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# Selected methods for improving operating conditions of three-phase systems working in the presence of current and voltage deformation – part II

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**Abstract:** The paper includes a summary of long-time research conducted by a research team in the Institute of Electrical Engineering and Computer Science at Silesian University of Technology. The research work has principally been related to selected problems in the field of analysis and synthesis of systems aimed at symmetrisation and improvement of some power quality parameters. This paper constitutes the second part of the report on the research. It has been devoted to three-phase system symmetrisation as well as effective elimination of higher harmonics and substantial improvement of power quality by means of hybrid active power filters.

**Key words:** active power filters, compensation of higher harmonics, hybrid active power filters, power quality, symmetrisation

## 1. Introduction

The motivation and the background behind the research work presented in this contribution have been described in part I which covers also solutions to power quality problems by means of active power filters as well as their sizing and placement optimal strategies. In the current paper, some results on symmetrisation and hybrid active power filters are described.

Symmetrisation is one of the methods of improving the power quality in systems with periodic voltage sources and with non-zero internal impedances and asymmetrical linear three-phase loads. The symmetrisation of the system is achieved by connection of a symmetrising circuit consisting of LC two-terminal networks. Their structure is determined after appropriate synthesis process. After symmetrisation the source currents are symmetrical and their RMS values are lower, so active power losses in source's internal impedances become also smaller; the source generates more active power after symmetrisation and reactive power compensation is ensured for each investigated voltage harmonic. The theory of symmetrical components is used to solve the problem. The solution of the problem of symmetrisation is suboptimisation, i.e. it enables the reduction of effective values of source currents and compensation of reactive power for each considered harmonic, but it does not allow to obtain currents with minimum RMS values.

The other solution to power quality problems is based on application of hybrid filters. The hybrid filter includes a passive part (resonance filter) and an active part (active power filter). The basic configuration of a hybrid active power filter, including a passive filter for a single harmonic, as well as some experimental results and stability analysis have been described in the paper.

## 2. Symmetrisation and compensation of three-phase systems

The problem of symmetrisation has already been considered in the available publications for three-phase systems mainly. Issues of symmetrisation of systems for different types of deformations have already been discussed in many publications (works [1–7] refer to sinusoidal deformations and works [8–11] refer to periodic deformations). In later works the problem of symmetrisation has been considered for $N$-phase systems as well for three phase systems with simplified structure of the symmetrising system [12–15]. The problem of symmetrisation is still an important issue of power quality [16].

In order to present the problem of symmetrisation in three-phase systems both three-wire systems (Fig. 1) and four-wire systems (Fig. 2) are considered. In each case, a system consisting of a three-phase source of periodically non-sinusoidal symmetrical voltages with non-zero different internal impedances of the source is considered. The system is loaded with a linear asymmetrical three-phase load connected into a star or delta configuration in three-wire systems (in Fig. 1 – load is delta connected) or a star configuration in four-wire systems (Fig. 2).

