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

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Abstract: The paper includes a summary and a background 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 a first part of the report on the research. It has been devoted to effective elimination of higher harmonics and reactive power compensation by means of parallel active power filters. The other problem discussed in this paper is related to this issue and it is very important from the economic point of view; it addresses optimal sizing and placement of active power filters in investigated power networks.

Key words: active power filters, APF, compensation of higher harmonics, optimal APF sizing and placement, power quality

1. Introduction

Power quality as well as its improvement methods are among problems attracting more and more attention recently. Electrical loads work in optimal or almost optimal conditions only if they are supplied with nominal voltage and values of all the other parameters defining power quality are in the range regarded as acceptable in accordance with standards. Power quality for AC circuits is defined by such parameters as RMS value of voltage across load terminals, supply voltage variation, voltage and current waveform deformation, symmetry in three-phase systems, frequency, overvoltages as well as short and long power outages. Analysis of phenomena in AC supply systems containing higher harmonics (caused by deformations of supply voltage and current waveforms) is a challenging research problem which should not be solely restricted to THD control. Higher harmonics in voltage and current waveforms can lead to:

- power network overloads due to increase of RMS values, among others, in neutral wires of three-phase systems,
- early ageing of electrical machines, insulation and capacitor banks used for reactive power compensation,
- dangerous breakdowns caused by ferroresonance and resonance phenomena.

It must be stressed that voltages generated by synchronous generators are sinusoidal and symmetrical and the waveform deformation is usually a result of large asymmetrical loads such as electric arc furnaces, power electronic devices and even a large number of low power electronic loads, e.g. switched-mode power supplies used in energy-saving lamps.

Power quality improvement can be attained with the help of active power filters (APFs) which are connected to selected nodes of power network. The general idea of such an approach, followed by analysis of the problem of delays occurring in APF control system and its exemplary solution using a predictive current controller, has been described in Section 2.

The third section is devoted to the problem of APF sizing and placement. It describes the current state of the art in the field of optimization approach to APF placement with particular reference to the results obtained by the authors.

2. Active power filters

Elimination of higher harmonics from current and voltage waveforms may be achieved by using compensators connected between the source and load. The best solution for that is an active power filter [1–10]. In general, an APF compensates instantaneous deviations of the current/voltage waveform from sinusoidal shape. It may be described as the power electronic source of additional current (or voltage), connected in parallel (or in series) to the load. Sum of filter current (voltage) and supply line current (voltage) will result in source current (or load voltage) being sinusoidal (in the ideal case). All undesirable components of voltage or current are closed in the load-APF circuit and do not have load impact on the supply source. Bridge inverters using an insulated gate bipolar transistor (IGBT) or a metal-oxide semiconductor field-effect transistor (MOSFET) are used to develop a current/voltage source (mostly voltage source inverters (VSIs) are used, with energy storage provided by a capacitor, rarely current inverters with inductive energy storage). The inverters are controlled in such a way that output waveforms follow up standard (model) waveforms.

APFs are designed to operate in different supply systems such as:

- single-phase,
- three-phase three-wire (this is the most common system),
- three-phase four-wire (the system, which makes it possible to compensate current in neutral wire).

One of the distinctive features of the active power filters is that they realize the function of a controlled voltage or current source. Thus, two basic types of APFs can be distinguished: a parallel one, injecting additional current into the system, and a series one, playing a role of an additional voltage source. In both cases, current or voltage generated by the APF results in elimination of unwanted components, e.g. higher harmonics in power system voltages and currents.

APFs could have many applications depending on their structure:

- filtration of current and voltage higher harmonics,
- voltage symmetrisation,
- elimination of voltage flicker,
- load balancing,
- reactive power compensation for fundamental frequency.

A parallel APF is usually developed with the help of a three-phase power inverter accompanied by reactors which is equivalent to a three-phase current source. In most applications the inverter is controlled by a tracking proportional-integral controller (PI) and the reference current is generated on the basis of a given power theory. The idea of the compensation using a parallel APF is presented in Fig. 1.

