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Regular paper

A comparative Study and implementation of Single-Phase PLL techniques for Grid-Connected Inverters Systems

The increasing number of electronic power inverters connected to the electricity grid means that their synchronization with the electricity grid is becoming increasingly important. Typically, a phase locked loop (PLL) is an essential part of power inverters for achieving synchronization with the utility grid. Throughout the phase angle of the grid voltage, a reference signal is generated to synchronize the operating condition of the renewable energy production systems with the utility grid. This paper presents quantified analyses and comparisons of the main PLL techniques based on different structures for single-phase systems, and a comparative study of the enhancement for conventional phase-locked loop using four different methods, including, PLL with notch filter, PLL with notch filter based on fuzzy logic, PLL with a second-order generalized integrator filter (SOGI-PLL), PLL with a second-order generalized integrator filter (SOGI-PLL) based on fuzzy logic. A comparison among these four studied improvements was conducted under normal operation condition. On the other hand, the performance of these filters was tested under three abnormal scenarios; Amplitude variations, amplitude and frequency variations, frequency and a phase jump variations. In addition, simulation results with PSIM software are developed to verify the performance and effectiveness of the strategy of each proposed method. Finally, experimental tests are used to extract the results and discuss the validity of the proposed quarter algorithms using the STM32F407 microcontroller board with phase angle and frequency estimation, which are visualized using a digital oscilloscope.

Keywords: Grid connected photovoltaic inverters systems, Phase-locked loop (PLL), Second-order generalized integrator (SOGI), single phase PV inverter, Notch filter, fuzzy logic controller.

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1. Introduction

The use of fossil fuels for electric power generation has imposed several problems on the environment, including global warming and greenhouse effect. This has led to an era in which the increasing power demand will be met by Distributed Generation (DG) system which is based on renewable energy sources such as solar power, wind power, etc. Among the green renewable energy sources, governments strongly support the application of solar energy to power generation systems [1]. For this reason, and in order to ensure the rapid development of solar energy, it is necessary to build low-voltage systems for connecting photovoltaic sources to distribution networks. Synchronization with the electrical grid is the key element for better stability and accuracy of the system control loop [1, 2].

For grid-connected inverters, amplitude, frequency and phase angle are vital information for accurate and efficient synchronization. A phase locked technique is necessary to achieve this synchronization. As part of this research, a specific type of phase-locked loop technology is studied based on four different filter structures. Then, the performance of the four filters studied based on phase-locked loop (PLL) is compared under normal and faulty operating conditions [2, 3].

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Voltage source inverters enable the use of next-generation technologies as a dynamic voltage regulator by dynamically controlling the voltage at the common coupling point. However, they have more controlled variables compared to conventional generation technologies [3, 4]. The fundamental phase angle of the grid voltage is a critical controlled variable for the grid synchronization. This angle is used to generate a reference signal to synchronize the operating condition of the photovoltaic inverters with the public grid. Therefore, a precise phase tracking method is required to obtain the grid phase angle information. [5]. Different phase tracking methods have been developed and can be classified into two approaches. This is an open-loop tracking approach (such as low-pass filters, Kalman method, etc.) and a closed-loop approach, such as a phase-locked loop (PLL) [6].

The PLL approach has been widely used in various systems such as grid fields; this technique has been adopted to provide fast and more accurate synchronization between the generation side and the grid [7, 8, and 9]. It should have high immunity to disturbances such as harmonics, noise, imbalances and other distortions.

Therefore, a phase locked loop (PLL) is an essential part of power inverters for achieving synchronization with the utility grid. Throughout the phase angle of the grid voltage, a reference signal is generated to synchronize the operating condition of the renewable energy production systems with the utility grid. This paper presents analyzes and comparisons of the different structures and main techniques of PLL for single-phase systems, and a comparative study of the enhancement for conventional phase-locked loop using four different methods, including, PLL with Notch filter, PLL based on fuzzy logic, PLL with a second-order generalized integrator filter (SOGI-PLL), PLL with a second-order generalized integrator filter (SOGI-PLL) based on fuzzy logic. A comparison among these four studied improvements was conducted under normal operation condition. On the other hand, the performance of these filters was tested under three abnormal scenarios; Amplitude variations, amplitude and frequency variations, frequency and a phase jump variations. In addition, simulation results with PSIM software are developed to verify effectiveness and the performance of the strategy of each proposed method. Finally, experimental tests are used to draw the results and discuss the validity of the different algorithms proposed using the STM32F407 microcontroller board with phase angle and frequency estimation, which are visualized using a digital oscilloscope [10].

2. Overview of the different PLL algorithms

2.1. Synchronous reference frame PLL

2.1.1. Mathematical model

In general, the photovoltaic inverter uses the phase locked loop (PLL) to synchronize its output current with the voltage of the electrical network.

Figure 1, shows the general structure of the PLL, which consists of a phase detection (PD) consisting of a Park transform, a loop filter (LPF) and a voltage controlled oscillator (VCO).

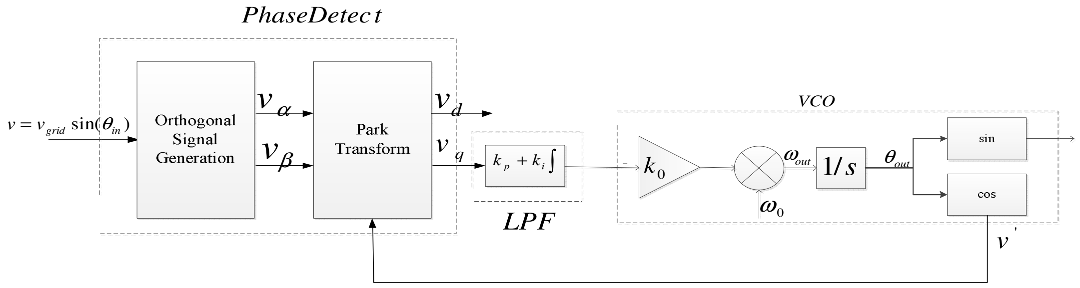

Fig.1. Basic PLL structure

The use of phase detection (PD) is an important for detecting phase error, therefore for this by producing an orthogonal signal and taking a Park transform. This method can selectively adjust the orthogonal signal generator to output all frequencies other than the mains frequency.

Supposing an arbitrary input signal and a PLL theta, the phase detection (PD) output is given by the following equation:

$$PD_{output} = v_{in}\begin{bmatrix} \cos(\theta_{out}) & \sin(\theta_{out}) \\ -\sin(\theta_{out}) & \cos(\theta_{out}) \end{bmatrix}\begin{bmatrix} \cos(\theta_{in}) \\ \sin\theta_{out}) \end{bmatrix} = v_{in}\begin{bmatrix} \cos(\theta_{in}-\theta_{out}) \\ \sin(\theta_{in}-\theta_{out}) \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \end{bmatrix} \tag{1}$$

Assuming that PLL is closed to be locked, such as:

$$\theta_{in} - \theta_{out} \approx 0 \rightarrow \sin(\theta_{in} - \theta_{out}) \approx \theta_{in} - \theta_{out} \tag{2}$$

Therefore is the error in the PLL angle lock.