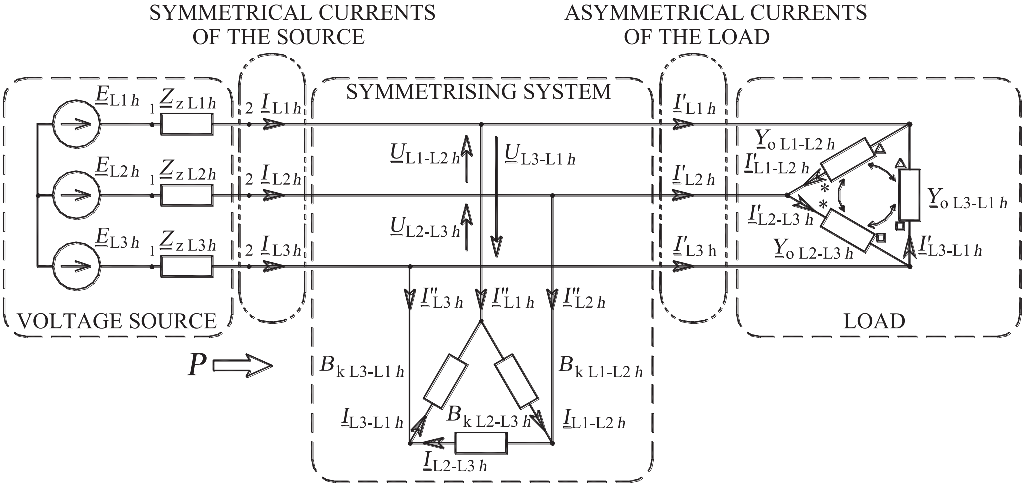


Fig. 1. The symmetrisation in a three-phase three-wire system with a delta-connected load

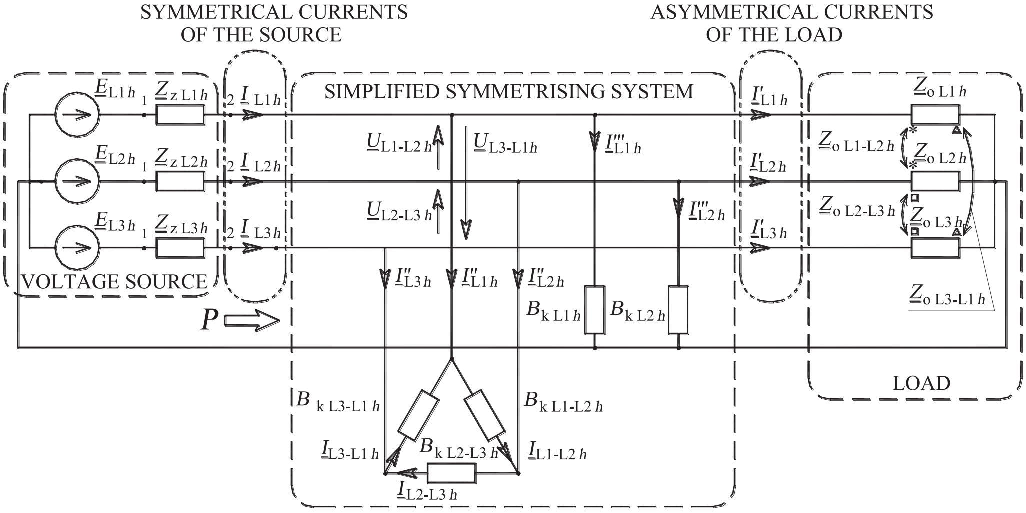


Fig. 2. The system with a star-connected load with a simplified structure of a symmetrising system

The simplified symmetrising system connected between the voltage source and the load is shown in Fig. 2. The simplification means that the symmetrising system has no susceptance connected between the third phase L3 and neutral wire. It means that symmetrisation of the discussed system is possible by using a smaller number of symmetrising susceptances.

The system shown in Fig. 2 is investigated in following sections of this paper.

It is assumed that the symmetrical three-phase voltage source with periodic nonsinusoidal waveforms has non-zero different asymmetrical internal impedances:

$$Z_{z\beta h} = R_{z\beta h} + \mathrm{j}X_{z\beta h}\,; \qquad \beta = \mathrm{L1, L2, L3}; \quad h = 1, 2, \ldots, N, \tag{1}$$

$$\boldsymbol{Z}_{\mathrm{z}\,h} = \boldsymbol{R}_{\mathrm{z}\,h} + \mathrm{j}\boldsymbol{X}_{\mathrm{z}\,h}\,; \qquad \boldsymbol{Z}_{\mathrm{z}\,h} = \boldsymbol{Z}^{T}_{\mathrm{z}\,h} \tag{2}$$

and generally

$$Z_{\mathrm{z\,L1}h} \neq Z_{\mathrm{z\,L2}h} \neq Z_{\mathrm{z\,L3}\,h}\,, \quad \forall\, h \in \{1, 2, \ldots, N\}.$$

