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Improved Grid Synchronization Algorithm for DG System using and UH PLL under Grid disturbances

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ABSTRACT : *Distributed Generation (DG) System is a small scale electric power generation at or near the user's facility as opposed to the normal mode of centralized power generation. In order to ensure safe and reliable operation of power system based on DS, grid synchronization algorithm plays a very important role. Unbalanced Harmonic (UH) based phase locked loop (PLL) aimed to provide an estimation of the angular frequency and both the positive and negative sequences of the fundamental component of an unbalanced three-phase signal. The UH PLL does not require transformation of variables into synchronous reference frame coordinates. Therefore, the proposed scheme is not based on the phase angle detection. Instead the angular frequency is detected and used for synchronization purposes. The design of this PLL is based on a complete description of the source voltage involving both positive and negative sequences in stationary coordinates and considering the angular frequency as an uncertain parameter. Therefore UHPLL is intended to perform properly under severe unbalanced conditions and to be robust against angular frequency variations, sags and swells in the three-phase utility voltage signal.*

INDEX TERMS: *Grid synchronization, phase locked loop, power quality, grid disturbances, positive and negative sequence detection, synthesis circuit, adaptive control, frequency estimation.*

I. INTRODUCTION

The power generation systems based on renewable energy systems are distributed near the user's facility. These Distributed Generation (DG) systems need to be controlled properly in order to ensure sinusoidal current injection into the grid. However, they have a poor controllability due to their intermittent characteristics [3]. The major issue associated with DG system is their synchronization with utility voltage vector [4]. Henceforth the study of grid synchronization algorithms is essential. Few of the earliest known synchronization algorithms Include Zero Crossing Detectors (ZCDs). The performance of ZCDs is badly affected by power quality problems, especially in the case of weak grid. The use of Phase Locked Loops (PLLs) for grid synchronization has shown much better results as it has been discussed in [5]. The Linear PLL is mainly used to detect phase for single phase supply. For balanced three phase supply, Synchronous Reference Frame (SRF) PLL is used. But it is found that this PLL fails to detect the phase for unbalanced supply [6]. Hence Decoupled Double Synchronous Reference Frame (DDSRF) PLL was proposed to deal with unbalanced grid conditions like voltage unbalance [7]. DDSRF PLL can detect the positive sequence phase angle in such conditions. Double Synchronous Reference PLL based on synthesis circuit was proposed in [6] which is more frequency adaptive and can be easily implemented.This paper also presents an algorithm to implement a PLL, which is able to provide an estimation of the angular frequency and both the positive and negative sequences of the fundamental component of an unbalanced three-phase signal. These sequences are provided in fixed-reference-frame coordinates. The synchronization process in the UH-PLL is based on the detection of the fundamental frequency [17]–[20]. The overall design of the UH-PLL does not assume a linearization process as in most conventional PLLs, which are based on the assumption sin x = x for x that is arbitrarily small. Instead, the design and analysis follow the Lyapunov approach. Therefore, the UH-PLL is aimed to perform properly under unbalanced conditions, voltage sags, swells, and angular frequency variations, among others, providing a fast and precise response. Moreover, due to the selective nature of the scheme, it owns certain robustness against harmonic distortion that is present in the source voltage signal. The rejection of low harmonics, however, is an issue that has not been explicitly considered in the present work.

II. ANALYSIS OF UNBALANCED AND HARMONIC BASED PLL

This section presents the model for the grid voltage, which is essential for the design of the UH-PLL. For a clear presentation, only the unbalance operation case is treated first, without harmonics, from which a basic scheme referred as U-PLL is presented [13]. Then, the effects of the harmonic distortion are included, which results in the addition of the UHCM to the basic model. This more complete scheme is thus referred as the UH-PLL.

