SMART GRIDS – GENERAL REVIEW OF SYNCHRONIZATION TECHNIQUES

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Abstract. *This paper deals with crucial aspect of synchronization in modern power grids. It presents the concept of intelligent networks ("smart grids"), as the future of today's grid infrastructure. The diversity of different grid codes in regards to the synchronization requirements for different Transmission System Operators (TSO) is discussed. This paper shows the applications of synchronizing algorithms, their role in power grid system.. The methods are classified according to application, the reference frame used and the possibility of using them in single and three phase systems. Proper selection of synchronization algorithms to meet the requirements of TSO's calls for creation of appropriate evaluation methods. For this reason, at the end of the article quality criteria for the evaluation of synchronizing algorithms were proposed and explained in detail. Finally, the last section states what are the most commonly used methods for grid synchronization.*

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

SIECI "SMART GRIDS" – WYZWANIA SYNCHRONIZACJI

Streszczenie. *Niniejszy artykuł zajmuje się kluczowym aspektem, jakim jest synchronizacja w nowoczesnych sieciach elektroenergetycznych. Przedstawia on koncepcję sieci inteligentnych („smart grids"),uważaną jako przyszłość dzisiejszej infrastruktury sieciowej. Omówiono w nim różnice w zakresie przepisów sieci energetycznych różnych operatorów w odniesieniu do wymagań synchronizacji z siecią. Opisane metody sklasyfikowano według ich typowych aplikacji, zastosowanego układu odniesienia i możliwości zastosowania w systemie jedno- lub trójfazowym. Odpowiedni dobór algorytmów synchronizacji by spełnić wymagania TSO postuluje powstanie właściwych metod oceny tych algorytmów. Z tego powodu ostatni punkt artykułu opisuje i wyjaśnia szczegółowo dobrane kryteria oceny jakości algorytmów do synchronizacji. W ostatniej sekcji artykułu pokazano jakie są najczęściej stosowane metody do synchronizacji z siecią.*

Słowa kluczowe: synchronizacja, sieci inteligentne, smart grids, kody sieci, pętla synchronizacji fazowej (PLL), energoelektronika

Introduction

Nowadays modern European societies focus heavily on environmental protection and rational use of its resources. The increasing role of renewable energy sources (RES) together with the provision of rise in efficient energy utilization is one of the main objectives of modern energy business. On the other hand transmission system operators (TSO's) expand their requirements to ensure high power quality, supply continuity and resistance to interference and faults. To address these challenges creation of new, dedicated regulatory systems and methods for controlling are required.

To have modern, sustainable energy systems the concept of intelligent networks is introduced – the so-called "Smart grids". There are many different concepts of smart grids. The common feature of all of the definitions is the fact, that these networks should be managed in a way to ensure high performance, reliability and increased opportunities for supplying the customers. One of the examples of smart grids definition is a Directive [5] of European Commission stating, that "smart grids" are reliable networks, which ensure safety and the quality of power, providing at the same time flexibility during uncertain and risk states. This network should also be economical, without violating the regulatory rules and non-discrimination of the energy market parties.

An important assumption is the flexibility to meet the needs of consumers, in cooperation with the users – in particular in renewable sources cases.

One of the most important elements defining the smart networks is a two-way flow of energy. This feature allows to transfer the produced energy to the grid, and to draw it from the grid when needed. Having appropriate/additional power electronics systems provides the possibility of having distributed energy sources working in a standard operation mode with the network. These systems minimize the drawbacks of RES, such as instability of the energy source, reduction of the reliability of the system, the deterioration of quality of energy. Power electronics devices are capable of improving todays grid infrastructure and could create "smart grid" base.

Increasing use of power electronic systems is one of the dominant trends. This is due to the possibilities offered by systems containing converters. They allow having energy management in an efficient manner, providing high power quality and supplying continuity. Basic information for systems connected to the grid converters are frequency and angle of the utility network. Phase angle of a current/voltage vector of the fundamental component at the connection point of system/inverter to the grid should be detected "online" in real time. The purpose of this article is to present and classify the existing synchronization methods for power converters in smart grids applications.

