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Frequency Adaptive Parameter Estimation of Unbalanced and Distorted Power Grid

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ABSTRACT Grid synchronization plays an important role in the grid integration of renewable energy sources. To achieve grid synchronization, accurate information of the grid voltage signal parameters are needed. Motivated by this important practical application, this paper proposes a state observer-based approach for the parameter estimation of unbalanced three-phase grid voltage signal. The proposed technique can extract the frequency of the distorted grid voltage signal and is able to quantify the grid unbalances. First, a dynamical model of the grid voltage signal is developed considering the disturbances. In the model, frequency of the grid is considered as a constant and/or slowly-varying but unknown quantity. Based on the developed dynamical model, a state observer is proposed. Then using Lyapunov function-based approach, a frequency adaptation law is proposed. The chosen frequency adaptation law guarantees the global convergence of the estimation error dynamics and as a consequence, ensures the global asymptotic convergence of the estimated parameters in the fundamental frequency case. Gain tuning of the proposed state observer is very simple and can be done using Matlab commands. Some guidelines are also provided in this regard. Matlab/Simulink based numerical simulation results and dSPACE 1104 board-based experimental results are provided. Test results demonstrate the superiority and effectiveness of the proposed approach over another state-of-the art technique.

INDEX TERMS Unbalance estimation, frequency estimation, phase estimation, adaptive estimation.

I. INTRODUCTION

Recent years have seen an exponential growth in the grid integration of renewable energy sources *e.g.* wind, solar. This has led to an increasing effort on the research and development activity in synchronization and control of renewable energy powered grid-connected converters [1]–[8]. In this regard, detecting the phase of the three-phase grid voltage's fundamental frequency positive sequence (FFPS) is an important technical challenge for the control and synchronization purposes. However, the ever increasing presence of harmonic disturbances and unbalances are making the problem challenging. Moreover, in addition to the phase, quantifying the unbalances are very important for monitoring and control purpose.

Phase-locked loop (PLL) [9]–[16] is the most popular technique available in the literature to detect the phase and frequency of the grid voltage signal. PLL can be used in both single and three-phase case. As such, PLL has been used in conjunction with many other techniques to estimate the phase and frequency of the FFPS. Synchronous reference frame (SRF-PLL) is the most popular one among them. However SRF-PLL suffers in the presence of unbalances. To overcome the limitation, a decoupled double synchronous reference frame PLL (DDSRF-PLL) is proposed in [11]. In similar line of research, many other PLLs have been proposed in the literature e.g. delayed signal cancellation PLL (DSC-PLL) [17], cascaded DSC-PLL (CDSC-PLL) [18], repetitive learning-based PLL [19] to name a few. For a detailed review on three-phase grid synchronization techniques, [20], [21] and the references therein can be consulted.

Some modifications of SRF-PLL rely on quadratic signal generator (QSG). Second order generalized integrator

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(SOGI) [22], [23] is a popular QSG technique. To deal with the unbalanced grid, Double SOGI filter-based PLL (DSOGI-PLL) has been proposed in [24], [25] to estimate the frequency and phase of FFPS. However, the presence of harmonics, may give rise to large errors. To overcome this issue, multiple SOGI filter-based technique have been proposed in the PLL [26] or frequency-locked loop (SOGI-FLL) [27] framework. Enhanced PLL [28] and adaptive notch filter (ANF) [29] are some other QSG-based techniques to estimate the phase of FFPS. All the above mentioned techniques have satisfactory performances, however, global convergence and zero steady-state error in the presence of harmonics and unbalances can not be guaranteed since only local stability analysis are available.

Observer-based technique is another recent addition in the grid synchronization literature [30]–[33]. Observer has also been applied to control of power electronic system [34]. In observer-based approach, using parameterized dynamical model, Luenberger observers are used to estimate the parameters of the grid voltage signal. However, using this type of approach, the design process can be very complex e.g. [30] or lead to lots of parameter to tune e.g. [31], [32] ($3 \times n$ parameters to tune, where n is the number of harmonic components). All techniques mentioned so far use closed-loop technique to estimate the parameters. It is to be mentioned here that there are some open or pseudo-open loop techniques [35] available in the literature as well to estimate the parameters.

From the literature review, it is clear that there is a need of fast and accurate estimator that is globally convergent (at least for the fundamental frequency component) with low number of parameters to tune and robust to unbalanced faults and harmonics. This paper aims to fill this gap. In this paper, following the directions of [33], a frequency adaptive state observer for three-phase system is proposed that is globally convergent for the fundamental frequency component and robust to unbalance and harmonics. In addition, quantifying the unbalances is another property of the proposed estimator. Proposed approach is time-domain based and filtering free. As such bandwidth is not an issue in this case. The proposed adaptive state observer is simple to tune using pole-placement principle and easy to implement in embedded hardware e.g. micro-controller, DSP, FPGA.

