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Remote micro-grid synchronization without measurements at the point of common coupling

Mateusz Litwin[1], Dariusz Zieliński[1], *Member, IEEE*, and Gopakumar K.[2], *Fellow, IEEE*

[1] Department of Electrical Drives and Machines, Lublin University of Technology, Lublin, Poland

[2] Department of Electronic Systems Engineering, Indian Institute of Science, Bengaluru 560 012, India

Corresponding author: Mateusz Litwin (e-mail: Mateusz.Litwin@pollub.edu.pl)

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ABSTRACT This paper presents a new strategy of active synchronization of an island micro-grid and the utility grid (UG) without measurements at the point of common coupling (PCC). This strategy is based on the assistance of Ethernet communication, GPS pulse-per-second device synchronization, and droop control parameter shift. A strategy with Ethernet-assisted synchronization is used instead of synchronization with dedicated low-bandwidth communication. This strategy is based on exchanging data between two proposed devices: synchronization data sender (SDS) and synchronization data controller (SDC). The SDS calculates the UG voltage parameters and sends these data to the SDC device. The SDC is responsible for receiving synchronization data and calculating droop control parameter shift. The use of GPS-based device synchronization adds very stable and accurate measurements of synchronization parameters that correspond to the stable synchronization signal. As this strategy uses droop control method parameter change, all distributed generators share loads adequately. This strategy introduces the possibility to remove the need for measurement of voltage directly on the switch location. The proposed devices could be connected even a long distance from the PCC. The strategy also introduces the possibility of working in synchronism with the main grid despite the island mode of the micro-grid. This introduces the possibility to connect the micro-grid at the same moment as fault clear or maintenance end.

INDEX TERMS active synchronization, distributed generation, droop control, Ethernet, micro-grids, power system restoration.

I. INTRODUCTION

The amount of electronic devices is constantly growing, which is the reason for an ever greater energy demand. Conventional energy sources lead to problems like fossil fuel depletion, poor energy efficiency, greenhouse gas emission, environmental pollution, and others, presented in [1] and [2], which makes them unsuitable in the longer term. Emission of greenhouse gases is the biggest problem, arguably contributing to global warming. Most countries around the globe signed agreements like the Kyoto protocol (2005), Paris agreement (2016) or Katowice (2018) and Madrid (2019) Climate Change Conference packages to try to control climate change, as maintained in [36]. The goal is to reduce greenhouse gas emissions. One possible solution is to use renewable energy sources (RESs) such as wind, water, sun, biomass or waves as argued in [24] etc.

The biggest advantage of using RESs is reduction of environmental pollution. Another gain is smaller transmission losses as RESs are typically small energy sources dispersed over many places and thus closer to consumers. This results in a strong and fast growth of RESs.

This type of generation is termed distributed generation, as opposed to conventional centrally operated generation presented in [1]. As a result of increased demand for environment-friendly renewable sources and the need for energy generation in reliable and secure ways mentioned in [29], the concept of a micro-grid (MG) was introduced by the consortium for electric reliability technology solutions (CERTS), presented in [4]. An MG consists of distributed energy resources (DERs) (wind turbines, micro turbines, fuel cells, photovoltaic panels, etc.), flexible loads and energy storage devices. This concept introduces the possibility of MGs working in connection with the electrical utility grid

(UG), or independently as illustrated in [23]. This increases energy reliability and resilience, because if any faults occur in the UG, an MG can be disconnected from it and continue to power consumers without interruption.

When an MG is working in an islanded mode, there is a necessity to resynchronize before reconnection to the UG, a case mentioned in [23]. Reconnection without synchronization is dangerous since an unsynchronized operation can lead to flow currents close to short circuits, risking damage connected to MG generators and blackouts. There are conditions that need to be met to successfully connect an islanded MG to the UG: the same phase order, matching phase voltages and a match of frequency and phase angle between the two systems.

A problem with active synchronization is the need for measurements and communication directly on the PCC. The paper proposes a new approach of an active synchronization model. The proposed solution argues for the possibility to synchronize an MG with the UG even when measurements at the PCC are impractical or there is no connection with that point. Thus the dependence on measurements and even a connection with the PCC is removed. For information exchange between a separated MG and the UG, Ethernet communication is used, which is cheaper and more reliable than a dedicated connection. Ethernet communication can be used by many different media like cable, public infrastructure, WiFi, 5G and others. Section II explains the reconnection requirements that need to be met for successful reconnection of an islanded MG to the UG. In section III there is a review of the synchronization techniques. The following section presents details of the presented method of synchronization without measurements at the PCC. Section V discusses the algorithm of the strategy in question. The next section describes the simulation model and its parameters. Section VII addresses the simulation results. Section VIII introduces the initial experimental test-stand scheme, the devices used, and the results. The final unit offers conclusions and the future steps to an improved solution.

II. REQUIREMENTS FOR MICRO-GRID RECONNECTION TO UTILITY GRID

The concept of an MG assumes that the grid is expected to provide consumer power and work without interruption even after the MG is disconnected from the UG. An island condition can happen if there is a fault or maintenance operation on the UG side. After restoring the UG to proper functionality, the MG is permitted to reconnect to the UG. Before reconnection, there should be a resynchronization of the MG to the UG. For a small MG the parameters required to be met are presented in [3], and can be simplified to the following:

- The voltage magnitude of both the MG and UG must match with a max error of 10 %;
- The frequency of the MG must be the same as that of the UG and the max acceptable error be below 0.3 Hz;
- The phase angle difference cannot be more than 20 degrees.

These rules need to be strictly met, otherwise connection of the MG to the UG will cause a high amount of inrush currents and overvoltage, which can lead to activating overcurrent or overvoltage protection and cause a blackout. The requirements for MG synchronization are listed in Table I.

TABLE I
REQUIREMENTS FOR MICRO-GRID RECONNECTION TO UG [4]

Rating of DERs (kVA)	Voltage difference (%)	Frequency difference (Hz)	Phase angle difference (°)
< 500	10	0,3	20
500-1500	5	0,2	15
> 1500	3	0,12	10

III. REVIEW OF MICRO-GRID SYNCHRONIZATION TECHNIQUES

There are three common strategies of synchronization: passive, open drain, and active. They are addressed in [4].

A. PASSIVE SYNCHRONIZATION

This method is based on monitoring MG and UG voltage at the PCC. The synchro-check device measures the magnitude, frequency and phase angle of voltage on the MG and UG side, as earlier presented in [37]. If the difference between the magnitude, frequency and phase of the voltages on each side of the switch is within preset limits, a close signal is sent to the switch to connect the MG to the UG. These limits are commonly set on the requirements given by the IEEE 1547.4 standard. A schematic diagram of a synchro-check device is shown in Fig. 1. This method is applied because in most cases the voltage magnitudes of the MG and UG are close to each other and their frequencies are only slightly different.

