A new Method and Device for High-Speed, Accurate and Reliable Phase Difference Measurement

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Abstract
Measuring of the phase differences of electrical signals is very important for metrology. Many of the most accurate sensors of non-electrical values are based of devices that convert these values into frequency. Laser measurement methods are based on the same principle. In these methods the measured values are converted into increments of frequencies or phases. The measurement of phase relationships is the highest level of accuracy, in comparison with frequency measurements. Traditional methods of phase measurements are already insufficiently accurate. Therefore it is extremely important to develop new methods based on other principles. The paper discusses in details a new method for fastest measuring of the phase differences with the highest accuracy and with the most effective noise suppression. This method is illustrated by examples of signals obtained by numerical modeling.

Keywords
Phase difference measurement, digital signal processing, phase meter, metrology, measurement noise

1. Introduction

In metrology, frequency measurements are extremely important [1-10]. Earlier, frequency measurements were carried out by counting of the number of pulses per time unit. These methods are not accurate enough, not fast enough, and are inoperable if the signal contains noises. Modern tasks of metrology require high speed and high accuracy of measurements with the most effective suppression of the influence of all types of noises. Such noises include additive and multiplicative noises, offset and its drift, deep amplitude modulation. The new method proposed in the paper is free from the disadvantages of the counting method. Its effectiveness is confirmed by modeling in the VisSim program. The paper gives the received calculated signals.

2. Analog-to-Digital Conversion of the Signal to Obtain a Difference Frequency

The method is based on the analog-to-digital conversion of a harmonic signal. If four samples for one period of the input frequency are obtained we propose to sort them into four independent sequences. Then after subtracting third sequence from the first one and fourth one from the second one, we will obtain two sequences of the difference frequency each shifted relatively other by a quarter of the period. These calculated samples are coherent and quadrature components, which together are known as analytical signal. It is easy to calculate the phase from the analytical signal. The proposed method for measuring phases is based on this principle. In addition, this method is supplemented with special relationships that allow locking of the counting to the same time, which significantly reduces the effect of noise and amplitude modulation on the result of phase measurement.

Figure 1 shows one of the input signals of the phase meter. The second signal is similar, but has a different phase, which should be measured. The proposed phase meter first measures the phase of each input signal relatively to the reference signal, and then it calculates the phase difference. Let the frequency of the input signal be f_1. We set the reference frequency f_0 is close to it but different, for example, it differ by 1%. If we perform an analog-to-digital conversion on this reference frequency, then we obtain the samples of the difference frequency $\Delta f = f_1 - f_0$. In the proposed method, the conversion is proposed to be performed at a frequency four times greater than the reference frequency $f_2 = 4f_0$.

The resulting samples are divided into four sequences, which are then used to calculate the current phase difference.

So, if samples $u_1, u_2, u_3 \ldots$ are obtained, we use them as follows:

$$X_1 = (u_1 - u_3),\quad X_2 = (u_5 - u_7),\ \ldots \tag{1}$$

$$Y_1 = (u_2 - u_4),\ Y_2 = (u_6 - u_8),\ \ldots \tag{2}$$

The calculated values X_1 and Y_1 are further interpreted as counts of the coherent and quadrature components. A pair of these signals is called an analytical signal, to calculate its phase there is a simple relation:

$$\varphi_{i0} = \begin{cases} arctg\,|Y/X|, & if\ \ |Y| \leq |X| \\ arcctg\,|X/Y|, & if\ \ |Y| > |X| \end{cases} \tag{3}$$

By the sign of the components X_1 and Y_1, it is easy to define a quadrant, and from this information correct value of the desired angle can be determines. In the first quadrant $\varphi_i = \varphi_{i0}$, in the second quadrant $\varphi_i = \pi - \varphi_{i0}$, in the third one $\varphi_i = \pi + \varphi_{i0}$ and in the fourth one $\varphi_i = 2\pi - \varphi_{i0}$. The hardware of the phase meter can contain only two analog-to-digital converters and a microcontroller that performs the simplest calculations.

3. Results of Modeling of the Phase Meter

In the simulation by the VisSim, this program used a signal containing a constant bias, high-frequency noise, additive low-frequency and high-frequency components. The form of this signal is shown in Figure 1.