It is assumed also that the source voltages with periodic nonsinusoidal waveforms are symmetrical of positive phase sequence of voltage for the basic harmonic, i.e.:

$$\begin{gathered} e_{\mathrm{L1}}(t) = \sqrt{2}\,\mathrm{Re}\sum_{h=1}^{N} E_{\mathrm{L1}h}\exp(\mathrm{j}h\omega\, t), \\ e_{\mathrm{L2}}(t) = e_{\mathrm{L1}}\left(t - \frac{T_{\mathrm{o}}}{3}\right), \qquad e_{\mathrm{L3}}(t) = e_{\mathrm{L1}}(t)\left(t + \frac{T_{\mathrm{o}}}{3}\right), \end{gathered} \tag{3}$$

where $E_{\mathrm{L1}h}$ is the RMS complex value of the voltage for harmonics $h = 1, 2, \ldots, N$.

The investigated linear three-phase load is described by means of asymmetrical phase impedances or admittances as the matrix $\underline{\boldsymbol{Y}}_{\mathrm{o}\,h}$.

Generally, in the system under consideration, the line currents $i_{\mathrm{L}1}(t)$, $i_{\mathrm{L}2}(t)$, $i_{\mathrm{L}3}(t)$, are asymmetrical without the connected symmetrising system. The goal is symmetrisation of this system. It is achieved by solving the problem defined in the following way:

- asymmetrical linear static load is connected into a star with a neutral wire,
- load is described with a full admittance matrix for the investigated harmonics $\underline{\boldsymbol{Y}}_{\mathrm{o}\,h}$,
- system is supplied from a non-ideal symmetrical voltage source with periodic nonsinusoidal waveforms with asymmetrical internal impedances,
- LC two-terminal units are used, these are connected to phase and phase-to-phase voltages (Fig. 2).

The system should be symmetrised from the point of view of the ideal source terminals (terminals "1" in Fig. 2). In addition, a requirement is made that after connecting the symmetrising system, no reactive power is consumed from the source for each harmonic voltage under consideration.

By applying the symmetrical components theory to the system under consideration, the symmetrical components of the system currents can be expressed by the symmetrical components of source voltages and system admittances with symmetrising system susceptances for symmetrical components in general forms:

$$I_{0\,h} = {}_{\mathrm{s}}\underline{Y}_{1\,1h}\underline{E}_{0\,h} + {}_{\mathrm{s}}\underline{Y}_{1\,2h}\underline{E}_{1h} + {}_{\mathrm{s}}\underline{Y}_{1\,3h}\underline{E}_{2h}\,, \tag{4a}$$

$$I_{1\,h} = {}_{\mathrm{s}}\underline{Y}_{21h}\underline{E}_{0\,h} + {}_{\mathrm{s}}\underline{Y}_{22h}\underline{E}_{1h} + {}_{\mathrm{s}}\underline{Y}_{23h}\underline{E}_{2h}\,, \tag{4b}$$

$$I_{2\,h} = {}_{\mathrm{s}}\underline{Y}_{31h}\underline{E}_{0\,h} + {}_{\mathrm{s}}\underline{Y}_{32h}\underline{E}_{1h} + {}_{\mathrm{s}}\underline{Y}_{33h}\underline{E}_{2h}\,. \tag{4c}$$

The source voltage is assumed to be symmetrical with the positive phase sequence for the basic harmonic. Therefore for harmonics of the $3n + 1$ order, a positive component is present in components of symmetrical source voltages; for harmonics of the $3n - 1$ order, a negative component is present; for harmonics of $3n$ order zero component is present.

The system shown in Fig. 2 will be symmetrical when the symmetrical voltage component corresponding to respective harmonic will result in the corresponding symmetrical component of the current, i.e.