So to keep this error at zero, the loop filter is implemented using a PI controller:

$$\frac{ylf\,(s)}{PhaseDectect\ \,(s)} = k_p + \frac{k_p}{T_i}\times\frac{1}{s} = k_p + \frac{k_i}{s} \tag{3}$$

According to the control theory, the closed-loop transfer function of the PLL is given as follows:

$$H_o(s) = \frac{\theta_{out}(s)}{\theta_{in}(s)} = \frac{LPF\ (s)\times {}^{1}\!/_{s}}{1 + LPF\ (s)\times {}^{1}\!/_{s}} = \frac{\left(k_p s + \frac{k_p}{T_i}\right)}{s^2 + k_p s + \frac{k_p}{T_i}} \tag{4}$$

So from the transfer function of the second-order system,

$$H(s) = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{5}$$

The natural frequency and the damping ratio of the PLL are given by:

$$\omega_n = \sqrt{\frac{k_p}{T_i}} \quad ; \quad \zeta = \sqrt{\frac{T_i k_p}{4}} \tag{6}$$

For good noise filtering and rejection and according to the conditions of the mains voltage, the damping factor must be 0.7071 and the frequency must be less than or equal to the mains frequency [11].

Therefore, the PLL control parameters are selected as follows:

$$\begin{cases} \xi = 0.7071 \\ \omega_n = \omega_0 \end{cases} \tag{7}$$

This PLL must be designed to have a fast interlock with a very low error between the obtained phase angle and the actual phase angle, especially at the moment of amplitude or frequency variation of the electrical network within a cycle, with the possibility of attenuating the low harmonics that may exist in a real network. These two objectives cannot be achieved simultaneously. Either to have a fast response with a high precision medium bandwidth or a slow response with good accuracy with slow locking time delayed a longer synchronization time. Most PLL systems are implemented with a PI controller that is very sensitive to disturbance changes as the controller parameters are synthesized around a precise operating point of the controller parameters. The main disadvantage of this corrector (PI) is its inability to react to sudden changes in the network signal.

For grid connected applications as the grid frequency is very low (50Hz-60Hz), the roll off provided by the PI is not satisfactory enough and introduces a high frequency element into the loop filter output, which affects the performance of the PLL [11,12].

So, LPF characteristic of the PI controller cannot be used to eliminate the twice to grid frequency component from the phase detect output in case of grid connected applications [11, 12].

The control device shall be optimized to achieve rapid locking with less bandwidth and acceptable accuracy for the different operating points. Hence, alternative methods must be used that linearize the PD block. In this work report, four PLL methods that linearize the PD output are illustrated [11, 12]:

- One uses a notch filter to filter out the grid frequency component from the PD output
- The other uses an orthogonal signal generation method to use stationary reference frame PLL technique in single phase PLL
- PLL with notch filter based on fuzzy logic
- PLL with a second-order generalized integrator filter (SOGI-PLL) based on fuzzy logic

2.2. PLL with Notch Filter

A notch filter can be used at the output of the phase detect block, which attenuates twice the grid frequency component very well. An adaptive notch filter can also be used to selectively notch the exact frequency in case there are variations in the grid frequency. The design of the adaptive notch filter is illustrated and a method to calculate the coefficients automatically, and on line is illustrated in Figure below [11, 12]:

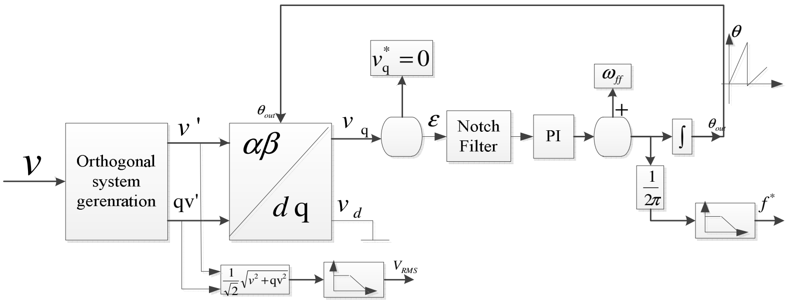

Fig.2. Single Phase PLL with Notch Filter

The loop filter or the PI is implemented as a digital controller with Equation (8):

$$y_{lf}[n] = A_1 \times y_{lf}[n-1] + PhaseDetec\ t[n] \times B_0 + PhaseDetec\ t[n-1] \times B_1 \tag{8}$$

The equation can be written as following according to the Z transform

$$\frac{y_{lf}(z)}{PhaseDetec\quad t(z)} = \frac{B_0 + B_1 z^{-1}}{1 - z^{-1}} \tag{9}$$

According to the bi-linear transformation on the LPF transfer function, replace $s = \frac{2}{T}\left(\frac{z-1}{z+1}\right)$

$$\frac{Y(z)}{PhaseDetec\ t(z)} = \frac{\left(\frac{2\times k_p + T\times k_i}{2}\right) - \left(\frac{2\times k_p - T\times k_i}{2}\right) z^{-1}}{1 - z^{-1}} \tag{10}$$

To determine the proportional and integral gain of the PI controller, from the analog domain to the digital domain [11, 12].

$$B_0 = \left(\frac{2\times k_p + T\times k_i}{2}\right) \text{ and } B_1 = \left(\frac{2\times k_p - T\times k_i}{2}\right) \tag{11}$$

The Figures 3, below shows the results of the PLL with Notch filter simulation in PSIM:

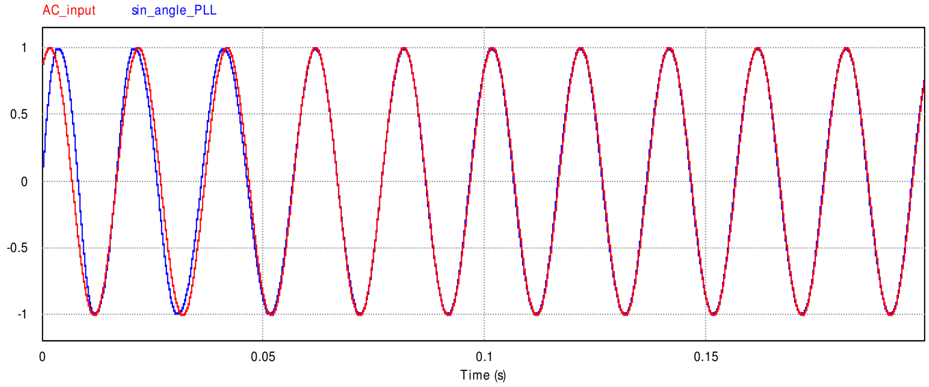

Fig.3. PLL results with classical PI

Figure 3, shows that the output signal from the PLL with notch filter could lock with the input signal after about two fault cycles, despite its ability to provide a locked output signal to the fundamental component of the input signal in its amplitude and frequency.