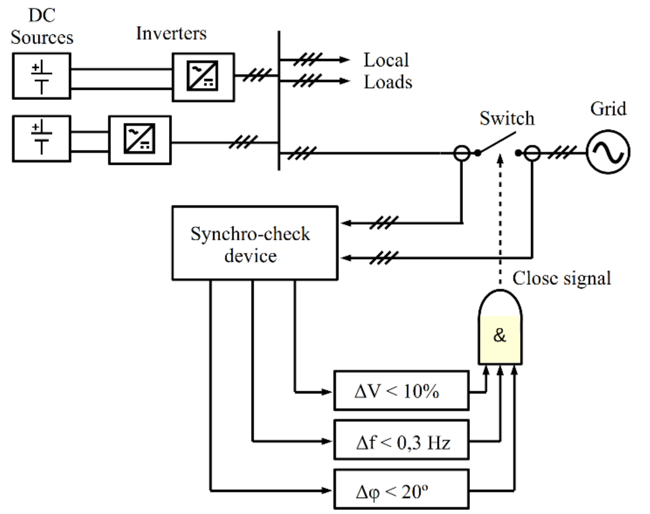

FIGURE 1. MG passive synchronization with requirements from the IEEE 1547.4 standard for small MG.

The advantage of the passive method is that it is easy to implement and does not need extra communication. A disadvantage here is that when voltage magnitudes of the MG and the UG differ from each other, at the moment of switch closing voltage spikes and inrush current occur. As argued in [37], this solution is acceptable for distributed generator (DG) based on power electronics, since PLL will draw inverters into synchronism with UG. But when a synchronous generator is used, even a small difference between an MG and the UG will cause problems during reconnection, as presented in [12]. Another problem is slow synchronization when the frequencies of the MG and the UG are close, which is pointed out in [5].

B. OPEN TRANSITION SYNCHRONIZATION

Open-transition synchronization is based on disabling inverter output and disconnecting the DG before reconnection of the MG to the UG. This is the safest solution in reconnecting MGs to the UG, but it reduces the level of reliability of the system.

Article [13] came up with a proposal for an improved open transition solution. The switch between the MG and the UG is closed without synchronization. If the phase angle difference between the MG and the UG is small, the proposed algorithm for fast voltage phase angle synchronization catches a new voltage phase angle and synchronization ends. If at switch close overvoltage or overcurrent occurs, the inverter goes into the proposed coast mode, as shown in [13]. In this mode all power transistors are off, after that the proposed algorithm catches a new voltage phase angle, and after synchronization with the new phase angle, changes the inverter to normal operation.

C. ACTIVE SYNCHRONIZATION

The active method uses additional control for faster and smoother grid connection, as mentioned in [5]. Additional communication is used to exchange information about voltage magnitude, frequency and phase angle difference between the intelligent switch at PCC and the MG controller or MG DERs. With this information the sources change their output parameters to be the same as in the UG. Fig. 2 shows a general concept of active synchronization applied in most solutions.

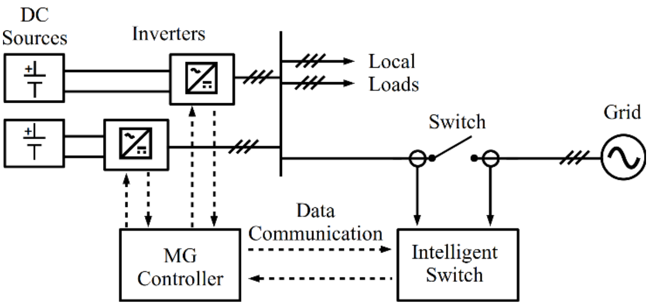

FIGURE 2. MG active synchronization concept.

Study [14] proposes the use of one of DGs as a dispatch unit. The proposed dispatch unit is responsible for synchronization of the MG to the UG. All other units are in droop control mode. Article [15] proposes a MG central controller. The MG central controller sends data independently to each DG unit to correct the voltage and frequency offset to all controllable DGs. The solution presented in [16] uses the shift of droop control curves. This solution has the advantage that even if communication between the controller and the DGs is lost, the MG can still operate in the island mode. The solution presented in article [17], proposes directly sending the calculated difference between voltage magnitude, frequency and phase angle to controllable DGs and using it as an input of active and reactive power loops. Article [18] proposes use the sine of the phase angle between both voltages to calculate the new theta value that should be used by the DG controller to synchronize with the UG. Article [19] presents a back-to-back inverter as an interconnection between the MG and the UG. The method presented in [20] is based on the combined use of different phase-locked loop (PLL) systems, to synchronize the phase angle and frequency of the MG with the UG. By means of the proposed PLLs the MG central controller calculates the voltage signal, which is directly used by DERs. The signal is synchronized with the GPS signal to synchronize zero crossing voltage. Article [21] talks about another problem, underestimated or ignored in other articles, concerning the fact that communication channels are prone to time delays, which should be considered in the design of controllers and the synchronization process.

Active synchronization is a very promising idea of future MG synchronization. Researchers are working to further improve this method. Most works are focusing on synchronization in the UG in stable conditions, but this may not always be true. Articles [6]-[8] and [26] address the problems with the synchronization of converters in the case of disturbances in the UG.

The advantage of the active method is fast and smooth connection of the MG to the UG. As the voltages have the same magnitude, frequency and phase angle, transient currents and voltages are close to zero.

IV. PROPOSED SYNCHRONIZATION STRATEGY WITHOUT MEASUREMENTS AT THE PCC

One of the problems with active synchronization is the need of measurements in the PCC. In conventional active synchronization voltages are probed from both sides of the intelligent switch, and then the difference is calculated and sent to the MG controller. As a result, in any connection point there is a need for a measurement device and dedicated connection. Also, an MG can be synchronized to the UG only if voltages are present on both sides of the switch at the PCC.

