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RECOGNITION OF WEAK HARMONIC SIGNAL COMPONENTS IN GENERATOR PROTECTION AGAINST SINGLE-PHASE EARTH FAULT

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For single-phase earth faults (SEF) in a generator network, the higher harmonic components are a good information base for relay protection of the generator against single-phase earth faults. Because of the low signal-to-noise ratio, they are not available for direct measurement. A new method of active-adaptive recognition of similar signals is proposed. The results of testing a prototype of the generator protection device with an active-adaptive analog-to-digital converter (ADC) path confirm the high effectiveness of the proposed method.

Keywords: active-adaptive method of signal recognition; analog-digital conversion; generator; relay protection.

It is known that the higher harmonics in a generator network are a broad information base for relay protection of the generator against earth faults of the stator winding [1, 2]. However, in practice the extraction of information contained in the higher harmonics is a rather complex task. This is associated with the fact that the level of the higher harmonics needs to be estimated against the background of the dominant fundamental harmonic. Traditional digital relay protection devices have a relatively small dynamic range of measurement of input currents, and are shifted toward larger multiples [3]. In this regard, their ADC paths do not generally distinguish the higher harmonics.

The classical approach to improving the resolution of an ADC circuit is understood to be the use of analog band-rejection filters with a high Q factor and adjusted to amplify the information component and suppress other components of the signal [4]. However, the expressed dependence of the transmission coefficient of the analog filter on frequency in the vicinity of the band-rejection frequency results in significant weakening of the selectivity of the filter when the frequency of the information component deviates, reducing sensitivity of protection. Therefore, the use of band-rejection filters for recognizing the information component appears insufficiently effective [5].

In this regard, there exists a need to improve the resolution capabilities of the ADC path for generator protection devices to recognize the information component against the background of the predominant components of the input signal. This article is devoted to the solution of this problem based on a new method of active-adaptive signal recognition.

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Active-adaptive signal recognition. The fundamental idea of active-adaptive recognition consists in the adaptive conversion of an input signal with weak information component into an intermediate continuous signal in which the level of the information component is relatively high and is in the region of ADC resolution. Figure 1 shows a schematic diagram of the ADC measurement path.

Let us clarify the principle of operation of the path circuit.

An electrical signal

$$x(t) = x_0(t) + x_s(t), \quad (1)$$

that is the sum of a weak information component $x_0(t)$ and a dominant spurious signal $x_s(t)$ will be converted into a digital signal $x(k)$ by the first ADC (ADC_1). Based on the digital signal in the first adaptive structural analysis unit ASA_1, a digital image $x_0(k)$ (component structure) of the dominant spurious signal $x_s(t)$ is formed, free from the information component. Then the mentioned digital signal $x_s(k)$ is converted back into a continuous signal $x_s(t)$ by the digital-to-analog converter DAC and is subtracted from the input signal $x(t)$. The intermediate continuous signal $x_0(t)$ thus obtained will consist of the unchanged information component and the noticeably suppressed spurious signal (ideally, the intermediate signal will include only the information component). The signal-to-noise ratio for the intermediate signal will be consid-

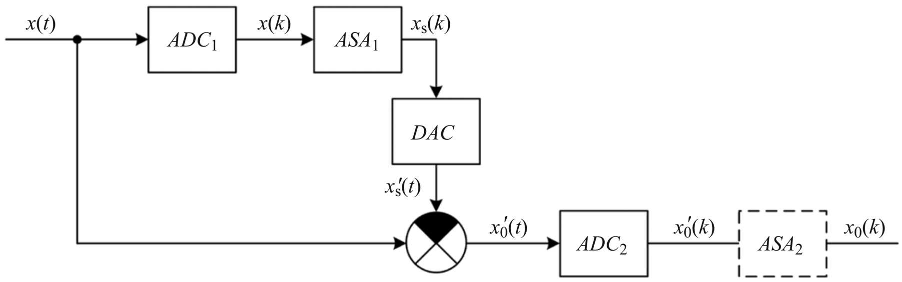

Fig. 1. Schematic diagram of the ADC measurement path for active-adaptive recognition of the weak information component of a signal: ADC_1 and ADC_2, first and second ADCs; ASA_1 and ASA_2, first and second adaptive structural analysis units; DAC) digital-to-analog converter.

