Multi-resonant observer PLL with estimation of grid unbalances

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***Abstract*—In this paper, a novel discrete Phase Locked Loop (PLL) algorithm is introduced to obtain an optimal grid synchronization. One of the major problems in the grid synchronization process, which occurs due to grid imperfections, is higher order harmonics which are treated as disturbances in the electric power system. The proposed control design of PLL is implemented with a reduced order observer of periodic disturbances and with RST controller structure. The design is performed completely in the discrete time domain, and two cases were considered: the first case is with one higher order harmonic, and the second case is with two higher order harmonics in the system. The theoretical findings are substantiated by extensive simulation examples.**

Keywords: Grid synchronization, PLL algorithm, Reduced order observer, RST controller

I. INTRODUCTION

One of the important aspects of designing grid connected power electronics systems is the synchronization of the inverter output with the grid itself. Synchronization with the grid means matching the phase and the magnitude of the inverter output voltage with grid voltage signal and implicitly control of power factor, active and reactive power flow in the system. If the grid is unbalanced, side effects such as short circuits, failures and power outages can occur. Also, due to the grid imperfections, higher order harmonics appear in the electric power system. They are especially significant and represent unwanted spectral components of a distorted signal whose frequencies are equal to an integer product of the base frequency. These polluting harmonics are treated as disturbances in the system and consequently, it is necessary to neutralize their influence in order of optimal functioning of the electric power system.

Some modern solutions for efficient and reliable integration with grid of renewable energy sources are grid side converters (GSC). These power electronics devices enable the injecting or receiving of electric energy from the utility grid and they must be precisely synchronized with grid voltage [1,2]. There are several different algorithms for grid synchronization and one of the most commonly used of them is the Phase Locked Loop or PLL algorithm [3]. Among existing PLL techniques, the Synchronous Reference Frame (SRF-PLL) [4] is commonly utilized in power engineering applications. Also, there are other solutions such as Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL) [5] or Double Second-Order Generalized Integrator PLL (DSOGI-PLL) [6]. These algorithms perform excellent with negligible grid imperfections and they can accurately extract voltage synchronization signal when the grid is unbalanced. In situations when the grid voltage contains harmonics of higher order, large oscillations may appear in the synchronization signal and then Multi-SOGI method proposed in [7] could be used.

Achieving phase synchronization despite voltage sags and higher order harmonics and identifying amplitudes and phase angles of the polluting harmonics are essential for real-time control of power systems. An effective PLL scheme for efficient simultaneous identification and quantification of grid unbalance and higher harmonics content is proposed in [8]. However, the proposed method is described in continuous time domain and the reliability of a discretized system depends upon the approximation made to their continuous equations. Some methods, as the Forward Euler, the Backward Euler and the Tustin (Trapezoidal) numerical integration offer a good performance when used for continuous filter discretization, but those methods, could be inadequate under certain conditions, due to necessity of additional sample delays. Therefore, in this paper procedure for multi resonant PLL is completely implemented in the discrete domain without using numerical discretization method. The main reason is to obtain expressions that can be directly applied in the implementation, i.e. to avoid the discretization procedure that would otherwise be necessary.

The organization of this paper is such that in section 2 the grid voltage signal is characterized and vector notation is introduced. The basic aspects of the PLL algorithm as well as the new proposed modification of the algorithm applicable in the discrete domain are given in section 3. Finally, the results of the numerical simulation are presented in section 4.

