DOI: 10.5604/20830157.1093209

COMPARISON OF PERFORMANCE OF SYNCHRONIZATION ALGORITHMS FOR GRID CONNECTED POWER ELECTRONICS CONVERTERS ACCORDING TO PROPOSED EVALUATION QUALITY CRITERIA

Piotr Lipnicki
Lublin University of Technology, Electrical Drive and Electrical Machines Department

Abstract. *In this paper a comparison of synchronization methods for power electronics converters is presented. Proposed evaluation criteria are based on Transmission System Operators requirements, as well as on criteria parameters based on requirements for design, computation and operation under normal/distorted conditions. Additionally a classification of various kinds of synchronization algorithms is discussed with a brief description of the role of power electronics in the modern power systems. All of the tested algorithms were subjected to appropriate tests validating the quality criteria for each of them. The tests were performed in terms of simulations. The investigation results are summarized in the table, which can serve as a basic selection guide.*

Keywords: synchronization, smart grids, grid codes, phase locked loop (PLL), power electronics, renewable energy systems

PORÓWNANIE DZIAŁANIA ALGORYTMÓW SYNCHRONIZACJI DLA ENERGOELEKTRONICZNYCH PRZEKSZTAŁTNIKÓW PODŁĄCZONYCH DO SIECI WEDŁUG ZAPROPONOWANYCH KRYTERIÓW OCENY

Streszczenie. *Niniejszy artykuł zajmuje się porównaniem metod synchronizacji z siecią dla energoelektronicznych przekształtników. Zaproponowane kryteria oceny opierają się na wymaganiach Operatorów Systemów Przesyłowych, a także na wymaganiach związanych z projektowaniem samych algorytmów, mocą obliczeniową i działaniem w warunkach normalnych lub przy zakłóceniach występujących w sieci. Przedstawiono również klasyfikację różnego rodzaju algorytmów służących do synchronizacji razem z ogólnym opisem roli energoelektronicznych układów we współczesnych systemach energetycznych. Wszystkie przedstawione algorytmy zostały zbadane według odpowiednich testów, które pozwoliły na ocenę kryteriów jakości dla każdego z nich. Badania zostały przeprowadzone w formie symulacji. Wszystkie wyniki są podsumowane w formie tabeli, która może służyć jako podstawowy przewodnik do doboru odpowiedniego algorytmu synchronizacji.*

Słowa kluczowe: synchronizacja, sieci inteligentne, kody sieci, pętla synchronizacji fazowej (PLL), energoelektronika, odnawialne źródła energii

Introduction

Modern industry is becoming more and more dependent on the correct operation of power converters. Power electronics is becoming one of the most important elements of today’s reality. Many of converters applications are being considered as critical for plant production process. The power electronics technology allows the systems and the electric machines (motors and generators) to run efficiently and sustainably. Lack of this solution would make the electric motors run at full speed, and the renewable sources such as solar and wind power, wave energy, fuel cells could not be fed into the power grid. Modern, sustainable energy systems introduce the concept of “Smart grids”, where the flow of the energy can be controlled in a sustainable way.

For grid connected power electronic converters basic information are frequency and angle of the utility network. For proper and safe operation phase angle of current or voltage of the fundamental component at the point of common coupling of a system or converter with the grid should be recognized “online” in a real time manner. If this condition is fulfilled the control of the flow of energy between the converter and the network can be achieved. Thus, the most efficient working mode of converters can be utilized.

It is worth noting that such performance mode of power electronics converters (maximum sync = ability to provide maximum efficiency) it is desirable from the point of view of the Transmission System Operators [7]. This due to the fact that having perfectly synchronized elements of the systems increases the stability margin of the system. Usually, various TSO’s have different synchronization requirements. The set of such rules is stated in so-called grid codes. Grid codes are technical interconnection requirements for power networks.