2.3. PLL based on the second order generalized integrator (SOGI-PLL)

The structure of the second order generalized integrator (SOGI) is illustrated in Figure 4. The input signal v' is the voltage signal measured at the PCC. As output signals, two sinusoidal waves v' and qv' with a phase shift of $\pi / 2$ are generated so that the component v' has the same phase and amplitude as the fundamental input voltage signal (v).

The Figure below shows the structure of the second order generalized integrator (SOGI) [11, 23, and 26]:

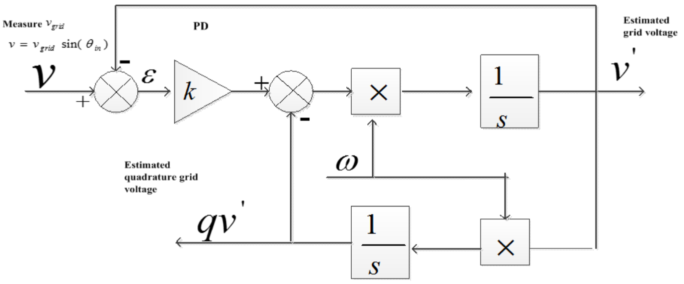

Fig.4. Orthogonal signal generator based on SOGI

The second-order generalized integrator (SOGI) acts as a band pass filter with infinite gain whose transfer function is defined in (12). The closed loop transfer functions $H_d(v'/v)$ and $H_d((qv'/v)$ of the structure shown in Fig.2 are defined as [12, 13, 14, and 15]:

$$H_{SOGI} = \frac{\omega_n s}{s^2 + \omega_n^2} \tag{12}$$

$$H_d(s) = \frac{v'}{v}(s) = \frac{k\omega_n s}{s^2 + k\omega_n s + \omega_n^2} \tag{13}$$

$$H_q(s) = \frac{qv'}{v}(s) = \frac{k\omega_n^2}{s^2 + k\omega_n s + \omega_n^2} \tag{14}$$

Where ω_n represents the unamortized natural frequency of the SOGI that is equal to the estimated frequency $\omega_n = \omega$ and k is the gain that affects the SOGI bandwidth.

The grid frequency can change; therefore, this orthogonal signal generator must be able to tune its coefficients in case of grid frequency change. To achieve this, bi-linear transformation is used to get the discrete transfer function as follows:

$$H_d(z) = \frac{k\omega_n \frac{2}{T_s}\frac{z-1}{z+1}}{\left(\frac{2}{T_s}\frac{z-1}{z+1}\right)^2 + k\omega_n \frac{2}{T_s}\frac{z-1}{z+1} + \omega_n^2} \tag{15}$$
$$= \frac{(2k\omega_n T_s)(z^2-1)}{4(z-1)^2 + (2k\omega_n T_s)(z^2-1) + (\omega_n T_s)^2 (z^2-1)^2}$$

Now, using $x = 2k\omega_n T_S$ and $y = (\omega_n T_s)^2$

$$H_d(z)=\frac{\left(\frac{x}{x+y+4}\right)+2\left(\frac{-x}{x+y+4}\right)^{2}}{\left(\frac{2(4-y)}{x+y+4}\right)z^{-1}-\left(\frac{x-y-4}{x+y+4}\right)z^{-2}}=\frac{b_0+b_2z^{-2}}{1-a_1z^{-1}-a_2z^{-2}} \tag{16}$$

$$H_q(z)=\frac{\left(\frac{k.y}{x+y+4}\right)+2\left(\frac{k.y}{x+y+4}\right)z^{-1}+\left(\frac{k.y}{x+y+4}\right)z^{-2}}{\left(\frac{2(4-y)}{x+y+4}\right)z^{-1}-\left(\frac{x-y-4}{x+y+4}\right)z^{-2}}=\frac{qb_0+qb_1z^{-1}+qb_2z^{-2}}{1-a_1z^{-1}-a_2z^{-2}} \tag{17}$$

Once the orthogonal signal has been generated, Park transform is used to detect the Q and D components on the rotating reference frame. This is then fed to the PI loop that controls the VCO of the PLL. The coefficients of the orthogonal signal generator can be tuned for varying grid frequency and sampling time [23, 26, and 32].

As can be seen, the transfer function for H_d resembles that of a Band Pass Filter, that filters out harmonic and random noise and whose output is in phase with that of the input signal. The transfer function for H_q is the same as that of a second order Low Pass Filter, that not only filters out harmonics and random noise, but also introduces a phase shift of $\pi/2$ radians [23, 26, 33].

Fig.5. shows the block diagram of the overall SOGI-PLL structure [23, 26, 34, and 35]:

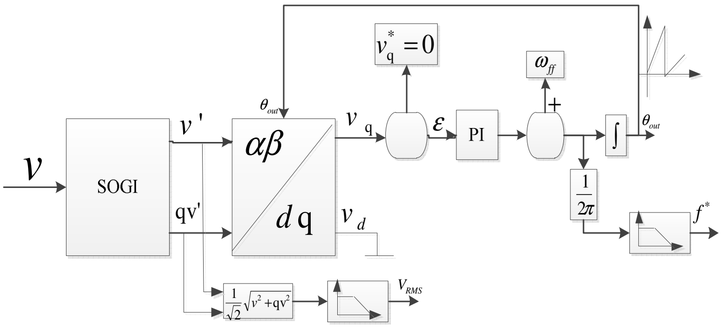

Fig.5. Structure of SOGI- PLL

The Figure 6, below shows the results of the SOGI-PLL simulation with classical PI in PSIM:

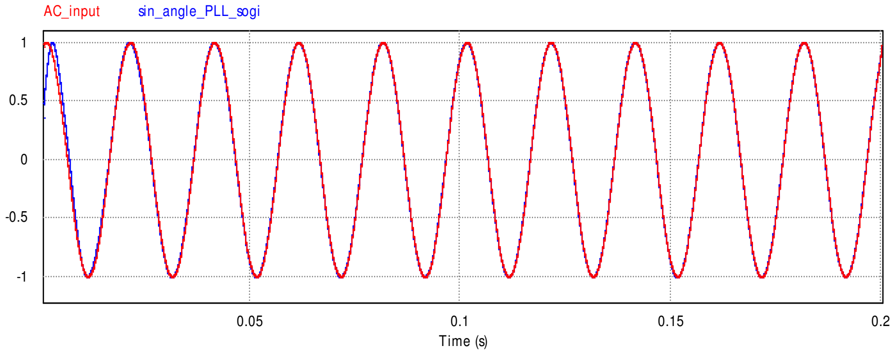

Fig.6. SOGI-PLL results with classical PI

Figure 6. A show that the second order generalized integrator based PLL has the fastest and the most efficient response. This result shows the ability of SOGI filter based PLL of tracking the input signal without delay due to its resonance at the fundamental frequency.