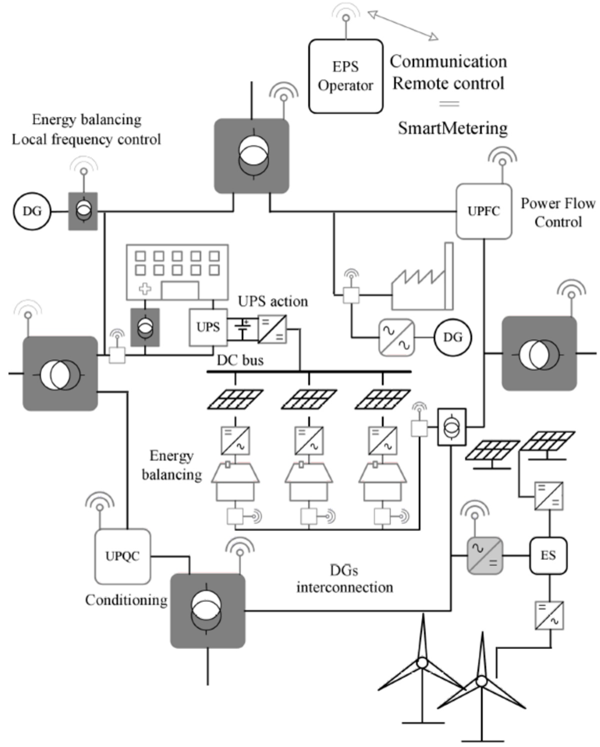

Fig. 1. SmartGrid with SmartMetering & SmartBuilding technology example [5]

An example of a "smart grid" network is shown in the Figure 1. It contains distributed generation systems connected to a grid, where energy flow is controlled by means of SmartMetering and conditioning.

1. Different synchronization requirements from various TSO

Grid codes are technical interconnection requirements of power network. Various TSO operators have many diverse requirements for the grid connection and synchronization. For different energy sources there are different regulations. This is due the fact, that many of the points of supplies vary in terms of quality, stability and availability of the energy source. As an example the definition from the Polish TSO (PSE Operator) is quoted: 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" [39].

For all network users – the TSO, producers and consumers – having a novel, modern grid would benefit in terms of economy, transparency and greater efficiency. To illustrate the differences between the traditional networks and „smart grids" table 1 is presented.

Table 1. Comparison of existing networks and smart grids: tendency [34]

Area	Smart Grid	Traditional Grid
Control	Digital, ubiquitous	Analog, limited
Communication	Two-way	One-way
Power Generation	Distributed	Centralized
Architecture	Web	Hierarchical
Sensors	Common	Few
Transparency	Self-monitoring	Opaque
Structure	Self-maintainable	Manual
Disaster recovery activities, failures	Adaptability, formation of islanding structures	Susceptible to disturbances
Control testing	Remote	Manual
Selection by user	Many choices	Few

It has to be mentioned that the synchronization requirements depend on different factors. These include: the type of the application, synchronization time, faults, transients and failures resistance, recovery time and ability to fulfill automatic synchronizing conditions. The synchronization can be considered not only in pure synchronization terms, but also in terms of active and reactive power regulations, frequency and voltage variations and fault ride through. A comparison of some example requirements for several countries can be seen in the Table 2.

Table 2. Comparison of different TSO requirements [31]

	Poland	Germany	Denmark	Norway
Voltage dip recovery time	600 ms	150 ms	100 ms	250 ms
Frequency variation	49.5 to 50.5Hz	49 to 50.5Hz	48.5 to 51Hz	47.5 to 52 Hz
Reactive power compensation	cosφ=0.95	Q/P = 0.45 or 0.3	Q/P = 0.1 or -0.1	cosφ=0.90
Active Power Ramp Rate range	1 min with 30% power decrease up to P<20%Pn	At least 10% of Grid capacity per 1 min	20-100% with Accuracy of 5% (5 min. Average)	-

Analyzing regulations shown in Table 2, it is possible to find that Polish demands has the longest FRT time. For a voltage dip, the maximal time before beginning of the recovery voltage is 600ms in Polish grid codes, while in Denmark it is 100ms, in Germany - 150ms and in Norway - 250ms. The time before which a voltage recovering process should finish respectively is in Poland - 3s, in Germany - 1.5s, in Denmark - 2s and in Norway only 0.75s. After this time line voltage should reach in Poland - 80% in Germany and Norway - 90% and in Denmark only 75% nominal voltage.

