Benchmarking of Grid Synchronization Algorithms Under Low-Voltage Grid Disturbances

Filip Filipović, Milutin Petronijević, Nebojša Mitrović and Bojan Banković

***Abstract*— Distributed generation is composed of various types of renewable energy sources with different voltage-current characteristics. In order to transfer the power to the power grid, various types of converter configurations and control algorithms are used. A synchronization of the distributed energy sources with the power grid is a complex task which requires the estimation of the grid voltage phase position and frequency. The difference in voltages, phases, and frequency between the grid quantities and the converter output may lead to its irregular operation. The purpose of this paper is to compare some of the most popular three-phase grid synchronization algorithms under anomalies that can occur in a low-voltage grid. Anomalies include voltage sags, harmonics and DC offset. Algorithms are created in MATLAB/Simulink and tests are performed on a dSPACE development platform DS1103.**

***Index Terms*—Grid synchronization, voltage sags, voltage harmonics**

I. Introduction

Unlike the traditional large thermal or hydro power plant with synchronous machines that can transfer the energy directly into the power system, most of renewable energy sources relies on power electronics as an additional energy conversion step. Also, unlike the traditional power plants where only the initial synchronization of the power source with the grid is needed, for the proper operation of renewable energy source, constant grid phase angle tracking is needed.

From the standpoint of power quality, in most cases, energy processed through power electronics devices leads to the voltage and current quality deterioration in the grid. These devices can contribute to abnormal grid conditions during regular and irregular grid states. As the number of these devices increase, power generation devices in low voltage grids will have more and more difficult job of maintaining proper operation.

Filip Filipović is with the Faculty of Electronic Engineering, University of Niš, 14 Aleksandra Medvedeva, 18000 Niš, Serbia (e-mail: filip.filipovic@elfak.ni.ac.rs).

Milutin Petronijević is with the Faculty of Electronic Engineering, University of Niš, 14 Aleksandra Medvedeva, 18000 Niš, Serbia (e-mail: milutin.petronijevic@elfak.ni.ac.rs).

Nebojša Mitrović is with the Faculty of Electronic Engineering, University of Niš, 14 Aleksandra Medvedeva, 18000 Niš, Serbia (e-mail: nebojsa.mitrovic@elfak.ni.ac.rs).

Bojan Banković is with the Faculty of Electronic Engineering, University of Niš, 14 Aleksandra Medvedeva, 18000 Niš, Serbia (e-mail: bojan.bankovic@elfak.ni.ac.rs).

Injection of electrical energy in the grid can be done safely only if tight synchronization is achieved. Synchronization unit is a crucial part of the inverter controller since it can affect inverter controllers, and as a result the entire system operation [1]. This paper evaluates the performance of some of the most popular three-phase synchronization algorithms. Tested algorithms are Synchronous Reference Frame Phase Locked Loop (SRF-PLL) [2], Decoupled Double Synchronous Reference Frame PLL (DDSRF-PLL) [3], Dual Second-Order Generalized Integrators Frequency Locked Loop (DSOGI-FLL) and Multiple SOGI-FLL (MSOGI-FLL) [4]. Synchronization algorithms are evaluated on occurrences expected in a low-voltage power grid (400 V). Voltage sags, harmonics and DC offset are considered. A general comparison of some of the upper mentioned algorithms can be seen in [5, 6].

II. Synchronisation Algorithms

First two synchronization algorithms use Clarke's *abc* to *αβ0*, and Park's *αβ0* to *dq0* transformation. Park's transformation uses synchronous rotating reference frame, and *d*-axis is aligned with *a*-axis. Measured grid voltages are transformed and *q*-component is used for synchronization. Block diagram of the SRF-PLL is presented in Fig. 1. In this synchronisation algorithm a proportional-integral (PI) controller is used. The output of the SRF-PLL is the estimated angle θ, and a second order transfer function of the closed loop system in the continuous and discrete time domain is given in [2].

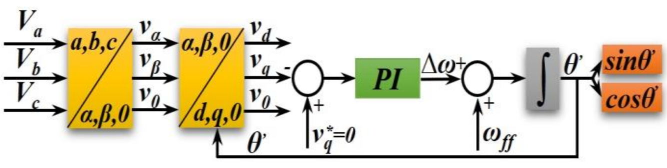

Fig. 1. Block diagram of the SRF PLL.

