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CONTROL IN TECHNICAL SYSTEMS

Prospects of Using Class D Amplifiers in Microgrid Systems with Nonlinear Loads

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Abstract—Modern methods for mitigating nonlinear inverter voltage distortions in low-power microgrid systems are considered: proportional-resonant/multi-resonant controllers, virtual impedance and droop control, dual voltage inverters, and self-oscillating class D amplifiers. The study outlines the fundamental properties and the principle of parasitic harmonic mitigation. Special attention is paid to the number of controllers required to implement each of the methods, the effectiveness of nonlinear distortion mitigation through the study of the number of harmonics, and the reduction of the total harmonic distortion with and without the application of each method. The compatibility of each method with the output power controller is also analyzed. The benefits and drawbacks of existing methods are analyzed, as well as the prospects of using a self-oscillating class D amplifier for the control of nonlinear distortions in microgrid systems.

Keywords: microgrid, voltage source inverter, total harmonic distortion, power quality, nonlinear load

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1. INTRODUCTION

Nowadays, research in the field of off-grid power systems and the additional storage and delivery of electrical energy (EE) to the AC grid is actively developing. A system consisting of an EE source and a converter, designed for parallel connection with another similar system or with a power grid, is called a microgrid system. AC systems are preferred for power distribution. At the core of an AC microgrid is a voltage-source inverter(VSI), which performs the conversion from direct current to alternating current (DC/AC conversion). In recent years, microgrid VSIs have developed significantly. Existing synchronization methods [1, 2] allow not only several inverters to operate parallel to each other but also to connect to a common power grid to supply electricity, as well as to control the output power using droop control technology [3]. However, in isolated systems consisting of several sources and inverters, as well as in low-power grids disconnected from large-scale power grids, the challenge of mitigating nonlinear distortion is critical. Connecting a load with a high nonlinearity index can lead to a severe distortion of the grid voltage. The nonlinearity index—total harmonic distortion (THD)—is regulated by GOST [4] and must be no more than 8%. Violation of this power quality indicator can lead to both the failure of connected electrical equipment and the incorrect operation of the phase-locked loop (PLL), resulting in the desynchronization of the VSI.

2. MODERN MICROGRID VSI

2.1. Isolated VSI

Before proceeding to the comparison of methods for mitigating nonlinear distortions, it is necessary to describe the system under study to which these methods are applied. A voltage source inverter, by definition [9], is a converter that transitions direct current to alternating current [10]. Modern DC/AC converters are based on full-bridge or half-bridge circuits [11]. Fundamentally, the control of full-bridge and half-bridge circuits has no significant differences. The main difference between these circuits is the number of power switches; transistors are most often used for this purpose. Due to this difference, restrictions are imposed on the inverter regarding the maximum DC voltage and current through each arm of the converter. In microgrid inverters, half-bridge circuits are more frequently used, requiring a higher input voltage, since working with alternative EE sources, such as wind or solar energy, often involves high DC voltages. Figure 1 shows a classic diagram of a half-bridge converter and a control loop. For the correct operation of this circuit, at least one current controller is required [11] to form the reference signal and pulse-width modulation (PWM) supplied to the gates of the switches. In the general case, the functions f, g can be arbitrary nonlinear functions of its variables. In the classical case, these functions describe a sinusoidal signal:

$$i_{ref}(t) = I \sin(\omega t + \varphi_0).$$

The compensator is most often a proportional-integral (PI) controller. In the case of synchronizing inverters with other similar inverters or with the grid, the description of the AC system cannot be set arbitrarily; the sinusoidal signal must be synchronized with respect to what is observed in the grid.

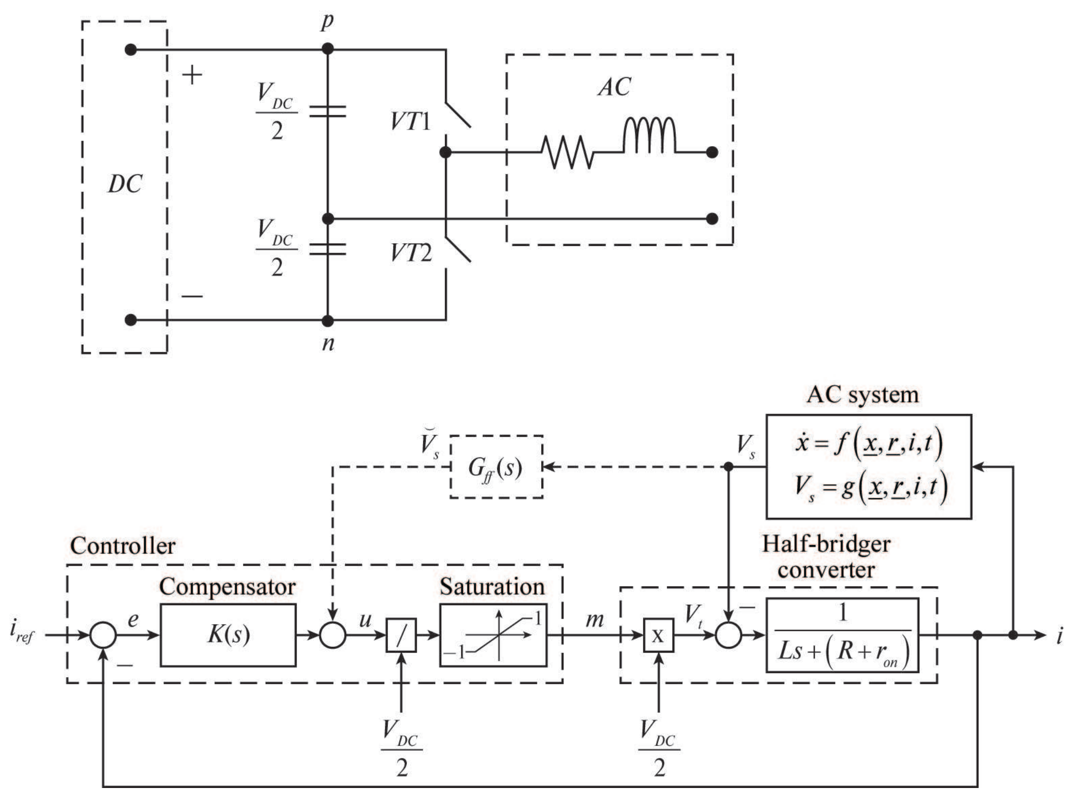

Fig. 1. Half-bridge converter.

