Approach to self-synchronization of a group of static power converters

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ABSTRACT

This study examines the control and synchronization of an orderly connected network of three-phase bidirectional power converters, serving as the grid interface for an energy storage system. The primary objective is to ensure stable operation under single-phase and non-symmetrical three-phase grid conditions. The control employs independent phase voltage regulation for compatibility. To achieve seamless coordination of an unlimited group of converters, the paper proposes a synchronization method based on a modified Kuramoto model. This method is designed to be compatible with independent phase control during asymmetric grid states. The proposed approach utilizes a structured connection graph, defined by phase shift magnitude, to synchronize the converter group. A brief overview of the tools for synchronizing oscillator groups is provided. A computer model was developed to study the operating modes of this converter class under both symmetrical and asymmetrical loads. Simulation studies confirmed the viability of the synchronization method. Furthermore, the research results were successfully applied in the design and implementation of a physical 10 kW grid - connected uninterruptible power supply prototype, demonstrating practical feasibility.

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1. INTRODUCTION

The concept of small autonomous networks, or microgrids, is actively developing in modern energy systems. This is due to the fact that in remote areas away from densely populated regions, the demand for electricity remains, but it is not always possible [1]-[6] or economically feasible to establish and maintain a transmission line to the nearest large power source. Such areas include mineral resource sites, medium and small inhabited islands in the oceans, and others. Another challenge is the integration of alternative energy sources, which allows for minimizing or eliminating the need for fuel delivery to rural areas.

To achieve normal functioning within the microgrid approach, it is necessary to use energy storage for balancing energy flows inside grid. As the grid capacity grows, the power of the energy storage system must also increase. A direct approach to increase storage power is to use a more powerful converter. It is a simple classic solution but has some disadvantages: lower efficiency under small loads and a large nomenclature of power converters for different power levels. Parallel connection of similar power converters is more complicated solution, but allows to use single converter for any power and increases efficiency by disabling unused converters. But the parallel approach requires to ensure stable synchronization of many power converters within a single network [7]. There are two main approaches [8] to synchronize power converter with the grid: grid forming [9], [10] and grid following [11], [12]. Grid following control is simplest solution but it is incompatible with such low inertia grids as microgrids [12], [13] due inertia reduction and grid following inverters also can't operate without any grid forming source. One of the possible solutions for grid forming control is virtual oscillator control [14]. Actual works [15]-[17] assume that direct injection of near oscillator output is enough to ensure synchronization. This article aims to define more correct conditions to synchronization in a group of oscillator-based power converters.

The subject of the article is the process of synchronizing a group of converters. This task is necessary for the coordinated operation of converters within a common network when the power and energy of a single converter are insufficient. The paper proposes a method for synchronizing a group of converters based on the phenomenon of self-synchronization of coupled oscillators. The method is based on the description of coupled Kuramoto oscillators [18], which is a simplified version of the description proposed by Winfree [19], [20] in 1967, as well as the structured graph proposed and studied by Wiley [21]. However, the proposed description introduces several changes that simplify the analysis but make the description highly specialized.

Section 2 provides a mathematical description of the self-synchronization method and the steps to achieve it. Section 3 implements the proposed method for synchronizing a group of three-phase inverters with an isolated neutral operating on a common load. The proposed synchronization algorithm is also adapted to the converter with independent phase synchronization for operation under asymmetrical network conditions discussed in the previous research.

2. METHOD FOR SELF-SYNCHRONIZATION OF A GROUP OF CONVERTERS

The study utilizes the phenomenon of self-synchronization to achieve synchronization of converters. Self-synchronization [22] occurs when several artificially created or natural objects (hereafter referred to as nodes), which, in the absence of interaction, perform oscillatory or rotational movements with different frequencies (angular velocities) and/or phases, begin to move with identical, multiple, or rationally related frequencies (angular velocities) upon the imposition of even weak connections. This results in the establishment of certain phase relationships between the oscillations (rotations).

A significant step towards utilizing self-synchronization was Winfree's description of a system of coupled oscillators [23], which described the circadian rhythms of plants and animals.

$$\dot{\theta}_i = \omega_i + \left[\frac{\varepsilon}{N}\sum_{j=1}^{N} P(\theta_j)\right] R(\theta_i), i = 1, \dots, N \quad (1)$$

Where θ_i – the phase of node i, ω_i – the intrinsic oscillation frequency of the node, P and R – periodic functions with a period of 2π that characterize the sensitivity and mutual influences of oscillators on each other, N – the number of elements (nodes), and $\varepsilon > 0$ – the common coupling parameter.

