# A Novel Phase locked Loop Scheme for Grid Voltage Synchronisation Using the Energy Operator

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## Keywords

«Estimation Technique», « Voltage Synchronization », « Phase Lock Loop », « Power Converters », «Energy Control».

## Abstract

A well-known issue with existing power systems is rapid and accurate synchronisation to grid voltages when the system is unbalanced under grid fault conditions and corrupted with harmonics. This paper presents a novel phase locked loop technique for grid synchronisation technique using the energy operator. A comparative study is undertaken to investigate the accuracy and robustness of this technique compared to existing grid synchronisation techniques.

## 1. Introduction

Grid synchronisation is one of the key issues for distributed power generation systems connected to the utility network through power electronic converters. It is also important for devices such as flexible AC transmission systems (FACTs), active power filters, and HVDC converters [1]. Among various methods, the synchronous reference frame phase-locked-loop (SRF-PLL), is widely known and the simplest. However, it is sensitive to grid voltage distortion and corruption by harmonics and cannot work for unbalanced voltages without additional filtering [2].

Practical systems involve various single phase loads with unequal loading of feeders, loads being continuously connected or disconnected, and loads which are nonlinear, unbalanced and distort the voltage at the point of common coupling (PCC). Accurate knowledge of phase and frequency of grid voltage under these conditions is hard to obtain but crucial for converter operation and control. Several new schemes have been reported to address the stated requirements and comparative studies of some of them have been carried out [3]. However analysis of their characteristics in terms of dynamic response speed and tracking precision, computational simplicity, capability in distortion rejection, and unbalanced robustness as a whole is lacking. In particular the latter has been overlooked where the voltage angle between any two phases is always assumed to be $120^o$ while this may not be true when there is a fault in the power system [ref]. Any schemes including SRF-PLL designed according to this assumption will not be able to provide the FACTs device, for example, a fault-ride-through capability. The energy operator concept has been introduced in [4] as a computationally efficient and high precision solution for fast tracking of the grid voltage frequency and is able to work under a wide range of voltage distortions including those with unequal magnitude and phase angle displacement. Originated from Hebert M. Teager [5] and first presented by Kaiser [6]. This technique has been vastly applied in signal processing in the demodulation of speech signals using the (DESA-2) algorithm [7], and only until recent times has been investigated for estimation of power systems amplitude and frequency characteristics[8-10]. Unlike this SRF-PLL, this scheme alone is not able to provide the information about the instantaneous phase angle of the grid voltage. The cross energy introduced in [11] measures the interaction between two real signals especially for time delay estimation of

communication signals [12]. In power system applications, this technique has been applied by D.A Kaiser et al [13] to compute the continuously changing active power flowing around the grid. A similar approach is adapted to estimate phase angle changes of voltages..

This paper introduces a new phase locked loop technique combining the features of two different energy operator methods; the basic energy operator is used to estimate the frequency of the grid voltages whilst the cross-energy operator estimates the phase of the grid voltages. Both are sample-based techniques and are unified to realise a grid synchronisation PLL structure which are robust and accurate tracking the grid voltage amplitude, frequency and phase angle.

A coherent investigation is performed with the proposed technique with four other advanced synchronisation schemes as listed; Decoupled Double Synchronous Reference Frame (DDSRF), Double Second Order Generalised Integrator (DSOGI), Fourier Series + Moving Average (FS+MVA) Comb Filter and Cascaded Delayed Signal Cancellation (CDSC) using MATLAB-SIMULINK. These schemes are well-known and have been investigated by researchers for power applications [2, 14]. The above mentioned grid synchronisation schemes are investigated for dynamic response speed, tracking precision, computational simplicity, harmonic rejection, and unbalanced voltage scenarios.

## 2. Energy Operator for Grid Synchronization

Crucial requirement in grid synchronization schemes is that it must remain synchronized with the grid voltage under all system operating conditions, voltage harmonics and when power system grid faults occur. Based on this, recent work proposed by Nwobu et al [4] investigated a frequency based approach using the energy operator technique for fast and accurate synchronisation in three-phase network. This technique was shown to have advantages of fast and accurate tracking of the grid frequency whilst under balanced and unbalanced case scenarios. This section improves on the initial scheme proposed to introduce a phase locked loop based scheme that takes into consideration frequency and phase tracking of the three-phase system. The scheme is compared with well-known techniques later in Section 4 for its performance under unbalanced voltages and harmonics.