A. Grid voltage under unbalanced condition: A model describing the grid voltage signal is presented [13]. This signal is originally described in three-phase coordinates v123 = $[v1, v2\ v3]^T$. The grid voltage signal is transformed to (fixed-frame) αβ-coordinates using Clarke's transformation. Moreover, both positive and negative sequences are considered to deal with the unbalanced case.

$$V_{\alpha\beta}=V^{p}_{\alpha\beta}+V^{n}_{\alpha\beta}=e^{J\theta}V^{p}{}_{dq}+e^{-J\theta}V^{n}{}_{dq} \quad (1) \qquad e^{J\theta}=\begin{bmatrix}\cos\theta_0 & \sin\theta_0\\ -\sin\theta_0 & \cos\theta_0\end{bmatrix} J=\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix} \quad (2)$$

Where $V^{p}_{\alpha\beta}$ and $V^{n}_{\alpha\beta}$ represent the positive and negative symmetric components of $V_{\alpha\beta}$ respectively. Based on this, the following model that completely describes the unbalanced sinusoidal signal generator $V_{\alpha\beta}$ is obtained as

$$\dot{V}_{\alpha\beta}=\omega_0 J\varphi_{\alpha\beta}$$

$$\dot{\varphi}_{\alpha\beta}=\omega_0 JV_{\alpha\beta}$$

Where ω_0 represents the fundamental frequency of the grid voltage
and the following auxiliary variable has been defined, which is necessary to complete the model.

$$\varphi_{\alpha\beta} \cong V^{p}_{\alpha\beta} - V^{n}_{\alpha\beta}$$

Based on definitions of $v_{\alpha\beta}$ and of $\phi_{\alpha\beta}$, it is possible to establish the following relationship

$$\begin{bmatrix}V_{\alpha\beta}\\ \varphi_{\alpha\beta}\end{bmatrix}=\begin{bmatrix}I_2 & I_2\\ I_2 & -I_2\end{bmatrix}\begin{bmatrix}V^{p}_{\alpha\beta}\\ V^{n}_{\alpha\beta}\end{bmatrix} \quad (3)$$

Where I_2 is the 2X2 Identity matrix.

B. Model of the grid voltage considering Harmonic distortion: In the case of the presence of harmonic distortion in the grid voltage, can be represented as follows

$$V_{\alpha\beta} = \sum_{K\in\{H\}}(V^{p}_{\alpha\beta,k}+V^{n}_{\alpha\beta,k})=\sum_{K\in\{H\}}(e^{JK\theta}V^{p}_{dq,k}+e^{-JK\theta}V^{n}_{dq,k}) \quad (4)$$

$$e^{Jk\theta}=\begin{bmatrix}\cos k\theta_0 & \sin k\theta_0\\ -\sin k\theta_0 & \cos k\theta_0\end{bmatrix}$$

As before it is possible to establish the following relationship for the fundamental component

$$\begin{bmatrix}V_{\alpha\beta,1}\\ \varphi_{\alpha\beta,1}\end{bmatrix}=\begin{bmatrix}I_2 & I_2\\ I_2 & -I_2\end{bmatrix}\begin{bmatrix}V^{p}_{\alpha\beta,1}\\ V^{n}_{\alpha\beta,1}\end{bmatrix} \quad (5)$$

C. Basic U-PLL for unbalanced operation: The objective of the proposed scheme is to deliver estimates for positive and negative sequences of the grid voltage, as well as an estimate of the fundamental frequency ω_0. An adaptive estimator for state variables $V_{\alpha\beta}$ and $\varphi_{\alpha\beta}$ is designed for this purpose. The adaptive estimator generates two pairs of quadrature signals, and thus, it will be referred as the adaptive quadrature signals generator under unbalanced conditions (U-AQSG) [13].

(i) ***Adaptive quadrature signals generator U-AQSG:*** The estimator U-AQSG is proposed for the estimation of the fundamental component of state variables $V_{\alpha\beta}$ and $\varphi_{\alpha\beta}$ Where γ is a positive design parameter used to get the required damping, and $\widehat{\omega_0}$ is the estimate of the unknown parameter ω_0 [13].

$$\dot{\hat{V}}_{\alpha\beta}=\widehat{\omega_0} J\,\hat{\varphi}_{\alpha\beta}+\gamma_1\tilde{V}_{\alpha\beta} \quad (6)$$

$$\dot{\hat{\varphi}}_{\alpha\beta}=\widehat{\omega_0} J\,\hat{V}_{\alpha\beta}$$

(ii) ***Fundamental frequency estimator – U-FFE :*** The reconstruction of $\widehat{\omega_0}$ is performed by means of the following adaptive law referred as the fundamental frequency estimator (U-FFE).

$$\dot{\hat{\omega}} = \lambda\tilde{V}_{\alpha\beta}{}^{T} J\hat{\varphi}_{\alpha\beta} \quad (7)$$

Where λ >0 is the adaptation gain. The design of this estimator follows the estimation by using Lyapunov's approach.