II. GRID CHARACTERIZATION

A non-ideal 3-phase utility grid voltage in steady state can be represented as [3]

$$\begin{aligned} u_i =& U^p \cos(\omega_0 t - k_i \frac{2\pi}{3} + \varphi^p) + U^n \cos(-\omega_0 t - k_i \frac{2\pi}{3} + \varphi^n) \\ &+ \sum_h U_{ih} \cos(h\omega_0 t - k_i \frac{2\pi}{3} + \varphi_{ih}) \,, \end{aligned} \tag{1}$$

where $k_{i\in\{a,b,c\}} = \{0, 1, -1\}$. Variables U^p, U^n are amplitudes and φ^p, φ^n are phases of the Fundamental Frequency

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Positive Sequence (FFPS) and Fundamental Frequency Negative Sequence (FFPN), respectively [4,10]. Magnitude ω_0 is the fundamental frequency which value is typically $2\pi \cdot 50 \frac{\text{rad}}{s}$ or $2\pi \cdot 60 \frac{\text{rad}}{s}$. The third term in (1) represents higher order harmonics, i.e. U_{ih} is amplitude and φ_{ih} is phase of h-th harmonic for phase i. If the grid voltage is balanced, without asymmetrical voltage sags and higher order harmonics, it is clear that $U^n = 0$ and $U_{ih} = 0$ [8].

In order to simplify the notation, (1) can be rewritten in the phasor form

$$\underline{U} = \underline{U}_1 + \sum_h \underline{U}_h \ , \tag{2}$$

where $\underline{U}$ is the phasor corresponding to signal u. Phasors in (2), $\underline{U}_1$ and $\underline{U}_h$, can be represented by their positive and negative sequence components

$$\begin{aligned} \underline{U}_1 &= U^p e^{j\omega_0 t} + U^n e^{-j(\omega_0 t + \varphi_n)} \ , \\ \underline{U}_h &= U_h^p e^{j(h\omega_0 t + \varphi_h^p)} + U_h^n e^{-j(h\omega_0 t + \varphi_h^n)} \ , \end{aligned} \tag{3}$$

where it was assumed that FFPS voltage component is the referent one with zero phase ($\varphi^p = 0$). It is common for 3-phase phenomena analysis to use rotating reference frame (dq) instead of staionary (abc), so Park transformation [9] is applied on (3) and one obtains

$$\begin{aligned} \underline{U}^{dq} &= \underline{U} e^{-j\omega_0 t} = U^p + U^n e^{-j(2\omega_0 t + \varphi_n)} + \\ &+ \sum_h U_h^p e^{\left[j(h-1)\omega_0 t + \varphi_h^p\right]} + U_h^n e^{\left[-j(h+1)\omega_0 t + \varphi_h^n\right]} \ . \end{aligned} \tag{4}$$

We can write $\underline{U}^{dq} = u_d + ju_q$ so (4) can be decoupled to d and q components

$$\begin{aligned} u_d &= U^p + U^n \cos(2\omega_0 t + \varphi_n) \\ &+ \sum_h U_h^p \cos\left[(h-1)\omega_0 t + \varphi_h^p\right] + U_h^n \cos\left[(h+1)\omega_0 t + \varphi_h^n\right], \\ u_q &= -U^n \sin(2\omega_0 t + \varphi_n) \\ &+ \sum_h U_h^p \sin\left[(h-1)\omega_0 t + \varphi_h^p\right] - U_h^n \sin\left[(h+1)\omega_0 t + \varphi_h^n\right] \ . \end{aligned} \tag{5}$$

Finally, from (5) can be concluded if the grid voltage is balanced and without polluting harmonics, d and q components in the steady-state appears as DC values, $u_d = U^p$ and $u_q = 0$.

III. The proposed PLL algorithm

Ideal PLL structure is resistant to disturbances and asymmetries and quickly and accurately determines the phase angle of the grid voltage. PLL control loop is presented in Fig. 1 where we have phase comparator that determines the difference between the phase angle of the input quantity and the estimated angle of the output quantity. This signal is fed to the controller and the output signal from the controller excites the signal generator which generates an estimated value of the grid phase angle that follows the phase angle of the input quantity. In the digital form of PLL algorithm, the most common controller structure is the PI controller [10].