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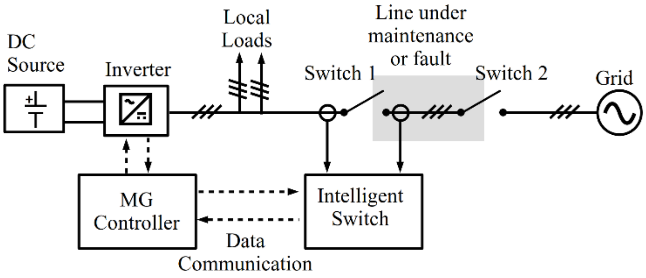

FIGURE 3. **Conventional synchronization scheme of the MG working in island mode with disabled line between the MG and the UG.**

Fig. 3 presents one of possibilities when conventional method cannot synchronize the MG to the UG. The MG is working in the island mode, because of the line between the MG and the UG is under maintenance or fault. In the conventional method, synchronization can only be done after the line is supplied with power. When this is the case, measurements at the PCC can start, and then synchronization starts.

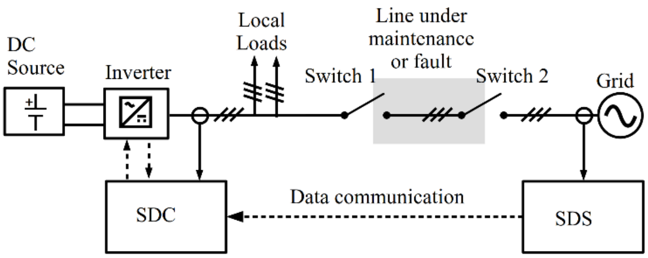

FIGURE 4. **Proposed synchronization scheme of the MG working in island mode with disabled line between the MG and the UG.**

In our solution, pictured in Fig. 4, the next supplied with power line can be used to collect data needed for synchronization and send them to the MG side. On the MG side a receiving device compares the data to measurements in a database and calculates the error signal. The concept of the database is presented in next chapter. Synchronization can be achieved before supplying with power the line in the middle. This solution provides a possibility to synchronize an MG with the UG even if there is more than one switch open between the MG and the UG or if the switch has no measurement or communication possibility.

The proposed device can send a synchronization signal right after change of the MG mode from grid-connected to islanded mode. Devices can work in the continuous mode and add a shift to the droop control algorithm. Even if there is a fault or maintenance in progress between the UG and the MG, synchronization between the two grids can be maintained. This means that the island could be in synchronism with the UG throughout the time of some fault or maintenance, despite the MG working in island mode. After removing a faulty condition or finishing maintenance, the switch can be closed immediately as both grids are working in synchronization all the time.

In this paper the authors propose a synchronization strategy without dependence on measurements at the PCC. The solution introduces the use of two devices: on the UG side there is a need for a synchronization data sender (SDS) and on the MG side a synchronization data controller (SDC). A scheme for the proposed solution is presented in Fig. 5. The solution put forward here introduces the use of a GPS pulse per second (PPS), Ethernet connection and the database for measurements. The GPS PPS signal is used to synchronize measurements and timestamp data. Ethernet connection is used to transport data between proposed devices, but other communication systems can also be used. The proposed database is responsible for compensation of delays caused by Ethernet connection. Both devices get voltage measurements and calculate voltage magnitude, frequency, and phase angle with the use of the PLL synchronous reference frame (SRF PLL) presented in [23]. Next, a timestamp is added to the calculated data from the GPS system. The SDC is also responsible for saving data needed for future comparison with data received from the SDS device. The SDS device sends data to the SDC device which receives them and computes new droop control parameters used by the converter to synchronize with the UG.

The idea of the proposed strategy considers random delays that can occur in the communication channel and introduces saving the calculated signal to be compared with that received from the UG side. Details about the algorithm used is presented in the next section. The use of this technique makes the proposed strategy resistant to random Ethernet communication delays that occur when exchanging data. Delays in communication slow down the dynamics, but do not change the accuracy of the synchronization.

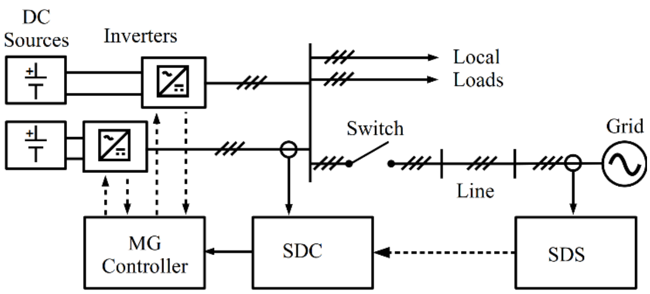

FIGURE 5. **Proposed synchronization scheme, SDS – synchronization data sender, SDC – synchronization data controller.**

The droop control method from articles [32]-[35], [41] and [42] is used to ensure a proportional share the transient and steady-state power flows in the MG, without using dedicated communication. This method is widely used in distributed generation systems because it provides a reliable solution of real and reactive balance in the MG. The proposed method uses droop control for LV networks which is presented in [34], and adjusts DG operation frequencies and phase angles through the frequency restoration of the Q-ω droop control and output voltage magnitudes through the V restoration of P-V droop control. As a result, the grid synchronization is accomplished with the proportional sharing of real power and reactive power.

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The proposed solution uses droop control by shifting the nominal parameter of frequency and voltage magnitude in the droop controller. Parameters are calculated by a PI controller with the use of phase angle, frequency and magnitude difference between the MG and the UG voltage. The calculation of the droop control shift parameter can be simplified to:

$$\delta\omega = k_{p\omega}\Delta\omega + k_{p\varphi}\Delta\varphi + \int(k_{i\omega}\Delta\omega + k_{i\varphi}\Delta\varphi)\,dt \quad (1)$$

$$\delta V = k_{pV}\Delta V + \int(k_{iV}\Delta V)\,dt \quad (2),$$

Where $\Delta\omega$, $\Delta\varphi$, and ΔV are the voltage frequency, phase angle, and amplitude differences between the MG and the UG, $k_{p\omega}$, $k_{p\varphi}$, k_{pV}, $k_{i\omega}$, $k_{i\varphi}$, and k_{iV} are the proportional and integral constants of the voltage frequency, phase angle error and amplitude between the MG and the UG voltage. As phase angle and frequency are coupled, they are used on one integral to avoid the control overflow effect. There is a need to point out that phase angle difference is limited before sending it to the PI synchronization controller. This adds the possibility of setting phase angle gains higher for better performance of the synchronization controller. These parameters are added to the droop controller. The droop controller for the grid-supporting current mode inverter is presented in Fig. 6.

