Mathematical modeling and analysis of electrical complexes for power quality improvement on the basis of active and passive filters

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Abstract. The necessity of usage of electrical complexes for power quality improvement on the basis of active and passive filters is proved in the paper. The main tasks, which must be solved by these complexes in the area of power quality improvement, are indicated. The mathematical models and relationships of the main topologies of these complexes are developed and proved. The computer simulation models have been developed on the basis of the mentioned mathematical models and relationships. The results, which have been obtained during simulation, showed the satisfactory level of power quality improvement. Also the obtained results should be considered as the theoretical basis for the structural and parametrical synthesis of the electrical complexes for power quality improvement on the basis of active and passive filters in centralized, distributed and combined power supply systems.

1. Introduction

The problem of efficient electric power quality control is relevant for power supply systems in almost all sectors of industry [1-4]. The level of electric power quality determines the actual lifespan of electrical equipment, the stability of electrical systems performance, the amount of active power losses in the elements of distribution networks. Currently, the most promising direction in the development of technologies for controlling the quality of electric power is the use of electro-technical complexes with active converters and filter-compensating devices [5-7]. These complexes, due to having a flexible structure, ensure the possibility to implement a specified set of functions under conditions of variation in the parameters of non-sinusoidal modes in centralized, stand-alone and combined power supply systems.

Most electro-technical complexes for controlling the electric power quality parameters (EPQPs), based on active converters and filter-compensating devices (FCDs), are based upon hybrid structures [8, 9], based on active filters (AFs) and passive filters (PFs). With the development of theory and the increased practical implementation of active correction methods, it became possible to control the parameters of PFs. The expediency of the practical implementation of active correction methods for these purposes becomes apparent with the following factors accounted for [10, 11]. Firstly, purely active correction systems have a large installed capacity of elements, since they are enabled to operate at voltages and currents, the maximum values of which are determined by the non-linear load (NL) total capacity, creating higher harmonic components (HHCs) in current. Therefore, the high cost of active systems limits their wide use in power supply systems. Secondly, the PFs, being a traditional means for improving the quality of electric power, do not require the creation of new technologies for
manufacturing thereof, and are a part of almost all electric networks in operation. Thus, the combined use of the PFs and the AFs within the framework of a single correction system allows optimizing technical and economic characteristics of AFs and expanding the functionality of traditional PFs [12], and also serves as the basis for the structural and parametric synthesis of electro-technical complexes for controlling the EPQPs.

2. Research method
Currently, various PF control methods are being developed based on the use of active correction systems that serve as an actuating member of the PF parameters controller. The installed capacity of the active system is reduced by more than an order of magnitude compared to the capacity of a parallel-connected AF. Also, it becomes possible to automatically control filter parameters while in operation. A filter, made on the basis of PFs with the active part based on various types of AFs, is called a hybrid filter (GF) or a hybrid system for correcting the EPQPs [13].

The hybrid correction system principle of operation is based on the creation of currents and voltages in AF circuits, by the power electronic device, that change the frequency response of the filter to increase its performance [14]. Devices, made according to AF circuits of various structures, i.e. operated by fully controllable pulse-modulated AC/DC power converters, are used as an electronic device that generates currents and voltages in a hybrid system [15].

The presence of a controller in the hybrid system based on AF circuit enables to solve the following main tasks [12, 13]: to improve the filtering efficiency under static modes of operation by correcting its frequency response; to reduce the negative impact of changes in filter parameters and frequency deviations of the filtered HHCs while in operation; to eliminate the occurrence of “antiresonance” in the electric network at frequencies close to the frequency of the filtered HHCs; to damp unwanted resonance phenomena, caused by passive elements of filters; to reduce the HHCs in the mains current, induced by various sources of the HHCs.

The tasks, being solved by means of the GF, are associated with the controller input signal spectral composition. To improve the quality of PF filtering at its adjustment frequency, it is sufficient to control only the HF part of the input signal of this frequency. In this case, the installed capacity of the GF active part is far less than during the signal processing in its entire frequency spectrum. This simplifies the signal modulation procedure. However, damping by the active resistance of the filter of resonance phenomena in the system is possible only when using a wide spectrum of the input signal of the GF controller. Thus, the theory of GF serves as the basis for the development of a methodology for performing the structural and parametric synthesis of electro-technical complexes for controlling the EPQPs on the basis of active converters and FCDS [14].