When comparing the grid code standards for different countries it is easy to see that they are significantly diverse. In most of the cases the dissimilarities are present for almost all of the operational requirements in the power system. This is due to different levels of development of each country power grids. Polish grid codes and their cooperating infrastructure are technically backwarded. As an example the fact of having the requirement of voltage dip recovery time for Wind Power Plants has the lowest range (600 ms). The same applies for reactive power compensation requirement. Wind plants are turned off by deviation above 0.5Hz, while in the UK have to work in the frequency range (47.5-52)Hz, in Denmark (48.5-51)Hz and In Germany (49-50.5)Hz.

Possession of a small amount of reserve power plants results in a obligation of having and maintaining the high rates of power coefficient at a level above 0.95. As a consequence the reactive power is delivered particularly by the main power grid stations instead of coming from distributed power plants. Non-application of stringent demands on individual generation energy systems and not stimulating the reactive power production capacity in terms of distributed power, results in stopping the development of an intelligent network infrastructure. This means putting greater demands requirements on transmission system operator.

To unify different demands of various TSO a project of the master document governing those requirements is being created [40]. The European Network of Transmission System Operators is community and organization responsible for the proposed parent document - Network Code for Requirements for Grid Connection.

The development of the ENTSO-E codes is a colossal step towards building modern "smart grids" concepts in reality. As a compromise between the interests of national transmission system operators and up-to-date trends in design and development of power grids with distributed energy sources. Implementation of this document with a practical realization of the "smart grids" concepts is crucial step for future development of the networks. It will ensure the flow of the newest energy technologies. As it can be noticed, the growth the energy network tends to go into so-called "prosument" direction. This will result in having more small energy producers in the network. To ensure right utilization of the latest technology trends appropriate synchronizing algorithms should be selected, depending on the several factors.

2. Applications of synchronization algorithms

The Distributed Generation Systems (DGS), consisting of RES and other power generating methods, are usually equipped with power electronic devices. Their purpose is to transfer the produced energy to the grid with fulfillment of the TSO requirements. This means that the power electronics used in each of the technologies has to be synchronized with the grid voltage. Power converters are also used as grid conditioners. This is done by using Flexible AC Transmission Systems (FACTS), protective power systems (i.e. Dynamic Voltage Restorer, Active Power Filters etc.). Another type of converters working with the grid synchronization are load devices. Utilizing so many, such diverse power electronics technologies in power grid leads to having many different synchronizing algorithms. The synchronization algorithms are used in variety of power applications. [15]:

- In terms of current control: reactive power and harmonics compensation [39]
- Support for "smart grid" management – fault ride through, carrying out the connection and disconnection process of network elements, islanding detection
- Grid monitoring – fault detection by frequency/angle determination, power factor estimation
- Reactive and active power regulation
- Dips and flicker compensation, voltage regulation
- In terms of RES integration in power systems – photovoltaic plants, wind power plants, wave energy plants etc.
- Different kinds of loads integration - AC loads with frequency converters, DC loads working with DC/AC converters

In this article different kinds of synchronizing algorithms are classified and presented. This is based on existing classifications, extended to a broader A set of evaluation features is presented.

3. Synchronization algorithms classification

There are many methods to synchronize with the grid. For power electronics this variety results also in volume. Until recently, the synchronization algorithms lacked classification. One of the possible means to classify the synchronization methods was described in [15]. It presents plain division based on reference frame coordinates in which algorithms operate. The classification focuses only on three-phase applications aimed for digital implementation on DSP platform. The idea is presented on Figure 2.

