Data Fusion in Phase Angle Measurement System

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Abstract-From many years in various science and technical areas there are introduced data fusion methods, lately also in metrological applications. Now there are conducted investigations connected with determining of importance of data fusion in classical metrology, complex measurement systems and also in measuring-control, diagnostic, classification systems, etc. The paper presents author's point of view on data fusion process. It pointed that using of data fusion methods in metrology is possible and purposeful. Data fusion process in the paper is presented on example of the phase angle measurement method with improved tolerance on harmonic distortions. The purpose of data fusion in this case is reduction of basic error of analysed method. It has been proposed introduction of an additional data processing line (as a source of new information in measurement process), and shows a method for combining information acquired from these two lines. The analysis presented in the paper indicates that using the method of information combining (data fusion) in measurement applications brings measurable effects (basic error of considered system lowered more than 200 times).

I. Introduction

The notion **data fusion** covers all formal methods enabling combination and processing knowledge on an examined object or phenomenon acquired from many different sources, in order to reduce the uncertainty of the final result, to increase classification effectiveness, to improve the quality of identification or diagnostics. Its purpose can also consist in taking advantage of *synergy* inherent in measurement data, so as to gain new or fuller information unattainable by other methods, nor accessible from each data source separately [1, 2]. Data fusion is thus a way of action by which great numbers of data (often very much differentiated), coming from various sources, can be combined into a coherent, accurate, and understandable whole.

Work connected with analyzing, applying, and implementing data fusion in metrology is being undertaken worldwide since several years. The aim is determining the role of data fusion both in primary metrology, as in the sphere of complex measurement systems. In the sphere of measurements two ranges can be indicated, in which data fusion can be applied successfully [3, 4].

The first area – is applying data fusion in metrological problems of classification, in which basing on measurements it is possible to determine essential features of objects or phenomena, and using them to assess the condition of the object, to determine its connection to a certain group, to find out its origin etc. The second area concerns the problem of minimizing the uncertainty of information gained from measurement data [4]. The problem of fusion can then be regarded in the aspect of such an analysis and processing data received in surplus, which shall assure the reduction of uncertainty of the final result. Such a situation occurs often in metrological problems, when measurement data come from instruments of different accuracy, having a different principle of operation, or are acquired at different times.

That scope includes also problems connected with the analysis and design of measurement systems in a way ensuring reduction of their error. The fusion process in that range can consist in analyzing the signals and parameters of the considered system, and seeking and determining their relations, which can lead to designing corrective methods to minimize the error of these systems.

In Author's opinion, data fusion includes not only the stage of processing measurement data (a particular algorithm, set of algorithms or methods serving to solve all possible problems). Data fusion is the whole process connected with the acquiring knowledge on the object or phenomenon (*a priori* knowledge, gained from measurement data, knowledge on similar phenomena or objects, experts' knowledge

etc.), with selecting and constructing a model of the object, and with selecting or elaborating adequately effective measurement methods or data processing algorithms.
A very important step is the analysis of properties, of the application range, determining the sphere of solution uniqueness of these algorithms, and finally designing the strategy of supervising data acquisition and processing. The supervision procedures should affect the selection of processing methods depending on the actual situation (number of data sources, number of data, their quality etc.), to make fusion a dynamic process, enabling obtainment of best effects from the point of view of the assumed aims.
This paper presents the fusion process in an example of a method for measuring the phase shift angle in presence of harmonic disturbances. The aim was minimizing the basic error of the analyzed angle measuring method.