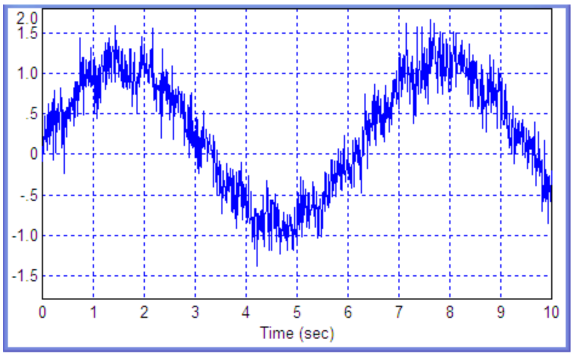

Fig. 1. Noisy input signal

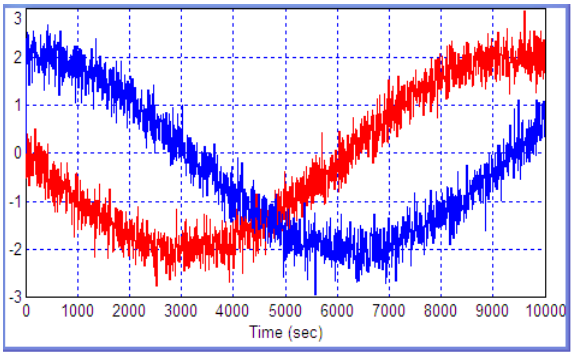

Fig. 2. The result of calculating of the difference frequency with the relations (1), (2) from the signal shown in Figure 1

4. Modification of the Phase Meter and Its Simulation

We propose modified ratios to calculate the analytical signal:

$$X_1 = [3(u_1 - u_3) + 5(u_5 - u_7)]/4,\quad X_2 = [3(u_5 - u_7) + 5(u_9 - u_{11})]/4,\ \ldots \tag{4}$$

$$Y_1 = [5(u_2 - u_4) + 3(u_6 - u_8)]/4,\quad Y_2 = [5(u_6 - u_8) + 3(u_{10} - u_{12})]/4,\ \ldots \tag{5}$$

These relationships are justified by the need to bring the samples to a single time scale. The effectiveness of the application of these relationships is evident from the comparison of Figure 3, which shows the phase portrait from the signals of Figure 2, calculated using relations (1) and (2), with the phase portrait in Figure 4, obtained from the same input signals using relations (4) and (5). The shown phase portraits display the displacement graph of the end of the vector, whose origin is located at the zero point. This vector is given by its projections (1) and (2) for the case of Figure 3 or projections (4) and (5) for the case of Figure 4.

The angle of rotation of the vector is the result of calculating the phase difference for the signal of the difference frequency $\Delta f = f_1 - f_0$. Since the difference frequency is not zero, the vector on the average rotates counterclockwise, as can be seen from the hodograph.

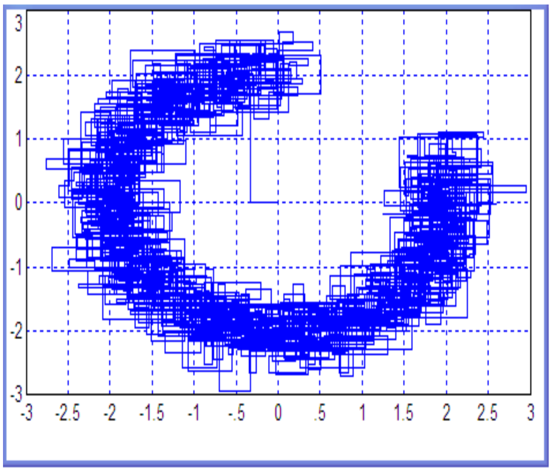

Fig. 3. The phase portrait from the signals shown in Fig. 2

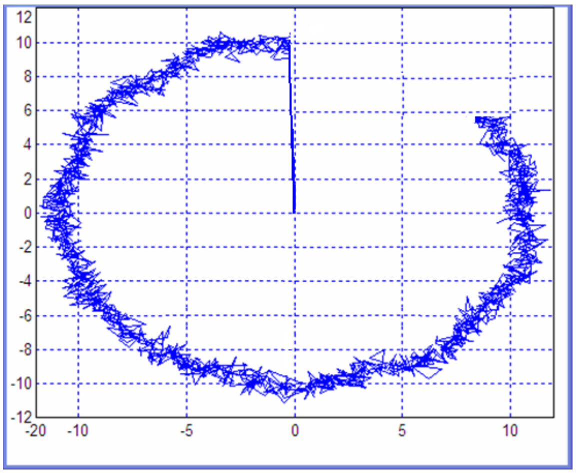

Fig. 4. The phase portrait from the signals calculated from (4), (5)

5. Hardware Phase Meter

The phase meter contains two channels of signal processing. Each of the channels computes and generates the first pair X_1 and Y_1 by the ratios (4) and (5) from the first eight samples of the input signal, and then calculates and generates each subsequent pair X_i and Y_i for each new four samples of the input signal.