Depending on the country, point of connection, grid condition, energy sources connected, load distribution, different requirements may occur. To show how the very definition of synchronization can be recognized, a quote from the polish TSO (PSE Operator) is presented: the synchronization is an “operation concerning the connection of the generating unit with the power system of connection of different power systems after their frequencies, phase and voltages are equalized to reduce the disparity of the vectors of connected voltages to a value close to zero” [8].

1. Proposed evaluation criteria

The selection and evaluation of the effectiveness of the synchronization algorithm is difficult. The choice should be relevant to the TSO requirements and depend on application type. As described in [1], there are currently no criteria for the selection of synchronization algorithm for power converters. Another important issue is the possibility of comparing the performance of different synchronization algorithms. In the absence of such standards, the choice of the appropriate method is very limited. This shows that the need for a selection guide is straightforward. In order to create a reference guide for choosing a suitable synchronization algorithm define quality criteria are needed. A set of such evaluation criteria is presented on Figure 1.

The proposed solution is based on so called “three-legged stool model” [2], which is suitably modified according to the needs. The three legs are determined as follows: synchronization criteria leg, computation criteria leg and design criteria leg. The evaluation criteria determining the algorithm design phase consists of the following elements: application, noise immunity, single phase utilization, algorithms protection modes, required additional features (signal filtering etc.), methods of realization (analog, digital) and proposed in [1] THD level of a sinus of estimated phase angle.

Looking at the performance of the method, a very important aspect to take into account the computation criteria. This is due to the fact, that respectively established constraints can make our algorithm fast “enough” with cheaper solution. Criteria in this subgroup are determined by total number of signals and variables, number of addition/subtractions and multiplications/scaling operations, transient response, state variable/integrations, computational load and order of signals processed in a cascade.

But the most important part of those rules, basically the core, is the synchronization criteria set. The group consists of following criteria: phase angle jump overshoot level, phase angle settling time, phase frequency jump overshoot, phase frequency settling time, frequency adaptive operation, frequency estimation accuracy, method bandwidth and high frequency characteristics.

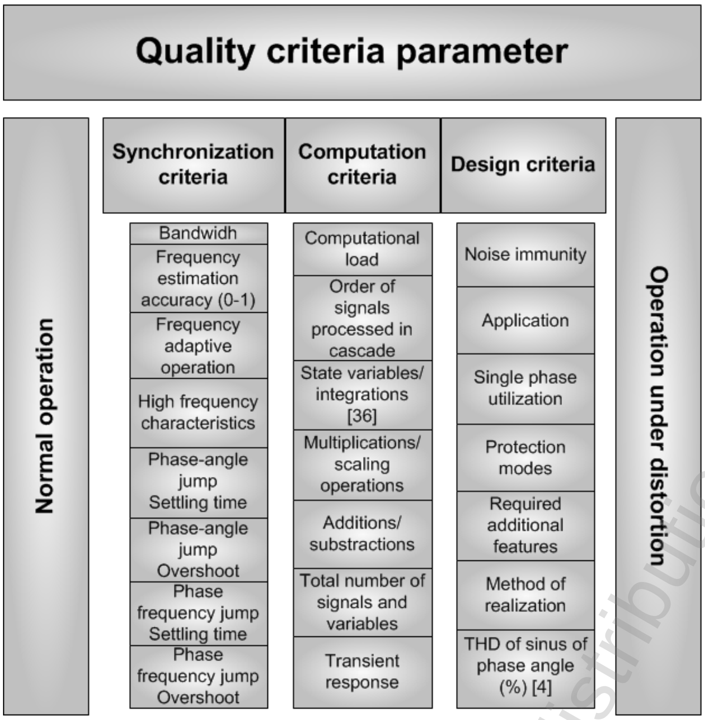

Fig. 1. Proposed quality criteria

Going throughout the whole quality criteria selection set, one has to take into account two possible circumstances. Assessment of different synchronization algorithms should be carried out under normal conditions and during grid distortions.

