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Review of Synchronization Algorithms used in Grid-Connected Renewable Agents

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Abstract. This paper presents a review of several synchronization algorithms used in Grid-Connected Renewable Agents. Different synchronization algorithm structures will be shown and their advantages and disadvantages will be discussed using MATLAB/SIMULINK tool from The MathWorks, Inc. Some simulations will be shown firstly, and secondly, a Real Time Digital Simulator (RTDS) platform will be used for testing and debugging the Synchronization Algorithms.

Key words

Synchronization Algorithms, Renewable Agent, Real Time Digital Simulations (RTDS) platform

1. Introduction

An important control algorithm used in grid-connected renewable agents is one that allows the synchronization between the renewable agent and the utility grid [1]. In a general way all Synchronization Algorithms must detect the phase of the 3-phase utility grid voltages with optimal dynamic response. Besides a reliable detection of the angle phase, it will ensure the proper inverter control strategy. There are several studies, which show different structures to estimate the utility-grid voltage phase angle in order to obtain the synchronization of the current inverter with the 3-phase utility grid voltages. Among the main synchronization methods, we can mention the following ones: Synchronous Reference Frame PLL (dq PLL) [2], Positive Sequence Detector plus a dq PLL (PSD+dqPLL) [3], Dual Second Order Generalized Integrator Phase-Lock Loop (DSOGI-PLL) [4] and Multiple Second Order Generalized Integrator Frequency-Lock Loop (MSOGI-FLL) [5]. The algorithms mentioned above have their advantages and disadvantages, being the dq PLL the simplest one, and the Multiple Second Order Generalized Integrator Frequency-Lock Loop (MSOGI-FLL) technique, the most sophisticated. All these algorithms might be used in different renewable agents, and the selection will depend on the requirements and/or regulations to be fulfilled. It is important to mention that Real Time Digital Simulations provides helpful testing control algorithms with the possibility of introducing conditions that are not considered within a real plant; besides this technique gives the opportunity to repeat a test under different scenarios with only making small modifications. So, preliminary experiments in order to test the synchronization algorithms mentioned in this paper can be carried out safely in a situation very similar to the real world but avoiding potential damages of the renewable agent. A DSPACE Real Time Digital Simulation (RTDS) platform will be used to study the real-time behaviour of the synchronizations algorithms shown in this review. Section 2 gives a description of the synchronization algorithms studied in this paper. Several Matlab/Simulink [6] simulations of the response of the synchronization algorithms will be performed and analyzed in Section 3. In Section 4 Real-Time experiments of the synchronization algorithms will be performed. Finally, some conclusions are shown in Section 5.

2. Synchronization Algorithms

In a grid-connected power system the synchronization algorithm allows the synchronization between the renewable agent and the utility grid. There are several studies, which show different structures to estimate the utility-grid voltage phase angle in order to obtain the synchronization of the current inverter with the 3-phase utility grid voltages [7]. Among of the main synchronization methods, we can mention:

A. Synchronous Reference Frame PLL (dq PLL)

A dq PLL is commonly used to estimate the utility-grid voltage phase angle in order to obtain the synchronization of the current inverter with the 3-phase utility grid voltages. The design of the dq PLL gain is a critical point within the process; from the point of view of dynamic systems high gains will imply higher dynamics than low gains, but stability will be compromised [8]. A dq PLL structure consists in two parts: on the one hand, the Park and Clarke transformations [9,10] and on the other hand, the control [11], which is formed by a PI regulator. Under the influence of some harmonic distortions and frequency variations of the 3-phase utility grid voltages, the dq PLL may have an acceptable operation, but its major disadvantage is its high sensibility to voltage unbalances [3,5], as well as the offset of the voltage sensors used due to accuracy errors, which produces second order harmonic distortions [12], worsening its behaviour response.

B. Positive Sequence Detector plus a dq PLL (PSD+dqPLL)

In order to overcome the high sensibility of the dq PLL to voltage unbalances, a Positive Sequence Detector (PSD) block is added. This block is based on the symmetrical component method or Fortescue theorem [13] and is used in order to extract the positive sequence of the 3-phase utility grid voltages. The PSD+dq PLL synchronization algorithm is a good alternative to synchronize the Renewable agent to the 3-phase utility grid, but the PSD block has a discrete filter named S90 [3], which is very sensitive to the variation of the nominal frequency of the utility grid, and may lead to the power factor degradation of the inverter-grid connection.

