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The Application of Kernel Density Estimation for Aided the Process of Locating Sources of Voltage Fluctuations

Abstract. *The paper presents the improvement of a multi-point method of identification of voltage fluctuation sources based on the analysis of voltage variability. The improvement consists in using the kernel density estimation for statistical analysis of voltage changes. At the beginning of the article the necessity of locating disturbing loads, resulting from the agreement between the power distributor and the power consumer, guaranteeing the power supply of the appropriate quality. The next part presents multi-point method using the analysis of voltage changes enabling aided of the location of disturbing loads. Problems were presented that could disturb the correct location process using this method. The results of simulation research are presented, showing the benefits of the proposed improvement of the multi-point method discussed. The possibility of automatic localization of voltage fluctuation sources and practical implementation of the method in measuring and recording instruments is discussed.*

Streszczenie. *W artykule przedstawiono ulepszenie wielopunktowej metody identyfikacji źródeł wahań napięcia bazującej na analizie zmienności napięcia. Ulepszenie polega na wykorzystaniu estymatora gęstości jądra do analizy statystycznej. Na początku artykułu przedstawiono konieczność lokalizacji niespokojnych odbiorników, wynikającą m.in. z umowy między dystrybutorem a konsumentem, gwarantującą dostarczenie energii elektrycznej o odpowiedniej jakości. W kolejnej części przedstawiono możliwości wsparcia procesu lokalizacji wielopunktową metodą wykorzystującą analizę zmienności amplitudy wahań napięcia. Przedstawiono problemy, mogące zaburzać przeprowadzenie poprawnego procesu lokalizacji z wykorzystaniem tej metody. Przedstawiono rezultaty badań symulacyjnych, pokazujące korzyści zaproponowanego ulepszenia omówionej metody wielopunktowej. Omówiono możliwość automatycznej lokalizacji źródeł wahań napięcia oraz praktycznej implementacji metody w przyrządach pomiarowo-rejestrujących.* ***(Zastosowanie estymatora jądrowego gęstości do wsparcia procesu lokalizacji źródeł wahań napięcia)***

Keywords: kernel density estimation, voltage variation, voltage fluctuations indices, source of disturbance, power quality
Słowa kluczowe: estymator jądrowy gęstości, wahania napięcia, wskaźniki wahań napięcia, źródło zaburzeń, jakość energii elektrycznej

Introduction

The intense development of the provision of electricity supply services has resulted in the fact, that pursuant to Act [1], referring to the regulation of the Minister of Economy [2], there is a requirement, that the power distributor guarantees a certain power standard.

If at the point of common coupling (PCC) (the border between the power distributor and the power consumer), the acceptable boundaries for parameters determining the power quality is exceeded, the consumer may claim compensation for poor power quality and may claim improvement of power quality (unless the problem of poor power quality in the contract between the power consumer and the power distributor has been solved differently). If the source of disturbance is not the power consumer, then the power distributor should locate the disturbing load and reduce the emitted disturbance, to increase the power quality at the PCC of the complaining power consumer.

One of the most common disturbances in the power grid today are voltage fluctuations. According to the standard [3], this phenomenon can be defined as fast changes of the rms value or the maximum value of voltage. Voltage fluctuations affect the operating state of electricity loads [4], in particular light sources. Voltage fluctuations, depending on the type of sources, cause nuisance light flicker. This is a serious factor that reduces the quality of human life. In unfavorable conditions, the light flicker deepens depression or induces epileptic states. Therefore, limiting the nuisance of flicker is an important diagnostic work, which requires the location of voltage fluctuation sources, i.e. indication of the point of supplying the disturbing load [5].

To aided the location of voltage fluctuation sources, one-point methods are used (e.g., correlation of P_{st} changes and power and/or current, examination of the interharmonic power flow direction, analysis of voltage fluctuations [6, 7, 8, 9, 10, 11], association of power changes with voltage changes [12]), or multi-point methods (e.g., analysis of voltage changes δV [13, 14, 15], association of voltage changes with current changes [14, 15, 16, 17], analysis of the individual flicker emission of specific disturbers [18], method using MLP neural networks and S-transform [19] or Discrete Wavelet Transform [20], method to calculate the gradient of voltage amplitudes [21]), or other, i.e. [22, 23, 24]. One-point methods allow to indicate the side, that is the source of disturbance, but do not create the direct possibility of locating a disturbing load in the power grid. The article focuses on the multi-point method of locating voltage fluctuation sources using voltage changes δV analysis. It has been proposed to improve this method by using the kernel density estimation. This improvement minimizes the limitations of the considered multi-point method and gives the opportunity to automate the location of voltage fluctuations sources process.

