

Scientific Papers of the  
Institute of Electrical Power Engineering of the  
Wrocław University of Technology

# PRESENT PROBLEMS OF POWER SYSTEM CONTROL

No 1

Wrocław 2011

*Keywords: phase-locked loop, orthogonal signal generator,  
frequency estimation, phase-angle detection,  
power electronics controller*

Michał WYSZOMIRSKI\*, Eugeniusz ROSOŁOWSKI\*

## **PHASE-LOCKED LOOP TECHNIQUE SYSTEM WITH ORTHOGONAL SIGNAL GENERATOR FOR POWER ELECTRONICS CONTROLLERS**

This paper presents a Phase-Locked Loop (PLL) scheme with Orthogonal Signal Generator (OSG). The proposed technique enables to eliminate the influence of distortions from the observed signal on proper determination of its parameters as a phase, magnitude or frequency. A simulation model of the system is developed and results of investigation are provided. Some recommendations on the scheme settings for elimination of harmonic and inter-harmonic components are also included. It was verified that the proposed PLL with OSG system can be considered as an useful and effective tool in implementations that require a great accuracy of the phase angle and frequency estimation. The system could be applied in three-phase power systems control units such as FACTS converters or doubly-fed induction generators control scheme. Simulation results demonstrate the effectiveness and robustness of the proposed solution.

### 1. INTRODUCTION

Almost all power electronic converters such as FACTS have indispensable component called a Phase-Locked Loop (PLL). IEEE defined the Flexible Alternating-Current Transmission Systems (FACTS) as “ac transmission systems incorporating power electronics-based and other static controllers to enhance controllability and increase power transfer capability” [2]. A most often structure PLL used in power electronics converters is the three-phase PLL based on dq-frame signals. For distortion-free input signal, this PLL estimates the input phase-angle without any double-

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\* Wrocław University of Technology, Institute of Electrical Power Engineering, Wybrzeże Wyspińskiego 27, 50 – 370 Wrocław, [michal.wyszomirski@pwr.wroc.pl](mailto:michal.wyszomirski@pwr.wroc.pl), [rose@pwr.wroc.pl](mailto:rose@pwr.wroc.pl)

frequency ripple in the loop. When the input is unbalanced or distorted the three-phase PLL does not provide the proper phase-angles.

Conventional single-phase PLL suffers from the presence of second-harmonic ripples. Such distortions do not appear for three-phase PLL due to the symmetry of the dq transformation for balanced signals. When input signals are unbalanced the three-phase PLL suffers from double-frequency ripples like for conventional single-phase PLL. The second-order harmonics can effectively be eliminated by included filters but this delaying the time response. An alternative PLL system that does not generate any double-frequency ripple was introduced in [4]. The paper presents an interesting scheme that is not based on the PLL at all [5], [6]. However, this method is vulnerable to inaccuracy due to the voltage disturbance.

This paper proposes a novel structure of the PLL scheme with the orthogonal signal generator which is tolerable under input signal disturbances. Generally, the proposed solution is based on schemes presented in [1], [7] but the new structure has essentially better characteristics. This new system may be used to estimate phase-angles of individual phases in case of unbalanced inputs.

The paper is organized as follows. First, a review of the PLL technique applied to signal estimation is presented. Then the proposed solution is presented in details. It was shown that it is capable to fundamentally remove all the impacts of harmonic/inter-harmonic components. Simulations compare the structures and verify performance of proposed structures. Finally, some concluded remarks are stated.

## 2. BASIC SCHEME CONSTRUCTION OF PHASE-LOCKED LOOP

Principle of the PLL with reference to harmonic signals is well-known in the radio-engineering and the telecommunication [3]. The conventional scheme of the PLL is shown in Fig. 1. Phase Detector (PD) is composed of a multiplier block, which realizes of the following operation:

$$u_d = K_d \cdot u_1 \cdot u_2 = \frac{K_d U_1 U_2}{2} \sin(\theta_1(t) - \theta_2(t)) + \frac{K_d U_1 U_2}{2} \sin(2\omega t + \theta_1(t) + \theta_2(t)) \quad (1)$$

where:  $u_1 = U_1 \sin(\omega t + \theta_1(t))$ ,  $u_2 = U_2 \cos(\omega t + \theta_2(t))$ ,  $K_d$  - gain coefficient.