- for harmonics of the $3n + 1$ order creating a positive component system:

$$E_{0\,h} = E_{2\,h} = 0, \qquad E_{1\,h} \neq 0, \quad \forall h \in \{3n{+}1\},$$

- so, the following conditions should be fulfilled:

$${}_{\mathrm{s}}\underline{Y}_{1\,2h} = 0, \qquad {}_{\mathrm{s}}\underline{Y}_{3\,2h} = 0, \quad \forall h \in \{3n{+}1\}, \tag{5}$$

- for harmonics of the $3n - 1$ order creating a negative component system:

$$E_{0\,h} = E_{1\,h} = 0, \qquad E_{2\,h} \neq 0, \quad \forall h \in \{3n{-}1\},$$

- so, the following conditions should be fulfilled:

$${}_{\mathrm{s}}\underline{Y}_{1\,3h} = 0, \qquad {}_{\mathrm{s}}\underline{Y}_{2\,3h} = 0, \quad \forall h \in \{3n{-}1\}, \tag{6}$$

– for harmonics of the $3n$ order creating a zero component system:

$$E_{1\,h} = E_{2\,h} = 0, \qquad E_{0\,h} \neq 0, \;\; \forall h \in \{3n\},$$

– so, the following conditions should be fulfilled:

$$_{\mathrm{s}}\underline{Y}_{2\,1h} = 0, \qquad _{\mathrm{s}}\underline{Y}_{3\,1h} = 0, \;\; \forall h \in \{3n\}. \tag{7}$$

It has been stated in the assumptions, that an additional condition is imposed: the system should consume no reactive power from the ideal source (terminals “1”) for each investigated harmonic. The system of five equations with five unknown values of susceptances $B_{\mathrm{k\,L1-L2}\,h}$, $B_{\mathrm{k\,L2-L3}\,h}$, $B_{\mathrm{k\,L3-L1}\,h}$, $B_{\mathrm{k\,L1}\,h}$, $B_{\mathrm{k\,L2}\,h}$ in the symmetrising system is obtained, following separation of the real and imaginary parts of equation systems (5), (6), (7) for a given harmonic and demand for zero reactive power for each harmonic. By connecting susceptances with determined values to the investigated system, it is possible to obtain symmetrical source currents and reactive power compensation for each considered source voltage harmonic.

**Example 1**

– System shown in Fig. 2 is considered. It is assumed that:

$$e_{\mathrm{L1}}(t) = \sqrt{2}\,[300\cos\omega t + 60\cos 5\omega t + 43\cos 7\omega t]\;V,$$

$$e_{\mathrm{L2}}(t) = e_{\mathrm{L1}}\left(t - \frac{T_{\mathrm{o}}}{3}\right), \qquad e_{\mathrm{L3}}(t) = e_{\mathrm{L1}}\left(t + \frac{T_{\mathrm{o}}}{3}\right), \qquad \omega = 314\ \text{rad/s}.$$

– Source internal impedances for the basic harmonic are equal to:
  line L1; $R_{\mathrm{z\,L1}} = 1\ \Omega$, $\omega\,\mathrm{L}_{\mathrm{z\,L1}} = 1\ \Omega$, line L2; $R_{\mathrm{z\,L2}} = 1.5\ \Omega$, $\omega\,\mathrm{L}_{\mathrm{z\,L2}} = 2\ \Omega$,
  line L3; $R_{\mathrm{z\,L3}} = 2\ \Omega$, $\omega\,\mathrm{L}_{\mathrm{z\,L3}} = 3\ \Omega$,
– Three-phase load impedances for the basic harmonic are equal to:
  line L1; $R_{\mathrm{o\,L1}} = 6\ \Omega$, $\omega\,\mathrm{L}_{\mathrm{o\,L1}} = 6\ \Omega$, line L2; $R_{\mathrm{o\,L2}} = 8\ \Omega$, $\omega\,\mathrm{L}_{\mathrm{o\,L2}} = 8\ \Omega$, line L3; $R_{\mathrm{o\,L3}} = 10\ \Omega$, $\omega\,\mathrm{L}_{\mathrm{o\,L3}} = 10\ \Omega$.