Identification of disturbing loads based on voltage changes δV analysis

This method consists in multipoint measurements of the power circuit and evaluation of propagation of voltage fluctuations using histograms [15] voltage changes δV [13] with dominant values δV_D.

The location of a disturbing load is equivalent to finding an extreme of local amplitudes of voltage fluctuations. To investigate the extreme, simultaneous measurements are required at at least three points, i.e. the measurement at the point of diturbance and in neighborhood points. The selection of neighborhood points is conditioned by the topology of the power grid and the possibility of using a measuring and recording device at a given point.

In general, the localization process comes down to the following works:

- power circuit analysis,
- measurement at predetermined points,
- choosing of periods associated with voltage fluctuations,
- creating histograms of voltage changes δV with specific dominant values δV_D for each period,
- dominant voltage changes analysis δV_D in the position function, allowing the determination of extremum.

To show the operation of the presented location method, an example diagram of the power grid was selected, which is shown in Fig. 1. The location process for the selected power grid is shown in Fig. 2. It was assumed that an disturbing load is powered from point P3.

A detailed discussion of the method of identifying disturbing loads based on the analysis of voltage changes δV, as well as the advantages and disadvantages of this method is presented in [15].

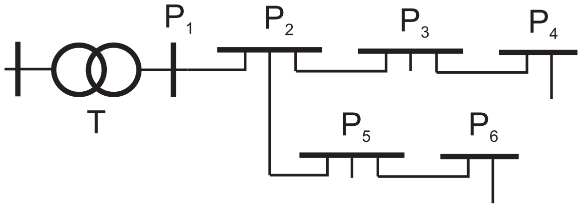

Fig. 1. Diagram of the example power grid

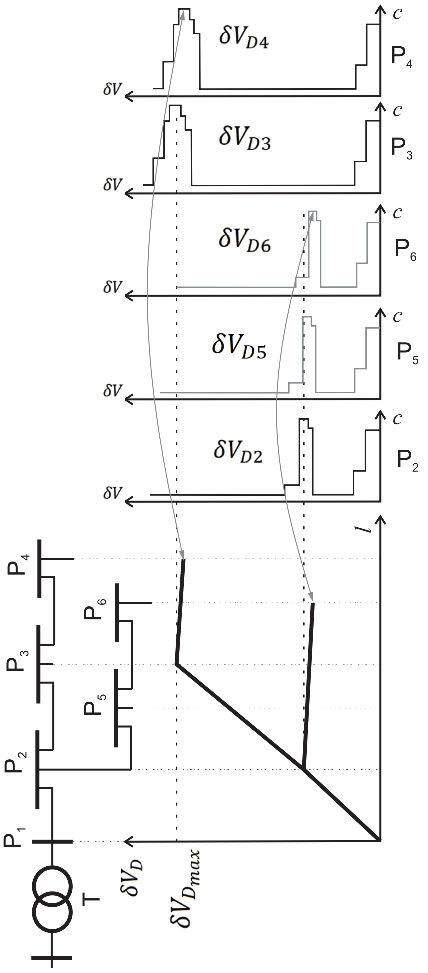

Fig. 2. The exemplary process of locating the point of supply of disturbing load - (P_3); c - contribution δV

Problem resulting from the use of a histogram for statistical evaluation of voltage changes δV

One of the basic problems resulting from applying the histogram to the statistical evaluation of voltage fluctuations, is the appropriate division of the entire range of voltage changes δV in the measurement period into a series of intervals (bins). Using too many bins can make analysis difficult, and a small number of bins may result in the loss of important information about the disturbing loads.