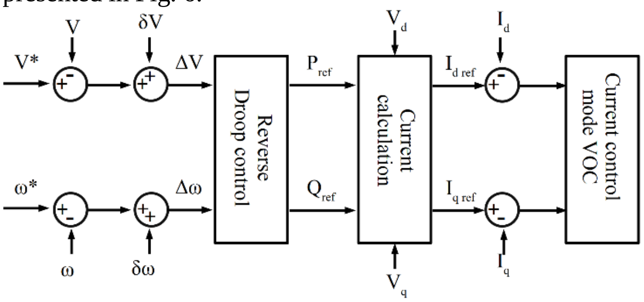

FIGURE 6. **Droop controller for an inverter working in current control mode, where *δV* and *δω* are the results of computations delivered by equations (9) and (10).**

Above, in Fig. 6, V^*, ω^* are the requested voltage and frequency of the inverter, ΔV and $\Delta\omega$ are the difference of voltage and frequency between requested and measured values, V_d, V_q, I_d, I_q are the calculated active and reactive voltage and current, and δV, $\delta\omega$ are the calculated droop control shift parameters in PI control loops determined by (1) and (2).

The characteristics of droop control for LV networks with the use of an additional parameter are presented in Fig. 7.

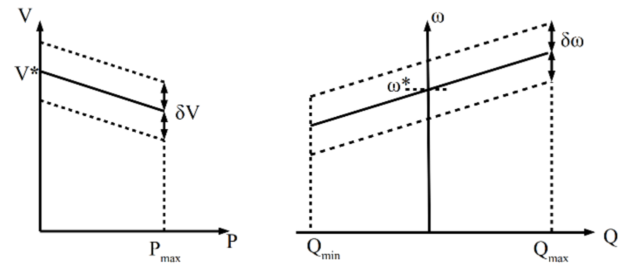

FIGURE 7. **Droop control characteristics after added shift.**

The use of droop control in the proposed synchronization strategy introduces the possibility of sharing active and reactive power between DGs in the MG without dedicated fast high bandwidth communication. To receive a droop control shift parameter all you need is a low bandwidth connection. The next advantage is that connection problems do not change the stability of the MG system.

V. SYNCHRONIZATION DATA EXCHANGE ALGORITMS

The analysis in this paper was done with the application of a conventional SRF PLL algorithm. In the proposed grid synchronization application, this PLL is suitable for stable symmetric states in the MG and the UG, a case mentioned in [27] and [28]. If severe asymmetrical disturbances, such as ground faults or two phase short circuits occur in the UG or the MG, then such an algorithm may not be suitable for the proposed synchronization, cf. [38]. For that reason the SRF PLL algorithm can be easily extended to any other synchronization algorithm suitable to synchronize the MG with the UG when such disturbances occur. Articles [6-8] and [26], [40] address problems with synchronization of converters in the case of such events on the MG or UG side.

Ethernet communication is working on two main types of packets: Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). The TCP is used when there is need to ensure that all packets are in correct order and not lost. The UDP has no facility of checking packet order or loss, but is a lot faster, better handles congestion, and works better on low bandwidth links. As the UDP is used every time a real time application is needed, the authors used this type of packet in the proposed strategy. We put forward algorithms which could resolve disadvantages of using the UDP and still work reliably and fast.

As the data are received with a random delay there is a need to implement an algorithm that is as robust as possible to communication delays, duplicates, and loss of data. There is no possibility to directly compare calculated voltage magnitude, frequency and phase angle with received data as they are measured and calculated in different time. The simplest solution is to predict the possible UG voltage phase angle by using the received data and calculated delay. This can be done by multiplying delay by frequency of the UG from the received signal and add to the received phase angle data. This solution has poor accuracy, as there is a need for a very precise calculation of the delay and frequency measurements, and is susceptible to any events that can occur in the UG.

In the proposed solution, measurements on both sides are synchronized and timestamped. For resolving any problems that can occur if measurements are done at slightly different time, both devices start measurements at the rising edge of the GPS PPS signal. This causes that measurements at both devices are synchronized. The GPS PPS is also used to synchronize the time in both devices and used to timestamp measurements. Measurements of local frequency, magnitude and phase angle voltage are saved to a database in an SDC device. When a packet with measurements data are received from a SDS device, the timestamp of received data is used to retrieve data from a database with the same timestamp. Difference calculation is done between data with the same timestamp, which corresponds to exactly the same time of measurement. With this solution, the difference between voltage magnitude, frequency and phase angle are calculated with data provided from the MG side and UG side at exactly the same time. Delay in sending a packet from the UG side is compensated, and the computed difference is always accurate.

The PI controller used is calculated to a maximum delay that can occur. The received packet is discarded if it is older than the threshold provided.

Figures 8 and 9 present algorithms of the proposed SDS and SDC device.

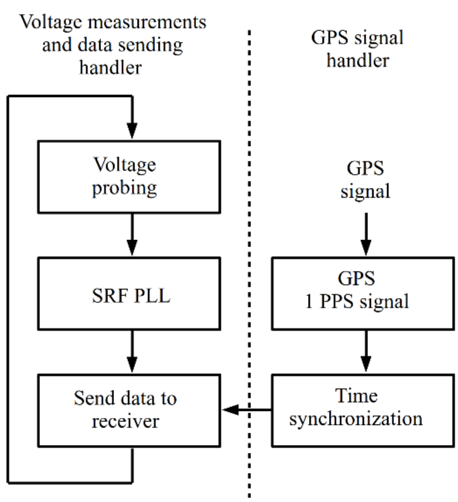

FIGURE 8. Proposed Ethernet SDS device sender algorithm, PPS – pulse per second, SRF – synchronous references frame PLL.

Fig. 8 illustrates the algorithm of the SDS device. The algorithm is divided into two modules. The right module is responsible for the synchronization time and measurements to the PPS signal from the GPS device. The left side module is responsible for the probing voltage and calculating the UG voltage frequency and its instantaneous phase angle and magnitude. Subsequently, the data are sent to the SDC device.

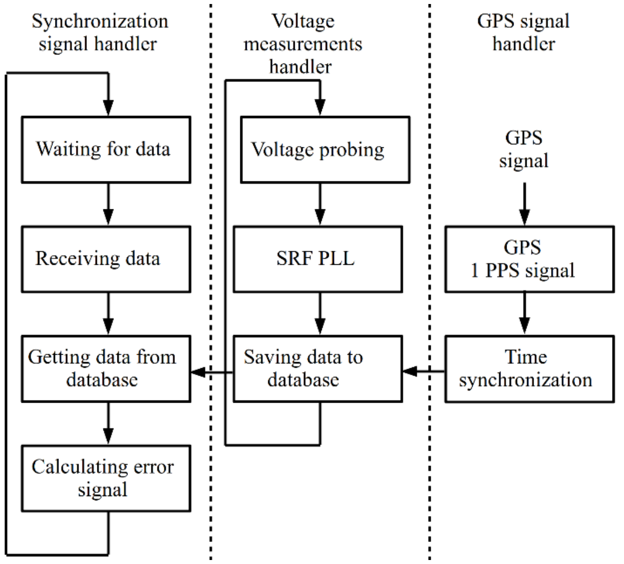

FIGURE 9. Proposed Ethernet SDC device algorithm, PPS – pulse per second, SRF – synchronous references frame PLL.

