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Design, stability analysis and uncertainty contribution of a voltage divider designed for a phase meter

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***Abstract* – Today uncertainties of a phase difference of two sinusoidal signals is commonly about 10 µrad for non coherent measurements and signal amplitudes up to several volts. Increasing voltage range of a phase meter requires special considerations. The construction of a special voltage divider intended for precise phase difference measurement is presented in this paper. The uncertainty contribution of the voltage divider was determined by repeated measurement and an Allan variance calculation. The result showed out the voltage range of the phase meter increased substantially with very small addition to the total uncertainty of the phase difference.**

I. INTRODUCTION

Formerly phase difference of two harmonic signals was measured by means as power measurements [1] or delay lines. These methods were useful for measurements of whole-number multiples and ratios of π and very unsuitable for measurements of arbitrary phase differences. Situation was changed by rapid development of analog to digital converters and sampling methods.

First modern sampling digital phase meters utilized fast Fourier transform for signal analysis [2, 3] with uncertainties about 70 µrad. Today it is possible to achieve uncertainties about 10 µrad [4]. Direct comparison of several methods of phase difference calculations is provided in [5]

Fast Fourier transform has some drawbacks, such as requirement of coherent sampling. This can be eliminated by fitting of the sampled waveform by various analytical functions [6, 7]. Unfortunately uncertainty analysis is much more complicated for the case of non-linear fitting. Standard GUM [8] approach is inapplicable. With computational power of modern computers this problem can be easily solved by means of the Monte Carlo method [9, 10]. For every point measured by analog to digital converter a two dimensional uncertainty can be assigned. For every uncertainty a random number is generated and the phase difference is calculated. If repeated a total uncertainty of the phase difference can be calculated.

Recently a newly developed non-coherent sampling phase meter together with full uncertainty analysis was presented in [11]. The input range of the phase meter was limited to an amplitude of 5 V. In this paper a newly developed voltage divider suitable for phase difference measurement is presented. Its effect on the total uncertainty of the measurement was determined by means of Allan variance calculation.

II. PHASE METER AND PHASE DIFFERENCE MEASUREMENT METHOD

A. *Phase meter*

The phase meter used for all measurements was based on National Instruments 5922 digitizer. It has two input channels each with 24 bit analog to digital converter at sampling frequency up to 500 kS/S. The digitizer was always synchronized to external frequency standard. The maximal signal amplitude without the divider is 5 V.

B. *Measurement method*

The measurement procedure composed of several steps. Initially first output of the generator of phase difference $\Delta\varphi$ was connected to the first channel of phase meter and the second output of the generator was connected to the second channel of the phase meter. Two coaxial cables of similar lengths were used. The signal was sampled by the phase meter. This measurement was marked as AB. Next coaxial cables were swapped in such way first output of the generator was connected to the second channel of the phase meter and second output of the generator was connected to the first channel of the phase meter. Signal was sampled again and measurement was marked as BA. For both AB and BA measurements phase meter measured the phase difference of the generator together with an unknown phase error ϵ caused by cables, digitizers, divider etc. Both measurements (i.e. four sampled waveforms) were processed by a newly developed calculation software. All sampled waveforms were fitted by sine wave with four parameters:

$$y = A \cdot \sin(2 \cdot \pi \cdot f + \varphi) + O, \quad (1)$$

where A is an amplitude of the source signal, f is a frequency, φ is a phase and O is an offset. Difference of phases calculated from waveforms of the first measurement was marked as $\Delta\varphi_{\mathrm{AB}}$, for the second measurement as $\Delta\varphi_{\mathrm{BA}}$. $\Delta\varphi'$ is the average phase difference of the gen-

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erator during the measurement time. The error caused by cables and the digitizer was supposed to be stable during both measurements, thus the calculated phase difference was obtained in following way:

$$\Delta\varphi_{\mathrm{AB}} = \Delta\varphi' + \epsilon,\ \Delta\varphi_{\mathrm{BA}} = -\Delta\varphi' + \epsilon, \qquad (2)$$

$$\Delta\varphi' = \frac{\Delta\varphi_{\mathrm{AB}} - \Delta\varphi_{\mathrm{BA}}}{2},\ \epsilon = \frac{\Delta\varphi_{\mathrm{AB}} + \Delta\varphi_{\mathrm{BA}}}{2}. \quad (3)$$

If the generator of the phase difference is sufficiently stable in time, it can be supposed that $\Delta\varphi' = \Delta\varphi$. In the opposite case the measurement and uncertainty estimation is faulty.

C. Measurement requirements

The measurement is valid only if ϵ and signal generator are sufficiently stable in time. Stability of the ϵ can be verified by repeated measurement of the same signal fetched to both channels of the phase meter. Drifts and noise can be estimated by means of Allan variance. If stability is better than time required for one measurement, the requirement for correct phase difference is fulfilled.

The stability of the phase generator has to be checked by another measurement. The phase meter is set to measure repeatedly the constant phase difference of the phase generator. If cables are swapped, stability of the phase meter is no concern for this measurement. The stability of the phase generator can be estimated by means of Allan variance.