The problem is presented on the example of the modeled voltage in the power grid in accordance with the equation:

$$u(t)=\sqrt{2}U_c\sin(2\pi f_c t)\cdot[1+u_{mod}(t)]\ , \tag{1}$$

where: f_c=50 Hz, U_c=230 V, $u_{mod}(t)$ is a modulating signal described by the equation:

$$u_{mod}(t)=u_{mod_{\mu VF}}(t)+u_{mod_{z1}}(t)+u_{mod_{z2}}(t)\ , \tag{2}$$

where: $u_{mod_{z1}}(t)$ i $u_{mod_{z2}}(t)$ describes the working of two disturbing loads, causing cyclic and significant voltage fluctuations, $u_{mod_{\mu VF}}(t)$ is described by the equation (3) and describes small voltage changes caused by the random operation of n loads:

$$u_{mod_{\mu VF}}(t)=\sum_{i=1}^{n}U_\gamma\gamma\,\mathrm{sgn}\left(\sin\left(2\pi f_\gamma\gamma t\right)\right), \tag{3}$$

where: γ is uniformly distributed pseudorandom number from the interval (0,1), U_γ and f_γ is the parameter of the scale of the upper limit of the random values of the magnitudes of the voltage changes and the frequency of voltage fluctuations, respectively. For numerical simulations, it was arbitrarily assumed, that: n=100, U_γ=0.0005, f_γ=20 Hz.

For signal (1), where the component signal $u_{mod_{z1}}(t)$ is described by the equation:

$$u_{mod_{z1}}(t)=U_{m1}\,\mathrm{sgn}\left(\sin(2\pi f_{m1}t)\right)\ , \tag{4}$$

and $u_{mod_{z2}}(t)$ is described by the equation:

$$u_{mod_{z2}}(t)=\begin{cases}0 & t:t\in[0,t_1)\\ U_{m2}\,\mathrm{sgn}\left(\sin(2\pi f_{m2}t)\right) & t:t\in[t_1,t_2)\end{cases}, \tag{5}$$

where: U_{m1}=0.01625, U_{m2}=0.075, f_{m1}=5 Hz and f_{m2}=1/300 Hz, voltage fluctuation indices (δV,f) [13] were calculated in the measurement period T_1=[0,t_1) and T_2=[t_1,t_2). For t_1 and t_2 time constants of 300 s and 600 s were arbitrarily adopted. Values: U_{m1}, U_{m2}, f_{m1}, f_{m2} were also arbitrarily selected.

On the basis of calculated voltage fluctuation indices, a histogram was created for the following accepted sub-ranges in relation to the maximum voltage change δV_{max}: [1.0,0.9], (0.9,0.8], (0.8,0.7], (0.7,0.5], (0.5,0.3], (0.3,0.1], (0.1,0). The exemplary sub-ranges of voltage changes are used in practical measurements, e.g., in [25]. In the period T_2 simulated work of the same disturbing loads as in T_1 and single switching on and switching off the high power load, which caused a much greater magnitude of voltage changes than voltage fluctuations in T_1. Histograms of voltage changes δV for T_1 and T_2 are shown in Fig. 3. The considered situation was marked as C1.

In Fig. 3 it can be seen, that information identifying sources of voltage fluctuations in the period T_1 has been narrowed down to two bins in the period T_2, which makes it difficult to correct inferences about working disturbing loads. In addition, the use of histograms does not provide a simple possibility to estimate the dominant value of voltage changes δV_D, necessary to carry out the process of locating the source of disturbance in the power grid. An example of a graphical determination of the dominant value of voltage changes δV_D is shown in the histogram for T_1 in Fig. 3 and in Fig. 4. Moreover, single switching on and switching off the high power loads causes, that the constructed histogram for this period may not have the dominant value δV_D, despite the cyclical influence of another source of voltage fluctuations, causing significant voltage changes.

Also considered the signal (1), where $u_{mod_{z1}}(t)$ is decribed by the equation (4) and $u_{mod_{z2}}(t)$ is described by the equation:

$$u_{mod_{z2}}(t)=U_{m2}\,\mathrm{sgn}\left(\sin(2\pi f_{m2}t)\right)\ , \tag{6}$$

where: U_{m2}=0.0175, f_{m2}=3.1 Hz. For the measurement period equal to 5 min voltage change indices (δV,f) [13] were calculated. Values: U_{m1}, U_{m2}, f_{m1}, f_{m2} were arbitrarily selected.

