

The assesement of the shunt active filter efficiency under varied power supply source and load parameters

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Article Info

Article history:

Received Oct 27, 2019

Revised May 16, 2020

Accepted May 28, 2020

Keywords:

Combined power supply

Distributed generation

Hybrid structure

Power quality

Shunt active filter

ABSTRACT

The results of theoretical and experimental studies on the problems of effective application of shunt active filters for power quality improvement and electromagnetic compatibility ensuring were presented in this article. Based on the different theories and methods, the most effective and well-studied control algorithms of shunt active filters were determined and analyzed to ensure their effective application in distributed generation systems and combined power supply systems. Mathematical and computer simulation models of shunt active filters with different control algorithms in distributed generation systems and combined power supply systems were developed. According to the results of mathematical modeling and computer simulation, the dependences were detected, reflecting the influences of internal and external parameters on the factors, determining the efficiency of the correction of power quality indicators. The range of permissible changes in the parameters of shunt active filters by saving the required efficiency level of power quality correction was detected under varied power supply system characteristics, load parameters and also in hybrid structures. The adaptive algorithm of the shunt active filter functioning under varied application conditions for automated power quality improvement is developed on the basis of the obtained range and dependences.

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1. INTRODUCTION

It is undeniable that ensuring power quality improvement and electromagnetic compatibility is critical in centralized power supply systems, distributed generation systems, and combined power supply systems [1-4]. The main negative influences of the poor power quality level on electrical equipment and power supply systems are well-known and have been studied in detail [5-10]. In particular, this problem has become more significant considering the intensive development of technologies and the principles of distributed generation from alternative and renewable power sources and combined power systems, where both centralized and distributed sources work in parallel mode.

Nowadays, there is a set of different devices and solutions for power quality improvement. Among them it is reasonable to indicate passive and active devices [5]. Passive devices are not so effective in the conditions of combined power systems [7]. Active devices, such as the shunt active filters, are able to improve power quality in the adaptive mode by means of the special control methods and algorithms [9]. But in case of the shunt active filters application in conditions of variable type of power source and connected load there is the problem of proper selection of the main parameters of these filters for saving the required power quality level, especially in the combined power systems. Also it is very important to

choose the optimal control method of shunt active filter for performing the adaptive power quality improvement mode. Besides an active filter is an expensive and multifunctional device for several power quality indicators improvement. The efficiency level of such improvement depends on the control method type and external factors [11-16].

Hereby in conditions of the combined power systems with variable source and load type and parameters there are the following main problems of the efficient shunt active filter application for power quality improvement [17-20]:

- The great amount of control methods for active filters, with some advantages and disadvantages, which have been studied and proved only for the special application conditions and limitations.
- The opportunity to improve several power quality indicators by one multifunctional device, such as the active filter, is limited by the absence of the universal adaptive control algorithm.
- The high cost of active filter, which can be decreased by the proper selection of the filter's main parameters or their decreasing in the permitted ranges according to the application conditions.

The complex solution of the mentioned problems is proposed in this paper by the developing of the universal adaptive algorithm of the shunt active filter functioning in conditions of the combined power systems with variable source and load parameters. The basis of the developed algorithm is the obtained dependences of the power quality improvement indicators from the internal and external parameters for the different types of active filter control method. The developed algorithm and the obtained dependences are new in the developing of the active filters application theory and practice.

The contributions of the proposed solution in the theory and practice of active filters application are the following:

- The improvement of shunt active filter performance in conditions of the combined power supply systems, when parameters of the source (centralized or distributed) varies in the wide range as well as parameters of the connected load in the case of changing power supply mode during failures in centralized network.
- The possibility to effectively realize the multifunctional device on the basis of one shunt active filter for improvement of several power quality indicators.
- The possibility of adaptive changing of shunt active filter parameters according to the given set of the internal and external factors with saving the required power quality improvement performance.

The indicated solution can be achieved due to the following research method.

2. RESEARCH METHOD

The main idea of the proposed research method is to detect and analyze the performance of different control ways of shunt active filter under variation of external and internal factors. Here the external factors are the parameters and characteristics of power source and connected load, and the internal factors are the parameters and characteristics of shunt active filter. The main purpose of such method is to determine the optimal control way of shunt active filter under the given set of different factors, when this filter is used as a stand-alone device or a part of multifunctional device for power quality improvement. The proposed research method consists of three main stages.

