Analysis of single-phase PLL with novel two-phase generator for grid-connected converters

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4 authors:

Srdjan Lale
University of East Sarajevo

Slobodan Lubura
University of East Sarajevo

Milomir Soja
University of East Sarajevo

Marko Ikić
University of East Sarajevo

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Srdjan Lale, Slobodan Lubura, Milomir Šoja, and Marko Ikić

Abstract — **It is very important for proper work of grid-connected converters to have accurate detection of phase angle, frequency and amplitude of grid voltage. Estimation of these grid parameters can be achieved using PLL (phase locked loop) based on SRF (synchronous reference frame) theory. This PLL should have robustness against noise and offset introduced by measurement and data conversion. This paper proposes an improved PLL alorithm that has excellent noise and offset rejection property. The main part of the proposed PLL is a novel two-phase generator which is used to obtain two quadrature signals for SRF block and PI regulator in closed control loop.**

Keywords — **PLL, two-phase generator, offset rejection.**

I. Introduction

In various grid-connected converters such as PWM rectifiers, uninterruptible power supply (UPS), distributed power systems, etc., it is very important to have information about phase angle, frequency and amplitude of grid voltage for their proper operation and control.

There is increasing interest for using PLL (phase locked loop) with different topologies for estimation of mentioned grid parameters [1]-[5]. In [3] is described PLL topology based on SRF (synchronous reference frame) for single-phase grid-connected converters. This topology requires the existence of two quadrature voltages (phase-shifted for π/2). In [3]-[6] is described a two-phase generator for obtaining these voltages using inverse Park's transformation. In [9] is proposed generating these signals using Hilbert transformer.

However, the main problem of these structures is the appearance of DC component (offset) in measured grid input voltage. This DC component is usually caused by measurement, i.e. A/D conversion process. The offset causes errors in grid parameters estimation. In [4] it is shown that this error for single-phase grid voltage has the same fundamental harmonic component as grid voltage.

Srdjan Lale is with the Faculty of Electrical Engineering, University of East Sarajevo, Vuka Karadzica 30, 71123 East Sarajevo, BIH (phone: 387-57-342788; e-mail: srdjan.lale@etf.unssa.rs.ba).

Slobodan Lubura is with the Faculty of Electrical Engineering, University of East Sarajevo, Vuka Karadzica 30, 71123 East Sarajevo, BIH (phone: 387-57-342788; e-mail: slobodan.lubura@etf.unssa.rs.ba).

Milomir Šoja is with the Faculty of Electrical Engineering, University of East Sarajevo, Vuka Karadzica 30, 71123 East Sarajevo, BIH (phone: 387-57-342788; e-mail: milomir.soja@etf.unssa.rs.ba).

Marko Ikić is with the Faculty of Electrical Engineering, University of East Sarajevo, Vuka Karadzica 30, 71123 East Sarajevo, BIH (phone: 387-57-342788; e-mail: marko.ikic@etf.unssa.rs.ba).

In order to eliminate this error, in this paper is proposed a novel two-phase generator which outputs two quadrature voltages and has the ability to eliminate grid offset. This generator is also robust against fast changes of grid parameters and successfully attenuates noise.

The proposed two-phase generator is adapted to grid frequency, so it can be used in all kinds of grid-connected converters. It is important to notice that this PLL is suitable for digital realization.

This paper is organized as follows: Section II describes the structure of proposed two-phase generator. Section III analyzes dynamical and frequency properties of new structure. Section IV gives corresponding simulation results. The conclusion is given in section V.

II. Novel Two-phase Generator With Offset Rejection

As noted in introduction of this paper, there are a lot of SRF PLL algorithms in literature for estimation of phase angle, frequency and amplitude of grid voltage. The key component is two-phase generator which produces two quadrature voltages (phase-shifted for π/2) u_d and u_q.

Typically, second-order filters are used [2], [5]. Transfer functions of these filters, in continuous domain, are given by:

$$W_d(s) = \frac{G\omega s}{s^2 + G\omega s + \omega^2} \tag{2}$$

$$W_q(s) = \frac{G\omega^2}{s^2 + G\omega s + \omega^2}. \tag{3}$$

The gain coefficient G can be used for adjusting filter bandwidth. ω represents estimated grid angular frequency. Obviously, filter with transfer function $W_d(s)$ is bandpass and $W_q(s)$ is low-pass filter. Transfer functions (2) and (3) can be realized using well-known canonical controlable forms. This was performed in Matlab/Simulink environment. Block-diagram is shown in Fig. 1.

