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ON THE ISSUE OF MICROGRID CONTROL WITH WIND ENERGY SYSTEMS AND PV USING AN LC FILTER

Abstract. *This paper addresses the problem of improving power quality in a microgrid that integrates renewable energy sources, specifically wind energy systems (WES) and photovoltaic (PV) installations, through the application of an LC filter at the output of an inverter-based distributed generation unit. The study examines the fundamental physical principles of LC filter operation, including its frequency response characteristics and its role in mitigating high-frequency harmonics generated by power electronic converters. Special attention is given to the influence of the LC filter on the overall stability and dynamic performance of the microgrid under varying load conditions.*

An engineering design and calculation of LC filter parameters are carried out for a 220 V microgrid with a rated power of 3 kW and a pulse-width modulation (PWM) frequency of 10 kHz. The results demonstrate that appropriately designed filter parameters ensure attenuation of high-frequency harmonics exceeding 50 dB, significantly reducing the total harmonic distortion (THD) of the output voltage. Furthermore, the proposed approach contributes to improved voltage waveform quality and enhanced reliability of the microgrid. The findings confirm the effectiveness and practical applicability of LC filters in distributed generation systems based on renewable energy sources.

Keywords: *microgrid, LC filter, wind energy system, photovoltaic system, inverter, harmonics, power quality, THD, distributed generation.*

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ЖЕЛ ЭЛЕКТР СТАНЦИЯСЫ ЖӘНЕ ФОТОЭЛЕКТРЛІК ЖҮЙЕЛЕРІ (PV) БАР МИКРОЖЕЛІНІ LC-СҮЗГІ АРҚЫЛЫ БАСҚАРУ МӘСЕЛЕСІНЕ

Аңдатпа. *Мақалада жаңартылатын энергия көздерін, атап айтқанда жел энергетикасы жүйелерін (ЖЭЖ) және фотоэлектрлік қондырғыларды (PV) біріктіретін микрожелідегі электр энергиясының сапасын жақсарту мәселесі инверторлы таратылған генератор қондырғысының шығысында LC сүзгісін қолдану арқылы қарастырылады. Зерттеу СКД сүзгісінің жұмысының негізгі физикалық принциптерін, соның ішінде оның жиілік сипаттамаларын және күштік электронды түрлендіргіштер тудыратын жоғары жиілікті гармониканы басудағы рөлін қарастырады. СКД сүзгісінің әртүрлі жүктемелер кезінде микрожелінің жалпы тұрақтылығы мен динамикалық сипаттамаларына әсеріне ерекше назар аударылады.*

Номиналды қуаты 3 кВт және ені-импульстік модуляция (PWM) жиілігі 10 кГц болатын кернеуі 220 В микрожеліге арналған LC-сүзгінің параметрлерін техникалық жобалау және есептеу орындалды. Нәтижелер дұрыс таңдалған сүзгі параметрлері 50 дБ-ден асатын жоғары жиілікті гармониканың әлсіреуін қамтамасыз ететінін көрсетеді, бұл Шығыс кернеуінің жалпы гармоникалық бұрмалануын (THD) айтарлықтай төмендетеді. Сонымен қатар, ұсынылған тәсіл кернеу сигналының сапасын жақсартуға және микрожелінің сенімділігін арттыруға көмектеседі. Нәтижелер жаңартылатын энергия көздеріне негізделген таратылған генерация жүйелерінде СКД сүзгілерінің тиімділігі мен практикалық қолданылуын растайды.

Түйінді сөздер: *микрожелі, LC-сүзгі, жел электр станциясы, фотоэлектрлік жүйе, инвертор, гармоникалар, электр энергиясының сапасы, THD, таратылған генерация.*

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К ВОПРОСУ УПРАВЛЕНИЯ МИКРОСЕТЬЮ С ВЕТРОВЫМИ ЭНЕРГЕТИЧЕСКИМИ УСТАНОВКАМИ И PV С ИСПОЛЬЗОВАНИЕМ LC-ФИЛЬТРА