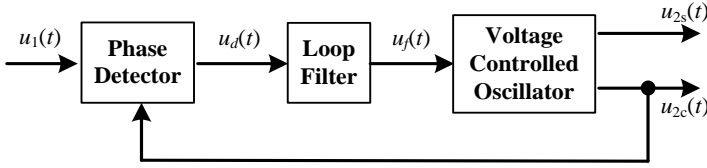


Fig. 1. Conventional PLL system

It can be seen from (1) the output of PD consist of two signals from which the first describes a function of a phase shifting between the input signals, while the second part depicts an oscillatory component of double frequency. This component is next filtered-out in a low-pass Loop Filter (LF) has a low-pass characteristic. Remaining dc component of the form:

$$u_f(t) = \frac{K_d U_1 U_2}{2} \sin(\theta_1(t) - \theta_2(t)) \quad (2)$$

is delivered to the Voltage Controlled Oscillator (VCO) which generates the harmonic orthogonal signals  $u_{2c}(t)$  and  $u_{2s}(t)$  of the unity magnitude and the frequency:

$$\omega_c = \omega_0 + K_v u_f(t) \quad (3)$$

where  $K_v$  is a gain and  $\omega_0$  is a nominal (reference) frequency.

The signal  $u_f(t)$  is called a VCO control signal. According to (3) the relation  $\omega_c = \omega_0$  occurs if the signal  $u_f(t)$  is equal to zero (full synchronization).

Instantaneous phase of the PLL output signal can be determined according to the following expression:

$$\theta_2(t) = 2\pi K_v \int_0^t u_f(t) dt \quad (4)$$

Range of changes in the output waveform with respect to the central pulse of generator  $\omega_0$  for which synchronization is achieved is called the capture range. If the pulsation of the input signal exceeds the pulsation range of capture, the loop is not able to bring to the synchronous state of two waveforms.

Basic dependencies of the conventional PLL are used to create new systems that estimate the input phase-angle without any double-frequency ripple in the loop. Single-phase system with such properties is the PLL magnitude estimator [5], [6] and the PLL with orthogonal signal generator (OSG) [1]. PLL with magnitude estimator is shown in Fig. 2. This system combines conventional PLL and the magnitude estimator

in the external feedback loop. More detailed description of the system shown in Fig. 2 can be found in [5], [6], [7].

Phase Locked Loop can be also combined with an Orthogonal Signal Generator (GSO) as in Fig. 3. This system is composed of conventional PLL and the orthogonal signal generator.

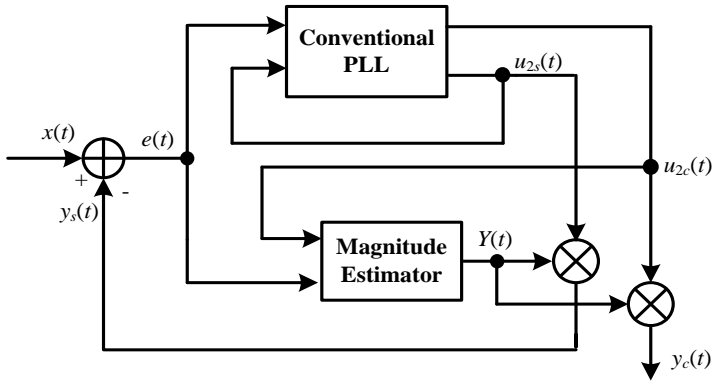


Fig. 2. PLL with magnitude estimator [5], [6], [7]

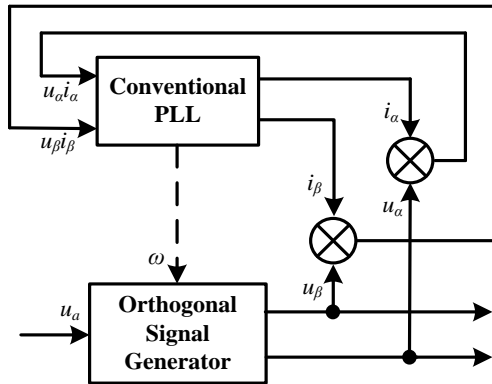


Fig. 3. PLL with orthogonal signal generator [1], [7]

Frequency from the conventional PLL is used in GSO. Structure of GSO is shown in Fig. 4. This scheme is based on the second order generalized integrator (SOGI) [1]. It can be seen that the system has a simple structure. Moreover, it is also independent on changing of the grid frequency.

Waveforms in Fig. 5 illustrate superiority of the PLL with magnitude estimator and the PLL with OSG over the conventional PLL. The last one could not remove a double-frequency component from the input signal. Input signal have 50 Hz fundamental frequency with no distortion in Fig. 5(a) and 5(b) with 55 Hz fundamental fre-

quency and no distortion. Fundamental frequency in VCO in all system is equal to 50 Hz. Magnitude of input signal is equal to one. The input signal is the same in all considered schemes. Parameters of conventional PLL in three models are the same. When changing the frequency from 5 Hz shown in Fig. 5(b) arrangement with OSG has the greatest momentum.