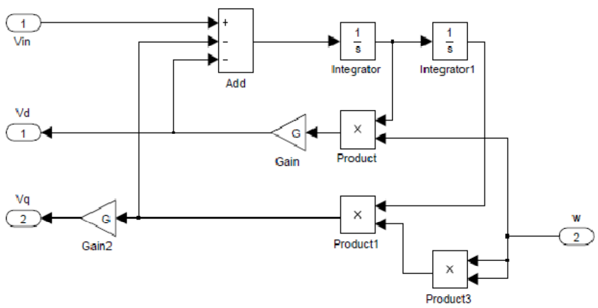

Fig. 1. Realization of two-phase generator (filters $W_d(s)$ and $W_q(s)$) in Matlab/Simulink environment.

This two-phase generator will work properly only if the grid frequency is matched to the resonant frequency of the filters. So, it is necessary to have adaptive resonant frequency, which is achieved through the feedback within PLL topology (in Fig. 1 resonant frequency ω is actually estimated grid frequency). The proposed generator has ability of noise attenuation, as shown in Fig. 2.

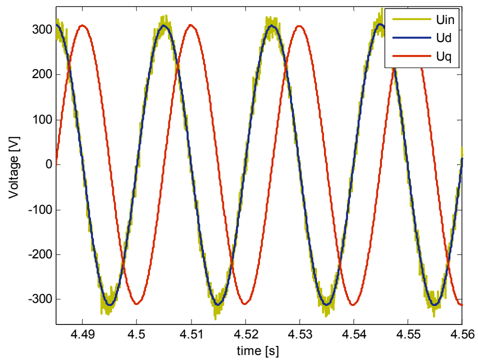

Fig. 2. The response of two-phase generator on grid voltage with noise.

However, this generator isn't robust against the existance of offset in grid voltage. This offset causes the ripple in estimated values of frequency and amplitude of grid voltage, as shown in Fig. 3.

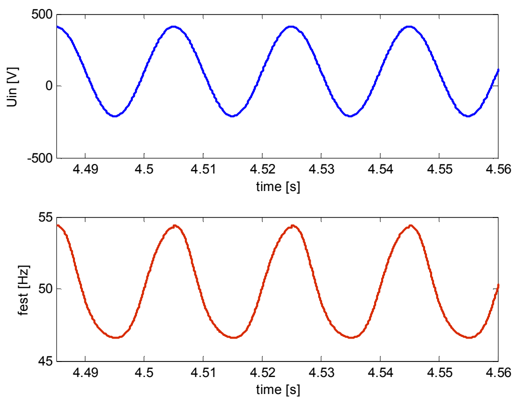

Fig. 3. Input grid voltage with offset and estimated grid frequency with ripple component.

It is obvious that grid offset causes the appearance of estimation errors. In [6] is proposed a solution to this problem by inserting a low-pass filter in the structure of two-phase generator. This paper proposes a new method of eliminating the offset, which is based on closed control loop with integrator, without low-pass filter. Block-diagram of this new two-phase generator is shown in Fig. 4. This structure consists of previous one (at Fig. 1) and added feedback loop with integrator. The value at the output of integral gain k_i is about negative value of the offset, so adding that value to the input voltage u_{in} eliminates ofsset.

The key part of proposed structure is gain k_i in the branch with integrator. The value of k_i determines the dynamics of the system's transient process. This value has main influence on speed of eliminating the estimation errors caused by grid offset.

The next section of this paper gives more detailed analysis of proposed new two-phase generator and especially influence of gain parameter k_i.

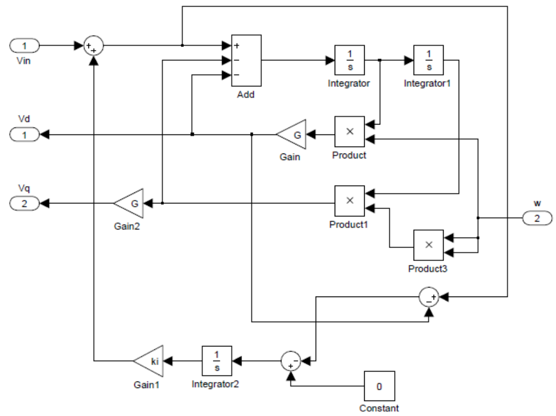

Fig. 4. The new two-phase generator with offset elimination realized in Matlab/Simulink environment.

