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Developing a hybrid filter structure and a control algorithm for hybrid power supply

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ABSTRACT

The paper presents the results of a study on hybrid filter operation and performance under hybrid power supply. In the study, a hybrid filter structure was developed and proved to perform a set of power quality improving functions. The paper demonstrates that it is necessary for the hybrid filter structure to be variable in order to adapt to changes in power supply. A case is made for using an additional passive filter at the active part output of the hybrid filter under distributed generation. The optimal structure and parameters of such an additional passive filter are identified and proved. Based on the experimental research results, the mathematical and computer simulation models of the proposed hybrid filter for hybrid power supply were developed. The modeling and simulation results showed the efficiency level to be satisfactory and power quality to improve due to applying the proposed hybrid filter. Using the modeling and simulation results, an adaptive algorithm to control the operation factors of the proposed hybrid filter under hybrid power supply was developed, tested, and evaluated. Practical recommendations for industrial application of the proposed hybrid filter are given.

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1. INTRODUCTION

Nowadays distributed generation technologies have a wide range of application in different industrial and public power supply systems [1]. Such technologies are based mainly on wind farms, solar power stations [2], and microturbine installations, which work on associated petroleum gas [3], [4]. They help to improve the reliability of power supply from public centralized networks. This is especially important for business and industrial users as voltage dips or interruptions can disrupt production [2]. In different countries, the role of distributed generation technologies depends on the structure of the existing power supply systems, electricity prices, and the features of power supply markets [5]. There are two ways in which distributed generation can be performed: it can work separately or in parallel with any existing centralized power supply system. The latter method for ensuring uninterruptible power supply is more widespread and can be called a hybrid power supply system or a grid-connected renewable energy system [3], [6]. In addition, in many countries, conventional centralized or public power supply systems are very old and unreliable but they cannot be replaced immediately by distributed generation [7]. Therefore, hybrid power supply systems may be considered as a real alternative to the existing public networks when the rated power of distributed generation systems is not enough to ensure that all industrial consumers are provided with enough energy [8], [9]. Within hybrid systems, centralized and distributed power supply should be considered as special cases of hybrid power supply [10], [11]. Also, in this case it is necessary to have a multifunctional device to improve power quality under changing power supply parameters and connected load characteristics [12], [13]. There are plenty of such devices, and it is reasonable to consider in detail hybrid filters which are based on active and passive filters [14], [15]. Any hybrid structure includes a series or shunt active filter with one or several resonance passive filters or with one wide-band passive filter.

When determining the efficiency level of a hybrid filter application, it is necessary to solve the following key problems:

- To determine the permitted decrease in the rated parameters of the active part in the given hybrid filter while maintaining the required degree of power quality correction [16].
- To identify a set of functions for the given hybrid filter in the conditions of centralized, distributed, and hybrid power supply systems [17], [18].
- To determine the influence of the passive filter configuration at the output of the active part on the performance of the hybrid filter in centralized, distributed, and hybrid power supply systems [19].
- To find the optimum configuration of the hybrid filter for centralized, distributed, and hybrid power supply systems [20].

A comprehensive approach is required to solve the problems above. Such a solution is presented in the article by means of developing an adaptive algorithm and a hybrid filter structure which allows for choosing the optimal structure, working mode, and performance of the given hybrid filter under variable parameters of the power source [21], [22]. The proposed adaptive algorithm is based on simulation results that reflect the behavior of power quality indicators when changing the hybrid filter structure and the type of the control system under variations in power source characteristics. Also, the proposed algorithm takes into account the permitted decrease in the active part parameters within the hybrid filter structure [23], [24]. The modeling was carried out in accordance with the following research method.