III. VOLTAGE DIVIDER

A. Requirements

The voltage divider consists of two independent dividers with identical schematic and components, one for each channel of the digitizer. The design was based on following requirements:

- frequency range up to 100 kHz,
- sufficient time and temperature stability,
- very small phase shift,
- drift of phase error sufficiently small in the time range of one measurement of phase difference.

The requirement of very small phase shift is not crucial as measurement consists of swapping cables connected to the phase meter. The most important is the time stability of the phase shift of both divider channels. The drift during the time of one measurement with swapping input cables should be much smaller than uncertainty of the whole measurement.

B. Design

The design of the divider is based on a resistance divider compensated by capacitors, see Fig. 1. The input impedance of the digitizing cards National Instruments 5922 is 1 MΩ, 60 pF and the input offset current is quite high. Therefore the output impedance of the divider was selected low to prevent build-up of dc voltage which would limit a dynamic range of the measurement system. The resistance divider is composed of two resistors of values $R_1 = 2$ MΩ, $R_2 = 50$ kΩ. Resistors with low temperature coefficients were selected. Dividing ratio was approximately 1 to 42. The power loss on R_1 was about 5 mW for input signal with amplitude 140 V. The effect of power heating was small since the heating coefficient of R_1 was 6.7 mW·°C^{-1} and temperature coefficient $15 \cdot 10^{-6}$ °C^{-1} according to the resistor manufacturer.

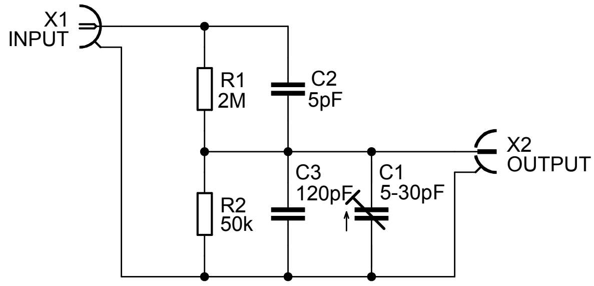

Fig. 1. Schematic of the voltage divider for one channel of the digitizer. The divider is composed of two resistors R_1 and R_2, capacitors C_1, C_2 and C_3 are used for frequency compensation.

The frequency compensation is achieved by two ceramic capacitors of fixed values $C_2 = 5$ pF, $C_3 = 120$ pF and one variable capacitor C_1 with range of values 2–30 pF. Capacitors with low temperature coefficients were selected. The variable capacitors of both dividers enable the compensation of the phase shift to value lower than ± 1 mrad. This value is part of ϵ and is compensated by measurement method. The adjustment of variable capacitors has to be done for every single digitizer as the input capacitance varies.

The input capacitance of the digitizer is part of the frequency compensation of the divider. Therefore the divider is connected directly to the digitizer without any cables. Bending of connection cables would cause changes of capacitance and phase instability. Dividers for both channels are placed in one case and variations of temperature affect both dividers equally. Dividers are separated by a electromagnetic shield placed in between, see Fig. 2. The voltage divider mounted on the digitizer is on the Fig. 3.

IV. DIVIDER STABILITY AND UNCERTAINTY

The measurement of the phase difference together with cable swapping takes about 30 seconds. For this time the stability of the divider should be better than the total uncertainty to fulfill assumptions stated in section IIB. The stability can be measured and calculated by means of Allan variance.

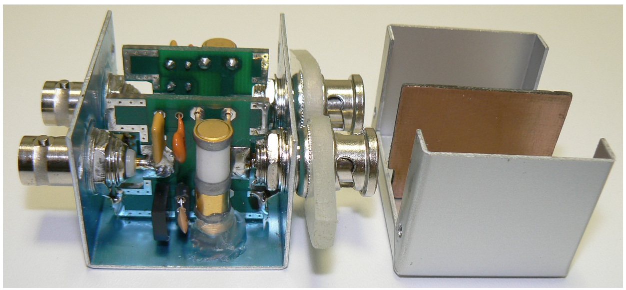

Fig. 2. The construction of the voltage divider on the left and the cover with electromagnetic shielding on the right.

Fig. 3. The voltage divider mounted on the National Instruments 5922 digitizer.

A. *Stability of the digitizer*

First the stability of the digitizer was measured. A sine wave generator was set to output signal of frequency 1 kHz and amplitude 3.25 V. This signal was split and fetched into both channels of the phase meter via coaxial cables of the same length. Because of the split the instability of the generator did not influenced the measurement. The phase meter was set to repeated measurement, duration of one reading was 11 s. Histogram of all measured values is in Fig. 4. The mean of all measurements was not zero. It was caused by phase shifts in the digitizer or unequal length of coaxial cables. This error is eliminated by swapping cables, however for stability measurements swapping of cables was unnecessary. The standard deviation of all measurements was about 0.4 µrad. It was very small value compared to the uncertainty of one measurement 10 µrad (for the uncertainty calculation see [11]). The distribution of all measured values was near to normal. The dependence of Allan variance on the observation time is in Fig. 5. The Allan deviation showed out drifts of the phase meter were smaller than noise even for observation period of 11 hours. The drift during 11 hours was smaller than 10 nrad. Proper estimation would require much longer measurement. Very small drift was probably caused by synchronization of digitizer card to the external frequency standard. Value of two pair Allan deviation was 0.2 µrad.