2. Types of synchronization algorithms

In the literature there are many examples of different synchronization algorithms types. Number of methods used for synchronization is extremely high. Proper selection of the algorithm, taking into account the application, resistance to distortions, implantation method, usually is quite difficult. This was mainly due to the lack of proper classification of the synchronization methods. One of the first classifications of those algorithms is proposed in [1] and can be seen in Figure 2. It is based on the reference frame in which the algorithm is operating.

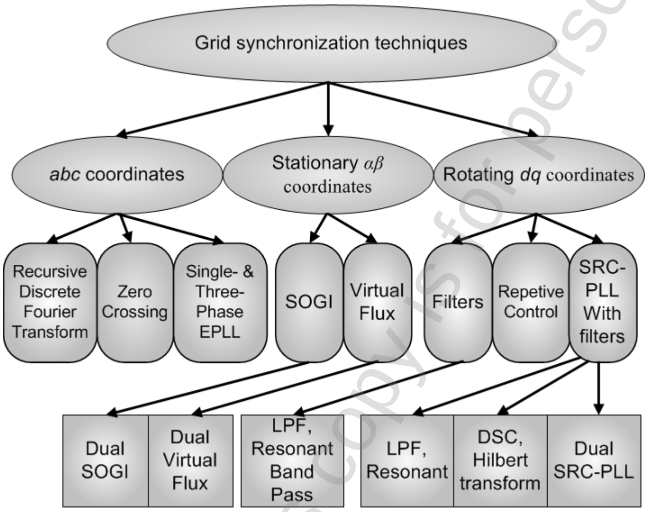

Fig. 2. Proposed classification method for synchronization algorithms [1]

Having in mind that power electronics converters cover a wide range of different kinds of applications and functions, a more detailed classification is proposed in [3], and the basic scheme of this classification can be seen in Figure 3.

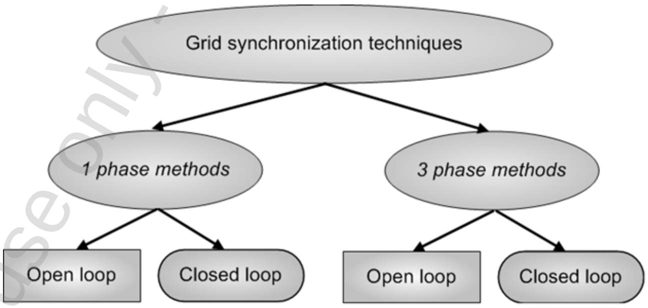

Fig. 3. The proposed general classification of synchronization algorithms [3]

For the purpose of the quality criteria evaluation several synchronization algorithms have been chosen. The following synchronization algorithms have been tested:

- Alpha beta filtering method [3];
- Simple Voltage Controlled Oscillator [3];
- Synchronous Reference Frame Phase Locked Loop (PLL-SRF) [4];
- Double Decoupled Synchronous Reference Frame PLL (DDSRF-PLL) [5, 6];
- Dual Second Order Generalized Integrators PLL (DSOGI-PLL) [5, 6];
- Dual Second Order Generalized Integrators with Quadrature Signals Generation and Positive Sequence Signals Cancelation (DSOGI-QSG-PSC) [4].

3. Methods evaluation

The selected methods are evaluated according to the proposed quality criteria. It has to be noted that only the operation in nominal (stable) conditions is considered. Only in the case of the frequency estimation accuracy and the THD calculation of a sinus of the estimated phase angle the evaluated synchronization algorithms were subjected to disturbed grid conditions. Figure 4 presents examined system structure. Simulated part is enveloped in gray rectangle. The other parts could be either sources of energy or loads, but for the grid-side converter (and synchronization algorithms) it does not matter.