2.1. The first stage

The first stage is the selection of character control ways from all plenty of the existing methods and theories for the further research. According to the results of numerous theoretical and experimental studies [7, 8, 21-26], the ways developed for the determination and correction of power quality indicators for shunt active filter control may be divided into three main groups [27-30]:

- Ways based on discrete (DFT) and fast Fourier (FFT) transformations [31-35].
- Ways that extract the reference values of current or voltage using the theories and methods of current physical components (CPC) [22, 23, 36].
- Ways based on phase transformations in different reference frameworks ($\alpha\beta$, dq, Clarke transformations) [25].
- Ways that use the theories and methods of instantaneous power components [24, 27] (p-q theory), developed by H. Akagi.
- Fuzzy logic ways [37, 38].

All of the mentioned ways have been described, studied, and proved [22-36] under special power source and connected load conditions, but there are no results on the comparative analysis of the efficiency levels of these ways under different power source and connected load conditions. The potential results of such analysis are determination of the main stage of the theory of structural and parametric synthesis of electrical complexes for power quality improvement on the basis of active and passive filters. Also, such

analysis is necessary because an active filter is a controllable part of any hybrid structure. That is why the main method of modeling and simulation is the comparative analysis of the mentioned ways under varied power source, connected load, and active filter conditions.

For this purpose, a simulation model of the power supply system with linear and non-linear loads was developed using Matlab Simulink software. Also, this model contains the shunt active filter with different control ways. For simulation purposes, the following widespread ways for shunt active filters control, which have been proven for application, were selected [22-36]:

- A way based on the p-q theory with a special regulator of the voltage of the storage capacitor (way #1).
- A way based on the phase transformations in the reference framework $\alpha\beta$ (way #2).
- A way based on the CPC theory with DFT or FFT (way #3).
- A way based on the phase transformations in the reference framework dq (way #4).
- A way based on the p-q theory without the special voltage regulator of the storage capacitor (way #5).

The initial rated parameters of the shunt active filter for each control way were the same.

The indicated control ways have some limitations and assumptions. According to the results from experimental studies and computer simulations [25, 34, 35] control ways #2 and #4 demonstrate the maximum efficiency level under conditions of traditional centralized power supply systems with little value placed on internal impedance and short-circuit power. Control way #3 can effectively eliminate harmonics under a constant current level, which is consumed by the connected non-linear load. As shown in some publications [26, 39], control ways #1 and #5 have maximal efficiency only under conditions of three-phase three-wire systems. Fuzzy logic control ways [37, 38] are the modern class of active filters control algorithms and their efficiency is defined by the special features of power source and connected load. That is why the area of such ways application is limited.

All parameters of the developed model, including the parameters of the source, power line, load node, and shunt active filter, were the same for each studied control way. These parameters were selected according to the results of experimental research [7, 8]. The initial parameters of the shunt active filter were set according to the optimal relationship between the rated current of the non-linear load I_{nm} and the rated current of the filter I_{saf} detected during experimental research [7, 8] using the criterion of harmonic minimization:

$$I_{saf} = (0.5 - 0.7)I_{nm} \quad (1)$$

During modeling, the parameters and settings of the regulators of the active filter control system for each studied control way were unchanged.

2.2. The second stage

The second stage is the indication of the simulation process sequence, which includes the following steps:

- A comparative analysis of the efficiency level of these control ways when changing the correlation β of active powers of non-linear (NN) PNN and linear (LN) PLN loads at the point of common coupling (PCC). The correlation factor β is calculated as follows:

$$\beta = \frac{P_{NN}}{P_{NN} + P_{LN}} \cdot 100 \% \quad (2)$$

- A comparative analysis of the efficiency level of these control ways when changing the internal reactance of the power source X_s [39].
- A comparative analysis of the efficiency level of these control ways when changing the reference voltage of the storage capacitor U_{dc} , the inductance of the output choke L , and the capacitance of the storage element C_{dc} of the shunt active filter.
- The comparative analysis of the efficiency level of these control ways when changing the point of connection of the shunt active filter's primary current and voltage sensors at the PCC, at the non-linear load terminals, and at the source side, as shown in Figure 1.

In the proposed research method, the parameters C_{dc} , L , and U_{dc} are considered as the internal factors and the parameters X_s and β are considered as the external factors during the analysis of the shunt active filter behavior.