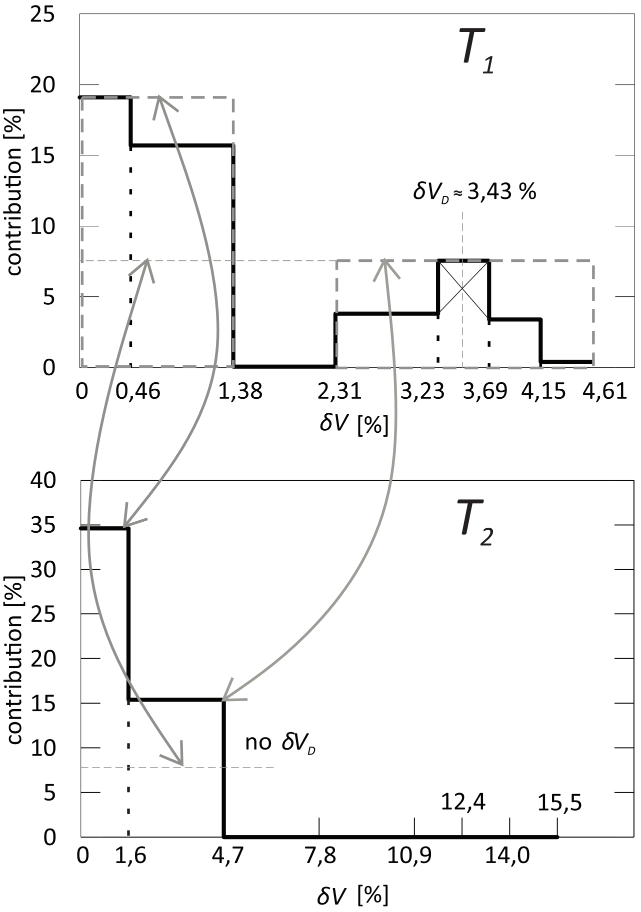

Fig. 3. Histograms of voltage changes δV for the registration period T_1 and T_2

Based on the calculated voltage fluctuation indices, a histogram was created for the same accepted sub-ranges as in the C1. During the registration period, the effect working of two cyclical and significant sources of voltage fluctuations was simulated, causing voltage changes similar to each other. The histogram of voltage changes δV for the analyzed situation is shown in Fig. 4. The considered situation was marked as C2.

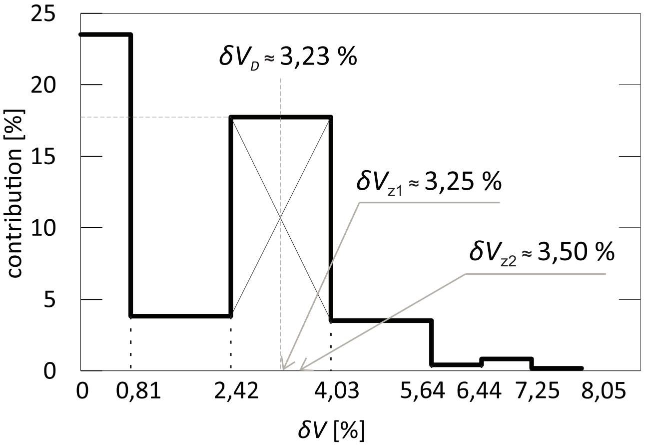

Fig. 4. The histogram of voltage changes δV for the measuring period, in which there are two cyclic and significant sources of voltage fluctuations, causing similar voltage changes

The example in Fig. 4 shows, that in some cases, the histogram of voltage changes δV does not allow to obtain information on the impact of individual sources of voltage fluctuations that causes similar voltage changes. As a consequence, there is a problem, it does not allow to the simultaneous localization of several sources of voltage fluctuations using the multi-point method.

The problems presented in the case C1 and C2, can be solved by increasing the number of bins of histogram. However, too many bins results in redundant storage of data needed to carry out the location process. In addition, the working of sources of voltage fluctuations is random, so both the maximum voltage changes, voltage changes associated with individual disturbing loads and the rate of change their operation state, do not have defined ranges of typical variability. This implies a problem of selecting the optimal number of bins and their width ensuring the improvement and reliability of the location of disturbing loads in the power grid. Moreover, the problem of estimating the dominant value of voltage changes δV_D based on histograms, makes it impossible to automate the location of sources of voltage fluctuations, by the analyzed multi-point method.