2.4. PLL classical proposed based on fuzzy logic

This section presents a new phase-locked loop control (PLL) for a grid-connected photovoltaic inverter. The originality of this work is to generate an orthogonal power supply voltage system based on fuzzy logic to obtain a fast detection and a more accurate image of the phase angle.

We started by the adaptive regulation to which will be added an intelligent supervision and then calculated the instructions of PI corrector autonomously thanks to local measures. This intelligent supervision is carried out thanks to the fuzzy logic [1, 36, 37, and 38]. The command of the fuzzy logic PI can be obtained by combining the fuzzy logic that is adaptive and independent of system parameter and the PI controller to get a quick response. In this controller gains are adjustable and they are determined by the fuzzy logic according to the operating point of the system for the entries defined.

The Figure 7, below shows the proposed structure of the PLL based on fuzzy logic:

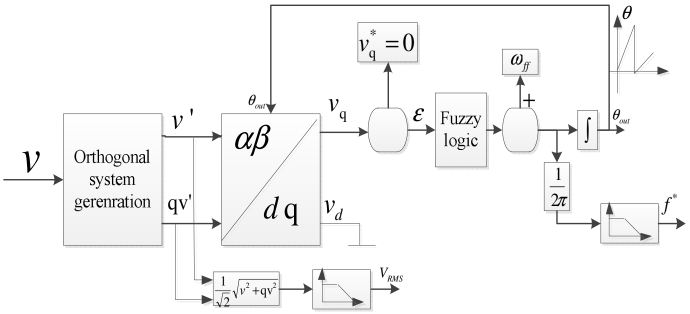

Fig.7. Structure of PLL based fuzzy logic

The Figure 8, below shows the results of the PLL based fuzzy logic simulation in PSIM:

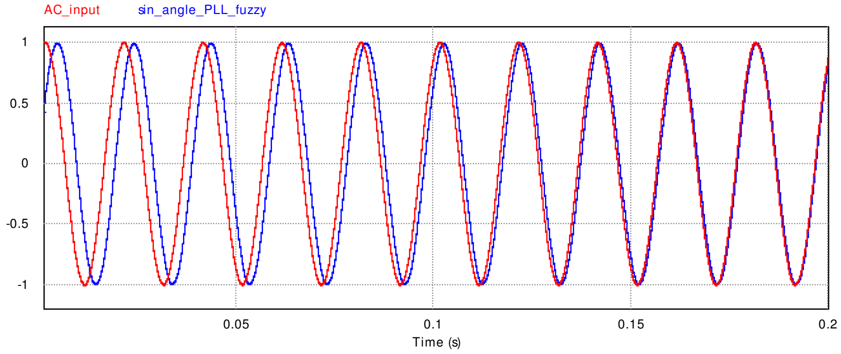

Fig.8. PLL results based fuzzy logic

Figure 8, shows that the output signal from the PLL with notch filter based on fuzzy logic could lock with the input signal after about five fault cycles, despite its ability to provide a locked output signal to the fundamental component of the input signal in its amplitude and frequency.

2.5. SOGI-PLL proposed based on fuzzy logic

This section presents a new phase-locked loop control (PLL) for a grid connected photovoltaic inverters. The originality in this work is to generate an orthogonal power voltage system based on a second order generalized integration structure (SOGI) driven by fuzzy logic to obtain fast detection and a more accurate image of the phase angle.

The Figure 9, below shows the proposed second order generalized integrator (SOGI) structure based on fuzzy logic:

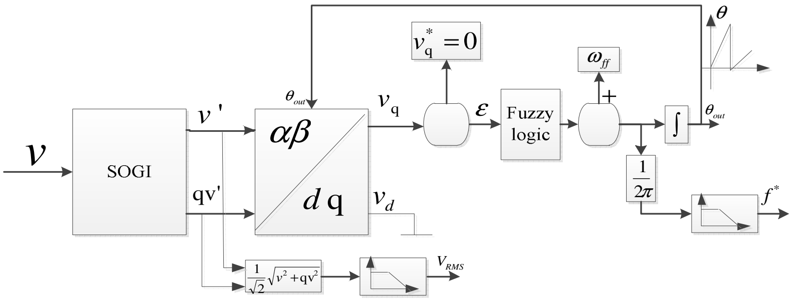

Fig.9. Proposed structure of SOGI-PLL based on fuzzy logic

The proposed method is based on the application of the fuzzy logic on the quadratic component of Park and its error compared to a reference value, to have a precise and fast correction of the frequency, which will be integrated to obtain the phase angle of the grid. For the validation of this method, we will perform the discretization and the implementation of the equations developed in the previous section, in the form of the functions in programming language C. Firstly, they will be used in the DLL block which executes the routines at each step simulation of the PSIM software. Secondly, they will be used for the generation of the program that will be embedded in the STM32F407 microcontroller for experimental validation.

The Figure 10, below shows the results of the SOGI-PLL based fuzzy logic simulation in PSIM:

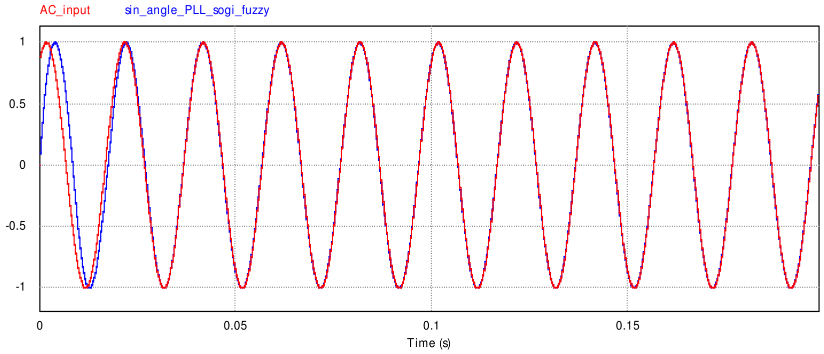

Fig.10. SOGI-PLL results based fuzzy logic

Figure 10, shows that the output signal from the SOGI-PLL based on fuzzy logic could lock with the input signal after about two fault cycles, despite its ability to provide a locked output signal to the fundamental component of the input signal in its amplitude and frequency.

