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Phase measurement methods based on timer modules

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***Abstract* – In this article, the methods of measuring the relative phase difference between two simple periodic signals, based on timer modules, are considered, with an analysis of a measurement system, its following problems, and proposed solutions. The basic motivation for this research is the necessity for a very precise and accurate measurement of the relative phase difference between the voltage signal and current signal of a two-channel source, when there is a degradation of the phase in the output stage of a two-channel source. To compensate for the deviation of the measured and real phase angle of voltage and current at the output of a two-channel source, phase measurement can be realized with timer modules. This approach requires the conversion of relatively high voltage and current into periodic pulse (rectangular) waves compatible with working with timer modules, and this conversion is achieved by utilizing comparators. Although the timer approach gives excellent results in measuring time intervals, they are rarely applied in phase measurement due to several important problems that appear during the conversion of analog signals into digital signals - the impact of analog noise, an offset of the comparators, as well as asymmetric low-pass filters intended for noise reduction.**

I. INTRODUCTION

In practical applications, there is a frequent need for the measurement of the phase difference between two signals of the same frequency [1-3]. Moreover, it is often necessary to measure the relative phase between two signals rather than the absolute phase of either individual signal [1-3].

According to [2], the methods for relative phase measurement can be divided into three distinct groups: event-counting methods, modulation-based methods, and sampling-based methods. Table 1 provides an overview of these methods along with the corresponding instrumentation employed.

A typical two-channel source of voltage and current commonly comprises several components, including a two-channel function generator, a voltage amplifier, a transconductance amplifier, a voltage output stage and a current output stage. The primary function of the voltage amplifier is to amplify voltage signal (order of magnitude - V) to a higher voltage level (order of magnitude – 10 V or 100 V). The transconductance amplifier converts the voltage signal (order of magnitude - V) to the corresponding current signal (order of magnitude – A).

Table 1. Relative phase measurement methods overview.

Methods	Instrumentation
Event-counting methods	Universal counter
Modulation-based methods	Vector Signal Analysers (VNA) Phase-to-Voltage Converters (PVC) Interferometers
Sampling-based methods	Phasor measurement units (PMU)

Table 2. One solution for correcting the effect of degradation of the relative phase difference.

Step	Description
1	Defining an initial relative phase difference in the input stage of the two-channel source.
2	Measurement of the relative phase difference of the voltage and current at the output of the two-channel source.
3	Determining the deviation of the measured relative phase difference from the initially defined relative phase difference.
4	Correction of relative phase difference deviation.

In the low-voltage stage, the relative phase difference can be achieved with high metrological performances, however, degradation of the relative phase difference occurs in the amplifying stage.

The degradation of the relative phase difference requires the implementation of correction and one correction-oriented solution consists of the steps elucidated in Table 2.

Converting a simple periodic signal into a pulse (rectangular) wave can be achieved by using a comparator. In an optimal situation, the duty cycle of this pulse wave is 50 %. However, in the presented system, several problems arise.

Firstly, the presence of high-frequency noise, which is added to the comparator input simple periodic signal, causes multiple passings of the signal through zero, ie. reference value, which results in the appearance of multiple rising and falling edges in the output pulse wave - so-called "bouncing". The solution to the problem of the presence of noise in the current and voltage signal can be approached in two ways: by using a comparator with hysteresis or using a low-pass filter. The hysteresis of the comparator is achieved by the positive feedback of the operational amplifier, using two resistors. The implementation of the low-pass filter involves the use of a passive low-pass filter configuration, consisting of one resistor-capacitor pair. Additional problems arise if the hysteresis of the comparator is set in such a way that no pulse wave can be generated at the output of the comparator, or if the RC value of the low-pass filters differs between two channels which results in different phase shifts in each channel.

Additionally, the offset of the comparator leads to a deviation of output pulse wave duty cycle from 50 %. The voltage offset at the input of the comparator is one of the characteristics of real comparators which should be included in the modeling of the measurement system. The output signal will be changed from low voltage level to high voltage level when the amplitude of the input simple periodic signal reaches the value of comparator voltage offset. Consequently, the voltage offset induces variations of the output pulse wave duty cycle (that is, the time duration of high and low voltage levels during the output signal period).

II. MEASUREMENT SYSTEM

Two proposals for solving the problems that arise when measuring the phase of timer methods, therefore, imply the use of:

a) Comparator with hysteresis
b) Low-pass filter and comparator without hysteresis

Therefore, two systems were considered in the paper. Both proposed measurement systems consist of two measurement channels. Each channel has a simple periodic analog signal at the input and a pulse (rectangular) wave at the output (Table 3).