The simplest hardware of the phase meter contains only two ADCs and a microcontroller. Further processing can be done programmatically, but we can also offer hardware, which is more useful for a clear explanation of the principle of operation, rather than for actual implementation. This device also can be made fully in hardware structure (like a finite automat), or as firmware.

Figure 5 shows a possible scheme for implementing of the phase meter on individual functional elements. Only one channel is shown, since the second channel is similar (but the microcontroller is the only and common for the both channels).

To obtain the first reading of the analytical signal, eight samples of the input signal are required. For their simultaneous processing, the first seven samples must be stored, that is, seven shift registers are necessary, since the last sample can be taken directly from the output of the ADC, that is, from the input of the first register.

The structure of each of the processing channels corresponds to the calculation algorithms described above and contains for this purpose seven shift registers and two algebraic adders with coefficients. The shown device realizes calculations by the relations (4) and (5); with each new clock cycle the samples are shifted upwards. After every four clock cycles, the information from the registers is transferred to the adder to calculate the analytical signal. The division by 4 in (4) and (5) is not necessary, since in calculating of the phase, the same change in the scale of the vector along the both axes does not change the angle result.

Conclusion

The paper has proposed an effective method for calculating of the phase difference of high-frequency electrical signals. Simulation has shown that such processing for the phase calculation successfully eliminates the effect of constant bias and low-frequency interference, also effectively attenuates the influence of high-frequency noise. The influence of high-frequency Gaussian noise does not lead to disruption of processing, since the resulting trajectory is far enough from the zero point (which is the origin of the vector), that is, the determination of the angle of rotation of the vector from the origin to any point of this graph can be carried out reliably and with a small error.

The initial signal is fundamentally unsuitable for measuring the phases in a countable method.

The proposed signal processing method for phase measurements is very important for applications such as the detection of earthquake precursors by continuous monitoring of lunar-solar tidal rock fluctuations, and also for monitoring of dams, bridges and other large engineering structures in order to prevent man-made disasters [4-8].

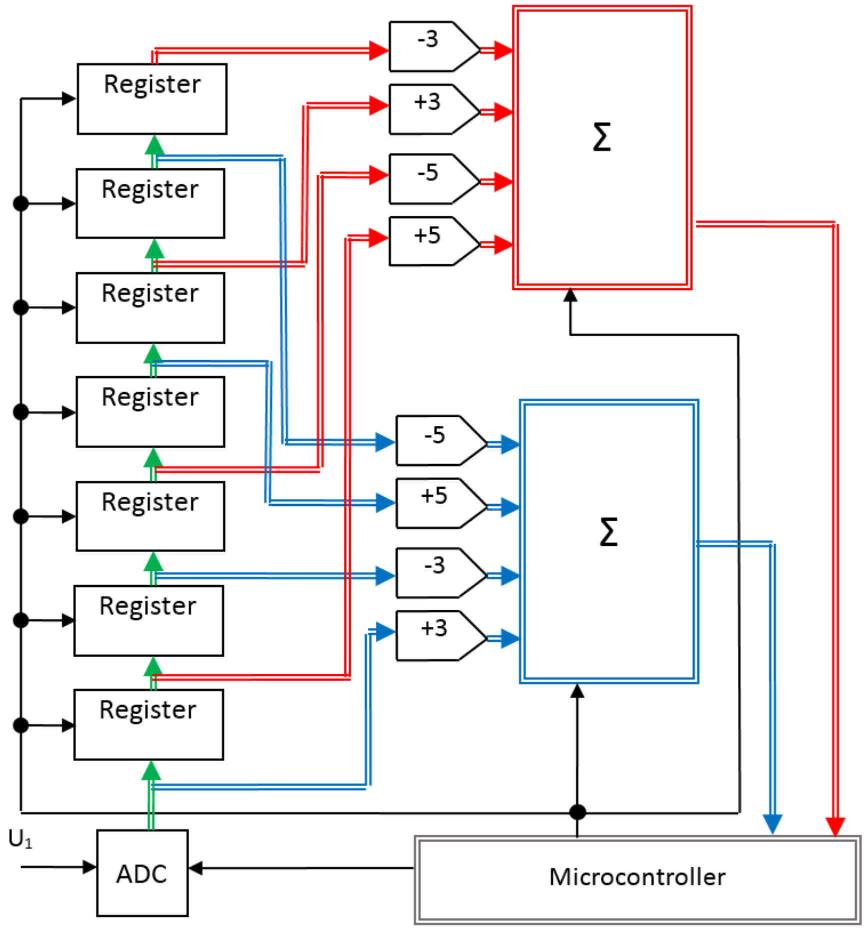

Fig. 5. Possible scheme for realization of the phase meter on separate discrete elements

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