### 2.1 Principle of Energy Operator

We start with a discretized version of the phase voltage signal and backward and forward sample shifts.

$$v_x(n) = V_x \cos(\Omega_x n + \phi_x) \tag{1}$$

$$v_x(n-1) = V_x \cos(\Omega_x(n-1) + \phi_x) \tag{2}$$

$$v_x(n+1) = V_x \cos(\Omega_x(n+1) + \phi_x) \tag{3}$$

where $\Omega_x = 2\pi f / f_s$ i.e. discrete angular frequency

Using the two trigonometric identities

$$\cos(A+B)\cos(A-B) = \frac{1}{2}\cos(2A) + \cos(2B)$$

$$\cos(2A) = 2\cos^2 A - 1$$

The product of the equations in (2) and (3) can expressed as

$$v_x(n+1)v_x(n-1) = V_x^2 \cos^2(\Omega_x n + \phi_x) - V_x^2 \sin^2(\Omega_x) \tag{4}$$

Substituting (1) into (4) the equation can be expressed as

$$V_x^2 \sin^2(\Omega_x) = v_x(n)^2 - v_x(n+1)v_x(n-1) = E[v_x(n)] \tag{5}$$

At a fast sampling frequency $f_s$, the error in estimation is further reduced as $\sin^2(\Omega_x) \approx \Omega_x$ and hence the discretized energy operator algorithm can be simplified as

$$E[v_x(n)] \approx \Omega_x^2 V_x^2 = v_x(n)^2 - v_x(n+1)v_x(n-1) \tag{6}$$

$$E[v_x(n)] \approx \Omega_f^2 V_x^2 = \frac{v_x(n)^2 - v_x(n+1)v_x(n-1)}{T_s^2} \tag{7}$$

where $\Omega_f = 2\pi f_x$ i.e. discrete angular frequency

The expression in (7) shows that with just two samples shifts of the original voltage signal, its instantaneous energy can be resolved. It is important to note a key benefit here is that the expression in (7) is able to estimate quickly at two samples instant that relates directly to sampling frequency $f_s$ i.e. at a faster sampling rates instantaneous energy estimated in 3 $f_s$ seconds. The expression is also shown to be independent of the phase angle $\phi_x$.

## 2.2 Frequency Estimation Using Modified Discrete Energy Separation Algorithm (DESA-2)

Several discrete versions of the energy operator exist [7, 15] and the calculation of the energy is classified based on derivative methods used for the input signals in this case voltage signals. The DESA-1a is based on an asymmetric two-sample difference whilst the DESA-1 based on forward two sample difference. In this paper DESA-2 is chosen for the estimation of frequency and phase characteristics as shown in the block diagram Figure 4 below. This is considered as the best approach because it avoids half-sample shifts in the estimated frequency signal [7].

Using three discrete samples of the signal $v_X(n), v_X(n+1), v_X(n-1)$ and its three-sample derivative $E[s_X(n)]$ at various time points and the instantaneous energy $E[v_X(n)]$ the frequency $f$ of the signal can be evaluated using trigonometric identity as the following formulae (1)-(2), where $f_s$ is the digital sampling frequency.

$$\frac{E[s_x(n)]}{E[v_x(n)]} = \frac{V_x^2 \sin^4 \Omega_x}{V_x^2 \sin^2 \Omega_x} = \sin^2 \Omega_x = \frac{1 - \cos 2\Omega_x}{2}$$

$$f_x = \frac{1}{2\pi T_s} \sin^{-1}\left(\sqrt{\frac{E[s_x(n)]}{E[v_x(n)]}}\right) \qquad (8)$$

$$\text{or} \quad \frac{1}{4\pi T_s} \cos^{-1}\left(\sqrt{1 - \frac{2E[s_x(n)]}{E[v_x(n)]}}\right)$$

