Mathematical modeling of harmonic correction by parallel active filter in conditions of distributed generation

Yu A Sychev, B N Abramovich, R Yu Zimin, P A Kuznetsov

Saint-Petersburg Mining University, 2, 21 Line Ave., Saint-Petersburg, 199106, Russia

E-mail: sychev_yura@mail.ru

Abstract. The methodology for selecting the parameters of a parallel active filter to compensate higher harmonics in a power supply system with distributed generation has been validated. The structure of the parallel active filter based on power transducer elements is proposed in the paper. A control system for the parallel active filter in conditions of power supply systems with distributed generation based on phase conversions and relay controllers with variable width of hysteresis has been developed. A mathematical model of the parallel active filter with the proposed control system in the power supply system with distributed generation has been developed. The dependences between the performances of higher harmonics compensation by the parallel active filter with the developed control system have been obtained according to the simulation results.

1. Introduction
Nowadays the technologies and principles of distributed generation from alternative and renewable energy sources in the form of wind-driven power-plants, solar electric generating stations and microturbine units, running on associated petroleum gas, are applied intensely in power supply systems [1, 2]. As a rule, such systems operate in the stand-alone mode or in parallel with the centralized power supply system, in the latter case a combined power supply is meant [3, 4]. Nevertheless, the issue concerning electric energy quality and ensuring electromagnetic compatibility of electrical equipment in terms of the level of higher harmonics in current and voltage remains a matter of urgency even in conditions of distributed generation and combined power supply [3, 4].

Currently, the Scandinavian countries, Germany, Denmark, the Netherlands are the leaders in the field of implementation of the distributed generation on the basis of alternative and renewable sources. In some of them, the share of sources with distributed generation exceeds 70%. Solar batteries and wind-powered generators appeare to be the most widely-spread. In Russia, the share of distributed generation sources running on the renewable energy sources has not yet reached such volumes however, the share of new projects to be introduced is continuing to grow. Thus, according to the data of Federal Environmental, Industrial and Nuclear Supervision Service of Russia, the share of distributed generation source should increase 10 times within the period from 2008 to 2015, and the total capacity of the new installations should be 1.8 GW [1, 2]. That is why the problem of power quality improvement in conditions of distributed generation becomes quite important and actual.

2. Research methods
The nonlinear load in the form of a variable-frequency electric drive of processing installations is the
main source of higher harmonics in current. Such load takes place in virtually all sectors of industry, regardless of the power supply system type (either centralized or distributed). The electrotechnical complexes of distributed generation sources in the absolute majority of cases [5, 6] comprise power converters in the form of voltage inverters with various pulse-width modulation algorithms [7]. The output voltage of the inverters comprises higher harmonic voltage components. Thus, the sum-total of higher harmonics in current on the side of the nonlinear load and higher harmonics in voltage on the side of the distributed generation sources forms a nonsinusoidal electric mains mode. Such mode should be subject of correction in compliance with the requirements of the national and international standards in the field of electric energy quality [5, 7].

Under emergency modes of operation, when the power supply mode is switched from a centralized network to a distributed generation system, the internal power supply source reactance varies considerably. This factor must be taken into account when selecting a technical means or a solution in order to correct nonsinusoidal modes [1, 2, 3]. Passive filters are adjusted to compensate for one or more canonical harmonics, taking into account the supply mains reactance and short-circuit power. On change of these parameters, when changing the power supply mode, the adjustment accuracy of the filters decreases. Serial and parallel type active filters, implemented on the basis of power converters, can be effectively used as a means to correct nonsinusoidal modes and as a component of electrotechnical complexes of alternative and renewable energy sources [8, 9].

Most renewable energy sources cannot be connected directly to the load. The integration of renewable energy sources with load has complexities associated with the system stability, voltage adjustment and electric power quality. For example, the output power, frequency and voltage of a standard wind-powered generator depend on the wind speed, which varies with time, and these variations cannot be predicted to the specified accuracy. Meanwhile, the consumer's load nonlinearity increases steadily with the increase in the utilization rate of any devices with a rectifier at the output. The load nonlinearity deflects current and voltage waveforms on the distribution bus from their sinusoidal shape, thereby increasing the total harmonic distortion (THD) and polluting the mains.

3. Structure of the parallel active filter

Let us consider the possibilities and features of correcting higher harmonics in conditions of distributed generation and combined power supply by the example of the parallel active filter.

Correction systems for current and voltage curves based on the active filters, built on the basis of modern power semiconductor devices, ensure more efficient compensation of higher harmonics in current and voltage compared to the passive filters. Introduction of IGBT, GTO and GCT power transducer elements made it possible, via using them, to correct the power factor of the load and suppress higher harmonics in current and voltage in power supply systems of oil-and-gas production enterprises [8]. The parallel active filter is effective for harmonics compensation in 0.4 kV distribution networks, regardless of the selected point of common coupling and the nonlinear load type.