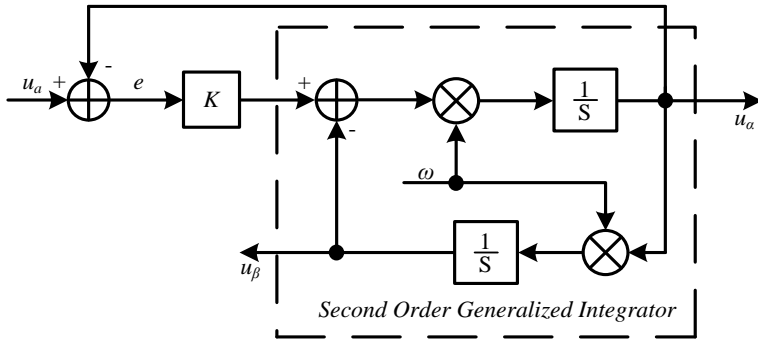


Fig. 4. Orthogonal signal generator based on Second Order Generalized Integrator

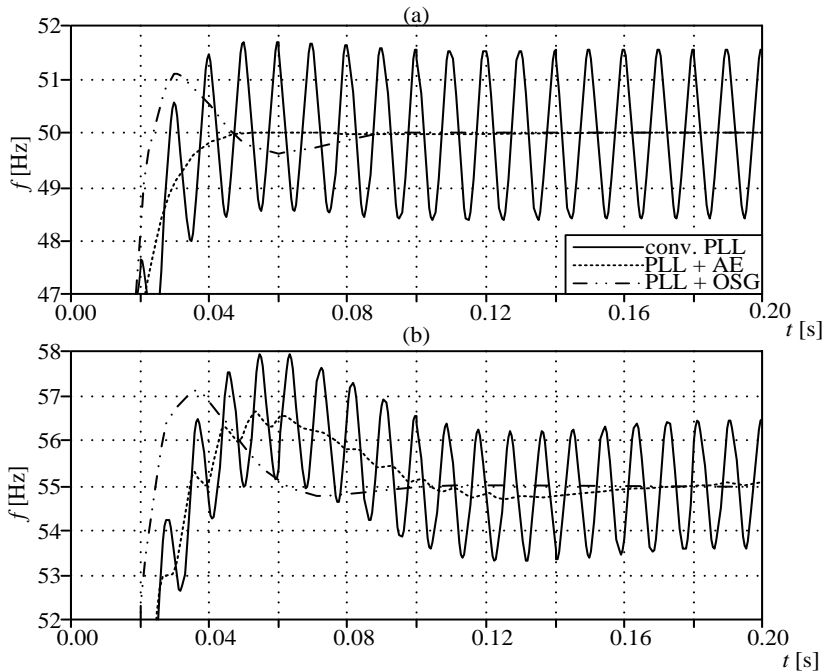


Fig. 5. Performance of the PLL systems in removing double-frequency ripples: (a) estimated frequencies of the conventional PLL, PLL with magnitude estimator and PLL with OSG for input frequency equal to 50 Hz and (b) for input frequency equal to 55 Hz

The PLL with magnitude estimator and OSG remove the double-frequency ripple and provide an error-free estimation of the phase angle and frequency when input signal is pure sinusoidal signal. Usually measurements of the voltage or current signals are corrupted by high-frequency distortions and noise. The case when signal is corrupted with 30% of the second harmonic (a) – and a 30% of the third harmonic (b) has been shown on Fig. 6. In such cases, the PLL with magnitude estimator and system with OSG cannot remove the harmonics either the conventional PLL.

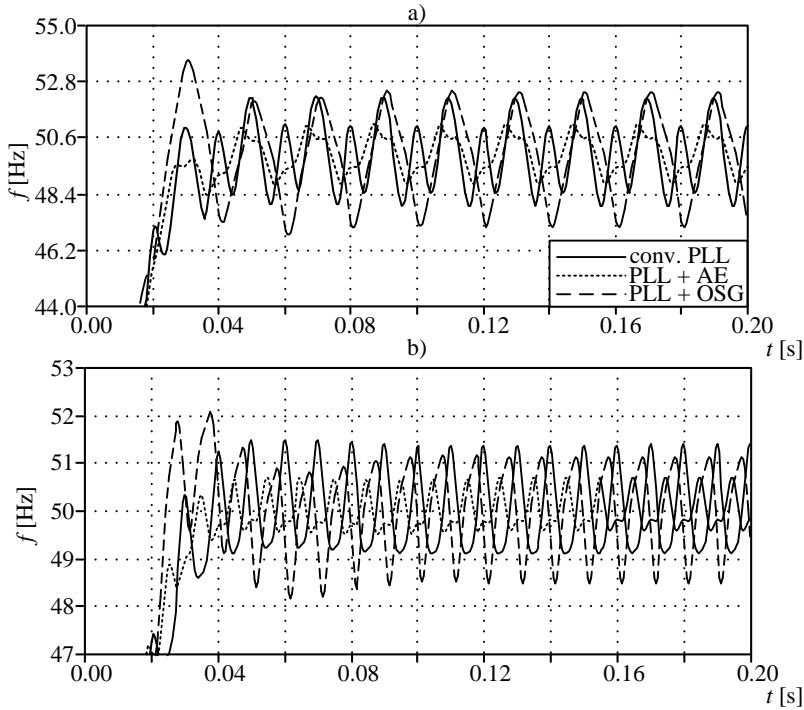


Fig. 6. Performance of the PLL systems when the input signal is distorted: estimated frequencies for (a) 30% of the second harmonic and (b) 30% of the third harmonic