Every three-phase unbalanced system can be represented as a sum of 3 symmetrical systems (positive, negative and zero sequence). Positive and negative sequences are of interest for three-phase algorithms. Implemented DDSRF PLL from [3] has an additional negative sequence rotating system, decupling network and low pass filter compared to SRF PLL. The block diagram of the DDSRF-PLL is presented in Fig. 2.

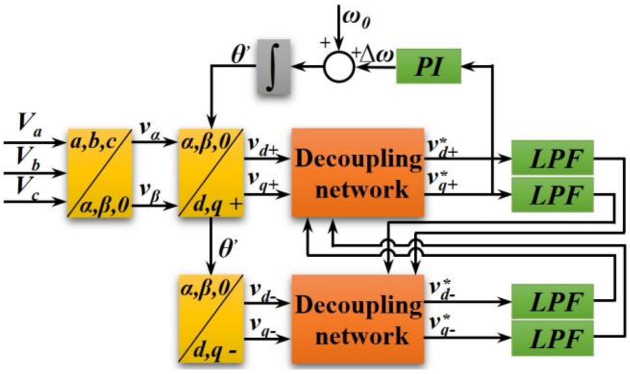

Fig. 2. Block diagram of the DDSRF PLL.

Decoupling network in the DDSRF PLL is an improvement that enables precise phase angle tracking in the grid where voltages are not perfectly symmetric. Since the purpose of this paper is to focus on grid anomalies that can be found in a low-voltage grid, voltage amplitude asymmetry is a good candidate. For that reason, capability of a precise angle estimation under unbalanced voltage conditions is highly desirable for a synchronization algorithm.

Other group of algorithms uses a stationary frame for a grid angle extraction. A system based on a dual second order generalized integrator with FLL is presented in [4, 8]. For a three phase system, one SOGI for each reference frame component is needed, and the model of it is shown in Fig. 3.

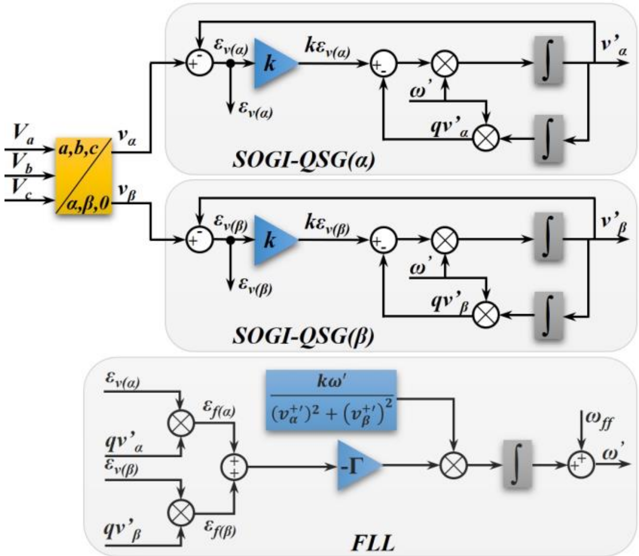

Fig. 3. Block diagram of the DSOGI FLL.

A multi-resonant frequency adaptive synchronization method for grid-connected power converters that allows estimation of not only the positive and negative sequence components of the power signal at the fundamental frequency, but also other sequence components at other harmonic frequencies is presented in [4]. A block diagram of multiple second-order generalized integrators is presented in Fig. 4. MSOGI FLL used in this paper uses a cross-feedback network enabled to detect 5th, 7th and 11th harmonic.