2.2. Phase-Locked Loop Synchronization

The most widely used method for generating a reference signal from the available AC grid voltage is the phase-locked loop (PLL). The block diagram of the classic PLL method for a three-phase grid [1, 2] is shown in Fig. 2. It is important that the voltage is regulated in a rotating dq0 reference frame, the transition to which is carried out using Clarke and Park transformations [12]. The angle θ obtained as a result of the method's operation is the rotation angle of the grid's quadrature basis. Specifically, this angle is the phase angle of the first phase. For a single-phase grid, this method is also applicable; it is necessary to artificially create an orthogonal signal β lagging behind the original one by $\pi/2$ [6–8, 13]. One of the fastest methods is the SOGI (Second Order Generalized Integrator) PLL method [7], which uses a second-order integrator applied to the original signal. Thus, the phase angle obtained using the PLL method can be used for the inverse Park–Clarke transformation. Combined with the control method outlined in the previous section, the system provides the minimum required number of controllers for the parallel operation of a voltage source inverter and an arbitrary AC power grid; however, such a control method has a significant drawback. Despite the ability to control the output current of the inverter, the resulting control loop does not allow one to control the values of active and reactive output powers. To be able to accurately control the output power, a droop controller is added to the system.

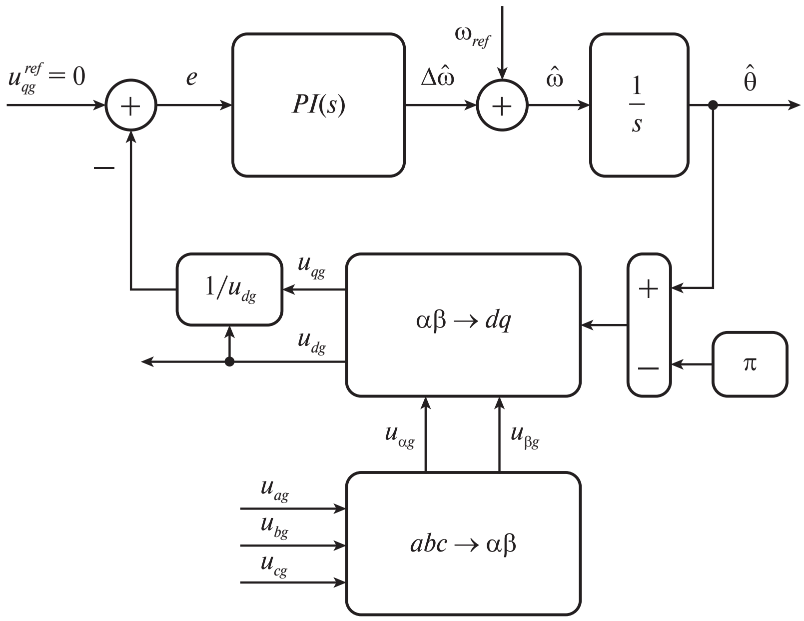

Fig. 2. PLL synchronization of a three-phase grid.

2.3. Droop Control

To control the active and reactive power, it is necessary to introduce at least two controllers that control the change in power. The classic droop control method can be written as follows:

$$f = f_0 - mP,$$
$$U = U_0 - nQ,$$

where f and U are the frequency and voltage values of the reference signal, respectively, and f_0 and U_0 are the voltage and frequency settings; in the case of a utility grid, $f_0 = 50$ Hz and $U_0 = 230$ V; m, n are the controller coefficients, and P, Q are the measured active and reactive

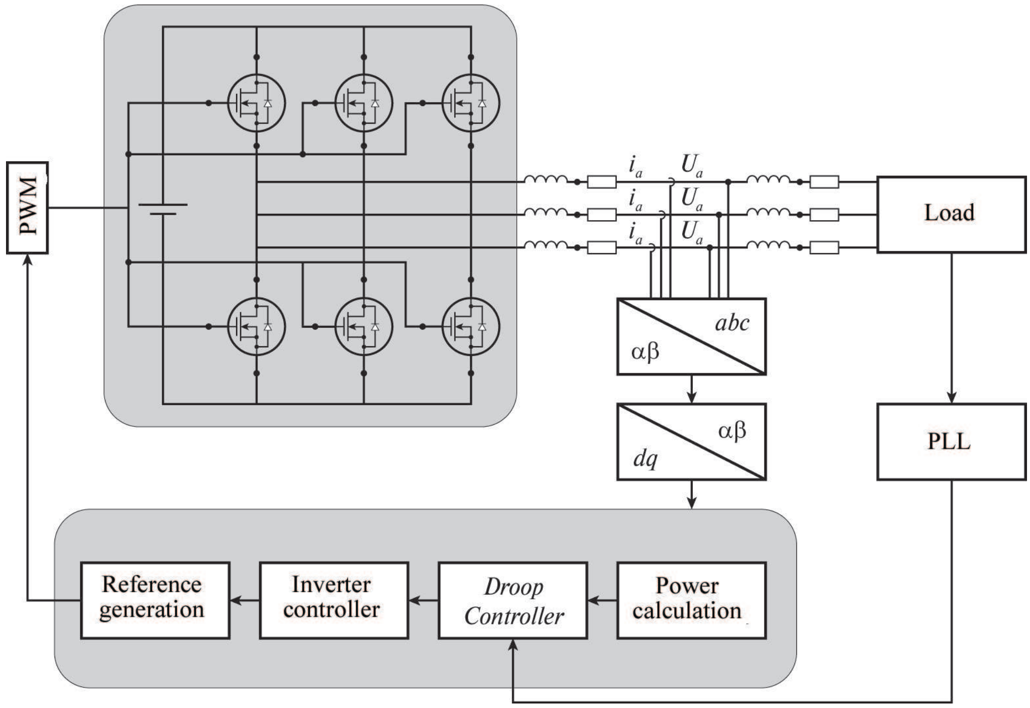

Fig. 3. Conventional control scheme of a microgrid voltage source inverter.

power. When operating in the $dq0$ basis, instantaneous power values are conveniently calculated using the equations:

$$P = V_d I_d + V_q I_q,$$
$$Q = V_q I_d - V_d I_q.$$

The block diagram for controlling the inverter using a PLL block and droop control is shown in Fig. 3. This control scheme has a total of at least four proportional or PI controllers. In [14–16], it is proposed to add or complicate droop controllers to improve transient characteristics and increase the accuracy of output power regulation. However, as part of the comparison of methods for mitigating nonlinear harmonics, additional droop controllers are omitted if the harmonic mitigation method does not suggest otherwise. Going forward, when comparing the number of controllers necessary to implement a particular method, the baseline will be the modified control scheme shown in Fig. 3.