Kuramoto [21], in turn, simplified Winfree's model and derived analytical solutions for it, significantly increasing interest in the self-synchronization phenomenon.

$$\dot{\theta}_i = \omega_i + \varepsilon\frac{K}{N}\sum_{j=1}^{N} \sin(\theta_j - \theta_i), i = 1, \dots, N \quad (2)$$

Where θ_i – the phase of node i, $\sin(\theta_j\text{-}\theta_i)$ – sinusoidal function that characterizes the connection between nodes, K – is the connectivity matrix, taking the value 1, if there is a connection and 0 if there is none, and 1/N – a scaling coefficient that ensures the system's limit as $N\rightarrow\infty$, ε – the common coupling parameter.

The principal differences between the Winfree and Kuramoto models lie in Kuramoto defining the coupling function as the sine of the phase difference between a pair of oscillators and separating the weight matrix to adjustment matrix and weight coefficient, thus greatly simplifying the analysis of oscillations. This simplification allowed the equations to be solved analytically and enabled the study of solutions [23] of coupled oscillator systems for oscillation stability and self-synchronization conditions. moreover, a graph structure [21] was proposed that guarantees synchronization of the entire system when the coupling coefficient exceeds a threshold value. The coupling coefficient is constant, and the K matrix only defines the graph's connectivity structure, which, for a network of six nodes, might look like (3).

$$K = \begin{bmatrix} 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 \end{bmatrix} \quad (3)$$

The weight of the connection is represented by a separate coefficient, denoted as ε. When visualizing the connectivity matrix K as a graph, the resulting diagram is shown in Figure 1 for different models: Figure 1(a) the model corresponding to the connectivity matrix (3) with bidirectional connections; Figure 1(b) the simplified model with unidirectional connections; Figure 1(c) the simplified model with synchronization to a reference oscillator.

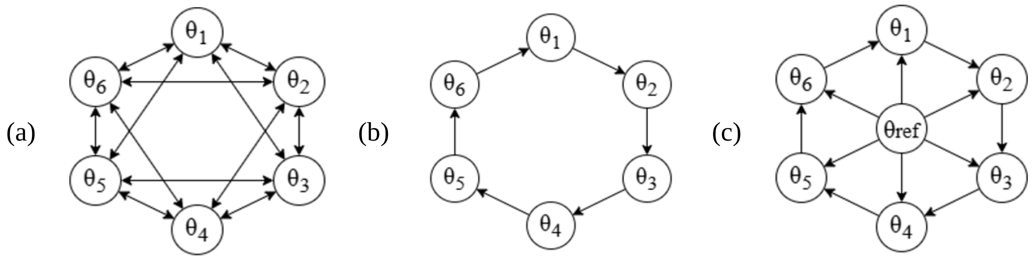

Figure 1. Connectivity graph of generalized oscillators: (a) complete model, (b) simplified model, and (c) simplified model with synchronization to a reference oscillator

Using a trigonometric function in the model description is justified because, generally, the phase of oscillators is not explicitly accessible. By observing only the output variables of the node, we obtain only periodic variables for establishing connections. However, the trigonometric function complicates the phase synchronization of oscillators. While guaranteed frequency alignment is achieved, the phases of oscillations do not align. In synchronizing artificial oscillators, adhering to the constraint of working only with harmonic signals is unnecessary, and we can introduce a direct phase coupling of the nodes. The system description, in this case, will look like (4).

$$\dot{\theta}_i = \omega_i + \varepsilon \frac{K}{N} \sum_{j=1}^{N} \left(\theta_j - \theta_i\right), i = 1, \dots, N \quad (4)$$

Structuring the connections remains unchanged. For the structure shown on Figure 1(a), with four connections per node and a constant frequency, the (4) takes the form of (5).

$$\dot{\theta}_i = \omega_i + \frac{\varepsilon}{N}\left(K_{ij}\left(\theta_j - \theta_i\right) + K_{il}(\theta_l - \theta_i) + K_{ip}\left(\theta_p - \theta_i\right) + K_{iq}\left(\theta_q - \theta_i\right)\right) \quad (5)$$