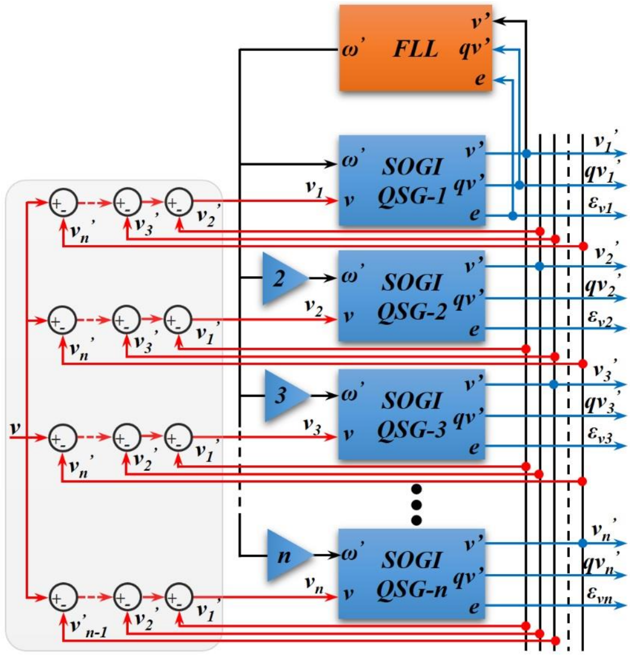

Fig. 4. Block diagram of the MSOGI FLL.

III. Experiment Setup

Algorithms were created in MATLAB/Simulink in a discrete time domain using recommendations from [7]. Estimated frequency of each algorithm is observed during the power grid anomalies. Algorithms were validated on a dSPACE board DS1103, with the discrete time step of 100 μs.

Generated sinusoids were fed through board's analog outputs into its analog inputs in order to simulate real voltages obtained via sensors. Sinusoids are generated using MATLAB's script. The script enables a user to define various aspects of three phase sinusoids. Output sinusoids are easily modified by modifying script's inputs. The process of test sinusoids definition is shown in Fig. 5.

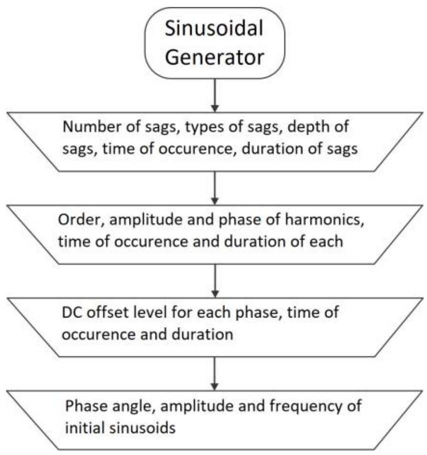

Fig. 5. Process of test sinusoids definition.

Testing was done on all seven types of voltage sags presented in [9], since sag appearance can be a consequence of a low-voltage grid disturbance, or propagation from a higher voltage level. Depth of all voltage sags is 0.7 p.u. and a duration of 200ms. Sags occurred on the point on waveform where phase A is crossing zero.

Maximal allowed level of odd harmonics (6 % of 5^{th}, 5 % of 7^{th} and 3.5 % of 11^{th}), according to the IEC EN 50160 standard, was used for testing. Grid frequency is held at 50 Hz in all cases. For sags and harmonics tests, rectangular sinusoid transition is used. In the test with the DC component, its amplitude is 0.5 % of peak-to-peak phase voltage value, and it exists only in phase A.

All tuneable values in algorithms are given in Table I.

TABLE I
VALUES OF PI REGULATOR PARAMETERS

Algorithm	**Value**		
	Param	**50Hz**	**60Hz**
SRF PLL	K_p	100•π	120•π
	K_i	1550	5358
DDSRF PLL	K_p	100•π	120•π
	K_i	1550	5358
DSOGI FLL	k	1.41	1.41
	Γ	50	50
MSOGI FLL	k	1.41	1.41
	Γ	50	50

IV. BENCHMARKING OF SELECTED ALGORITHMS

Presented results are obtained from MATLAB/Simulink model while all algorithms worked in parallel. The data obtained from artificially generated sinusoids is used in a first group of tests. The second group of tests is conducted on real recorded sags, obtained from www.igrid.com [10].

A. *Artificial Data Tests*

The testing of the synchronisation algorithms is performed firstly for a case of voltage sags occurrence. SRF PLL and DDSRF PLL use rotating system (*dq*) and other two algorithms use stationary system (αβ) for synchronization. Negative sequence system is observed from a standpoint of positive sequence system as a system that rotates twice the speed of the actual rotation, hence frequency of oscillations in SRF PLL estimation is 100 Hz.

In the case of type A voltage sag, a SRF PLL gives the best result compared to other three synchronisations algorithms. Frequency estimation for this case is given in Fig. 6a. In this test, similar settling time is observed for all algorithms other than SRF PLL. DDSRF shows the biggest deviation on frequency estimation following sag.