These are simple arithmetic formulae which can be implemented on-line for analysing individual phase voltages. To implement the energy operator for synchronization to the utility grid voltage in real time, five discrete samples $v_x(n), v_x(n+1), v_x(n-1), v_x(n+2), v_x(n-2)$ of the grid voltage signal is required at a sampling time of $t_s$ to calculate the derivative of the energy $E[S_X(n)]$.
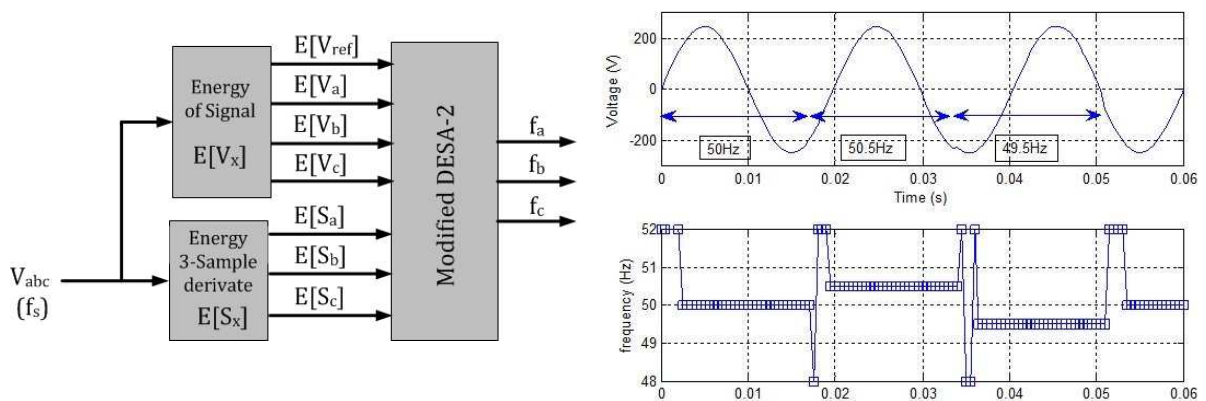


Fig 1: (a) Discrete Energy Separation Algorithm (DESA-2), (b) Frequency Estimation Using DESA-2

Fig1a. shows a block diagram of the DESA-2 algorithm. A moving data window is used to store the voltage samples in a first in-first out (FIFO) order. The width of this window frame is a fixed length of

5 samples; consequently there will be a 4-sample delay at the start of this algorithm but an advantage is that time delay is dependent on the sampling frequency of the voltage signal. i.e. the faster the sampling frequency the shorter the delay. Fig. 1b show the result of a test of this scheme when it is applied to a voltage waveform sampled at 2 kHz. The simulated waveform was disturbed by changing its frequency from initial 50 Hz to 50.5 Hz and 49.5 Hz    at time duration 0.017s and 0.034s, respectively. These changes of frequency are detected quickly as shown with a 4-sample delay of 800μs ($4 \times T_s$).

## 2.3 Power Angle Estimation Using Cross-Energy Operator Product

It is well-known in grid synchronisation that accurate phase estimation of the phase voltages as well its frequency is needed for grid synchronisation.  The energy operator proposed above does not take into account the phase characteristics of the voltage signals which limit it for frequency estimation. The cross energy operator product has been recently proposed by D. Kaiser et al [13] estimation of phase characteristics of power systems using the useful properties of the energy operator explained in [11].  . The energy operator cross product for power angle is defined as

$$E\,[vi(n)] = v(n)i(n) - v(n+1) - i(n-1)$$
$$E\,[iv(n)] = i(n)v(n) - i(n+1) - v(n-1)$$

(9)

where,

$$v(n \pm 1) = V \sin\big(\Omega(n \pm 1) + \phi_{v_x}\big)$$
$$i(n \pm 1) = I \sin\big(\Omega(n \pm 1) + \phi_{i_x}\big)$$

(10)

$$\theta = \phi_v - \phi_i$$

Using $\Omega = \omega t_s$ from (8) and substituting (10) into (9) using various trigonometric identities the power factor angle $(\theta)$ is be expressed in two forms as shown in (11)-(12).

$$\theta = \cos^{-1}\left(\frac{E\,[vi(n)] + E\,[iv(n)]}{2\sqrt{E[v(n)] \times E[i(n)]}}\right)$$

(11)

$$\theta = \sin^{-1}\left(\tan(\Omega)\left(\frac{E\,[iv(n)] - E\,[vi(n)]}{2\sqrt{E[v(n)] \times E[i(n)]}}\right)\right)$$

(12)

Using (12) is takes into consideration if the power angle is leading or lagging in the control.