Where j, l, p and q - indexes of nodes with which there is a connection. The (5) can be rewritten in matrix form as (6).

$$\dot{\theta} = \omega + \frac{\varepsilon}{N}(-4E + K)\theta \quad (6)$$

Where E – the identity matrix. The reference motion of the system is described as (7).

$$\dot{\theta}_{ref} = \omega_{ref}, \quad (7)$$

Synchronization condition will look like (8).

$$\frac{\varepsilon}{N}(-4E + K)\theta = 0 \quad (8)$$

Condition (8) is achievable when the vector θ = 0, which is not permissible due to (6), or the matrix K−4E is singular, det(K) = 0 (the matrix K proposed in (3) ensures this condition). For the stability of such a system, it is necessary that all eigenvalues of the matrix K−4E lie in the left half-plane, except for one zero eigenvalue, which ensures the singularity of the matrix.

However, four connections per node still result in a complex network structure. For practical implementation, further simplification is required. This necessitates investigating the stability of structures with fewer connections. An example of a minimal structure that ensures graph connectivity is presented on depicted as in Figure 1(b). For that case, the matrix K is singular and looks like (9).

$$K = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \quad (9)$$

In (9), each row and column has only one non-zero component, which is not on the diagonal. The resulting system will look like (10).

$$\dot{\theta} = \omega + c(-E + K)\theta, \quad (10)$$

Where c – the coupling parameter obtained by replacing the value ε/N with a single coefficient, and K is described by form (9).

It should be noted that if the oscillation frequencies of the nodes differ, synchronization will not be achieved. This problem can be solved by adding an integral component. In this case, the system will become more complex as (11).

$$\begin{cases} \dot{\theta} = \omega + c_1(K - E)\theta + c_2 x; \\ \dot{x} = (K - E)\theta, \end{cases} \quad (11)$$

Where x – an artificial variable, the output of the I-controller. The resulting matrix of the differential equation system will look like (12).

$$A = \begin{bmatrix} c_1(K - E) & c_2 E \\ K - E & 0 \end{bmatrix} \quad (12)$$

The block matrix (12) with the choice of matrix K type (9) can ensure system stability with the appropriate choice of coefficients c1 and c2. The stability boundary can be defined as c2 = 2 c1. For c2 < 2c1 < 0, the system has stable movements; in such a case, the integrator ensures frequency synchronization. In the task of synchronizing oscillators with a reference oscillator, unidirectional coupling from the reference oscillator can be used. Implementation can be done as an additional parallel control loop with a P-controller. In the case of different frequencies, an integral component must also be introduced, which, with zero error, will provide constant corrective action. The structure of such a system is shown in Figure 1(c).

Since frequency correction is also introduced, the condition of equal frequencies of individual oscillators can be disregarded, as the final system exhibits astaticism with respect to the frequency of the external node. Thus, the proposed system has the following properties: i) minimal set of connections for each node, ii) each node is an autonomous oscillator, iii) initial deviations in phase and frequency are suppressed, iv) regulator parameters allow achieving the desired synchronization dynamics, but have limitations to ensure stability. All these conditions can be ensured in a network of frequency converters.

3. SYNCHRONIZATION OF A GROUP OF OSCILLATORS TO A COMMON LOAD

To ensure synchronization of the oscillators, it is first necessary to define the oscillator itself. Consider the operation of the network based on a simple linear oscillator as in (13).

$$\begin{cases} \dot{\theta} = \omega; \\ x = A\sin(\theta). \end{cases} \quad (13)$$

A group of six identical linear oscillators with introduced feedback on the phase error of the nearest oscillator and the phase error with the reference oscillator is shown in Figure 2. For the synchronization experiment, only the phase error with the nearest oscillator is used, and for synchronization with the reference, the phase error with the reference is also used. In Figure 2, the coupling coefficient ε is denoted as K.

For the analysis of the proposed method, a model of six oscillators was built, corresponding to the graph presented in Figure 1(b). The result of synchronization is shown in Figure 3. In the synchronization process, each oscillator has different intrinsic frequencies, randomly generated in the range of 45 to 55 Hz, and initial phases with a random distribution in the range of 0 to 2π. As seen in Figure 3, the phases of the oscillators converge and no further divergence occurs, allowing for seamless synchronization regardless of the switching dynamics of the equipment.