In all other types of voltage sags the SRF PLL and DDSRF PLL algorithms have a significantly bigger frequency oscillation compared to DSOGI FLL and MSOGI FLL. The settling time is the same for all algorithms, except for SRF PLL where the frequency oscillates constantly during the voltage sag. The frequency estimation of all four synchronous algorithms is presented in Fig. 6(b-g).

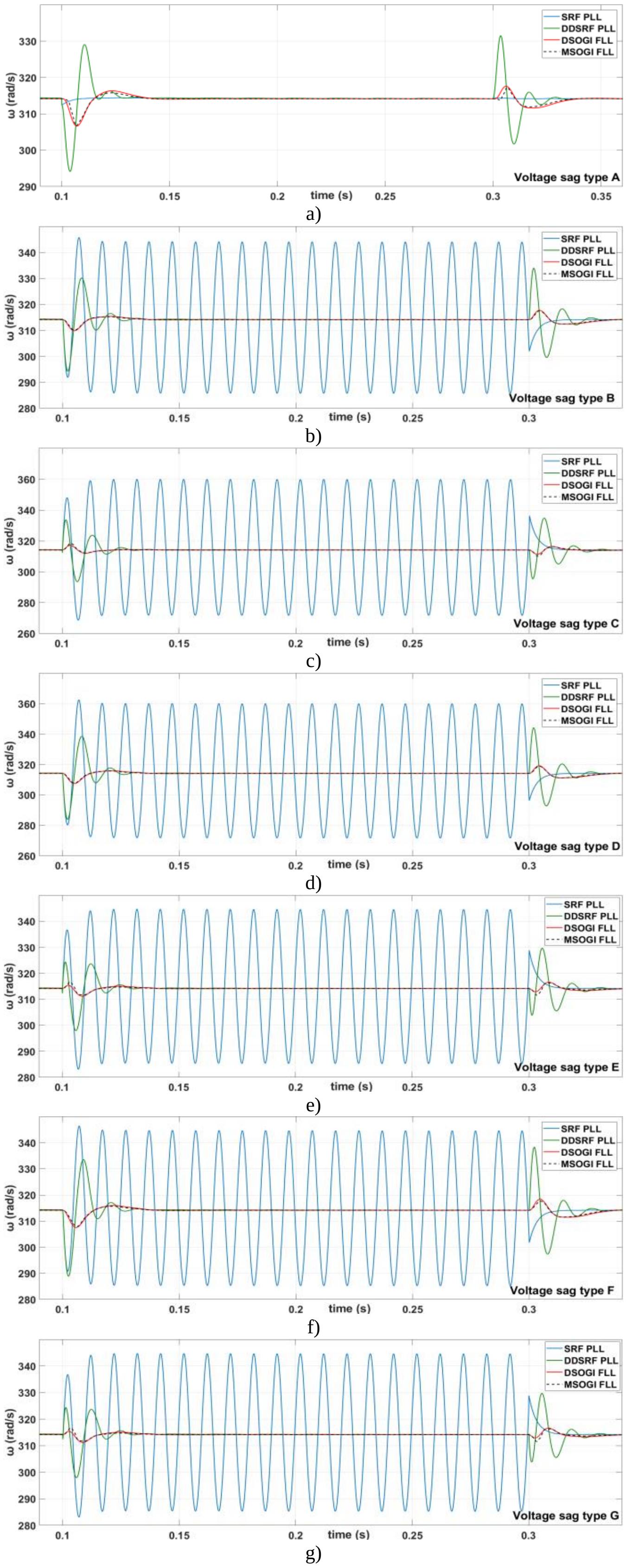

Fig. 6. Behaviour of tested algorithms during a) Voltage sag type A, b) Voltage sag type B, c) Voltage sag type C, d) Voltage sag type D, e) Voltage sag type E, f) Voltage sag type F, g) Voltage sag type G.