(iii) ***Positive and negative sequences generator – PNSG:***

Having the estimates $\hat{V}_{\alpha\beta}$ and $\hat{\varphi}_{\alpha\beta}$ the positive and negative sequences of the grid voltage can now be reconstructed as follows

$$V^{p}_{\alpha\beta} = \frac{1}{2}(\hat{V}_{\alpha\beta}+\hat{\varphi}_{\alpha\beta}) \qquad (8)$$

$$V^{n}_{\alpha\beta} = \frac{1}{2}(\hat{V}_{\alpha\beta}-\hat{\varphi}_{\alpha\beta})$$

this is referred as the positive and negative sequences generator (PNSG)

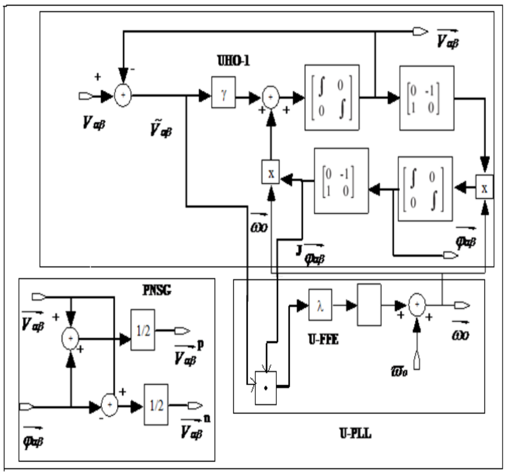


Fig 1: Block diagram of the proposed U-PLL algorithm considering a sinusoidal unbalanced reference signal $V_{\alpha\beta}$

D. Proposed UH-PLL considering unbalance and harmonic distortion**:** The previous scheme U-PLL is extended to consider harmonic distortion present in the grid voltage. For this purpose it is proposed to introduce a harmonic compensation mechanism (UHCM) .The scheme is referred as UH-PLL as it considers the operation under unbalanced and harmonic distortion. Previous algorithms in [13] and [20] did not include any explicit mechanism for harmonic cancelation. And thus a slight ripple was present in the responses. This effect could be alleviated by limiting the bandwidth of the overall scheme; however, the speed of response is reduced. Hence a trade off between the speed of response and the harmonic compensation properties was established. In the UH-PLL scheme this trade-off is relaxed by the introduction of the UHCM, which allows fast and clean responses.

E. Unbalanced harmonic compensation mechanism – UHCM **:** The UHCM can be seen as plug-in block that can be easily added to the basic scheme U-PLL. This scheme represents an alternative to the harmonic compensation scheme reported in [15].

The estimator for the kth harmonic component (k ∈ H) can be proposed as follows

$$\dot{\hat{V}}_{\alpha\beta,k} = k\widehat{\omega_0} J\, \hat{\varphi}_{\alpha\beta,k} + \gamma_k \tilde{V}_{\alpha\beta} \qquad (9)$$

$$\dot{\hat{\varphi}}_{\alpha\beta,k} = k\widehat{\omega_0} J\, \hat{V}_{\alpha\beta,k}$$

Where γ_k is a positive design parameter used to introduce the required damping.