The rest of the paper is organized as follows: Development of the parameterized dynamical model and design of the observer is given in Sec. II. Comparative experimental results are given in Sec. III. Finally Sec. IV concludes this paper.

II. PARAMETER ESTIMATION APPROACH

A. PARAMETERIZED DYNAMICAL MODEL DEVELOPMENT

Unbalanced and harmonically distorted three-phase grid voltage signal can be written as,

$$V_i = \sum_{k=1,3,}^{2n-1} V_k^+ \cos\{\underbrace{k\omega t + \varphi_k^+ - \frac{2\pi i}{3}}_{\psi_k^+}\} + \sum_{k=1,3,}^{2n-1} V_k^- \cos\{\underbrace{k\omega t + \varphi_k^- + \frac{2\pi i}{3}}_{\psi_k^-}\} \quad (1)$$

where $i = 0, 1, 2$ represent the phase a, b, and, c respectively, $V_k^+(V_k^-)$ and $\psi_k^+(\psi_k^-)$ represent the amplitude and phase angle of the positive (negative) sequence k-th harmonic components. By applying the Clarke transformation [36]:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \underbrace{\frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}}_{T_{\alpha\beta}} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

grid voltage signal (1) can be represented in the $\alpha\beta$- coordinate as:

$$V_\alpha = \sum_{k=1,3,}^{2n-1} V_{\alpha k}^+ \cos(\underbrace{k\omega t + \phi_{\alpha k}^+}_{\psi_{\alpha k}^+}) + V_{\alpha k}^- \cos(\underbrace{k\omega t + \phi_{\alpha k}^-}_{\psi_{\alpha k}^-}) \quad (2a)$$

$$V_\beta = \sum_{k=1,3,}^{2n-1} V_{\beta k}^+ \sin(\underbrace{k\omega t + \phi_{\beta k}^+}_{\psi_{\beta k}^+}) - V_{\beta k}^- \sin(\underbrace{k\omega t + \phi_{\beta k}^-}_{\psi_{\beta k}^-}) \quad (2b)$$

where $V_{\alpha k}^+, V_{\beta k}^+, (V_{\alpha k}^-, V_{\beta k}^-)$ and $\psi_{\alpha k}^+, \psi_{\beta k}^+(\psi_{\alpha k}^-, \psi_{\beta k}^-)$ represent the amplitude and phase angle of the positive (negative) sequence of the k-th harmonic components in the $\alpha\beta$-coordinate. Then, the problem being considered in this paper is to estimate the grid frequency, phase and amplitude of positive and negative sequence voltages from the available measurement V_α and V_β.

To solve the above-mentioned problem, a observer-based framework is considered in this paper. For further consideration, let us assume that for $j = 1, 2, \ldots, n-1$:

$$\begin{aligned} x_{j\alpha} &= V_{\alpha k}^+ \cos\psi_{\alpha k}^+ + V_{\alpha k}^- \cos\psi_{\alpha k}^-, \\ x_{(j+1)\alpha} &= \dot{x}_{j\alpha} = -k\omega(V_{\alpha k}^+ \sin\psi_{\alpha k}^+ + V_{\alpha k}^- \sin\psi_{\alpha k}^-), \\ x_{(j+2)\alpha} &= \ddot{x}_{j\alpha} = -k^2\omega^2 x_{j\alpha} = -\tau k^2 \omega_n^2 x_{j\alpha} \end{aligned}$$

with $\omega^2 = \tau\omega_n^2$ where $\omega_n = 2\pi 50$ is the nominal grid frequency. Then the dynamics of the V_α can be written as,

$$\dot{\zeta}_\alpha = Q_\alpha \zeta_\alpha \quad (3a)$$

$$y_\alpha = R_\alpha \zeta_\alpha \quad (3b)$$

where $\zeta_\alpha = [\,x_{1\alpha}\ x_{2\alpha}\ \ldots\ x_{(2n-1)\alpha}\ x_{2n\alpha}\,]^T$ and the matrices Q_α and R_α are given by,

$$\begin{aligned} R_\alpha &= [\,1 \quad 0 \quad 1 \quad 0 \quad \ldots \quad 1 \quad 0 \quad 1\,], \\ Q_\alpha &= \text{blkdiag}\{Q_1\ Q_3\ \ldots Q_{2n-1}\}, \\ Q_k &= \begin{bmatrix} 0 & 1 \\ -\tau k^2 \omega_n^2 & 0 \end{bmatrix}. \end{aligned}$$

where blkdiag represents the block diagonal matrix.