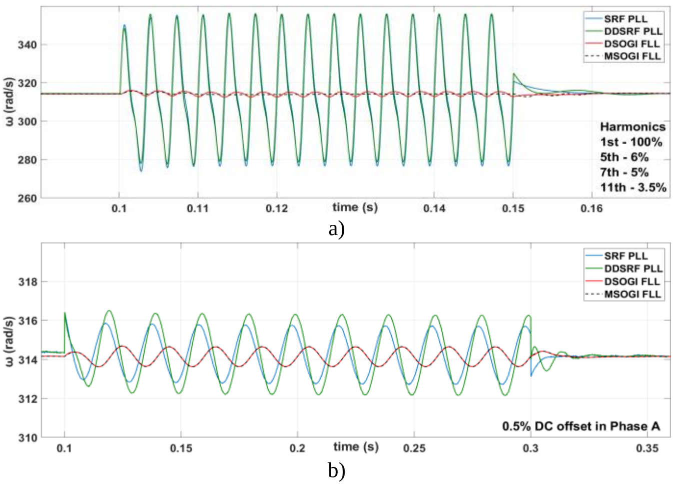

Fig. 7. Behaviour of tested algorithms during a) Harmonics polluted voltages, b) Phase-A DC offset amplitude of 0.5 % peak-to-peak phase voltage.

The behaviour of synchronisation algorithms under present harmonics is presented in Fig 7. a), or phase-A DC offset of 0.5 % peak-to-peak phase voltage amplitude is presented in Fig 7. b). The DSOGI FLL and MSOGI FLL algorithms are almost immune to harmonics presence while SRF PLL and DSRF PLL have a significant frequency oscillation. In the Fig. 7b it can be seen that all compared algorithms are not immune to the presence of the DC voltage component.

B. *Real Data Tests*

Artificial data generated only by following the sag type classification from [9] can be different from the real recorded data. In the algorithm for sinusoid generation, rectangular sinusoids transition is used, the effect of electric arc and the behaviour of other consumers during sag is neglected. For that reason, real recorded voltage sags from [10] are used for testing. Testing was done on openly available dataset for the frequency of 60 Hz. All datasets are resampled and downloaded to the dSPACE 1103 development platform. The development platform uses matrix form of recorded data that is preprocessed.

Four datasets are used, with single phase sag, two phase sag, three phase sag, and two phase sag with transition to three phase sag. Obtained data had a non-uniform sampling time of, on average, 1 ms and only half of the period before and after the sag. All tested algorithms have settling time of about 50 ms, which implies that not enough time is given for algorithms to lock on to the grid frequency. In order to overcome that problem, sinusoid interpolation is done before and after the recorded data. The Gauss–Newton algorithm is used to obtain amplitude and phase angle of each phase, and frequency. Parameters of PI regulators for SRF PLL and DDSRF PLL are recalculated for 60 Hz.

Behaviour of synchronization algorithms during single phase voltage sag, and the voltage waveform can be seen in Fig. 8. Very low impact of sag on frequency estimation of DSOFI and MSOGI FLL, some impact on DDSRF PLL and the greatest impact on SRF PLL is observed. The voltage restoration caused the biggest estimation error with all algorithms.

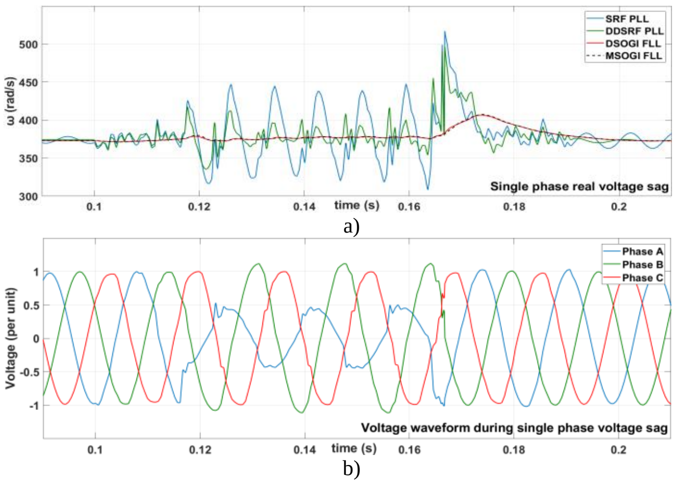

Fig. 8. Single phase voltage sag a) Estimated grid frequency, b) Voltage waveform

Behaviour of tested algorithms on two phase voltage sag is shown in Fig. 9. The SRF PLL has the biggest oscillations, followed by the DDSRF PLL, and lastly DSOGI and MSOGI FLL have good frequency estimation and similar behaviour. During sag, due to the occurrence of an inverse sequence voltage, SRF PLL has an undamped oscillation with a frequency of 100 Hz. DDSRF PLL can cope with this more effectively.