Fig. 9 present the SDC device algorithm. The algorithm is divided into three modules. The right module, like in the SDS device algorithm, is responsible for the synchronization time and measurements to the PPS signal from the GPS device. The module in the middle is responsible for collecting probed voltages, calculating voltage frequency, its instantaneous phase angle and magnitude. Then computed data are saved to the database and sent to the synchronization signal handler module. Subsequently, with the data received from the SDS device and those retrieved from the database, voltage magnitude, frequency and phase angle difference are calculated. With the use of the PI the controller error signal is calculated according to (1) and (2) and sent to the converter.

VI. SIMULATION OF THE PROPOSED SYNCHONIZATION STRATEGY

For checking the working of the solution, a grid side inverter with a voltage oriented control was used, developed in the authors' department laboratory. It is presented in [6]-[8] and [26]. In this model the authors change the control of the inverter from grid-feeding to grid-supporting current control. The change is needed for successful work in the island and grid-connected mode. This control uses reversed droop control as presented in articles [41] and [42]. The use of this solution also provides the possibility of a seamless transition from grid-connected to island mode without changing the inverter control mode.

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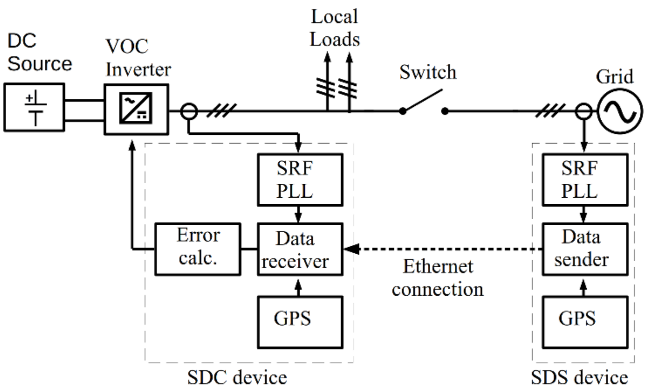

FIGURE 10. **Scheme of an MG used in the proposed solution. VOC – voltage oriented control inverter, SRF PLL – synchronous reference frame PLL, SDC – proposed synchronization data controller, SDS – proposed synchronization data sender.**

A scheme of the model is presented in Fig. 10. The parameters of the devices used in the model are shown in Table II. The parameters used are typical of small village line parameters. The loads and inverter are connected together into the MG.

TABLE II
PARAMETERS OF THE SYSTEM USED IN THE MODEL

Parameter	Symbol	Value
Inverter	*VOC*	VOC SRF Droop-control 5kW LC filter
Line	*L*	2km 35mm^2
Consumers	*P*	3kW, 0.5kvar ind
DC source	*DC*	700 V, 0.01 Ω
Reverse droop control voltage gain	$1/k_V$	0.0065 V/W
Reverse droop control frequency gain	$1/k_\omega$	0.00625 (rad/s)/VAr
Voltage synchronization controller	k_{pV} k_{iV}	0.01 0.25
Frequency/Phase synchronization controller	$k_{P\omega}$ $k_{P\phi}$ $k_{I\omega}$ $k_{I\phi}$	0.25 6 10 2.5

The MG has a converter that works in the grid-supporting current control mode. A linear load is connected to the inverter. Voltage measurements in the MG are located close to the DG and on the grid side it is connected to the switch from the UG side.

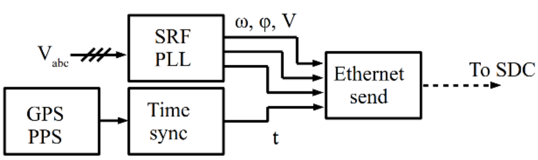

FIGURE 11. **Schematic model of the proposed SDS device, GPS PPS – GPS pulse per second signal, SRF PLL – synchronous reference frame PLL.**

Fig. 11 shows the proposed and developed SDS device. The device is responsible for taking data from voltage measurements, next the timestamps provided by a GPS receiver are added, and sent by the Ethernet.

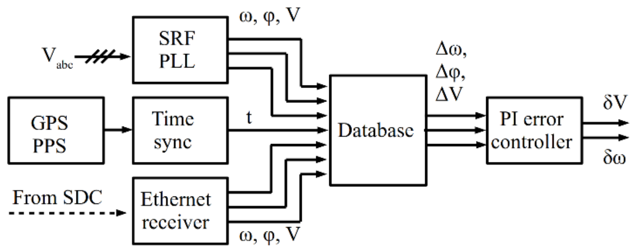

FIGURE 12. **Schematic model of the proposed SDC device, GPS PPS – GPS pulse per second signal, SRF PLL – synchronous reference frame PLL.**

The main device of the proposed strategy is presented in Fig. 12. A model of the proposed SDC is displayed. The SDC device is responsible for three main things. First is the calculation of the voltage magnitude, frequency, and the phase angle of the MG voltage and saving it in the database. Secondly, data are received from the proposed SDS device. Lastly, after collecting these data and with the use of time from the GPS receiver, the output error signal is sent to the VOC converter.

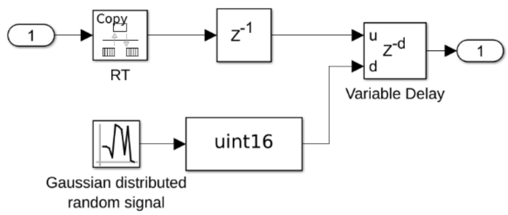

FIGURE 13. **Simple Ethernet delay approximation.**

The Ethernet is very complicated network. Delay of the packets depends on many factors like count of the routers on the road, bandwidth and connection type between each router, every link load, and many other factors. On the internet there are only few very complicated models, which work only for very specific Ethernet configurations, which makes those models not the best solution to test with. To resolve this problem the authors have developed and used a simple approximation of the Ethernet connection delay. As presented in Fig. 13, the Ethernet connection delay approximation is based on three main blocks. The block first applied is an element that rates transmission to simulate the frequency of sending packets. The next block is the element creating variable integer delay to simulate delays in transmission. The last block used is a uniform random number generator, as it consists of a good approximation of a stable load of the Ethernet connection. This method is a useful approximation of the UDP connection used in various solutions, as it simulates packet drop, reordering and duplication, which can occur in the use of the UDP connection. A similar solution applied to the actual system, but with the use of Pareto distribution, can be found in [39].