To obtain the linearly parameterized dynamical model of the voltage V_β, let us assume that for $j = 1, 2, \ldots, n-1$

$$\begin{aligned} x_{j\beta} &= V_{\beta k}^{+} \sin \psi_{\beta k}^{+} - V_{\beta k}^{-} \sin \psi_{\beta k}^{-}, \\ x_{(j+1)\beta} &= \dot{x}_{j\beta} = k\omega(V_{\beta k}^{+} \cos \psi_{\beta k}^{+} - V_{\beta k}^{-} \cos \psi_{\beta k}^{-}) \\ x_{(j+2)\beta} &= \ddot{x}_{j\beta} = -k^2\omega^2 x_{j\beta} = -\tau k^2 \omega_n^2 x_{j\beta} \end{aligned}$$

Then the dynamics of the V_β can be written as,

$$\dot{\zeta}_\beta = Q_\beta \zeta_\beta \quad (4a)$$

$$y_\beta = R_\beta \zeta_\beta \quad (4b)$$

where $\zeta_\beta = [x_{1\beta}\ x_{2\beta}\ \ldots\ x_{(2n-1)\beta}\ x_{2n\beta}]^T$ and the matrices Q_β and R_β are given by,

$$\begin{aligned} R_\beta &= [1 \quad 0 \quad 1 \quad 0 \quad \ldots \quad 1 \quad 0 \quad 1], \\ Q_\beta &= \text{blkdiag}\{Q_1\ Q_3\ \ldots Q_{2n-1}\}, \\ Q_k &= P\begin{bmatrix} 0 & 1 \\ -\tau k^2\omega_n^2 & 0 \end{bmatrix}. \end{aligned}$$

System (3) and (4) are observable as the observability matrix is of full rank. Then the design of a state observer is straightforward and will be considered in the following section. Since both state and output matrices are the same for α and β dynamics, instead of writing everything separately in α and β coordinates, α/β notation would be used from now on for compact representation.

B. STATE OBSERVER DESIGN

To facilitate the observer design for the $V_{\alpha/\beta}$ dynamics, let us introduce the following coordinate transformation:

$$\begin{aligned} \eta_{\alpha/\beta} &= W\zeta_{\alpha/\beta}, \\ W &= \text{blkdiag}\{W_1\ W_3\ \ldots W_{2n-1}\}, \\ W_k &= \frac{(1+\tau)^{-1}}{k^2\omega_n^2}\begin{bmatrix} 1 & -\frac{1}{k\omega_n} \\ \tau k\omega_n & 1 \end{bmatrix} \end{aligned}$$

In the transformed coordinates, systems representing $V_{\alpha/\beta}$ dynamics (3) and (4) become:

$$\dot{\eta}_{\alpha/\beta} = A\eta_{\alpha/\beta} \quad (5a)$$

$$y_{\alpha/\beta} = C\eta_{\alpha/\beta} \quad (5b)$$

where $A = WQ_{\alpha/\beta}W^{-1} = Q_{\alpha/\beta}$ and $C = R_{\alpha/\beta}W^{-1}$. Then for system (5), the following state observer can be designed:

$$\dot{\hat{\eta}}_{\alpha/\beta} = \hat{A}\hat{\eta}_{\alpha/\beta} + L\left(y_{\alpha/\beta} - C\hat{\eta}_{\alpha/\beta}\right) \quad (6a)$$

$$\hat{y}_{\alpha/\beta} = C\hat{\eta}_{\alpha/\beta} \quad (6b)$$

$$\begin{aligned} \hat{A} &= \text{blkdiag}\{\hat{A}_1\ \hat{A}_3\ \ldots \hat{A}_{2n-1}\}, \\ \hat{A}_k &= \begin{bmatrix} 0 & 1 \\ -\hat{\tau}k^2\omega_n^2 & 0 \end{bmatrix}. \end{aligned}$$

where $\hat{\eta}_{\alpha/\beta}$ is the estimated value of $\eta_{\alpha/\beta}$, $\hat{y}$ is the estimated value of $y_{\alpha/\beta}$, $\hat{A}$ is the estimate of A with $\hat{\tau}$ being the estimated value of τ and L is the observer gain matrix (with $A - LC$ being Hurwitz) to be designed later. To check the convergence of the observer, let us consider the state estimation error as, $\eta_\epsilon = \eta - \hat{\eta}$ and the parameter estimation error as, $\tau_\epsilon = \tau - \hat{\tau}$. Moreover, for the sake of mathematical simplicity, assume that only the fundamental component is present i.e. $k = 1$. In this case, the state estimation error dynamics can be written as:

$$\begin{aligned} \dot{\eta}_\epsilon &= (A - LC)\eta_\epsilon + (A - \hat{A})\hat{\eta} \\ &= \tilde{A}\eta_\epsilon + B\tau_\epsilon\omega_n^2\hat{\eta}_{1\alpha} \end{aligned}$$

where $\tilde{A} = A - LC$ and $B = [0\ \ 1]^T$. Since $\tilde{A}$ is Hurwitz, then it is straight forward to show that the system is strictly positive real and as such there exists a positive definite matrix $P > 0$ for which $\tilde{A}^T P + P\tilde{A} < 0$. Moreover, $PB = C^T$ [37]. Then consider the following Lyapunov function:

$$\begin{aligned} V &= \eta_\epsilon^T P\eta_\epsilon + \kappa^{-1}\tau_\epsilon^2, \kappa > 0 \\ \dot{V} &= \eta_\epsilon^T(\tilde{A}^T P + P\tilde{A})\eta_\epsilon + 2\eta_\epsilon^T PB\tau_\epsilon\omega_n^2\hat{\eta}_{1\alpha} - 2\kappa^{-1}\tau_\epsilon\dot{\hat{\tau}} \end{aligned} \quad (7)$$

