

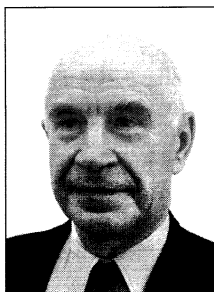
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# Computer synchronization of power generators

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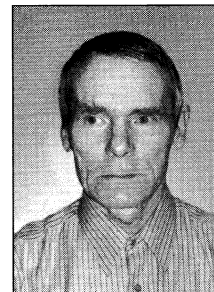
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### Abstract

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

$$t_{pi} = \frac{T_1}{|T_1 - T_2|} t_{Bi} \quad (1)$$

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.

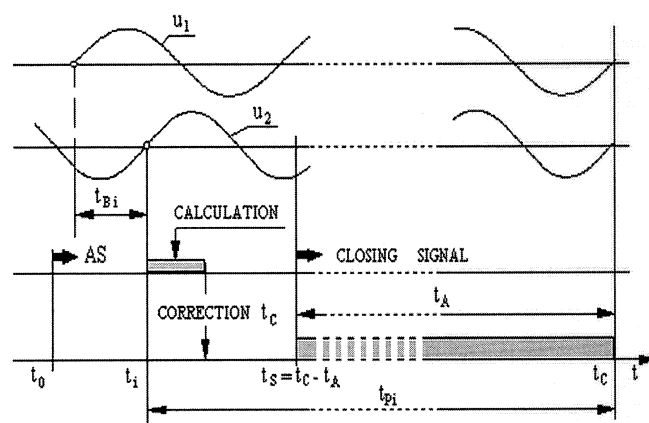


Fig. 1. Illustration of the timing relationships in the considered synchronizing procedure

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  $t_0$

$$t_{ci} = t_i + t_{pi} \quad (2)$$

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

$$t \geq t_c - t_A \quad (3)$$

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.

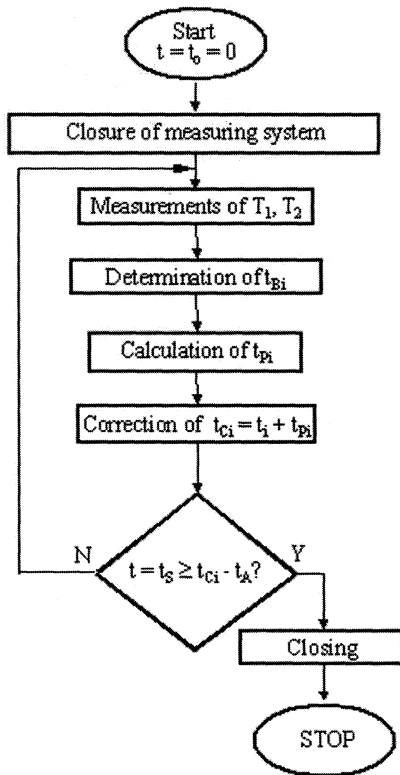


Fig. 2. The flow diagram of the considered algorithm

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  $\delta_E$  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  $\alpha$  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

$$u_1 = \sin 2\pi f_1 t \quad (4)$$

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

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

Table 1 provides the ranges of  $\Delta f_C$ ,  $\alpha$ , and  $t_A$  to be expected in real applications; the ranges are specified separately for (L) low-power ( $P \leq 1$  MW), (M) medium-power ( $P \in (1; 10)$  MW), and (H) high-power ( $P \geq 10$  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
$\Delta f_C$	Hz	0.25	2.00	0.25	1.00	0.05	0.25
$\alpha$	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  $\delta_E$  (in degrees), corresponding to the different sets of parameters:  $\Delta f_C$ ,  $t_A$ ,  $\alpha$  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

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

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

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  $t_{B1}$  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  $\delta_E$  were finally evaluated from the following expression

$$\delta_E = 0,36 \Delta f_C \Delta t_E \quad (8)$$

where  $\delta_E$  is in degrees, the frequency difference  $\Delta f_c$  is in hertz, and  $\Delta t_E$  (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  $-0.66^\circ$ . As a practical matter, the synchronizing of low-power generators can safely be performed up to about  $8^\circ$  of the phase-angle displacement.