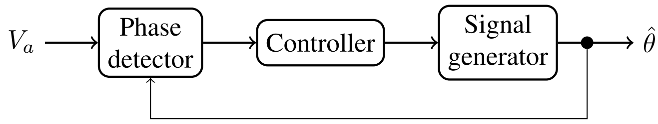

Figure 1: *Generalized PLL control loop*

Nowdays there are various modifications of the PLL algorithm caused by the development of different implementation techniques and different reference coordinate systems in which the estimation of the grid phase angle is performed. One of the most commonly used modifications is Synchronous Frame PLL algorithm or SF-PLL algorithm [11].

SF-PLL algorithm is adapted synchronization algorithm to the specifics of 3-phase systems, which conventional control loop is presented in Fig. 2. By applying this variation of the algorithm, the estimation is performed by setting one component of the grid voltage to zero value and in that way the estimated angle is connected to the vector representation of the grid voltage.

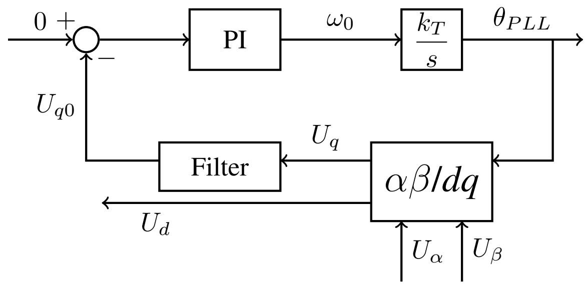

Figure 2: *PLL control loop*

The plant in PLL algorithm can be modelled by transfer function $G_p(s) = \frac{k_T}{s}$, where k_T is linearization gain equal to the grid voltage amplitude, $k_T = U$. Filter in Fig. 2 is not needed if utility voltage is balanced and without higher order harmonics, but without it, PI controller can't cope with oscillations induced by imperfection of grid voltage [8]. Accordingly, the main purpose of all advanced PLL algorithms is to neutralize (filter) oscillatory components.

In this paper, SF-PLL algorithm with multi-resonant disturbance observer was implemented in discrete time domain, as illustrated in Fig. 3. Input variables in control loop shown in Fig. 3 are measured phase voltages u_a, u_b and u_c. After applying Park transformation, 3-phase voltages u_a, u_b, u_c are transformed into u_d and u_q in a synchronously rotating 2-phase system. For these transformed signals, observers were designed to estimate value of higher order harmonics. Since observers used for d and q axis are identical, only the q-axis observer will be described in sequel. Finally, obtained estimated grid frequency and angle are denote $\hat{\omega}$ and $\hat{\theta}$.

A. Observer design

Estimation is the process of evaluating the value of an immeasurable quantity on the basis of available data [2]. In the field of control, it is of interest to estimate values of disturbance signals and states of process. The algorithms

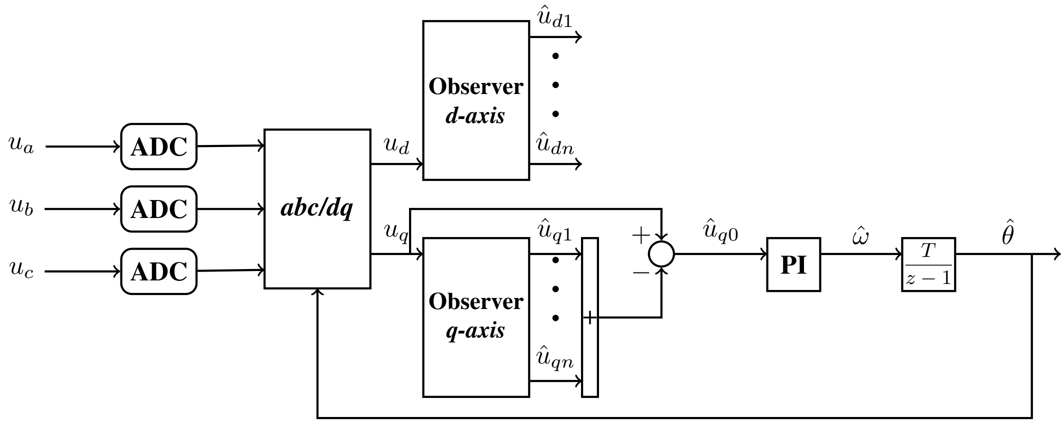

Figure 3: *PLL algorithm with multi-resonant observer (blocks* ***ADC*** *represent analog to digital converters)*

used to perform this estimation are observers and in this paper, multi-resonant observer was designed in discrete time domain.