III. Frequency, Stability and Response Analysis of New Two-phase Generator

Referring to Fig. 4. transfer functions of new filters are:

$$W_{md}(s) = \frac{G\omega s^2}{s^3 + (G\omega + k_i)s^2 + \omega^2 s + k_i\omega^2} \tag{4}$$

$$W_{mq}(s) = \frac{G\omega^2 s}{s^3 + (G\omega + k_i)s^2 + \omega^2 s + k_i\omega^2}\,. \tag{5}$$

It is obvious that these filters are both bandpass, which means that they don't pass DC component (offset) of input grid voltage. In the earlier structure (Fig. 1.) this wasn□t case, because filter $W_q(s)$ was low-pass, so it couldn□t eliminate offset.

Let input measured grid voltage $u_{in}(t) = u_{in0}(t) + C$, where $u_{in0}(t)$ is pure sine without offset and C is offset value. Complex Laplace characters of voltages u_d and u_q are given by:

$$U_d(s) = W_{md}(s)U_{in0}(s) + W_{md}(s)\frac{C}{s} \tag{6}$$

$$U_q(s) = W_{mq}(s)U_{in0}(s) + W_{mq}(s)\frac{C}{s}\,. \tag{7}$$

Using expression $\lim_{t\to\infty} f(t) = \lim_{s\to 0} s\,F(s)$, where $F(s) = \mathcal{L}\{f(t)\}$, components of voltages u_d and u_q caused by offset C vanish in stationary state:

$$\lim_{s\to 0}\left(sW_{md}(s)\frac{C}{s}\right) = \lim_{s\to 0}\left(W_{md}(s)C\right) \tag{8}$$
$$= \lim_{s\to 0}\left(\frac{G\omega s^2 C}{s^3 + (G\omega + k_i)s^2 + \omega^2 s + k_i\omega^2}\right) = 0$$

$$\lim_{s\to 0}\left(sW_{mq}(s)\frac{C}{s}\right) = \lim_{s\to 0}\left(W_{mq}(s)C\right) \tag{9}$$
$$= \lim_{s\to 0}\left(\frac{G\omega^2 s C}{s^3 + (G\omega + k_i)s^2 + \omega^2 s + k_i\omega^2}\right) = 0.$$

From (8) and (9) is obvious that proposed two-phase generator eliminates grid offset.

The only control parameter in proposed structure is integral gain k_i. Its value has key influence on behavior of whole system. In Fig. 5 and Fig. 6 is shown how k_i affects the shape of Bode diagrams of filters $W_{md}(s)$ and $W_{mq}(s)$, respectively. The bandwidth of both filters spreads with smaller k_i.

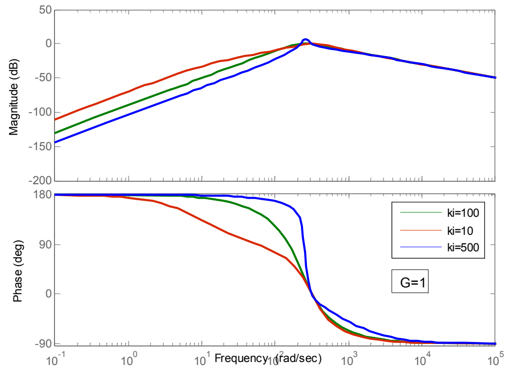

Fig. 5. Amplitude and phase characteristics of filter $W_{md}(s)$ for different values of gain k_i.

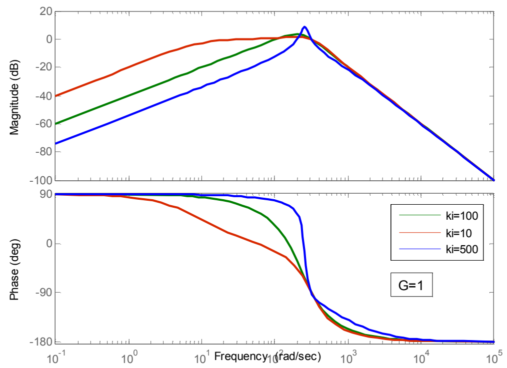

Fig. 6. Amplitude and phase characteristics of filter $W_{mq}(s)$ for different values of gain k_i.