The comparator is the fundamental element in each channel. The analysis of the impact of the comparator offset voltage, as well as the investigation into the influence of comparator hysteresis (modeled using resistors in a positive feedback loop), were key focal points in the analysis of the first proposed measurement system. On the other hand, the assessment of the influence of the comparator offset voltage and a low-pass filter's influence were the primary areas of interest in the analysis of the second proposed measurement system.

Table 3. Phase measurement method based on timer module: measurement channel structure.

Measurement channel input	*Simple periodic analog signal*
Measurement channel output	*Pulse (rectangular) wave*
Measurement channel elements	*Comparator*
	Comparator offset voltage
	a) Comparator hysteresis resistors *b) Comparator input low-pass filter*
	Comparator input switching element
	Comparator output inverter

From the standpoint of measurement error reduction, the key elements of each channel are comparator input switching elements (which have the role of switching the inputs connected to the comparator in appropriate time intervals) and comparator output inverters (which have the role of inverting comparator output in appropriate time intervals).

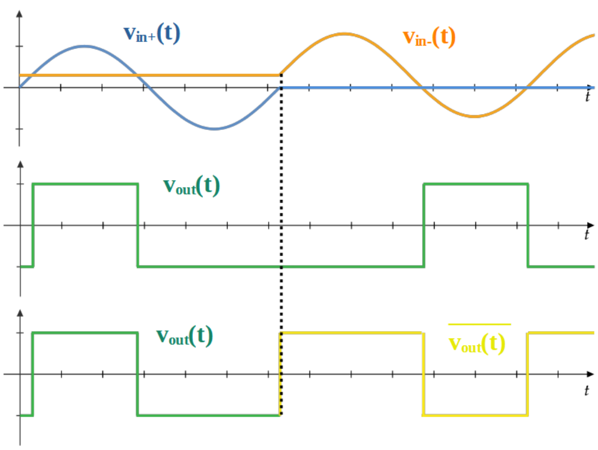

Fig. 1. Proposed solution to the problem due to the comparator offset: changing the comparator input and inverting the comparator output.

In order to solve the problem of the comparator offset voltage that causes deviation of the duty cycle of the pulse wave (from 50 %), a method is proposed that consists of successively changing the comparator input and inverting the comparator output (Figure 1). Namely, during a time interval lasting one period of the input simple periodic signal, the input simple periodic signal is applied to the non-inverting input of the comparator, while the ground is connected to the inverting, offset input. In the upper graph from Figure 1, the voltages at the comparator inputs are shown in two consecutive periods, where the value of the offset voltage is positive. The logic level of the output signal, due to the presence of an offset on the inverting input, does not change when the value of the input signal is zero, but when the amplitude of the simple periodic input signal reaches a certain value greater than zero (offset voltage), the duration of the high voltage level at the output is shorter compared to the duration of the low voltage level.

During the subsequent time interval of one period of the input signal, the signals at the comparator inputs alternate, i.e., the ground is connected to the non-inverting input of the comparator, while the inverting input supplies a periodic signal, the amplitude of which is affected by the offset of the comparator. In this case, due to the amplitude of the simple periodic signal increased by the offset voltage at the inverting input, in most of the period the voltage at the non-inverting input of the comparator is lower than the voltage at the inverting input of the comparator, and during the second period, the duration of the low voltage level in the output signal is longer than the duration of the high voltage level. In order to achieve a total duty cycle of 50 % in the entire output signal for the given two periods, during the second period the output pulse wave is inverted. The output signal is shown in the lower graph in Figure 1.

III. RESULTS

Extensive simulations and experiments based on the described measurement systems were performed. The simulation analysis involved consideration of the influence of individual problems on the phase error, as well as the influence of a combination of problems.

The phase measurement error as a result of the comparator voltage offset and comparator hysteresis, according to the simulation setup of the first measurement system, before and after applying the method of changing the comparator input and inverting the comparator output is presented in Figure 2. In Figure 2. R2 is the value of the comparator hysteresis resistor. The phase measurement error as a result of the comparator voltage offset and difference of low-pass filters, according to the simulation setup of the second measurement system, before and after applying the method of changing the comparator input and inverting the comparator output is presented in Figure 3. Rx in Figure 3. presents the resistance value in the low-pass filter.