To verify the stability of the synchronized state, the synchronization time for a group of six nodes was checked. The value of ε varies from 0.1 to 15, with 10 experiments performed for each value. A PI controller is used for synchronization with the common reference, based on the phase error of the node with the reference, with coefficients of 1 and 25, respectively. The results with different conditions are shown in Figure 4. Figure 4(a) illustrate synchronization of nodes with a spread of 2π with the linear connection. Figure 4(b) illustrates dynamic of nodes for the frequency spread of ± 5% and a random initial phase from 0 to 2π and connected as in Kuramoto model. Figure 4(c) depicts nodes dynamic for an initial phase spread of π with the linear interconnections and equal oscillator frequencies. Points with a time of 30 s on the graphs correspond to a lack of phase synchronization.

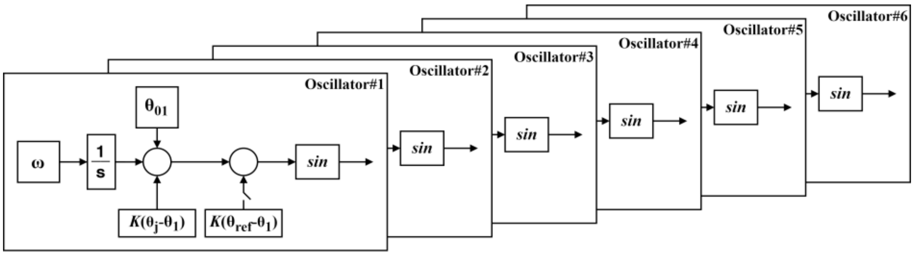

Figure 2. Structural model with oscillators

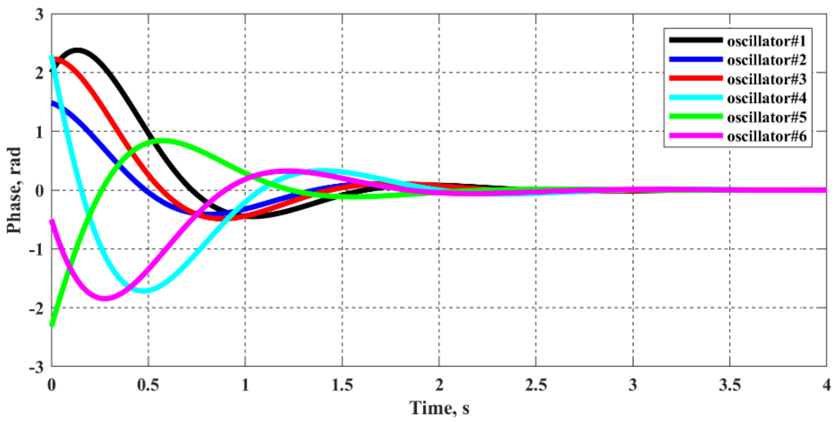

Figure 3. Phase discrepancy graph during the synchronization process of six oscillators to the reference