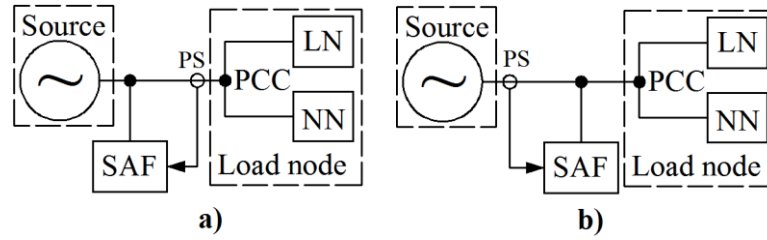


Figure 1. The point of connection of the primary sensors (PS) of the shunt active filter (SAF), (a) at the point of common coupling (PCC); (b) at the source side

2.3. The third stage

The third stage is the detection of the efficiency indicators, which reflects the degree of power quality improvement due to application of shunt active filter with different control ways. For the evaluation of the shunt active filter efficiency with different control ways, the following indicators were considered. The indicator of the degree of voltage total harmonic distortion factor (THD_U) correction was determined as follows:

$$\Delta THD_U = \frac{THD_U' - THD_U''}{THD_U'} \cdot 100 \% \quad (3)$$

In (3), THD_U' and THD_U'' are the total harmonic distortion factors [40] for voltage at the PCC before and after shunt active filter connection. A similar indicator is applicable for the evaluation of the degree of current total harmonic distortion factor THD_I correction (ΔTHD_I) and also for the degree of correction of the voltage (Δk_{U2}) and current (Δk_{I2}) unbalances factors [41] for the negative sequence components of voltage U_{ns2} and current I_{ns2} . One should note here that the voltage unbalance factor k_{U2} [41] for the negative sequence components is determined and regulated using the Russian national standard GOST 32144-2013 of power quality [41] according to the following:

$$k_{U2} = \frac{U_{ns2}}{U_{ps1}} \cdot 100 \% , \quad (4)$$

where U_{ns2} and U_{ps1} are the negative and positive voltage sequence components, respectively. The current unbalance factor k_{I2} can be determined similarly to equation (4) for the evaluation of the influence of the load unbalance on the power quality level. The indicator of the degree of correction of voltage dips and deviations ΔU is determined according to the following:

$$\Delta U_s = \frac{U_1 - U_2}{U_r} \cdot 100 \% = \frac{(U_r \pm \Delta U_1) - (U_r \pm \Delta U_2)}{U_r} \cdot 100 \% , \quad (5)$$

where U_r is the rated value of the network voltage, and U_1 and U_2 are the network voltages before and after shunt active filter installation. The indicator ΔU_s helps to determine the efficiency of correction of both positive and negative voltage deviations [42, 43].

The indicator, which reflects the degree of decrease in the current consumed by the load node due to elimination of the reactive and non-active power components, is determined as follows:

$$\Delta I_l = \frac{I_1 - I_2}{I_1} \cdot 100 \% , \quad (6)$$

where I_1 and I_2 are the currents consumed by the load node before and after shunt active filter installation.

Hence, the values of the mentioned efficiency indicators will show the features of each studied control way when the shunt active filter application under the different set of internal and external factors [44-47]. Hereby the all stages of the presented research method allow obtaining the required regularities, assessing the presented indicator's values and developing the adaptive algorithm of shunt active filter control under variation of external and internal factors.

3. RESULTS

The dependences of the indicators of the efficiency of power quality correction by means of the shunt active filter with different control ways (#1-5) at the PCC determined from the variation of the internal reactance of the power source X_s are presented in the Figure 2. The similar dependences were obtained for the variation of other factors C_{dc} , L , U_{dc} and β . In the Table 1 the results of power quality indicators correction by means of the shunt active filter with different control ways are presented for the initial parameters of power source, load and filter.

