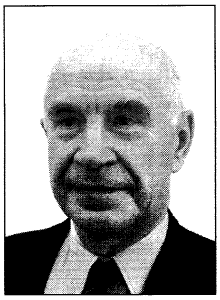
Andrzej J. GRONO, Jan P. WŁODARSKI
GDANSK UNIVERSITY OF TECHNOLOGY, FACULTY OF ELECTRICAL AND CONTROL ENGINEERING, DEPARTMENT OF CONTROL ENGINEERING

Computer synchronization of power generators

Prof. dr hab. inż. Andrzej J. GRONO

He was born in 1938 in Poland and received his BSEE, MSEE, PhD and DSc degrees from Gdansk University of Technology. His research area is control engineering in power and energy systems, particularly automatic synchronization of power generating units. He has more than 160 papers, patents, and conference presentations (at that number 4 books) and more than 190 reports. He worked as a site inspector in a hydro power station. He is a full professor in the faculty of Electrical and Control Engineering at Gdansk University of Technology. He is devoted to teaching, research, and project guidance. He is a member of IEEE and PES.

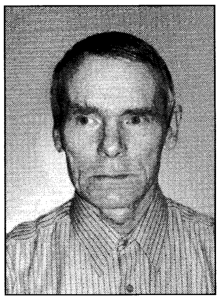
agrono@ely.pg.gda.pl



Mgr inż. Jan P. WŁODARSKI

He was born in 1939 in Poland and received his BSEE and MSEE from the Gdansk University of Technology, where he is currently working as an electronic and information specialist. He has more than 30 papers, conference presentations, patents, and completed many reports and projects in control engineering in power and energy systems.

wlod@ely.pg.gda.pl



Abstract

Automatic synchronizers, which are in use at present, have the construction of separate independent devices. Numerous producers manufacture them all over the world. Widespread use of computers for control and adjustment in power plants and stations makes it reasonable to use them also for the tasks, which have been done by the automatic synchronizers. It involves the development of new measuring and computing algorithms, which will allow the computer to execute directly the process of automatic synchronization. In this paper the method of computer synchronization is presented.

Streszczenie

Rosnący stopień automatyzacji w energetyce pociąga za sobą konieczność pełnej automatyzacji procesu synchronizacji prądnic. Obecnie automatyczne synchronizatory są produkowane przez liczne firmy na całym świecie. Powszechne wykorzystanie komputerów do kontroli i sterowania w elektrowniach oraz stacjach elektroenergetycznych skłania do powierzenia im również roli dotychczas sprawowanej przez automatyczne synchronizatory. Aktualną staje się zatem kwestia opracowania odpowiednich algorytmów pomiarów i obliczeń, według których będzie możliwe prowadzenie procesu automatycznej synchronizacji bezpośrednio z wykorzystaniem komputera. W artykule przedstawiono komputerową metodę realizacji warunku fazowego podczas synchronizacji oraz podano wyniki jej badań symulacyjnych oraz badań na obiektach rzeczywistych.

Keywords: Automatic synchronization, computer-based methods, simulations
Słowa kluczowe: Synchronizacja automatyczna, metody komputerowe, badania symulacyjne

1. Introduction

Automatic synchronization of power generating units still present great interest, despite rich literature in the subject and numerous patents [1, 2]. The works on direct application of computers to automatic synchronization were published relatively long ago [3-6], but limited operational speed and small memory capacity of those computers made it impossible to obtain satisfactory results. The goal of this paper is to present a new, convenient in computerized execution method and the results of its application.

2. Exposition of the proposed method

The adopted method is a modification of the one presented in [5]. The modification, which is the subject of a patent application [7], draws upon the state-of-the-art in computing technology and relies on a more effective algorithm of processing voltage waveforms at the terminals of the objects being synchronized.

The satisfaction of the phase condition in the automatic synchronizing involves predicting the time instant t_C (fig. 1), where two voltage waveforms, u_1 and u_2, produced by the sources under the synchronizing process, become phase coincident. The periods of these two voltages, T_1 and T_2, are different (although close to each other), which means that the phase difference between u_1 and u_2 is time varying. Assuming T_1 and T_2 to be constant over the synchronizing process, the phase difference can be considered as a linear function of time, whereby the time t_{Pi} that remains to the closest occurrence of phase coincidence can be predicted as

$$t_{Pi} = \frac{T_1}{|T_1 - T_2|} t_{Bi} \tag{1}$$

The evaluation of t_{Pi} proceeds as follows. After starting of the automatic synchronizing process (AS at time t_0 in fig. 1), each positive-going zero crossing of the lower-frequency voltage (here u_1) triggers the measurement of the time t_{Bi} that elapses to the closest positive-going zero crossing of the other voltage (here u_2); the same applies the respective pairs of negative-going zero crossings.