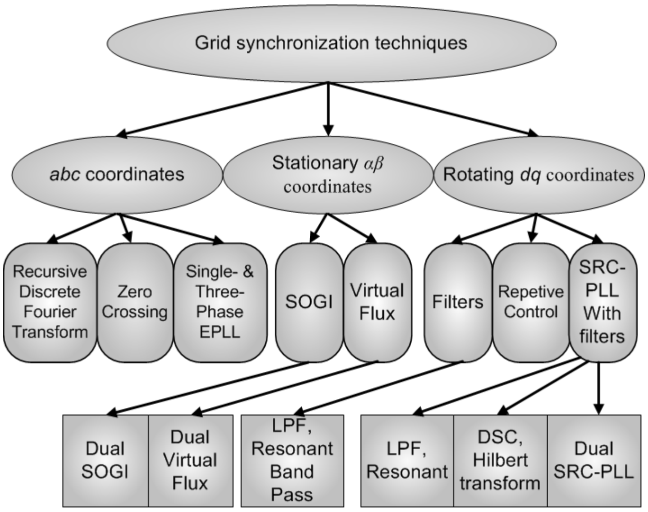

Fig. 2. Classification of synchronizing techniques according to [15]

This type of defining the kinds of synchronizing algorithms is a transparent and easy to understand way, but it limits the ability to show the full picture. As it was described in section one and section two, the operation modes of power electronics converters cover a wide range of different kinds of applications and functions. This necessitates, at first a detailed and comprehensive classification of the methods, and at second providing a set of appropriate quality/evaluation criteria. For this purpose, the following classification of synchronization algorithms is proposed. A general scheme is presented on Figure 3.

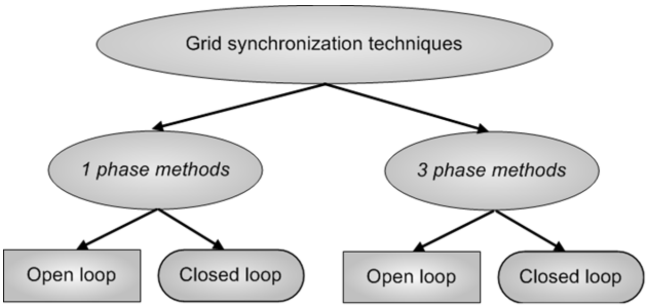

Fig. 3. The proposed general classification of synchronization algorithms

The methods are divided into two groups – utilized for 1 phase applications and 3 phase applications. Those are further subdivided into operating in an open loop manner and into a closed loop manner. Each of those groups is presented on following figures. The classification is divided into several drawings due to the fact of having a multitude of algorithms types.

Figure 4 illustrates the classification of synchronization algorithms for one phase utilization. For the open loop a method based on zero crossing detection is specified. The zero-crossing method detects the transition of a signal waveform from negative and positive, and vice versa, providing a narrow pulse that connected with the zero voltage condition. This method [13] is one of the first and basic method designed for synchronization.