Kerndel density estimation

Kernel density estimation $\hat{f}(x)$ is described by the equation [26, 27]:

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right), \tag{7}$$

where: x_i are values obtained from measurements, n is the number of received measurement data, h is a positive smoothing parameter (equivalent to the width of the histogram bins), $K(x)$ is the kernel. The kernel is a measurable function, symmetrical in relation to zero, having a global maximum at this point, and satisfying the condition:

$$K : \mathbb{R}^n \to [0, \infty) \Rightarrow \int_{\mathbb{R}^n} K(x)dx = 1. \tag{8}$$

In the one-dimensional case, the most effective in the sense of the mean square error criterion is the use of the Epanechnikov kernel described by the equation [28]:

$$K(x) = \begin{cases} \frac{3}{4}\left(1 - x^2\right) & x : \quad x \in [-1, 1] \\ 0 & x : \quad x \in (-\infty, -1) \cup (1, \infty) \end{cases} . \tag{9}$$

Proof of this fact is in [28].

From the point of view of function density estimation for one-dimensional data, the most important is selecting the smoothing parameter appropriately. This parameter can be selected optimally for the obtained values from measurements using the cross-validation method. This method is based on the search for the minimum of the function of the real variable $g : (0, \infty) \to \mathbb{R}$, which is described by the equation [28]:

$$g(x) = \frac{1}{hn^2}\sum_i \sum_j \tilde{K}\left(\frac{x_j - x_i}{h}\right) + \frac{2}{nh}K(0), \tag{10}$$

where:

$$\tilde{K}(x) = K^{(2)}(x) - 2K(x),$$

$$K^{(2)}(x) = \int K(x - y)K(y)dy.$$

Proof of this fact is in [28].

The application of the kernel density estimation to aided the process of locating sources of voltage fluctuations

The operation of the kernel density estimation to aided the location of sources of voltage fluctuations is presented for case C1 and C2. Density functions for individual cases were obtained using the algorithm of fast kernel density estimation with the optimal selection of smoothing parameter using the cross-validation method [29].

The effect of the kernel density estimation method for the statistical evaluation of voltage changes δV for case C1 is shown in Fig. 5.

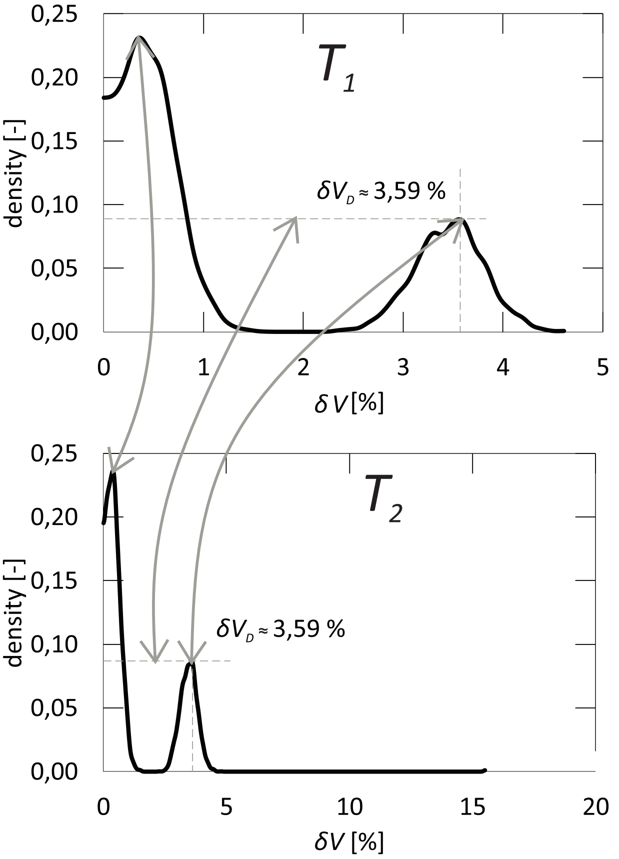

Fig. 5. Estimated density function of voltage changes δV for the period T_1 and T_2

In Fig. 5 it can be seen that the application of the kernel density estimation, without forcing any additional parameters, enabled a accurate distribution of the probability of occurrence of individual voltage changes, even in the case of single switching on and switching off high power load (period T_2). Accurate reconstruction of the probability distribution of voltage changes in particular periods allows for accurate reconstruction of the resultant distribution from long-term measurements. In addition, the use of a kernel density estimation makes it simple to determine dominant values of voltage changes δV_D. This is accomplished by searching for the local extreme of the obtained density function, e.g., on the basis of its first and second derivative. This creates the possibility of automating the process of locating disturbing loads using the multi-point method.

The effect of the kernel density estimation method for the statistical evaluation of voltage changes δV for case C2 is shown in Fig. 6.