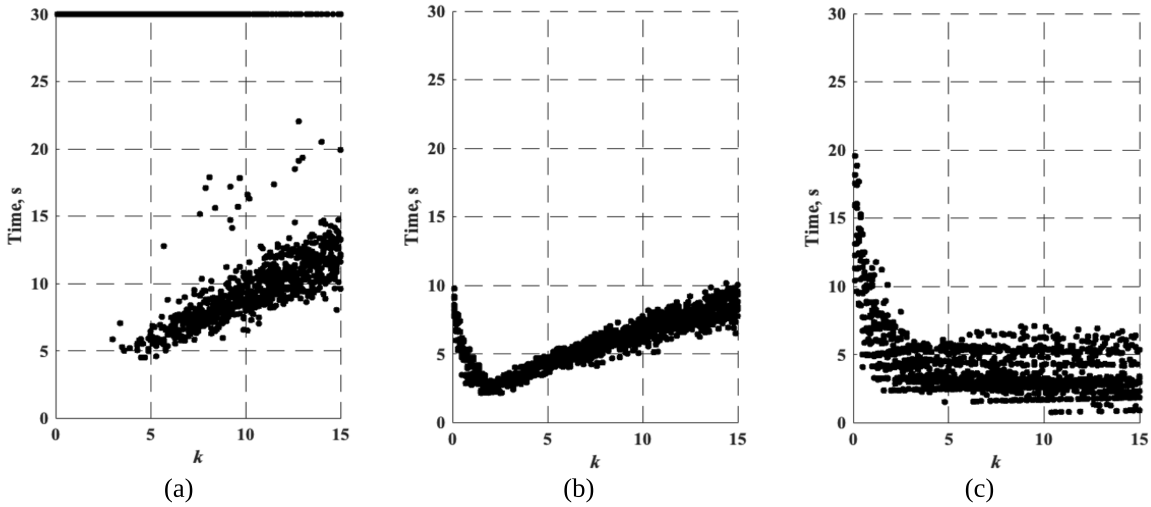

Figure 4. Stability verification of synchronization: (a) linear connections with initial phase spread 2π, (b) Kuramoto with frequency and phase spread, and (c) linear with same frequency and π phase spread

As shown in Figure 4(c), if the initial sign of the output variable is the same for all oscillators (the initial phase spread is from 0 to π), synchronization is achieved in finite time with a relative accuracy of 0.16 % for linear interconnections with fixed oscillator frequencies. However, with a larger spread and different frequencies as shown in Figure 4(a) in linear interconnected net, static states with equal frequency but different phases, distributed across stable levels of $2\pi/N$, where N is the number of oscillators, can arise. If the initial sign is different (the initial phase spread is from $-\pi$ to π), precise synchronization with an accuracy of 0.16 % does not occur in some cases. Even relaxing the criterion to 1%, unsynchronized oscillators remain. In the Kuramoto system, as shown in Figure 4(b), synchronization is ensured at any coupling coefficient value, with an optimal value at which synchronization occurs faster, and with further growth, the synchronization time only increases.

Thus, we have developed a tool for synchronizing many identical oscillators. Next, it is necessary to verify synchronization within static converters. To check this, a circuit consisting of six three-phase autonomous voltage inverters with an isolated neutral was studied, as shown in Figure 5. In it, a three-phase scalar pulse-width modulation (PWM) generator and a two-level inverter operating from a DC source were added to each oscillator.

Simulation results for a group of six inverters operating on a common load with oscillators setting the reference voltage as in (7) are shown in Figure 6. In the simulation, the DC link voltage was set to 530 V, the inverter output filter was purely inductive at 1 mH, and the load was an active-inductive combination of 0.1 mH and 3 Ohms. For illustration of the synchronization process, Figure 6 shows synchronous graphs from top to bottom: the current through the inverter phase during unsynchronized PWM operation and the reference signal of the PWM generators. The PWM frequencies for the inverters during unsynchronized modulation were set from 3 to 5.5 kHz with a step of 500 Hz. Unsynchronized PWM frequencies increase current ripple, but do not affect synchronization. At the beginning (up to ~0.1 s) synchronization occurs between the inverters until the phase difference is less than 10^{-5} radians. After reaching such a mismatch, the inverter is connected to the network.