Аннотация. *В данной статье рассматривается проблема улучшения качества электроэнергии в микросети, которая объединяет возобновляемые источники энергии, в частности ветроэнергетические системы (ВЭС) и фотоэлектрические установки (PV), за счет применения LC-фильтра на выходе инверторной распределенной генераторной установки. В исследовании рассматриваются фундаментальные физические принципы работы ЖК-фильтра, включая его частотные характеристики и его роль в подавлении высокочастотных гармоник, генерируемых силовыми электронными преобразователями. Особое внимание уделяется влиянию ЖК-фильтра на общую стабильность и динамические характеристики микросети при различных нагрузках.*

Выполнено техническое проектирование и расчет параметров LC-фильтра для микросети напряжением 220 В с номинальной мощностью 3 кВт и частотой широтно-импульсной модуляции (ШИМ) 10 кГц. Результаты показывают, что правильно подобранные параметры фильтра обеспечивают ослабление высокочастотных гармоник, превышающих 50 дБ, что значительно снижает общее гармоническое искажение (THD) выходного напряжения. Кроме того, предлагаемый подход способствует улучшению качества сигнала напряжения и повышению надежности микросети. Полученные результаты подтверждают эффективность и практическую применимость ЖК-фильтров в системах распределенной генерации на основе возобновляемых источников энергии.

Ключевые слова: *микросеть, LC-фильтр, ветровая энергетическая установка, фотоэлектрическая система, инвертор, гармоники, качество электроэнергии, THD, распределённая генерация.*

INTRODUCTION

The modern electric power industry is developing towards decentralization and digitalization, which is associated with the active introduction of renewable energy sources, energy storage systems and intelligent control algorithms (Guerrero et al., 2022). One of the most promising forms of distributed generation organization is microgrids, which are local power systems capable of operating both as part of a centralized network and autonomously (Memon et al., 2024).

Microgrids with wind power plants and PV provide environmental friendliness, flexibility and reliability of energy supply, especially in remote areas and facilities with high demands on electricity quality (Memon et al., 2024) . However, the use of inverter sources leads to the appearance of high-frequency harmonics, an increase in the coefficient of nonlinear distortion and a deterioration in the dynamic stability of the system (Kim et al., 2024).

One of the effective solutions to this problem is the use of passive LC filters installed at the output of the inverter (Rohit & Kishor, 2024). Their use makes it possible to smooth the shape of the output voltage and ensure compliance with electricity quality standards (Rohit & Kishor, 2024).

In the context of the active development of distributed generation and the growing share of power electronic converters in the structure of local power systems, the task of ensuring the quality of electricity is becoming one of the key ones (Kim et al., 2024). The most vulnerable from this point of view are microgrids, in which energy sources based on wind power plants and photovoltaic systems are connected to the load via inverter interfaces (Memon et al., 2024). Pulse width modulation, being an effective way of energy conversion, simultaneously causes the appearance of higher harmonics, an increase in electromagnetic interference and a deterioration in the sinusoidal output voltage (Kim et al., 2024).

In this regard, the use of an LC filter at the output of the inverter is an engineering justified solution that allows for a pronounced smoothing effect with a relatively simple structure (Rohit & Kishor, 2024). Scientific interest in this task is due to the need to reconcile conflicting requirements: on the one hand, the filter should effectively suppress high–frequency harmonics, and on the other, it should not introduce unacceptable phase distortions in the fundamental frequency region of the network and worsen the dynamics of the microgrid (Kim et al., 2024).

The scientific novelty of this study lies in the fact that LC filter analysis is not considered in isolation, but in the context of microgrid management with two types of renewable energy sources – wind and photovoltaic (Memon et al., 2024). The practical significance of the work lies in the possibility of using the proposed calculation ratios and structural solutions in the design of low-power 220 V microgrids with an inverter interface and distributed generation.

The aim of the work is to analyze the effect of the LC filter on the quality of electricity and the stability of the microgrid with wind power plants and PV (Guerrero et al., 2022).