It is necessary to determine a range of stabilizing parameters k_i. Applying conventional algebraic stability criteriums, such as Routh criterium, to characteristic polynom $D(s) = s^3 + (G\omega + k_i)s^2 + \omega^2 s + k_i\omega^2$, it is obtained that two-phase generator is stable for every positive value of k_i. However, although the system is stable for $\forall k_i > 0$, it is important to chose its proper value, because it affects the roots of characteristic eq. $D(s) = 0$, which determine the system's dynamics.

Let $u_{in}(t) = 220\sqrt{2}\cos(\omega t) + 100$, where $\omega = 2\pi f$, $f = 50$Hz. Performing inverse Laplace transformation of Eq. (6) and (7) follows that voltages u_d and u_q equal to:

$$u_d(t) = 220\sqrt{2}\cos(\omega t) - A_1 e^{-t/\tau_1} - A_2 e^{-t/\tau_2}\cos(\omega_1 t) + A_3 e^{-t/\tau_2}\sin(\omega_1 t) \quad (10)$$

$$u_q(t) = 220\sqrt{2}\sin(\omega t) + A_4 e^{-t/\tau_1} - A_5 e^{-t/\tau_2}\cos(\omega_1 t) - A_6 e^{-t/\tau_2}\sin(\omega_1 t). \quad (11)$$

Obviously, after enough time (several time constants τ_1 and τ_2) voltage $u_d(t) = 220\sqrt{2}\cos(\omega t)$ and $u_q(t) = 220\sqrt{2}\sin(\omega t)$ (phase-shifted for π/2). The value of k_i determines the size of time constants τ_1 and τ_2, amplitudes $A_i, i = 1, 2, \ldots, 6$, and frequency ω_1, which affects the response of the generator in transient process. In Table 1 these values are shown for different sizes of parameter k_i. It can be noticed that the optimal value of k_i is about 100, because in that case both time constants τ_1 and τ_2 are small, so exponential members of voltages u_d and u_q can be neglected.

TABLE 1: PARAMETERS OF RESPONSE OF TWO-PHASE GENERATOR FOR DIFFERENT VALUES OF GAIN k_i.

k_i	10	50	100	400	500	1000
τ_1[s]	0,0967	0,0162	0,0057	0,0015	0,0013	0,0007
τ_2[s]	0,0064	0,0066	0,0083	0,0341	0,0445	0,1148
ω_1[rad/s]	266,14	239,10	206,04	243,60	252,28	275,7
A_1[V]	3,5	33,1	207,6	161,1	142,6	92,5
A_2[V]	307,6	277,9	103,5	150,1	168,5	218,6
A_3[V]	303,8	355,8	391,8	78,8	62,2	26,6
A_4[V]	107,3	168,8	376,5	77,2	58,3	22,4
A_5[V]	107,3	168,8	376,5	77,2	58,3	22,4
A_6[V]	426,3	472,1	377,8	202,8	215,1	249,8

IV. SIMULATION RESULTS OF PROPOSED PLL TOPOLOGY

Performances of proposed two-phase generator as part of single-phase PLL were tested through simulations in Matlab/Simulink. The input voltage u_{in} with 30% offset was connected to two-phase generator. Two cases were analized. The first one is without loop with integrator and second one includes this control loop. Integral gain k_i was fixed and equal to optimal value 100. At simulation time of 0.5s grid frequency was changed from 47Hz to 53Hz in order to check estimation dynamics. The simulation results are shown in Fig. 7.