2. RESEARCH METHOD

The proposed research method is intended to evaluate the performance of the multifunctional hybrid filter with different structural components under variable power source parameters. Here it must be noticed that the variations of power supply characteristics influence on the power quality indicators that should be taken into account when selecting the structure of multifunctional hybrid filter. That is why we use such method to get the novel technical results in terms of the methodology to select properly the parameters and structure of any multifunctional hybrid filter. Also, the proposed research method allows detecting the efficiency of the separated and combined functioning of several parts of the multifunctional filter device under different conditions of the hybrid power supply when power quality indicators may change according to the power supply mode.

The proposed research method provides to identify the following new dependences and results:

- The dependences of the power quality indicators values on the passive filter type at the output of the active one as the part of the multifunctional hybrid filter.
- The permitted level to decrease the rated parameters of the active part of the hybrid structure to save the required power quality indicators values under the hybrid power supply.
- The adaptive algorithm to control multifunctional hybrid filters under the hybrid power supply when changing parameters of the distributed and centralized sources.
- Let us consider the proposed research method on the example of a hybrid structure including a shunt active filter and two passive filters tuned to eliminate 5th and 7th current harmonics [25], [26].

The proposed research method includes the following key steps:

- Determining the possible structure of the passive filter at the output of the active one within the hybrid filter structure [27]. During this step we consider the most widespread and well-known structures of the passive filters at the output of the active one and evaluate their performance according to the power quality indicators in terms of voltage and current harmonics, voltage deviations, current and voltage unbalance.
- Analyzing the values of power quality indicators when changing the output passive filter structure. Here we consider the values of power quality indicators to detect the influence of each output filter configuration on the power quality level. The character of this influence may be considered as the novel technical result in terms of the creation and proving of the hybrid filter structure for the hybrid power systems.

- Finding the optimum output filter structure to minimize the value of the given power quality indicator [28]. As the result of this step we identify the optimal structure of the output passive filter for each case when we want to minimize one or several power quality indicators according to the given application aims and tasks.
- Analyzing how the standalone passive, the active, and the output passive filters work together within a multifunctional hybrid electric power system under variations in the internal impedance of the power supply source (centralized or distributed generation) [29], [30].

All the indicated steps are necessary to take when developing an adaptive algorithm, which also should be considered as the novel technical result in terms of control of multifunctional filter devices under the hybrid power supply. The sequence of simulation under the proposed research method is presented in Figure 1. This sequence may be reproduced with any similar devices under the hybrid power supply. Figure 1(a) shows the usage only two passive filters for harmonic elimination, Figure 1(b) shows the usage two passive filters with one shunt active filter, Figure 1(c) shows the usage two passive filters with one shunt active filter with the output passive filter.

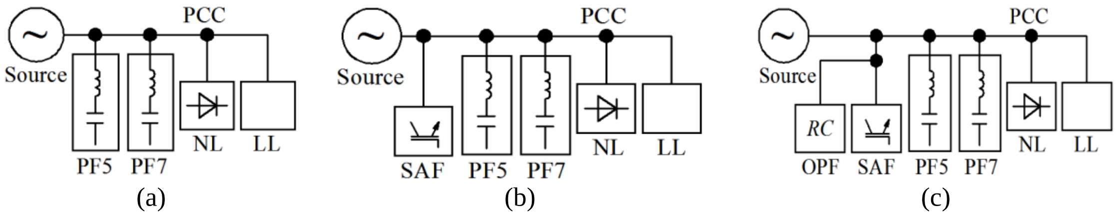

Figure 1. The sequence of simulation under the proposed research method (a) two passive filters, (b) two passive filters with a shunt active filter, and (c) two passive filters with an additional passive filter at the output of the shunt active filter

There are the following designations in Figure 1 sustainable aviation fuel (SAF) is the shunt active filter; PF5 and PF7 are the passive filters tuned to eliminate 5th and 7th harmonics, respectively; NL is the non-linear load; LL is the linear load; PCC is the point of common coupling; OPF is the passive filter at the output of the SAF. The parameters of the SAF, PF5, PF7, OPF, NL and LL were selected due to the results obtained during experimental research with serial SAF. This SAF is presented in Figure 2. The laboratory installation is presented in Figure 2(a) and the industrial one is presented in Figure 2(b) The results, obtained during research in laboratory and industrial power supply system, were the basis of the implementation of the proposed research method.