In the above calculation, we have assumed that the grid frequency is unknown but constant and/or slowly varying *i.e.* $\dot{\tau} = 0$. This assumption may seems restrictive. However, it simplifies the calculation. Through experimental results in Sec. III, it is shown that this assumption is not restrictive in practice. The first term in Eq. (7) is always < 0. Next,

$$2\eta_\epsilon^T PB\tau_\epsilon\omega_n^2\hat{\eta}_{1\alpha} = 2y_\epsilon\tau_\epsilon\omega_n^2\hat{\eta}_{1\alpha}$$

where $y_\epsilon = y - C\hat{\eta}$. If the parameter update law is selected as:

$$\dot{\hat{\tau}} = \kappa y_\epsilon\omega_n^2\hat{\eta}_{1\alpha} \quad (8)$$

Then eq. (7) becomes, $\dot{V} \le 0$. This ensures the global stability of the observer according to Lyapunov's second method. Then by applying, LaSalle's invariance principle [37], the asymptotic stability of the observer error dynamics can be easily shown and avoided here for the purpose of brevity. In the case of harmonics, the following parameter update law can be considered:

$$\dot{\hat{\tau}} = -\kappa\omega_n^3(\hat{\eta}_{1\alpha} + 3^3\hat{\eta}_{3\alpha} + (2n-1)^3\hat{\eta}_{(2n-1)\alpha})y_\epsilon \quad (9)$$

However, in this case, the global convergence can not be guaranteed.

With the estimated values of τ and $\eta_{\alpha/\beta}$, the original state variables can be calculated using the following formula:

$$\begin{aligned} \hat{\zeta}_{\alpha/\beta} &= \hat{W}^{-1}\hat{\eta}_{\alpha/\beta}, \\ \hat{W}^{-1} &= \text{blkdiag}\{\hat{W}_1^{-1}\ \hat{W}_3^{-1}\ \ldots \hat{W}_{2n-1}^{-1}\}, \\ \hat{W}_k^{-1} &= (k\omega_n)^2\begin{bmatrix} 1 & \frac{1}{k\omega_n} \\ -\hat{\tau}k\omega_n & 1 \end{bmatrix} \end{aligned} \quad (10)$$

where $\hat{W}$ is the estimate of W with τ is being replaced by $\hat{\tau}$. From the estimated $\hat{\zeta}_{\alpha/\beta}$, fundamental positive and negative sequence voltages can be estimated as:

$$\hat{V}_{i\alpha}^{+} = \frac{\hat{x}_{i\alpha} + \frac{\hat{x}_{(i+1)\beta}}{\hat{\omega}_i}}{2}, \hat{V}_{i\alpha}^{-} = \frac{\hat{x}_{i\alpha} - \frac{\hat{x}_{(i+1)\beta}}{\hat{\omega}_i}}{2} \quad (11a)$$

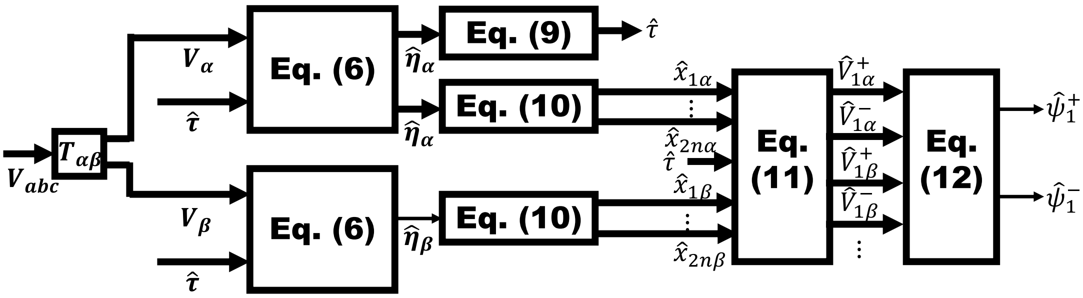


FIGURE 1. Block diagram of the proposed adaptive observer.

$$\hat{V}_{i\beta}^{+} = \frac{-\frac{\hat{x}_{(i+1)\alpha}}{\hat{\omega}_i} + \hat{x}_{i\beta}}{2}, \hat{V}_{i\beta}^{-} = \frac{\frac{\hat{x}_{(i+1)\alpha}}{\hat{\omega}_i} + \hat{x}_{i\beta}}{2} \quad (11b)$$