## 2.4 Energy Operator Phase Locked Loop (EO-PLL)

Using the cross-energy product described in (12) with the DESA 2 in (8) a new phase locked loop scheme in proposed as shown in Fig2. The scheme applies the cross –energy operator product to estimate the phase angle difference in real-time and the DESA to track the frequency changes of the three phase voltages respectively.

In other to estimate the phase angle difference between voltages the cross energy operator product formula is modified as shown in (13)

$$\theta_{V_{xy}} = \sin^{-1}\left(\tan(\Omega)\left(\frac{E\,[v_{yx}(t)] - E\,[v_{xy}(t)]}{2\sqrt{E[v_x(t)] \times E[v_y(t)]}}\right)\right)$$

(13)

where, $\theta_{V_{xy}}$ corresponds to the phase angle difference $\theta_{V_{xy}} = \theta_{V_x} - \theta_{V_y}$.

In conventional phase-locked loop techniques, the a-b-c voltages are resolved with respect to positons in a reference frame. Here instead in the EO-PLL, a feedback loop of the frequency of Phase A voltages is used to create a reference rotating voltage vector $V_{ref}$ using an angle generator. This voltage vector $V_{ref}$ is independent of the phase angle of Phase A voltage and thus keeps track of the reference point.

The phase angle difference $\theta_{V_{ref\,a}}$, $\theta_{ab}$, $\theta_{ac}$ are estimated using (13) and angles generated with a PLL generator with the use of estimated phase frequencies $f_a$, $f_b$, $f_c$. This generates independent phase locked loop signals for each phase. This scheme has an advantage in the sense that the three phase voltages are synchronised independently under unbalanced voltage scenarios and hence positive-sequence decoupling is of voltage vectors is not required
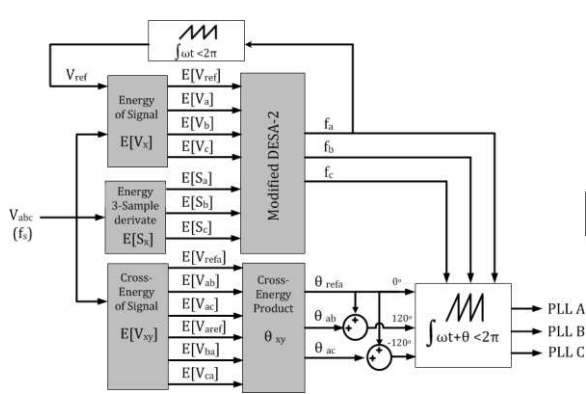


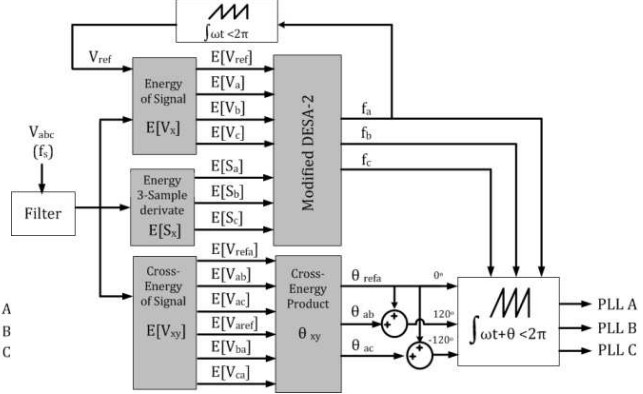Fig. 2: Block diagram of EO-PLL        Fig. 3: Block diagram of EO-PLL+ Filter

## 2.5 Energy Operator Phase Locked Loop (EO-PLL + Filter)

A drawback is that the EO-PLL technique is very sensitive to noise or harmonics in the power system. This is because the algorithm is sample based and relies on the nature of the waveform to be sinusoidal [6]. Like other grid synchronisation a filter is applied before the synchronisation technique. Here, a second order filter is used in this paper to filter off the harmonics of the estimated grid voltage frequencies and phases. It is important to note that with the EO-PLL careful selection of digital discrete filter design is crucial in improving the accuracy whilst under harmonics. The block diagram of the EO-PLL + Filter is as shown in Fig3.