All PLL systems can not remove error from frequency measurement when input signal is corrupted by high-frequency distortion and noise. The purpose of this paper is to overcome this drawback of the conventional PLL and the PLL with magnitude estimator and PLL with OSG which is sensitivity to the presence of harmonics. A developed structure is based on the system of PLL [4] with magnitude estimator and new PLL with OSG [1], [7] which is able to completely remove impacts of harmonics.

### 3. DISTORTION-FREE PHASE LOCKED LOOP SYSTEMS

Structure of the system is based on multiple units of the PLL with magnitude estimator and units of the PLL with OSG. First possible scheme is shown in Fig. 7 for PLL with magnitude estimator [4] and in Fig. 8 for PLL with OSG. Unit 1 (with shown details) is intended to the fundamental component of frequency 50 Hz. Unit 1 in both cases are the open loop part of PLL as shown in Fig. 7 and 8. The errors of signals in new systems depend on all units. Unit 1 to Unit  $N$  have similar but operate within a pre-specified frequency range. Each pre-specified frequency range is primarily determined by the value of the nominal frequency of its VCO. Unit 2 has frequency  $2\omega_0$ , Unit 3 -  $3\omega_0$  and Unit  $N$  -  $N\omega_0$ . More details can be found in [4].

Examples of performance of the proposed system from Figs. 7 and 8 are presented in Fig. 9. It was considered two different input signals were considered: first one with 30% of the second harmonic and the second - with 30% of the third harmonic. In each case the proposed PLL has  $N = 3$  units with adequate nominal frequency of each unit. It can be seen that the frequency of the input signal is estimated with no error.

Two proposed PLL systems provides absolutely error-free estimate of the phase-angle and frequency if the harmonic components of the input signal are all detected by the units. This is the case when the number of units is no fewer than the number of harmonics presented in the signal. In practice, signals are contaminated with a wide

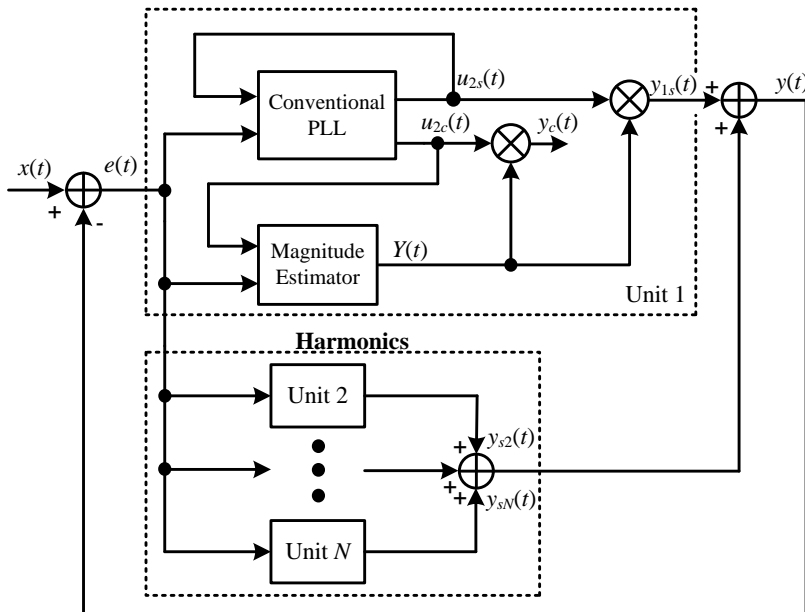


Fig. 7. PLL system with magnitude estimator from [4]



