World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:15, No:4, 2021

A Grid Synchronization Phase Locked Loop Method for Grid-Connected Inverters Systems

Naima Ikken, Abdelhadi Bouknadel, Nour-eddine Tariba Ahmed Haddou, Hafsa El Omari

Abstract—The operation of grid-connected inverters necessity a single-phase phase locked loop (PLL) is proposed in this article to accurately and quickly estimate and detect the grid phase angle. This article presents the improvement of a method of phase-locked loop. The novelty is to generate a method (PLL) of synchronizing the grid with a Notch filter based on adaptive fuzzy logic for inverter systems connected to the grid. The performance of the proposed method was tested under normal and abnormal operating conditions (amplitude, frequency and phase shift variations). In addition, simulation results with ISPM software are developed to verify the effectiveness of the proposed method strategy. Finally, the experimental test will be used to extract the result and discuss the validity of the proposed algorithm.

Keywords—Phase locked loop, PLL, notch filter, fuzzy logic control.

I. Introduction

ENERGY demand and environmental problems are increasing, renewable energy sources such as solar and wind energy have become very important as an alternative to conventional fossil energy sources. And since distributed power generation units feed into the grid, they also bring additional pollution into the grid if grid-connected inverters use inaccurate phase information of grid voltages to synchronize with the grid [1]- [2]. In addition, the accurate information of the phase angle, frequency and the magnitude of the network voltage are essential for the synchronization of inverters connected to the network. Therefore synchronization algorithms are of great importance in the control of inverters connected to the network as an integral part of the decentralized production units. For this there are different synchronization techniques for detecting the phase angle have been proposed in the literature. The zero crossing detection methods [1], the space-vector filtering (SVF) method [1]- [3], the artificial neural networks (ANN) method [3], the recursive weighted least-squares estimation (WLSE) algorithm [1], [2], [4], the discrete Fourier transform (DFT) and its modifications [2], [3], the method based on the concept of adaptive notch filtering (ANF) [2]- [4], the Kalman filtering technique [1]- [3], the frequency-locked loop (FLL) method [5], three-phase open-loop phase-locked method [5], [6], and the phase-locked loop (PLL) based on algorithms [1] are among the existing synchronization techniques [7]. This article presents the improvement of a phase locked loop method. The novelty is to generate a method (PLL) of network synchronization with a Notch Filter based on adaptive fuzzy logic control for grid connected inverter systems [8]. The proposed method is a good choice for creating an orthogonal system in single-phase systems compared to the known process. The performance of the proposed method was performed under normal operating conditions and tested under three abnormal scenarios: voltage variations, amplitude and frequency variations, frequency variations and phase jump. In addition, simulation results with the PSIM software are developed to verify the effectiveness of the proposed method strategy. Finally, an experimental test is used to extract the result and discuss the validity of the proposed algorithm using the STM32F407 microcontroller card with the estimation of the phase angle and frequency that are visualized using a digital oscilloscope.

Naima Ikken is with the Department of the Physics and Engineering Science, Laboratory ERED, Hassan I University, Morocco (e-mail: naima.ikken@gmail.com).

II. 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 [6], [7]. An adaptive notch filter can also be used to selectively notch the exact frequency in case there are variations in the grid frequency.

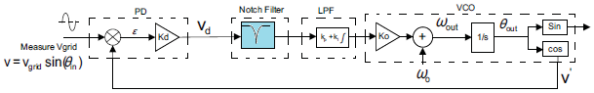

Fig. 1 Single Phase PLL with Notch Filter

With the addition of the notch filter, the PI tuning can be done solely based on dynamic response of the PLL [9], [10]. Section II A illustrates digital implementation of the PI controller and the selection of the coefficients for the PI controller to be used [11], [12].

A. Discrets Implementation of PI Controller

The loop filter or the PI is implemented as a digital controller with (1):

$$Y[n] + A_1 Y[n-1] = B_0.y_{notch}[n] + B_1.y_{notch}[n-1] \quad (1)$$

Using z transform, (1) can be re-written as:

$$Y[z](1 + A_1 z^{-1}) = y_{notch}[z](B_0 + B_1.z^{-1}) \quad (2)$$

Using bi-linear transformation, we replace $s = \frac{2}{T}(\frac{z-1}{z+1})$, where T = Sampling Time.

$$\frac{Y(z)}{y_{notch}(z)} = \frac{(\frac{2k_p+Tk_i}{2}) - (\frac{2k_p-Tk_i}{2})}{1 - z^{-1}} \quad (3)$$