C. Dual Second Order Generalized Integrator dq PLL (DSOGI-PLL)

A solution to overcome the problems caused by the voltage unbalance at the moment of phase detection is presented in [14], where a Dual Second Order Generalized Integrator PLL (DSOGI-PLL) is proposed. In this, Clarke transformation for the three phase utility voltages is performed for calculating the $\alpha\beta$ voltage components, whereas a Second Order Generalized Integrator with a Quadrature Signal Generation (SOGI-QSG) is used to obtain the 90^{o} shifted version of the $\alpha\beta$ voltage components. Then, the shifted $\alpha\beta$ voltage components are feeding to a Positive Sequence Calculator (PSC). Finally, the positive sequences of the $\alpha\beta$ voltage components ($V_{\alpha\beta}+$) are used to estimate the frequency with a Phase Lock Loop (PLL) block. The DSOGI-PLL is a good choice when voltage unbalances occur, but it is not a good alternative when voltage harmonic distortions are present.

D. Multiple Second Order Generalized Integrator Frequency-Lock Loop (MSOGI- FLL)

A reliable phase and frequency detection is necessary when harmonics, voltage unbalances and frequency variations occur. For this, the Multiple Second Order Generalized Integrator Frequency-Lock Loop (MSOGI-FLL) is proposed in [5] as the synchronization algorithm. The MSOGI-FLL structure is formed by a set of adaptive filters, based on the Quadrature Signal Generation (SOGI-QSG), that are designed at different resonant frequencies working in parallel [5], by a Positive-Negative-Sequence Calculator (PNSC) block in order to calculate the positive and the negative sequence of the 3-phase grid voltages, and by an Harmonic Decoupling Network (HDN) in order to isolate the effect of the utility grid harmonics at the input signal of the DSOGI-FLLs.
The MSOGI-FLL synchronization algorithm is able to obtain an ideal detection of the phase and frequency when low order harmonics close to the fundamental frequency arises in the utility grid, being this its main innovation.

3. Simulations

In order to evaluate the behaviour of the synchronization algorithms, some simulations will be performed using the MATLAB/SIMULINK model of a 3-phase PV grid-connected system, shown in Fig. 1, of 6kW of nominal power at standard conditions (1000 W/m^2 and 25°C). This system can be divided into the Power and the Control subsystems [1], and its parameters are listed in Table I.

Table I. - Parameters of the Power and Control Subsystems for the PV Agent

PARAMETERS	VALUE
Three-phase inverter	SKS22FB6U+E1CIF+B6CI ,SEMISTACK-IGBT
Outer Filter	M80-3,9-10,from PREMO, L=3.9mH C=1.5μF R=20mΩ (Y connection)
Distribution transformer	REIM, Dyn11, 50Hz, 308/232V, S_{nom}=6kVA
3-phase utility grid	Vrms=220V (ph- ph),50Hz
PV generator power	P=6kW
DC bus voltage	Vcc= 350V
Gain of the inverter	$K_{PWM}=\frac{2}{3}\boldsymbol{Vcc}$
Switching freq.	Fsw=10kHz
Current crossover frequency	fc_I=333.4Hz

Link capacitor	Clink=1360µF
Voltage crossover freq.	fc_V=10.0Hz
Damping factor of the 2nd order transfer function	$\zeta_c = \frac{\sqrt{2}}{2}$
Phase margin	PM= 63.5°

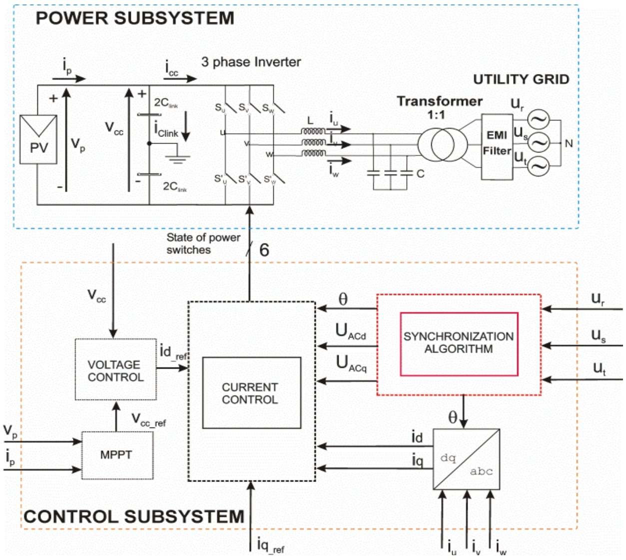


Fig. 1. Block diagram of the Power and Control Subsystems of the 3-phase PV grid-connected system used for testing the synchronization algorithms in the paper.