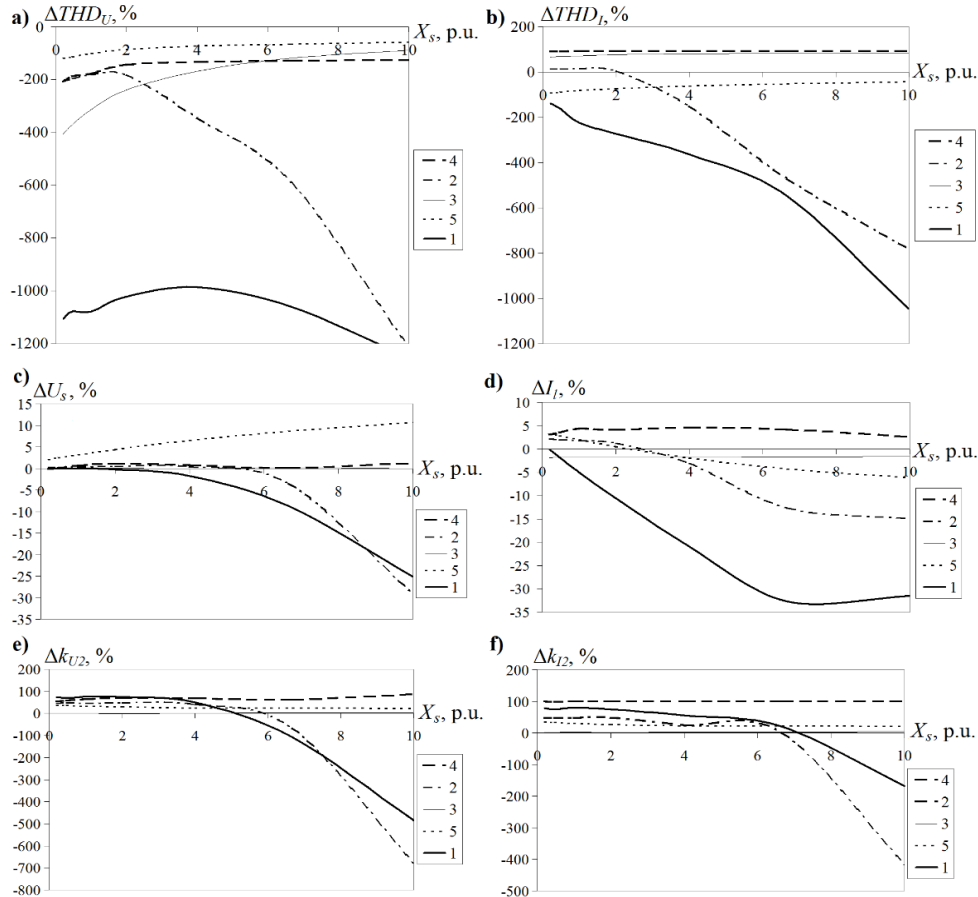


Figure 2. The dependences of the indicators of the efficiency of power quality correction at the PCC determined from the variation of the internal reactance of the power source X_s , (a) ΔTHD_U ; (b) ΔTHD_I ; (c) ΔU_s ; (d) ΔI_i ; (e) Δk_{U2} ; (f) Δk_{I2}

Table 1. The results of power quality indicators correction

Algorithm	ΔU_s , %	ΔTHD_U , %	ΔI_i , %	ΔTHD_I , %	Δk_{I2} , %	Δk_{U2} , %
#1	-0.10	-1078.6	-5.00	26.37	79.06	75.61
#2	0.39	-180.66	1.83	41.29	47.64	46.34
#3	0.07	-313.79	-1.78	80.58	2.27	0.00
#4	0.62	-192.59	4.35	93.67	99.13	63.41
#5	3.15	-101.23	2.03	-40.81	30.89	32.93

According to the results of the simulation and during the analysis of the obtained regularities the following main conclusions were made:

- None of the studied algorithms allow the voltage harmonics from the source to be corrected efficiently when changing internal and external factors.
- The most effective algorithm for the stable correction of current harmonics, unbalance, and non-active power components is the method based on the phase transformations in the reference framework dq (way #4). The satisfactory level of the efficiency of this algorithm is fully saved in a whole range of internal impedances of the source and internal parameters of the shunt active filter.