So with the PSIM software, Fig. 2 represents the PLL response with the Notch Filter under normal network conditions:

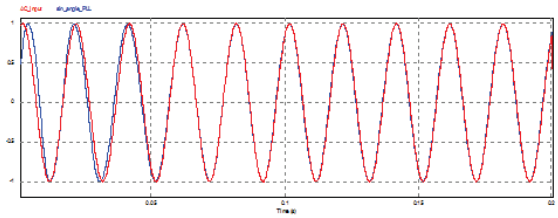

Fig. 2 PLL response with ideal grid conditions

Fig. 2 shows that with ideal network conditions, the PLL with Notch filter converges with the network reference voltage and relatively follows the phase angle but after a period of three cycles about 50 ms. Thus, different non-ideal conditions (voltage variation, frequency variation and phase jump variation) were simulated and most of them were processed by the system. Figs. 3-5 show the PLL output signals with phase shift of the input signals.

- Voltage variation

In this scenario, as shown in Fig. 3, the phase locked loop (PLL) with conventional Notch filter is locked by the network input signal and shows the ability and efficiency of the method to continue to follow the input signal, even in case of amplitude variations in the network.

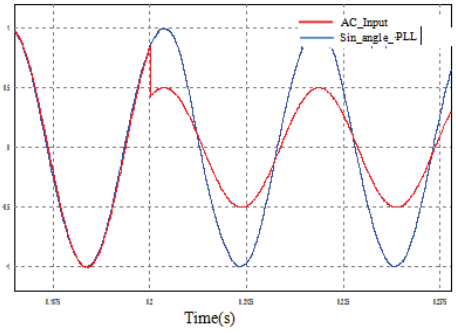

Fig. 3 PLL response with voltage variation

- Voltage and frequency variation

In this scenario, a change in amplification and frequency occurs after about 200 ms. As shown in Fig. 4, the phase locked loop (PLL) with Notch filter is strongly affected by frequency variation.

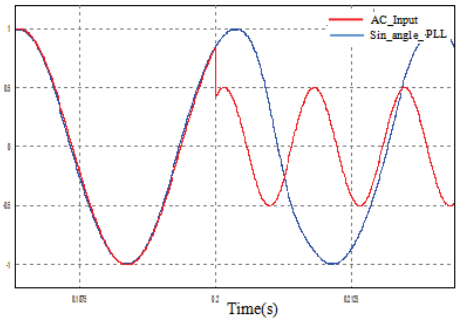

Fig. 4 PLL response with voltage and frequency variation

- Frequency and phase jump variation

During this scenario, a phase jump occurs after about 200 ms. As illustrated in Fig. 5, the PLL with Notch filter substitutes the input signal during cycles after the onset of defects. This result shows that the PLL based on the Notch filter is strongly affected by the variation of the frequency and the phase jump. In addition, the PLL error signal based on the Notch filter undergoes a high oscillation once the fault has occurred. This severe response is attributed to the fact that the PLL output signal based on the filter is locked to the fundamental component of the input signal in its amplitude and frequency, which results in a high oscillation error as soon as a distortion occurs affects the input signal.

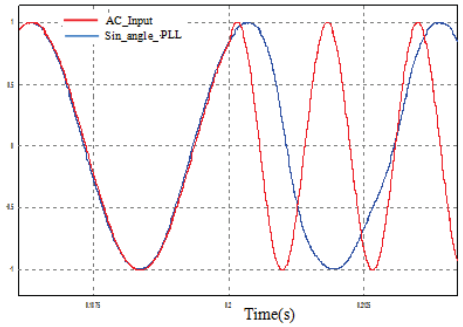

Fig. 5 PLL response with frequency and phase jump variation

B. Problem Formulation

When the phase jump is present in the input signals, the PLL system with notch filter does not actually operate as a low pass filter and does not follow the phase angle. The PLL with Notch Filter controller must be designed to have a quick lock to the inside of a cycle with the opportunity to mitigate the bottom of harmonics which may exist in a real network. These two objectives cannot be achieved simultaneously. Either to have a quick response with a wide bandwidth or slow response with the interlock time delayed. Most of the PLL with Notch Filter systems are implemented with PI controller which is very sensitive to changes in the parameters of the controller. The main disadvantage of the PI corrector is their inability to react to sudden changes in signal the network. The control device must be optimized in such a way as to achieve the quick-lock with less bandwidth. This challenge will be presented in the next section where the PLL with Notch Filter corrector will be redrafted using the control of fuzzy logic, which allows you to have, the robust functionality and the noise immunity hoses to match the network. The fuzzy controller is much more efficient since it is used to obtain both a quick response.