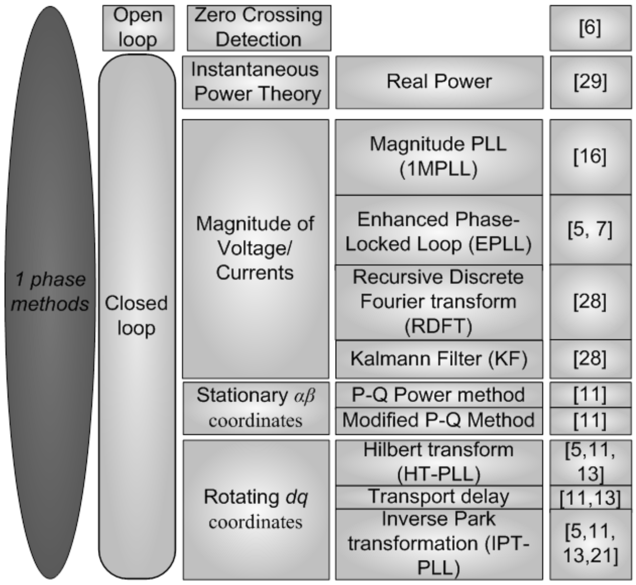

Fig. 4. Illustration of 1 phase subgroup of synchronization algorithms

The disadvantage of the zero crossing method is its sensitivity to any voltage distortion [13]. The closed loop section is divided into subsections taking into account the reference frame in which algorithms operates, like it is presented in Figure 2. The algorithms use different kinds of transformations techniques (Fourier transform, Hilbert transform, inverse Park transform) [6, 8, 35]. The RDFT method implements a band-pass filter and transform function to the frequency domain and vice versa [21]. The drawback in this case is high dependency on fundamental frequency, which implies low resistance to frequency variation.

The synchronization methods for the open loop operation in a three phase system are summarized in the Figure 5.

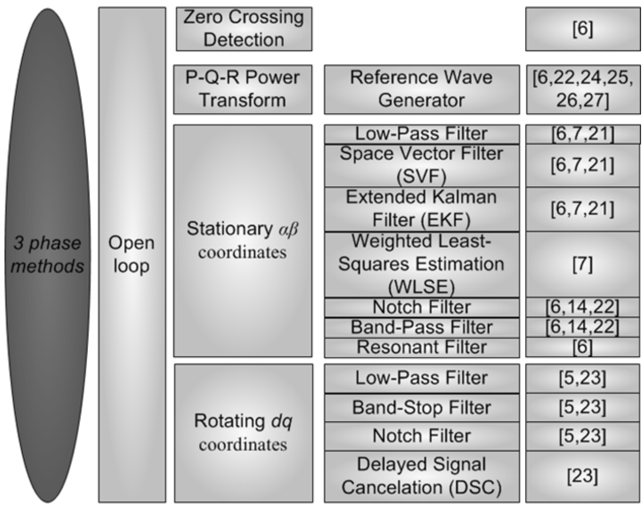

Fig. 5. Illustration of 3 phase for open loop operation subgroup of synchronization algorithms

As in single phase systems the basic algorithm is the zero crossing detection is the basic one. The rest of the algorithms are operating either in stationary or rotating coordinates or are based on P-Q-R transformation. The main drawback of the algorithms operating in rotating reference frame is their vulnerability to distortion of the grid voltage. This distortion propagates to the algorithms causing imprecise angle estimation. This usually solved by adding appropriate filtering technique (like LPF, Band-stop filter etc.) [6, 36]. Similar efforts are used in systems based on stationary reference frame [4, 13, 24, 33, 38]. Different filtering techniques perform with various dynamics responses and can introduce phase shifts.

In three phase system synchronization methods based on closed loop operation are shown in Figure 6 and Figure 7.