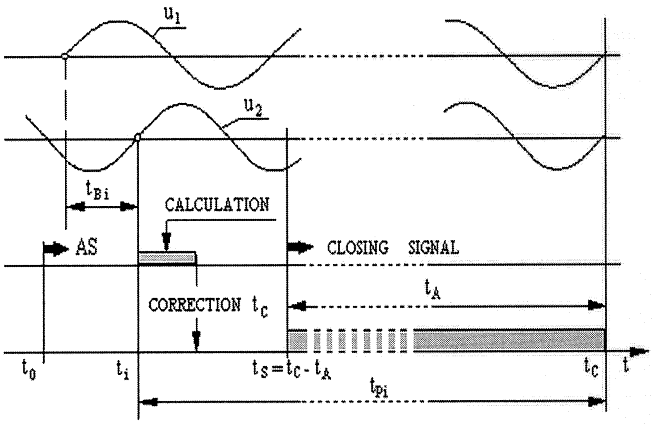


Fig. 1. Illustration of the timing relationships in the considered synchronizing procedure
Rys. 1. Przebiegi napięć synchronizowanych obiektów oraz mierzone, zadane i obliczane wartości czasu

Based on these measurements and the measured periods T_1 and T_2, the t_{Pi} intervals are computed from (1). Each t_{Pi} value represents the interval between t_i (the time instant at which the corresponding t_{Bi} interval terminates) and the expected occurrence of phase coincidence. The time origin for the measurement of t_i is the synchronizing start time t_0; stated differently, the sum of t_i and t_{Pi} is the *i*-th *predicted coincidence time* t_{Ci} as measured with respect to t_0

$$t_{Ci} = t_i + t_{Pi} \tag{2}$$

Note that while t_i and t_{Pi} will change from one prediction cycle to another, their sum should remain constant with a reasonable accuracy. Certain differences between consecutive values of t_{Ci} may occur due to measurement errors, as well as the variation in the periods of the both voltage waveforms. It is always the most recent prediction of t_{Ci} that is taken as applicable, providing it does not deviate by more than a predefined margin from the average value over the preceding cycles. The signal initiating the closing of the circuit breaker should be issued once the current time t has become equal to or greater than the predicted coincidence time t_C decreased by the closing time t_A of the circuit breaker (t_S in fig. 1); that is

$$t \geq t_C - t_A \tag{3}$$

where t_C is the most recent, applicable t_{Ci} value. The above discussed procedure is summarized in the form of a flow diagram in fig. 2.

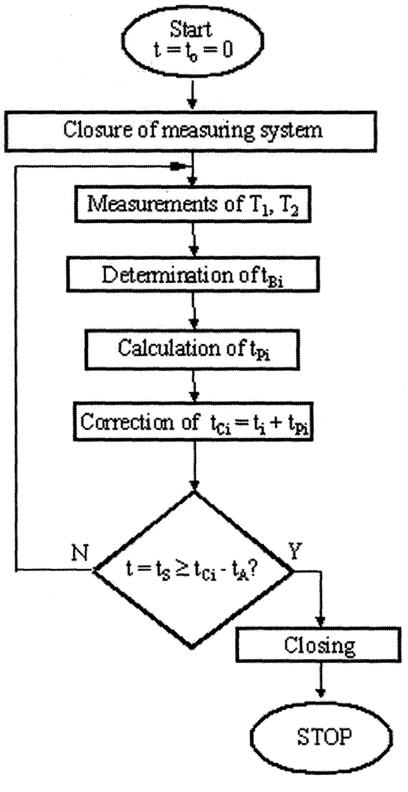


Fig. 2. The flow diagram of the considered algorithm

Rys. 2. Algorytm prowadzenia pomiarów i obliczeń według proponowanej metody

3. Investigations

3.1. Simulations

Extensive simulation analyses have been performed to assess the adequacy of the above introduced synchronizing method, and particularly to evaluate the phase-angle error δ_E with which the synchronized generator would be enter the power system. The effect of variation in the closing time of the circuit breaker was left out throughout the analyses [8].