# 3. Overview of Advanced Grid Synchronization Techniques

In advanced voltage synchronisation schemes as mentioned in Section 1, the fundamental positive sequence components (PSCs) of the PCC voltages are extracted before the phase estimation is performed using SRF-PLL in most cases. This extraction technique employed by each of these schemes is the main feature which makes it distinctive from the others. This section reviews the principles of these schemes. Detailed comparisons have been discussed in detail in [16] and are summarised here briefly

## 3.1 Decoupled Double Synchronous Reference Frame (DDSRF)

DDSRF is the extension of the standard SRF-PLL and has been developed mainly for unbalanced grid voltage synchronisation [2]. Its distinctive feature is the two Clarke-Park transformations employed to obtain the dq components of the grid voltages. These are based on two reference frames, one rotating in synch to the frequency and the other opposite direction. At the outputs of the former, there exist two component sets; the first is a set of DC components which represents the positive sequence component of the voltage while the second is the AC component due to negative sequence component. The reverse is true for the outputs of the oppositely rotating reference frame based transformation. A decoupling network is used to cancel the AC components to extract positive sequence component (PSC) vectors as shown in Fig. 4a. The positive sequence vectors are used for grid phase estimation using the conventional SRF-PLL technique

## 3.2 Double Second Order Generalised Integrator (DSOGI)

Based on the adaptive notch filtering technique, DSOGI based technique estimates the phase angle through the extracted PSCs in the $\alpha\beta$ domain which are in general written as (14)

$$\mathbf{V}_{\alpha\beta}^{+} = \begin{bmatrix} v_{\alpha}^{+} \\ v_{\beta}^{+} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & q \\ -q & 1 \end{bmatrix} \mathbf{V}_{\alpha\beta} \tag{14}$$

where, $\mathbf{V}_{\alpha\beta}$ is the stationary reference frame based voltage vector for the measured three phase grid voltages while $q = e^{-j\pi/2}$ is a delay operator by $90^{\circ}$. The latter is produced by applying a second order generalised integration (SOGI) on each element in $\mathbf{V}_{\alpha\beta}$. The general configuration of a DSOGI is illustrated in Fig. 4b.

## 3.3 Cascaded Delayed Signal Cancellation (CDSC)

The Cascaded Delayed Signal Cancellation (CDSC) synchronisation scheme removes a group of harmonics from the measured grid voltage signals before the fundamental PSCs and the phase are estimated but the harmonics removal is actually performed by CDSC operators which are based on the following expression:

$$DSC_{n} = \frac{1}{2}\left[ v_{x}(t) + v_{x}\left(t - \frac{T}{n}\right)\right] \tag{15}$$

where $v_{x}(t)$ is the instantaneous measured signal and $T/n$ is the time delay with $1/T$ = grid frequency and n is a positive integer. For a value of n, several harmonics can be removed simultaneously and if the measured signal is processed in several stages by $DSC_{n}$ operations with different n values, a combination of several harmonics can be eliminated. One example of CDSC scheme is shown in Fig. 5a. With a combination of $DSC_{n}$ operators, having n = 2, 4, 8 and 16, it is able to remove almost all even and odd harmonics up to $30^{th}$ order. Note that SRF-PLL is needed employed for phase angle estimation.

## 3.4 Fourier Series + Moving Average (FS + MA)

This technique uses a moving average comb filter (MVA) in processing the grid voltage measurements to obtain the fundamental PSCs, which will be used to compute the phase angle directly. These are achieved by multiplying each phase voltage with two sinusoidal signals, ($v_{m} = \sin(\omega_{1}t + \theta_{o})$ and $v_{n} = \cos(\omega_{1}t + \theta_{o})$), which are orthogonal to each other.