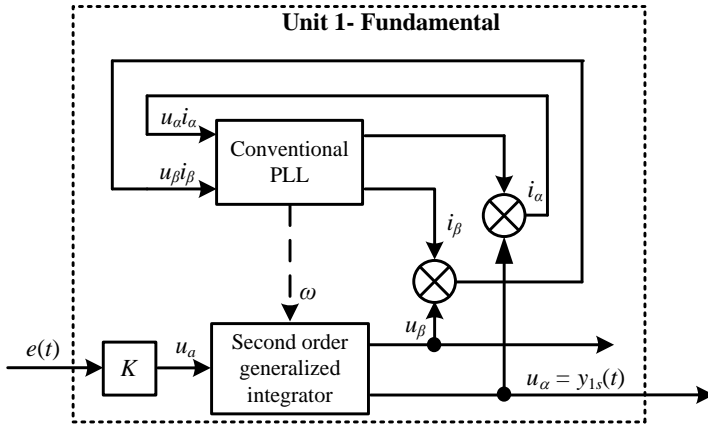


Fig. 8. Structure of Unit 1 in the proposed PLL system with OSG

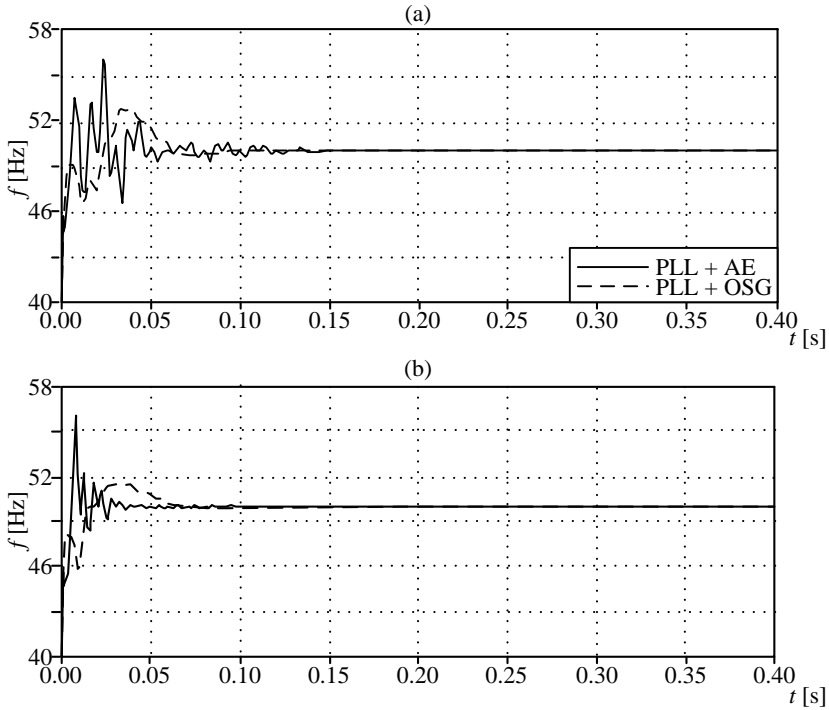


Fig. 9. Performance of PLL system of Fig. 7 and Fig. 8 when the input signal is distorted: estimated frequency for (a) 30% of the second harmonic and (b) 30% of the third harmonic

range of harmonics from low-frequency range to high frequencies. The error will decrease with increasing the number of applied units.

#### 4. SIMULATION STUDY

The proposed PLL schemes from Figs. 7 and 8 were examined by simulation against the input signal contamination. Tested systems were represented in ATP-EMTP program. The parameters of systems with OSG and the magnitude estimators were chosen independently. Parameters of tested schemes were selected to adjust to the input signal harmonics and inter-harmonics and to immune to the fundamental frequency deviation with the range of 5 Hz. More details regarding the selection of parameters can be read in [1], [4], [5], [6], [7]. For the examples considered in this section,  $N = 5$  units are taken each of which is set to operate in the frequency range of  $[k\omega_0 - \omega_0/2, k\omega_0 + \omega_0/2]$ ,  $k = 1 \dots 5$  with  $\omega_0 = 100\pi \text{ s}^{-1}$ .

For the first case study, the input signal is comprised of 40% of the second harmonic and 10% of fifth harmonic, i.e.:

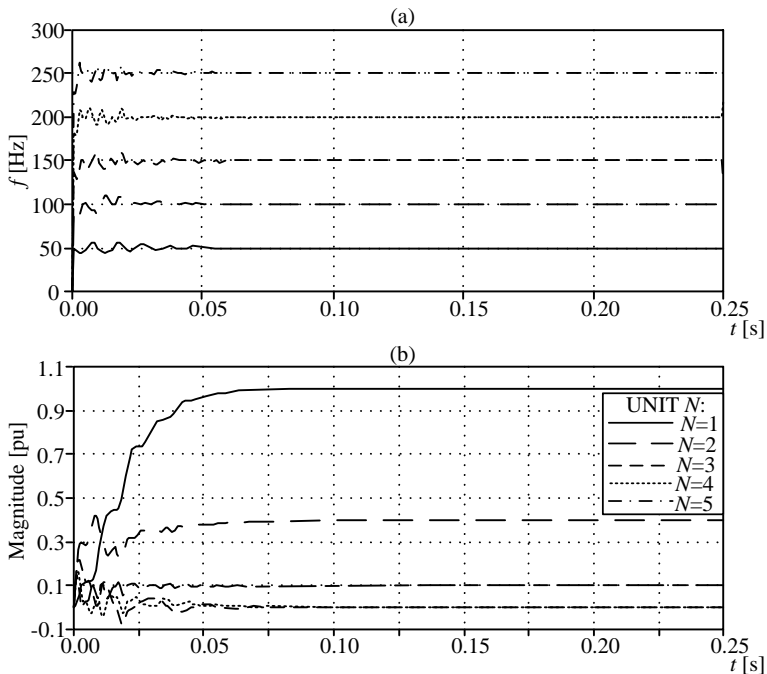


Fig. 10. Performance of PLL system with amplitude estimator with  $N = 5$  Units as in Fig. 7 for input signal (5): (a) estimated frequencies, and (b) estimated magnitudes