$\widehat{\omega_0}$ is the estimate of parameter ω_0 to be defined later; and $\tilde{V}_{\alpha\beta} \cong V_{\alpha\beta} - \hat{V}_{\alpha\beta}$, with $\hat{V}_{\alpha\beta}$ representing the estimated voltage .In fact, the estimated voltage signal $\hat{V}_{\alpha\beta}$ can be decomposed as follows

$$\hat{V}_{\alpha\beta} = \hat{V}_{\alpha\beta,1} + \hat{V}_{\alpha\beta,h} \qquad (10)$$

Where $\hat{V}_{\alpha\beta,1}$ represents the estimate of the fundamental component and $\hat{V}_{\alpha\beta,h}$ represents the estimate of the harmonic distortion components of the grid voltage. The fundamental component $\hat{V}_{\alpha\beta,1}$ is reconstructed according to

$$\dot{\hat{V}}_{\alpha\beta,1} = \widehat{\omega_0} J\, \hat{\varphi}_{\alpha\beta,1} + \gamma_1 \tilde{V}_{\alpha\beta} \qquad (11)$$

$$\dot{\hat{\varphi}}_{\alpha\beta,1} = k\widehat{\omega_0} J\, \hat{V}_{\alpha\beta,1}$$

The harmonic distortion component $\hat{V}_{\alpha\beta,h}$ computed in block UHCM is performed as follows [13]. First, each harmonic component is reconstructed for k ∈{3, 5, ...}. Second, all harmonic components are accumulated in a single signal as follows.

$\hat{V}_{\alpha\beta,h}=\sum_{K\in\{3,5\,...\}}\hat{V}_{\alpha\beta,k}$

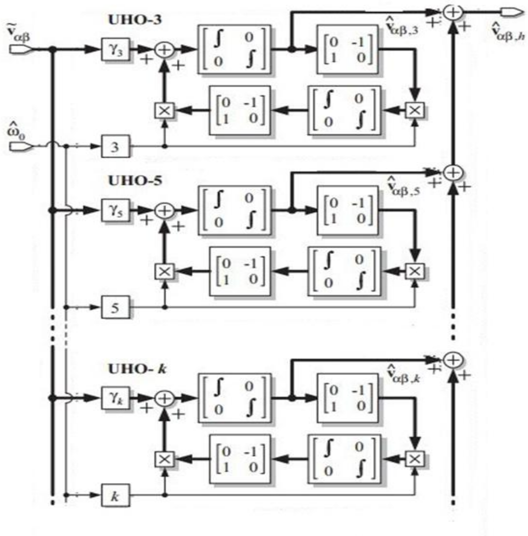


Fig 2 Block diagram of the unbalanced harmonic compensation mechanism UHCM including unbalanced harmonic oscillators tuned at 3th, 5th and k_{th} harmonic

Reconstruction of signal $\widehat{\omega_0}$ is performed by the following adaptive law

$$\dot{\widehat{\omega}}_0 = \lambda\tilde{V}_{\alpha\beta}{}^{T}J\hat{\varphi}_{\alpha\beta,1}$$

Whereas before, λ > 0 represents the adaptation gain,

$$V^{p}_{\alpha\beta,1} = \frac{1}{2}(\hat{V}_{\alpha\beta,1}+\hat{\varphi}_{\alpha\beta,1})$$

$$V^{n}_{\alpha\beta,1} = \frac{1}{2}(\hat{V}_{\alpha\beta,1}-\hat{\varphi}_{\alpha\beta,1})$$

***F. Tuning of the UH-PLL algorithm*:** Some rules for a tuning of control parameters λ and γ_k (k ∈ H) are presented [13]. For this purpose, some simplifications are considered. First, Non distorted case is considered, i.e., no UHCM block is included. Second, it is considered that the system is in balanced operation, that is, ϕαβ~= vαβ. Finally, a linearization process is considered. These simplifications yield a LTI system which coincides with the one studied in [16], where they propose to tune the parameters according to the following expressions.

$\lambda \cong \sqrt{2}\omega_{BW}$

$\gamma_1 = \left(\frac{\omega_{BW}}{|\,V_{\alpha\beta}|}\right)^2$

Where ω_{BW} is basically the desired bandwidth of the fundamental frequency estimator, which is recommended to be selected in the range $\frac{\omega_0}{5} \leq \omega_{BW} \leq \frac{\omega_0}{2}$. For the rest of the gains γ_k (k ∈ {3, 5, ...}) a first tuning rule can be stated as follows.