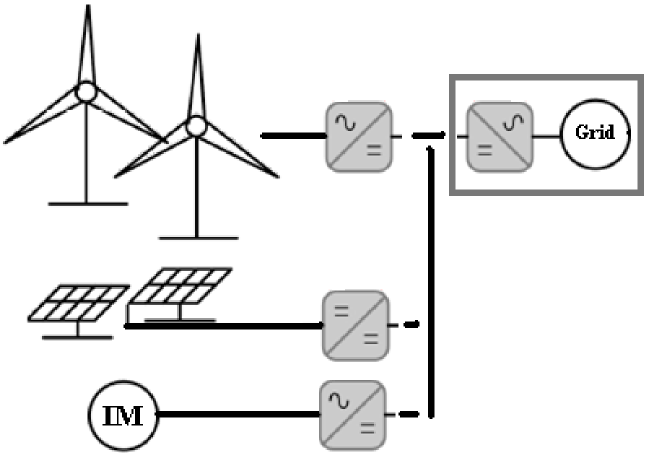

Fig. 4. Examined system structure

For determining the methods transient response algorithms start-up characteristics is taken into consideration. Figure 5 presents these characteristics for example selected algorithms.

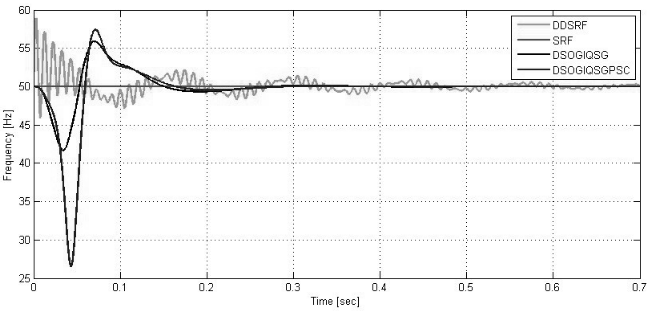

Fig. 5. Start-up of the selected synchronization methods

The fastest response is coming from SRF-PLL, which is achieving the settling time at 10 ms. The DDSRF-PLL has the settles at 350 ms and the DSOGIQSG-PLL, with the DSOGIQSG-PLL with the positive sequence cancelation have the settling time of 250 ms value. An example of the operation under distorted conditions during voltage disturbance for SRF-PLL can be seen in Figure 6.

It can be easily observed that during normal operation the algorithm can accurately determine the grid angle. However, in the case of grid voltage disturbance the estimation is not working well. As a result undulation in the angle signal appears.

It can be easily observed that during normal operation the algorithm can accurately determine the grid angle. However, in the case of grid voltage disturbance the estimation is not working well. As a result undulation in the angle signal appears.

Figure 7 presents the example algorithms operation during 15% THD grid distortion. The DDSRF-PLL, DSOGIQSG-PLL and the DSOGIQSGPSC-PLL synchronization algorithms settle down after 200 ms. The estimation error in their case is around ±1. This performance is acceptable. The SRF-PLL estimates the frequency with an error of ±10%. The estimated signal is oscillating form 45 Hz to 50 Hz.

One of the proposed design criteria is the THD of sinus of an estimated phase angle. During normal operation all of the methods having the level of the THD below 1%. However, the appearance of any kinds of disturbances (for example harmonics), results in different performance for the algorithms. For testing the of the methods performance 15% THD distortion is applied to the grid voltage. Each of the methods achieves different result. Namely the DSOGIQSGPSC-PLL is achieving 0.1% THD of the sinus of the estimated grid angle, the DSOGIQSG-PLL has 0.5%, the DDSRF-PLL has 0.2%, SRF-PLL hast the 1.5% THD level and the αβ-filtering method with SVCO have 15% THD level. Table 1 present the performance of the selected algorithm in terms of synchronization criteria.