The phase and amplitude of the individual positive and negative sequence voltages can be estimated as,

$$\hat{\psi}_i^{+} = \arctan\left(\frac{\hat{V}_{i\beta}^{+}}{\hat{V}_{i\alpha}^{+}}\right), \hat{\psi}_i^{-} = \arctan\left(\frac{-\hat{V}_{i\beta}^{-}}{\hat{V}_{i\alpha}^{-}}\right) \quad (12a)$$

$$\hat{V}_i^{+} = \sqrt{(\hat{V}_{i\alpha}^{+})^2 + (\hat{V}_{i\beta}^{+})^2}, \hat{V}_i^{-} = \sqrt{(\hat{V}_{i\alpha}^{-})^2 + (\hat{V}_{i\beta}^{-})^2} \quad (12b)$$

To implement the proposed adaptive observer, eq. (6) and (9)-(12) are required. Block diagram of the proposed adaptive observer is given in Fig. 1.

Proposed observers as designed above, use time-domain technique. Here some lights will be shed on the frequency domain characteristics. The observers are designed for any number of harmonic components. However, this will make the frequency domain analysis complicated. To simplify the analysis, let us assume that the three-phase grid voltage has only fundamental component. In this case, the state variables in the transformed coordinates are $\boldsymbol{\eta} = [\eta_1 \ \eta_2]_{\alpha/\beta}^T$. The proposed technique uses idea similar to frequency-locked loop (FLL) and the closed-loop system is nonlinear. In this case, linear system analysis tool e.g. frequency response based on transfer function can not be applied directly. However, in the FLL literature [38], quasi-locked state (i.e. $\omega \approx \hat{\omega}$) is often assumed for the analysis purpose. This approach will be used here as well. In the quasi-locked case, the observer dynamics (6) can be written as:

$$\begin{bmatrix} \dot{\hat{\eta}}_1 \\ \eta_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\hat{\omega}^2 & 0 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} + \underbrace{\begin{bmatrix} l_1 \\ l_2 \end{bmatrix}}_{L} \underbrace{(y - C\eta)}_{e} \quad (13)$$

where the subscript α/β are avoided for notional simplicity. From (13), the following transfer functions can be obtained:

$$\frac{\hat{\eta}_1}{y}(s) = \frac{l_1 s + l_2}{s^2 + (l_1\omega_n^2 + l_2\omega_n)s + l_2\omega_n^2 - l_1\hat{\omega}^2\omega_n + \hat{\omega}^2} \quad (14a)$$

$$\frac{\hat{\eta}_2}{y}(s) = \frac{l_2 s - l_1\hat{\omega}^2}{s^2 + (l_1\omega_n^2 + l_2\omega_n)s + l_2\omega_n^2 - l_1\hat{\omega}^2\omega_n + \hat{\omega}^2} \quad (14b)$$

$$\frac{e}{y}(s) = \frac{s^2 + \hat{\omega}^2}{s^2 + (l_1\omega_n^2 + l_2\omega_n)s + l_2\omega_n^2 - l_1\hat{\omega}^2\omega_n + \hat{\omega}^2} \quad (14c)$$

Bode diagram for the transfer function (14a) and (14b) are given in Fig. 2 where the considered parameters are:

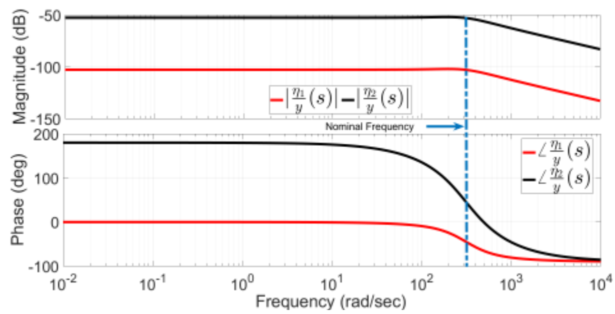


FIGURE 2. Bode diagram of the transfer function (14a) and (14b).

$l_1 = 0.0023$, $l_2 = 0.7071$ and $\hat{\omega} = \omega_n = 100\pi$. From the Bode diagram, it can be seen that both transfer function behave similar to low-pass filter with the fundamental frequency being the cut-off frequency. This can be very useful to reject various disturbances e.g. noise.

1) OBSERVER PARAMETER TUNING

The proposed observer has two tuning parameters, the observer gain matrix, L and the frequency identification parameter, κ. To tune the gain matrix L, pole placement can be used. For the closed-loop system, one potential choice is to select the poles as $-1.5\omega_n \pm i\omega_n$, $-1.5 \times (3\omega_n) \pm i(3\omega_n)$ etc. Once the desired poles are selected, then the observer gain matrix L can be easily found by using the Matlab command `acker` or `place`. Frequency identification parameter κ determines the transient response (speed of convergence, maximum peak-overshoot *etc.*). Higher value of κ speeds up the convergence but at the cost of accuracy and very large peak-overshoot. As such κ can be selected as a trade-off between accuracy and convergence speed. Through extensive simulation, we found 2.5 to be a good value for κ offering a balance between convergence speed and accuracy.