Discrete-time observer

After applying Park transformation and considering the fact that a superposition of any two harmonic signals of equal frequencies will give another harmonic signal of the same frequency, (5) can be written as

$$\begin{aligned} u_q &= u_{q0} + \sum_{h=1}^{n} u_{qh} \ , \\ u_{qh} &= U_{qhm} \sin(\omega_h kT - \varphi_{qh}) = U_{qhm} \sin(\theta_h k - \varphi_{qh}) \ , \end{aligned} \tag{6}$$

where U_{qhm} is total amplitude and φ_{qh} is the total phase angle of h-th harmonic in dq reference frame, $\theta_h = \omega_h T$ is discrete (digital) frequency, T is sample time and k is ordinal number of samples in the discrete time domain. Higher order harmonics are treated as disturbances in system and reduced-order observer was designed to estimate values of additional harmonics from measured signal. Estimation is performed by imitating a process that generates magnitude of interest. Hence, a linear system was constructed with impulse response equal to the (6) [12]

$$u_{qh}(k+2) - 2\cos(\theta_h) u_{qh}(k+1) + u_{qh}(k) = 0 \ . \tag{7}$$

In order to develop an reduced-order observer, a selection of variable states was made [13]

$$\begin{aligned} x_1(k) &= u_q(k) \ , \\ x_{2h}(k) &= u_{qh}(k) \ , \\ x_{2h+1}(k) &= u_{qh}(k+1) \ . \end{aligned} \tag{8}$$

In shifted discrete time domain variables are

$$\begin{aligned} x_1(k+1) &= x_1(k) - \sum_{h=1}^{n} x_{2h}(k) + \sum_{h=1}^{n} x_{2h+1}(k) \ , \\ x_{2h}(k+1) &= x_{2h+1}(k) \ , \\ x_{2h+1}(k+1) &= -x_{2h}(k) + 2\cos(\theta_h) x_{2h+1}(k) \ , \end{aligned} \tag{9}$$

or in matrix form

$$x(k+1) = \begin{bmatrix} 1 & -1 & 1 & -1 & 1 & \dots \\ 0 & 0 & 1 & 0 & 0 & \dots \\ 0 & -1 & 2\cos(\theta_1) & 0 & 0 & \dots \\ 0 & 0 & 0 & 0 & 1 & \dots \\ 0 & 0 & 0 & -1 & 2\cos(\theta_2) & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} x(k) \ . \tag{10}$$

After selecting state vector $x(k)$, it is convenient to split state vector into to parts: a directly measurable variables $x_1(k)$ and the remaining states $x_{2:}(k) = \begin{bmatrix} x_2(k) & x_3(k) & \dots & x_{2h+1}(k) \end{bmatrix}^T$ [13]. Subsequently, (10) can be rewritten as

$$\begin{aligned} x_1(k+1) &= A_{11} x_1(k) + A_{12} x_2(k) \ , \\ x_{2:}(k+1) &= A_{21} x_1(k) + A_{22} x_2(k) \ , \end{aligned} \tag{11}$$

where

$$\begin{aligned} A_{11} &= 1 \ , \\ A_{12} &= \begin{bmatrix} -1 & 1 & -1 & \dots & 1 \end{bmatrix}_{2n} \ , \\ A_{21} &= \begin{bmatrix} 0 & 0 & 0 & \dots \end{bmatrix}_{2n}^T \ , \\ A_{22} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & \dots \\ -1 & 2\cos(\theta_1) & 0 & 0 & 0 & 0 & \dots \\ 0 & 0 & 0 & 1 & 0 & 0 & \dots \\ 0 & 0 & -1 & 2\cos(\theta_2) & 0 & 0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}_{2n \times 2n} \ . \end{aligned}$$

