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RECOGNITION OF ELECTRICAL QUANTITIES IN MEASUREMENTS FROM VARIOUS DIGITAL RELAY PROTECTION AND AUTOMATION DEVICES

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Intelligent systems for the control and support of operating services for electrical of electrical networks use a number of oscillograms of the same emergency processes obtained from different digital relay protection and automation devices. In this regard, one and the same electrical quantity turns out to be presented in different digital oscillograms which bear the imprint of the entire range of settings of the measurement paths for their devices. An unambiguous estimate of the components of an electrical quantity taking into account the features of its representation in the multiple digital oscillograms is achieved by their joint processing. This paper proposes methods for joint recognition of an electrical quantity based on a single model of its informational components which excludes the multiplicity of recognition problem solving and increases the recognition ability by invoking a set of readings of the digital signals in a superstructure of adaptive models with a distributed structure. Here the introduction of a residual signal filter into the general structural unit of the adaptive models and delegating to it the problems of accounting in its structure for the components which do not enter the unitary model of the informational components forms an effective environment for recognition of the informational series of the filter for the electrical quantity. To prevent an unjustified increase in the order of the filter for the residual signal, it is recommended that digital signals with different sampling frequencies be converted into signals with the same sampling frequency by thinning out (decimation) of the samples.

Keywords: joint digital signal processing; adaptive structural analysis; adaptive models with distributed structure; canonical component filter; composite filter; residual signal filter; general residual signal filter.

Subsystems for the collection and long-term storage of information in many intelligent systems for control and support of the operating services of electrical networks, in particular, systems for support of the acquisition of solutions, and systems for automatic monitoring and analysis of the operation of relay protection and automation (RPA), concentrate a multitude of files of oscillograms in themselves from similar emergency processes from different RPA digital devices [1]. As a consequence, a given electrical quantity turns out to be represented in different digital oscillograms bearing in itself an impression of an entire set of adjustments for the measurement circuits of the measurements of their structures. The subsystems for processing the electrical quantities for intelligent systems must take into account this feature of the representation of an electrical quantity in digital oscillograms and ensure the uniqueness of an estimate of its components. The problem of joint processing of the measurements of a given electrical quantity by different devices ultimately arises.

In this regard, in this article we examine the theoretical foundations of the joint processing of measurements (digital oscillograms) of an electrical quantity obtained from different devices for relay protection and automation.

Features of the representation of an electrical quantity in different digital devices

Measurements of a continuous electrical quantity $x(t)$ are presented in analog-digital conversion (ADC) circuits with a sampling period T_s^n and a conversion function $ADC_{T_s^n}$ in the form of digital signals

$$x^n(kT_s^n) = ADC_{T_s^n}\{x(t)\}, \tag{1}$$

where the upper index $n = \overline{1, N}$ corresponds to the number of the signal; N is the number of signals; and k is the reading number (Fig. 1). Since the digital signals $x^n(kT_s^n)$ appear as a result of one and the same electrical quantity $x(t)$, we shall refer to them as uniform. For simplification of the mathemat-

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ical expressions in the following we shall use a shortened notation for the signal $x^n(k)$, assuming that the upper index n also uniquely determines the sampling period of the signal T_s^n.

It is important to keep in mind that, despite their uniformity, the signals (1) may also contain additional components owing to features of the measurement circuits of the devices. In addition, because of noise, which is inevitable during transformation of electrical quantity, additional components develop in the models of the signals which do not belong to the recognized signal but are received by the processing algorithm as part of the useful signal [2, 3]. Thus, when processing uniform digital signals separately, a multitude of solutions is possible.

An adaptive filter as a structural model of the distinguishable signal

It is known [2, 4, 5] that the structure of the digital signal $x^n(k)$ will be recognized if part of the roots of the characteristic equation of the adaptive filter

$$e^n(k) = N \sum_{m=0}^{M} a_m x^n(k-m), \tag{2}$$

built on its barrier, is matched to the components of the signal. Here M and a_m are the order and coefficients of the filter. It is evident that the conditions for tuning the filter will differ, which eventually leads to a multiplying of the number of representations of the components of the electrical quantity.

A multiplicity of solutions can be avoided if it is postulated that the informational components of uniform signals are unique, and differences in the signals are unrealizable in principle, since separating the classical model into separate units becomes possible only after it is fully tuned. Thus, the approach to constructing the model of the signal must be cardinally changed. It is necessary that the model of the signal be a set of models of its different parts, representing the mechanisms for tuning each of them further in stages of tuning the entire model. This possibility shows up because of the application in the joint recognition of the signals (1) of models with a distributed structure, first proposed in a patent [6] and further developed in [7 – 9].

