algorithm of electricity receivers identification

Calculation of total signal wavelet-coefficients is presented in Table 1.

Table 1. Deviations of wavelet-coefficients from standard

LED Lamp wavelet-function		Laptop wavelet-function		Electric kettle wavelet-function	
LED Lamp and Laptop signal					
Scale 1	7090618291	Scale 1	0,60641333	**Scale 1**	**6,0341E+48**
Lamp and Electric kettle signal					
Scale 1	8420385789	**Scale 1**	**5,38924183**	Scale 1	6,1113E+47
Laptop and Electric kettle signal					
Scale 1	**9336881166**	Scale 1	5,38579427	Scale 1	1,8538E+48

The results of coefficients deviations calculation presented in Table 1 shows that the total load signals decomposed in the basis of wavelet-function adapted for electric receiver which signal is presented in the total load signal gives smaller value of the deviation. For instance, in case of total load signals decomposed in the basis the lamp's wavelet-function lowest values of deviations were obtained for LED Lamp, Laptop and Electric kettle signals. The highest value of deviation (bold) was obtained for Laptop and Electric kettle signal. The same results were obtained in decomposition of total load signals by another basis wavelet-functions.

5. Conclusions

1. The algorithm of Wavelet-transform was proposed as mathematical technique for signal identification. Wavelet-transform is able to allocate local features of signals due to multiscale analysis. The latter is a significant advantage for load identification task.

2. The unique mother wavelet was created for each measured load signal. Using created unique mother wavelet function in signal decomposition it is possible to identify electric device for which the unique wavelet was created.

3. The algorithm for load identification was proposed. It includes 3 basic steps: determination of standard wavelet-coefficients values, obtaining coefficients for total load signals, calculation of coefficients deviation at small scales.

4. The further work will be devoted to improvement of the possibilities of load structure identification using Wavelet-transform by the increase of sampling frequency of measured signals.

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