B. *Stability of the Phase meter with the divider*

Similar measurement was accomplished with the voltage divider mounted on the digitizer. The amplitude of the sine wave signal was set to 140 V. The amplitude on the output of the divider was 3.5 V. In the case of whole measurement procedure with cable swapping, the divider did not contributed to the mean value of the measurement. However for stability measurement swapping of cables was unnecessary. Histogram of all measured values is in Fig. 6. One can see the histogram has several peaks and distribution is far from normal. The standard deviation of 5.4 µrad is caused by drifts and is one order of magnitude higher compared to previous measurement. The dependence of Allan variance on the observation time is in Fig. 7. Drift is comparable to the noise at the observation time of about 1 minute and Allan deviation at $\tau = 60$ s is 0.4 µrad. Two pair Allan deviation was 0.5 µrad. One proper measurement of phase difference with swapping of cables takes about 30 s therefore the drift of the voltage divider should be included into uncertainty calculation. The uncertainty contribution of the voltage divider was set to 0.6 µrad.

V. CONCLUSION

Construction of simple voltage divider suitable for phase meter was presented. The divider expands the voltage range of the phase meter for signals with amplitude up to 140 V. Stability of the phase meter and phase meter with divider was measured. The stability of the whole system decreased considerably and drifts are dominating for measurement times longer than one minute. Fortunately typical measurement time of the phase meter is about 30 s. A contribution to the total uncertainty of the phase difference was estimated to 0.6 µrad. Together with swapping input cables, the phase meter has total uncertainty about 11 µrad for the signal amplitudes up to 140 V and frequency 1 kHz.

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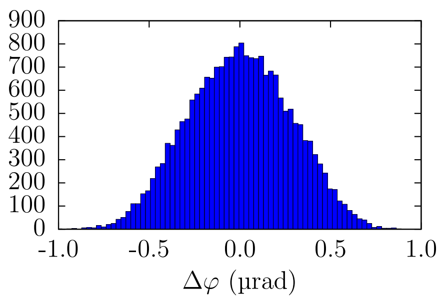

Fig. 4. Histogram of 20 500 consecutive readings of phase difference without voltage divider. The histogram is centered to the mean value of all readings $\overline{\Delta\varphi} = -1.7$ µrad.

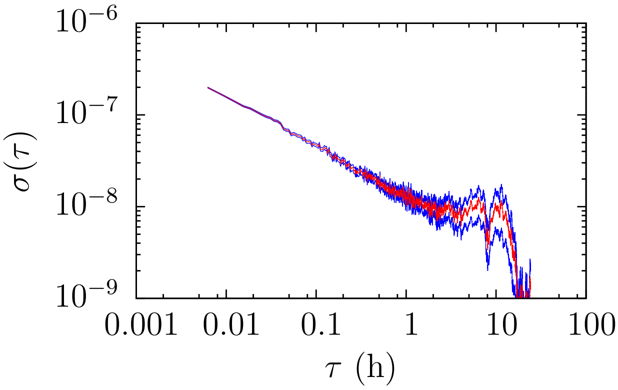

Fig. 5. Allan deviation $\sigma(\tau)$ of 20 500 readings of phase difference without voltage divider for different observation times τ. Red line is Allan deviation, blue lines are uncertainties.

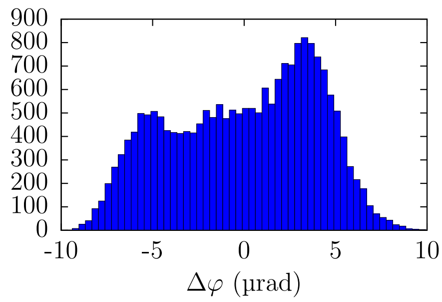

Fig. 6. Histogram of 21 000 consecutive readings of phase difference with voltage divider. The histogram is centered to the mean value of all readings $\overline{\Delta\varphi} = -16$ µrad.

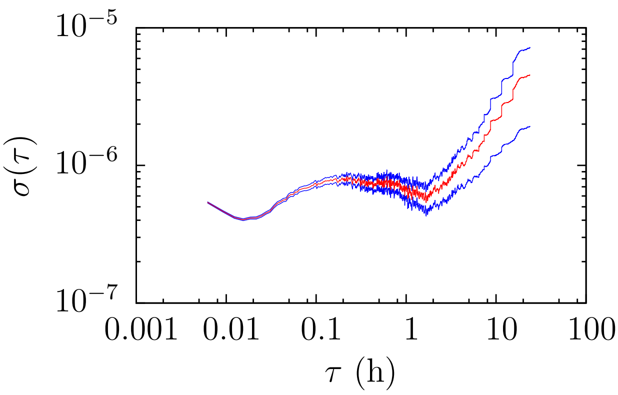

Fig. 7. Allan deviation $\sigma(\tau)$ of 21 000 readings of phase difference with voltage divider for different observation times τ. Red line is Allan deviation, blue lines are uncertainties.