where:

v_P - output voltage of the PV Generator
i_P - output current of the PV Generator
v_{CC} - dc bus voltage
i_{CC} - current delivered to the 3-phase inverter
i_{Cink} - current through the dc-link capacitor
i_u, i_v, i_w - 3-phase inverter line currents
i_r, i_s, i_t - 3-phase utility grid currents
u_R, u_S, u_T - 3-phase utility grid voltages
S_u, $S_u\backslash$, S_v, $S_v\backslash$, S_w, $S_w\backslash$ - status of the power switches of the 3-phase inverter
L - Inductor of the Outer Filter
C – Capacitor
u_d, u_q - *d-q* components of space vector **u**
i_d, i_q - *d-q* components of space vector **i**
u_{ACd}, u_{ACq} - *d-q* components of space vector $\mathbf{u_{AC}}$
i_{d_ref} - *d* reference component of space vector $\mathbf{i}^*$
v_{CC_ref} - dc bus voltage reference
$q_{\_ref}$ - instantaneous reactive power reference
θ - phase of the 3-phase utility grid voltages

The simulation of the time evolution of the frequency detections by the synchronization algorithms discussed in this overview are shown in Fig. 2. The rms values of the 3-phase utility grid voltage is Vrms=220V (ph-ph) and a step of frequency from 50 to 100Hz is exerted at 0.5s. The dq PLL frequency detection is shown in Fig. 2a; in order to attain a trade-off between the dynamic, stability and proper harmonic attenuation, a crossover frequency of 346rad/s is set, which leads to the constants of the PI regulator (K_I=842.6 and K_P=2.432), which produces an overshoot of 12%. Adding, the PSD block, the frequency detection of the PSD+dqPLL is shown in Fig. 2b; the S90 filter has been designed for a nominal frequency of 50Hz and an acceptable response with an overshoot of 14% is achieved. The frequency detection by the DSOGI-PLL is show in Fig. 2c; the DSOGI gain k =1.41 and the same constants for the PLL PI regulator are used: an overshoot of 29% is achieved in this case. Finally the frequency detection by the MSOGI-FLL is shown in Fig. 2d; a SOGI gain of k =1.41and a FLL gain of γ =1/2 are used: an ideal detection is attained.

4. Experiments

Some Real-Time Digital simulations will be carried out using a Real Time Digital Simulation DSPACE platform with several I/O and DAC blocks and an oscilloscope for parameters monitoring. The configuration setup is shown in Fig. 3: the model blocks of the control and power subsystems are built in MATLAB/SIMULINK Inc., the C-code is generated with Real Time Workshop from SIMULINK and downloaded into the DSPACE platform.

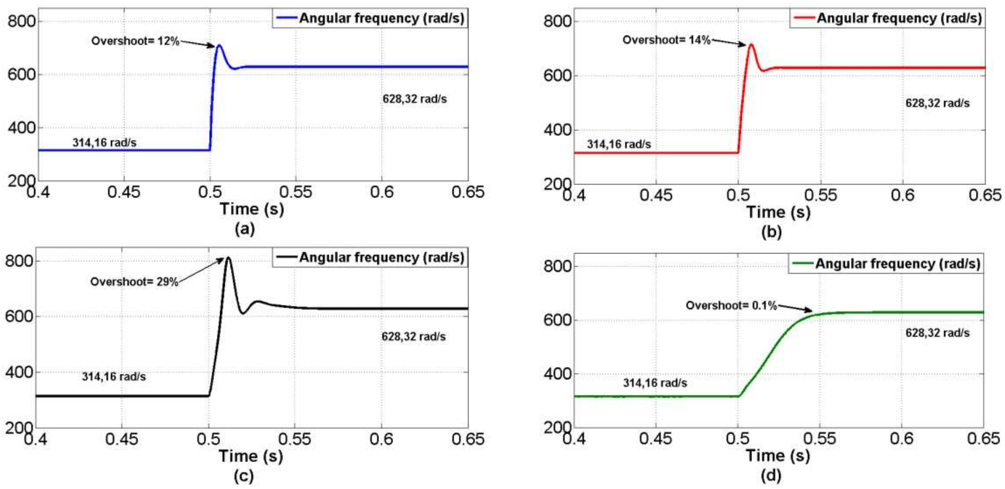


Fig. 2. Time evolution of the detected frequency when a step of frequency is exerted. a) dq PLL, b) PSD+dpPLL, c) DSOGI-PLL, d) MSOGI-FLL.