Before symmetrisation the phase currents of the source have the following waveforms (Fig. 3):

$$i_{\mathrm{L1}}(t) = \sqrt{2}\,[17.7\cos(\omega t + 315^\circ) + 0.98\cos(5\omega t + 281^\circ) + 0.51\cos(7\omega t + 278^\circ)]\;A,$$

$$i_{\mathrm{L2}}(t) = \sqrt{2}\,[13.3\cos(\omega t + 195^\circ) + 0.74\cos(5\omega t + 41^\circ) + 0.38\cos(7\omega t + 158^\circ)]\;A,$$

$$i_{\mathrm{L3}}(t) = \sqrt{2}\,[10.6\cos(\omega t + 75^\circ) + 0.59\cos(5\omega t + 161^\circ) + 0.30\cos(7\omega t + 38^\circ)]\;A.$$

After symmetrisation, that is after determining the values of symmetrising two-terminal networks and their connection to the considered system, the line currents of the source will assume the following waveforms (Fig. 4):

$$i_{\mathrm{L1}}(t) = \sqrt{2}\,[10.2\cos\omega t + 0.28\cos 5\omega t + 0.03\cos 7\omega t]\;A,$$

$$i_{\mathrm{L2}}(t) = i_{\mathrm{L1}}\left(t - \frac{T_{\mathrm{o}}}{3}\right), \qquad i_{\mathrm{L3}}(t) = i_{\mathrm{L1}}\left(t + \frac{T_{\mathrm{o}}}{3}\right).$$

Thus, symmetrical currents of the voltage source are obtained. The solution to the problem of symmetrisation is the suboptimization of the system, i.e. it is possible to reduce RMS values of the source currents and compensate reactive power for each investigated harmonic, but it is not possible to obtain currents with minimum RMS values.