It should be noted that in microgrids, the quality of electricity is determined not only by the parameters of the sources themselves, but also by the nature of the interaction between converters, lines, energy storage devices and loads (Guerrero et al., 2022). In real-world conditions, microgrid loads are often nonlinear: consumers include switching power supplies, frequency-controlled electric motors, power electronics, and other devices sensitive to voltage distortion (Kim et al., 2024). Therefore, the problem of harmonics in microgrids is of a dual nature: some of the distortion occurs from the source side, and some from the load side (Kim et al., 2024).

Of particular difficulty is the fact that the power of wind power plants and PV is stochastic in nature (Memon et al., 2024). The wind speed and the level of solar insolation change over time, which causes fluctuations in the active power at the input of the inverter (Memon et al., 2024). In the absence of a properly selected filter, such fluctuations can increase current and voltage fluctuations, which negatively affects the stability of the entire microgrid (Kim et al., 2024).

In this regard, the use of an LC filter should be considered not only as a means of suppressing harmonics, but also as an element influencing the dynamic behavior of the system (Rohit & Kishor, 2024). Its parameters should be selected in such a way as to ensure a compromise between the filtration depth, the permissible dimensions and mass of the inductance, the reactive load on the source, as well as stability under various operating modes (Kim et al., 2024).

To achieve this goal, the following tasks are being solved:

• analyze the physical basis of the LC filter functioning as part of a microgrid;
• define engineering criteria for selecting filter parameters;
• calculate the inductance and capacitance for the specified parameters of the microgrid;
• investigate the frequency characteristics of the filter;
• evaluate the effect of the filter on harmonic suppression and stability of the system.

RESEARCH MATERIALS AND METHODS

With the global energy transition towards low–carbon energy sources, special attention is being paid to distributed energy systems - microgrids (Guerrero et al., 2022). Microgrids are capable of efficiently integrating renewable energy sources such as wind turbines and solar photovoltaic (PV) panels, providing a sustainable, autonomous or semi-autonomous energy supply (Memon et al., 2024).

The concept of microgrids is based on the creation of local power systems capable of operating both as part of a large power grid and autonomously (Guerrero et al., 2022). This is critical for remote areas, island territories, industries with stable electricity supply requirements, and structures with critical infrastructure (Memon et al., 2024). A microgrid is an electric power system with distributed energy sources, control systems, energy storage elements and consumers, which can operate in two modes: inside the main grid (grid-connected mode); offline (island mode) – when disconnected from the external network infrastructure (Kim et al., 2024). Microgrids are designed taking into account energy consumption, generating elements, and balancing mechanisms. Through intelligent load management, energy generation and storage are optimized in real time (Guerrero et al., 2022).

The main task of microgrid management is to ensure a balance between energy generation and consumption.

The issues of filter design for distributed generation systems have been discussed in numerous studies in recent years. For example, Chen et al. analyzes various types of passive filters, including LC and LCL filters, and compares their characteristics under unstable load conditions (Chen et al., 2023). The authors emphasize that LC filters provide acceptable efficiency at moderate cost and ease of implementation (Lim et al., 2025).

Zhang and Lee's work examines the effect of LC filters on the dynamic characteristics of microgrids with a high proportion of solar panels. It shows that optimizing the filter parameters reduces voltage fluctuations and improves the stability of the system with rapid changes in generation and load (Rodriguez et al., 2023).

The review by Kumar et al provides a comparative analysis of passive and active harmonic compensation methods. The authors conclude that with limited resources, passive LC filters remain an effective solution due to the absence of complex electronics and the need for control (Lim et al., 2025).

Other studies, such as Smith & Patel, focus on modeling LC filters taking into account the parasitic parameters of the elements, which is critical at frequencies typical of modern energy converters (Agelidis et al., 2021).

The paper uses methods of theoretical analysis of second-order linear electrical circuits, frequency analysis, and engineering calculation of LC filter parameters (Miura, 2021).

he LC filter consists of an inductance L and a capacitance C, which are fundamental elements of passive power conditioning systems (Kim et al., 2024).