3. Mathematical models of electro-technical complexes with active converters and filter-compensating devices
Figure 1a illustrates the structure of the GF, consisting of a parallel connection of two PFs and a sequential active filter (SAF), operating under the mode of a controllable voltage source, connected in parallel to the compensated NL. This hybrid system is described by the following expressions [16-18]:

\[ U_c + U_{pf} = U_s; \]
\[ U_{pf} = U_{NL}; \]
\[ U_s = k_s U_c = 2 k_{inv} U_{dc} - \Delta U_{LF}; \]

\[ U_{pf} = L_{pf} \frac{dI_{pf}}{dt} + U_{cpf}; \]
\[ \Delta U_{LF} = L_f \frac{dI_f}{dt}; \]
\[ I_f = I_{LF} + I_c; \]

\[ I_c = I_{c5} + I_{c7}; \]
\[ I_{c5} = C_5 \frac{dU_{c5}}{dt}; \]
\[ I_{c7} = C_7 \frac{dU_{c7}}{dt}. \]

In Equation (1) \( U_c \) is the SAF output voltage, \( U_s \) is the network voltage, \( U_{pf} \) is the passive filters voltage, \( U_{NL} \) is the NL voltage, \( I_f \) is the passive filters compensation current, \( I_{LF} \) is the NL current, \( I_c \) is the network current, \( L_s, C_5, L_f, C_f \) are the passive filters parameters, \( U_{dc} \) is the direct current voltage of the inverter, \( L_{pf}, C_f \) are the output filter parameters, \( L_{c5}, I_{c5} \) are the
passive filters currents, $k_T$ is the SAF output transformer transformation factor, $k_{inv}$ is the functioning mode factor of the inverter power elements [16-18].

**Figure 1.** a – the structure of a hybrid system based on the parallel connection of the SAF and the PFs, connected in parallel to the compensated NL; b – the equivalent circuit at the frequency of the $n$-th HHC.

Figure 1b illustrates the equivalent circuit of this hybrid structure at the frequency of the $n$-th HHC, wherein the harmonic voltage of the point of common coupling (PCC) can be determined as follows [16-18]:

$$U_{PCCn} = \frac{k}{Z_{sn} + k} U_{cn} + \frac{Z_{sn}}{Z_{sn} + k} U_{NLn}$$  \hspace{1cm} (2)

In case of $k \gg Z_s$ this hybrid structure insulates the PCC from voltage harmonics from the NL side. In Figure 1b $U_{in}$ is the network voltage, $U_{cn}$ is the SAF output voltage, $U_{NLn}$ is the NL voltage, $U_{PCCn}$ is the point of common coupling voltage, $I_{sn}$ is the network current, $I_{in}$ is the passive filters current, $I_{NLn}$ is the NL current, $Z_{sn}$ is the passive filters impedance, $Z_{cn}$ is the network impedance [13-15]. All these parameters are presented at the frequency of the $n$-th HHC. In Figure 1b and Equation (2) $k$ is the generalized factor, which determine the connection between the SAF output voltage $U_{cn}$ and the network current $I_{in}$ [16-18].

Figure 2a illustrates a hybrid structure, similar to the one shown in Figure 1a, except for the use of a parallel active filter (PAF) instead of the SAF [16-18].

**Figure 2.** a – the structure of a hybrid system based on the parallel connection of the PAF and PFs, connected in parallel to the compensated NL; b – the structure of a hybrid system based on the PAF with an output PF, connected in parallel to the compensated NL.

In Figure 2a the symbols are similar to those in Figure 1a and $I_{PAF}$ is the PAF output current, $I_{PF}$ is the passive filters current [16-18].

This hybrid structure is described by the following relationships [16-18]:

$$I_s = I_{PAF} + I_{PF} + I_{NL}; \quad U_{NL} = U_s = U_{PF}; \quad U_{PAF} + \Delta U_{lf} = U_{NL};$$

$$\Delta U_{lf} = L_f \frac{dI_{PAF}}{dt}; \quad U_{PAF} = 2k_{inv} U_{dc}; \quad I_{PF} = L_L \frac{dU_{CS}}{dt} + C_7 \frac{dU_{C7}}{dt}. \hspace{1cm} (3)$$
Figure 2b shows a hybrid structure, similar to the one illustrated in Figure 1a, except for the use of the PAF instead of the SAF and parallel connection of the PF to the PAF. This hybrid structure is described by the following relationships [16-18]:

\[
I_s = I_{PAF} + I_{PE} + I_{NL}; \quad U_{NL} = U_s = U_{PF}; \quad U_{PAF} + \Delta U_{t_f} = U_{NL};
\]

\[
\Delta U_{t_f} = L_f \frac{dI_{PAF}}{dt}; \quad U_{PAF} = 2k_{min}U_{dc}; \quad I_{PE} = C \frac{dU_c}{dt}.
\]  

In Figure 2b, \(L, C\) are the parameters of the PAF output passive filter.