The frequency of the voltage u_1 in the power system was fixed at f_1=50 Hz, while the frequency f_2 of the generator to be synchronized with the system was assumed to vary linearly with time at the rate of α Hz/s. It was also assumed that the frequency difference, f_1-f_2, reaches a predetermined value of $\Delta f_C = f_1 - f_{2C}$ at the occurrence of the phase coincidence (f_{2C} being the generator frequency at the instant of its connection with the system). The sequences of voltage samples were taken from the following envelopes

$$u_1 = \sin 2\pi f_1 t \tag{4}$$

$$u_2 = \sin\left[2\pi\left(f_1 + \Delta f_C + \frac{\alpha}{2}t\right)t\right] \tag{5}$$

with t ranging -0.5 s through +0.5 s in one millisecond steps. For the so defined voltage waveforms their phase coincidence occurs at time t=0, meaning that a perfect prediction is t_C=0. Stated differently, the error in determining t_C is the same as t_C itself, which greatly simplifies the computations.

The simulations were carried out for:

- advance time: $t_A \in \langle 0.02; 0.25 \rangle$ s,
- frequency difference at the instant of closing: $\Delta f_C \in \langle 0.25; 2.00 \rangle$ Hz,
- rate of change of generator frequency: $\alpha \in \langle 0; 0.5 \rangle$ Hz/s,
- sampling period Δt = 0.001 s,
- resolution of a A/D converter: 8, 10, 12, 14, 16 bits.

Table 1 provides the ranges of Df_C, a, and t_A to be expected in real applications; the ranges are specified separately for (L) low-power (P≤1 MW), (M) medium-power (P∈(1;10 MW)), and (H) high-power (P≥10 MW) generators.

Table 1. Typical ranges of selected synchronizing parameters for low-power (L), medium-power (M), and high-power (H) generators

Tabela 1. Wartości parametrów synchronizacji przyjęte do badań symulacyjnych dla prądnic małej (L), średniej (M) i dużej (H) mocy

Generator		L		M		H	
Parameter	Units	From	To	From	To	From	To
Δf_C	Hz	0.25	2.00	0.25	1.00	0.05	0.25
α	Hz/s	0.10	0.50	0.05	0.30	0.01	0.10
t_A	s	0.02	0.05	0.05	0.15	0.10	0.25

The computed values of the phase-angle error δ_E (in degrees), corresponding to the different sets of parameters: Δf_C, t_A, α and different resolution of a A/D converter are given in fig. 3. This error has essentially the following three components:

- an error due to variation in the generator frequency (f_2),
- a quantization error due to finite resolution of the A/D converter,
- an error caused by inaccuracies in the location of zero crossings from discrete-time voltage samples.

In order to evaluate the effect that the A/D converter resolution has on the phase-angle error, the voltage samples were quantized using the following expressions

$$u_1 = \frac{1}{N} E\left\{N \sin(2\pi f_1 t)\right\} \tag{6}$$

$$u_2 = \frac{1}{N} E\left\{N \sin\left[2\pi\left(f_1 + \Delta f_C + \frac{\alpha}{2}t\right)t\right]\right\} \tag{7}$$

where E{·} denotes the formation of the integral part of a number, while N represents the number of quantization levels available for encoding each polarity of the voltage waveforms.

The voltage samples, computed from equation (6) and equation (7), were stored in look-up tables; during simulations, they were fetched sequentially at the sampling instants, that is, every 0.001 s, between -0.5 s and +0.5 s. The zero crossing times of the two voltages involved were computed as mean square approximations, each based on 6 voltage samples: 3 directly preceding, and 3 directly following the polarity reversal. Using the so established zero crossing times, the t_{Bi} intervals and the periods of voltage waveforms were determined, thus permitting the predictions of the coincidence time from equation (1). The predictions were successively stored in an auxiliary table together with their acquisition times. Based on the above data, the phase-angle errors δ_E were finally evaluated from the following expression

$$\delta_E = 0{,}36\ \Delta f_C\ \Delta t_E \tag{8}$$

where δ_E is in degrees, the frequency difference Δf_C is in hertz, and Δt_E (i.e. the error in the prediction of t_C) is in milliseconds.