- The most effective algorithm for the stable correction of voltage dips and deviations is the method based on phase transformations that uses p-q theory without the special regulator of voltage of the storage capacitor (way #5). A satisfactory level of efficiency of this algorithm is fully conserved across the whole range of internal impedances of the source.
- None of the studied algorithms allow the voltage unbalance of the source to be corrected efficiently when changing the internal and external factors across the whole range.
- In areas with small internal impedance values of the source (traditional centralized power supply systems), ways #2, #3, and #4 possess the maximal current harmonic correction efficiency.
- In areas of small internal impedance values of the source (traditional centralized power supply systems), all studied algorithms allow the voltage unbalance and deviations and the current unbalance of the load to be corrected, with the exception of way #3.
- Under conditions of variation in the correlation between the rated active powers of the linear and non-linear loads β in the PCC, the most efficient current harmonic correction is shown by ways #3 and #4.
- In areas with large internal impedance values of the source (distributed generation systems), the greatest efficiency in the elimination of current harmonics and non-active current components is shown by way #4.
- Changes in the capacitance of the storage capacitor of the shunt active filter within the set range do not significantly influence the indicators of the efficiency of the power quality correction for ways #2, #3, #4.
- The increase in the inductance of the output chokes of the shunt active filter allows the efficiency of the voltage and current harmonic correction to be improved for all algorithms. However, for way #2, the significant increase in such inductance leads to a sharp decrease in the efficiency of the voltage and current unbalance correction, the voltage dips elimination, and the non-active power components compensation.
- Changes in the reference voltage for the storage capacitor of the shunt active filter significantly influence the indicators of the efficiency of power quality improvement only in the case of way #4.
- The efficiency level of the shunt active filter in the case of primary sensors connection at the PCC is better on the whole than in the case of primary sensors connection at the source side. However, when way #4 is applied, the placement of primary sensors at the source side allows the maximal level of the efficiency of voltage deviation correction to be reached compared with other algorithms and with the placement of such sensors at the PCC.

It must be noted that the obtained results help to properly select a control way for shunt active filter control according to the given conditions of the filter's installation and application [48-52]. The obtained results have given an opportunity to develop the adaptive algorithm of the shunt active filter functioning under varied application conditions for automated power quality improvement. The developed adaptive algorithm is presented in the Figure 3. This algorithm allows shunt active filter to be integrated into the automated monitoring and control systems as one of the main elements, taking part in the forming of informational and control interactions.

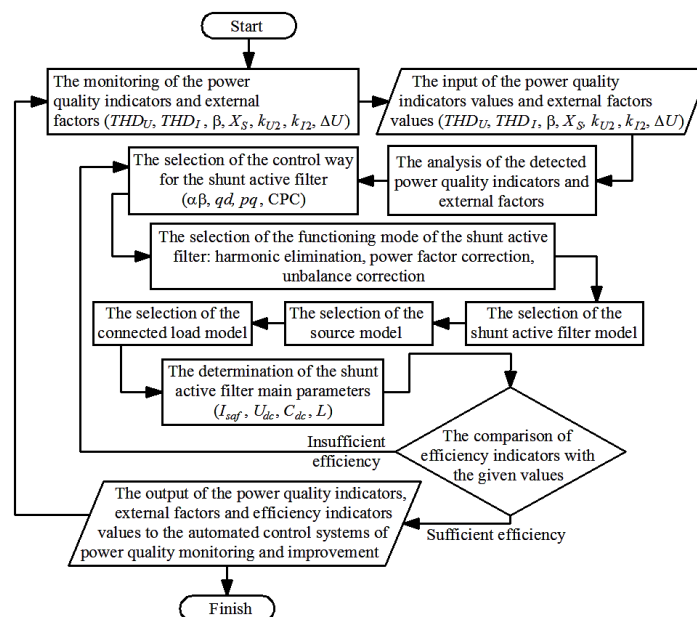


Figure 3. The adaptive algorithm of the shunt active filter functioning under varied application conditions for automated power quality improvement

4. DISCUSSION

The first thing that needs to be said is that the problem of power quality improvement by means of active, passive, and hybrid filters has been considered in many scientific publications. In these publications, authors have focused on the structure of hybrid filters, the control algorithm of the shunt or series active filters, and the evaluation of the efficiency of certain structures under specified conditions of the power source, network, and connected load [1]. From a theoretical point of view, such research is very useful and may be used as the basis for more significant research.

Here, special attention should be paid to modern trends in electrical energy technologies. The first trend is the complex application of distributed generation technologies on the basis of alternative and renewable energy sources such as wind farms, solar stations, and micro turbine installations working on natural or associated petroleum gas. The second trend is the technologies and methods used for the parallel functioning of centralized and distributed sources in the framework of combined power supply systems [39, 42, 43]. The third trend is the usage of active converters as the main elements of electrical complexes of alternative and renewable sources. The fourth trend is the implementation of several different functions in the framework of one active converter, active filter, or hybrid filter. According to the mentioned trends, for active converters and filters to be presented as parts of an electrical complex of a power source, as elements of a distribution network (e.g., UPFC) [12], and as parts of a connected load, it is necessary to have unified theoretical and methodical propositions for the development and application of such converters and filters under different conditions. Also, we cannot ignore the fact that the centralized and distributed power supply systems possess different parameters and characteristics which must be taken into account in the selection of structures, key parameters, and control algorithms of active converters, active, passive, and hybrid filters, and their applications [33, 34]. That is why it is necessary to research the behavior of active and hybrid filters under varied conditions of internal impedance of the power source when we need to change the power supply mode from centralized to distributed and vice versa in emergency cases in combined power supply systems.