III. NUMERICAL SIMULATION AND EXPERIMENTAL RESULTS

In this Section, Matlab/Simulink-based simulation and dSPACE 1104 board-based hardware-in-the-loop experimental studies are considered to verify the feasibility and performance of the proposed approach. An overview of the experimental setup is given in Fig. 3. The setup used in this work use the dSPACE 1104 board to generate the three-phase grid voltage signals. The generated grid voltage signals are

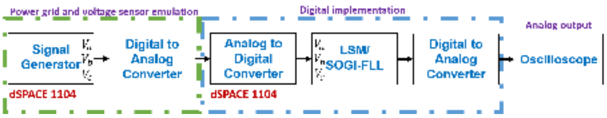


FIGURE 3. Hardware in the loop experimental setup overview [35].

TABLE 1. Number of mathematical operations involved in the implementation of proposed technique and multi-resonant double SOGI-FLL.

	×	±	÷	SQRT	arctan	$\int$
SOGI-FLL	20	13	1	1	1	5
Proposed	26	3	4	2	1	5

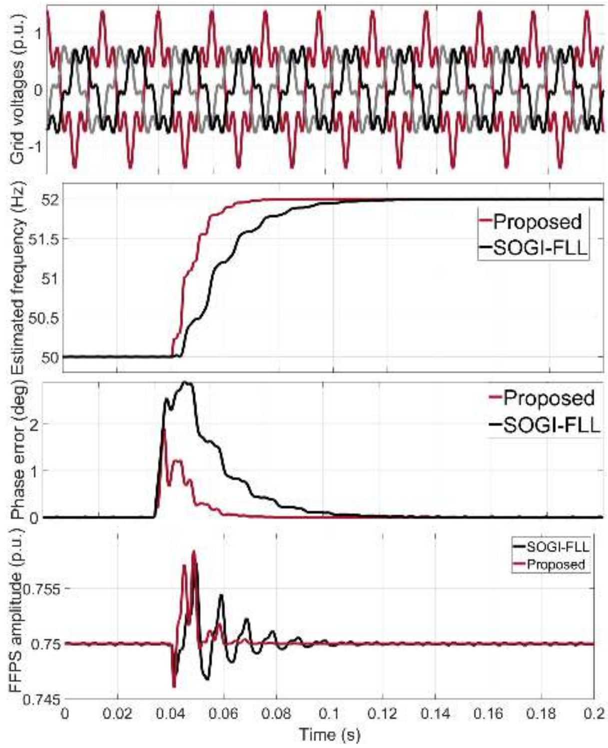
SQRT - square root, $\int$ - integrators

first passed through the digital to analog converter (DAC) outputs to create the physical signal. These physical signals are then passed through the analog to digital converter (ADC) input block to make them suitable for the algorithms implemented in digital form. This is achieved by physically connecting the DAC output to ADC input. This constitutes the complete hardware in the loop (HIL) experimental setup. In grid synchronization literature, HIL experimental study is not uncommon [35], [39].

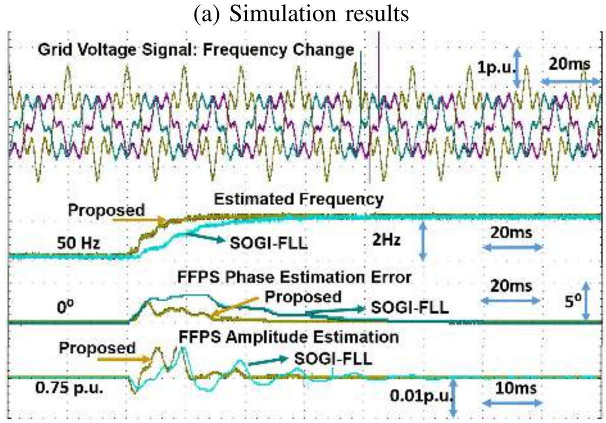
For the performance verification purpose, an unbalanced three-phase grid voltage signal has been considered with fundamental and fifth-order harmonics. The base signal is given by: $\overrightarrow{V}^{+1} = 0.75\angle 0°$, $\overrightarrow{V}^{-1} = 0.25\angle 0°$, $\overrightarrow{V}^{+5} = 0.7\angle 0°$, $\overrightarrow{V}^{-5} = 0.2\angle 0°$. Following the guidelines in II-B1, closed-loop poles are selected as $-1.5\omega_n \pm i\omega_n$ and $-7.5\omega_n \pm i5\omega_n$. The using `place` command in Matlab, the value of L is found. Frequency identification parameter is selected as $\kappa = 2.5$ With the selected values of L and κ, the proposed observer (Fig. 1) is implemented in Matlab/Simulink with a sampling frequency of 10KHz. As a comparison technique, state-of-the-art multi-resonant double SOGI-FLL [27] is selected. Parameters of the SOGI-FLL are selected as $k = \sqrt{2}$ and $\gamma = 50$. Number of mathematical operations involved in the proposed technique and the comparative technique one are given in Table 1. It is to be noted here that only the fundamental frequency component with unbalanced grid case is considered. From Table 1, it can be seen that the proposed technique requires few more mathematical operations than double SOGI-FLL. However, the comparative performances as presented in this Section justifies the additional mathematical operations. Moreover, in today's high-performance micro-controllers, the implementation of few more mathematical operations will not increase the computational complexity significantly. In the presence of harmonic components, the computational complexity of both techniques will increase linearly according to the number of harmonic components. That is why the computational complexity comparison part considers the fundamental frequency case only.