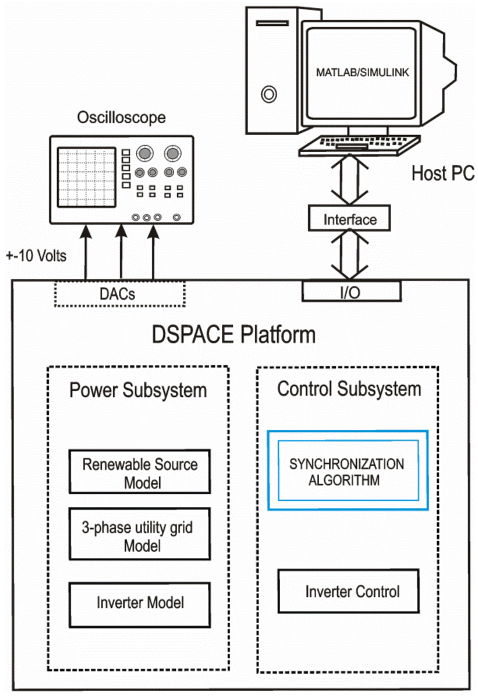


Fig. 3. Configuration of the DSPACE platform for the real time testing using a host PC, a DS1006 DSPACE board with a digital to analog converter interface and an oscilloscope for parameters monitoring.

A. Testing the influence of the nominal frequency variation

The first Real-Time digital test that will be performed is a step of frequency from 50 to 100Hz. The responses of the synchronization algorithms are shown in Fig. 4. Acceptable frequency detection is attained by the dq PLL when a frequency step of 50 to 100Hz is exerted. In the case of the PSD+dqPLL it is possible to observe that its response is similar to the response of the dq PLL, but the PSD block has a discrete filter which is very sensitive to the variation of the nominal frequency of the utility grid, and may lead to the power factor degradation of the inverter-grid connection. The frequency detection by the DSOGI-PLL is attained but it can be seen an overshoot when the step of frequency is exerted. Perfect frequency detection is attained when the MSOGI-FLL is used due to the use of a combination of multiple DSOGIs blocks and the use of Frequency-Lock Loop (FLL), allowing good dynamics.

B. Testing the influence of the Harmonic Distortions

In this second test, the 5^{th} and 7^{th} harmonics are introduced in the 3-phase utility grid voltages with an amplitude distortion of 25%. The phase detection by the synchronization algorithms is shown in Fig. 5. A poor harmonic attenuation can be observed in the detected phase when using the dq PLL and the PSD+dqPLL synchronization algorithms; this is mainly due to the choice of the crossover frequency of the PI regulator (346rad/s) in which a tradeoff between a good attenuation rate for harmonics and a high dynamics is mandatory. When using only the dq PLL, the 6^{th} harmonic in the detected phase can be observed due to the application of the Park transformation of the 3-phase voltages, which transforms the 5^{th} (negative sequence) and the 7^{th} (positive sequence) harmonics into the 6^{th} harmonic in *dq* components (rotating at the fundamental angular speed). When using the PSD block together with the dq PLL, a certain attenuation of the 6^{th} harmonic is observed in Fig. 5b because of the contribution of the negative sequence 5^{th} harmonic is "removed" by the PSD block, only allowing the contribution of the positive sequence 7^{th} harmonic.