Mathematical model of reduce-order observer is

$$\begin{aligned} z(k+1) &= A_o z(k) + G u_q(k) \ , \\ \hat{x}_{2:}(k) &= z(k) + L u_q(k) \ . \end{aligned} \tag{12}$$

where z is $2n \times 1$ vector of internal observers states and A_o, G and L are constant parameter matrices of dimension $2n \times 2$, $2n \times 1$ and $2n \times 1$, respectively. Vector L is observer gain matrix [13]. Parameter matrices A_o and G are determined according to

$$\begin{aligned} A_o &= A_{22} - L A_{12} \ , \\ G &= A_{21} - L A_{11} + A_o L \ . \end{aligned} \tag{13}$$

The vector L is selected in such a way to place eigenvalues of A_o at desired locations [8]. Observer characteristic polynomial is calculated on the basis of desired poles

$$f_o(z) = z^{2n} + p_{2n-1}z^{2n-1} + \cdots + p_1 z + p_0 \ . \tag{14}$$

Accordingly, elements of the observer gain vector L can be calculated from

$$f_o(z) = det(zI - A_{22} + LA_{12}) \ . \tag{15}$$

After the observer gain vector L is determined, matrices A_o and G can be calculated from (13). Finally, DC component or utility signal component for synchronization can be reconstructed by subtracting estimated harmonic signals from the measured voltage

$$\hat{u}_{q0} = x_1 - \sum_{h=1}^{n} \hat{x}_{2h} \ , \tag{16}$$

where magnitude $\hat{u}_{q0}$ is used as the input of PLL controller [8].

B. Controller design

Controller was implemented in discrete time domain by means of pole-placement procedure and RST synthesis [14]. In both time domains, desired closed loop characteristic polynomial, i.e. poles of the system in closed loop are selected. These poles completely determine stability and behavior of the system in closed loop. Finally, parameters of observer and controller are selected so to ensure that the actual characteristic polynomial of the closed loop system matches the desired one.

Discrete-time controller

Magnitude $\hat{u}_{q0}$, calculated from (16), is input signal of PLL algorithm, so observer transfer function relating u_q and u_{q0} is [8]

$$G_o(z) = \frac{U_{q0}(z)}{U_q(z)} = k_o \frac{\prod_h (z^2 - 2z\cos(\theta_h) + 1)}{f_o(z)} \ , \tag{17}$$

where z is complex variable in discrete time domain, $f_o(z)$ is the characteristic polynomial of the observer and k_o is its gain. Observer transfer function must have zeros at frequencies ω_h and additional zeros are not allowed, since this can make transfer function $G_o(z)$ improper (degree of the polynomial in the numerator would be greater than the degree of the polynomial in the denominator). Value of the gain k_o can be calculated from the fact that static gain of (17) must be 1

$$\lim_{z \to 1} G_o(z) = 1 \Rightarrow k_o = \frac{f_o(1)}{\prod_h (2 - 2\cos(\theta_h))} \ . \tag{18}$$

RST controllers are a modern management solution in whose structure there are two degrees of freedom of movement and three polynomials - R, S and T. Namely, classic PID controllers have one degree of freedom of movement and can be effective in monitoring setpoints, but not so good in eliminating disturbances. Accordingly, it is desirable to use controllers that have a component of direct control and feedback control such as RST controllers. Typical structure of RST controller is $R(z)U(z) = -S(z)Y(z) + T(z)R_{ref}(z)$, where $R(z)$, $S(z)$ and $T(z)$ are polynomials in RST controller structure, $R_{ref}(z)$ is reference signal and $Y(z)$ is output signal.