(a) (b)

Figure 2. The serial SAF, which was used to implement the proposed research method: (a) in the laboratory during maintaining and (b) in industrial power supply system during experimental research

Similar structures can be considered if a series active filter is incorporated as part of a hybrid structure instead of the shunt one [31], [32]. But the series active filter as a controllable voltage source often has an output transformer with special parameters and in some modes this transformer can be considered as the output passive filter [33]. In spite of this feature the proposed method is fully applicable to hybrid structures that include the series active filter. Such structures are the subject of further research on hybrid power supply [34], [35].

3. SIMULATION MODEL

The computer simulation model that we developed for the evaluation of hybrid filter efficiency under hybrid power supply includes the following key elements:

- A power supply source with the option to generate voltage harmonics of the selected numbers and change the internal impedance Z_s.
- A non-linear load as a controllable rectifier with an active-inductive load.
- A linear load as an active-inductive load.
- A hybrid filter based on a shunt active filter with an output passive filter and two standalone passive filters tuned to eliminate 5th and 7th current harmonics, respectively.

The parameters and characteristics of all elements of the model were chosen according to the experimental research results [10], [14]. During simulation, the internal impedance Z_s was set in p.u. with the basis value of the impedance of the ideal centralized power system. The Z_s changed in a range of 0.1 to 10 to correspond to the transfer of power supply mode from the centralized to the distributed and vice versa [17], [36]. Using the previous research results [14], the most effective control method of the shunt active filter was identified under changes in the parameters of the power source and the connected load. This method based on phase conversions in the *dq* reference framework was used to control the shunt active filter. During simulation, the output passive filter configuration was changed as shown in Figure 3 [37].

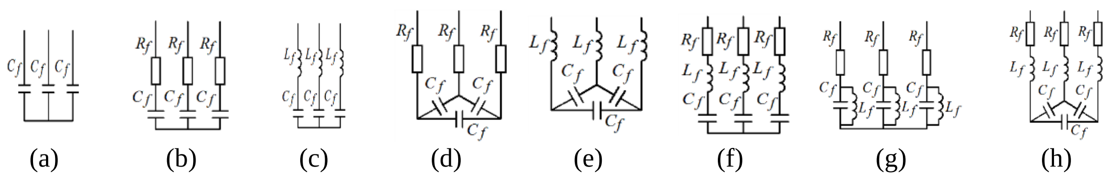

Figure 3. The configurations of the additional passive filter at the output of the shunt active filter in the hybrid structure (a) *C* filter, (b) series *RC* filter, (c) series *LC* filter, (d) triangle *RC* filter, (e) triangle *LC* filter, (f) series *RLC* filter, (g) combined *RLC* filter, and (h) triangle *RLC* filter

Figure 3(a) shows the sample capacitive filter, Figure 3(b) shows the series resistive-capacitive filter, Figure 3(c) shows the series inductive-capacitive filter, Figure 3(d) shows the resistive-capacitive filter with triangle connection of the capacitances, Figure 3(e) shows the inductive-capacitive filter with triangle connection of the capacitances, Figure 3(f) shows the series resistive-inductive-capacitive filter, Figure 3(g) shows the resistive-inductive-capacitive filter with shunt connection of the inductances and capacitances, Figure 3(h) shows the series resistive-inductive-capacitive filter with triangle connection of the capacitances. To implement the proposed research method, we used MATLAB/Simulink to develop a simulation model (see Figure 4).