The simulation results indicate that the proposed synchronizing method ensures very small phase-angle errors in the case of low-power generators; this remains true even for the lowest-resolution A/D converter considered (8 bits). For this class of generators the largest error observed was -0.66°. As a practical matter, the synchronizing of low-power generators can safely be performed up to about 8° of the phase-angle displacement.

Concerning the medium-power generators, the errors tend to be larger (the worst cases observed were -1.34° when using an 8-bit A/D converter, and -0.99° for a 10-bit device), while still remaining well below the maximum permissible magnitude of 5°.

As for the highest-power generators, whose safe synchronizing requires that the phase-angle displacement should not exceed 2° in magnitude, the results are no longer satisfactory for an 8-bit A/D converter (+2.32° of the worst-case error observed), while again being fully acceptable for the bit size of 10 or higher (approximately -1.2°). The results given in fig. 3 also show that the effect of the resolution of the A/D converter becomes negligible above the bit size of 12. As a final observation, the examination of the simulation results obtained indicates that the synchronizing accuracy deteriorates significantly as the closing time increases; this is particularly true for larger values of α, that is, when the rate of change of the generator frequency is relatively high. Fig. 3 shows the effect of the bit size of the A/D converter on the error δ_E in determining the circuit breaker closing instant; the error values, expressed in degrees, correspond to the most unfavorable sets of synchronizing parameters.

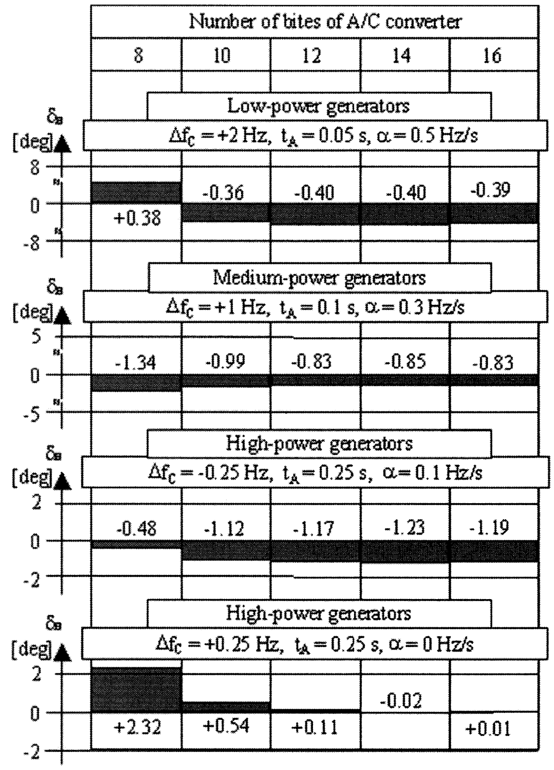


Fig. 3. The effect of the resolution of the A/D converter for some sets of other parameters

Rys. 3. Wpływ rozdzielczości przetwornika A/C na błąd kątowy załączania dla różnych zestawów parametrów synchronizacji

Based on the numbers collected in fig. 3, it can be inferred that δ_E has a tendency of assuming a particular sign, usually negative. This can be interpreted as a kind of bias that might be compensated for to enhance the ultimate accuracy. The above issue was discussed at the IASTED conference in Orlando [8], where the considered synchronizing method was presented. Certainly, further insight into this phenomenon is necessary before it can exploited in practice. The most straightforward solution, however, is to rely on A/D converters of 10-bit or higher resolution, in which case the timing accuracy of the closing instant is satisfactory without resorting to any added complexity.

As a supplementary observation, an examination of all simulation results obtained indicates that the synchronizing accuracy deteriorates significantly as the advance time increases; this is particularly manifest for larger values of α, that is, when the rate of change of the generator frequency is relatively high. This effect has clear physical grounds. As a practical matter, though, the rate of change of the generator frequency tends to be low, but not constant ($\alpha \neq$ const). The latter issue calls for further research, with the objective of finding an appropriate approximation. It is anticipated that an approximation based on a second-order polynomial should yield satisfactory results. The above problem is now under study.