During algorithms testing on synthetic data, the three phase voltage sag was the only test where the SRF PLL showed superior performance right after a voltage sag occurrence and a normal voltage restoration. The recorded data shows in Fig. 10. three phase voltage sag with unequal sag depth for all phases and a phase jump. All of the upper mentioned has an inverse sequence voltage induction as a consequence, and as a result the SRF PLL algorithm has the worst frequency estimation of all four tested algorithms.

During the two phase sag shown in Fig. 11. SRF and DDSRF PLL have oscillations while DSOGI and MSOGI FLL have only small estimation bump. Recorded three phase voltage sag is quite symmetrical and all algorithms show good estimation.

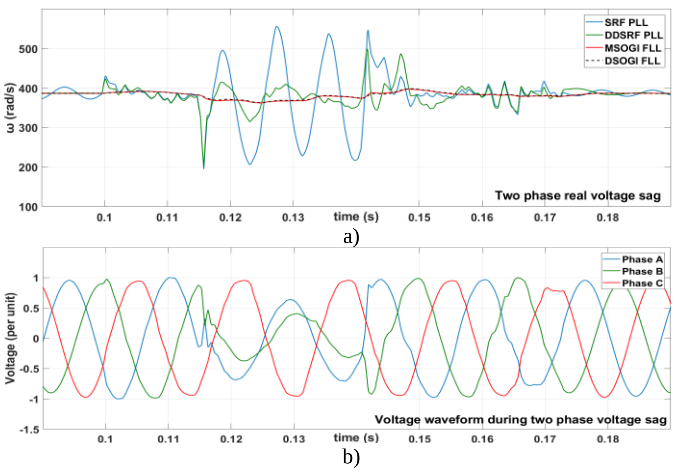

Fig. 9. Two phase voltage sag a) Estimated grid frequency, b) Voltage waveform

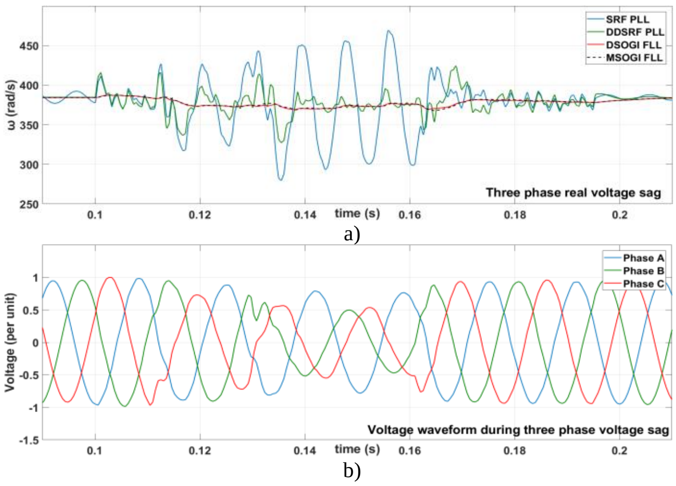

Fig. 10. Three phase voltage sag a) Estimated grid frequency, b) Voltage waveform

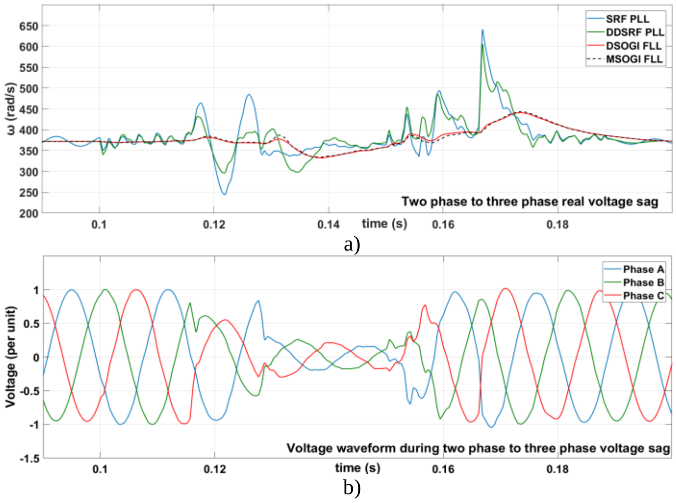

Fig. 11. Two phase to three phase voltage sag a) Estimated grid frequency, b) Voltage waveform