II. Method of Phase Shift Angle Measurement

The phase angle, in the most general case of periodical phenomena, determines the time (expressed in angular measure and measured in relation to the starting time of signal observation) until a specific state of the observed phenomenon achieves a preset value. In most cases, that characteristic value is the zero value or the maximum of the examined periodic event [6]. The necessity to measure the phase shift angle occurs in many technological problems, as e.g. power and energy measurements, impedance parameter measurements, measuring four-terminal network parameters, identification of dynamic objects, testing dielectric materials, diagnosing power systems, distance measurements, etc. Obviously, that list does not limit all possible applications but it indicates the importance of the problem of measuring the phase angle shift, and by the same, the necessity to seek proper measurement methods and ensuring maximum accuracy of these methods. One of the possible ways to increase measurement accuracy is looking for additional information sources, applying alternative signal processing methods, and employing methods for combining all information gained.
The method of measuring the phase shift angle presented in this paper can be of great importance, especially in power applications, where the measuring signals can very likely include harmonic interference apart of random noise. The block diagram illustrating the method of measuring the phase shift angle in presence of harmonic interference is presented in Fig. 1 [5, 6].

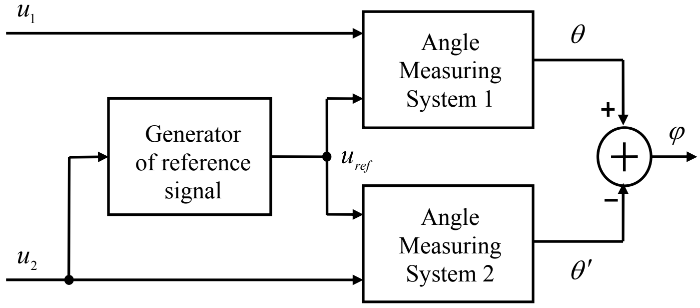

Fig. 1. Block diagram illustrating the method of measuring the phase shift angle using a reference signal

The phase shift angle between two disturbed input signals (harmonic noise) is being determined by simultaneous measurement of the phase angle of each fundamental in relation to a sinusoidal reference signal of the same frequency. Then, the difference of angles found in that way is to be established, resulting in the sought value of the phase shift angle. The assumption is that one of the input signals is so feebly disturbed that it crosses zero not more than twice in a cycle (such a postulation is also assumed often in other methods of measuring the phase shift angle, e.g. in [7, 8]). That sufficiently so feebly disturbed signal is transformed into a sinusoidal one, which is then taken as the reference signal.
Fig. 2 shows the basic configuration of a singular Angle Measuring System (AMS). In broader interpretation, that system can be considered as a phase angle detector, provided with the capacity to implement the *arccos* function, either by instrumental or computational way [6].
Assuming that $u_1(t)$ is the input signal including higher harmonics, and $u_{ref}(t)$ is the sinusoidal reference signal, the following formula describe the relationships:

$$u_1(t) = U_1 \sin(\omega t + \theta) + U_{12} \sin(2\omega t + \theta_2) + U_{13} \sin(3\omega t + \theta_3) + ... \quad (1)$$

$$u_{ref}(t) = U_{ref} \sin \omega t \tag{2}$$

where U_1 and U_{ref} are the amplitudes of base harmonics of these signals, ω is the base angular frequency, and θ the phase angle of the basic harmonic of the signal $u_1(t)$.

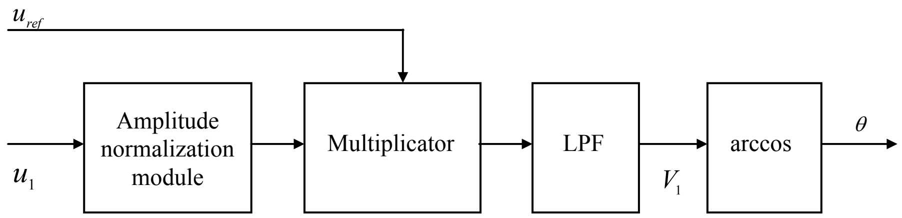

Fig. 2. The basic version of the AMS structure (LPF = low-pass filter)