2.5.1. Fuzzy logic controller design and discretization of the different methods

2.5.1.1 Fuzzy logic controller design

Defining input and output variables, and controller functions is one of the most important steps in the fuzzy logic design process. In this study, the selection of members and the number of rules had to be minimized. Blurred affiliations and rules must act quickly to speed up or move backwards the d-q axis until it reaches synchronization speed and position, then lock the axis to its correct synchronization state. This requires more attention to the design of exit rules [1, 36]

The fuzzy logic controller is designed with two variables (quadrature component of Park and its error to a reference value) defined as input variables. These two input variables have five triangle membership functions for each of them. The linguistic variables "positive large

(PL)","positive small (PS)","zero (Z)","negative small (NS)","negative large (NL)" for two input variables are used to express the fuzzy variables. Thus the control action is defuzzified in a unit range also with five membership functions defined as output variable of fuzzy logic to express the values of frequency correction [1, 36, 37, and 38].

The detailed design of the fuzzy membership functions is illustrated below:

- Fuzzification:

Table 1: Quadrature voltage membership function Vq (Input)

Vq	(-1)-(-0.5)	(-0.8)-(0)	(-0.2)-(0.2)	(0)-(0.8)	(0.5)-(1)
Définition	NL	NS	Z	PS	PL

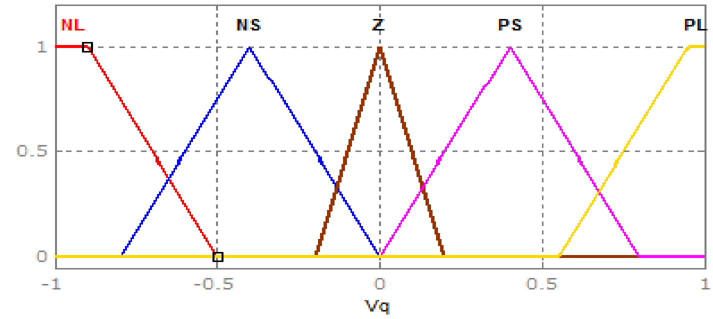

Fig.11. Quadrature voltage membership function Vq (Input)

Table 2: Membership function of the error (Input)

Err	(-1)-(-0.5)	(-0.8)-(0)	(-0.2)-(0.2)	(0)-(0.8)	(0.5)-(1)
Définition	NL	NS	Z	PS	PL

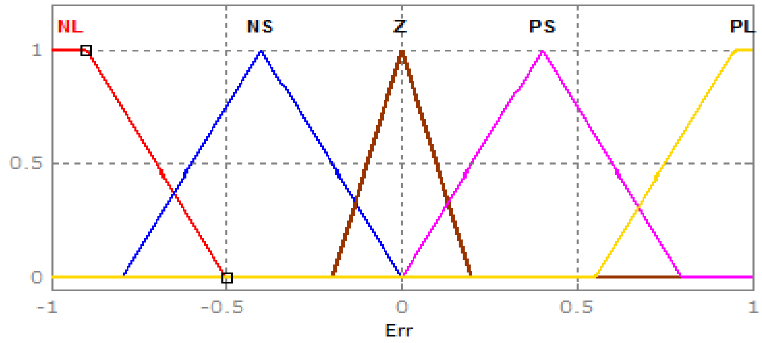

Fig.12. Membership function of the error (Input)

- Inference

Table 3: Inference

Inference table		Vq				
		NL	NS	Z	PS	PL
Err	NL	L	L	M	S	S
	NS	L	M	M	M	S
	Z	M	M	M	M	M
	PS	S	S	M	L	S
	PL	S	M	M	L	S

- Défuzzification

Table 4: Control Membership Function (Output)

Control	(-1)-(-0.3)	(-0.4)-(0)	(-0.1)-(0.1)	(0)-(0.4)	(0.3)-(1)
Définition	NL	NS	Z	PS	PL

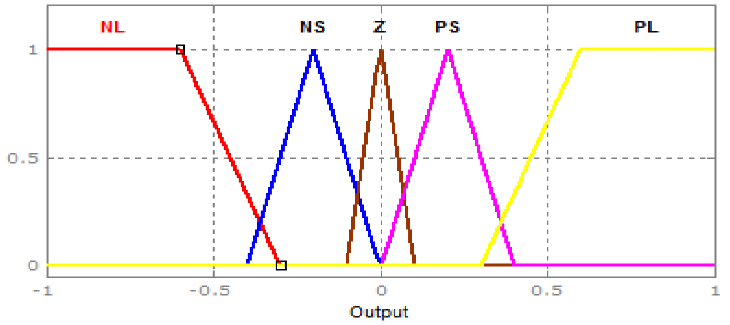

Fig.13. Control Membership Function (Output)

3. Simulation, experimental results and discussion

3.1. Simulation Results

In this section, we present the simulation results of the four methods under the PSIM software, the Figure 13, below represents the two blocks used in the simulation, a C block that generates a sinusoidal signal controlled in frequency and amplitude to simulate the disturbances of the grid, and a DLL block that contains the functions PLL with classical PI, SOGI, Park, fuzzy logic and VCO for the estimation of the phase angle of the grid.

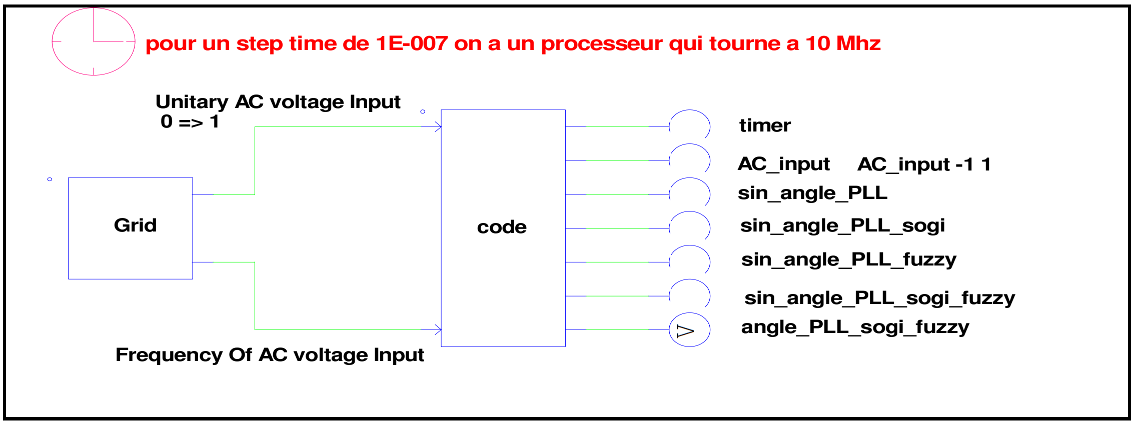

Fig.13. Simulation results of the four different methods of the PLL codes under the PSIM software

Now, the performance of the four filters based PLL are simulated for three different fault scenarios. The following is a detailed presentation of these scenarios.