VII. SIMULATION RESULTS

Figures 14-18 present the result of the proposed synchronization strategy. Synchronization is tested for 3 delays with the average value of 30 ms, 90 ms and 150 ms. As an Ethernet UDP connection is used, there are duplicates and missing packets, but solutions consider this and the system works as expected.

For up to 1.3 seconds, the MG works in a standalone mode. The inverter works with the use of droop control to produce correct frequency and voltage for consumers.

At 1.3 seconds (synchronization start time) of the simulation the phase angle difference between the MG and the UG has a value of 82 degrees. At this point synchronization starts. The MG frequency changes below that of the UG and the phase angle difference decreases. At about 0.45 s from the start of synchronization the phase angle difference is almost zero. At 4 seconds the switch between the UG and the MG is closed.

Fig. 14 presents the voltage of phase A from the MG and the UG for an average delay of 150 ms. This result is the same for cases with an average delay of 30 ms and 90 ms.

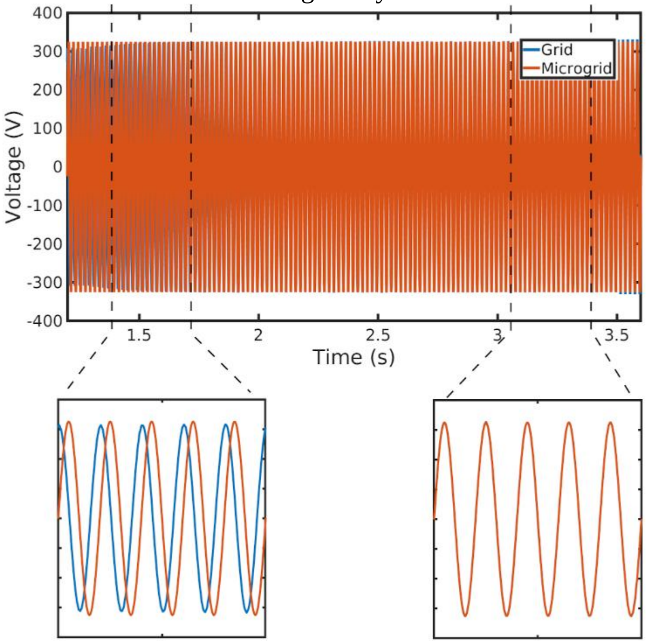

FIGURE 14. Voltage in phase A of the MG and the UG, for the average delay of 150 ms.

Figures 15-18 present the results of the proposed synchronization strategy. Fig. 15 presents frequency difference between the MG and the UG. The next figure presents the respective phase angle difference. The last two figures is the droop control parameters shift during synchronization. All results are present for three delays of 30ms, 90ms, and 150ms.

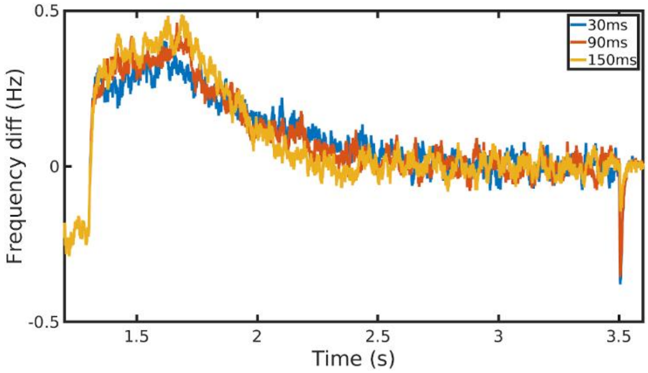

FIGURE 15. Frequency difference between the MG and the UG for the average delay of 30 ms, 90 ms and 150 ms.

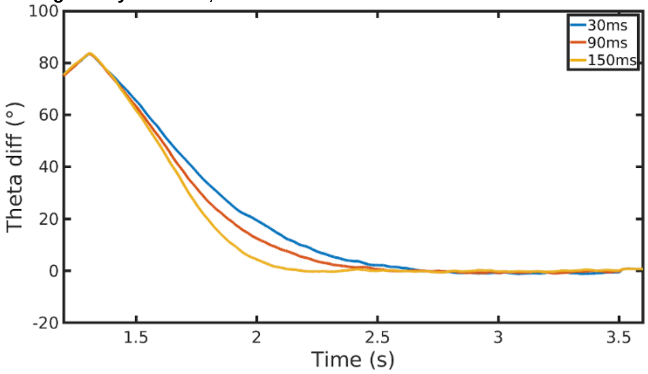

FIGURE 16. Phase angle difference between the MG and the UG for the average delay of 30 ms, 90 ms and 150 ms.

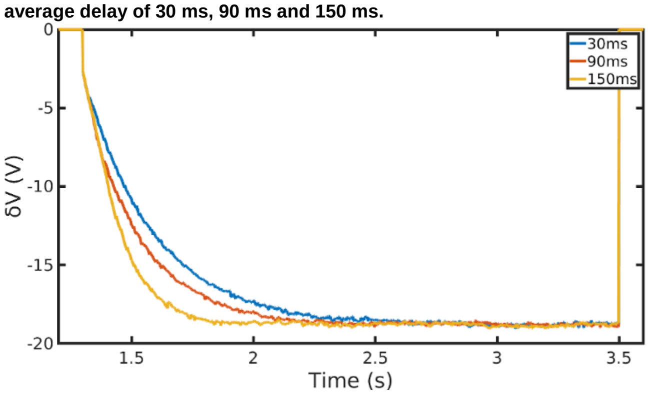

FIGURE 17. Shift added to the droop control parameter of the requested voltage for the average delay of 30ms, 90ms and 150ms.

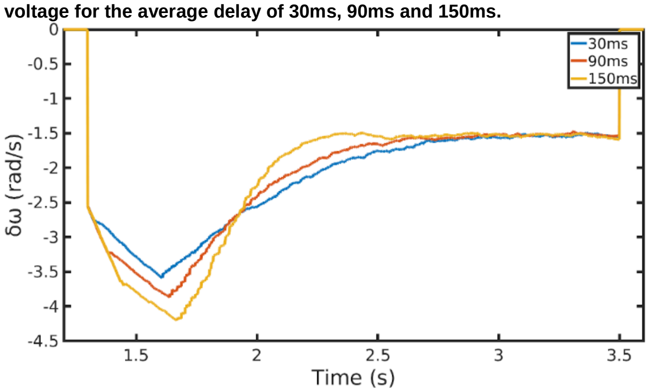

FIGURE 18. Shift added to droop control parameter of the requested frequency, for the average delay of 30 ms, 90 ms and 150 ms.

