Grid synchronization methods

TN107 | Posted on June 20, 2024 | Updated on July 3, 2025

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This technical note presents some of the most common grid synchronization methods for power converters connected to the grid. These different methods allow the power converter to safely inject quality power into the grid, even during disturbed conditions.

First, the general principle of grid synchronization is introduced. Then, different methods to achieve great synchronization are presented. Finally, experimental results of the various grid synchronization methods under different disturbed conditions are shown.

The different implementations of grid synchronization methods are available for download in Simulink and PLECS on their respective pages (i.e., SOGI-PLL and SRF-PLL).

What is grid synchronization?

Grid synchronization is the process by which power converters, especially those connected to renewable energy sources, ensure that the power injected by the inverter is aligned with the grid. This includes estimating and matching the phase angle, frequency, and voltage magnitude.

Indeed, the estimated phase is commonly used for performing power flux calculations and transformations in the synchronous reference frame (dq). Nevertheless, from a broader perspective, the alignment with the grid is essential for maintaining the stability and reliability of the power system. Without proper synchronization, discrepancies between the inverter output and the grid can lead to power quality issues or potential damage to the grid infrastructure. This becomes especially important when a fault occurs on the grid, and the power converter must ride through the disturbance.

Grid synchronization can be achieved using various control techniques. The primary tool for achieving this is the phase-locked loop (PLL) [1]. The latter consists of a feedback control loop that follows the frequency and phase of its input signal. In grid-tied applications, the PLL input is the grid voltage. Moreover, some advanced grid synchronization methods combine the PLL with filters applied to the input voltage. Such a combination allows for robust and precise estimation of the above-mentioned grid parameters even under unbalanced voltages, harmonic distortions, or voltage sags.

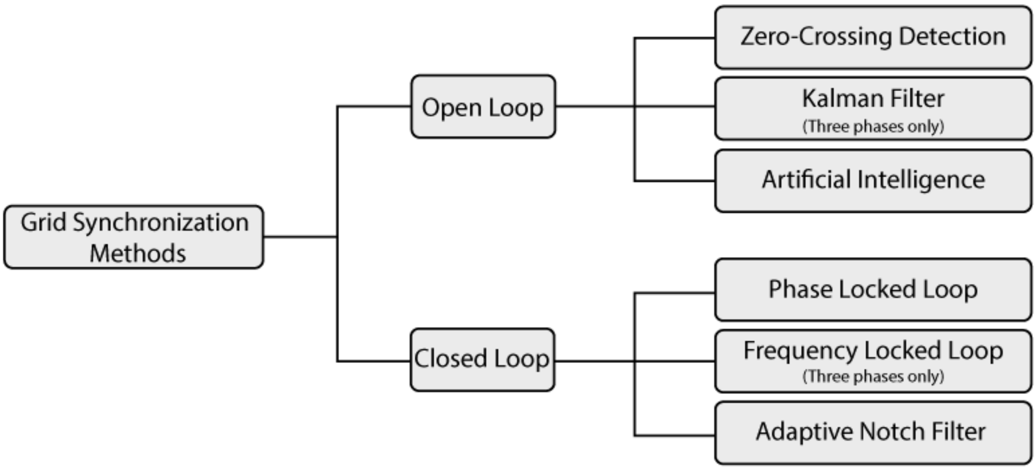
Conventional grid synchronization methods

Numerous techniques exist for achieving grid synchronization, which can be broadly categorized into open-loop and closed-loop approaches.

Open-loop methods include techniques such as zero-crossing detection and Kalman filters [2]. These methods are often simpler and, in most cases, less computationally demanding than closed-loop methods. However, they may turn out insufficient under unbalanced or distorted grid conditions.

Closed-loop methods involve continuous monitoring and feedback to ensure synchronization. Beyond the well-known phase-locked loop (PLL) techniques, closed-loop methods may also include adaptive notch filters [3] and feedback mechanisms that adjust to real-time grid conditions changes. These approaches are more complex but provide superior accuracy and reliability against grid disturbances.

A hierarchical classification is shown below, providing a non-exhaustive list of the different open and closed-loop grid synchronization techniques.