The influence of the second order system frequency response, each gain γ_k can be fixed at

$\gamma_k = \left(\frac{2.2}{T_{sk}}\right)$, k ∈ {3, 5, ...}

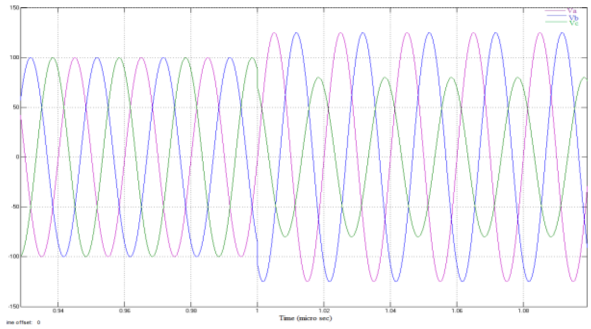
Where T_{sk} is the response time of each harmonic component (evaluated between 10%-90% of a step response of the amplitude of the corresponding sinusoidal perturbation).

III. RESULTS AND DISCUSSIONS

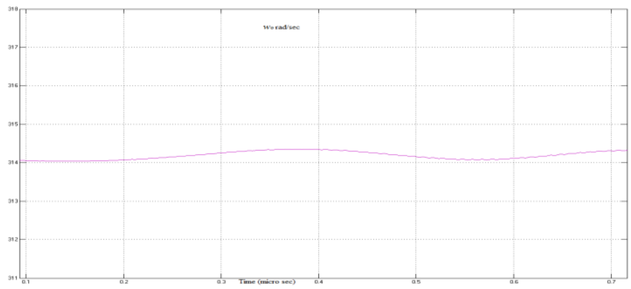
A. Response of UH PLL during unbalanced grid voltages:

The following parameters have been selected $\lambda = 300$ and $\gamma 1 = 1.5$, which correspond approximately for a bandwidth of ω_{BW} =150 rad/s (24 Hz). It is assumed that the grid voltage signal contains 3rd and 5th harmonics, and thus the UHCM contains UHOs tuned at these harmonics. The grid voltage has a nominal frequency of ω_0=314.16 rad/s (50 Hz), and an approximate amplitude of $|v\alpha\beta|$ = 100 V.

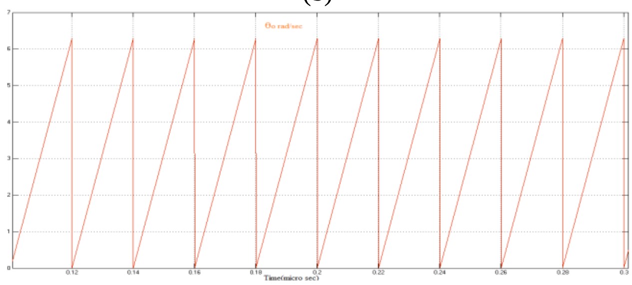
The following cases have been considered for the utility voltage:
(i) **Unbalanced condition:**. The voltage source includes both a positive and negative sequence components. The positive sequence has 100 V of amplitude at 314.16 rad/s (50 Hz) and zero phase shift. For the negative sequence amplitude of 10V approximately and zero phase shift are considered.
(ii) **Harmonic distortion:** Harmonics 3rd and 5th are added to the previous unbalanced signal to create a periodic distortion. Both harmonics have also a negative sequence component to allow unbalance in harmonics as well. Both positive and negative sequences of these harmonics have 10 V of amplitude and zero phase shift.



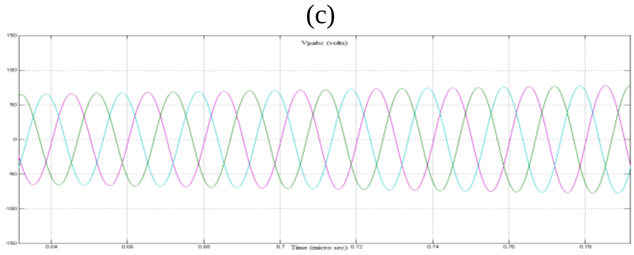
(a)



(b)



(c)