The basic parameters required for the correct selection of the parallel active filter when connecting to the electric mains are the following [10, 11]:
- the frequency range width ensuring the suppression of the majority of harmonic components in the load current, within statistical limits. Generally, the frequency range from 2 to 23 harmonics is considered sufficient;
- the response time sufficient for effective compensation of harmonics both in steady-state and in transition mode (several fractions of a ms);
- the rated power (or rated current) of the filter, determined by the power of higher harmonics generated by the nonlinear load, and the distortion power.

The correct choice of these three key parameters ensures the efficiency of compensation of higher harmonics by the parallel active filter. It is possible due to the self-adapting ability of the filter and the absence of the risk of resonant interactions with the electric mains reactance when switching power supply from one source to another. The parallel active filter, as shown in Figure 1a, consists of three main parts: the power part, the control system and the storage element.
The power part is designed in the form of a reversing inverter and an output smoothing passive filter or reactor.

The reversing inverter performs two main functions: generating compensation current to the mains and charging the storage element ($C_s$) to maintain the required voltage level. Thus, the reversibility of the inverter is the ability to generate energy to the mains or consume energy from the mains. The reversing inverter, as was already mentioned, is designed on the basis of IGBT-type transistors ($k_1$, $k_2$, ..., $k_6$), which are bypassed by diodes. The latter are necessary for rectifying the alternating current, consumed from the mains, to charge the storage element. Smoothing chokes ($L_a$, $L_b$, $L_c$) are required to reduce the ripple of the current generated to the mains, since the inverter operates in the pulse-width modulation (PWM) mode, and the inductance helps to smooth the stepped configuration of generated current [10].

A capacitor acts as a storage element, the voltage on the capacitor plates is applied to a reversing inverter, with the compensation current flowing through and the waveform of which is determined by the operation mode of inverter power switches [12].

4. Algorithm of higher harmonics compensation via using the parallel active filter in conditions of the distributed generation

The developed control system includes a microprocessor of data processing or a special controller, current and voltage sensors, a pulse shaper, an amplifying device for converting low-level control signals into control signals of power elements for the inverter [13].

Current sensors measure the distorted nonlinear load current ($i_{an}$, $i_{bn}$, $i_{cn}$) and current generated by the inverter ($i_{af}$, $i_{bf}$, $i_{cf}$). The obtained measuring data enters to the inputs of the microprocessor of the control system [14].

The microprocessor processes the data obtained from the measuring transducers and, in accordance with the preprogrammed algorithm of higher harmonics compensation, generates reference current signals ($i_r$). The obtained reference signals and measuring signals of current generated by the inverter ($i_f$) enter the input of the pulse shaper, wherein a hysteresis current controller serves as the pulse shaper. Since the inverter, operating in the PWM mode, creates a certain error when generating circulating current, it is necessary to compare the reference signal with actual generated current ($i_f$). This function is performed by a relay current controller. Having processed the signals, the relay current controller generates control pulses, then control signals are fed to control electrodes of power switches [14]. Thus, the waveform and the harmonic spectrum of current generated by the inverter are defined by the law of controlling the power switches. This law is formed by the control system on the basis of measuring data on the waveform and the spectral composition of the distorted mains current.

Due to the fact that the parallel active filter is controlled on the basis of data obtained from current sensors, it dynamically adapts to shifts in the harmonic spectrum generated by the nonlinear load.
5. Simulation of the parallel active filter with the proposed control system in conditions of the distributed generation

A mathematical model of the parallel active filter has been developed according to the MathLab mathematical computing system, the Simulink software package, based on the schematic diagram presented in Figure 1b.

According to Figure 1b, the nonlinear load is represented as a three-phase bridge diode rectifier, to which the load, having the parameters \( R_r \) and \( X_s \), is connected. The main features of the rectifier operation mode depend on the commutating angle \( \gamma \). The linear active induction load with the parameters \( R_{lna}, R_{lnb}, R_{lnc} \) and \( X_{lna}, X_{lnb}, X_{lnc} \) is connected to the 0.4 kV mains. Both loads are connected to the mains via lines, represented in the form of resistances \( X_{lna}, X_{lnb}, X_{lnc} \) for the nonlinear load and \( X_{l2a}, X_{l2b}, X_{l2c} \) for the linear load. A three-phase alternating voltage source of 380 V with internal reactance \( X_1 = 3.14 \) mOhm is used as the supply mains. The linear load with the parameters \( R_{ln} = 0.1 \) Ohm, \( X_{ln} = 3.14 \) Ohm is connected to the mains through a line with the reactance of \( X_{l2} = 0.02 \) Ohm. The parallel active filter is presented in the form of an inverter on the basis of IGBT-type transistors, a storage capacitor with a capacity of \( C_{dc} = 15 \) mF, a control system and a smoothing choke with the following parameters: \( R_f = 0.2 \) mOhm; \( X_f = 0.157 \) Ohm.