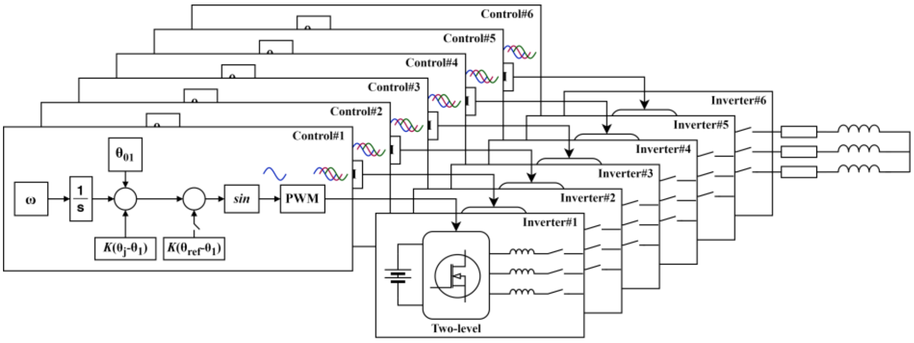

Figure 5. Structural diagram of the studied system

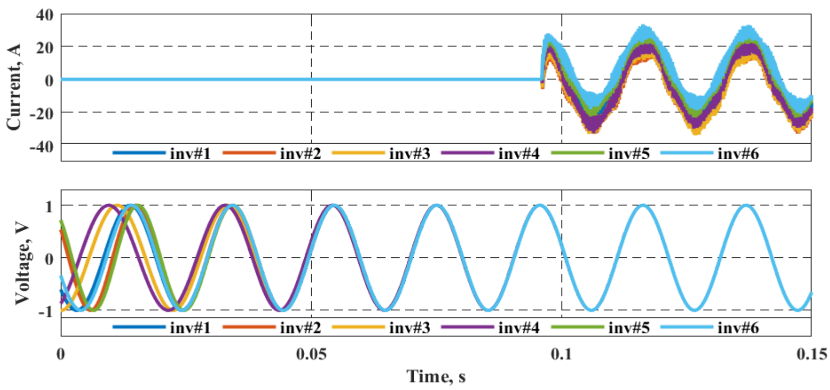

Figure 6. Simulation of inverter synchronization

Previously in [24], an uninterruptible power supply (UPS) was considered for operation in asymmetric AC networks, with a general scheme shown in Figure 7, similar to that in [25], [26]. The converter includes: battery energy storage, a bidirectional DC-DC converter with galvanic isolation (the main structures of such converters are considered, for example, in [27], [28]), a bidirectional AC-DC converter, and an L-filter.

Consider the synchronization system applied to the converter in [29]. The structural diagram of the control system, including the introduction of an additive synchronizing effect, is shown in Figure 8. The parameters of the converter control system are provided in Table 1. To integrate the proposed synchronization method, it is only necessary to modify the connection from the phase-locked loop (PLL), which sets the frequency for the reverse Clarke transformation for each phase, ensuring an additive component in the form of phase error with the neighboring converter and the reference. The simulation results of a group of six converters operating on a common load, with the electrical diagram corresponding to Figure 7 and the control algorithm corresponding to Figure 8, are shown in Figures 9 and 10.

As can be seen from Figures 9 and 10, the independent phase synchronization successfully achieved the task and did not interfere with the operation of the three-dimensional PWM formation algorithm. From 0 to 2.5 s, the inverters are connected to the network, but do not transmit power. At this time, synchronization occurs according to Figure 6, which takes about 0,1 s, the rest of the time, the inverters wait for connection to the load. At time 2.5 s, in Figure 9, inverters have been connected to the load with 20 uF parallel filtering capacitance. As we can see, there are no synchronization currents. At time 4 s, on Figure 10, nonsymmetrical load disturbance in phase B has been added. Voltage as we can see not affected, but phase B current vas changed to compensate load deviation. Synchronous state doesn't affect by disturbance.