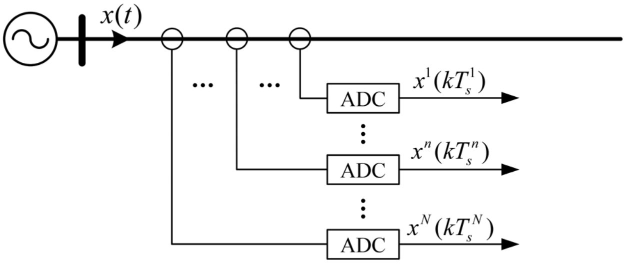

Fig. 1. Measurement of an electrical quantity $x(t)$, the LEP current, by different relay protection devices. The ADC circuit for each device converts an electrical quantity into a digital signal: n is the number of the signal.

An adaptive filter with a distributed structure as a basis for joint processing of signals

A model with a distributed structure is a cascade of models for information components that includes successive connected adaptive canonical filters of the components $C_1^n - C_{N_C}^n$ (N_C is the number of recognized components) and a filter for the residual signal F_r^n. The latter is intended for obstruction of the components that have been neglected by the pre-included canonical filters, and the use of functions for a noise filter [10] (Fig. 2).

The advantage of the model with a distributed structure lies in the possibility of estimating the characteristic parameters (damping coefficients and frequencies) of the informational components of the signal $x^n(k)$ directly from the vectors of the coefficients of the canonical filters $\mathbf{A}^n = [\mathbf{a}_1^n \ldots \mathbf{a}_i^n \ldots \mathbf{a}_{N_C}^n]$. For example, a harmonic and an aperiodic component of the signal $x^n(k)$ are represented by adaptive filters in the form of canonical vectors of the coefficients

$$\mathbf{a}_i^n = [1 a_{i,h}^n 1]^T \tag{3}$$

and

$$\mathbf{a}_i^n = [1 a_{i,e}^n]^T, \tag{4}$$

in connection with which, estimates of the frequency $\hat{\omega}_i^n$ of the harmonic and the damping coefficient $\hat{\alpha}_i^n$ of an aperiodic component may be obtained directly from the expressions

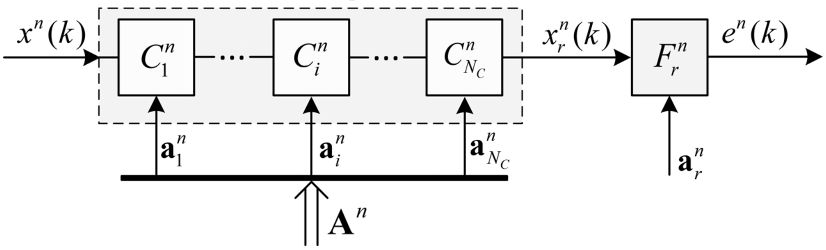

Fig. 2. Model with a distributed structure.