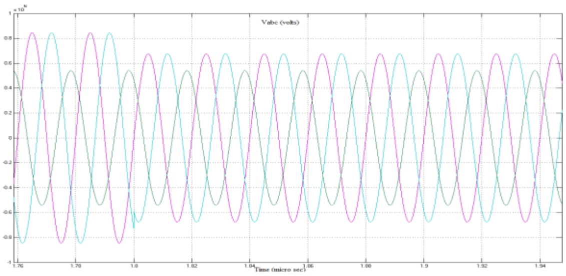
(d)

Fig.3 Response of UH PLL during unbalanced grid voltages
(a) Unbalanced Supply Voltage (b) ω_0 estimate (rad/sec)
(c) θ_0 Estimate (rad) (d) estimated positive sequence voltage in three-phase coordinates.

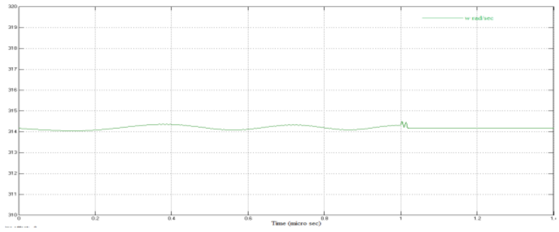
Fig 3(a) shows the transient response obtained with the pro-posed UH-PLL when the utility voltage goes from a balanced to an unbalanced operation condition at time t=1s.In Fig 3(b) notice that, after a relatively short transient the signal returns to their desired value of 100π.In Fig 3(c) the phase angle which is the time integration of angular frequency is perfectly triangular as there were only small transients in the angular frequency.

B. Response of UHPLL during distorted harmonic grid condition

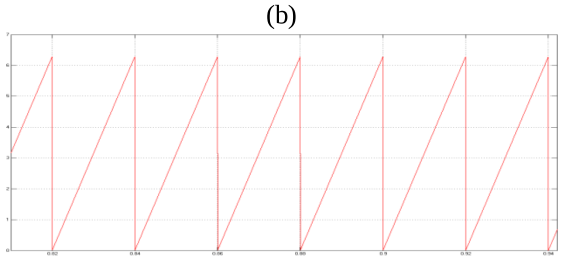
Figure 4 shows the transient response of the proposed UH-PLL when harmonic distortion is added to the already unbalanced grid voltage at t = 1.8s.



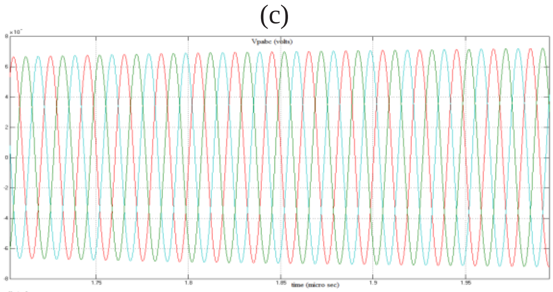
(a)



(b)



(c)



(d)

Fig.4 Response of UH PLL during distorted harmonic grid condition (a) Unbalanced Supply Voltage (b) ω_0 estimate (rad/sec)(c) θ_0 estimate (rad) (d) estimated positive-sequence voltage in three-phase coordinate

In Fig 4(a) it is noticed that, after a relatively short transient, all signals return to their desired values From Fig 4(b) in particular, notice that the estimated frequency is also maintained in its reference fixed to 314.14 rad /s after a small transient, without further fluctuations. In Fig 4(c) the phase angle which is the time integration of angular frequency is perfectly triangular as there were only small transients in the angular frequency. It can be observed that in Fig 4(d) the estimated positive-sequence voltages have an almost imperceptible transient.

IV. CONCLUSIONS

It was observed that in spite of an unbalanced and distorted reference signal the UH-PLL was able to deliver pure balanced sinusoidal signal represented by the positive sequence component of the reference signal, plus a ripple free fundamental frequency estimated signal. As the UH-PLL includes an explicit mechanism to compensate harmonics, it reduced considerably the effect of disturbances without compromising the speed of response of the overall scheme. In cases of low distortion, this mechanism can be easily disconnected and rely on the selective nature of a basic method, which can be enhanced at the expenses of reducing the speed of response of the overall scheme.

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