3. METHODS FOR MITIGATING NONLINEAR DISTORTIONS

Before moving directly to the methods for mitigating nonlinear distortions in voltage source inverters, the following important definitions are introduced. A nonlinear load is any load whose current depends on the voltage nonlinearly. Parasitic or nonlinear harmonics are voltage components at frequencies different from the fundamental frequency; in the case of a utility grid, this means any voltage harmonics other than 50 Hz. To assess the level of nonlinear distortions, various metrics are used, such as: THD—the ratio of the root mean square (RMS) value of parasitic harmonics to the RMS of the fundamental; total rated current distortion (TRD)—calculated similarly to THD but for the load current; total demand distortion—the ratio of the RMS of parasitic current harmonics to the RMS value of the load current. These metrics are regulated by international standards IEEE 519 and IEEE 1547, as well as GOST 32144-2013 [4]. The voltage signal is the most sensitive regarding nonlinear distortions, as severe distortions can lead to incorrect PLL operation, which in turn can cause the inverter to fail.

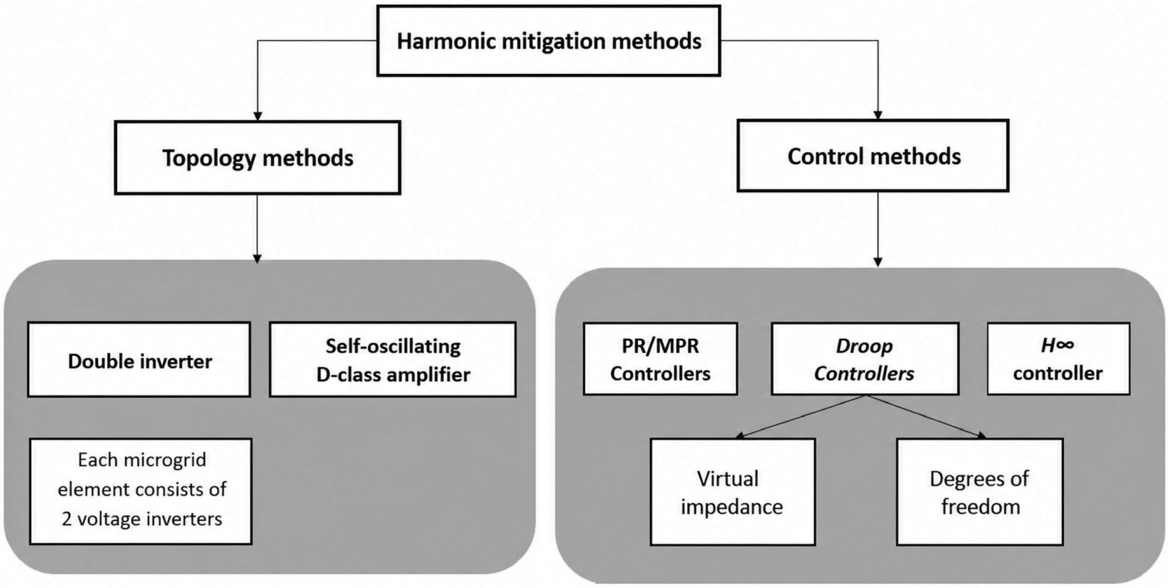

Fig. 4. Categorization of harmonic mitigation algorithms.

Methods for mitigating nonlinear harmonics can be roughly divided into two main categories: controller-based and topological. Controller-based methods include those based on changing the system's control loop, thereby mitigating voltage nonlinearities. These methods can be further divided into two main categories: methods using resonant controllers (introducing proportional resonant or multiresonant (PR or MPR) controllers into the control loop [17–21]), and methods modifying the droop controller (by introducing additional controllers and modifying the droop controller, an improvement in the voltage signal was achieved [14, 22–27]). Separately, it is worth mentioning the H∞ controller, which also allows mitigating nonlinear distortions, although currently, this controller is practically not used. Topological methods refer to modifying the inverter topology, moving away from the classical half-bridge circuit. Thus, in [28], a circuit with counter-connection of two inverters is used for harmonic mitigation. In [5, 29], a self-oscillating class D amplifier is used as an inverter; however, this method is poorly studied in the field of microgrids. A conditional breakdown of modern methods is presented in Fig. 4.

3.1. PR and MPR Controllers

One of the most common methods for improving power quality in microgrid inverters is the use of a PR controller instead of a classic PI current controller [17–19]. Such a controller has infinite gain when the input signal has a resonant frequency. In real systems, achieving such a transfer function is impossible; besides, in a real system, the signal frequency will slightly differ from the carrier frequency due to the inevitable presence of higher-order harmonics. To describe a real PR controller, a damping frequency $\omega_c \ll \omega_0$ is introduced, where ω_0 is the frequency limiting the gain near the resonant frequency. The transfer function of such a controller is written as follows:

$$W(s) = K_p + \frac{2K_r\omega_c s}{s^2 + \omega_0^2}.$$

In [18, 19, 21], the process of designing an inverter with a PR controller to improve power quality is described in detail. Figure 5 shows the block diagram for controlling such an inverter. In [30], a comparative analysis of the operation of an inverter with PI and PR controllers in three-phase systems with an unbalanced load was carried out, and the THD index was analyzed. An unbalanced