The Figure below shows the results of the different methods with different variations (amplitude, frequency and phase shift variations):

- Scenario 1: Amplitude variation:

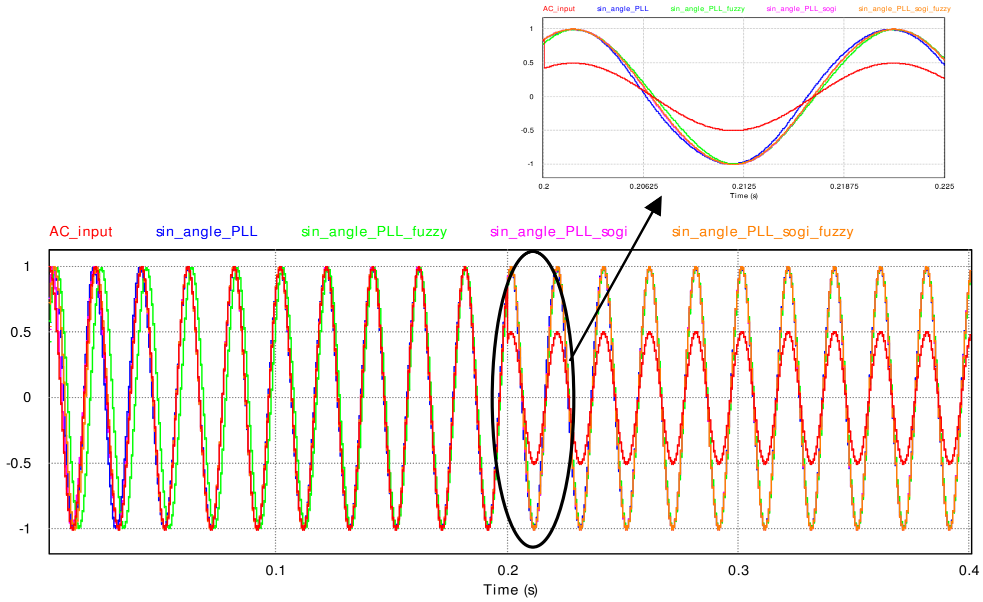

Fig.14. Results of the simulation with amplitude variation

During this scenario, as depicted in Figure 1(4), the PLL with notch filter based on fuzzy logic output signal was able to lock with the input signal about three cycles from fault, despite of its ability for providing an output signal locked to the fundamental component of the input signal in its amplitude and frequency, while the SOGI-based PLL keeps tracking the input signal even during fault. In contrast, SOGI-PLL based on fuzzy logic and PLL with notch filter based on fuzzy logic show acceptable level of immunity against of the amplitude variations.

Clearly, the SOGI filter-based PLL has the lowest error indices among other filter-based PLLs, as shown in Figure (14). In addition, the PLL with notch filter based on fuzzy logic has the highest indices due to its operation principle as discussed in Figure (14).

- Scenario 2: Amplitude and frequency variations:

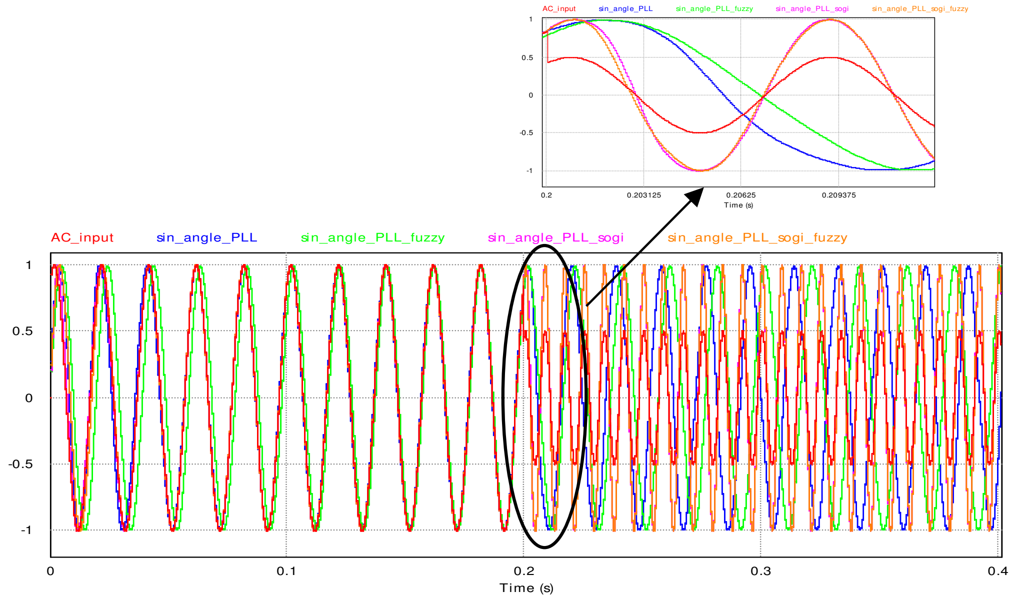

Fig.15. Amplitude and frequency variations

During this scenario, Amplitude and frequency variations occur. The second order generalized integrator based PLL has the fastest and the most efficient response, as depicted in Figure (15), compared with other filters based PLLs. This result shows the ability of SOGI filter based PLL of tracking the input signal without delay due to its resonance at the fundamental frequency. SOGI-PLL based on fuzzy logic has the second best response, as illustrated in Figure (15), where it locked the reference signal during the first cycle. While the PLL with notch filter based on fuzzy logic tracking the input signal, after about 70 ms, makes it the slowest tracking technique among the four filters.