The input signal u_1 and the reference signal are multiplied. The product of multiplication of the variables has the form of a component the frequency of which is the difference of the frequency of these signals and a component with a frequency, which is the sum of these frequencies.
Multiplying signals of the same frequency only can result in a zero frequency constituent, i.e. an offset voltage, which can be isolated from the output signal of the multiplier by a low-pass filter. The offset voltage so determined is a function of the phase shift angle between the reference signal and the basic harmonic of the input signal, following the formula:

$$V_1 = A \cos \theta \tag{3}$$

where: $A = \frac{1}{2} U_1 U_{ref}$, assuming unitary amplification of the filter. The V_1 does neither depend on harmonic disturbances, provided ideal low-pass filtration.
It was assumed here that the reference signal is generated with the amplitude two, and the input signal amplitude is normalized to the value of one. That choice of the reference signal amplitude and the normalization of input signals were done in order to ensure that the variable *A* in the above formula has a maximum of 1, and by the same, that the variable V_1 can also achieve a value of not more than 1. This is essential in view of implementing the function *arccos*.
The value of V_1 is positive when the angle θ lies in the range -90° to +90°; outside that range, it is negative. That signal is then processed in a system implementing the function *arccos* and in effect results in an output signal, which is proportional to the value of the phase angle θ (unique in the angle range 0° to 180°). Irrespective of the way of implementing the above method, there arise problems connected with the accuracy of determining the phase angle using the *arccos* function. That problem results from the fact that the low-pass filter connected to the multiplier output does not remove completely the variable component, in consequence of which an even small variability of the signal, which is the argument of that function, results in a variability depending on the actual value of the measured angle. In the case of numerical implementation, the inaccuracy in finding the angle θ was determined applying the *arccos* function of the Matlab program. The maximum absolute value of the difference between the set value of the angle and the computed value was taken as the inaccuracy measure. The results apply to the case, in which the reference signal frequency is equal to the frequency of input signals. The tested function arguments consisted of samples of the signal resulting from multiplying two sinusoidal signals, which then was filtered by a digital low-pass filter. A fourth order Butterworth filter was used, with a cut off frequency ten times lower than frequency of signals for which the phase angle had to be determined.
The attenuation of such a filter for a variable constituent with a frequency twice as high as the input signal frequency (summary constituent) is about 100 dB. It follows from Fig. 3 that the inaccuracy of angle determination achieves maximum values for angles close to 0°, where the characteristic curve of the signal V_1 in function of the angle is flat, and even a small change in the value of that signal causes a considerable change in the determined angle. In given conditions, the error achieves a maximum of 0.37°. A similar effect occurs at angles close to 180°.

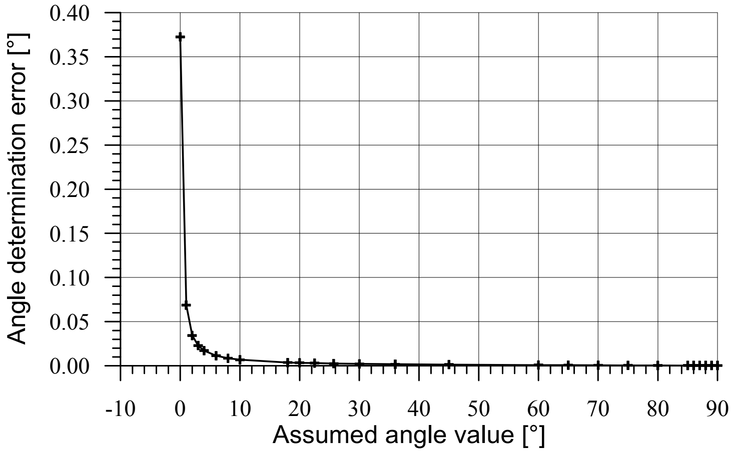

Fig. 3. Angle θ determination error when using the function arccos, depending on the assumed angle

It follows from the above that methods are necessary, to minimize the angle determination error in regions where the error value is particularly large. Introducing an additional processing line for input signal offers such a possibility, basing of the *arcsin* function, complementary to the one applied previously. Such a processing line must operate with a reference signal shifted by 90°. The signal delivered by the low-pass filter has then the following form:

$$V_2 = A \sin \theta \qquad (4)$$

It assumes positive values for angles in the range 0° to 180°. The value of constant A is the same as in formula (3). That signal is then modified into a signal proportional to the angle θ in a system implementing the function *arcsin*, which determines unique the angle value in the range -90° to +90°. The maximum errors occur on that processing line when the measured angles are close to 90° and -90° (Fig. 4).