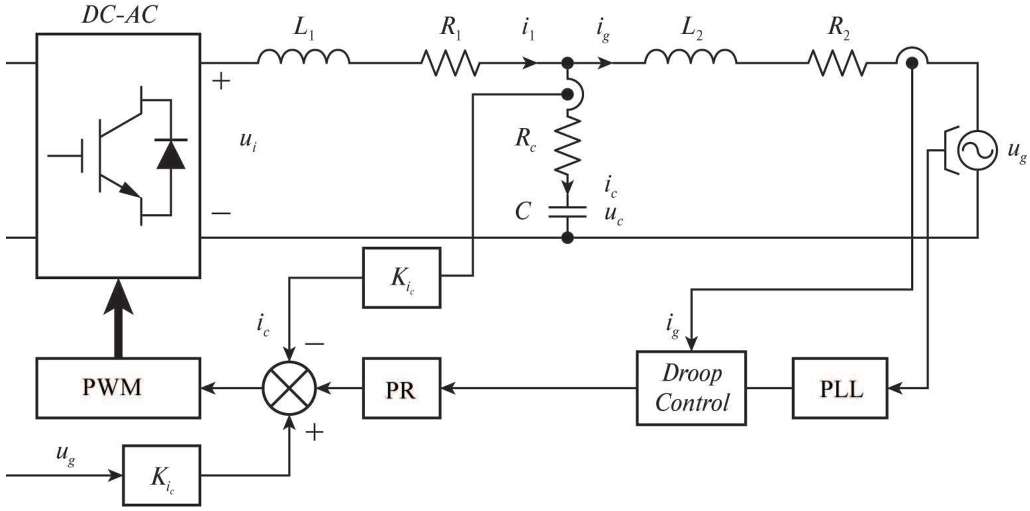

Fig. 5. Block diagram of inverter control with a PR controller.

load can introduce small nonlinear distortions into the voltage signal, which are well mitigated by a PR controller added to the control scheme. However, with a high degree of distortion, [31, 32] propose using a MPR controller. It proposes to add additional components operating at $n\omega_0$ to the transfer function of a simple PR controller, where n is the number of the harmonic introducing strong nonlinear distortions. Thus, the additional component of the controller has a higher gain the higher the amplitude of the nth harmonic. The transfer function of such a controller is described by the equation:

$$W(s) = K + \frac{2K_r\omega_c s}{s^2 + \omega_0^2} + \sum_n \frac{2K_{r,n}\omega_c s}{s^2 + 2\omega_c s + n\omega_0}.$$

The equation uses a sum over harmonics that are multiples of the carrier; in the general case, the frequency of the additional resonance can be an arbitrary frequency introducing distortions into the signal; however, in electrical systems, parasitic harmonics are multiples of the fundamental, which simplifies the application of the controller. The advantages and disadvantages of these controllers are evaluated below.

Advantages:

- PR controller mitigates small distortions without adding and tuning additional controllers.
- MPR controller allows for nonlinear harmonic mitigation even for severe distortions.
- Both controllers show good results when working with an unbalanced load.
- The methods are widely studied in various scientific papers; there are detailed guidelines for designing microgrid inverters using PR and MPR controllers.

Limitations:

- When mitigation is required, the number of resonant components increases significantly, each of which requires additional tuning. In [20, 22], a method for automatic tuning is proposed; however, tuning is still necessary.
- With a large number of resonant controller components, the computational complexity of the system increases significantly. In the case of using automatic coefficient tuning, the computational power required increases multiplicatively.

3.2. Droop Controller-Based Methods

The second large group of controller-based compensators can be considered methods for mitigating nonlinear harmonics based on the modification of the droop controller. They can be roughly divided into the virtual impedance modification method [24, 26] and the multiple degrees of freedom controller method [23].

The study examines methods using virtual impedance [26]. Initially, this method was used to improve the stability indicators of microgrid systems connecting reactive loads. The essence of the method is the artificial formation of impedance in the system and adding it to the result of the droop control module. This allows controlling the output power of the system more precisely, and according to [14], also increases system stability in the event of incorrect tuning of the droop coefficients. Figure 6 shows the basic scheme for constructing a virtual impedance. In [25], it is proposed to use two droop controllers (before and after the addition of virtual impedance), as well as additional controllers that monitor the magnitude of the generated virtual impedance. As a result of the system operating on a rectifier load with an RC circuit, the TRD indicator was reduced by 22.70%. In [26], a two-stage virtual impedance generation scheme is proposed, consisting of a classic virtual impedance shaper, to the input of which the load current is supplied. The second part of the shaper is an active impedance component shaper based on the inverter output current. The study also applied PR current and voltage controllers, as a result of which the system THD decreases by 12.5%. The fastest mitigation method is proposed in [27]. Current and voltage controllers, when using virtual impedance in this work, use a matrix of separated harmonics; each element of the proposed matrix carries information about a specific harmonic, as a function of the other harmonics of the signal and the amplitude of this harmonic. As a result of the experiments conducted in this study, the high response speed of such a system when connecting a nonlinear load was revealed. The THD index in this case decreases to 2%. The advantages and limitations of using these methods are summarized below.

Advantages:

- Allows mitigating strong nonlinear distortions; with certain tuning, it also allows controlling the THD value of the output voltage.
- Based on the droop control method, which guarantees the ability to control the inverter's output power.

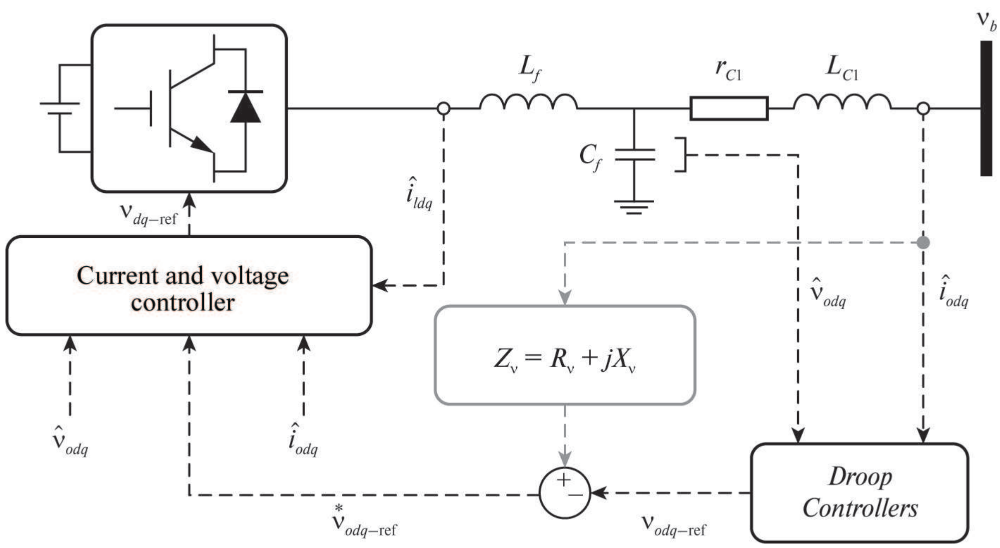

Fig. 6. Block diagram of virtual impedance controllers.