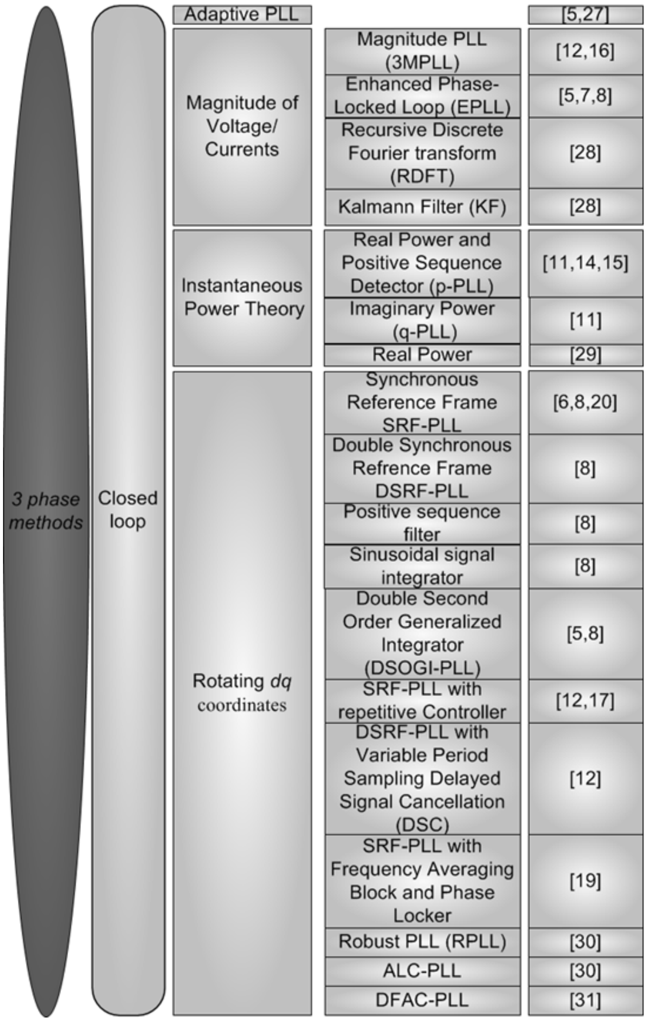

Fig. 6. Illustration of 3 phase for closed loop operation subgroup of synchronization algorithms PART I

The classification on Figure 6 is based on putting the synchronization method into four subgroups: Adaptive PLL, Magnitude of Voltages/Currents, Instantaneous Power Theory and Rotating dq coordinates. The Magnitude of Voltages/Currents are just methods adapted from one phase utilization with all their advantage and disadvantages.

The adaptive PLL utilizes three control blocks which individually manage the frequency, phase angle and voltage magnitude. The main drawback of this scheme is the large algorithm (3x3 controllers) – which results in high computational load.

The synchronizing algorithms based on instantaneous power theory can be explained by the example of p-PLL where the input signal of the PLL system is the measured single-phase voltage which is assumed to be equal to the coordinate alpha coordinate of stationary reference frame. The beta coordinate is obtained by introducing a phase delay of pi/2 of the alpha component. The operation principle is to cancel the dc component p' of the fictitious instantaneous power [35].

Algorithms placed in the rotating dq reference frame use the reference frame property as their working principle. This property, thanks to mathematical signal transformation, allows to transform the voltage signals for natural reference frame to synchronous reference frame, where when having ideal conditions the three-phase sinusoidal voltages become two DC signals. This feature allows using the PI controller for estimating the grid voltage phase angle.

One of the good examples of the working synchronization algorithms is the Double Synchronous Reference Frame Phase Locked Loop (DSRF-PLL) method [16]. It is based on transforming the positive and negative sequence components of the grid voltage into the a synchronous frame, separate for each of the sequences. Both of the reference frames are decoupled from each other by means of decoupling network. This allows for elimination of the detection errors of the conventional SRF-PLL. The uniqueness of the proposed decoupling network is due to the ability of canceling out the double frequency oscillations, and as a result there is no need to reduce the algorithm bandwidth. The accuracy in estimating the positive sequence component is superior compared to the conventional SRF-PLL. This method is very suitable for the control of grid-interfaced converters operating in the severe frequency disturbances and grid unbalanced conditions.

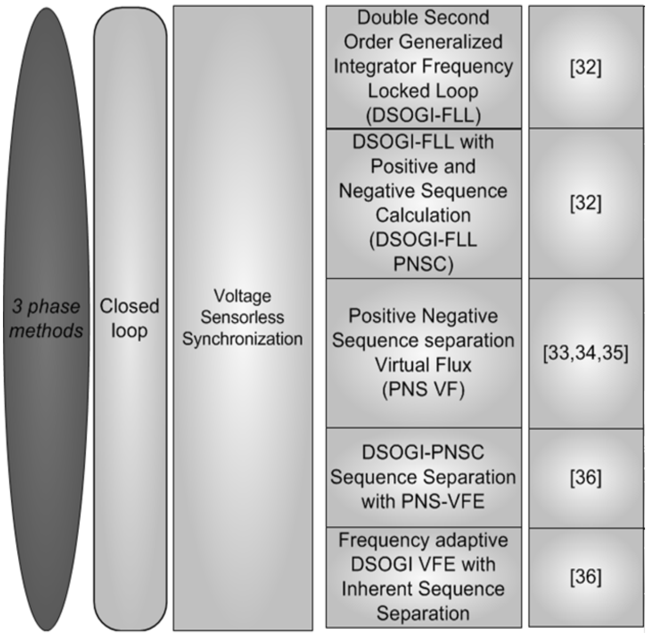

Fig. 7. Illustration of 3 phase for closed loop operation subgroup of synchronization algorithms PART II