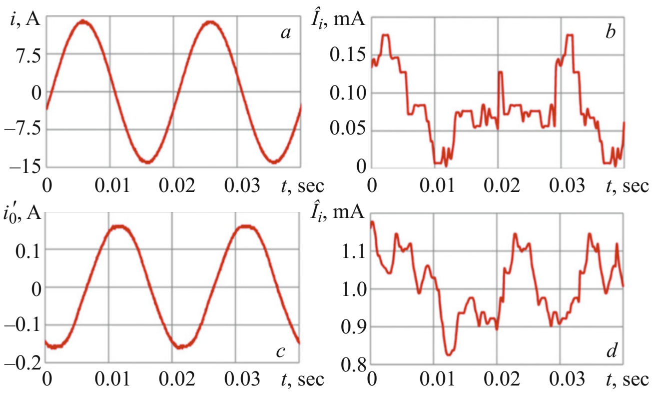

Fig. 2. Active-adaptive recognition of the third harmonic of the current of the signal information component by expression (2) for $I_0 = 0.001$ A and $I_s = 10$ A (signal-to-noise ratio is 10^{-4}): *a*, input signal; *b*, estimate of actual value of the information component directly from readings of the signal $i(k)$; *c*, signal $i_0(k)$ after active-adaptive suppression of the spurious signal (signal-to-noise ratio is increased to 110×10^{-4}); *d*, estimate of actual value of information component in signal $i_0(k)$; Q factor of all ADCs and DACs.

erably increased. Hence in the digital signal $x_0(k)$, obtained after analog-to-digital conversion of the intermediate signal $x_0(t)$ by the second ADC ADC_2, the information component is presented with adequate accuracy.

Of course, in the general case the digital signal $x_0(k)$ can contain traces of the spurious signal $x_s(k)$, but these can be easily eliminated in subsequent processing. This is usually done by software (the ASA_2 unit in Fig. 1).

The effectiveness of the system is easily proven. We will demonstrate it using the example of estimating the actual value of the third harmonic (information component) on the background of a dominant fundamental harmonic of the signal:

$$x(t) = X_0 \cos(\omega_0 t + \psi_0) + X_s \cos(\omega_s t + \psi_s) \tag{2}$$

where X_s, X_0, and $\omega_s = 100\pi$, $\omega_0 = 3\omega_s = 300\pi$ are the amplitudes and frequencies of the spurious signal (dominant component) and information component, respectively.

According to expression (2), the signal is converted by analog-to-digital conversion into the digital signal

$$x(k) = ADC_1 x(t), \tag{3}$$

where k is discrete time, associated with continuous time t by $t = kT_s$, T_s is the sampling period of the signal, and $ADC_1x(t)$ is the ADC function. The precision of the ADC ADC_1 in this case is selected by starting from the maximum value X_{max} of the signal from expression (2), derived at the upper boundary of the range of values $X_{0,\,max}$ and $X_{s,\,max}$ for the information $x_0(t)$ and spurious $x_s(t)$ components, respectively:

$$X_{max} = X_{0,\,max} + X_{s,\,max}. \tag{4}$$

It is clear that if the ratio $X_{0,\,max}/X_{s,\,max}$ which characterizes the relative level of the information component in the signal will be small, then the estimate $\hat{X}_0$ of the complex amplitude X_0 will have significant error, or be unmeasurable by the ADC. The later is clearly visible from Fig. 2*b*: for a signal-to-noise ratio equal to 10^{-4}, calculated as the ratio of the amplitude of the third harmonic to the amplitude of the fundamental harmonic, the estimate $\hat{X}_0$ does not reflect the true content of the information component in the signal.

In order to improve the resolution capability of the analog-to-digital conversion, the spurious signal $x_s(t)$ is removed from the electrical signal. For this purpose the digital signal $x(k)$ according to expression (2) is subjected to adaptive structural analysis in the ASA_1 unit, and a digital model of the spurious signal $x_s(k)$ is formulated from its results. In our case this will be a model of the fundamental harmonic

$$x_s(k) = \sqrt{2}\hat{X}_s \cos(\hat{\omega}_s kT_s + \hat{\psi}_s), \tag{5}$$

all parameters of which (estimates of the actual value of $\hat{X}_s$, frequency $\hat{\omega}_s$, and initial phase $\hat{\psi}_s$) are determined in the ASA_1 block from the $x(k)$ readings.