Each of the products is sent through an MVA filter whose discrete time transfer function is written as

$$H(z) = \frac{2}{n}\frac{1 - z^{-n}}{1 - z^{-1}} \tag{16}$$

where
$$n = \frac{sampling\ frequency}{\omega_{1}}$$

and two signals containing only the DC component are obtained. The filtered output are respectively multiplied by $(2 \times v_{m})$ and $(2 \times v_{n})$ before summing them together to extract the fundamental component as $v_{sinx} = A_{1}\sin(\omega_{1}t + \theta_{i1})$. Similar process can be carried out to obtain $v_{cosx} = A_{1}\cos(\omega_{1}t + \theta_{i1})$ through swapping around the orthogonal signals. The two resulting signals are then used to obtain phase angle of the fundamental PSCs.



PSC – positive sequence component
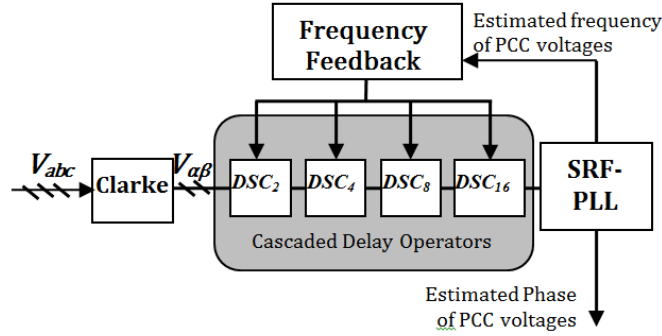NSC – negative sequence component
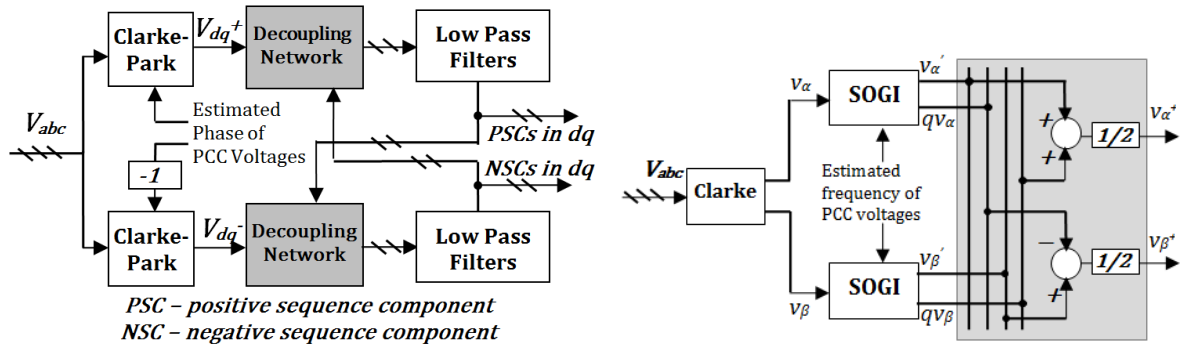
Fig 4: (a) Configuration of a DDSRF Scheme, (b) Overall of implementation DSOGI synchronisation, (c) Synchronisation scheme based on CDSC having DSC2, DSC4, DSC8 and DSC16 operators.


## 4. Analysis and Simulation Results

MATLAB-SIMULINK was used to investigate the performance of grid synchronisation when three-phase voltage is unbalanced and corrupted with harmonics. Simulation results are investigated for unbalanced grid voltages, unbalanced grid voltages with phase jump, unbalanced voltages with DC offset and grid voltages with harmonics as shown in Figure 8a. At the start of the simulation, the three-phase grid voltages are balanced.  At t= 0.08s, a disturbance with unbalanced voltage condition is introduced. At 0.1s a DC off set introduced on Phase A and at 0.16s phase jump in Phase A and Phase B. For the harmonic investigation, odd order harmonics (5, 7, 9,11th) are injected in the grid voltage.

Fig 5b, show results for the DDSRF scheme. This scheme only works well when the grid voltages become unbalanced but takes about half cycle to achieve steady state. Under high order harmonics under balanced and unbalanced case, the phase angle becomes erroneous and cannot be tracked accurately.