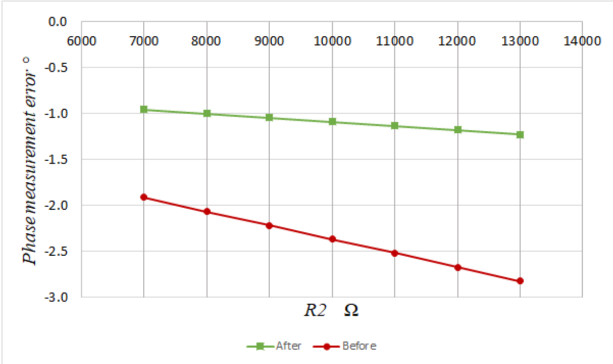

Fig. 2. Simulation results: phase measurement error related to the comparator offset and comparator hysteresis before and after applying the method of changing the comparator input and inverting the comparator output.

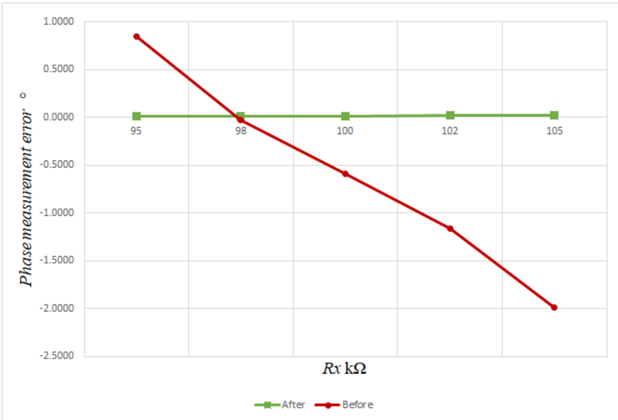

Fig. 3. Simulation results: phase measurement error related to the comparator offset and low-pass filter difference before and after applying the method of changing the comparator input and inverting the comparator output.

As the second proposed measurement system, which involves the use of comparators without hysteresis and low-pass filters, showed better performance through simulations, the hardware implementation of this system was carried out, and a series of experiments were performed.

Table 4. Phase measurement system configuration.

Case	Channel 1 comparator			Channel 2 comparator		
	IN-	IN+	OUT	IN-	IN+	OUT
1	V_{in1}	GND	V_{out1}	V_{in2}	GND	V_{out2}
2	GND	V_{in1}	$\overline{V_{out1}}$	GND	V_{in2}	$\overline{V_{out2}}$
3	V_{in2}	GND	V_{out2}	V_{in1}	GND	V_{out1}
4	GND	V_{in2}	$\overline{V_{out2}}$	GND	V_{in1}	$\overline{V_{out1}}$

Measured time intervals between the falling edges of the output pulse wave related to the input simple periodic signal phase, according to the experimental setup of the measurement system, are presented in Figure 4. The experimental setup includes four system configuration cases, described in Table 4.

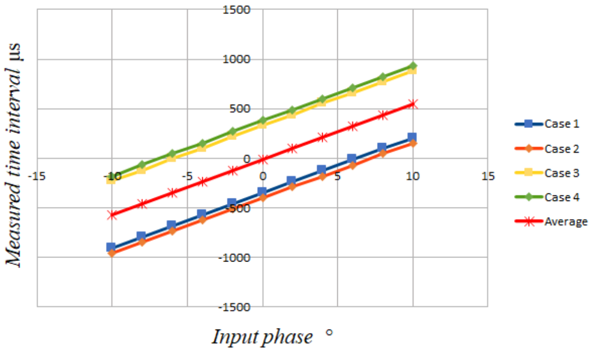

Fig. 4. Experimental results: measured time intervals between the falling edges of the output pulse wave related to the input simple periodic signal phase.

IV. DISCUSSION AND CONCLUSION

At first, simulation results indicated that phase measurement error related to the comparator offset and difference between the low-pass filters decreased, after applying the method of changing the comparator input and inverting the comparator output.

Under the influence of the systematic error due to the difference between the low-pass filters and the comparator offset, in cases 1, 2, 3, and 4, an offset of the time shift phase-related dependence is observed. If cases 1 and 3 are observed, the same configurations of the + and - inputs of the comparators are noticed. However, the simple periodic signals fed to the comparators are changed, which also applies to cases 2 and 4. It is observed that the value of the systematic error is approximately the same for cases 1 and 3, while the sign of the systematic error is the opposite. Also, the value of the systematic error is approximately equal, but of the opposite sign, for cases 2 and 4. It is possible to conclude that due to the application of the input signal-changing method, the systematic error changes its sign, and by averaging the value of the measured time interval, we eliminate the influence of the systematic error.

Therefore, the system in practical implementation shows the performance predicted by the simulation analysis and gives desirable results, that is, the proposed solution successfully eliminates errors caused by the comparator offset and the difference of the low-pass filters on two channels.

Further development of the experimental measurement system is planned, and it involves integrating the implemented system with a microcontroller system, and the use of timer/counter modules of the microcontroller to measure the time shift of the signal.

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