3.2. Experimental research

3.2.1. Electronic measurement system

Experimental research have been performed in measurement system as shown in fig. 4. This system consists two PCs and electronic module. PC No 1 was used as the sine voltage waveform generators and the PC No 2 - as a control program for electronic module [9, 10, 11].

The frequency of the voltage u_1 of the electric power system was fixed at f_1=50 Hz, while the frequency f_2 of the generator to be synchronized with the power system was assumed to vary linearly with time at the rate of a factor α Hz/s. It was also assumed that the frequency difference (f_1-f_2) reaches a predetermined value of Δf_C=f_1-f_{2C} at the occurrence of the phase coincidence (f_{2C} is the generator frequency at the instant of its connection with the system). The voltage waveforms samples were taken from the equations (4) and (5), with t ranging -0.5 s through +0.5 s in 50 μs steps. After filtering the voltage waveforms were obtained and than were given to electronic module. For the so defined voltage waveforms their phase coincidence occurs at time t=0, meaning that a perfect prediction is t_C=0. Stated differently, the error in determining t_C is the same as t_C itself, which greatly simplifies the measurements. Than the effect of variation in the closing time of the circuit breaker was left out throughout the analyses.

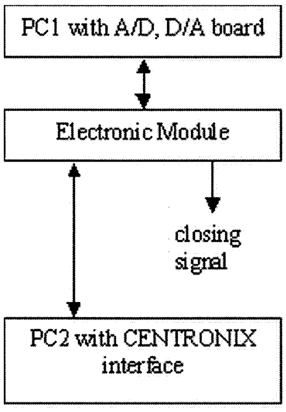


Fig. 4. A block diagram of the measurement system

Rys. 4. Schemat blokowy systemu pomiarowego

The measurements were carried out for both constant (α = 0) and time varying (α ≠ 0) frequency difference and numerous values of t_A and Δf_C. The measured values of the phase-angle error δ_E (in degrees), corresponding to the most different sets of parameters are listed in Table 2 [10].

Table 2. Worst-case phase-angle error δ_E (in degrees) for electronic measurement system, where $\delta_{E\,av}$ means average value of the phase-angle error
Tabela 2. Błąd kąta załączania (w stopniach) dla elektronicznego systemu pomiarowego, gdzie $\delta_{E\,av}$ oznacza średnią wartość kąta załączania

Gen.	Δf_C	t_A	α	δ_{Eav}
	Hz	s	Hz/s	deg
L	2.00	0.05	0.5	0.91
	-2.00	0.05	0.5	-0.26
	2.00	0.05	0	0.32
	-2.00	0.05	0	0.18
M	1.00	0.10	0.3	1.27
	-1.00	0.10	0.3	-0.76
	1.00	0.10	0	0.10
	-1.00	0.10	0	0.15
H	0.25	0.25	0.1	1.19
	-0.25	0.25	0.1	-1.50
	0.25	0.25	0	0.07
	-0.25	0.25	0	-0.14

3.2.2. Alternator of range power 1 VA

The measured values of the phase-angle error d_E, in the case of application of low-power alternator as a source of voltage, are listed in Table 3 [10]. Alternator was driven by DC motor with computer and quartz stabilization of frequency.

Table 3. Phase-angle error δ_E (in degrees) for alternator of range power 1 VA and α=0 Hz/s, where $\delta_{E\,av}$ means average value of the phase-angle error
Tabela 3. Błąd kąta załączania (w stopniach) dla generatora o mocy 1 VA i α=0 Hz/s, gdzie $\delta_{E\,av}$ oznacza średnią wartość kąta załączania

Δf_C	t_A	δ_{Eav}
[Hz]	[s]	[deg]
-2.00	0.05	-0.45
-1.00	0.10	1.42
-0.25	0.25	0.04
+2.00	0.05	-0.26
+1.00	0.10	0.30
+0.25	0.25	-0.25

3.2.3. Alternator of range power 27 kVA

The measured values of the phase-angle error δ_E, in the case of application of alternator of range power 27 kVA as a source of voltage, are listed in Table 4 [10].