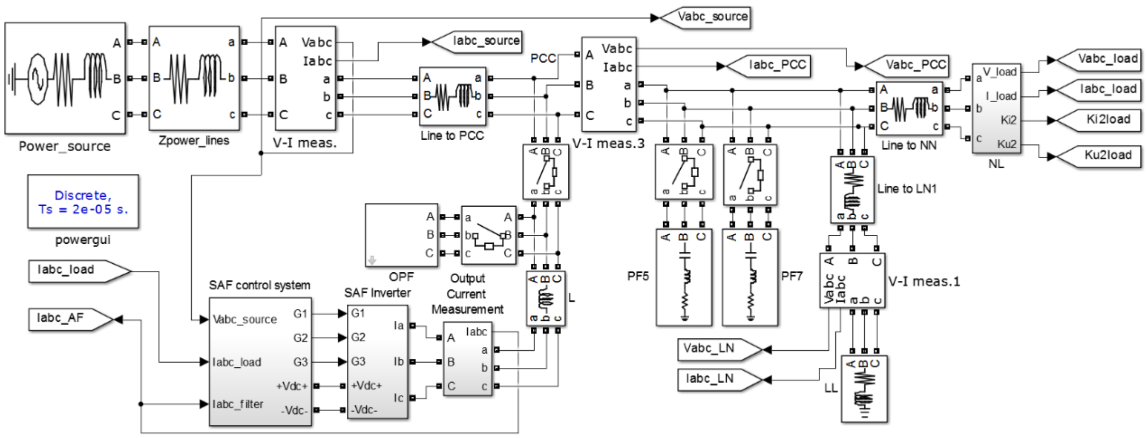

Figure 4. The resulting simulation model of a power supply system with linear and non-linear loads and a hybrid filter in MATLAB/Simulink

4. RESULTS AND ANALYSIS

The main results of computer simulation according to the proposed research method are presented in Tables 1-3. Table 1 shows the results which demonstrate that power quality indicators decrease when changing the structure of the passive filter at the output of the shunt active filter according to Figure 2. In Table 1, Δk_U and Δk_I are the degrees of decrease in total harmonic distortion for voltage and current, respectively, as shown in [14]. ΔU_s is the degree of decrease in source voltage deviation as shown in [14]. ΔI_s is the degree of decrease in source current as shown in [14]. Δk_{U2} and Δk_{I2} are the degrees of decrease in the unbalance factor for voltage and current, respectively, as shown in [14]. The most effective configuration of the output passive filter was selected to use in further simulation of hybrid filter performance as shown in Table 2.

In Table 2, you can see the results of hybrid filter performance under the minimum (1 p.u.) and maximum (10 p.u.) values of the internal impedance Z_s with the most effective configuration of the passive filter at the output of the shunt active filter. Table 3 demonstrates the results of hybrid filter performance under the maximum value of the internal impedance Z_s when the rated parameters of the shunt active filter decrease. The specified voltage of the storage capacitor decreases by 25%, the capacitance of the storage capacitor decreases by a factor of 4, and the inductance of the output chokes decreases by a factor of 2.

Table 1. The results of testing output passive filters with different configurations

Output passive filter with configuration shown in	Δk_U, %	Δk_I, %	ΔU_s, %	ΔI_s, %	Δk_{U2}, %	Δk_{I2}, %
Figure 2(a)	11.87	80	3.16	5.09	83.33	99.68
Figure 2(b)	11.03	72.73	2.27	6.10	83.33	99.60
Figure 2(c)	11.78	79.55	3.12	5.09	83.33	99.60
Figure 2(d)	11.59	80.47	2.95	5.21	80	99.60
Figure 2(e)	11.64	80.61	3	5.11	83.33	99.52
Figure 2(f)	11.77	79.76	3.16	5.09	83.33	99.69
Figure 2(g)	13.19	83.62	4.80	-1.91	66.67	99.62
Figure 2(h)	11.73	80.34	2.95	5.18	83.33	99.68

Table 2. The results of hybrid filter performance under the minimum (1 p.u.) and maximum (10 p.u.) values of the internal impedance Z_s