$$u(t) = \sin(\omega_0 + \delta_0) + 0.4\sin(2\omega_0 + \delta_2) + 0.1\sin(5\omega_0 + \delta_5) \quad (5)$$

where the initial phase-angles,  $\delta_i$ 's, are chosen randomly between  $-2\pi$  and  $2\pi$ . Figs. 10 and 11 show the estimated frequencies and magnitudes by the units of PLL system with the amplitude estimator and OSG. In two cases estimated magnitudes Fig. 10(b) and Fig. 11(b) take the following values 1 for fundamental unit and 0.4, 0, 0, 0.1 for successive units  $k = 1 \dots 5$ . The frequencies of fundamental, second and the fifth are estimated with no error for both systems. The third and fourth harmonic is estimated but the amplitude of this signals is equal zero. The results confirm the correctness of both systems in the measurement of signal (5).

Comparing the results of two analyzed schemes (Figs. 10 and 11) one can see that the PLL system with OSG has considerable better dynamics in the frequency estimation while the time delays for magnitude estimation are similar and equal to 0.05 s.

One of the important characteristics of the considered estimators is the ability to deal with inter-harmonics. The proposed structures have its adaptive properties and there are able to detect inter-harmonics in the frequency range of units in the system. The signal components can be determined without error when the frequency of inter-

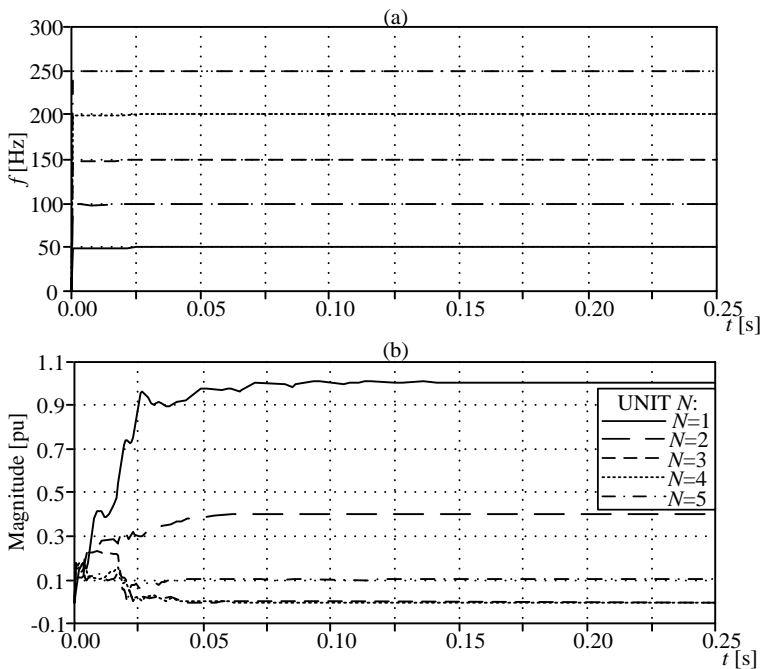


Fig. 11. Performance of PLL system with OSG as in Fig. 8 with  $N = 5$  Units for input signal (5):  
(a) estimated frequencies, and (b) estimated magnitudes

harmonic is in the capture range of loops located in units of the system. Results of measurement of the signal having inter-harmonic component are shown in Fig. 12 - for the system with the amplitude estimator and in Fig. 13 - for the system with OSG. The input signal comprises three components at the fundamental frequency of 50 Hz, an inter-harmonic component at 130 Hz, and fifth harmonic. The magnitudes of these components are the same as in the previous example. For smoothing out of the input signal the LPF is included at the input of PLL. It can be seen that the magnitudes and frequencies are accurately estimated in both systems. The inter-harmonic component falls within the range of the third unit and is detected by that unit. Time of reaching a steady state in measurement of inter-harmonic frequency is worse than that in the estimation of the harmonic frequency. This delay is related to the synchronization time of PLL. However, for both systems for inter-harmonic measurements are successful. There are some insignificant differences in the output waveforms but, generally, both systems have the similar response.