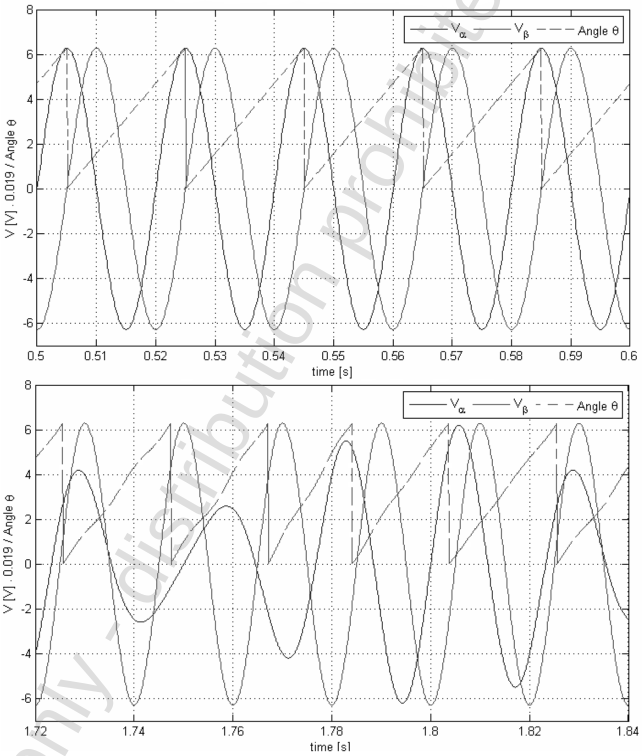

Fig. 6. The SRF-PLL method performance during voltage distortion

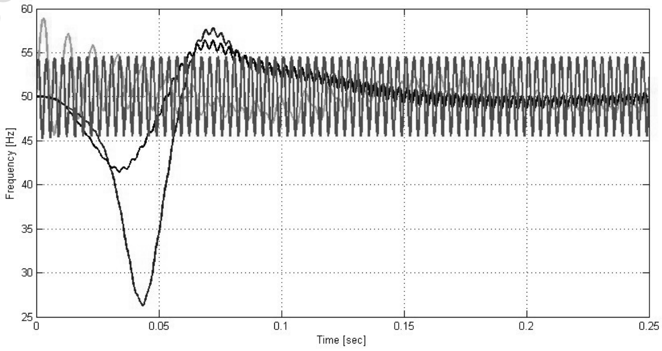

Fig. 7. Frequency estimation accuracy during grid operation with 15% THD

Table 2 presents the performance of the selected algorithms in terms of computation criteria. As it can be observed the more complex synchronization algorithm (order of signal processed, total number of mathematical operation – scaling, addition, multiplications) the better performance it can achieve. This also applies to the possibility of working under different disturbances, as it was presented before. On the other hand with the more complex synchronization structure higher computational load is needed, the transient response can be longer. But overall performance, the frequency estimation accuracy, frequency adaptive operation possibility are higher. But overall performance, the frequency estimation accuracy, frequency adaptive operation possibility are higher. But overall performance, the frequency estimation accuracy, frequency adaptive operation possibility are higher.

Table 1. The selected methods performance for the synchronization criteria

Synchronization criteria	Synchronization algorithm	Performance
Phase frequency jump overshoot	αβ - filtering	15%
	SVCO	15%
	SRF-PLL	2%
	DDSRF-PLL	10%
	DSOGIQSG-PLL	10%
	DSOGIQSGPSC-PLL	8%
Phase frequency jump settling time	αβ - filtering	150 ms
	SVCO	200 ms
	SRF-PLL	10 ms
	DDSRF-PLL	350 ms
	DSOGIQSG-PLL	250 ms
	DSOGIQSGPSC-PLL	250 ms
Phase angle jump overshoot	αβ - filtering	15%
	SVCO	15%
	SRF-PLL	2%
	DDSRF-PLL	10%
	DSOGIQSG-PLL	10%
	DSOGIQSGPSC-PLL	8%
Phase angle jump settling time	αβ - filtering	150 ms
	SVCO	200ms
	SRF-PLL	10 ms
	DDSRF-PLL	300 ms
	DSOGIQSG-PLL	200 ms
	DSOGIQSGPSC-PLL	200 ms
Frequency estimation accuracy	αβ - filtering	0.4
	SVCO	0.4
	SRF-PLL	0.8
	DDSRF-PLL	0.9
	DSOGIQSG-PLL	0.8
	DSOGIQSGPSC-PLL	0.9
Frequency adaptive operation	αβ - filtering	No
	SVCO	No
	SRF-PLL	Yes/No
	DDSRF-PLL	Yes
	DSOGIQSG-PLL	Yes/No
	DSOGIQSGPSC-PLL	Yes

4. Conclusions

This paper presents the evaluation of selected synchronization algorithms based on the proposed evaluation criteria. Choosing the appropriate synchronization method should be based on the determination of the application, power grid stiffness (with the emphasis on the power/voltage quality), possible ways of implementation. For helping in decision making, each of the selected methods were subjected to different types of tests. All of the results were collected in tablets, as well as presented in the article.