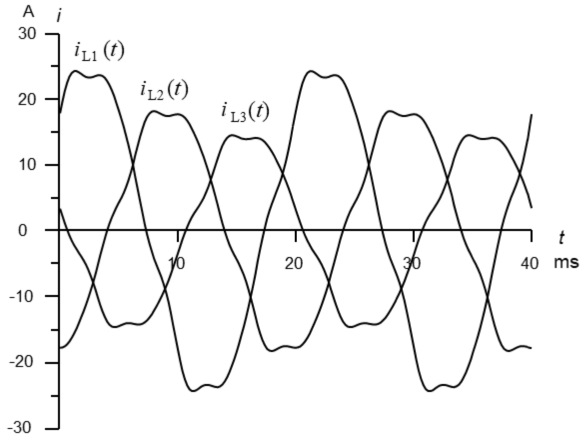


Fig. 3. Waveforms of the source currents before symmetrisation

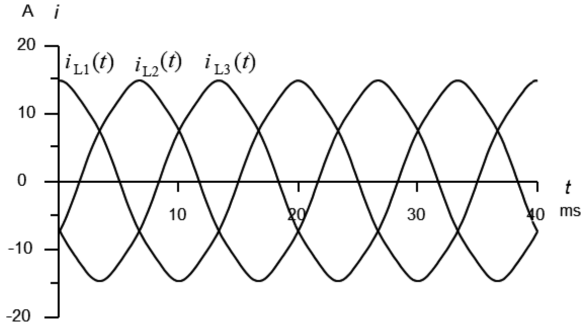


Fig. 4. Waveforms of the source currents after symmetrisation

## 3. Hybrid active power filters

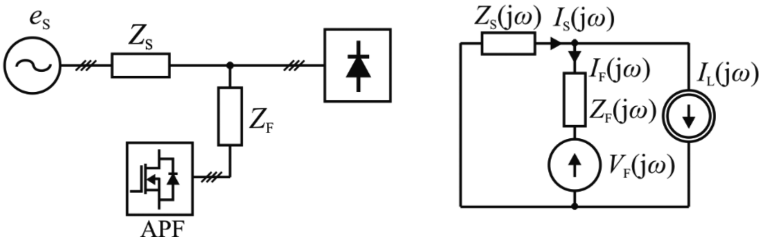
Hybrid filters are a combination of active power filters with traditional resonant passive filters [17, 18]. The combination of a passive and active filter in one application was first described in [19]. Since that time, there have been publications concerning more and more new system solutions and methods of controlling hybrid filters. Thus, two main directions of research can be distinguished. The first, concerning new system solutions, consists in indicating a new one or modification of existing configuration of a hybrid active power filters in order to improve certain system properties. Modifications usually consist in changing the configuration of the passive filter [20–22], its connection with the active part [23–26] or adopting new converter structures [27, 28]. The other research direction is the search for new control algorithms. In addition to attempts to apply one of the power theories [29–32], the authors use techniques such as: artificial neural networks [33–35], fuzzy logic [24, 36], adaptive filters [21, 37, 38] or generalized integrators [39, 40]. Significant issues here are also methods of controlling the voltage $u_{dc}$ of the converter [27, 41, 42] or elimination of the influence of voltage distortion on the operation of the hybrid system [24, 43, 44].

Due to the possibility of using a shunt as well as series passive filters or active power filters (APFs) and their various combinations, eight basic configurations of the hybrid power filter (HAPF) system are distinguished. The most popular configuration is the series connection of a shunt passive filter with a shunt active filter [45–53] shown in Fig. 5. The idea of controlling the active part in this case consists in generating a voltage $V_F$ proportional to the higher harmonics of the source current [45]. In the frequency domain this voltage may be expressed as:

$$V_{\mathrm{F}}(\mathrm{j}\omega) = K I_{\mathrm{S}(h\,h)}(\mathrm{j}\omega), \tag{8}$$

$$I_{\mathrm{S}\,(h\,h)}(\mathrm{j}\omega) = \int\limits_{-\infty}^{\infty} (i_{\mathrm{S}} - i_{\mathrm{S}(1)})\mathrm{e}^{-\mathrm{j}\omega t}\,\mathrm{d}\,t, \tag{9}$$

where $K$ is the hybrid filter gain, $i_{\mathrm{S}(1)}$ is the fundamental harmonic of the source current.



(a) (b)

Fig. 5. Hybrid active power filter. Series connection of a shunt passive filter with a shunt active power filter (APF): (a) general diagram; (b) single-phase equivalent circuit for the higher harmonics [45]

Assuming that the higher harmonics of the source current ($i_{\mathrm{S}(h\,h)}$) will be determined in an ideal way, the coefficient of higher harmonics damping can be written as:

$$\gamma(\mathrm{j}\omega) = \frac{I_{\mathrm{S}(h\,h)}(\mathrm{j}\omega)}{I_{\mathrm{L}(h\,h)}(\mathrm{j}\omega)} = \frac{Z_{\mathrm{F}}(\mathrm{j}\omega)}{Z_{\mathrm{F}}(\mathrm{j}\omega) + Z_{\mathrm{S}}(\mathrm{j}\omega) + K}\,. \tag{10}$$

The filtration characteristics then depend on hybrid filter gain $K$ and this results in:

- improvement of filtration properties in relation to passive filters,
- low impact of network impedance on the shape of the characteristic,
- reduction of resonance between the passive filter and the impedance of the network.

In addition, the required apparent power of the HAPF system is relatively small, which results from the lower voltages at its output terminals. The sample frequency responses of the module of a higher harmonics damping coefficient for different $K$ gain values are shown in Fig. 6.