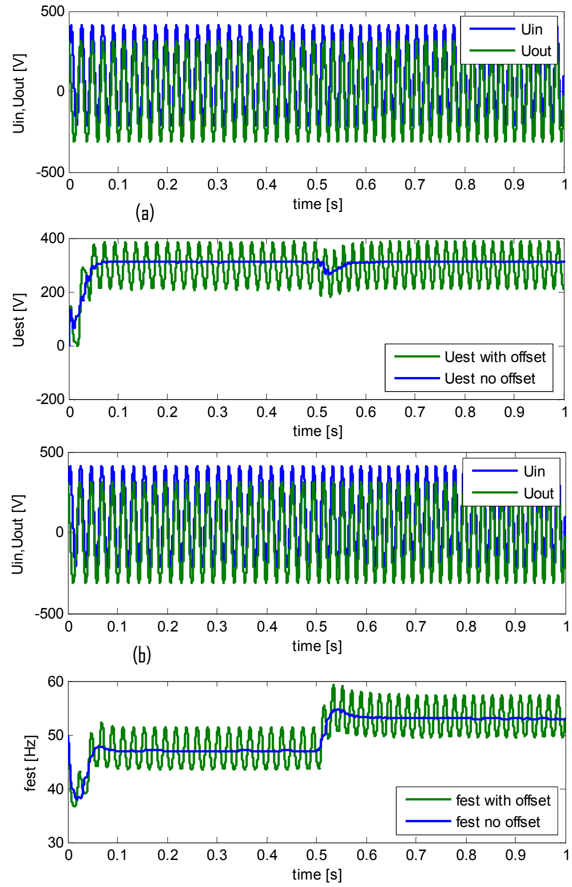

Fig. 7. (a) Input grid voltage with added 30% offset and generated reference voltage at the output of PLL (top), estimated amplitude for two mentioned cases (bottom);
(b) Input grid voltage with added 30% offset and generated reference voltage at the output of PLL (top), estimated frequency for two mentioned cases (bottom).

In first case (no loop for offset elimination) it is obvious that estimated amplitude and frequency of grid voltage contain ripple component, which makes estimation process impossible. In second case (included control loop) offset is completely eliminated and there is no ripple in estimated parameters. Also, PLL has excellent transient response and zero steady state error.

In order to verify the influence of parameter k_i on estimation process, simulations were done for three values of k_i: 10, 100 and 500. The results are shown in Fig. 8.

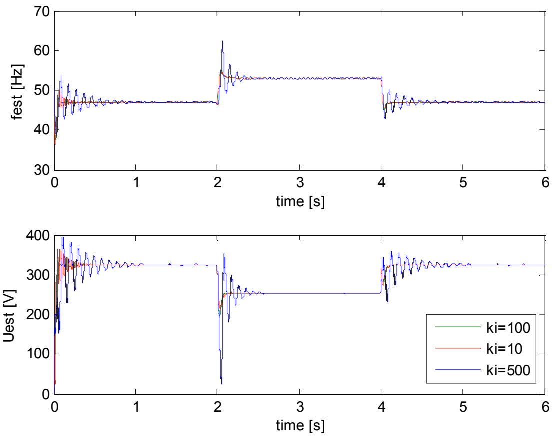

Fig. 8. Estimated frequency (top) and amplitude (bottom) of grid voltage for k_i = 10, 100 and 500.

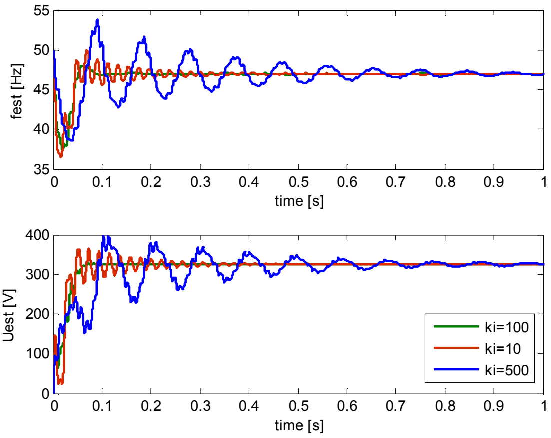

Fig. 9. Zoomed part of Fig. 8 for $t \in (0, 1)$s.

At the time of 2s amplitude of grid voltage was rapidly changed from $230\sqrt{2}$ V to $180\sqrt{2}$ V and reverse at the time of 4s. At the same time, grid frequency rapidly changed from 47Hz to 53Hz and reverse. From Fig. 8 it can be seen that in stationary state estimation is excellent for all values of k_i. In transient process (better view from Fig. 9), the best response is for $k_i = 100$, while for $k_i = 10$ and 500 oscillations appear. The worst case is when $k_i = 500$. Obviously, the proposed PLL topology has excellent behavior when grid parameters change rapidly. Ofcourse, topology is much less sensitive to noise, thanks to bandpass filters.

V. Conclusion

In this paper we proposed a novel two-phase generator suitable for SRF PLL topology. Important problem of presence of the offset in measured values of grid voltage was solved. Therefore, proposed PLL can be used for both, grid-connected systems (e.g. Photovoltaic and Wind turbines) and power condition equipment (uninterruptible power supply (UPS), active filters) which rely on PLL based synchronization. Results of simulations verify performances and robustness of proposed offset rejection method. The further work should be implementation of proposed PLL topology on digital platform.

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