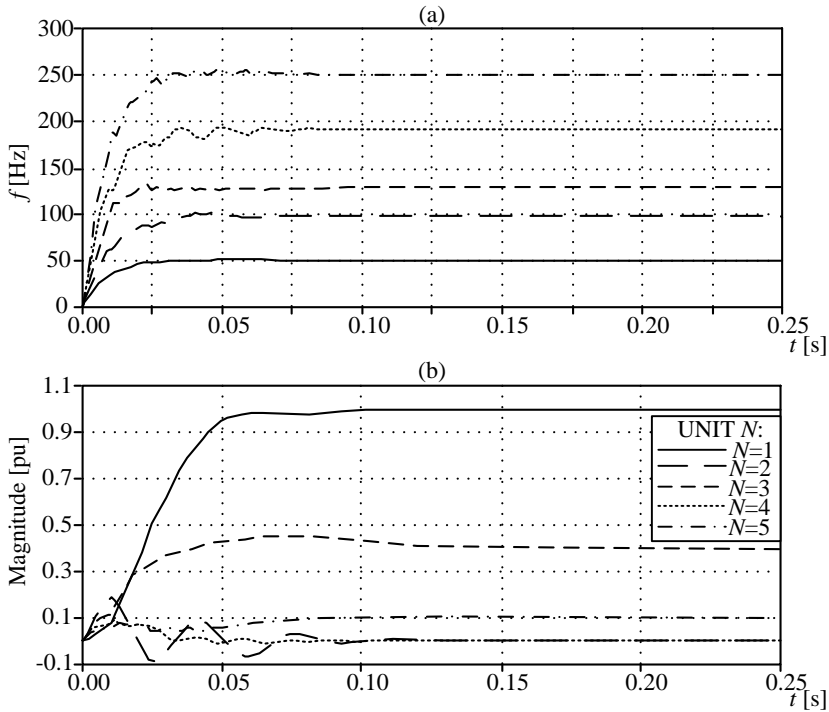


Fig. 12. Performance of PLL scheme for amplitude estimator as in Fig. 7 with  $N = 5$ ; input signal has 40% of 30 Hz component and 10% of fifth harmonic: (a) estimated frequencies; (b) estimated magnitudes

The last example of simulation shows the effect of reducing number of units in the system for quality of the frequency estimation. The input signal is described by the equation:

$$u(t) = \sin(\omega_0 + \delta_0) + 0.4\sin(2\omega_0 + \delta_2) + 0.1\sin(5\omega_0 + \delta_5) + 0.4\sin(7\omega_0 + \delta_7) \quad (6)$$

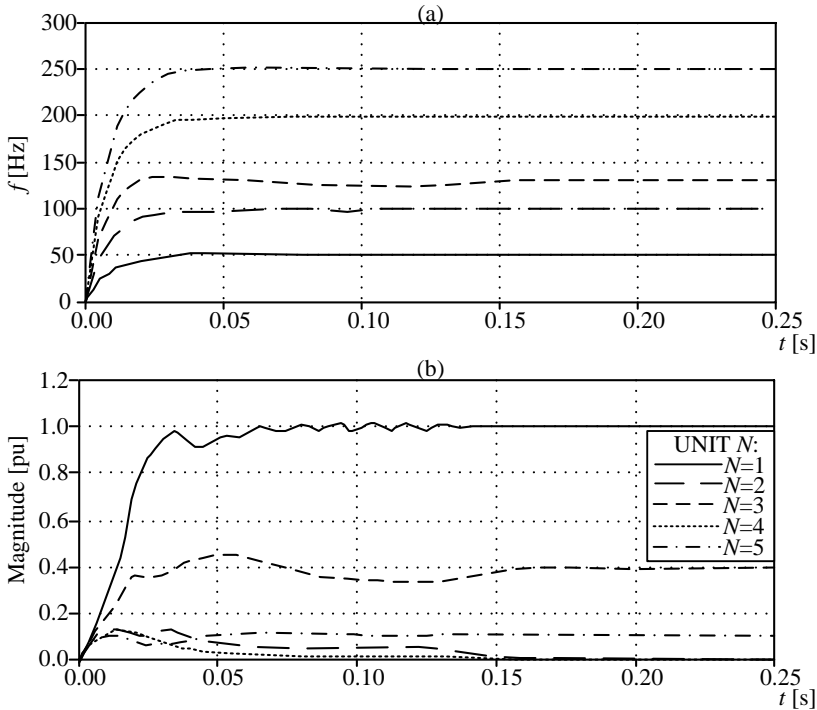


Fig. 13. Performance of PLL with OSG system as in Fig. 8 with 5 Units; input signal has 40% of 30 Hz component and 10% of fifth harmonic: (a) estimated frequencies, and (b) estimated magnitudes

Fig. 14(a) shows the input signal. The measured signal is applied to the proposed PLL schemes (Figs. 7 and 8). Figs. 14(b) to 14(d) show results of the frequency measurements for different number of applied units. It can be seen that the measurement accuracy dramatically decrease if  $N$  is reduced from  $N = 5$  to  $N = 1$ .