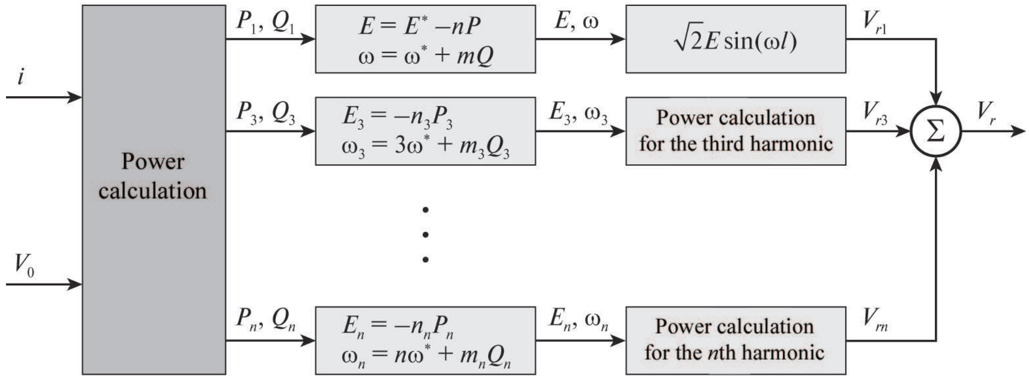

Fig. 7. Droop controller with multiple degrees of freedom.

- The methods are widely studied in various scientific papers.

Limitations:

- To use this method, it is necessary to introduce at least three additional controllers; applying modern methods based on virtual impedance control also requires the use of additional voltage control loops or droop controllers.
- The use of method [27] requires extremely complex computational operations, which significantly increases the need for computing power of the control processor.

The discussion now shifts to the droop controller method with multiple degrees of freedom [23]. The paper proposes dividing the classical method into several constituent parts, each of which will be responsible for a specific harmonic. The controller for each harmonic can be written as follows:

$$E_i = -n_i P_i,$$
$$\omega_i = n\omega - m_i Q_i,$$

where n_i, m_i are the controller coefficients for each harmonic, and P_i, Q_i are the power of the ith harmonic. The structural diagram of this method is presented in Fig. 7. In this case, to calculate the power of the ith harmonic, the method of separate power calculation [33] is used. The result of the controller's operation is the voltage setting of the inverter taking into account the mitigation of parasitic harmonics. The effectiveness of this method is shown when operating isolated microgrid systems; however, this method has both advantages and significant limitations.

Advantages:

- Allows mitigating arbitrary nonlinear distortions caused by various nonlinear loads.
- Allows mitigating individual harmonics by introducing only one additional calculation link.
- Based on the droop control method, which allows for highly accurate control of the inverter's output power.

Limitations:

- To mitigate a large number of parasitic harmonics, it requires additional tuning of the controllers for each harmonic, which significantly increases computing power requirements.
- Calculating active and reactive power for each individual harmonic requires large computing power.
- Complex tuning of controllers for each of the harmonics.
- The method is poorly researched, which can lead to difficulties in system design.

3.3. H∞ controller

In [34], an inverter control method based on the use of an H∞ current controller and an internal low-pass filter is proposed. The proposed strategy consists of a cascaded current, voltage controller and control loops that are created on H∞ controllers. Modeling of both isolated network operation and connection to a utility grid was carried out. The proposed methods have a number of advantages and limitations.

Advantages:

- The proposed method copes with small nonlinear grid distortions.
- The controller provides a smooth transition from autonomous operation to grid-connected operation.
- The controller does not require high computing power; tuning the controller boils down to a convex problem.

Limitations:

- The application of this method is poorly researched; works are based on mathematical modeling.
- The H∞ controller is difficult to implement in discrete systems.
- The possibility of connecting droop control in the proposed system has not been investigated.

3.4. Dual VSI

Dual voltage inverter The discussion now shifts to topological methods for parasitic harmonic control. Of special attention is the method proposed in [28]. The method is based on changing the inverter topology. Thus, rather than a classic half-bridge circuit, two voltage source inverters are used. The first main inverter provides the payload and is synchronized using the PLL method. The additional inverter operates in opposition to the main one and creates a signal that, when added

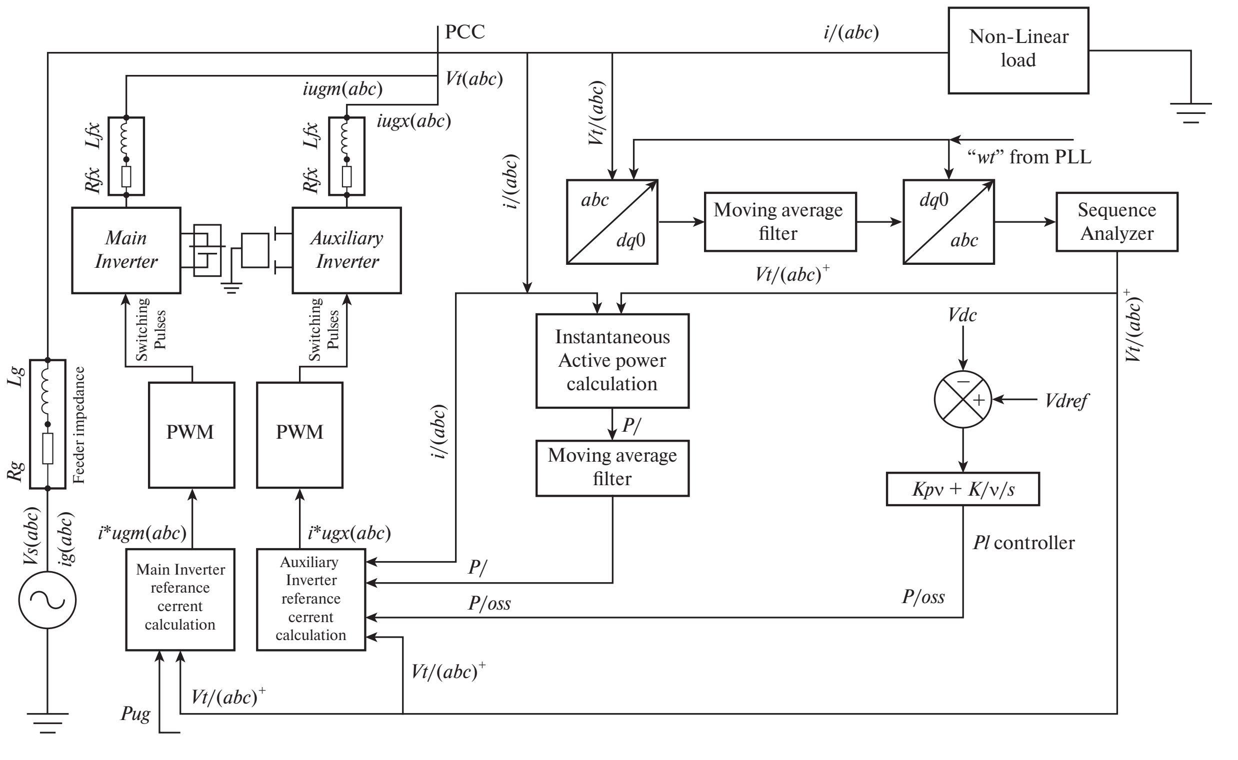

Fig. 8. Control loop of a dual voltage source inverter.