According to the simulation results, the value of the total harmonic distortion (\( k_t \)) in current at the connection point of the filter has decreased from 22.74% to 2.02%, and the value of the total harmonic distortion (\( k_U \)) in voltage at the connection point of the filter has decreased from 10.16% to 2.6%.

Figures 2a and 2b, correspondingly, show the dependences of the total harmonic distortion in current \( k_t \) and voltage \( k_U \) of the mains before (curve 1) and after (curve 2) compensation depending on the length of the line connecting the nonlinear load with the mains \( l_{nn} \). Figure 2c shows the dependences of the performance levels of compensation the total harmonic distortion in voltage (\( \Delta k_U \) – curve 1) and in current (\( \Delta k_t \) – curve 2) by the parallel active filter, and the value of the supply mains internal reactance \( X_s \) in relative units (p.u.), wherein the internal reactance value of the ideal centralized power supply system is taken as the basis (3.14 mOhm).

Figure 2a shows that with an increase in the length of the line, connecting the nonlinear load to the mains, the nonsinusoidal ratio of the mains current before compensation decreases. This fact is associated with the smoothing effect of inductance, and the nonsinusoidal ratio of the mains current after compensation remains near constant, ranging from 2.2 to 2.5%.

Thus, according to the results of the mathematical simulation, the limited efficiency of the conventional parallel active filter is shown in conditions of variation in the supply mains internal reactance when switching from the centralized to the stand-alone power supply mode.

The simulation results showed the necessity of installation of the high-frequency passive filter at the output of the inverter of the parallel active filter in the conditions of the distributed generation at a significant value of internal reactance of the source. When this filter is installed, the performance of the parallel active filter in the conditions of the distributed generation increases significantly. Meanwhile, according to the simulation results, the performance of the correction \( k_U \) reaches 30%, the performance of the correction \( k_t \) reaches 80%.

Figure 3a shows the dependences of the total harmonic distortion in current \( k_t \) of nonlinear load input current (curve 1), of total network current before compensation (curve 2) and of total network current after compensation (curve 3) depending on the ratio of rated active power of nonlinear load \( P_{nn} \) to total active power of linear and nonlinear loads \( (P_{nn} + P_{ln}) \). Figure 3b shows the dependences of the total harmonic distortion in voltage \( k_U \) before (curve 1) and after (curve 2) compensation depending on the ratio \( \beta \). Figure 3c shows the dependence of power factor \( k_{pf} \) after correction depending on the ratio \( \beta \).
Figure 2. a – the dependences of $k_I$ of the mains before (curve 1) and after (curve 2) compensation depending on the $I_{mn}$; b – the dependences of the $k_U$ of the mains before (curve 1) and after (curve 2) compensation depending on the $I_{mn}$; c – the dependences of the $\Delta k_U$ (curve 1) and $\Delta k_I$ (curve 2) by the parallel active filter depending on the $X_s$.

The point A (see Figure 3a, when $\beta=0.72$) shows the moment when the character of changing $k_I$ after compensation becomes similar to $k_I$ before compensation. Also the point A (see Figure 3b) shows the limit when the installation of the parallel active filter is needed according to the requirements of Russian standard in power quality area. The point B (see Figure 3a, when $\beta=0.2$) shows the moment when the value of $k_I$ of total current is the same before and after compensation. The point C (see Figure 3a, when $\beta=0.88$) shows the moment when the parallel active filter turns to overcompensation mode. All these moments should be considered when developing the parallel active filter structure, control algorithm and choosing of its main parameters.
Figure 3. a – the dependences of total harmonic distortion in current $k_I$ of nonlinear load input current (curve 1), of total network current before compensation (curve 2) and of total network current after compensation (curve 3) depending on the ratio $\beta$; b – the dependences of total harmonic distortion in voltage $k_U$ before (curve 1) and after (curve 2) compensation depending on the ratio $\beta$; c – the dependence of power factor $k_M$ after compensation depending on the ratio $\beta$

So it is clear from the obtained dependences, presented in Figures 2 and 3, that the traditional parallel active filter possess a limited efficiency in conditions of variations of internal reactance of network. Such variations correspond to change of power supply from centralized source to autonomous one, and in conditions of variation of ratio of linear and nonlinear part in total load node.