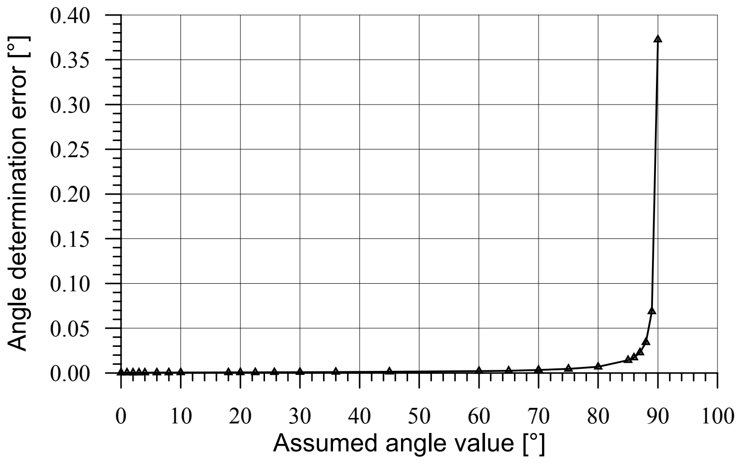

Fig. 4. Angle θ determination error when using the function arcsin, depending on the assumed angle

It follows thus, that we can combine data from both signal processing lines, watching the angle value achieved at the outputs. This, however, does not correct the functioning of the method in view of ambiguous angle determination in each line. That problem can be also solved by using information from the neighboring line. The signs of signals V_1 and V_2 supply that information. Thus, the Ambiguity Reduction Blocks (ARB) were introduced into each processing line, which by acquiring information on the value and signs of these signals makes it possible to determine the value and sign of θ in its full range of variability. The ARB, in order to provide functional correctness of the method, carries out the following logical functions:

For **arccos** branch:

$$\text{if} \quad V_2 \geq 0 \Rightarrow \theta = \theta_c \tag{5}$$

$$\text{if} \quad V_2 < 0 \Rightarrow \theta = -\theta_c \tag{6}$$

For **arcsin** branch:

$$\text{if} \quad V_1 \geq 0 \Rightarrow \theta = \theta_c \tag{7}$$

$$\text{if} \quad V_1 < 0 \quad i \quad V_2 \geq 0 \quad \Rightarrow \quad \theta = 180^\circ - \theta_c \tag{8}$$

$$\text{if} \quad V_1 < 0 \quad i \quad V_2 < 0 \quad \Rightarrow \quad \theta = -180^\circ - \theta_c \tag{9}$$

where θ denotes the angle value at ARB output, and θ_c the angle value computed by the functions *arccos* or *arcsin*.

All these operations result in two values of the angle and its sign. Therefore, the program shall assume as the final result that outlet angle value, which provides greater accuracy in the prevailing circumstances. This is the task of the Decision System. The decision is taken by comparing the modules of voltage values V_1 and V_2. When $|V_1| \leq |V_2|$, then the result of branch *arccos* is selected, whereas when $|V_1| > |V_2|$, then the branch *arcsin* result is selected. The condition $|V_1| \leq |V_2|$ denotes angles from the range 45° to 90°, where the function $\cos\theta$ is steeper; therefore the accuracy of angle determination in that range is higher in case of noise. A similar conclusion applies for the range 0° to 45°, in which the function $\sin\theta$ is steeper. The requirement of adequate steepness of the function follows from the circumstance that in case of noise in the signals $|V_1|$ and $|V_2|$ the range of angles corresponding to a signal change is then narrower, and by the same, the uncertainty of angle determination is smaller.

Fig. 5 shows the full structure of a singular Angle Measuring System, taking into account the foregoing considerations.