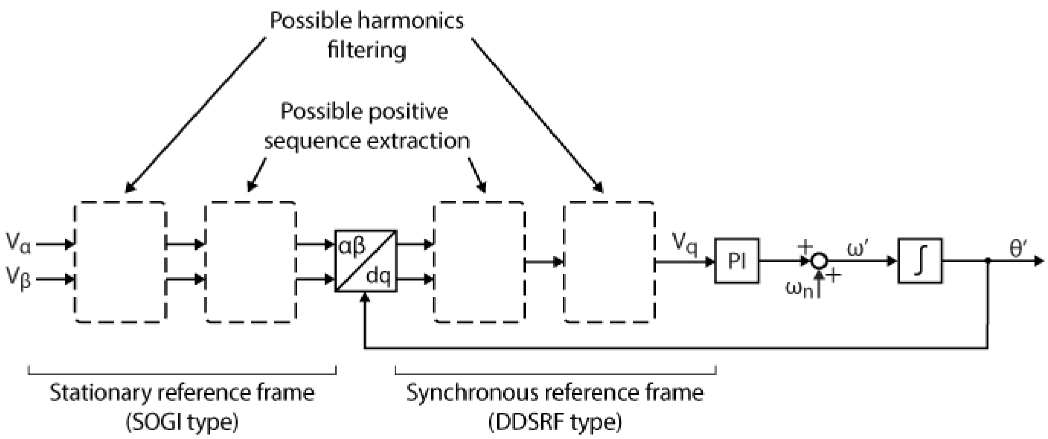
Conventional grid synchronization methods

In general, closed-loop methods, particularly PLL-based techniques, are preferred for their precision, robustness, and relatively simple implementation.

PLL-based methods

The three most commonly used types of PLL in three-phase systems are the SRF-PLL and two of its derivatives. These improved derivatives, namely the Double Decoupled SRF-PLL (DDSRF) and the Decoupled SOGI-PLL (DSOGI), offer enhanced robustness against unbalanced conditions due to their positive sequence estimation carried out in the stationary reference frame (αβ) or the rotating reference frame (dq).

The image below illustrates the potential modifications that can be made to the SRF-PLL to estimate the positive sequence and filter out harmonics.



SRF-PLL modifications

SRF-PLL

This PLL is the fundamental type used in grid synchronization methods. It is simple and effective under normal operating conditions but can lose accuracy when disturbances occur. For more detailed information about this PLL, including its implementation in Simulink and PLECS, please refer to the SRF-PLL page.

DDSRF-PLL

This PLL is a modified SRF-PLL designed to decouple positive and negative sequences in the synchronous reference frame (dq). This enhancement improves the accuracy of parameter estimation under unbalanced grid voltage conditions. More detailed information about this PLL, including its implementation in Simulink and PLECS, can be found in DDSRF-PLL.

DSOGI-PLL

This PLL is a modified SRF-PLL that can estimate both positive and negative sequences in the stationary reference frame (αβ) while also filtering high and low-frequency distortions. An additional modification, the Multiple SOGI, further enhances its ability to target specific harmonic filtering. More detailed information about this PLL, including its implementation in Simulink and PLECS, can be found in MSOGI-PLL.

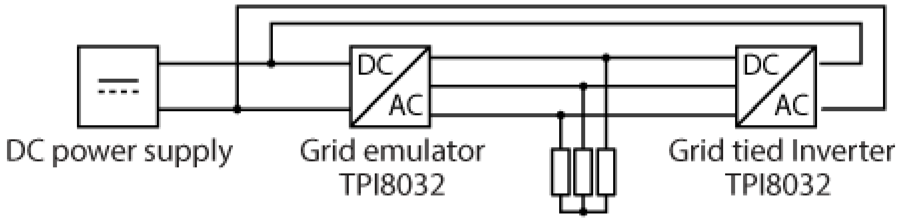
Performance evaluation of grid synchronization methods during disturbed conditions

The three PLLs mentioned above will be compared to observe their responses under disturbed conditions. For benchmarking purposes, disturbances will include i) a 60° phase jump, ii) a 2 Hz frequency jump, iii) 5th harmonic distortion with an amplitude of 0.1 p.u., and iv) a phase-to-phase fault in the grid.