Another thing about this method is that there is a great number of different control algorithms that can be used for active converters and filters as controllable devices, especially for shunt active filters. These algorithms have been created, described, and proven in many scientific publications for specified conditions of its application [22]-[36]. Besides, some algorithms are improved versions of previous similar algorithms with no significant and minimal changes. That is why it is necessary and reasonable to give a general classification of all existing and proven algorithms of active filter control and to extract the most effective and fundamental ones. On the assumption of application conditions of active filters as standalone devices or as part of a hybrid structure in centralized, distributed, and combined power supply systems, it is necessary to research the efficiency levels of the extracted algorithms. The results of such studies allow the methodology for the proper selection of the control method for active filters to be created. Also, these results are a key part of the theory of structural and parametric synthesis of electrical complexes for power quality improvement on the basis of active and passive filters [37-44].

It is undeniable that any hybrid filter structure is intended to decrease the rated parameters of the active part by means of the properly tuned passive filters, because the active part is the most expensive part. That is why it is reasonable to detect the degree of this decrease under different application conditions and for the most widespread types of hybrid structures [35, 43]. Also, one of the main ideas of the presented paper is to show the range in which the parameters C_{dc} , L , and U_{dc} can be changed when the active filter is the part of the hybrid structure or when it is working under combined power supply conditions when the internal impedance of the power source is changed [45-48].

In addition, when we select the parameters C_{dc} , L , and U_{dc} for specific operating conditions, we do not take into account the fact that these conditions may change (due to failures in power systems, faults, and changes in the power source). That is why it is useful and reasonable to know the ranges of selection of the parameters C_{dc} , L , and U_{dc} during the application of the active filter under complicated conditions without resetting the regulators' parameters and while saving the filters' operating efficiency. An active filter is quite an expensive device and it should be rated to work not only under special conditions but under a wide range of conditions with minimal changes in C_{dc} , L , and U_{dc} and regulator settings. Also, the presented ranges of selection of the parameters C_{dc} , L , and U_{dc} help us to detect the possible decrease in the cost of the active filter while retaining the filters' operating efficiency [49-52].

Also, in case of adjustment of the active filter on-side, it is very difficult to choose and tune the parameters of regulators if the real parameters of the power system differ from those designed. This fact has been proven during our experimental research experience [7, 8]. The above-mentioned facts illustrate a very important, serious, and actual problem of the theory and methodology of structural and parametric synthesis of electrical complexes for power quality improvement on the basis of active and passive filters [43]. The presented results are only one of the several stages of this theory and methodology. The main

subject of future research in this area is the development of theory and methodology for the complex integration of multifunctional active converters and active and passive filters in the structure of combined power supply systems, working on the basis of parallel functioning of centralized and distributed sources.

5. CONCLUSION

The results of theoretical and experimental research in the area of the proper selection of control algorithm and main parameters of the shunt active filter under variation of the characteristics of power source and connected load were presented in this article. The presented results are intended to aid in the design and development of the theory and methodology of the selection of the structure, content, functional mode, key parameters, and control algorithm of the electrical complexes related to power quality improvement on the basis of active and passive filters. Using mathematical modeling and computer simulation, the dependences of the indexes of power quality correction efficiency under varied external and internal factors were obtained. These dependences should be considered as the key stage of the design and development of the theory and methodology of structural and parametric synthesis of the electrical complexes related to power quality improvement on the basis of active and passive filters.

The main contribution of the results presented in this paper is the determination of the ranges in which the main parameters of shunt active filters may be changed in the framework of hybrid structures and under conditions of variation in the power supply system characteristics while retaining the required efficiency level for power quality indicator correction. These ranges also allow the cost of the active part, which is the most expensive part of any hybrid structure, to decrease. The detected dependences and proposed adaptive algorithm are intended to help properly choose the structure and control way of shunt active filter under variable power source parameters and connected load characteristics. Also the proposed adaptive algorithm allows integrating the shunt active filter into the complex systems of automated power quality control, monitoring and improvement.

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