The level of the information component has no effect on the process of defining a model of the dominant signal $x_s(k)$, and the information component will in any case be excluded

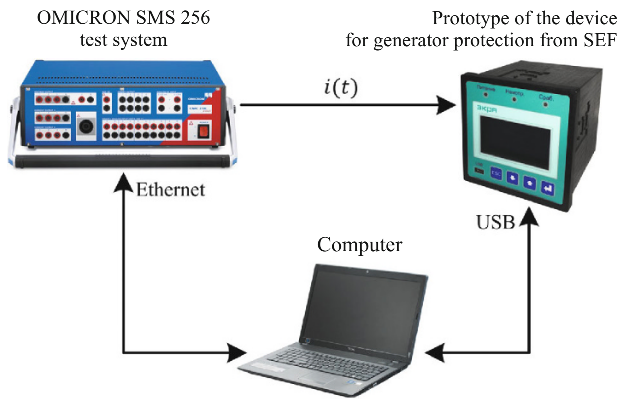

Fig. 3. Test setup for a prototype of a device for generator protection from SEF with an ADC path for active-adaptive recognition of a weak information signal component.

from it. Then the continuous signal $x_s(t)$ is formed by the DAC from the digital model of the spurious signal $x_s(k)$ by expression (5). Hence the maximum amplitude of the signal at input to the second ADC ADC_2 will be theoretically

$$X_{\max} = X_{0,\max}, \tag{6}$$

which is much less than the maximum amplitude according to formula (4). This will make it possible to reduce the weight of the lowest order of the second ADC. As follows from expressions (4) and (6), the reduction of the weight of the lowest order of the ADC will be the multiple

$$\eta = \frac{X_{0,\max} + X_{s,\max}}{X_{0,\max}} = 1 + \chi,$$

where $\chi = X_{s,\max}/X_{0,\max}$.

This means that the effect from using a system of active-adaptive recognition is greater, the larger the ratio of amplitudes of the spurious $x_s(t)$ and the extracted $x_0(t)$ component (the larger the χ).

The system preserves its operational fitness as the frequency of the extracted component varies between broad limits, since it uses operations whose properties do not depend on frequency.

Test studies. A prototype of the device for generator protection from SEF using an active-adaptive ADC path (Fig. 3) was developed and tested with the objective of confirming the characteristics of the method set forth. In the course of the tests, recognition of the third harmonic of the current against the predominant fundamental harmonic was carried out.

Figures 2 and 4 show the results of recognizing the third harmonic of the current, for ratios of the amplitude of the third harmonic to the amplitude of the fundamental harmonic being 10^{-4} and 5×10^{-4}, respectively. It is clear that the proposed system of active-adaptive recognition estimates the actual values of the information component at the 1% precision level for the ratio $I_0/I_s = 5 \times 10^{-4}$ (Fig. 4*d*). At the same time, recognition directly from readings of the signal $i(k)$ has an impermissibly large error (approximately 32%, Fig. 4*b*). Reduction of the ration I_0/I_s to 10^{-4} makes the estimation of the actual value of the information component directly from readings of $i(k)$ impossible (Fig. 2*b*), although at the same time the active-adaptive recognition system estimates the amplitude of the information component at the 18% precision level (Fig. 2*d*).

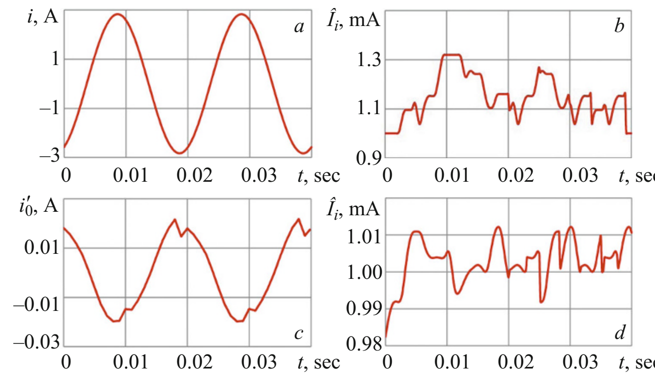

Fig. 4. Recognition of the information component of a signal according to expression (2) for $I_0 = 0.001$ A and $I_s = 2$ A (the signal-to-noise ratio is 5×10^{-4}): *a*, input signal; *b*, estimate of the actual value of the information component directly from readings of the signal $i(k)$; *c*, the signal $i_0(k)$ after active-adaptive suppression of the spurious signal (the signal-to-noise ratio is increased to 600×10^{-4}); *d*, estimate of actual value of the information component in the signal $i_0(k)$.

CONCLUSIONS

1. The method of active-adaptive signal recognition makes it possible to extract the information component, which is not available to direct measurement. Unlike the classical approach based on application of analog band-rejection filters with high Q factor, this method possesses stability of the characteristics of conversion and maintains high precision when the frequency of the information component varies.

2. Tests of a prototype of the device for generator protection from SEF with an active-adaptive ADC path confirmed the technical excellence of the proposed method. The active-adaptive method of signal recognition opens the possibility of developing high-sensitivity generator protection from SEF within a broad working range of frequencies.

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