The inductance stores energy in a magnetic field:

$$W_L = \frac{1}{2}LI^2 \qquad (1)$$

A capacitor stores energy in an electric field:

$$W_C = \frac{1}{2}CU^2 \qquad (2)$$

The reactants of the elements are determined by the expressions:

$$X_L = \omega L \qquad X_C = \frac{1}{\omega C} \qquad (3)$$

Where

$$\omega = 2\pi f \qquad (4)$$

The resonant frequency of the circuit:

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (5)$$

Transfer function of an ideal second-order LC filter:

$$H(s) = \frac{1}{LCs^2+1} \qquad (6)$$

For the engineering calculation, the initial data is taken:
• the voltage of the microgrid is 220 V;
• load capacity – 3 kW;
• Network frequency – 50 Hz;
• The frequency of the pulse width modulation of the inverter is 10 kHz.

The cutoff frequency is set to 500 Hz to ensure separation between fundamental and switching harmonics (Kim et al., 2024).

As part of the engineering analysis, we will additionally introduce an equivalent load resistance. For an active load with a power of 3 kW at a voltage of 220 V, its approximate resistance can be estimated by the expression:

$$R_{load} = \frac{U^2}{P} = \frac{220^2}{3000} \approx 16.13\ \Omega \qquad (7)$$

The corresponding load current is:

$$I_{load} = \frac{P}{U} = \frac{3000}{220} \approx 13.64\ A \qquad (8)$$

These values are important for ensuring correct filter behavior under real operating conditions (Chen et al., 2023).

The choice of the cutoff frequency f_c is based on two engineering requirements. On the one hand, it should be significantly higher than the fundamental frequency of 50 Hz, so as not to weaken the useful harmonic and not introduce noticeable distortions into the operating range. On the other hand, the cutoff frequency should be significantly lower than the pulse width modulation frequency f_{PWM} = 10 kHz to ensure effective suppression of switching harmonics. The 500 Hz value satisfies both conditions and allows us to obtain the ratio:

$$\frac{f_{PWM}}{f_c} = \frac{10000}{500} = 20 \qquad (9)$$

For a second–order filter, the theoretical attenuation in the region significantly higher than the cutoff frequency is proportional to the square of the frequency ratio, and on a logarithmic scale corresponds to a slope of 40 dB per decade.

Let's define the product LC from the cutoff frequency selection condition:

$$LC = \frac{1}{(2\pi f_c)^2} \qquad (10)$$

Substituting fc= 500 Hz, we get:

$$LC = \frac{1}{(2\pi \cdot 500)^2} \approx 1.013 \times 10^{-7} \quad (11)$$

If we accept the inductance:

$$L = 2 \text{ мГн} = 2 \times 10^{-3} \text{ Гн}, \quad (12)$$

then the capacity will be:

$$C = \frac{LC}{L} = \frac{1.013 \times 10^{-7}}{2 \times 10^{-3}} \approx 5.065 \times 10^{-5} \text{ F} = 50.65 \text{ UF} \quad (13)$$

Reactance analysis:

At 50 Hz, inductive impedance is low and capacitive impedance is high, allowing fundamental frequency passage (Miura, 2021).

At 10 kHz, inductive impedance increases significantly while capacitive impedance decreases, enabling harmonic suppression (Agelidis et al., 2021).

At a basic frequency of 50 Hz:

$$X_L = 2\pi \cdot 50 \cdot 0.002 \approx 0.628\,\Omega \quad (14)$$

$$X_C = \frac{1}{2\pi \cdot 50 \cdot 50 \times 10^{-6}} \approx 63.66\,\Omega \quad (15)$$

This means that at the fundamental frequency, the inductance has a relatively small resistance, and the capacitor has a large one. Consequently, the useful harmonic passes to the load practically without significant attenuation (Rustamov et al., 2025).

At a frequency of pulse width modulation of 10 kHz:

$$X_L = 2\pi \cdot 10000 \cdot 0.002 \approx 125.66\,\Omega \quad (16)$$

$$X_C = \frac{1}{2\pi \cdot 10000 \cdot 50 \times 10^{-6}} \approx 0.318\,\Omega \quad (17)$$

Here the situation is reversed: the inductance creates a large resistance, and the capacitor easily shunts the high-frequency component. This explains the filtering effect of the LC chain with respect to the harmonics of pulse width modulation.