As denote on Fig. 3 input signal to the controller is q component of the grid voltage and the output is the estimated grid frequency $\hat{\omega}$. Due to the reference signal is equal to zero, as shown in Fig. 2, which implies that $T(z) = 0$, controller form is

$$R(z)U(z) = -S(z)Y(z) \Rightarrow R(z)U_q(z) = -S(z)\hat{\Omega}(z) \ , \tag{19}$$

where $R(z)$ is denominator, $S(z)$ is numerator of the controller transfer function, $\hat{\Omega}(z)$ and $U_q(z)$ are $\mathcal{Z}$ transforms of the estimated frequency and q component of the grid voltages, respectively. Observer is part of the controller so structure of polynomials $R(z)$ and $S(z)$ should be [8]

$$R(z) = (z-1)f_o(z)R_1(z) \ ,$$
$$S(z) = k_o \prod_h (z^2 - 2zcos(\theta_h))S_1(z) \ ,$$

where $R_1(z)$ and $S_1(z)$ contain remaining factors to be determined in the sequel. Additional integrator is paramount for the ability of the control loop to follow grid angle signal, which has ramp-like behavior [8]. As two integrators are required to follow ramp signal without steady state error, second integrator is in the plant transfer function $G_p(z) = \frac{k_T}{z-1}$.

Characteristic polynomial of the closed loop system is

$$\begin{aligned} f_c(z) = (z-1)^2 f_o(z)R_1(z) + \\ + k_o k_T S_1(z) \prod_h (z^2 - 2z\cos(\theta_h) + 1) \ . \end{aligned} \tag{20}$$

Unknown parameters in (20) can be calculated from the fact that actual characteristic polynomial of the closed loop system must be equal the desired one. This means that number of variables must be equal to the degree of the characteristic polynomial and solution of minimal order is

$$R_1(z) = 1, \ S_1(z) = k_p(z + \sigma) \ ,$$

where k_p and σ are real constants. In fact, kp is the proportional gain and $\sigma = \frac{1}{T_i}$ is the reciprocal of the integral time constant. Finally, obtained characteristic polynomial of the closed loop system is

$$\begin{aligned} f_c(z) = (z-1)^2 f_o(z) + \\ + k_o k_T k_p (z + \sigma) \prod_h (z^2 - 2z\cos(\theta_h) + 1) \ . \end{aligned} \tag{21}$$

In section IV, all previous consideration will be shown in two different simulations: first is case with one harmonic in system and other is case with two harmonics in system.

IV. Simulation results

A. The case with one harmonic

The proposed PLL algorithm has been implemented and tested through simulation in case when grid is symmetrical until $t = 0.1$s, when fifth harmonic amplitude 0.2 [p.u.] appears. In that case there is one polluting harmonic in system ($h = 1$) and characteristic polynomial of closed loop system given by (21), can be written as

$$f_c(z) = (z-1)^2(z^2 + p_1 z + p_0) + \\ + k_o k_T k_p (z+\sigma)(z^2 - 2z\cos(\theta_1) + 1)\ . \tag{22}$$

Desired characteristic polynomial is formed based on the poles a_i that determine stability and performance of the system. Choosing a poles we make a compromise between response speed, disturbance rejection properties, sensitivity to measurement noise, robustness and other characteristics. In this paper, a pair of dominant poles have natural frequency equal to ω_0 ($\omega_0 = 2\pi \cdot 50\frac{\text{rad}}{s}$) and high damping ($\xi \geq 0.7$), while the remaining poles are located deeper within the unit circle. Poles are

$$a_{1,2} = e^{-\frac{\omega_0 \xi}{\sqrt{1-\xi^2}}T \pm j\omega_0 T}\ , \\ a_3 = e^{-2\omega_0 T}\ , \\ a_4 = e^{-4\omega_0 T}\ .$$

where T is sampling time chosen to satisfy Nyquist theorem. In this case, polluting harmonic is at frequency ω_1, so sampling frequency is chosen so that it is equal $\omega_s = 5\omega_1$, where $T = \frac{2\pi}{\omega_s}$ and $\theta_1 = \omega_1 T$. Desired characteristic polynomial is

$$f_c = (z-a_1)(z-a_2)(z-a_3)(z-a_4)\ . \tag{23}$$

Higher order harmonic of interest is fifth harmonic which is seen as harmonic at the frequency $\omega_1 = 4\cdot\omega_0$ in dq reference frame.