References

[1] Bobrowska-Rafal M., Rafal K., Jasiński M., Kaźmierkowski M.P.: 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.

[2] Duarte N.: Slide:ology: The Art and Science of Creating Great Presentations, ISBN0596522347, 2008.

[3] Lipnicki P.: Smart Grids - general review of synchronization techniques, PHDW Conference, Lublin 2013.

[4] Rodríguez P., Teodorescu R., Candela I., Timbus A.V., Liserre M., Blaabjerg F.: New Positive sequence Voltage Detector for Grid Synchronization of Power Converters under Faulty Grid Conditions.

Table 2. The selected methods performance for the computation criteria

Synchronization criteria	Synchronization algorithm	Performance
Transient response	αβ - filtering	150 ms
	SVCO	200 ms
	SRF-PLL	10 ms
	DDSRF-PLL	350 ms
	DSOGIQSG-PLL	250 ms
	DSOGIQSGPSC-PLL	250 ms
Total number of signals and variables	αβ - filtering	6
	SVCO	6
	SRF-PLL	10
	DDSRF-PLL	14
	DSOGIQSG-PLL	16
	DSOGIQSGPSC-PLL	18
Total number of additions and subtractions	αβ - filtering	2
	SVCO	3
	SRF-PLL	3
	DDSRF-PLL	10
	DSOGIQSG-PLL	7
	DSOGIQSGPSC-PLL	9
Total number of multiplications and scaling	αβ - filtering	4
	SVCO	4
	SRF-PLL	3
	DDSRF-PLL	11
	DSOGIQSG-PLL	9
	DSOGIQSGPSC-PLL	9
Order of signals processed	αβ - filtering	2
	SVCO	1
	SRF-PLL	1
	DDSRF-PLL	1
	DSOGIQSG-PLL	2
	DSOGIQSGPSC-PLL	2
Computational load	αβ - filtering	10%
	SVCO	10%
	SRF-PLL	40%
	DDSRF-PLL	60%
	DSOGIQSG-PLL	50%
	DSOGIQSGPSC-PLL	60%

[5] Teodorescu R., Liserre M., Rodriguez P.: Grid Converters for Photovoltaic and Wind Power Systems, IEEE - J. Wiley, 2011.

[6] Timbus, A.; Teodorescu, R.; Blaabjerg, F.; Liserre, M.; Synchronization Methods for Three Phase Distributed Power Generation Systems. An Overview and Evaluation, Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th 16-16 June 2005.

[7] ENTSO-E Draft Network Code for Requirements for Grid Connection applicable to all Generators, European Network of Transmission System Operators for Electricity, 24 January 2012, http://www.entsoe.eu.

[8] Instrukcja Ruchu i Eksploatacji Sieci Przesyłowej – IRiESP, PSE Operator, 1-10-2011.

M.Sc. Eng. Piotr Lipnicki
e-mail: piotr.lipnicki86@gmail.com

Received M.Sc. degrees in electrical engineering from the Aalborg University, and Lublin University of Technology in 2010, and 2010 respectively. He is a PhD Student of Lublin University of Technology. He dealt with the issue of reactive power compensation for wind farms. He worked on the issue of control voltage converters connected in parallel. Interested in the issue of intelligent network "smart grids", in the doctoral thesis deals with algorithms for synchronization of power converters to the network.

otrzymano/received: 23.06.2013 *przyjęto do druku/accepted: 12.01.2014*