Figure 7 illustrates the synchronization methods operating in closed loop for three phase systems based on voltage sensor less synchronization based on virtual flux estimation, as well as based on double second order generalized integrators.

The DSOGI-PLL [9] algorithm is operating in stationary reference frame and it uses the SOGI integrator for frequency-adaptive positive-sequence detection. The use of those integrator results in good performance in filtering the distortions [9].

The concept of the Virtual Flux is based on the assumption that the voltage flux of the grid voltage can be found by the means of estimation, where the voltage sensors are eliminated [37]. There are a couple of aspects that should be addressed for practical implementation of Virtual Flux estimation. Taking into account he switching characteristics of the voltage source converter when estimating the converter output voltage, if accurate estimation of the Virtual Flux should be achieved.

One of the disadvantages of incorporation the virtual flux into synchronization algorithm is the slower response in time domain. This is due to the LPF usage for elimination of the DC offset, which appears when a pure integrator for estimation VF is used. This also should be avoided.

Different kinds of method in upgrading the Virtual Flux method resulted in different kinds of algorithms. Namely Positive and Negative sequence separation (PNS), combination of DSOGI with positive and negative sequence calculation and PNS-VFE, DSOGI VFE with inherent sequence separation [1, 2, 9, 19, 37].

4. Quality criteria for the evaluation of synchronization algorithms

Having so many different kinds of synchronization algorithms it could be difficult to choose appropriate solution. The suitable choice strongly depends on the application and specific requirements. Those can be specified by the application type or by TSO. As stated in [15] no simple criteria have been set yet, to compare the performance of the synchronization algorithms. The basic need for the methods, meaning the ability to estimate the amplitude, phase and frequency of the input signal in a precise manner, even under distortions, disturbances, sounds like a fundamental must.

In some of the papers a so-called "good practice" for defining requirements for synchronization algorithms is presented [9, 12]. Those are namely, estimations of the fundamental positive or negative sequences (used in the flexible power control of grid-interfaced converters for distributed power generation and active power filters) under grid disturbances and distortions.

The need for a selection guide is clear. Taking this into consideration a set of quality criteria parameters is required. With appropriate indicators to assess all of the methods it would be easy to create the selection guide. A set of such quality criteria parameters is proposed on Figure 8.

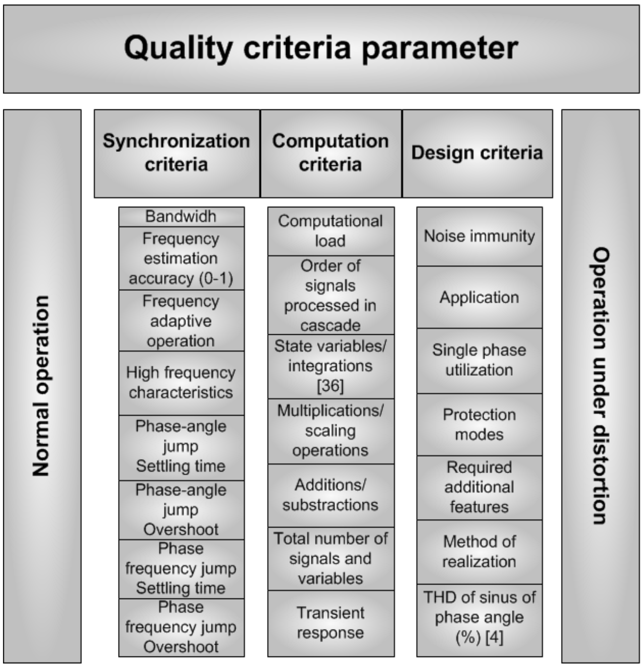

Fig. 8. A set of quality/evaluation criteria for synchronization methods assessment

Method of the synchronization algorithms evaluation is based on three basic quality criteria parameters groups. The criteria parameters are divided into three subsets:

- synchronization criteria,
- computation criteria,
- design criteria.