	Hybrid filter configuration	Passive filters PF5 and PF7 only	Passive filters PF5, PF7 and a shunt active filter	Passive filters PF5, PF7 and a shunt active filter with an OPF
Z_s = 10 p.u.	Δk_I, %	64.92	81.05	85.48
	ΔI_c, %	-1.06	1.60	0.87
	Δk_{I2}, %	-1.76	99.01	99.12
	Δk_U, %	49.76	-114.06	78.61
	ΔU_c, %	0.93	3.09	4.42
	Δk_{U2}, %	-1.53	98.47	98.47
Z_s = 1 p.u.	Δk_I, %	38.58	84.07	77.54
	ΔI_c, %	0.07	4.85	5.17
	Δk_{I2}, %	-0.52	98.95	98.78
	Δk_U, %	26.11	-168.47	49.75
	ΔU_c, %	0.13	0.44	0.63
	Δk_{U2}, %	-0.29	97.69	97.11

Based on the simulation results, the following main conclusions were made:

- The hybrid filter whose structure includes standalone passive filters for eliminating characteristic harmonics and a shunt active filter with an output passive filter is capable to eliminate voltage and current harmonics effectively under centralized, distributed, and hybrid power supply.
- The decrease in the rated parameters of the shunt active filter in the hybrid structure allows for maintaining the required level of current and voltage unbalance elimination, current reactive component compensation, and the efficiency of eliminating voltage dips and deviations under distributed power supply.
- The application of standalone passive filters for eliminating characteristic harmonics together with a shunt active filter with an additional output passive filter gives the opportunity to decrease the rated parameters of the shunt active filter as the most complex and expensive part of any hybrid filter.
- The presence of passive filters leads to an improvement in shunt active filter efficiency under distributed generation by a factor greater than 2.
- The structure of a hybrid filter based on active and passive filters should be variable according to the power quality indicators being corrected, the power supply mode, and the required residual level of power quality after compensation. The amplitude-frequency characteristic of the passive filter connected at the

active filter output is presented in Figure 5. This characteristic was obtained during modeling, and we can see that the impedance of the passive filter at the output of the active part should be within a range of 1 to 9 Ohm when eliminating harmonics from 5th to 40th.

Table 3. The results of hybrid filter performance under the maximum (10 p.u.) value of the internal impedance Z_s when the rated parameters of the shunt active filter decrease

Hybrid filter configuration	Passive filters PF5 and PF7 only	Passive filters PF5, PF7 and a shunt active filter	Passive filters PF5, PF7 and a shunt active filter with an OPF
Δk_I, %	64.92	24.19	78.63
ΔI_c, %	-1.06	-0.10	0.80
Δk_{I2}, %	-1.76	78.02	93.41
Δk_U, %	49.76	-6.97	74.16
ΔU_c, %	0.93	1.45	4.27
Δk_{U2}, %	-1.53	77.10	94.27

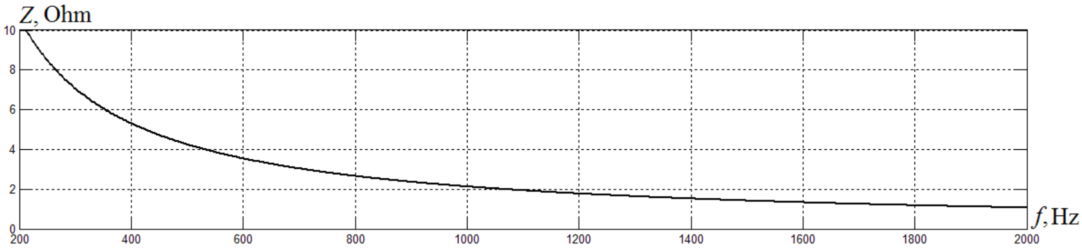

Figure 5. The amplitude-frequency characteristic of the passive filter connected at the active filter output

5. ADAPTIVE ALGORITHM TO CONTROL HYBRID FILTERS

An adaptive control algorithm to control hybrid filters should provide the following main stages and procedures to improve the power quality level and to ensure the multifunctional performance of such filters under hybrid power supply:

- The detection of power supply mode: centralized, autonomous, or hybrid. In the case of hybrid power supply mode, it is also necessary to know how the total load is distributed between the centralized source and the autonomous one. Besides, there is the case to be taken into account when the total load is connected to a busbar powered by a centralized source and an autonomous one working in parallel [38].
- The detection of connected load parameters: the correlation between linear and non-linear load, the responsibility level of each load according to the possibility of disconnection in the case of power supply shutdown [39].
- Power quality analysis to detect the critical values of power quality indicators to be reduced separately by several devices or simultaneously by one device. In the latter case, we have one multifunctional hybrid device based on active and passive filters whose structure depends on the given set of power quality indicators to correct [40].
- The detection of the primary source of poor power quality according to several indicators including voltage and current harmonics, voltage dips and deviations, source and load asymmetry. This stage helps to select properly the point of hybrid filter device installation when the primary reason of poor power quality is the power supply source, connected load, or network elements [38].

Also, all the stages indicated above may be considered as a methodology to select the structure and parameters of multifunctional hybrid filter devices under variations in power source and connected load characteristics. Besides, any complex multifunctional device should have the adaptivity feature to adjust its parameters, function mode, and structure according to changing external and internal factors. The proposed adaptive algorithm to control multifunctional hybrid filters under variations in source and load parameters is presented in Figure 6.

First of all, the proposed adaptive algorithm detects a power supply mode, including quantity of sources, their rated power and demand factor. Then there is a necessity to monitor power quality indicators and specify their critical values. Besides, we should know the primary origin of the poor power quality level. There are three main origins of the poor power quality level: the power supply source, the connected non-linear load and the network elements such as power lines, transformers and reactors. This stage helps to detect the type of active part and connection method of the hybrid structure under the given conditions. If current distortions from the non-linear load or the total load are the primary origin of the poor power quality we will use the current source converter or the shunt active filter as the active part of the hybrid structure. If voltage distortions from the local power source or the public network are the primary origin of the poor power quality we will use the voltage source converter or the series active filter as the active part of the hybrid structure. Also, the detected critical level of the certain harmonics determines number and tuning of the stand-alone passive filters as the part of the hybrid structure.

The following stages of the proposed adaptive algorithm deal with the model and control system of the active part. The different efficiency of the several widespread control systems of active filters under variable parameters of power source and connected load was detected in the researches [14]. Then the different parts of the selected hybrid filter are launched, during which power quality indicators are measured and evaluated. This stage helps to evaluate an influence of the active and passive parts within the selected hybrid structure on the power quality indicators. Using the results of the previous stages the hybrid filter adjusts parameters of the active and passive parts to improve the performance under variable parameters of power sources and connected load. Here the special attention should be paid on the potential permitted decrease of the active part parameters. Also, the proposed adaptive algorithm comprises the selection of the optimal configuration of the additional passive filter at the active part output. Finally the proposed adaptive algorithm ensures the flexible structure of the hybrid filters as multifunctional devices for the hybrid power supply systems.