Thus, in conditions of the distributed generation, a hybrid structure based on the parallel active filter, the output of which is equipped with the high-frequency passive filter is an effective means of correction of higher harmonics in current and voltage [10, 13]. The parameters of this filter are selected based on the variation in the internal reactance of the source and analysis of the amplitude-frequency curves of the mains to avoid the occurrence of resonant phenomena. According to the modeling results in order to save the efficiency of active filter functioning, the impedance of this high-frequency passive filter must be in the range of 1 to 10 Ohm for harmonic order from 2 to 40 when internal reactance of the source changes in wide range.
6. Conclusion
The urgency of the issue of improving the electric energy quality in terms of correcting higher harmonics in current and voltage in conditions of distributed generation and combined power supply has been validated. The efficiency of usage the parallel active filter with the control system based on relay controllers for compensation of higher harmonics in conditions of centralized and stand-alone sources has been shown. The main parameters of the parallel active filter, which should be accounted for when correcting non-sinusoidal modes of power supply systems of various structures, have been revealed. A mathematical model of the parallel active filter in conditions of the distributed generation and combined power supply has been developed. The dependences between the performance parameters for correction of higher harmonics by the parallel active filter and the supply mains internal reactance and the parameters of the load node have been revealed. The necessity of installation of the high-frequency passive filter on the output of the parallel active filter in conditions of the distributed generation has been proven.

7. Acknowledgments
The presented results were obtained as a part of scientific researches according to the contract № 13.3746.2017.8.9 “The designing on the basis of systematic and logic probability evaluations of rational and economically proved structure of centralized, autonomous and combined power supply systems with the high reliability and stability level with usage of alternative and renewable power sources for uninterrupted power supply of enterprises with continuous technological cycle”.

References
[1] Zhukovskiy Y L, Starshaia V V, Batueva D E and Buldysko A D 2018 Analysis of technological changes in integrated intelligent power supply systems Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects - 11th conference of the Russian-German Raw Materials (Saint-Petersburg: Saint-Petersburg mining university) vol 1 pp 249-258
[2] Zhukovskiy Y, Malov D 2018 Concept of Smart Cyberspace for Smart Grid Implementation Journal of Physics: Conference Series 1015 042067
[3] Turysheva A V, Baburin S V 2016 Justification of power supply system’s structure of oil and gas facilities using backup energy sources with associated petroleum gas as the energy carrier International Journal of Applied Engineering Research 11(1) 749-755
[4] Baburin S V, Kovalchuk M S 2018 Analysis of power supply systems reliability for gas pumping compressor stations Proc. of the 2018 IEEE Conf. of Russian Young Researchers in Electrical and Electronic Engineering (Saint-Petersburg: IEEE Xplore) vol 1 pp 566-569
[5] Kovalchuk M S, Baburin S V 2018 Modelling and control system of multi motor conveyor IOP Conference Series: Materials Science and Engineering 327 022065
[6] Malarev V I, Kopteva A V and Nogtev R A 2018 Electric Drive Simulation for Drilling Machine Spinner IOP Conference Series: Earth and Environmental Science 194 052012
[7] Kopteva A V, Malarev V I 2018 Studying thermal dynamic processes in an isolated type borehole electrode heater for high-viscosity oil extraction Proc. of the 2018 IEEE Conf. of Russian Young Researchers in Electrical and Electronic Engineering (Saint-Petersburg: IEEE Xplore) vol 1 pp 678-681
[8] Marinescu R F, Nicolae P M, Firiucă D G, Popa L D, Cristina M D and Cătălin P 2017 Aspects of power quality improvement in a driving system using an active filter Proc. - 2017 International Conf. on Modern Power Systems (Cluj-Napoca: Technical university of Cluj-Napoca) vol 1 7974415
[9] Zhou X, Wei K, Ma Y and Gao Z 2018 A review of reactive power compensation devices Proc. of 2018 IEEE Int. Conf. on Mechatronics and Automation (Changchun: IEEE Xplore) vol 1 pp 2020-2024
[10] Abramovich B N, Sychev Yu A 2016 The evaluation of hybrid active filter efficiency Conference Proc. - 2016 Int. Conf. on Actual Problems of Electron Devices Engineering (Saratov: IEEE Xplore) vol 2 7879064

[11] Saveliev A, Malov D, Tamashakin M and Budkov V 2017 Service and multimedia data transmission in IoT networks using hybrid communication devices MATEC Web of Conferences– EDP Sciences 113 02010

[12] Heilig A, Mamaev I, Hein B and Malov D 2018 Adaptive particle filter for localization problem in service robotics MATEC Web of Conferences 161 01004

[13] Pankov I A, Frolov V Ya 2017 Increase of Electric Power Quality in Autonomous Electric Power Systems Journal of Mining Institute 227 563-568

[14] Kopyrin V A, Smirnov O V, Portnyagin A L and Khamitov R N 2018 Influence of downhole compensator on voltage drop in elements of a production well electrical system Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering 329(9) 117-124