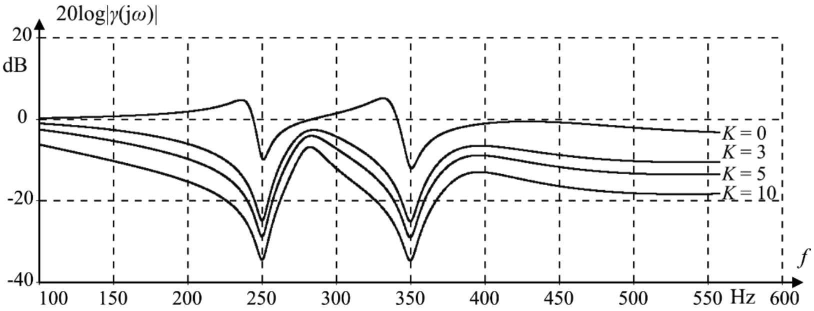


Fig. 6. Frequency response of the module of a higher harmonics damping coefficient for different $K$ gain coefficients [45]

### 3.1. Hybrid power filter with single tuned passive filter

Originally, hybrid filters were used in the case of high power systems networks, where the use of passive filters did not give the expected results, and the use of active filters was impossible (e.g. due to high voltages) or for economic reasons unprofitable. However, in recent years the share of small and medium-sized loads in general non-linear loads has increased, these are the sources of higher harmonics in grid currents and voltages. Therefore, the interest in hybrid filters working with lower power loads and systems with reduced passive part has increased [39, 45, 49, 53–57]. For example publications [47–49] have focused on the proposed control algorithm, which allowed the filtration of selected higher harmonics.

The exemplary characteristics of higher harmonic suppression for the passive system (harmonic filter 7) of the HEFA system controlled in a standard way and the system with the proposed control algorithm are shown in Fig. 7. It may be observed that the modification of the control

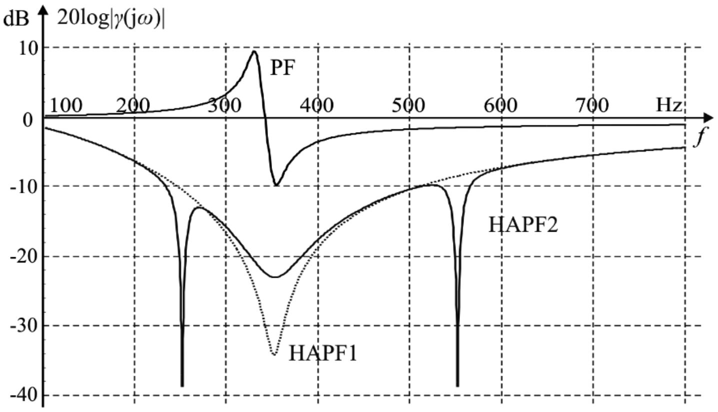


Fig. 7. Comparison of filter characteristics for a passive filter (PF), HEFA system (HAPF1) controlled in a standard way and a HAPF system controlled in a closed and open system (HAPF2)

algorithm allowed the filtration of 5th, 7th and 11th harmonics. Fig. 8 shows examples of test results for the constructed hybrid system. The prototype of the hybrid system contained a passive filter tuned to the seventh harmonic [50]. The system was adapted to work in a three-wire network with a phase-to-phase voltage of 246 V. The apparent power of the voltage inverter was set at 0.6 kV·A, and the switching frequency of the transistors was set to 25 kHz. With such operating parameters of the hybrid system it is possible to compensate for higher harmonics of the grid currents, when the circuit is loaded with nonlinear receivers with a maximum apparent power of the order of (5–10) kV·A.