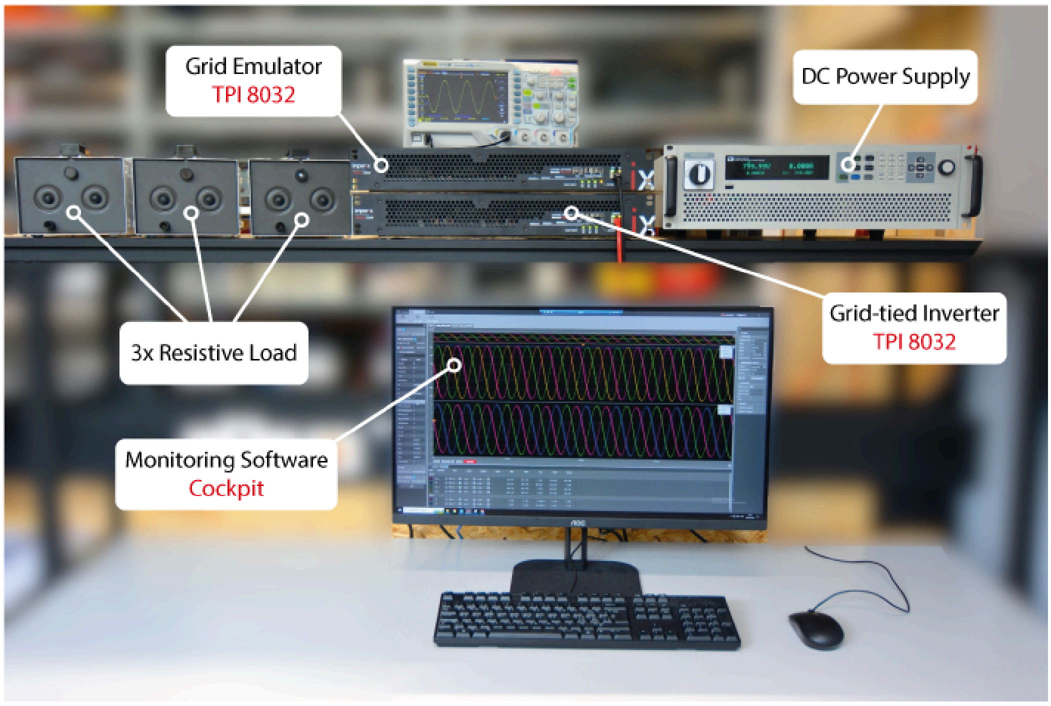
Experimental results

To test these grid synchronization methods, a grid emulator is used to replicate specific conditions, as these cannot be reproduced on a real grid. Here, the grid emulator and the grid-tied inverter are physically implemented on two TPI 8032 in a back-to-back configuration. This arrangement allows for the safe and reliable reproduction of disturbed conditions but also to test the grid synchronization methods from an independent device.

The experimental setup used for conducting these tests is presented below :