Additionally, we note that the dynamics of the LC filter can be described by a system of differential equations:

$$L\frac{di_L}{dt} = u_{inv} - u_C \quad (18)$$

$$C\frac{du_C}{dt} = i_L - i_{load} \quad (19)$$

where u_{inv} is the output voltage of the inverter, u_C is the voltage across the capacitor, and i_L is the current through the inductor. This system shows that the filter is a dynamic link of the second order and is capable of both smoothing high-frequency components and influencing transients in the microgrid (Wang et al., 2023).

In practical design, it is necessary to take into account that too small values of L and C lead to insufficient harmonic suppression, and too large values lead to an increase in mass, cost, and possible resonance phenomena. Therefore, the choice of filter parameters is an engineering optimization task between the quality of electricity, dynamic stability and cost-effectiveness of implementation (Agelidis et al., 2021).

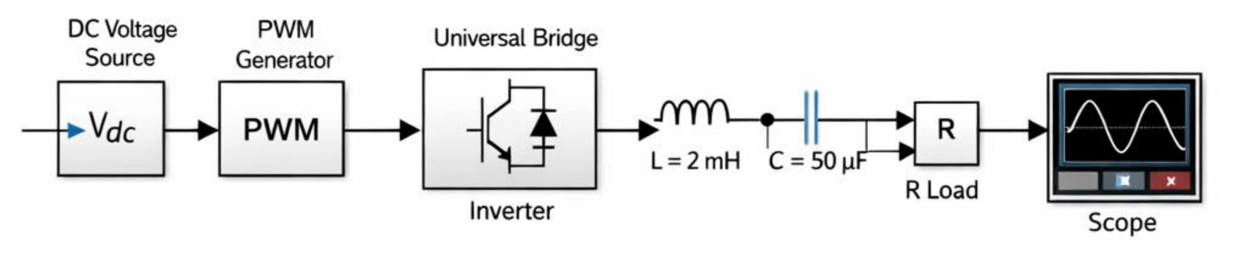

Figure 1. Simulation model of a microgrid with an LC filter in the MATLAB/Simulink environment.

To confirm the analytical calculations, a simulation model of a microgrid in the MATLAB/Simulink environment has been developed (Figure 1). The model includes a pulse-width voltage modulation source, an LC filter, and a load. A frequency analysis of the system was carried out, confirming compliance with theoretical calculations.

When constructing the model in MATLAB/Simulink, the inverter source was set as an equivalent voltage generator with pulse width modulation, forming a high-frequency pulse sequence followed by smoothing with an LC filter. This approach makes it possible to reproduce the real structure of the output stage of a distributed generation source without unnecessarily complicating the model (Kim et al., 2024).

The load in the model was considered as an equivalent active load, which corresponds to the basic engineering scenario for evaluating the filter (Chen et al., 2023). At the same time, the proposed approach can be extended to the case of active-inductive or nonlinear load, which is especially important for industrial microgrids (Eldeeb et al., 2022).

Frequency analysis was performed to determine the amplitude-frequency and phase-frequency characteristics of the filter, as well as to assess the level of suppression of harmonic components in the frequency range of pulse width modulation. Such an analysis is important because it allows not only to obtain numerical values of the filter parameters, but also to understand its effect on the stability of the system and the phase reserve.

RESULTS AND DISCUSSION

The calculation showed that the product LC is:

$$LC \approx 1.01 \times 10^{-7}$$

When choosing the inductance L = 2 MH, a capacitance C ≈ 50 Uf was obtained.

The ratio of the pulse width modulation frequency to the cutoff frequency is 20. Since the LC filter is a second-order system, the attenuation of high-frequency harmonics is proportional to the square of the frequency ratio (Kim et al., 2024):

$$20^2 = 400$$

this corresponds to a suppression of about 52 dB.

In order to analyze the frequency properties of the filter, the amplitude-frequency characteristics of the second-order system were constructed. Figure 2 shows the amplitude-frequency response of an LC filter calculated for a cutoff frequency of 500 Hz. The graph allows you to visually evaluate the behavior of the system in the area of the main frequency of the network (50 Hz), near the resonant frequency and in the area of suppression of high-frequency harmonics (Eldeeb et al., 2022).