Simulation was done for an average delay of 30ms, 90ms, and 150ms. From a delay above 250ms the system starts to have overshot at phase angle synchronization, and a delay bigger than 500ms causes the proposed method to become unstable. In newer Ethernet connections such big delays become unlikely. A solution is secure for such a big delay, and disables controller output if such event occurs. There is a wait for better connection conditions. Also, newer technologies that can be used as a wireless connection like 5G have such small delays that can be measured in a few milliseconds.

As the voltage magnitude, frequency and phase angle are almost exactly the same on both sides of the switch, there is no inrush current or voltage spikes at the moment of switch close. Transition from stand-alone to grid-tided mode is seamless.

Next figures present a comparison of the proposed method to the conventional method that uses measurements on the PCC side. The proposed method is simulated with an Ethernet connection with a big average delay of 150 ms. A conventional method is simulated with an ideal condition, without any delay, as the dedicated connection is typically shorter and less congested. Also for the dedicated connection there is no drop of information and all the data are received in the order of sending. Synchronization for both cases is started at the same time, by enabling signal output of the PI controller. A calculation of voltage magnitude, frequency and phase angle difference is taken from an article which is presented in [38]. A typical PI controller is used as a synchronization controller.

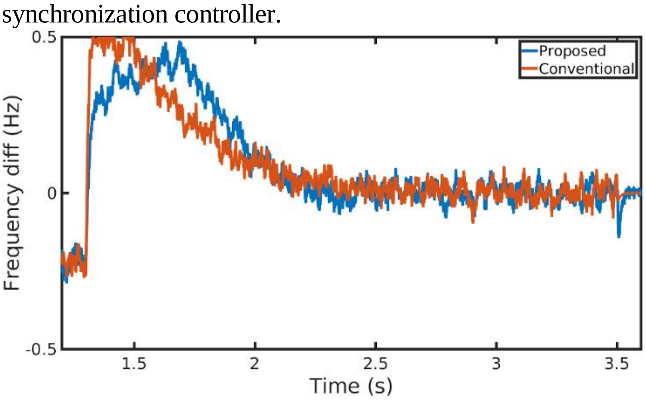

FIGURE 19. **Voltage frequency difference between the MG and the UG at synchronization with the conventional and proposed methods.**

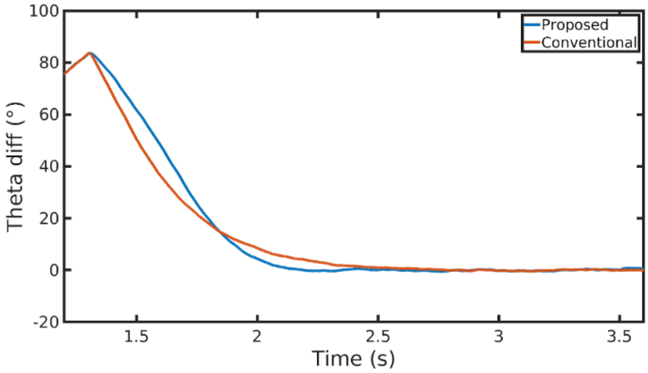

FIGURE 20. **Voltage phase difference between the MG and the UG at synchronization with the conventional and proposed methods.**

As is shown in the figures provided, the proposed synchronization strategy works as well as the conventional synchronization method with no latency connection and measurements at the PCC. Compared to the conventional method, the proposed strategy has the advantage of the islanded MG working in synchronization with the UG, without dependency on the PCC, as well as if more than one switch between the MG and the UG is open.

VIII. INITIAL EXPERIMETAL TEST STAND AND MEASURMENTS

For the proposed strategy an initial test stand was built. Fig. 21 shows a schematic representation of the test stand.

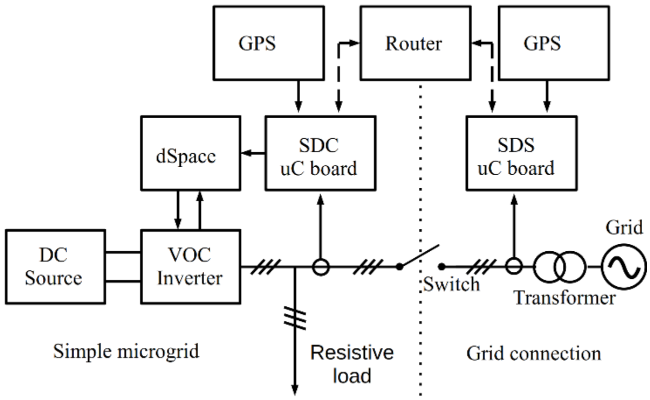

FIGURE 21. **Experimental test stand schematic. uC board – microcontroller board.**

The scheme could be divided into two separate sides. One side is on the left of the switch and has the load and inverter to create a simple microgrid. The inverter has a DC source connected as energy source. At the right of the switch there is a transformer. The transformer is used to improve the security of the experiments. The grid is connected to the transformer by fuses.

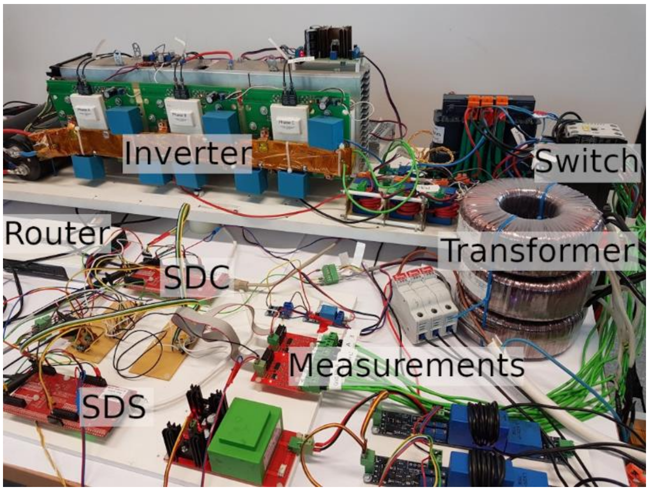

FIGURE 22. Picture of initial experimental test stand.

The dSPACE prototyping platform is used as inverter controller and for measurements of inverter parameters like voltage and current. The initial experimental stand of the system is presented in Fig. 22. The MG side and the UG side are separated from each other and information is exchanged only by a router. Initial versions of the algorithms are implemented to both microprocessor boards. Separate GPS modules are connected independently to the boards to synchronize time and measurements.