The reduction of unit numbers causes much deterioration in the quality of the measurement. This behavior is visible in both considered systems: with amplitude estimator and with added OSG. The conclusion for this example is that the more units in the system, the better quality and range for frequency measurement.

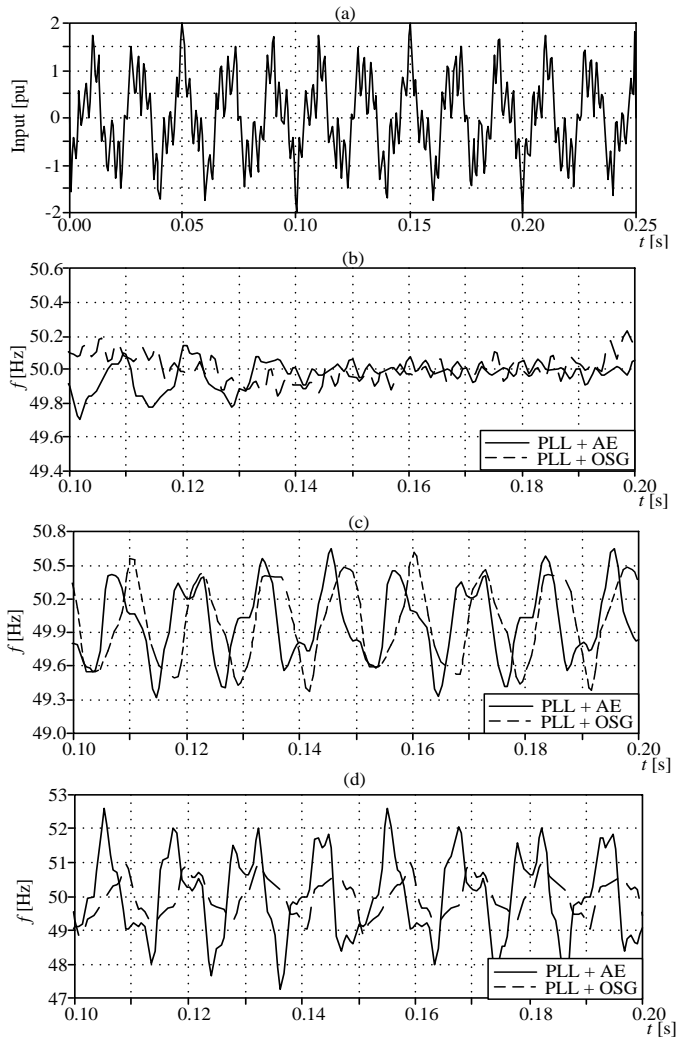


Fig. 14. Results of frequency estimation: input signal (a); results for system with units number  $N = 5$  (b);  $N = 2$  (c) and  $N = 1$  (d)

## 5. CONCLUSIONS

The proposed PLL scheme with OSG obviates the fundamental drawback of the conventional single phase PLL system which has double-frequency ripples in the output and is sensitive to harmonics. The considered circuit is as reliable as the structure presented in [4] with amplitude estimator. Thus, the proposed PLL provides errorless estimate of the phase-angle and frequency in the presence of harmonic and inter-

harmonic components. Performed simulation studies have shown the performance of the proposed system. Multiple generic units can compose a complex scheme which can be applied to estimate the phase-angles of the individual phases of a multi-phase unbalanced system. PLL with OSG can also be successfully adapted for amplitude estimation without any double-frequency ripples at the output.

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#### WYKORZYSTANIE UKŁADU PĘTLI SYNCHRONIZACJI FAZOWEJ Z ZASTOSOWANIEM GENERATORA SYGNAŁÓW ORTOGONALNYCH W ENERGOELEKTRONICZNYCH UKŁADACH STEROWANIA

W artykule przedstawiono układ pętli synchronizacji fazowej (PSF) z generatorem sygnałów ortogonalnych (GSO). Proponowana technika umożliwi wyeliminowanie wpływu zakłóceń zanalizowanego sygnału na określenie jego parametrów takich jak faza, amplituda czy częstotliwość. Przedstawiono model symulacyjny proponowanego układu i zaprezentowano wyniki doświadczeń. Zawarto także niektóre z zalecanych konfiguracji schematu w celu eliminacji składowych harmonicznnych i interharmonicznnych sygnału. Dowiedziono, że proponowany system PSF z GSO może być rozpatrywany jako użyteczne i efektywne narzędzie w implementacjach wymagających dużej dokładności estymacji fazy i częstotliwości. Proponowany system może być stosowany w układach sterowania trójfazowych systemów takich jak FACTS lub w układach sterowania generatorów indukcyjnych dwustronnie zasilanych (DFIG). Wyniki symulacji wskazują na skuteczność i poprawność działania zaproponowanego rozwiązania.