- Scenario 3: Frequency and phase jump variations

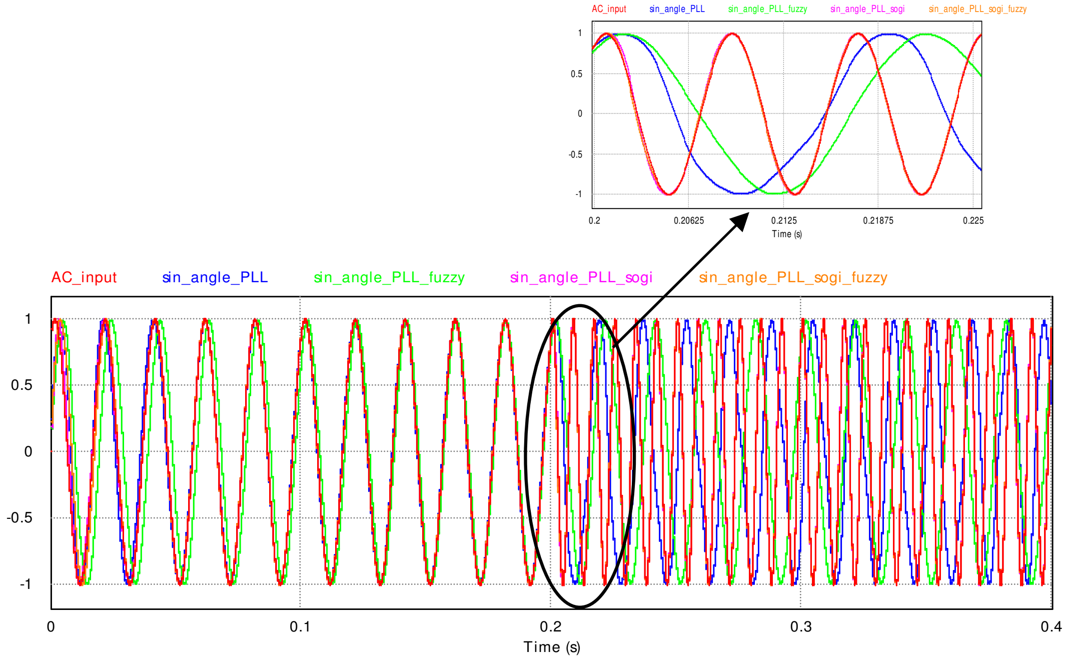

Fig.16. Frequency and phase jump variations

During this scenario, frequency and a phase jump variations occurs. As illustrated in Figure (16), the PLL with notch filter based on fuzzy logic mist races the input signal for about five cycles after the faults occur. This result shows that the PLL with notch filter based on fuzzy logic is highly affected by phase jump, in comparison with the other three filters, which are able to keep locked with the input signal even after the phase jump take place.

However, the SOGI-based PLL has the lowest error response during frequency and a phase jump variations, as shown in Figure (16). The same result was reported by experimentally during phase.

The Figure (17), below shows the error signal under normal operating conditions for the four methods:

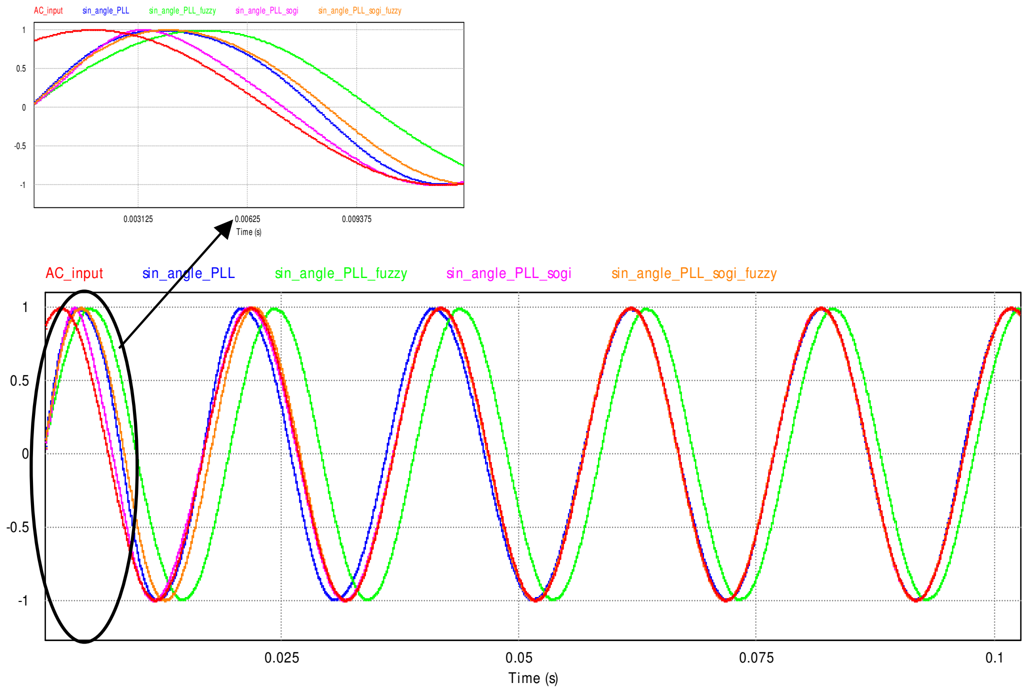

Fig.17. Error signal under normal operation

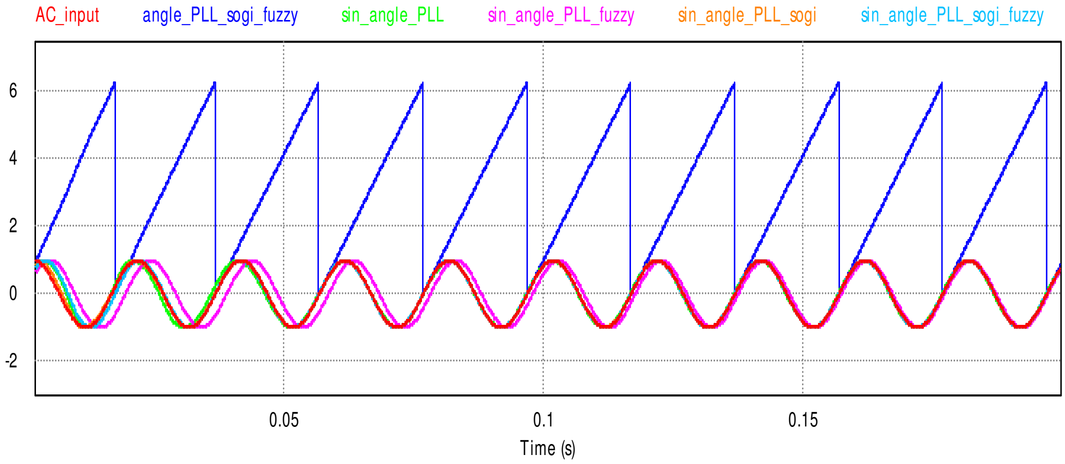

Fig.18. Phase angle with different methods

Moreover, Figure (17) illustrates the error signal of the four proposed techniques. Clearly, the SOGI filter-based PLL has zero error signals faster than the other three filter-based PLLs. In addition, the error signal of SOGI-PLL based on fuzzy logic has almost the same response. The PLL with notch filter based on fuzzy logic do not act ideally for the sinusoidal input signal. Moreover, the error signal of SOGI filter-based PLL reaches zero steady state much faster than other filters.