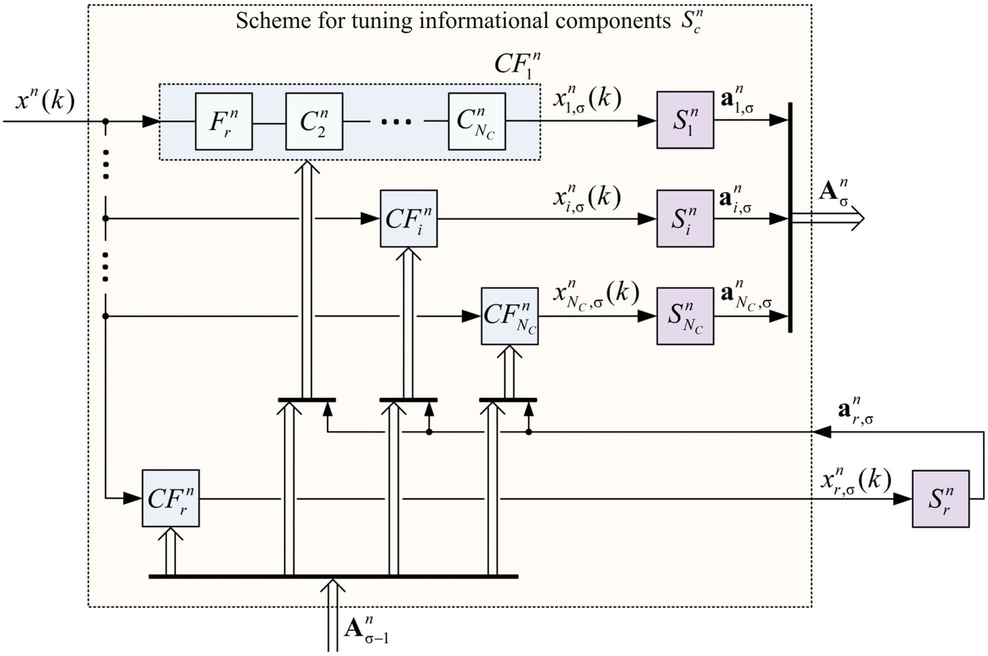

Fig. 3. Scheme for tuning an adaptive model with a distributed structure.

for the corresponding coefficients of the vectors (3) and (4) in the following way [5]:

$$\hat{\omega}_i^n T_s^n = \operatorname{acos}(-a_{i,h}^n/2) \tag{5}$$

and

$$\hat{\alpha}_i^n T_s^n = \ln(-a_{i,e}^n). \tag{6}$$

Here the upper index *T* denotes the operation of transposition.

Precisely this sort of organization of the model in the form of an adaptive filter with a distributed structure, in which the canonical models of the components may be combined into a single model of informational components, creates a platform for joint processing of the entire set of signals (1).

Features of the tuning of an adaptive model with a distributed structure

Tuning of a model with a distributed structure cannot be carried out in the ordinary sequence, since now the model is not homogeneous and includes structural units of a different order. Thus, the recognition of a signal by this kind of model involves individual tuning of separately standing structural units, assuming that together they form a joint signal model.

The structural units of the model are adjusted iteratively in the individual channels (Fig. 3), obtaining individual tuning of the separately standing structural units σ in an optimal local solution [7 – 9]. The adjustment channel consists of a component filter of the distinguished component and a block for adjustment of the structural unit. In accordance with its intent, at its input the component filter forms a constituent component that is proportional either to the *i*th component $x_{i,\sigma}^n(k)$ or to the residual signal $x_{r,\sigma}^n(k)$. A signal proportional to the distinguished component is obtained by a component filter directly from the input signal $x^n(k)$ as a result of obstruction of all its components, except for the distinguished component. Following this rule, the composite filter of the component CF_i^n or the residual signal CF_r^n is formed by exclusion from the common filter (Fig. 2) that blocks the filter of the component C_i^m or the residual signal F_r^n [2].

The chosen (informational) components of the signal $x_{i,\sigma}^n(k)$ are distinguished in the tuning blocks C_i^m $(i=\overline{1,N_C}$ of the tuning scheme for the canonical filters of the components S_C^m. The tuning block of the filter for the residual signal C_r^n is an isolated object, since its status is supportive — an adaptive filter of general form (2) in the general structure of the model for the signal $x^n(k)$ is determined in the course of its being recognized. In addition, in the assumed scheme for adjustment of the filter for the residual signal F_r^n is adjusted in each step of the iteration σ by the first, to form a component of the residual signal $x_{r,\sigma}^n(k)$ using a composite filter CF_r^n (Fig. 3) in the assumed tuning structure, that includes the entire cascade of canonical filters of the components of the previous step σ – 1 of the tuning.

The principles for tuning an adaptive model with a distributed structure are discussed in detail in [11, 12]. We note only that the tuning of the filters is carried out in several stages, including a stage of initialization and adjustment stages. Thanks to the distributed structure of the adaptive model, in the initialization stage ($\sigma = 0$) the initial values of the coefficients $a^n_{i,o}$ are specified only for the canonical filters of the components C^n_i. This circumstance also determines the order of tuning of the different parts of the active filter in the tuning stages ($\sigma \geq 1$): first the filter of the residual signal F^n_r is tuned, and then, with its participation, the canonical filters of the components C^n_i.