To test the algorithms, following test cases are considered:

1) Test-I: +2Hz. frequency jump.
2) Test-II: −25% voltage sag
3) Test-III: +45° phase change in positive sequence and −45° in negative sequence.



(a) Simulation results

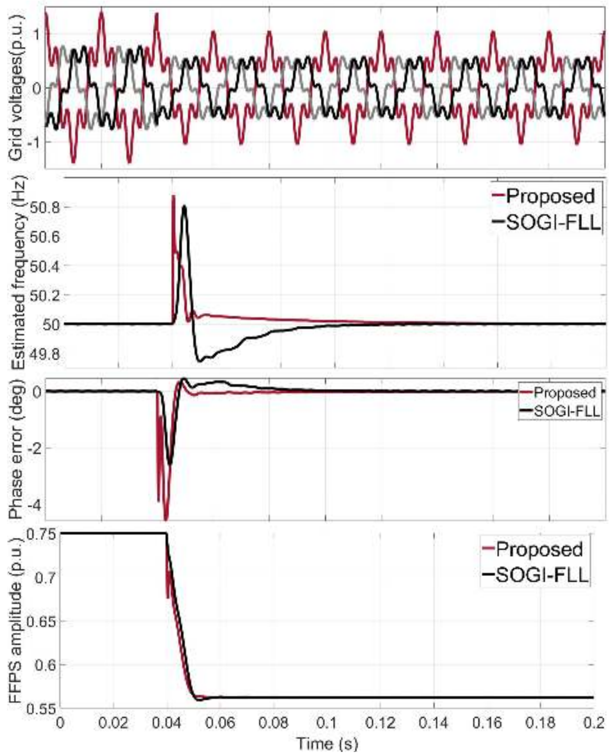


(b) Experimental results

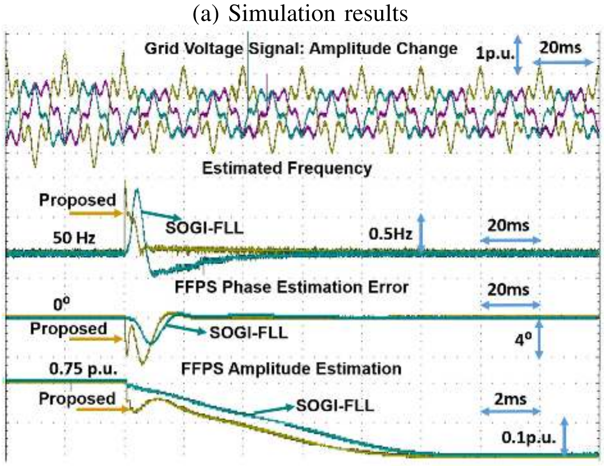
FIGURE 4. Simulation and experimental results for Test-I.

A. TEST-I: +2HZ. FREQUENCY JUMP

In this test scenario, sudden jump in the frequency of the grid voltage signal is considered. The grid voltage signal, estimated frequencies, phase estimation errors and the amplitude of the FFPS for this test are given in Fig. 4. From the test results shown in Fig. 4, it can be seen that the proposed technique has very fast convergence rate w.r.t. the comparative technique SOGI-FLL. The frequency estimated the proposed technique converged very fast in slightly more than 1 cycle while SOGI-FLL took more than 2 cycles. In terms of phase estimation error, proposed technique converged in ≈ 1 cycle with 50% smaller peak overshoot w.r.t. SOGI-FLL. Similar excellent performance by the proposed technique can be seen in estimating the FFPS amplitude as well. These results clearly demonstrate that the proposed technique is very capable to deal with sudden change in the grid voltage signal.