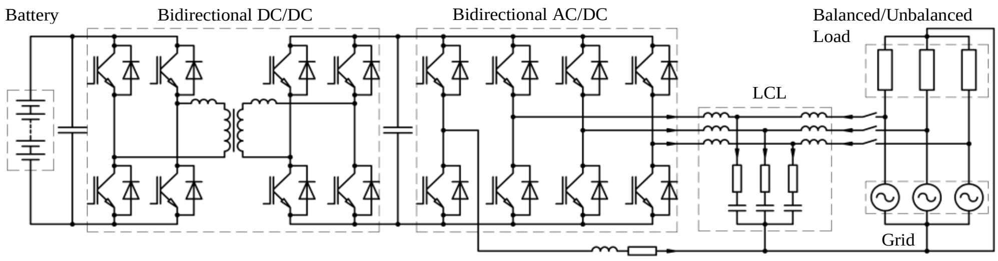

Figure 7. Electrical diagram of the power part of the energy storage system

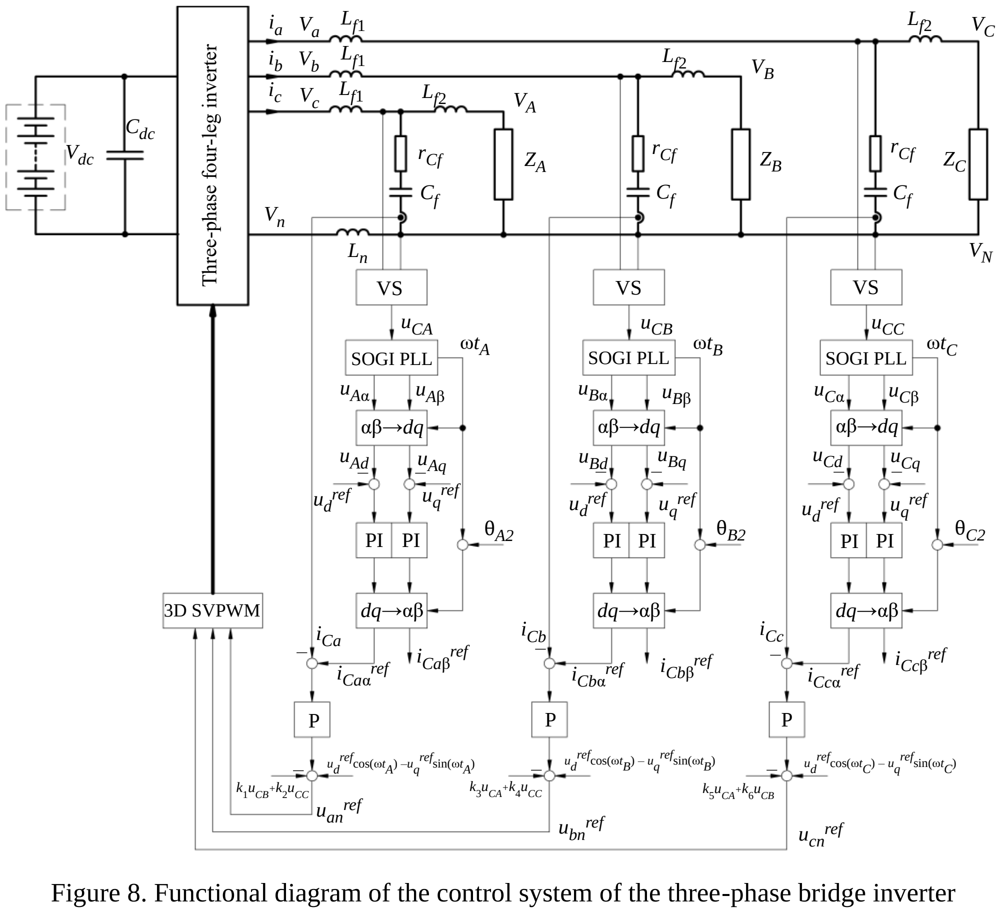

Figure 8. Functional diagram of the control system of the three-phase bridge inverter

Table 1. Parameters of the control system and simulation scheme for the UPS

Regulator	Parameters	Value and units
SOGI regulator	Proportional component, k	0.8
SOGI-PLL regulator	Proportional component, k_P	10
	Integral component, k_I	30
PI voltage regulator	Proportional component, k_{uP}	0.15
	Integral component, k_{uI}	50
	Saturation of the integral component	± 800
P current regulator	Proportional component, k_{iP}	1.25
Output L-filter	Inductive reactance grid side, L, uH	1000
	Resistance of the inductor on the inverter/grid side, R, mOhm	1
Battery	Nominal voltage, V	530 V