In Fig. 6 it can be seen, that the application of the kernel density estimation makes it possible to determine the dominant values of voltage changes δV_D for individual significant disturbing loads, even if they causing similar voltage changes. Consequently, kernel density estimation method creates the possibility of simultaneously finding more disturbing loads. An example of a concurrently finding disturbing loads using the kernel density estimation, for the exemplary structure of the power grid shown in Fig. 1, is shown in Fig. 7. In this case, sources of disturbances are powered from point P2 and P4. Based on the analysis of voltage changes at point P2, the estimated density function is obtained, which is shown in Fig. 6.

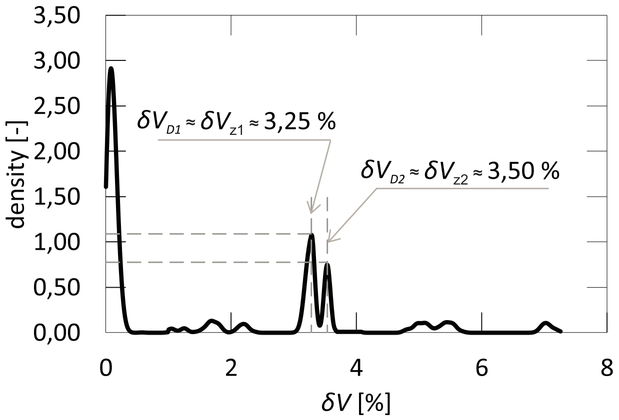

Fig. 6. Estimated density function of voltage changes δV for the measuring period, in which there are two cyclic and significant sources of voltage fluctuations, causing similar voltage changes

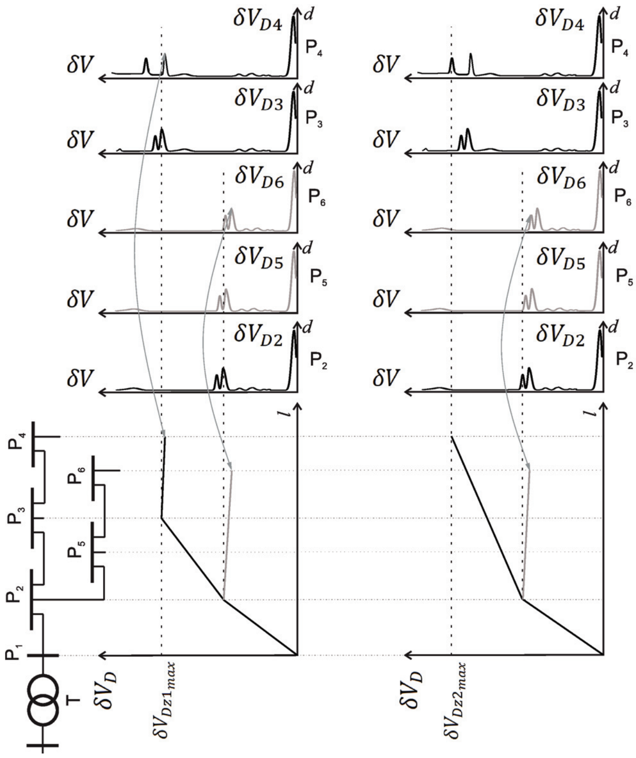

Fig. 7. The exemplary process of locating the point of supply of disturbing loads - (P_2 and P_4); d - density of the function

In practical implementations, where there is a need to limit the data stored in the memory of the measuring and recording device, it is possible to store only the resultant density function, or individual dominant values of voltage changes δV_D from subsequent measurement periods.

Conclusion

The article presents the improvement of the multipoint method, which uses the analysis of voltage changes δV in the power grid. Statistical analysis was proposed using the kernel density estimation. The presented solution enables solving the problems of the process of locating sources of voltage fluctuations, resulting from the use of a histogram to evaluate statistical voltage changes δV. Numerical simulation tests show, that the used kernel density estimation method adjusts to the measurement results, thus eliminating the problem of selecting the number and width of bins of histograms. This is important due to the random nature of disturbing loads. The use of the proposed nonparametric estimator makes it possible to identify sources of disturbances that cause similar voltage changes. Moreover, for the estimated density function, the determination of the dominant values of voltage changes δV_D is simpler and more accurate than in the case of histogram analysis for individual measurement periods. As a consequence, it makes it possible to carry out an automatic process of locating sources of voltage fluctuations, that do not require assessment and expert knowledge.

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