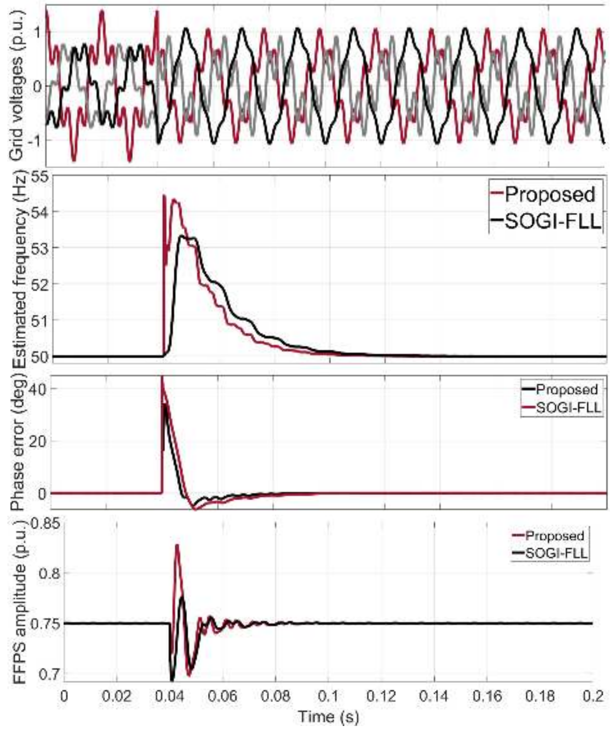


(a) Simulation results

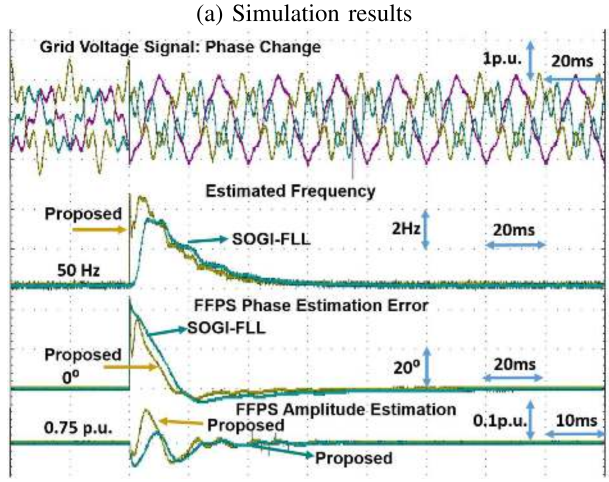


(b) Experimental results

FIGURE 5. Simulation and experimental results for Test-II.



(a) Simulation results



(b) Experimental results

FIGURE 6. Simulation and experimental results for Test-III.

B. TEST-II:−25% VOLTAGE SAG

Due to various faults in the grid, amplitude of the grid voltage signal may drop suddenly. This kind of challenging test condition is considered in Test-II. The grid voltage signal, estimated frequencies, phase estimation errors and the amplitude of the FFPS for this test are given in Fig. 5. From the test results, fast convergence rate can be observed for the proposed technique similar to Test-I. Fig. 5 shows that both techniques are very quick to detect the change in the grid voltage. The frequency estimation error took $\approx$ 1 cycle to converge by the proposed technique while it is at least two time more for the SOGI-FLL although both techniques have similar peak overshoot. In terms of phase estimation error, proposed technique took $\approx$ 0.5 cycle to converge while SOGI-FLL took $\approx$ 2 cycles although with lower peak overshoot. Finally, very similar performances can be observed for the FFPS amplitude estimation. Test results show that the amplitude estimated by the proposed technique converged slightly faster than the comparative technique. Test results in Fig. 5 show that the proposed technique is very suitable to deal with sudden change in the grid voltage amplitude.

C. TEST-III: SUDDEN CHANGE IN PHASE ANGLE

Sudden change in phase angle is a very challenging test scenario for any grid synchronization technique. In this test, simultaneous change in phase angle of the positive and negative sequence components are considered. The grid voltage signal, estimated frequencies, phase estimation errors and the amplitude of the FFPS for this test are given in Fig. 6. According to the test results, both techniques have similar convergence time, however, the proposed technique reacts much faster than SOGI-FLL. This can be very useful when the grid synchronization technique is used in conjunction with grid synchronizing current controller. Fast rise time may be very helpful to stabilize the closed-loop control system when sudden phase angle change happens.

IV. CONCLUSION AND FUTURE WORKS

This paper has proposed a state observer-based parameter estimation approach for three-phase grid voltage signal subject to unbalanced faults and harmonics. In addition, real-time quantification of the unbalances is another property of the proposed technique. The proposed solution is based on a linear model of the grid voltage signal with unknown frequency. Lyapunov function-based approach is used to analyze the stability and convergence of the observer and to obtain the frequency update law. Proposed frequency adaptive observer guarantees global asymptotic stability of the parameter estimation error in the fundamental frequency case which is a very desirable theoretical property in practice. Three challenging test scenarios are considered for simulation and experimental verifications. Test scenarios are generated by considering discontinuous jump in amplitude, frequency and phase. Test results demonstrate the suitability and effectiveness of the proposed technique. In the classical PLL, there is a trade-off between fast dynamic response and disturbance rejection capability. Proposed approach can be very useful in this regard as no filtering is involved. In this paper, only HIL experimental study is considered. The application of proposed technique in the grid synchronization of three-phase grid connected inverter will be considered in a future work.

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