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

As for the highest-power generators, whose safe synchronizing requires that the phase-angle displacement should not exceed  $2^\circ$  in magnitude, the results are no longer satisfactory for an 8-bit A/D converter ( $+2.32^\circ$  of the worst-case error observed), while again being fully acceptable for the bit size of 10 or higher (approximately  $-1.2^\circ$ ). 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  $\alpha$ , 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  $\delta_E$  in determining the circuit breaker closing instant; the error values, expressed in degrees, correspond to the most unfavorable sets of synchronizing parameters.

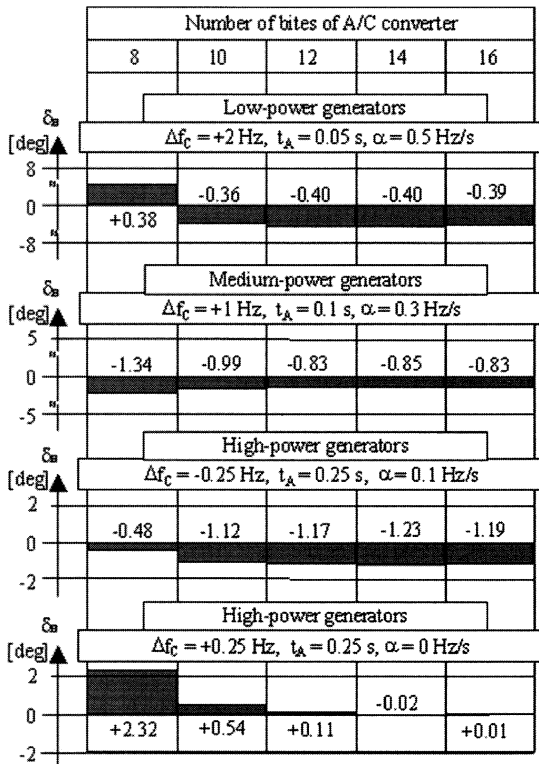


Fig. 3. The effect of the resolution of the A/D converter for some sets of other parameters

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  $\delta_E$  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 synchro-

nizing method was presented. Certainly, further insight into this phenomenon is necessary before it can be 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  $\alpha$ , 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 ( $\alpha \neq \text{const}$ ). 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  $\alpha$  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 ( $f_{2c}$  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  $50 \mu\text{s}$  steps. After filtering the voltage waveforms were obtained and then 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.

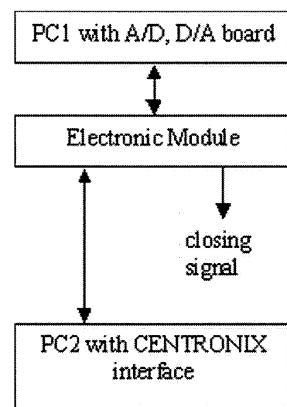


Fig. 4. A block diagram of the measurement system  
Rys. 4. Schemat blokowy systemu pomiarowego

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

**Table 2.** Worst-case phase-angle error  $\delta_E$  (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.	$\Delta f_C$	$t_A$	$\alpha$	$\delta_{E,av}$
	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  $d_{E,av}$  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  $\delta_E$  (in degrees) for alternator of range power 1 VA and  $\alpha=0$  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  $\alpha=0$  Hz/s, gdzie  $\delta_{E,av}$  oznacza średnią wartość kąta załączania

$\Delta f_C$	$t_A$	$\delta_{E,av}$
[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  $\delta_{E,av}$  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  $\delta_E$  (in degrees) for alternator of range power 27 kVA and  $\alpha \approx 0$  Hz/s

**Tabela 4.** Błąd kąta załączania  $\delta_E$  (w stopniach) dla generatora o mocy 27 kVA i  $\alpha \approx 0$  Hz/s

$\Delta f_C$	-1.55	-0.40	-0.29	0.20	1.40	1.76	1.90
[Hz]							
$t_A$	0.10	0.25	0.25	0.25	0.10	0.10	0.10
[s]							
$\delta_E$	0.58	-0.35	0.07	1.25	0.04	0.91	0.65
[deg]							

## 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. Grimdsdale, C. C. Wheeler. Alternator synchronization using an on-line 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. Zadarški 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. Włodarski. 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. Włodarski. 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. Włodarski. 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