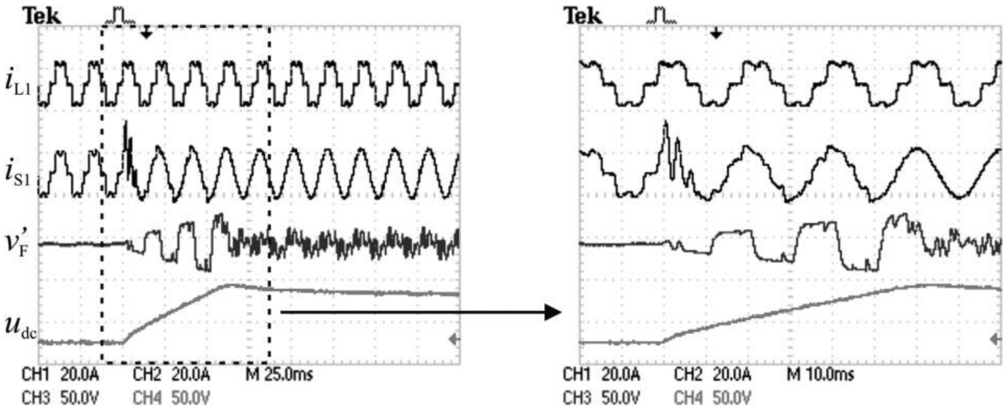


Fig. 8. Examples of test results for the hybrid active power system [50]

### 3.2. Frequency domain model and stability analysis

Paper [52] shows how to transform a time-controlled system into a frequency domain model. A full model of a three-phase system was derived, which allowed to determine the frequency characteristics independently for the positive and negative sequence components and to subject them to further analysis. Using the derived model in the frequency domain, it was possible to analyze the stability of the system [51]. The feedback transmittance introduced into the system (source-receiver) via a hybrid system has been derived. The obtained transmittances were independent for the positive and negative sequence components, which allowed the use of the Nyquist criterion for stability analysis. In addition to the basic parameters of the HAPF system, the delay in the control system was taken into account in this analysis. The next step was to analyze the impact of the hybrid system parameters due to stability of this system. The sample results of the analysis in the form of the critical gain of the filter from the delay and the value of the passive filter capacity are shown in Fig. 9. This allowed the selection of the HEFA system parameters, taking into account stability of the system.

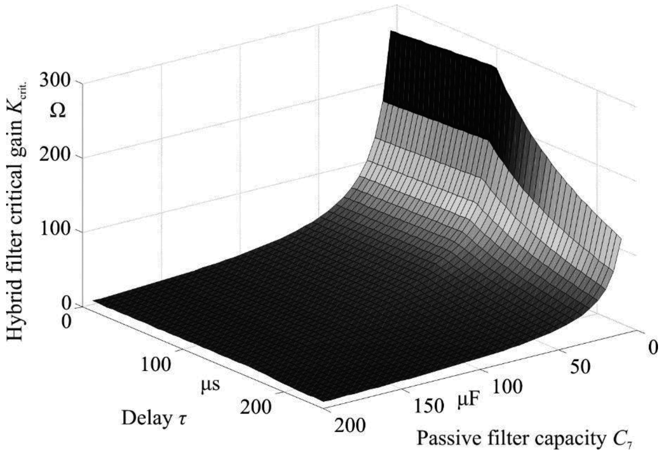


Fig. 9. Graph of critical HAPF gain $K_{\text{crit}} = f(\tau, C_7)$, $Q_7 = 18$, $C_7$, $L_7$ = const [51]

## 4. Conclusions

This paper constitutes the second part of the report on long-time research conducted in the Institute of Electrical Engineering and Computer Science at Silesian University of Technology by team of scientists led by Prof. Marian Pasko. The research has been mainly related to selected problems in the field of analysis and synthesis of systems aimed at symmetrisation and improvement of some power quality parameters. Theoretical analysis and verification of the results by means of simulation and laboratory experiments using developed prototypes have been carried out. In effect, many national and international conference papers and journal papers, including those on the JCR list, as well as 6 monographs have been published.

Symmetrisation of three-phase systems and effective elimination of higher harmonics based on hybrid active power filters, which have been described in this paper (part II), lead to significant power quality improvement. The high APF costs are among reasons for increased interest in hybrid solutions for either high or low power applications. The research results show that a suitable APF control algorithm in connection with a single harmonic passive filter can lead to harmonic suppression at the level obtained by standard APFs. In this case, the required power of the active part of a hybrid filter is much lower and so are the costs of the installation.

The subject area has not been closed yet and investigations in this field are under way in many academic and industrial research centres.

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