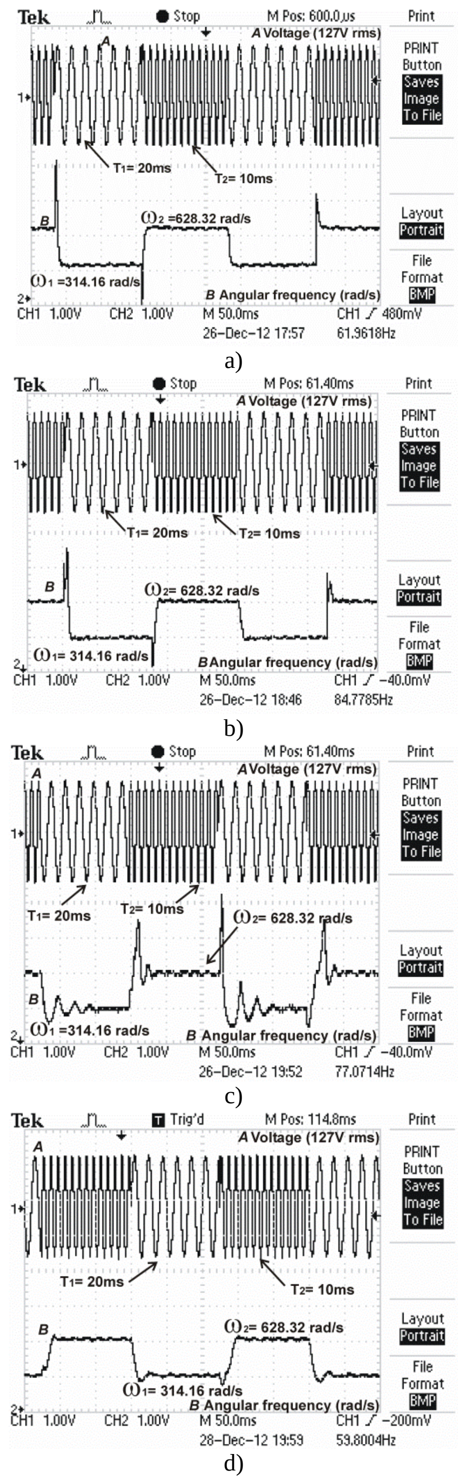
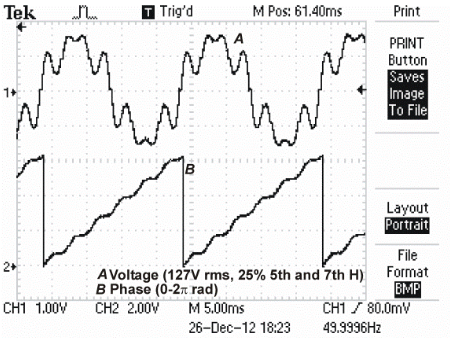
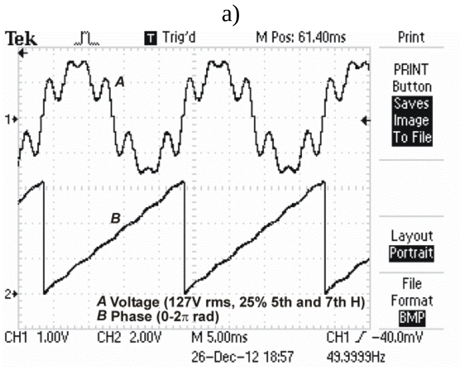


Fig. 4. Time evolution of the real-time frequency detection when a step of frequency from 50 to 100Hz is exerted. a) dqPLL, b) PSD+dqPLL, c) DSOGI-PLL, d) MSOGI-FLL.

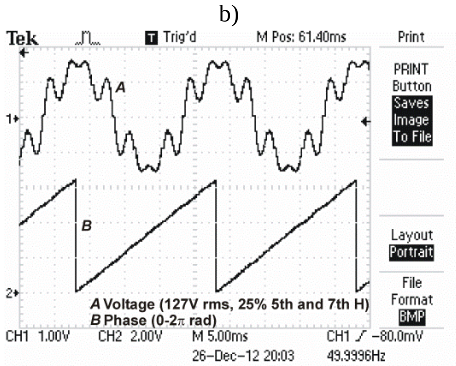
When using the DSOGI-PLL algorithm, a better phase detection is attained but is not the required phase estimation to ensure a good performance of the PV system. Finally, when using the MDSOGI-FLL, almost a perfect phase detection can be observed: good detection under harmonics influence is achieved because of the use of an Harmonic Decoupled Network (HDN).



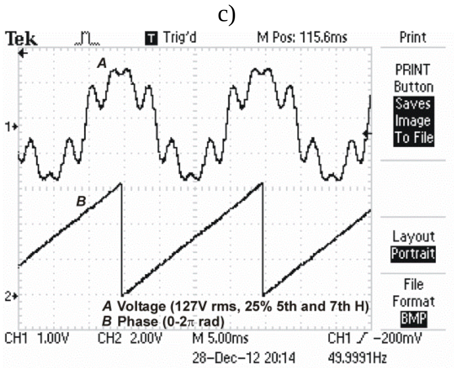
a)



b)

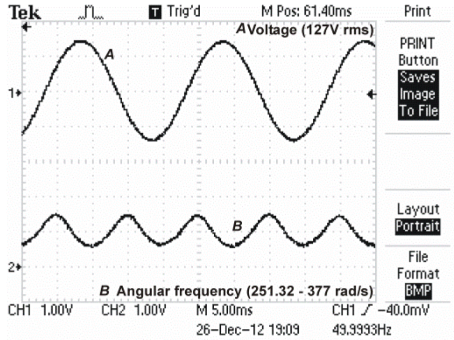


c)