to the signal from the main inverter, provides a common output signal with minimized distortions. For the operation of the additional inverter, in addition to the usual control circuit setting the reference voltage and mitigating nonlinear distortions, it is required to account for ohmic losses at the inverter output; for this, an additional PI controller is introduced into the control loop, to the input of which the difference between the target inverter voltage and the constant DC bus voltage is fed. The complete control circuit for the proposed dual inverter is presented in Fig. 8. According to the experiments conducted in the work, the proposed microgrid inverter copes excellently with mitigating nonlinear harmonic components and provides a decrease in THD by more than 8 times. The advantages of such an inverter:

Advantages:

- High output voltage stability provided by the compensating additional inverter.
- Low need for computational load, since this inverter requires the introduction of an additional five controllers to control the additional inverter.
- The ability to mitigate arbitrary harmonics by setting a special reference signal for the additional inverter.

Limitations:

- The need to design an additional voltage inverter based on a half-bridge circuit, as well as an additional output filter.
- Increased power consumption caused by ohmic losses at the output of the additional inverter.
- High system cost due to the use of two inverters.

3.5. Self-Oscillating Class D Amplifier

One of the methods for mitigating nonlinear distortions at the inverter output is based on the use of a self-oscillating class D amplifier [9]. Such an amplifier circuit has not previously been used in microgrid systems. This amplifier performed well in acoustic systems. This topology copes excellently with suppressing interference when amplifying an acoustic signal [35]. In [29], a method for using such an inverter as a power microgrid inverter is proposed, and in [5], the operation of a class-D inverter as part of both an isolated and a grid connected microgrid system is modeled. An analysis of operation on a nonlinear rectifier load and a comparison with the classic inverter described in Section 2 of this article was carried out.

3.5.1. Amplifier Control

The control system of the self-oscillating class D amplifier is examined in greater detail below. Figure 9 presents the electrical and structural diagrams of the auto-generating class D amplifier in operational form. Here the operators W_1–W_8 are frequency response functions of the circuit consisting of passive elements, and $W_n(A)$ is the frequency response function of the series-connected comparator D_2 and half-bridge converter D_3, where A is the auto-generation voltage magnitude. In this system, the condition for self-oscillations is satisfying the harmonic balance equation for the frequency response functions of the power switch $W_n(A)$ and the linear part of the system $W_t(2\pi jf)$, i.e., the presence of a purely imaginary root of the linearized system:

$$W_n(A)W_t(2\pi jf) = -1. \tag{1}$$

As a result of solving equation (1), obtained in [29], the auto-generation condition is met at a frequency $f_0 = 92.5$ kHz. The transfer functions of the amplifier are expressed as follows:

$$W_{fb} = W_5W_6W_7W_n(-1), \tag{2}$$

$$W_d = \frac{W_{fb}W_4}{1 + W_{fb}W_8}. \tag{3}$$

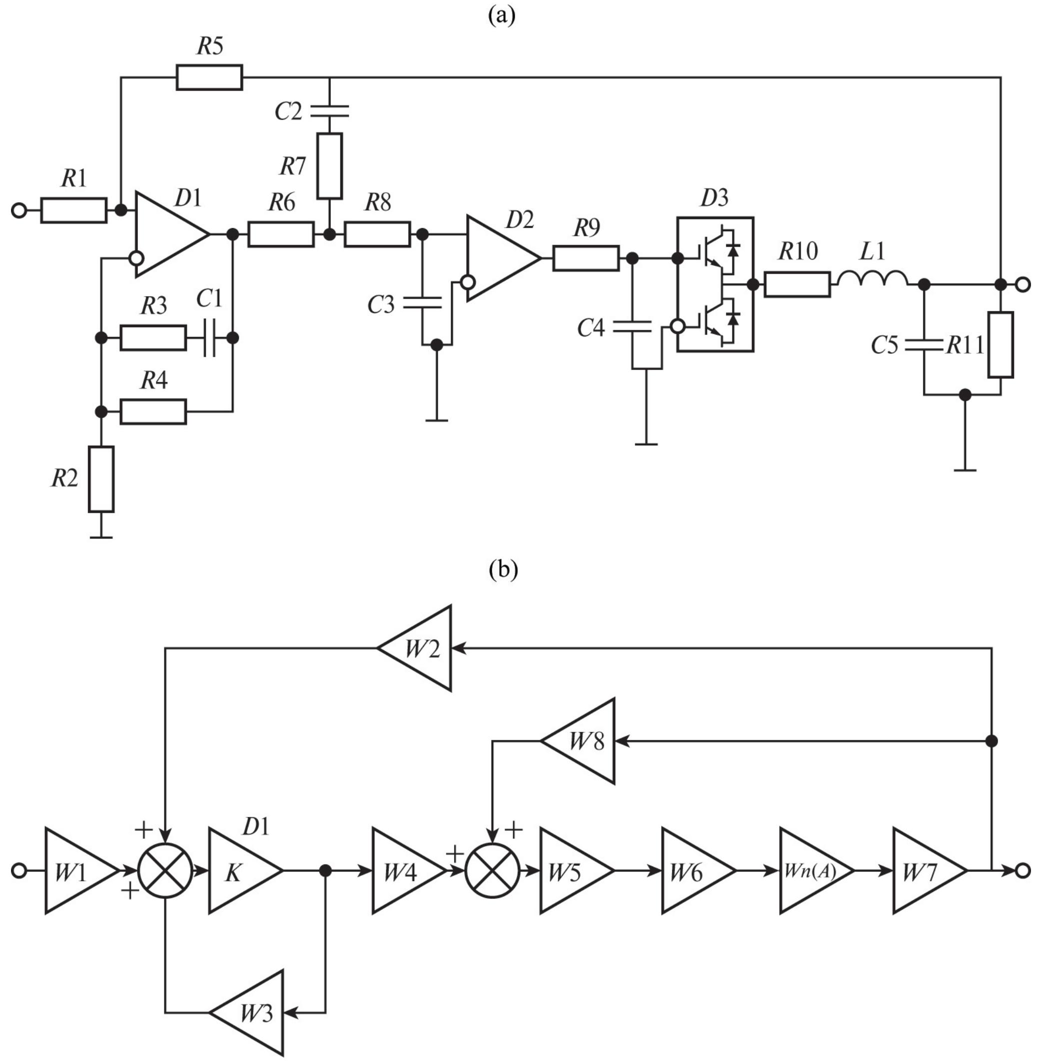

Fig. 9. (a) Electrical circuit, (b) block diagram of a self-oscillating class-D amplifier.

Here (2) is the open transfer function of the class D amplifier, and equation (3) is the frequency response function taking into account the negative feedback W_8 and the integrating link W_4. The system described in relation (3) has a significant drawback: the transmission coefficient of such an amplifier changes by more than 4 times, and the phase shift is from $\pi/2$ to π radians. The introduction of an additional feedback W_2 closed through an operational amplifier D_1 covered by its own feedback W_3 allows solving this problem. From the frequency response function of an ideal operational amplifier (gain $K \to \infty$) (4) and the transfer function of the amplifier, the system transfer function (5) is derived:

$$W_o = \frac{K}{1 + KW_3} \approx \frac{1}{W_3}, \tag{4}$$

$$W = \frac{W_d W_1}{W_3(1 + \frac{W_d}{W_3} W_2)}. \tag{5}$$

In [5, 29] it is demonstrated, through modeling, the high stability of the self-oscillating class D amplifier to nonlinear distortions introduced by a rectifier capacitive load; according to the simulation results, the THD index of the system decreased by more than 10 times. It is also noteworthy that

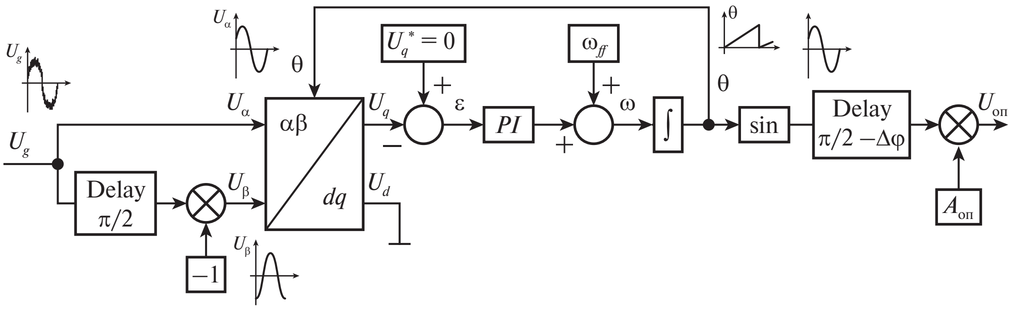

Fig. 10. PLL scheme for synchronization of a self-oscillating class D amplifier.

PWM generation and the current control loop in this inverter are implemented via analog means, and a small-amplitude sinusoidal signal is applied to the amplifier input.

3.5.2. Synchronisation Control

Attention is now directed toward the synchronization control method of the class D self–oscillating amplifier to form an isolated microgrid system. One of the main features of this inverter control method is the analog PWM circuit; because of this, unlike the aforementioned control methods, an analog sinusoidal signal of small amplitude is supplied to the input of the electrical system, which subsequently forms discrete signals on the gates of the power transistors. This feature allows significantly reducing the PLL loop processing frequency. When designing a PLL for this inverter, it is also necessary to take into account the presence of a constant DC offset of the output signal relative to the input by an angle $\Delta\varphi$. Figure 10 shows the structural diagram of PLL control for a self-oscillating class-D amplifier. It can be observed that the primary difference from the classic single-phase PLL is the presence of a phase shift at the output of the loop. In addition to accounting for the phase shift when working with analog PWM, it is also necessary to take into account the difference in the amplitude of the PLL input signal, measured directly at the inverter output (in the case of a utility grid, the amplitude of such a signal will be 310 V) and the amplifier input signal. Simulation data [5] and experiments show that this signal varies in the range of 3–5 V. Therefore, a multiplier is added to the output of the PLL loop, which allows forming the reference signal using the formula:

$$U_{ref} = A_{ref} \sin(\theta + 2\pi - \Delta\varphi),$$

where A is calculated when the converter is launched before turning on to the common microgrid network using the formula:

$$A_{ref} = \left.\frac{U_{in}}{U_{out}}\right|_{U_{out}=220\ \mathrm{V}}.$$

Consequently, to control the synchronization of the inverter based on a class D amplifier, a simple modification of the classic PLL control circuit with computationally simple modifications that take into account the features of the self-oscillating class D amplifier is used.

3.5.3. Benefits and Drawbacks of the Method

The advantages and limitations of this method for mitigating nonlinear distortions in a microgrid inverter are evaluated below.

Advantages:

- Nonlinear harmonic mitigation regardless of the connected load without the use of additional controllers.
- Analog implementation of current and voltage feedback and PWM generation, allowing to significantly reduce the computational load on the control processor.

- The ability to form a reference signal using the droop control method and virtual impedance.
- Mitigation of an arbitrary number of parasitic harmonics.

Limitations:

- More complex design of the inverter's electrical circuit.
- Insufficiently researched in the field of microgrid inverters.
- The need to generate an analog reference signal to control the inverter.

4. COMPARISON OF THE DESCRIBED METHODS

Several methods for mitigating nonlinear distortions in microgrid voltage source inverters have been described. Each of the listed methods presents a certain amount of both advantages and disadvantages. PR, MPR, and virtual impedance controllers are currently well studied and cope with mitigating nonlinear loads; however, the more distorted the voltage signal, the greater the computing power required for this. The $H\infty$ controller performs excellently in transitioning from autonomous operation to grid-connected operation, and also copes with nonlinear distortion mitigation; however, the implementation of an $H\infty$ controller in a discrete system requires additional study. Also, an inverter based on such a controller requires additional experimental research, since most modern studies in this area describe mathematical models of the system. The dual voltage inverter topology allows mitigating any nonlinear distortions without a significant increase in computational load, but requires designing two power inverters, which also increases system losses. The self-oscillating class-D amplifier has not previously been used in microgrid systems, but has performed well in isolated operation on nonlinear loads and, according to simulation results, is capable of operating as part of a microgrid without losing its properties. In addition, simple analog current control and PWM generation reduce the computational burden on the system. For further comparison of the proposed methods, we define the main parameters by which one can make a choice in favor of using one or another method for mitigating nonlinear harmonics.