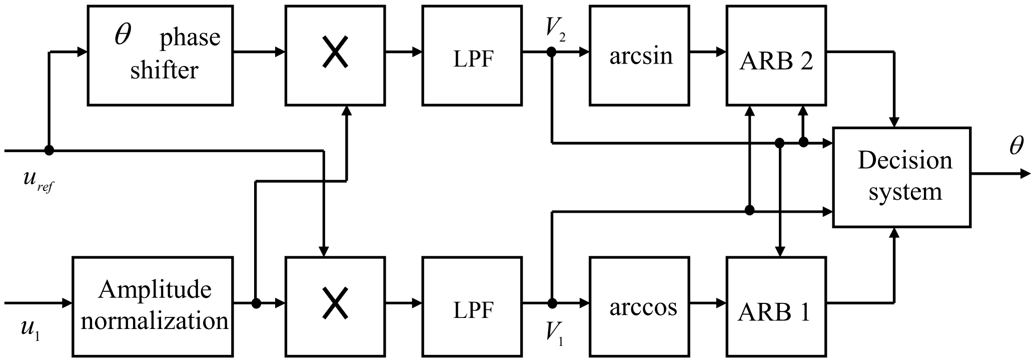

Fig. 5. Complete structure of a single Angle Measuring System using information exchange between the channels

The second input signal undergoes similar processing, determining the value of the angle θ' between the second input signal and the reference signal. The value of the phase shift angle between the basic constituents of input signals containing higher harmonics is finally calculated as the difference of θ and θ'. Fig. 6 shows the error characteristic curve of measuring the phase shift angle between undisturbed input signals, using the information fusion methodology.

The maximum error value occurs at odd multiples of 45° (at which the Decision System switches over between the functions *arcsin* and *arccos*) and amounts to approximately 0.0016°. That value, compared with the maximum error in case of processing in one line, shows an over 200 times reduction of the angle measurement uncertainty.

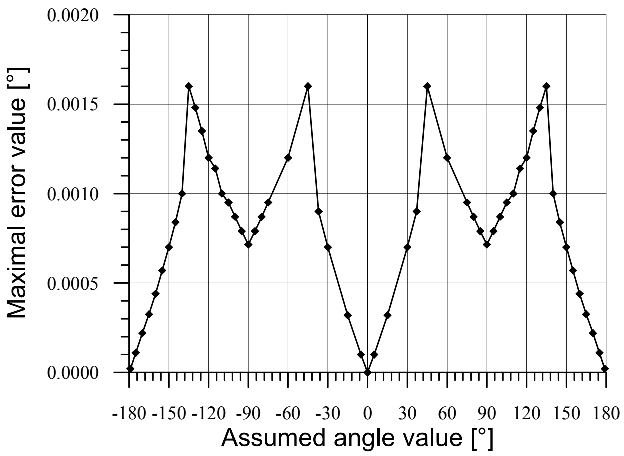

Fig. 6. Error in determining the phase shift angle versus set angle, in case of undisturbed input signals

III. Conclusions

The paper presents an analysis of the method for measuring the phase shift angle and its errors, suggests introduction of an additional data processing line (as a source of new information in measurement process), and shows a method for combining information acquired from these two lines. Adding a second processing line in the analyzed measuring method of the phase shift angle and combining information gained in both lines (signs and values of V_1 and V_2 voltage) complicates to some extent the structure of the method, but enables achieving unequivocal results in each line (full range of angle measurement) and using the Decision System, a radically reduces the error of the original method.

It should be stressed that data fusion is a complex process. It includes not only the stage of processing data according to an algorithm, which combines data in a particular way, but the total of actions connected also with acquiring and storing knowledge used later in the processing stage (both *a priori* knowledge, and also information and connections resulting from tests carried out on data gained from the object). The analysis presented in the paper indicates that using the method of information combining (data fusion) in measurement applications is possible and purposeful, and brings measurable effects (basic error lowered more than 200 times). The accuracy of the presented method depends naturally from other numerous factors, like angle constancy during measurement, equality of the input signal frequency and the reference signal frequency, amplitude fluctuations of input signal and sampling rate, number and amplitudes of higher spectrum components, and the quality of the applied low-pass filter. These problems are studied and presented closer in [6].

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The paper was realized as statute work.