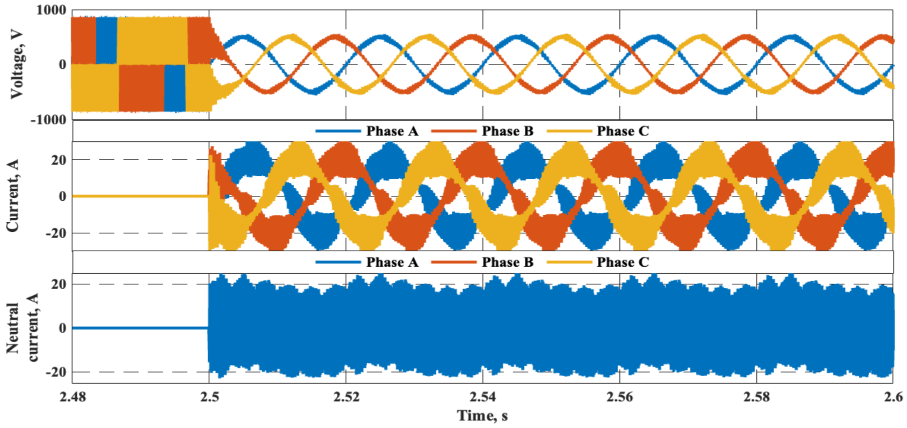

Figure 9. Currents of one of the converters during synchronization

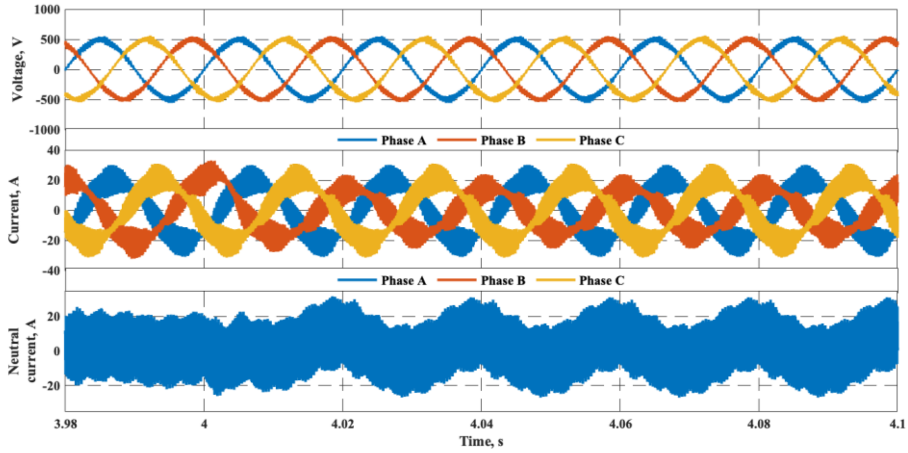

Figure 10. Currents of one of the converters during reduction of active load in phase B from 180 to 100 kW

4. RESULTS AND DISCUSSION

Several numerical experiments were conducted, demonstrating that synchronization occurs with any coupling parameter, but the higher the parameter, the faster the synchronization. On the other hand, a large value of the coupling parameter will lead to overshoot, so choosing the value is a separate task. The presented work shows that the linearized Kuramoto model allows synchronization of oscillating systems. However, it is only valid to perform such linearization when the phase deviation is less than $\pi/6$. Also, this approach to synchronization is well-suited for implementation in virtual oscillator control methods, although it has limitations. With a large phase deviation in a group of oscillators, simply introducing the voltage of the nearest node is not enough. An experiment with a phase deviation in the range of 2π showed that the order parameter may not stabilize in synchronized states. The proposed synchronization method illustrates why converters with virtual oscillator control are synchronizing and why they may not. In the context of converter technology, the use of a PLL to recover the phase of the grid or neighboring converter is standard. The introduced simplification is, first, equivalent for small deviations since for x < π/6, sin(x) = x. Second, for converter technology, determining the phase of a signal is a solvable task and is used in most control systems.

This article did not address issues of load distribution and reactive power generation these are future works that will be based on the virtual oscillator control technique. A continuation of the work involves the elimination of coordinate transformation and a shift towards artificial oscillators and resonant regulators to create distributed control of modular multilevel battery energy storage system in a nonsymmetrical grid. Further development of the proposed work includes several tasks: i) Creating nonlinear feedback compatible with common nonlinear Kuramoto model based on second order generalized integrator to ensure synchronization with any starting phase deviation; ii) Modifying dispatching to disabling and enabling converter in group and compensated phase load deviation; and iii) Making independent phase control based on second order generalized integrator with frequency adaptation to operate in nonsymmetrical grid states.

The presented work shows that the linearized Kuramoto model allows synchronization of oscillating systems. However, it is only valid to perform such linearization when the phase deviation is less than π/6. Also, this approach to synchronization is well suited for implementation in virtual oscillator control methods, although it has limitations. With a large phase deviation in a group of oscillators, simply introducing the voltage of the nearest node is not enough. An experiment with a phase deviation in the range of 2π showed that the order parameter may not stabilize in synchronized states.

5. CONCLUSION

The study investigates and implements synchronization algorithms for a group of oscillators among themselves and with an external grid, using computer models. The synchronization process in a symmetrical grid is demonstrated with six inverters operating on a common load. For an asymmetrical grid, the synchronization of four three-phase four-wire converters operating in inverter mode on a common load is considered. One of the significant challenges in integrating sources, storage units, and consumers into a unified grid within a microgrid is the synchronization problem, which currently requires a complex synchronization procedure. Therefore, the study proposes an approach to synchronization that ensures the self-synchronization of devices before they are connected to the grid. The research results have been used to design a prototype of UPS based on a grid-forming inverter with a nominal apparent power of 10 kVA.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that no conflicts of interest regarding finances, ideology, scientific content or anything else arose during the work on this article.

DATA AVAILABILITY

The original model considered in the study is available on request from the corresponding author.

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