(1) Number of controllers. This parameter reflects the computational load on the control processor, as well as the complexity of setting up the final system. A smaller number of controllers corresponds to a lower system need for computing power. For fair evaluation, Section 2 provides the minimum number of controllers for controlling each inverter; at the same time, the analog implementation of these controllers will not be taken into account in the total number of controllers, since it does not carry a computational load during the inverter operation.

(2) Mitigated harmonics. This parameter allows evaluating the complexity of the nonlinear load connected as part of the experiment. This parameter is especially critical for methods that use additional controllers to mitigate each voltage harmonic.

(3) Absolute THD decrease, %. Allows evaluating the overall usefulness of the method in mitigating nonlinear harmonics. The final THD indicator according to GOST [4] must strictly be less than 8% for the correct operation of the system.

(4) THD ratio. Calculated as the ratio of the THD indicator without using a particular method to the THD indicator using this method. Allows quantifying the effectiveness of each method in mitigating nonlinear distortions.

(5) Droop control compatibility. Potentially, each of the methods is compatible with the Droop control method; however, within the framework of modern research, this technology has not been applied to each of the described methods, which, in turn, can open the way to new research.

(6) Investigated nonlinear loads. Most studies describe the nonlinear load used. Understanding the load topology will significantly help in designing a distortion-resistant voltage source inverter. The most dangerous for inverter operation is a rectifier load with an RC cha in; inverters that handle such a load well are most resistant to nonlinear voltage distortions.

Comparison of the described methods for mitigating nonlinear distortions

Criterion	MPR	Virtual impedance	Dual inverter	H∞ controller	Multiple degrees of freedom	Class D inverter
Number of controllers	$^{3}N+3$	Min. 8, max. N^2+3	7	$^{2}5$	$N+3$	$^{1}3$
Harmonics mitigated	^{3}Up to 11	^{1}Up to 15	^{3}Up to 11	^{2}Up to 13	1, 5, 7, 11	^{1}Up to 15
THD decrease, %	5.28–2.806	29.85–6.37	28.37–3.22	5.31–2.00	N/A	11.75–1.16
THD ratio	1.88	^{3}4.69	^{2}8.81	2.655	N/A	^{1}10.13
Droop control compatibility	^{1}Compatible	Required	^{2}Not investigated	^{2}Not investigated	Required	^{2}Not investigated
Investigated load	^{2}DBR + R, RL, RC	^{1}DBR + R, RL, RC, LC	N/A	^{3}DBR + RL, LC	Unbalanced reactive load	^{2}DBR + R, RL, RC

Table provides a comparative characteristic of the proposed methods for mitigating nonlinear harmonics. The indices 1, 2, 3 in the table mark those cells whose method parameters are most effective for a given criterion; the smaller the index—the more effective the method. For methods that use controllers to mitigate each of the harmonics, the designation N is used in the first criterion—the number of harmonic controllers.

4.1. Prospects of using the class D amplifier

The primary advantages and prospects for using a self-oscillating class-D amplifier in microgrid systems are described below.

(1) Comparative characteristics provided in table, indicate that the self-oscillating class D amplifier requires the smallest number of controllers to ensure the operation of the control loop. Since each of the methods uses feedback controllers similar in their action, the computational load introduced by each of the controllers can be considered additive. In view of this, it can be stated that the self-oscillating class D amplifier requires the least computational cost to implement a control loop for a microgrid inverter with the ability to mitigate nonlinear harmonics.

(2) Based on the results of comparing the number of mitigated harmonics, as well as the decrease in the THD level, it is concluded that the use of a self-oscillating class D amplifier is more effective than many modern methods in the quality of nonlinear load mitigation, which indicates the possibility of use not only in microgrid systems with strict requirements for allowable computing power but also in systems with high requirements for the quality of supplied electricity.

(3) In view of the use of analog PWM generation for controlling the synchronization of a self-oscillating class D amplifier, calculating the pulse length of the discrete signal supplied to the gates of power transistors is not required. This factor also allows reducing the computational load on the controller unit, since a significant reduction in the frequency of the control loop operation is permissible.

Based on the aforementioned factors, the primary applications of a self-oscillating class D amplifier in microgrid systems are deducted: these are systems that require a stable sinusoidal signal under conditions of high nonlinearity of the connected load, for example, high-power chargers; these are microgrid systems that impose restrictions on computing power, for example, small-sized ones. The self-oscillating class-D amplifier ensures operation in microgrid systems with the described requirements.

5. CONCLUSION

Based on the results presented in table, it can be concluded that further research into self-oscillating class-D amplifiers within the framework of microgrid systems is necessary. Such a voltage source inverter requires less computational power, while excellently handling regulation under conditions of high load nonlinearity. Experimental validation of the results presented in [5] is the next research step. Additionally, it is necessary to conduct research into the compatibility of such an inverter with droop control technology. When designing low-power grid-connected microgrid systems, as well as isolated ones based solely on identical voltage source inverters, the property of system invariance with respect to the connected load is extremely important. The use of a self-oscillating class D amplifier at the core of such a system will allow this task to be handled effectively, requiring less computational power than when using other harmonic mitigation methods.

In addition to research on the self-oscillating class-D amplifier, attention should also be paid to research on the $h\infty$ controller. Experimental validation of the results presented in [34], as well as research into the droop control method as part of such an inverter, will potentially reveal the benefits of this method compared to the most frequently used ones.

THD mitigation indicator for the dual inverter method [28] also deserves special attention. With a small increase in computational power, the authors managed to achieve a better indicator than when using MPR and virtual impedance methods. Further research in this area may also reveal additional benefits of the proposed method.

Most of the proposed methods, according to [36], are potentially applicable to the issue of controlling circulating currents arising as a result of the parallel operation of several inverters. Research in this area is also currently extremely relevant, as the control and minimization of circulating currents will increase system operation efficiency and reduce ohmic losses.

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