The general case of joint signal processing

As already noted previously, measurements of one and the same continuous electrical quantity $x(t)$ by different relay protection devices will be presented in the general case of a set of digital signals (1) with different sampling periods T^n_s. Thus, the adaptive filter which recognizes the digital signal $x^n(k)$ will, at the beginning of each iteration σ, actuate the parameters of its model for the informational components in accordance with the parameters of the unified model for the preceding ($\sigma - 1$)-st step taking the difference in the sampling periods of its own and the other signal into account

$$\mathbf{A}^n_{\sigma-1} \xleftarrow{T^n_s,\,T^{n-1}_s} \mathbf{A}^{n-1}_{\sigma-1}. \tag{7}$$

The rule (7) is not unique, since during the exchange of coefficients for the unitary model, the adaptive filters may participate in different combinations. But, the very concept of a rule is of substantial importance, since accepting it supports the mutual relationship of the solutions of the tuning schemes for adaptive filters, establishing the dependence of the parameters of the unitary model for a tunable adaptive filter on the corresponding parameters obtained during the processing of another digital signal (Fig. 4).

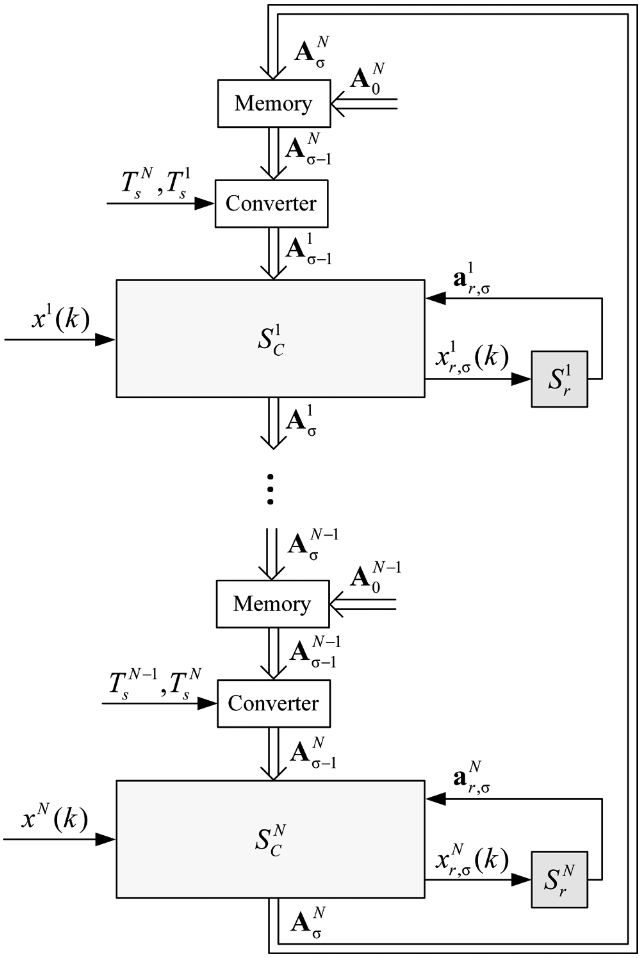

Fig. 4. General scheme for joint processing of digital signals.

It is assumed that the adjustment of the models proceeds in the direction from the first to the Nth adaptive filter. In order to ensure mutual coupling of the solutions, the coefficients of the model for the information components $\mathbf{A}^{n-1}$ of the preceding ($n - 1$)-st filter arriving with a delay by a step (owing to the Memory unit) are transformed according to rule (7) in a converter (Converter unit) and are used in the next nth filter. $\mathbf{A}^n_0$ are the values of the model coefficients for the informational components of the nth filter in the initialization stage $\sigma = 0$.

Thus, for example, in a scheme for tuning the informational components S^N_c of the signal $x^N(k)$, canonical filters of the components are used, tuned for blocking of the informational components of another digital signal $x^{N-1}(k)$. Since the sampling frequencies of the digital signals in the general case may not coincide, in accordance with rule (7) in the scheme for tuning the Nth adaptive filter S^N_c the coefficients of the canonical filters of the components for another digital signal $x^{N-1}(k)$ are converted taking the sampling periods of its own T^N_s and the other T^{N-1}_s digital signals into account. The necessary expressions for the new coefficients are obtained taking into account their dependence on the estimates of the characteristic parameters (5) and (6) of the distinguishable component. For the canonical filter of a harmonic, the transformation involves the coefficient in the vector (3),

$$a^n_{i,\sigma-1,h} = -2\cos(\hat{\omega}^{n-1}_{i,\sigma-1} T^n_s) = -2\cos\left[\frac{T^n_s}{T^{n-1}_s} \operatorname{acos}\left(-\frac{a^{n-1}_{i,\sigma-1,h}}{2}\right)\right] \tag{8}$$

and for the canonical filter of an aperiodic component, the coefficient in the vector (4),

$$a^n_{i,\sigma-1,e} = -\exp(\hat{\alpha}^{n-1}_{i,\sigma-1} T^n_s) = -\exp\left[\frac{T^n_s}{T^{n-1}_s} \ln(-a^{n-1}_{i,\sigma-1,e})\right]. \tag{9}$$