Table 4. Phase-angle error δ_E (in degrees) for alternator of range power 27 kVA and $\alpha \approx 0$ Hz/s
Tabela 4. Błąd kąta załączania δ_E (w stopniach) dla generatora o mocy 27 kVA i $\alpha \approx 0$ Hz/s

Δf_C [Hz]	-1.55	-0.40	-0.29	0.20	1.40	1.76	1.90
t_A [s]	0.10	0.25	0.25	0.25	0.10	0.10	0.10
δ_E [deg]	0.58	-0.35	0.07	1.25	0.04	0.91	0.65

4. Conclusions

A novel method has been proposed for predicting the occurrence time of the phase coincidence between the voltages of AC sources to be synchronized with one another. The method is intended for software implementation on the computing resources already available in power plants, whereby the costly stand-alone synchronizers could be eliminated.

The results of the simulations performed to assess the method can be summarized as follows:

- the proposed method for predicting the occurrence time of phase coincidence is well suited for software implementation,
- for low- and medium-power generators, the maximum magnitudes of the phase-angle error occurring at the closing of the circuit breaker remain well within the acceptable limits independent of the resolution of the A/D converter used,
- in the case of high-power generators, a bit size of 10 (or higher) of the A/D converter is necessary to satisfy the phase-angle accuracy requirements,
- the use of A/D converters of bit size above 12 does not lead to meaningful improvement in the phase-angle accuracy,
- large values of the closing time tend to adversely affect the synchronizing accuracy, especially for high rates of change of the generator frequency.

The results of the experimental research performed to assess the method can be summarized as follows:

- in the worst-case the value of the phase-angle error is less than permissible value,
- large values of the closing time tend to adversely affect the synchronizing accuracy, especially for high rates of change of the generator frequency,
- the results obtained thus far are sufficiently optimistic to justify continuation of the presented work towards further experimental verification in real conditions and prototyping.

References

[1] W. M. Strang, C. J. Mozina, B. Beckwith, T. R. Beckwith, S. Chhak, E. C. Fennell, E. W. Kalkstein, K. C. Kozminski, A. C. Pierce, P. W. Powell, D. W. Smaha, J. T. Uchiyama, S. M. Usman, W. P. Waudby: Generator synchronizing industry survey results. IEEE Power System Relaying Committee Report. *IEEE Transactions on Power Delivery* 11 (1) (1996). p. 174-183.

[2] H. H. Hwang. A. Louie. Synchronization of second-generation wind turbine generator with power system. *International Journal of Power and Energy Systems* 16 (5) (1996). p. 158-162.

[3] J. J. Bobrov. Impulsnyj avtomatičeskij sinchronizator. *Električestvo* (3) (1967). p. 14-19 (in Russian only).

[4] R. L. Grimsdale. C. C. Wheeler. Alternator synchronization using an online computer. in: IEE (ed). *Proceedings of the IEE Conference on trends in on-line computer control systems* (Yorkshire. 18-20 April 1972). p. 15-24.

[5] A. Grono. A digital synchronization method for ship alternators. in: *Proceedings of 17. Zadarski Simpozij - Etan u Pomorstvu* (Zadar. 23-25 lipnja 1975). p. 211-216.

[6] A. Grono. New solution for automatic synchronizers of power generating units. *Gdansk Technical University Works* 471 (1991). p. 1-124, (D.Sc. dissertation - in Polish only).

[7] A. Grono. J. Włodarski. The computer method of synchronization of power generating units. *Polish patent* No 180430 of 17.09.1996 (in Polish only).

[8] A. J. Grono. J. P. Wlodarski. Computer-based method for synchronizing power generators. in: IASTED (ed). *Proceedings of the IASTED International Conference High Technology in the Power Industry.* (Orlando. 27-30 October 1997). p. 291-294.

[9] A. J. Grono, J. P. Wlodarski. Experimental research of computer-based method for synchronizing power generators. in: St. Petersburg TU (ed). *Proceedings of the IV International Conference on Unconventional Electromechanical and Electrical Systems UEES'9* (St. Petersburg. 21-24 June 1999). p. 1069-1074.

[10] A. J. Grono, J. P. Wlodarski. A new method for synchronizing of power generators and its application. in: Warsaw University of Technology (ed). *Proceedings of International Conference MECHATRONICS 2000* (Warsaw September 21-23, 2000). Vol. 1 p. 161-164.

[11] A. J. Grono: Komputerowa synchronizacja prądnic. Wydawnictwo Politechniki Gdańskiej Gdańsk, 2001.

Tytuł: Komputerowa synchronizacja prądnic

Artykuł recenzowany