V. Conclusion

Based on conducted tests, first conclusion that can be drawn is that behaviour of synchronization algorithms during artificial and real data tests can be very different. Voltage sags created by following the classification from [9] are good for initial estimation. SRF PLL is superior to all other algorithms during an artificial type A voltage sag. It is inferior during all other types of voltage sags, since it is the only one of all tested that has undamped oscillations during sags. It has the same behaviour as DDSRF PLL when sinusoids are polluted with harmonics. It has slightly better estimation of frequency than DDSRF PLL when DC offset is present.

DDSRF PLL is, as expected, the improvement on SRF PLL in most cases. Voltage sags do not affect steady state estimation of grid frequency. It showed the worst results in a DC offset test.

DSOGI FLL and MSOGI FLL are arguably the best algorithms on these tests. They showed no steady state estimation error during voltage sags, and the lowest overshoot. Since MSOGI FLL had cross-feedback network with 5th, 7th and 11th harmonics cancelation, it had no trouble of estimating frequency in harmonics polluted signal. DSOGI FLL had low amplitude oscillations in this test. In the DC offset test both behaved identically with low amplitude oscillations.

Real voltage sags can be quite different from simulated ones. For that reason, corner cases where a SRF PLL had better results than the rest, in general, were not backed up with testing on real data. For the real data testing, DSOGI and MSOGI FLL showed best results.

Acknowledgment

This work was supported by the Ministry of Science and Technological Development, Republic of Serbia (Project number: III 44006).

References

[1] L. Hadjidemetriou, Y. Yang, E. Kyriakides and F. Blaabjerg, "A Synchronization Scheme for Single-Phase Grid-Tied Inverters Under Harmonic Distortion and Grid Disturbances", *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 2784-2793, 2017.

[2] Se-Kyo Chung, "A phase tracking system for three phase utility interface inverters", *IEEE Transactions on Power Electronics*, vol. 15, no. 3, pp. 431-438, 2000.

[3] P. Rodriguez, J. Pou, J. Bergas, J. Candela, R. Burgos and D. Boroyevich, "Decoupled Double Synchronous Reference Frame PLL for Power Converters Control", *IEEE Transactions on Power Electronics*, vol. 22, no. 2, pp. 584-592, 2007.

[4] P. Rodriguez, A. Luna, I. Candela, R. Mujal, R. Teodorescu and F. Blaabjerg, "Multiresonant Frequency-Locked Loop for Grid Synchronization of Power Converters Under Distorted Grid Conditions", *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 127-138, 2011.

[5] N. Guerrero-Rodríguez, A. Rey-Boué, A. Rigas and V. Kleftakis, "Review of Synchronization Algorithms used in Grid-Connected Renewable Agents", *Renewable Energy and Power Quality Journal*, pp. 240-245, 2014.

[6] M. Bobrowska-Rafal, K. Rafal, M. Jasinski and M. Kazmierkowski, "Grid synchronization and symmetrical components extraction with PLL algorithm for grid connected power electronic converters - a review", *Bulletin of the Polish Academy of Sciences: Technical Sciences*, vol. 59, no. 4, 2011.

[7] A. Luna, C. Citro, C. Gavriluta, J. Hermoso, I. Candela and P. Rodriguez, "Advanced PLL structures for grid synchronization in distributed generation", *Renewable Energy and Power Quality Journal*, pp. 1747-1756, 2012.

[8] P. Rodriguez, A. Luna, M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, "Advanced grid synchronization system for power converters under unbalanced and distorted operating conditions," *in Proc. 32nd Annu. Conf. IEEE Ind. Electron*., pp. 5173–5178, 2006.

[9] M. Bollen and L. Zhang, "Different methods for classification of three-phase unbalanced voltage dips due to faults", *Electric Power Systems Research*, vol. 66, no. 1, pp. 59-69, 2003.

[10] "i-Grid: Home", *Igrid.com*, 2018. [Online]. Available: https://www.igrid.com/igrid/. [Accessed: 01- Apr- 2018].