Despite the different functional purpose of the GFs, illustrated in Figures 2a, b, their generalized mathematical formulation is virtually identical according to expressions (3) and (4) [16-18]. In the first case, the PAF, being a part of the GF, compensates the residual harmonic distortions after two PFs, configured to suppress canonical HHCs [19, 20]. In the second case, the PF at the output of the PAF prevents the occurrence of resonance phenomena and reduces the mains voltage ripple during the PAF operation [21, 22].

4. Simulation results

Simulation of electro-technical complexes for controlling the EPQPs, presented in Figures 1 and 2, was carried out according to the following steps:

- simulation of the efficiency when controlling the EPQPs by active converters with output PFs of various configuration;
- simulation of the efficiency when controlling the EPQPs by active converters in combination with the PFs, configured to suppress canonical HHCs;
- simulation of the efficiency when controlling the EPQPs by active converters with output PFs of various configuration in combination with the PFs, configured to suppress canonical HHCs.

Based on the results of simulation of the operating modes of the electro-technical complex for controlling the EPQPs, presented in Figure 1, the following conclusions were made:

- the results of theoretical and experimental studies have proved the need to install a PF at the output of the PAF to improve the efficiency when controlling HHCs in current and voltage;
- the presence of a PF at the output of the PAF ensures efficiency when controlling HHCs in the mains voltage under conditions of centralized and stand-alone power supply (distributed generation);
- the PF modulus of impedance at the PAF output should fall within the range from 1 to 15 Ohms in the frequency range from 2 to 40 HHCs to maintain the efficiency when controlling the EPQPs of the PAF [17];
- the amplitude-frequency response of the PF, installed at the output of the PAF, should be hyperbolic by shape without resonance points in the frequency range from 2 to 40 HHCs to maintain the efficiency when correcting the EPQPs of the PAF;
- the greatest efficiency, when correcting a set of the EPQPs, including the HHCs in current and voltage, the asymmetry of current and voltage, voltage deviations, as well as the level of reduction in the current consumed by the load, is demonstrated at the output of the PAF by an active-capacitive PF, wherein the capacitors are connected in a triangle [13-15];
- the maximum efficiency, when correcting deviations and the HHCs in voltage, as well as the HHCs in current, is demonstrated at the output of the PAF by an active-inductive-capacitive PF, wherein the capacitor and inductance are connected in parallel, and a resistor is connected with them in series [13];
- the maximum efficiency, when correcting the asymmetry of voltage and current, is demonstrated by several output PFs, wherein a capacitive PF is the simplest;
- the maximum efficiency, when compensating the inactive components of current consumed by the linear and non-linear loads, and the reactive power, is demonstrated at the output of the PAF by an active-capacitive PF, wherein the capacitor and the resistor are connected in series [15].
Based on the results of simulation of the operating modes of the electro-technical complex for controlling the EPQPs, presented in Figure 2, the following conclusions were made:

- the electro-technical complex for controlling the EPQPs, implemented on the basis of PFs, configured to suppress canonical HHCs, and the SAF with PFs at the output is enabled to advantageously compensate for the HHCs in current and voltage under conditions of centralized, stand-alone and combined power supply [14];
- under conditions of stand-alone power supply systems (high internal resistance of the supply mains), the presence of PFs, configured to suppress canonical HHCs, installed from the applied load side, enables to improve the efficiency when correcting HHCs in voltage of the SAF;
- under conditions of the combined use of the SAF and PFs, configured to suppress canonical HHCs, it is possible to reduce the SAF rated values within a certain range while maintaining a sufficient level of efficiency when correcting the EPQPs, wherein the specified voltage of the SAF storage capacitor $U_{dc}$ can be within wider limits (up to 50% of the rated value), than the rated capacity of the SAF output transformer $S_t$ (up to 25% of the rated value);
- a change in the capacitance of the SAF storage capacitor within the limits similar for the PAF does not have a significant impact on the level of efficiency when correcting the EPQPs.

The obtained results serve as a theoretical basis for the structural and parametric synthesis of electro-technical complexes for correcting the quality of electric power with active converters and filter-compensating devices under conditions of centralized, stand-alone and combined power supply systems [23, 24].

5. Conclusion

The necessity of power quality improvement by means of the electro-technical complexes with active and passive filters has been proved. The key functions of power quality improvement have been determined for these complexes. The main topologies of the electro-technical complexes with active and passive filters have been detected and mathematically described. The simulation models of these topologies have been developed. The simulation process has been provided in accordance with the proposed methodology under variation of the internal and external factors. The obtained simulation results have allowed one to make the conclusions, which should be considered as a theoretical basis for the structural and parametric synthesis of electro-technical complexes for power quality improvement. These conclusions reflect the dependences of the efficiency level of power quality improvement from the topology, main parameters and control method of the mentioned complexes.

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