Fig. 5c, show results for the DSOGI scheme. It can be observed that the estimated phase is relatively correct even when the grid voltages become corrupted with harmonics and contain a DC component. This scheme is slower and takes about 1.5 cycles to achieve steady state.

Fig. 5d, show results for the CDSC scheme. This scheme also works well with grid voltages unbalanced and voltage with harmonics. Compared to the DSOGI scheme it is faster and takes about 1 cycle to achieve steady state.

Fig. 5e, show results for the FS+MA scheme. Besides having the capability of synchronising individual grid phase voltages, this scheme works well when they become distorted, unbalanced and are no longer $120^{o}$ degrees from each other.

Fig. 5f, show results for the EO-PLL scheme. Besides having the capability of synchronising individual grid phase voltages, this scheme works well under all unbalanced conditions but requires filtering for harmonic distortion.

### 4.1 Further Discussions

Table 1 summarises the ability of the above schemes to synchronise to the grid voltages under the mentioned conditions whilst Table 2 summarise the computational complexity of each scheme.

EO-PLL and FS+MA allow independent synchronisation of individual phase voltages and both work under unbalanced voltage conditions. The FS+MA's included with the moving average filter which allows for synchronisation with harmonics. A second order filter is used here in this case the EO-PLL and also synchronises under harmonics.  It is important to note any filter type with good low frequency cut-off characteristics can also be used. EO-PLL has the fastest response among all the schemes

investigated so far which makes it a more attractive approach. DDSRF is limited only to unbalance conditions and DSOGI does not work well for all distortion types. When compared EO-PLL is a better alternative. CDSC and FS+MA appear to be desirable synchronisation techniques as they work well with voltages which are unbalanced and corrupted with harmonics and DC offsets. However, its design is more complicated when compared to the EO-PLL. It is also important to note that all synchronisation schemes apart from EO-PLL and FS+MA extract positive sequence component (PSC's) voltage vectors and use closed loop SRF-PLL generators. The EO-PLL on the other hand doesn't need to extract PSC's and is a sampled-based open loop scheme with no need for P+I control. The EO-PLL is hence the good approach for grid synchronisation based on its simplicity, accuracy and speed
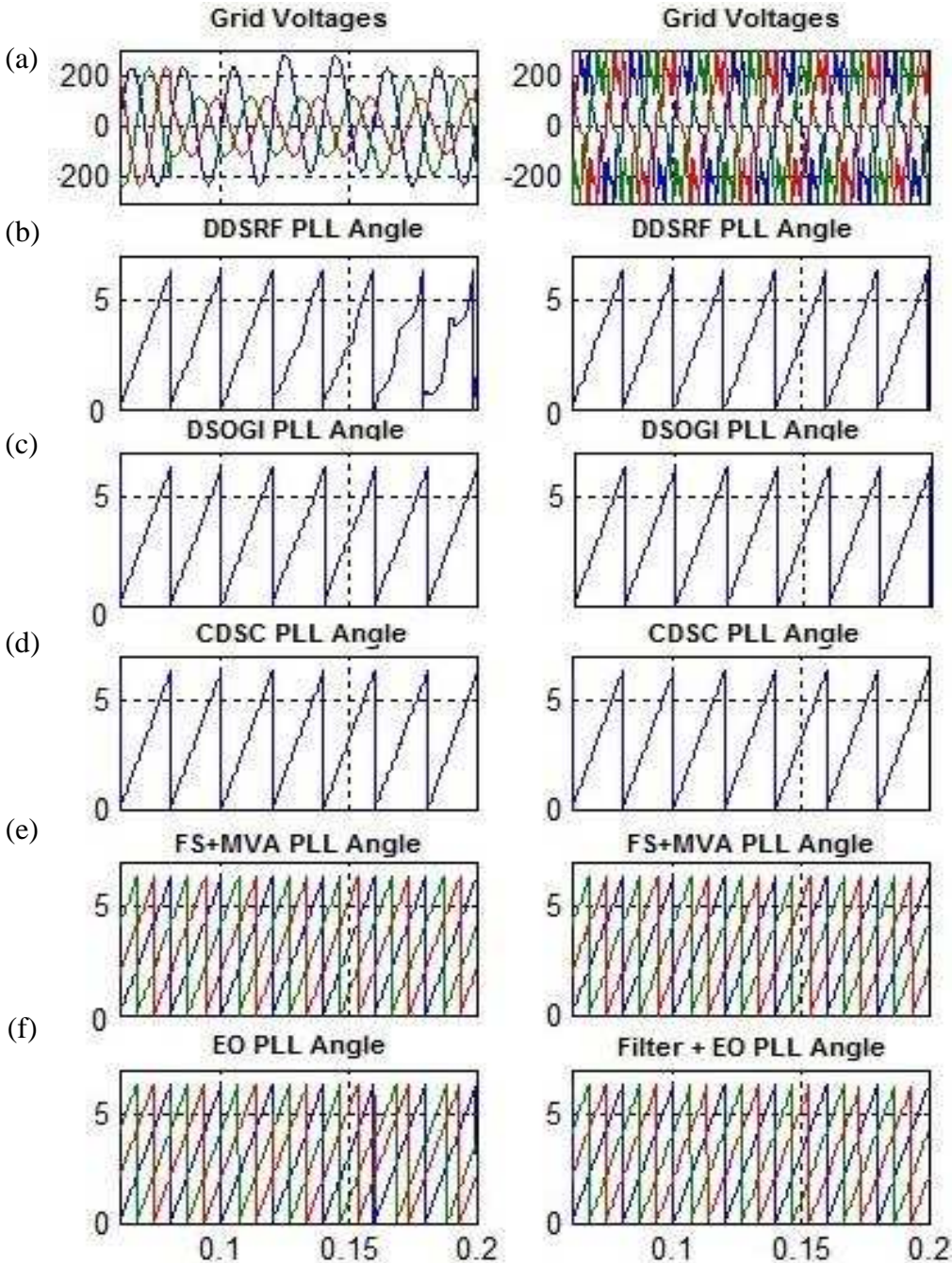.