The design criteria take into account features such as application, noise immunity, single phase utilization, algorithms protection modes, required additional features (signal filtering etc.), methods of realization (analog, digital) and proposed in [15] THD level of a sinus of estimated phase angle. This quality set purpose is to assess the design of a method.

The computation criteria focus on total number of signals and variables, number of addition/subtractions and multiplications/scaling operations, transient response, state variable/integrations [36], computational load and order of signals processed in a cascade. These criteria set purpose is to assess the performance of the algorithm.

The synchronization criteria set draws attention to the core of the synchronization purpose. It validates properties such as method bandwidth, frequency estimation accuracy, frequency adaptive operation, high frequency characteristics, phase-angle jump settling time and overshoot and phase frequency jump and overshoot. It focuses on how good the synchronization algorithm is.

All of those evaluation properties are taken into account in two cases: normal operation and operation under distortions. The operation under distortions meaning ability to perform under:

- voltage sags and dips,
- frequency variations,
- flicker occurrence,
- harmonics occurrence,
- short supply interrupts – recovery time,
- short circuits.

5. Machine learning techniques

When facing the idea of having "smart grid" future infrastructure can lead to the conclusion that there are still many things to do. Having a transmission network where flexible and reliable transmission capabilities can be realized by the advanced FACTS systems, where the RES sources are fully integrated by the means of smart substations with advanced control interfaces and power electronics devices, where the micro grids are fully integrated by the same means, where the number of nonlinear loads with variable speed drives is increasing, the power electronics usage will rise in a tremendous manner. All of those devices need proper grid synchronization algorithms. All of the can encounter different kinds of distortions caused by harmonics, voltage sags or swells, commutation notches, noise, and phase-angle jump and frequency deviations.

This lead to a conclusion that not only a detailed classification of synchronization algorithms is needed. Not only the classification with quality criteria for the evaluation of the methods, which leads to having a choice guide. One of the main challenges is to utilize all of the power electronics devices in terms of synchronization in a whole smart grid system.

Here advanced synchronization algorithms should be used. One of the way is to employ experts system, fuzzy logic algorithms, genetic algorithms or artificial neural networks [17].

Such idea is incorporated in [29] where an adaptive linear neural network (ADALINE) algorithm is used. This method is used to estimate the time-varying magnitudes and phases of the fundamental and harmonics from a distorted waveform. The uses of neural networks in combination with a standard PLL technique results in a robust and well performing synchronization algorithm, which is bale to govern the grid angle estimation under different disturbances.

6. Conclusions

The author believes that the electrical power systems are under a transition to the smart grid concept. This is being achieved by the means in power electronics technology wide utilization, modern control usage and newest communication technologies incorporation. In the smart grids the components including power electronic converter are widely utilized - FACTS, grid interconnectors, RES integrators and so on. Thus, the accurate grid synchronization of those devices is a important issue for the modern grid concepts. Accurate - meaning fast, robust, fault and distortion resistant.

Nowadays there is no common practice in terms of choosing appropriate synchronization algorithms for power converters. The choice of the synchronization method should be determined by TSO requirements, application and type of grid.

One of the main criteria in the selection of an appropriate algorithm is the frequency estimation accuracy. The second would be the transient response (the speed of the method) and the ability to work under distortions explained in previous section. The most popular algorithm are SRF-PLL, DDSRF-PLL, DSOGI-PLL. The last two are performing well under the distortions.

Stable operation of the power electronic converters is a critical issue for intelligent networks. This is due to the fact that they are the fundamental building blocks for the smart grid infrastructure.

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