III. PLL with Notch Filter Based Fuzzy Logic

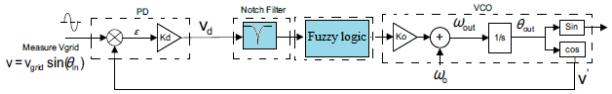

Fig. 6 Single Phase PLL with Notch Filter based Fuzzy logic

We started with adaptive control, to which intelligent supervision will be added, and then calculated PI controller instructions autonomously using local measurements. This intelligent supervision is achieved thanks to the fuzzy logic [13]- [16]. Fuzzy PI control can be achieved by combining fuzzy logic that is adaptive and independent of the system parameter and PI controller for fast response. In this controller the gains are adjustable and are determined by the fuzzy logic according to the operating point of the system for the defined inputs [17]. This section presents the simulation results of the controller design approach given in this report. The control algorithm is implemented in C bloc of PSIM software; the results of simulation are shown below:

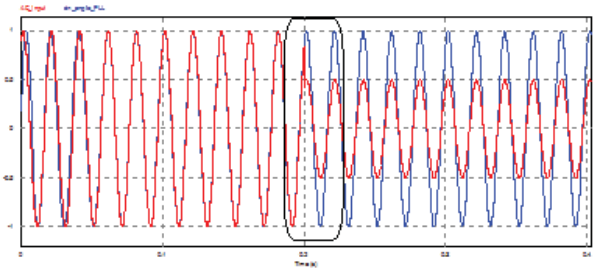

Fig. 7 PLL response with not ideal grid conditions

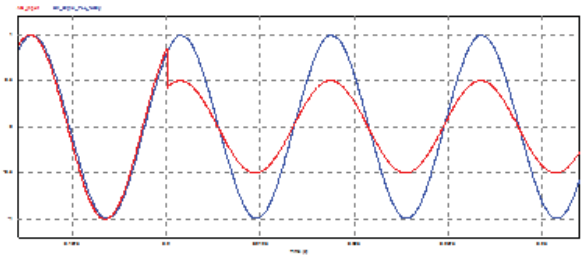

Fig. 8 Zoom of the boxed area

Fig. 8 represents the efficiency of the PLL response with Notch filter based on fuzzy logic control. Thus, it shows the ability and efficiency of the proposed method to continue to follow the input signal, even in case of variations in the network.

IV. Experimental Result and Discussion

The proposed PLL is verified and evaluated by comprehensive tests. The test platform is sketched in Fig. 9. During the test, the PLL algorithm is implemented in a development board STM32F407 discovery micro controller. The estimated phase angle and frequency are visualized by a digital oscillator.

The proposed methods of PLL is verified and evaluated by an experimental test, 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 PLL with Notch filter based fuzzy logic, we visualize using a digital scoop the sinusoid of the estimated phase angle in the DAC with the offset gate voltage. So

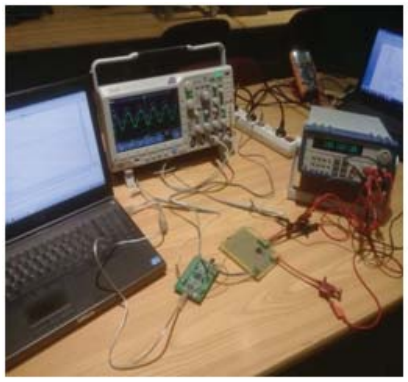

Fig. 9 Results of experimental tests

Fig. 9 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. PLL with Notch filter based fuzzy logic based to a quicker and more efficient response, as shown in Fig. 9. So this result shows the ability of PLL to automatically follow the input signal without delay despite the different variations of the network (amplitude variations, amplitude and frequency variations, frequency variations and a phase jump). Finally, based on the results of simulations and experimental tests with different ideal and non-ideal variations of the network, we conclude that the proposed method has a better response.

V. Conclusion

In order to synchronize with the public network, a phase-locked loop is used. It generates a reference signal to synchronize the operating state of the inverter side with the power grid. In this study, an improvement for an approach to the conventional phase locked loop. Subsequently, improvements to the proposed method were made under normal and three abnormal operating conditions: amplitude variations, amplitude and frequency variations, frequency variations, frequency variations and phase jumps. The results show that PLL with Notch filter based fuzzy logic has an efficient and fast performance under normal conditions and faulty operation. Under normal conditions, the PLL with Notch filter based fuzzy logic has locked with the input signal very quickly and precisely. In addition, it continued to follow the input signal even after a fault condition, such as a phase jump or amplitude variations, appeared.