Fig. 5 (a)-(f): (a) Grid voltage unbalanced voltage conditions, (b) PLL Angle for DDSRF scheme, (c) PLL Angle for DSOGI scheme, (d) PLL Angle for CDSC scheme, (e) PLL Angle for FS+MVA Scheme, (f) PLL Angle for EO scheme

| Schemes | Ability to synchronise | | | |
|---|---|---|---|---|
| | Unbalanced Voltage | Unbalanced Voltage & Phase Displaced | Unbalanced Voltage & With Harmonics | Unbalanced Voltage & With DC Offset |
| DDSRF | Yes | No | No | No |
| DSOGI | Yes | Yes | No | No |
| FS+MA | Yes | Yes | Yes | Yes |
| CDSC | Yes | Yes | Yes | Yes |
| EO-PLL | Yes | Yes | Yes | Yes |

Table 1: Ability of various schemes for synchronization

| Type of frame | Method | Number of Operators | | | | Settling Time |
|---|---|---|---|---|---|---|
| | | Arithmetic | Cos & Sin | Buffer | Filter | |
| A-B-C frame | EO-PLL | 30 | 7 | 3 | 3 | 5×fs |
| | FS+MA | 33 | 6 | 6 | 6 | ≈ 0.3 cycle |
| dq frame | DDSRF | 17 | 8 | 0 | 4 | 0.5 cycle |
| $\alpha\beta$ frame | CDSC | 76 | 16 | 8 | 0 | 1 cycle |
| | DSOGI | 22 | 0 | 0 | 0 | 1.5 cycle |

Table 2: Complexity of the schemes and their transient performance

# Conclusion

The energy operator phase locked loop (EO-PLL) has been introduced and s detailed review and a coherent comparison for grid voltages synchronisation has been performed on four different schemes. All these schemes have been tested and the comparison has been verified through simulation results. The common trait in all these schemes apart from the EO-PLL is that they all aim to extract the fundamental PSCs from the measured grid voltages signals and the phases are either estimated directly from the extracted PSCs or conventional SRF-PLL scheme. Every scheme has its own merits and its application should depend on the severity of the distortions and the resources available (i.e. hardware or software) for the implementation. Based on its simplicity and faster transient response the EO-PLL offers a relatively definitive solution for synchronisation of grid voltages.

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