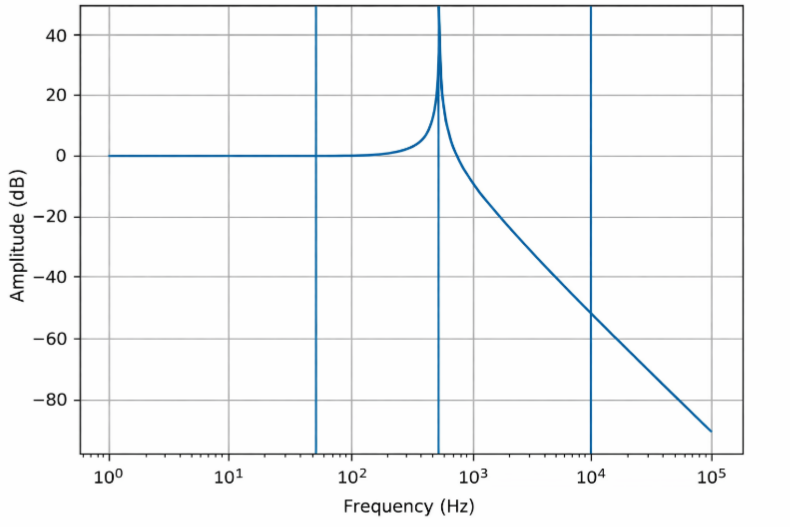

Figure 2. Amplitude-frequency response of the LC filter.

Thus, the filter effectively suppresses the harmonics of pulse width modulation, reduces THD and improves the shape of the output voltage (Rohit & Kishor, 2024).

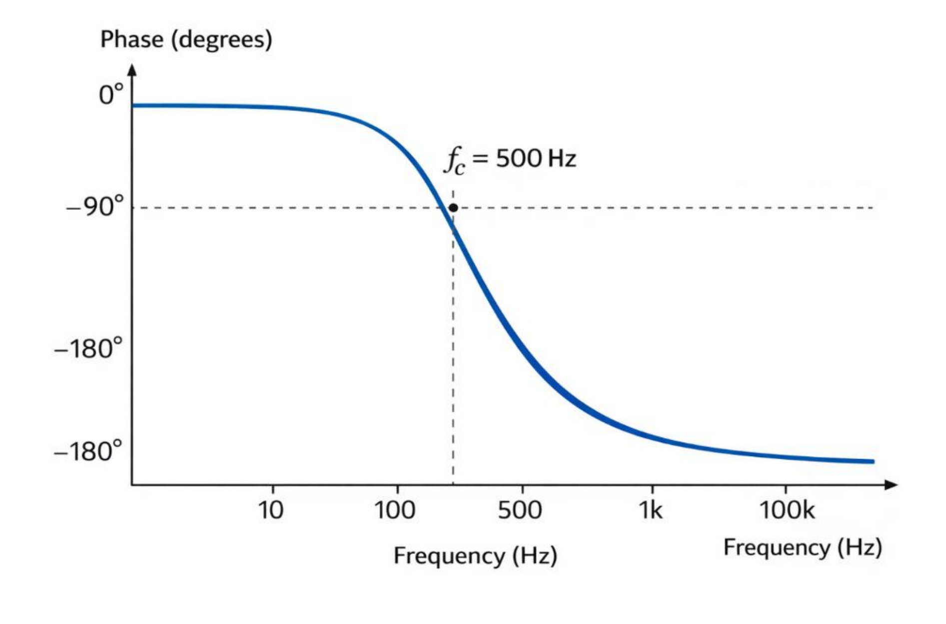

Figure 3. Phase-frequency response of a second-order LC filter.

Figure 3 shows the phase-frequency response of the LC filter. It can be seen that at low frequencies the phase shift is close to zero, which ensures the transmission of the fundamental harmonic without distortion. A phase change is observed in the region of the cutoff frequency, and at high frequencies the phase shift tends to -180°, which is typical for a second-order system (Miura, 2021).

Physically, the LC filter acts as an energy buffer, accumulating the pulsed energy of the inverter and transferring it to the load in a smoothed form. This is especially important when using a microgrid with wind power plants and PV, where the generation capacity is subject to rapid changes (Memon et al., 2024).