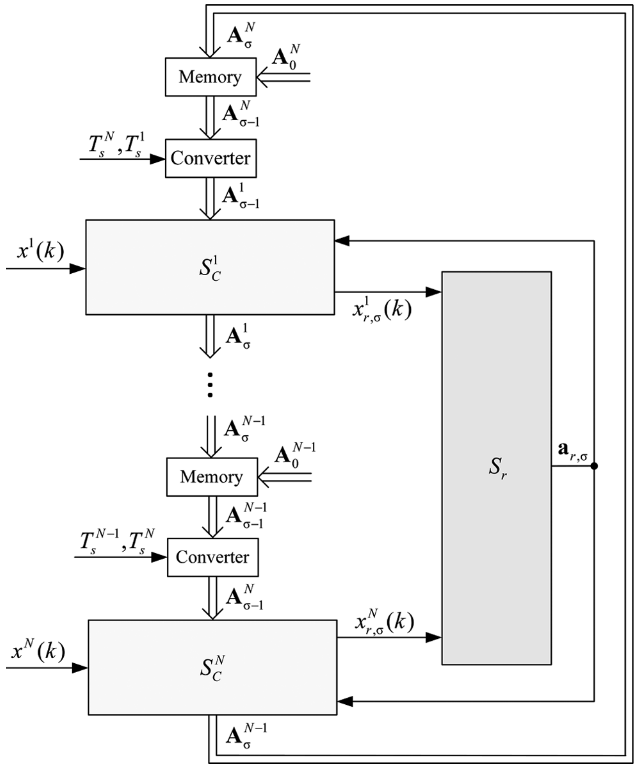

Fig. 5. A scheme for joint processing of a set of uniform digital signals employing a common filter for the residual signal.

Although each of the signals $x^n(k)$ is a digital image of the electrical quantity $x(t)$, in the general case their adaptive models, although also based on a common model of the informational components, will be different; and this difference will be taken into account in the medium of the filter for the residual signal F_r^n of each of them.

Joint filter for the residual signal

Theoretically the uniformity property of the signals $x^n(k)$ postulates that the entire set of them may be represented by a unified model which includes a successively combined model of the informational components and a filter for the residual signal. Thus, further development of the concept of joint processing shows up in the organization of processing of the residual signals after all the models of the informational components $\mathbf{A}^{n-1}$ in the joint filter for the residual signal F_r (Fig. 5). In this case it is tuned in the common unit S_r, which combines, at its inputs, the residual signals $x_r^n(k)$ of all the channels for processing of the signals $x^n(k)$.

An attempt to make full use of the advantages of combined processing of uniform signals, however, does require that the technological features of its organization be taken into account.

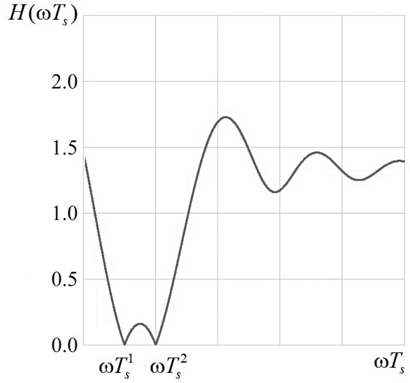

Fig. 6. A fragment of the amplitude-frequency characteristic of a joint filter for a residual signal when it blocks the component of the frequency ω introduced at the inputs of the filter simultaneously with the sampling periods T_s^1 and T_s^2.

Features of joint signal processing

The joint filter for the residual signal immediately recognizes the set of residual signals $x_r^n(k)$, which arrive simultaneously at the inputs of the circuits for its adjustment S_r, despite the difference in their sampling periods T_s^n, and forms its characteristics, which are optimal for recognition of the informational components of the digital signals $x^n(k)$.