By equating desired characteristic polynomial (23) with characteristic polynomial of closed loop system (22), observer gain matrix and controller parameters are obtained:

$$L = \begin{bmatrix} 0.3982 & 0.5676 \end{bmatrix}^T\ , \\ k_p = 0.3866\ , \sigma = -0.8524\ .$$

Phase voltages are shown in Fig. 4, while on Fig. 5 is shown estimated frequency of grid voltage and on Fig. 6 is shown estimation error which represents the difference between actual and estimated value of the phase angle.

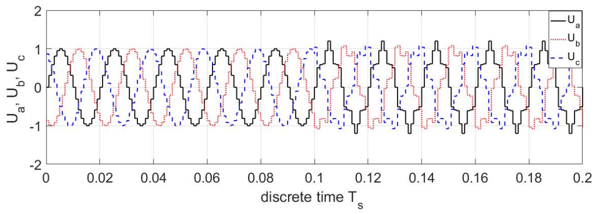

Figure 4: Phase voltages

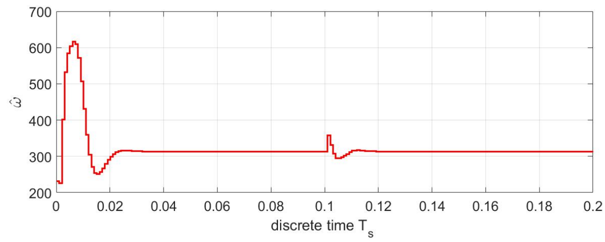

Figure 5: Estimated grid frequency

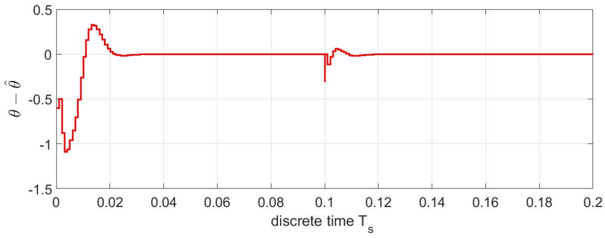

Figure 6: Phase estimation error

B. The case with two harmonics

The proposed PLL algorithm has been implemented and tested through simulation in case when grid is symmetrical until $t = 0.1$s, when fifth harmonic amplitude 0.2 [p.u.] appears and then in $t = 0.2$s seventh harmonic amplitude 0.5 [p.u.] appears. In that case there are two polluting harmonics in system ($h = 2$) and characteristic polynomial of closed loop system given by (21), can be written as

$$f_c(z) = (z-1)^2(z^4 + p_3 z^3 + p_2 z^2 + p_1 z + p_0) + \\ + k_o k_T k_p (z+\sigma)(z^2 - 2z\cos(\theta_1) + 1)(z^2 - 2z\cos(\theta_2) + 1)\ . \tag{24}$$

As in the first case, desired characteristic polynomial is formed based on the poles a_i that determine stability and performances of the system. A pair od dominant poles have natural frequency $\omega_0 = 2\pi\cdot 50\frac{\text{rad}}{s}$ and damping ratio $\xi = 0.7$, while the remaining poles are located deeper within the unit circle. Poles are

$$a_{1,2} = e^{-\frac{\omega_0 \xi}{\sqrt{1-\xi^2}}T \pm j\omega_0 T}\ , \\ a_{3,4} = e^{-2\omega_0 T}\ , \\ a_{5,6} = e^{-4\omega_0 T}\ .$$