In practical implementation, it is necessary to take into account the parasitic resistances of the elements, the ESR of the capacitor and possible resonant phenomena that occur when the filter interacts with the load (Agelidis et al., 2021).

The calculated results allow us to draw several important engineering conclusions. Firstly, the selected parameters L=22 MH and C=50 UF ensure the required selectivity of the filter without excessive growth of reactive currents at the fundamental frequency. This means that the filter is able to perform two functions simultaneously: to transfer the useful energy of the fundamental harmonic and effectively attenuate the high-frequency components associated with the switching of the inverter.

Secondly, the suppression depth of about 52 dB indicates a significant decrease in the harmonic amplitude of pulse width modulation in the output voltage. In practice, this means improving the sinusoidal nature of the load voltage, reducing equipment heating, reducing electromagnetic interference, and increasing the life of sensitive consumers.

Thirdly, the frequency response analysis shows that the effect of the filter on the phase in the operating range remains acceptable. This is important not only for a single load, but also for the case of a microgrid operating as part of a more complex control system, where phase reserves and dynamic delays determine the stability of regulation.

From an engineering point of view, the chosen LC filter structure is justified for a low-power microgrid. Compared to more complex LCL filters, the classical LC structure is easier to set up, less sensitive to parametric variations, and does not require the mandatory introduction of active damping. This is a significant advantage for autonomous and semi-autonomous microgrids, where reliability and simplicity are often more important than maximum efficiency.

However, the limitations of the approach under study should also be taken into account. An idealized transfer function:

$$H(s) = \frac{1}{LCs^2+1} \qquad (20)$$

It does not explicitly take into account active losses in inductance, ESR of the capacitor and load resistance. In a real system, the presence of these parameters leads to attenuation of vibrations and a change in the shape of the frequency response near the resonant frequency. Therefore, when switching from a design scheme to a full-scale implementation, it is necessary to use a refined model with active resistances.

In addition, in conditions of variable power by wind power plants and PV, the issue of filter adaptability becomes important. Although the passive LC filter does not require a separate control system, its parameters are selected based on a certain nominal mode. With a significant change in the composition of the load or the generation power, the frequency properties of the system may shift, which requires either a compromise choice of parameters or a transition to more complex filtering structures.

Nevertheless, for the considered 220 V, 3 kW, 50 Hz microgrid with pulse width modulation of 10 kHz, the results show that the LC filter provides the required output voltage quality and can be recommended as an effective means of improving the quality of electricity in distributed generation systems based on wind power plants and PV.

CONCLUSION

The paper analyzes the application of an LC filter in a microgrid with wind power plants and PV. It is shown that the LC filter is an effective means of suppressing the high-frequency harmonics of the inverter and ensuring the required quality of electricity (Kim et al., 2024).

For a 220 V microgrid with a power of 3 kW at a pulse width modulation frequency of 10 kHz, the rational filter parameters are:

L=2 MH C=50 UF

The use of an LC filter ensures a reduction in the coefficient of nonlinear distortion, an increase in the dynamic stability of the system and reliable integration of renewable energy sources.

The prospects for further research are related to optimizing the filter parameters under variable load, analyzing LCL structures, and developing adaptive microgrid control algorithms.

Thus, the study shows that even a relatively simple passive LC structure can significantly improve the quality of electricity in a microgrid with distributed generation. This is especially important for local power supply systems, where it is required to ensure stable load operation with minimal complexity and cost of technical implementation.

The main practical result of the work is to determine the rational filter parameters for a specific class of low-power microgrids and to confirm that a correctly selected cutoff frequency simultaneously preserves the useful harmonics and suppresses the high-frequency components of the inverter output signal.

The results obtained can be used in the design of autonomous and networked microgrids with wind power plants and photovoltaic systems, as well as in the further development of more complex filtration and quality management systems for electricity. In subsequent studies, it is advisable to take into account the active losses of elements, the imperfection of the inverter, the influence of energy storage devices, as well as experimental verification of the model under conditions of real load and variable generation.

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