If all the significant components of the uniform signals $x^n(k)$ are taken into account in the joint model for the informational components $\mathbf{A}^{n-1}$, then the residual signals for all the channels $x_r^n(k)$ only contain noise at the end of tuning. In this case the joint filter for a residual signal serves exclusively as a noise filter [10], applying all its resources for improvement of the conditions for identification of informational components. In the other case, when the joint model for the informational components $\mathbf{A}^{n-1}$ is incomplete, the common filter for the residual signal F_r will be required to take upon itself the problem of identifying the components that have not been taken into account and forming blocking filters for them with their time scale taken into account. This phenomenon for the residual signal filter is illustrated by the fragment of its amplitude-frequency characteristic for their blocking of the component with frequency ω represented in the digital signals $x^1(k)$ and $x^2(k)$ with sampling periods of T_s^1 and T_s^2, respectively (Fig. 6). It is clear that the filter receives one and the same component in the signals as dissimilar components and necessarily builds up its order in order to block it in both signals.

Reduction of the sampling frequencies of the signals

During identification of digital signals with multiple sampling frequencies it is possible to avoid an unjustified increase in the order M_r of the residual signal filter F_r by reducing them to digital signals with a single sampling period

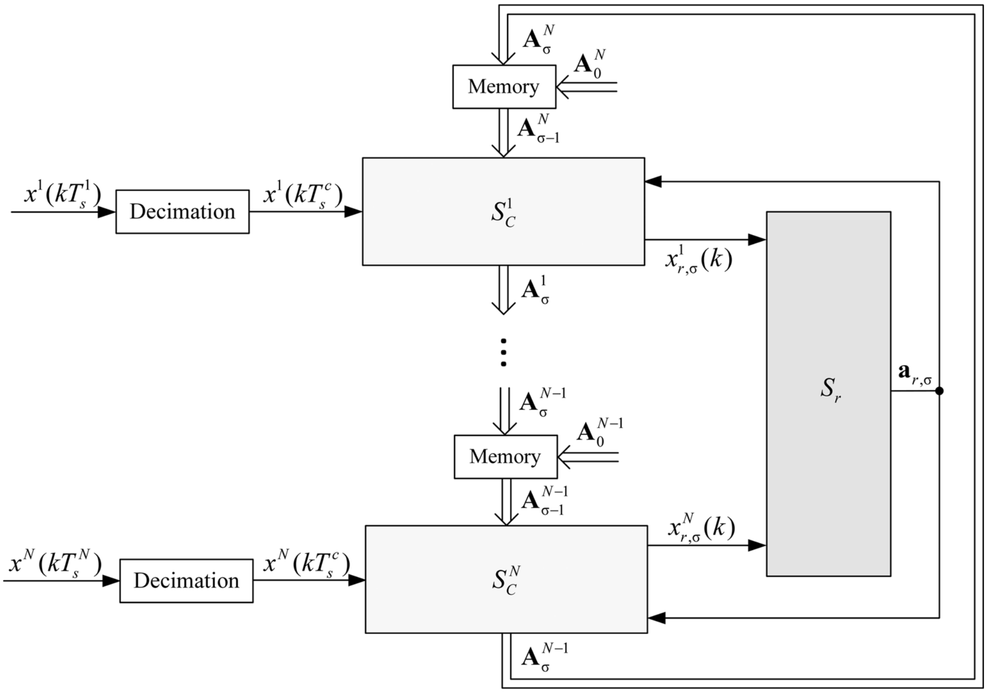

Fig. 7. Scheme for joint processing of a set of digital signals with reduction of the sampling frequencies in decimation (thinned out) units.

T_s^c by thinning out (decimation) of the readings (Fig. 7). Here the single sampling frequency is defined as the largest common divisor of the sampling frequencies for the digital signals.

In this case, both as a single model of informational components S_C^n and a filter for the residual signal S_r, digital signals with a single sampling frequency are delivered to the tuning schemes. Reduction of the sampling frequencies of the signals eliminates the need for using converters of the coefficients of the models (Converter units) and enhances the efficiency of the residual signal filter, avoiding doubling of the blocking filters for the neglected components.

CONCLUSIONS

1. Combined processing of digital measurements of an electrical quantity obtained from different devices avoids the multiplicity of solutions for the problem of identifying an electrical quantity, using a single model for its informational components, and enhances the resolving capacity for identifying it by invoking a set of readings of all the digital signals in the tuning of adaptive filters.

2. A filter for the residual signal that is common for all the digital signals forms an effective medium for identifying the informational components of the signals owing to an artificial increase in its observation window and thereby ensuring a reduction in the required size of the observation window for the filters of the informational components.

3. The conversion of digital signals with different sampling frequencies into signals with a single sampling frequency by thinning out (decimation) of the readings raises the efficiency of the filter for the residual signal, preventing an unjustified increase in its order.

Compliance with ethical standards

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