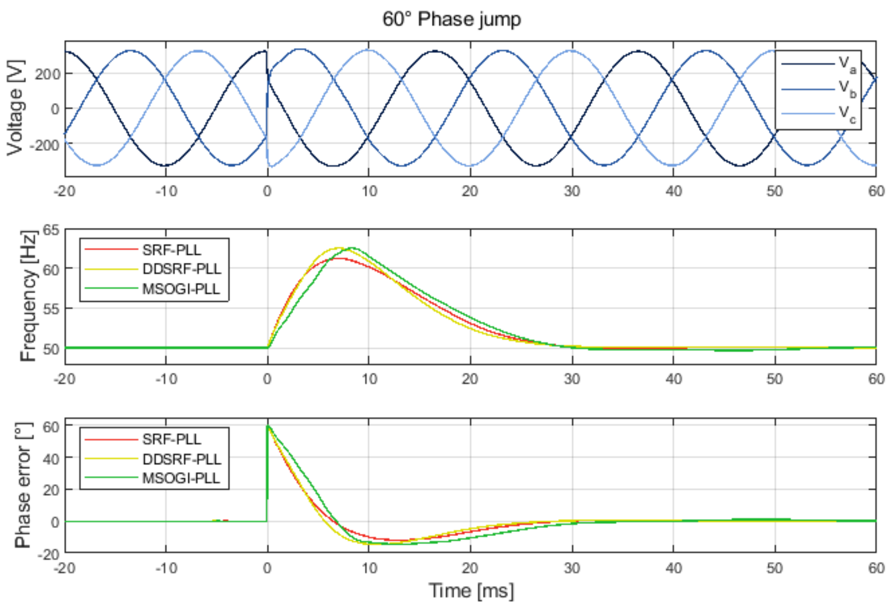


Electrical diagram of the setup

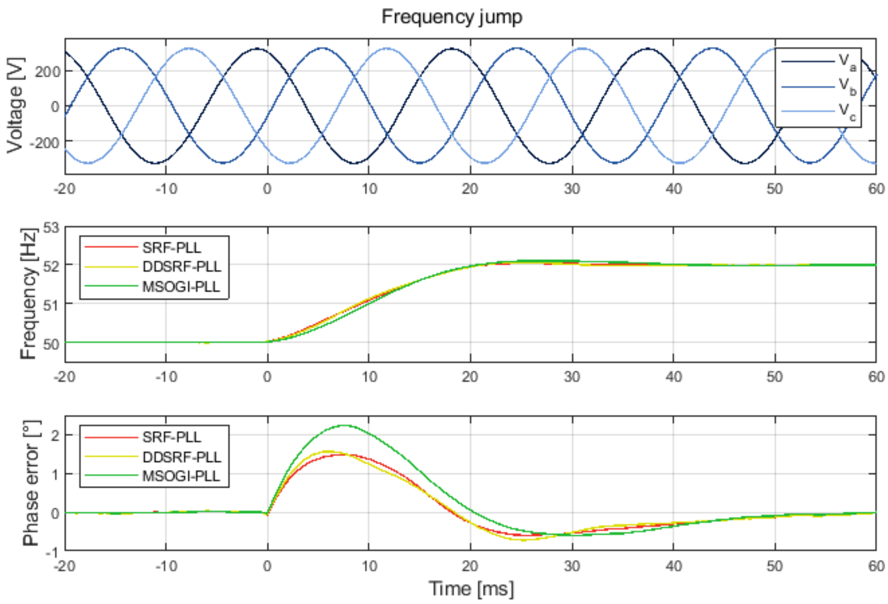


Experimental setup for PLL testing

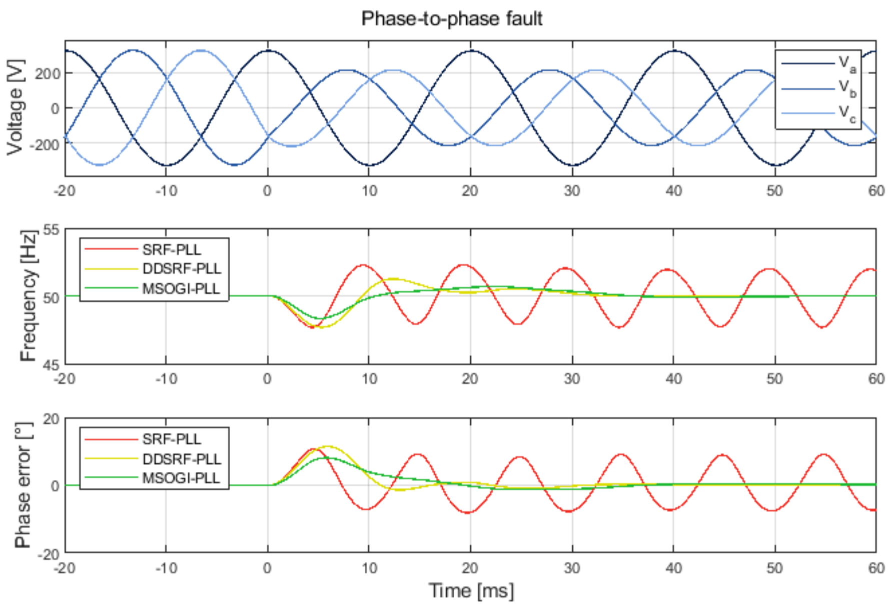
Using this experimental setup, along with the downloadable files from the [(DD)SRF-PLL] and [(M)SOGI-PLL] pages, the obtained experimental results are displayed in the following graphs.