Acknowledgment

The authors would like to thank IRESEN (Moroccan Research Institute for Solar and New Energy) for the financial support of the research project on 6kVA inverters.

References

[1] IKKEN, N., BOUKNADEL, A., EL OMARI, Hafsa, et al. : Design and implementation of intelligent PI-fuzzy logic control for grid connected inverters. p. 1111-1117. Renewable and Sustainable Energy Conference (IRSEC), 2016 International. IEEE, (2016).

[2] IKKEN, N., BOUKNADEL, A., HADDOU, A., et al. A comparative Study and implementation of Single-Phase PLL techniques for Grid-Connected Inverters Systems. Journal of Electrical Systems, 2018, vol. 14, no 4.
[3] IKKEN, Naima, BOUKNADEL, Abdelahdi, HADDOU, Ahmed, et al. PLL Synchronization Method Based on Second-Order Generalized Integrator for Single Phase Grid Connected Inverters Systems during Grid Abnormalities. In : 2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS). IEEE, 2019. p. 1-5.
[4] Texas Instrumeent Software Phase Locked Loop Design Using C2000 Microcontrollers for Three Phase Grid Connected Applications.
[5] FREIJEDO, Francisco D., DOVAL-GANDOY, Jesus, LOPEZ, Oscar, et al.: Robust phase locked loops optimized for DSP implementation in power quality applications. p. 3052-3057. Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE. IEEE, (2008)..
[6] HAN, Yang, XU, Lin, KHAN, Muhammad Mansoor, et al. :A novel synchronization scheme for grid-connected converters by using adaptive linear optimal filter based PLL (ALOFPLL). vol. 17, no 7, p. 1299-1345.Simulation Modelling Practice and Theory, (2009)
[7] LEE, Kyoung-Jun, LEE, Jong-Pil, SHIN, Dongsul, et al. A novel grid synchronization PLL method based on adaptive low-pass notch filter for grid-connected PCS. vol. 61, no 1, p. 292-301. IEEE Transactions on Industrial Electronics,(2014)
[8] XU, Lin, HAN, Yang, ZHOU, Li-Dan, et al.:Novel phase-locked loop using adaptive notch filter. vol. 92, no 4, p. 7-12.Elektronika ir Elektrotechnika,(2009).
[9] FREIJEDO, Francisco D., YEPES, Alejandro G., LPEZ, scar, et al. :An optimized implementation of phase locked loops for grid applications. vol. 60, no 9, p. 3110-3119.IEEE Transactions on Instrumentation and Measurement, (2011).
[10] R. Teodorescu, M. Liserre, and P. Rodriguez, : Grid Converter for Photovoltaic and Wind Power Systems. Hoboken, NJ: Wiley, (2011).
[11] KOBOU NGANI, Patrick, HADJI-MINAGLOU, Jean-Rgis, MARSO, Michel, et al. :A new Single-phase PLL based on the input voltage magnitude estimation. (2015).
[12] BHARDWAJ, M. Software phased-locked loop design using C2000 microcontrollers for single phase grid connected inverter. Application Report, Texas Instruments, (2013).
[13] HAMED, Hany A., BAYOUMI, Ehab HE, et EL-KHOLY, E. E. Fuzzy PLL for three-level neutral point clamped active rectifiers. , vol. 2, no 3, p. 170-190. International Journal of Industrial Electronics and Drives, (2015).
[14] Digitally Controlled Solar Micro Inverter Design using C2000 Piccolo Microcontroller, Application Report, Texas Instruments, (2013).
[15] Manish S Trivedi, Uday B Mujumdar. Study and Simulation of Parks Transform PLL for robust single phase grid connected system. 2321-8169 Vol. 3, no 2; p149-152 . International Journal on Recent and Innovation Trends in Computing and Communication.
[16] RODRGUEZ GUERRA, Juan Carlos. Test bench evaluation of the main synchronization methods for grid-connected voltage source converters. (2012).
[17] PALLE, Sreeshailam, ARAFAT, N., SOZER, Y., et al. : Voltage harmonic control of weak utility grid through distributed energy systems. p. 1982-1989. Energy Conversion Congress and Exposition (ECCE), (2012).