3.2. Experimental results

The different PLL methods are verified and evaluated by an experimental tests, using a differential voltage level shift circuit to sample the network voltage with the CAN of the STM32F4-discovery evaluation board, to evaluate the accuracy of the four proposed methods, we visualize using a digital scoop the sinusoid of the estimated phase angle in the DAC with the offset gate voltage. The Figure below shows the connection between the test equipment used in the experimental prototype.

The Figure 19, below shows the assembly of the practical test of the different methods:

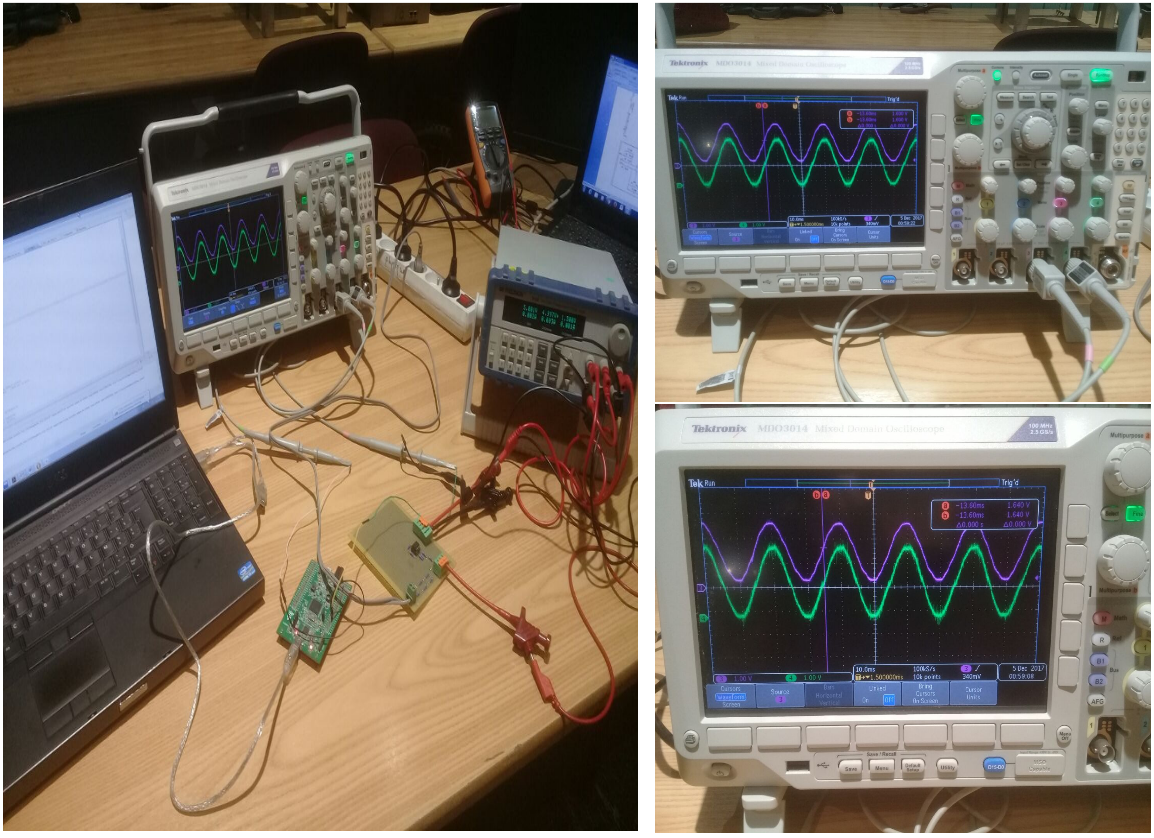

Fig.19. Connection of the experimental equipment and results of experimental tests, results of the digital oscilloscope with the different methods synchronized with PLL classic

3.3. Discussion

Once the simulation task is complete, the process of reading the analog signal and generating the sinusoidal signal using the estimated phase angle is done with the STM32F407-discovery evaluation board. The different function of PLL methods runs in an interrupt with a frequency of 10 kHz; the complete program is compiled using the COOCOX software that generates a Hex file which will be sent to the microcontroller of the evaluation board STM32F407-discovery. So in Figure (19), shows the sinusoidal signal generated by the DAC bloc (shifted by a voltage of 1.65V), with the grid voltage signal scaled by the differential voltage level shift circuit.

The second order generalized integrator based PLL has the fastest and the most efficient response, as depicted in Figure (14), compared with other filters based PLLs. This result shows the ability of SOGI filter based PLL of tracking the input signal without delay due to its resonance at the fundamental frequency. SOGI-PLL based on fuzzy logic has the second best response, where it locked the reference signal during the first cycle. While the PLL based on fuzzy logic tracking the input signal, after about 70 ms, makes it the slowest tracking technique among the four filters. Moreover, Figure (17) illustrates the error signal of the four proposed techniques. Clearly, the SOGI filter-based PLL has zero error signals faster than the other three filter-based PLLs. In addition, the error signals of PLL classic and SOGI-PLL based on fuzzy logic have almost the same response. Despite various variations in the network (amplitude variations, frequency and a phase jump variations...), the error signal of SOGI filter-based PLL reaches zero steady state much faster than other filters. And the amplitude integrator in PLL classical based fuzzy logic filter do not act ideally for the sinusoidal input signal, as mentioned in Figure (15 and 16). So based on the results of simulations and experimental tests with different ideal and non-ideal variations of the network, we conclude that, it is obvious that SOGI filter-based PLL has the best response, compared with the other three filters under normal operation condition. In comparison, PLL with notch filter based on fuzzy logic has the worst phase locking characteristics among the four proposed filters

4. Conclusion

In order to achieve synchronization with the utility grid, a phase locked loop is used. It generates a reference signal to synchronize the operation condition of the inverter side with the utility grid. In the present study, an enhancement for a conventional phase locked loop using four different filters, including classical filter, second order generalized integrator filter, classical filter based on fuzzy logic and second order generalized integrator filter based on fuzzy logic. Then a comparison between these four proposed improvements was conducted under normal and two abnormal operation condition scenarios: amplitude variations, frequency and a phase jump variations.

The results show that the second order generalized integrator based PLL has a superior performance over other filters-based PLL under both normal and fault operation conditions. During normal condition, the SOGI based PLL locked the input signal very fast and accurate. Moreover, it kept tracking the input signal even after the occurrence of a fault condition, such as a phase jump or amplitude variations. And SOGI-PLL based on fuzzy logic has the second best response, where it locked the reference signal during the first cycle.

The PLL with notch filter based on fuzzy logic had a sluggish response to reach zero steady state error signals during normal operation condition as well as during voltage sag. In addition, its error signal experienced a high oscillation during phase jump at which the output signal of this PLL missed the input signal and relock back again after 100ms.

In general, the four different filter techniques have an acceptable performance during the proposed operation conditions. The prefer ability of any of these filters-based PLL depends on its application in power system environment.

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