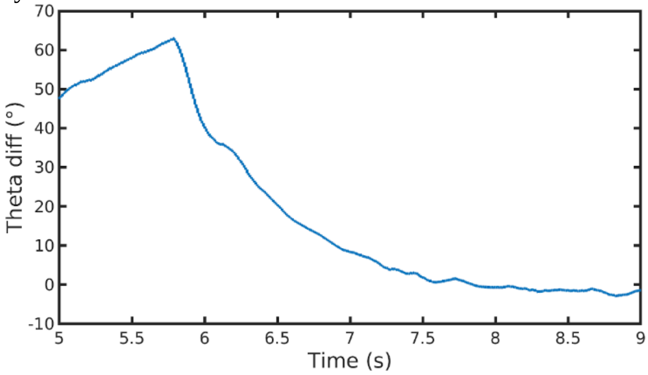

FIGURE 23. Phase angle difference between the MG and the UG at synchronization.

Fig. 23 presents the phase angle difference between the MG and the UG at synchronization. Synchronization starts at 5,8 s from experiment start. After about 2 seconds from synchronization start, the MG is synchronized to the UG.

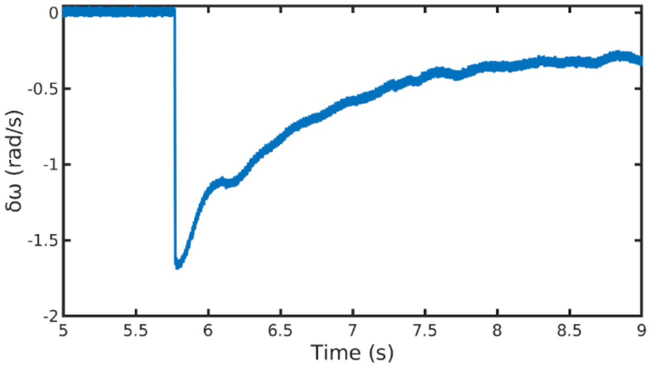

FIGURE 24. Droop control parameter change at the MG synchronization with the UG.

Fig. 24 presents a change of the droop control parameter of the requested MG frequency. After synchronization the frequency of the MG is the same as the frequency of the UG.

The experimental results shown are taken with the use of public infrastructure. The delay of the transport packet between the SDS and the SDC device was 25 ms on average.

IX. CONCLUSIONS

Synchronization of the MG and the UG is a crucial point of the reliability of energy production. The possibility of working in standalone mode allows for grid maintenance without the necessity to disconnect consumers.

Synchronization is needed when changing standalone mode to grid-connected mode. Active synchronization offers fast and secure alignment of the MG and the UG, but the cost of this is the need of an intelligent switch at the PCC to measure voltage for both sides of the switch, which is not always easily accessible. Also if there are more than one connection point between the MG and the UG, at every such point an intelligent switch is needed. The next problem is expensive dedicated communication. The last thing is not considered in most of the proposed techniques. The connection could have a random latency, a drop of information or could be damaged.

The proposed strategy removes dependence on the measurements from the PCC. There is no requirement to have any extra equipment at the PCC. The proposed devices can be added in any place of the UG and the MG. An SDS device needs to be attached to the UG and an SDC to the MG, and can be connected close to the DG or MG controller. Even in the case of more than one open switch between the MG and the UG, the two can still be synchronized.

For connection between the proposed devices an Ethernet connection was used. This type of connection is less expensive and easy to access. Additionally, this type of connection is decentralized, which results in its better reliability. Between any two points in the Ethernet there are many possible routes. If there is any damage along one route, another route can be used in order to ensure connection. It is flexible and can be achieved both by wire and in a wireless fashion. Moreover, long distances are not a problem. Ethernet connection can be established by different media:

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mobile, Wi-Fi, fiber, 4G, 5G, or public infrastructure. The devices required for it are easily and widely available, and thus less expensive to use.

The proposed solution uses inexpensive, easily accessible, general purpose microcontrollers. Also if distributed control is used, this algorithm can be easily added to the inverter control algorithm, which makes a solution cheaper and easier to integrate.

Introducing the concept of a database to calculate voltage difference adds the possibility of providing a synchronization strategy that is resistant to random delays of this type of connection.

The proposed devices can work in parallel. This introduces the possibility of using many proposed synchronization devices to remove a single point of failure.

Simulation of the proposed strategy shows that this type of communication can be used to synchronize the MG with the UG. Synchronization is very fast and precise. Final phase angle error is close to 1 degree, which is almost ideal synchronization.

The solution works as well as the conventional solution with measurements at the PCC and with a dedicated connection.

Initial experimental results provide information that the solution works correctly even with the use of public infrastructure with random delays around 25 ms. After 1 second from synchronization start, the MG is within the limits and is ready to be connected to the UG.

In the future, the proposed solution will be investigated to use with other connection methods like 4G, 5G, CAN-bus and others. Also, the use of precision time protocol will be investigated to remove dependence on the GPS signal and use only an Ethernet connection. As the solution can work in multiple device scenarios, research on its use in mesh networks will also be done.

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MATEUSZ LITWIN received his B.S. and M.S. degrees in Electrical engineering from the Lublin University of Technology, Lublin, in 2012 and 2014 respectively. He is currently pursuing a Ph.D. degree in electrical engineering at the Lublin University of Technology, Lublin, Poland.

His research interests include the development of a remote synchronization strategy for future smart grids.

DARIUSZ ZIELIŃSKI (M'15) received the Ph. D. degree in Electrical Engineering from the Lublin University of Technology in 2017.

His research covers power electronics, grid-tied converters, microgrids and energy storages. His most significant works focus on control algorithms for multi-channel power converters, bidirectional power converters, hybrid energy storage systems, grid synchronization, and island mode detection methods.

K. Gopakumar (M'94-SM'96-F'11) received the B.E., M.Sc. (Engg.), and Ph.D. degrees in electrical engineering from the Indian Institute of Science, Bangalore, India.

He was with the Indian Space Research Organization, Bangalore, India from 1984 to 1987. He currently holds the position of professor at the Department of Electronics System Engineering, Indian Institute of Science. Dr. Gopakumar is a Fellow of IEEE, IETE India and INAE. He was a Co-Editor in Chief of IEEE Transaction on Industrial Electronics and now a Distinguished Lecturer of IEEE Industrial Electronics Society(IES). He is also the recipient of the IEEE IE Eugene Mittelmann award in 2019. His research interests include PWM converters and high power drives.