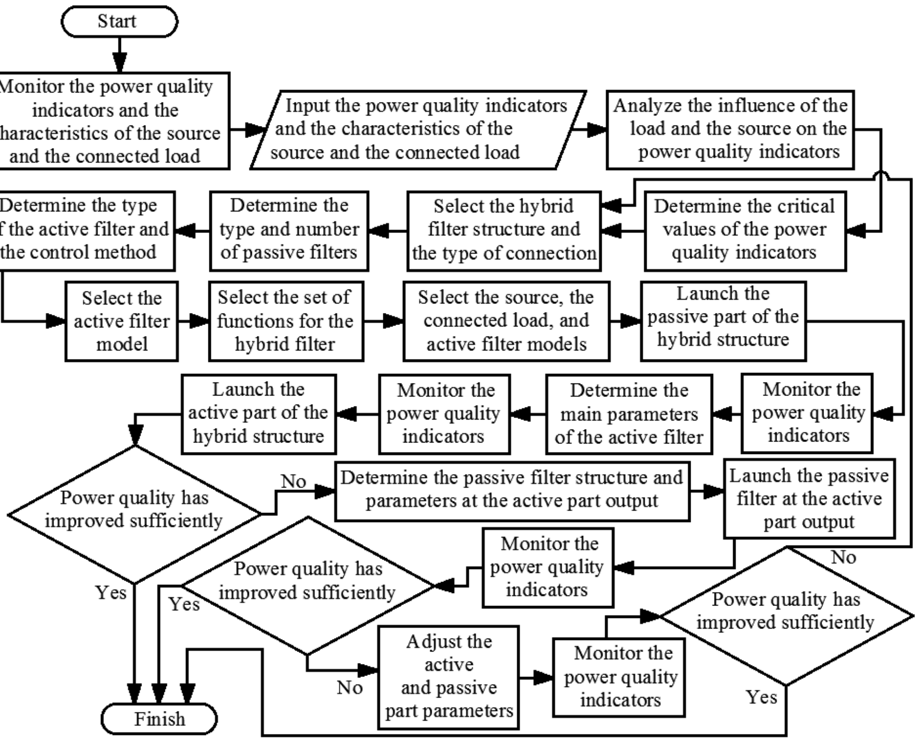

Figure 6. The proposed adaptive algorithm to control hybrid filters

6. DISCUSSION

The results obtained show the main idea of a paper that makes a case for using any hybrid filter based on active and passive parts as a multifunctional device for power quality improvement according to several indicators. Such a solution is quite reasonable because any hybrid filter is an expensive device [41] and we should try to use it for maximum functional performance. Besides, any multifunctional device or system should be integrated into more complex systems, for example, into hybrid power supply. According to the results of the study (see Table 3), it is obvious that a hybrid filter based on a shunt active filter is able to influence a wide range of power quality indicators, including voltage and current values. This feature enables such a hybrid filter to control both power supply and consumption, which is very important in hybrid power supply systems. A great number of Russian [42], [43] and international publications [44], [45], [46] consider active and hybrid filters as devices that can only be used for power quality improvement. Some articles prove the ability of shunt active filters to ensure an uninterrupted power supply. However, all of them do not take into account possible variations in power source and connected load parameters when studying the performance of hybrid and active filters. The articles mentioned present a theoretical framework for designing the structure, parameters, and characteristics of multifunctional hybrid filters to control power supply and consumption in hybrid power supply systems. The best way would be to develop a theory of multifunctional hybrid filters under variations in external conditions.

Similar results may also be obtained for hybrid structures based on a series active filter to eliminate voltage dips, deviations, and harmonics. This is the aim of further research. Any kind of active filter gives an opportunity to create a hybrid structure with different functional sets. The main advantage of using both active and passive filters within one hybrid structure is the opportunity to decrease the rated parameters of the active part as the most expensive one. Besides, creating more complex multifunctional devices based on shunt and series active filters such as unified power flow conditioners or unified power quality conditioner with additional passive elements is a very important research problem to solve [47], [48].

7. CONCLUSION

The article proves the necessity to have a multifunctional technical device to improve power quality according to several indicators under variations in power supply and consumption. Using hybrid filters is suggested for this purpose. In the study discussed, a hybrid filter was designed based on standalone passive filters and a shunt active filter with an output passive filter. A research method is proposed to analyze the performance of the given hybrid structure under variations in several factors. A simulation model of the hybrid structure was developed to implement the proposed research method. The results obtained show that the hybrid filter should have a variable structure to improve power quality under changing external factors and according to the given limitations of the residual values of power quality indicators. An adaptive algorithm to control multifunctional hybrid filters under variable external conditions is proposed. The results presented create a foundation for further research in the area of designing unified power quality conditioners based on active and passive filters.

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