where T is sampling time chosen to satisfy Nyquist theorem. In this case, polluting harmonics are at frequencies ω_1 and ω_2 ($\omega_1 < \omega_2$), so sampling frequency is chosen so that it is equal $\omega_s = 5\omega_2$, where $T = \frac{2\pi}{\omega_s}$, $\theta_1 = \omega_1 T$ and $\theta_2 = \omega_2 T$. Desired characteristic polynomial is

$$f_c = (z-a_1)(z-a_2)(z-a_3)(z-a_4)(z-a_5)(z-a_6)\ . \tag{25}$$

Higher order harmonics of interest are fifth and seventh harmonics which are seen as harmonics at the frequencies $\omega_1 = 4\cdot\omega_0$ and $\omega_2 = 6\cdot\omega_0$ in dq reference frame, respectively.

By equating desired characteristic polynomial (25) with characteristic polynomial of closed loop system (24), observer gain matrix and controller parameters are obtained:

$$L = \begin{bmatrix}0.4898 & 0.8004 & -0.5634 & 0.2361\end{bmatrix}^T ,$$
$$k_p = 551.391 \, , \sigma = -0.865 \, .$$

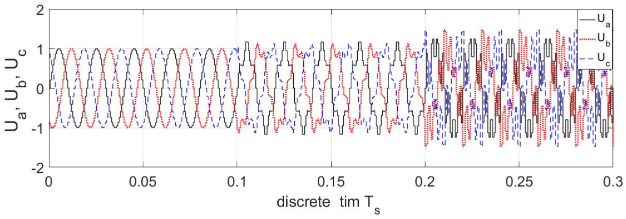

Figure 7: Phase voltages

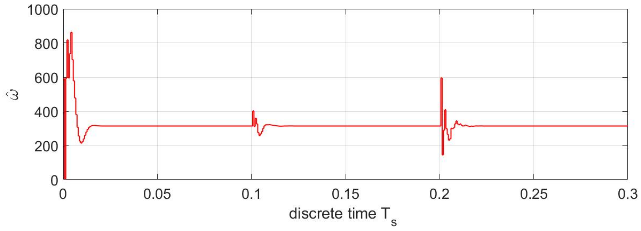

Figure 8: Estimated grid frequency

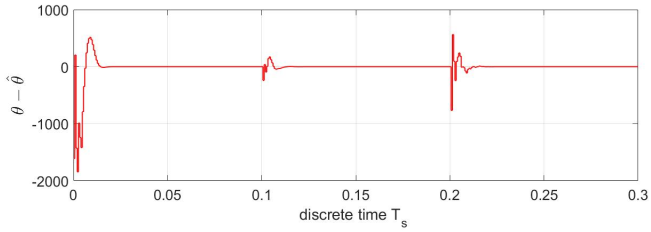

Figure 9: Phase estimation error

Phase voltages are shown in Fig. 7, while on Fig. 8 is shown estimated frequency of grid voltage and on Fig. 9 is shown estimation error which represents the difference between actual and estimated value of the phase angle.

V. Conclusion

Most modern devices are connected to the grid via power electronics devices and it is very important to achieve synchronization between them. Magnitudes of interest for grid synchronization are frequency and phase angle of grid voltage. In this paper, we proposed PLL algorithm for grid synchronization based on multi-resonant observer. Algorithm is implemented with observer which estimate unknown values of polluting higher order harmonics which occur due to the grid imperfection and we treat them as disturbances in system. The proposed PLL algorithm designing process is established as a simple four steps algorithm:

1) Choose the frequencies ω_h of higher order harmonics of interest.
2) Specify the desired closed loop polynomial $f_c(d)$.
3) Compute unknown parameters of controller (k_p, σ) and observer polynomial (p_0, p_1, $\cdots$, p_{2n-1}).
4) Compute observer matrix gain L.

Algorithm control loop is implemented in discrete time domain. After algorithm designing, simulations were done in case when fifth and seventh harmonics appear as disturbances in the system. The results demonstrated the efficiency of the proposed PLL algorithm which is capable of achieving phase synchronization despite voltage unbalances and higher order harmonics.

VI. Acknowledgment

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