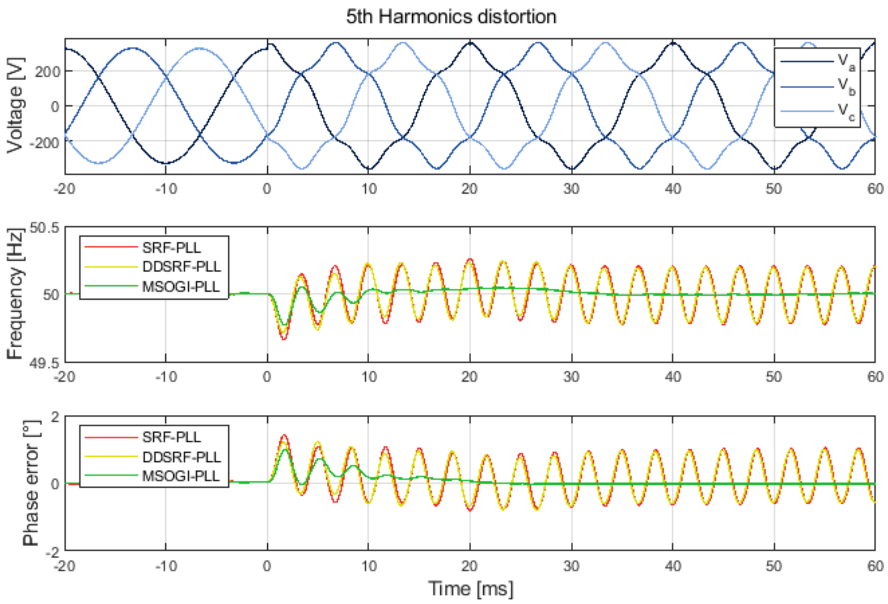
Responses to a 60° phase step



Responses to a 2Hz frequency step



Responses to unbalanced conditions



Responses to 5th harmonics distortion

During single events such as a phase or frequency step, the three analyzed PLLs exhibit similar frequency and phase responses. However, the MSOGI-PLL suffers from a slightly longer settling time and larger overshoot during frequency steps. This is because SOGI filters utilize frequency feedback, unlike other PLLs.

Under unbalanced conditions, the basic SRF-PLL shows significant distortion in the phase and frequency estimates. The (M)SOGI-PLL and DDSRF-PLL do not exhibit this drawback, because they effectively reject the negative sequence, hence relying solely on the positive sequence for the phase and frequency estimation.

Finally, in the presence of harmonic distortion, the DDSRF and SRF PLLs show similarly distorted responses, as adding a decoupling stage does not affect the harmonics filtering. The MSOGI-PLL naturally behaves as a band-pass filter and includes a SOGI filter tuned to the 5th harmonic, further attenuating this specific harmonic.

In conclusion, the MSOGI-PLL satisfactorily mitigates a broader range of distortions over the DDSRF-PLL while maintaining a relatively simple implementation. An enhancement of the DDSRF-PLL that enables the decoupling of the zero, positive, and negative sequences, as well as harmonic attenuation, exists under the name HIHDO-PLL [4]. However, its implementation is considerably more complex.

Academic references

[1] H.S. Kamil, D.M. Said and M.W. Mustafa, “Recent advances in phase-locked loop based synchronization methods for inverter-based renewable energy sources,”

Indonesian Journal of Electrical Engineering and Computer Science, vol. 18, no. 1, pp. 1-8, April 2020.

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[3] D. Yazdani, A. Bakhshai, G. Joos and M. Mojiri, "A Nonlinear Adaptive Synchronization Techniquefor Grid-Connected Distributed Energy Sources," in *IEEE Transactions on Power Electronics*, vol. 23, no. 4, pp. 2181-2186, July 2008

[4] Ali, Z., Christofides, N., Hadjidemetriou, L. and Kyriakides, "Design of an advanced PLL for accurate phase angle extraction under grid voltage HIHs and DC offset," IET Power Electronics, vol. 11, no. 6, April 2018.