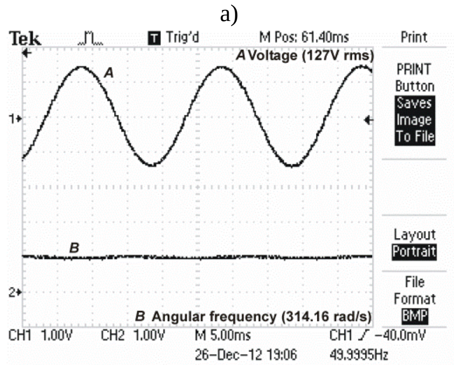


d)

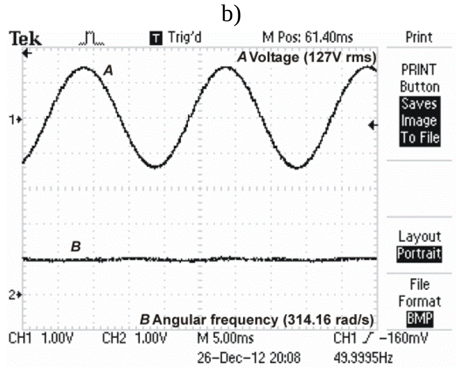
Fig. 5. Time evolution of the real-time phase detection when a magnitude distortion of 25% in the 5th and 7th harmonics in the 3-phase utility grid voltages is present. a) dqPLL, b) PSD+dqPLL, c) DSOGI-PLL, d) MSOGI-FLL.



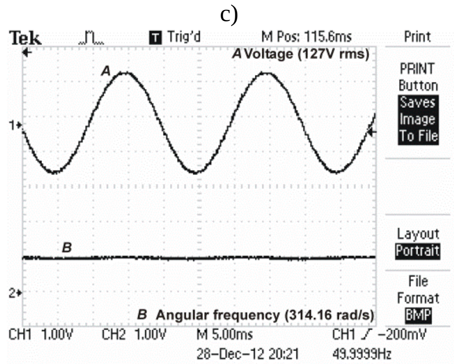
a)



b)



c)



d)

Fig. 6. Time evolution of the real-time frequency detection when voltage unbalances occurs. a) dqPLL, b) PSD+dqPLL, c) DSOGI-PLL, d) MSOGI-FLL.

C. Testing the influence of the Voltage Unbalances

In order to analyze the response of the synchronization algorithms when voltage unbalances occur in the low voltage 3-phase utility grid, Fig. 6 shows the time evolution of the real-time frequencies detection obtained by the dq PLL, the PSD+dqPLL, the DSOGI-PLL and the MSOGI-FLL algorithms when voltage unbalances (modelled as $V_{\_r}$=179V_{peak} $V_{\_s}$=78V_{peak} $V_{\_t}$=39V_{peak}) occur in the 3-phase utility grid. When using the dq PLL method, it can be observed the presence of the 2nd order harmonic in the detected frequency, being the main drawback of the dq PLL. This is solved by adding the PSD block, in which acceptable frequency detection is attained (2nd order harmonic free). In the case of the DSOGI-PLL and the MSOGI-FLL, the positive sequence component of the frequency is detected due to the use of the PSC and the PNSC blocks, respectively.

Finally, a summary with a comparative study of the synchronization algorithms in this review is shown in Table II.

Table. II – Comparative study of the Synchronization Algorithms

NAME	STRONG POINT	WEAK POINT
dq PLL	Simplicity, Frequency Variations	Harmonic, Voltage Unbalances
PSD+dqPLL	Voltage Unbalances, Simplicity	Frequency variations, Harmonics
DSOGI-PLL	Frequency Variations, Voltage Unbalances	Harmonics
MSOGI-FLL	Harmonics, Frequency Variations, Voltage Unbalances	High Computational Burden

5. Conclusions

This paper has shown a review of some synchronization algorithms that are used in grid-connected renewable agents. The algorithms were studied using simulation techniques and experimental tests in a Real Time Digital Simulator Platform. The behaviours of the synchronization algorithms under several perturbations in the 3-phase utility grid were analyzed. An important aim was to make a comparative summary where the strong and weak points of each synchronization algorithm are shown. After a detail analysis carried out to the four synchronization algorithms, it can be said that the most complete and reliable synchronization algorithm is the MSOGI-FLL, although a very high computational burden is involved.

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