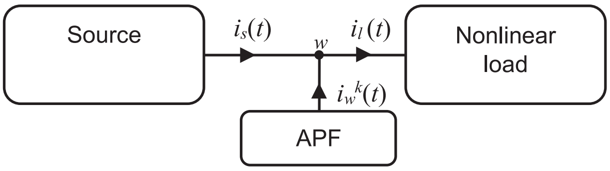

Fig. 1. Diagram of supply system with parallel active power filter

2.1. Control system

The control system is the basic element of the active power filter. Its task is to determine the reference currents or voltages and inject them into the supply system (usually through a voltage inverter - VSI). Determining the reference (optimal in a given sense) compensating currents requires use of power theory [3, 11]. Its task is to describe energy phenomena occurring in the electrical circuit and to define their properties. The instantaneous power *pq* [1–3, 11] theory is most often used in control systems of active power filters. As part of research conducted in this field, the possibility of using fixed-point and floating-point digital signal processors was analysed. Performance of different control algorithms has also been tested using PSpice and Matlab packages. This software makes it possible to develop effective control algorithms. They can be used to improve selected power quality coefficients in various power supply configurations.

2.2. Dynamic properties of APF

Another research area was the analysis and development of methods for improving the dynamic properties of active power filters. As part of these studies, the time dependencies occurring in the real control system were analysed. For this purpose, a detailed model of the active power filter (APF) system was developed in the PSpice environment [12]. As a result of the analysis, two basic sources of delays occurring in the control system were identified. The first one will occur in reference currents as a result of calculation time and the working cycle of the system. The negative effect will be a shift in time of reference currents. However, it was found that the delay in the follow-up regulator of the compensator's current has a greater effect on the system operation. The results of simulations were verified with an APF laboratory model. The results of analysis of signal filters influence in the control system has been presented in subsequent publications [12, 13]. It has been shown that with proper selection of filter parameters for instantaneous power decomposition in the APF control algorithm it is possible to obtain a steady state after 5 ms (i.e. after ¼ of the 50 Hz signal period) from the instant of load change. However, the choice of a filter requires a certain compromise – better dynamics of the system or worse filtration of higher harmonics or incomplete symmetrisation. A sample of the instantaneous power component filtration results is shown in Fig. 2.

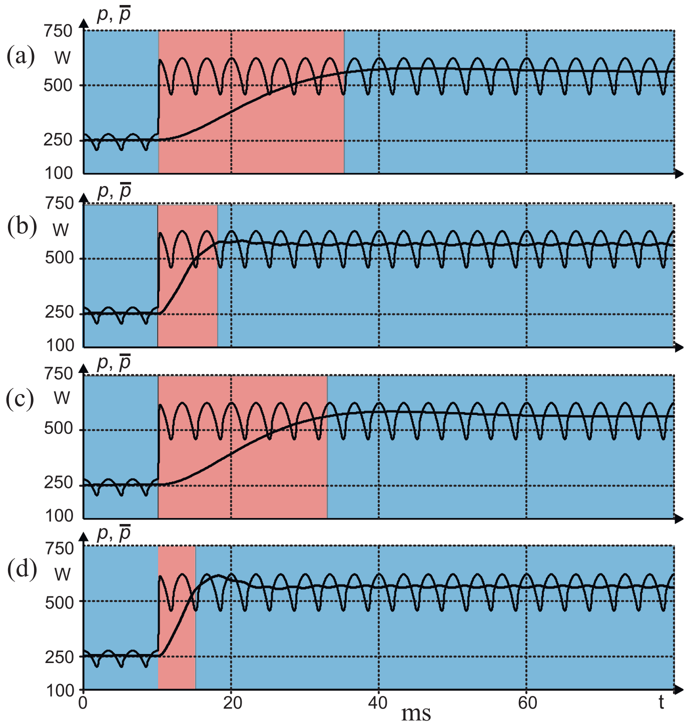

Fig. 2. Sample of instantaneous power $p(t)$ filtration results (low-pass filter), Butterworth approximation: (a) $f_p = 20$ Hz; (b) $f_p = 70$ Hz, Chebyshev approximation; (c) $f_p = 20$ Hz, (d) $f_p = 70$ Hz. The steady state is marked as blue and the transition state as red

Elimination of negative impact of delays occurring in the control system was described in article [14], where the use of a predictive control system was proposed. This type of control system requires a software development of an APF circuit discrete model, on the basis of which predictive values of the inverter output voltages will be generated. The proposed solution has been simulated in the Matlab/SIMULINK environment and compared to the hysteresis and proportional-integral regulators traditionally used for this purpose. The analysis of the simulation results has shown that the predictive control system makes it possible to obtain much better results of harmonics elimination and better dynamics of the control system than using the hysteresis or proportional-integral controller – Fig. 3.

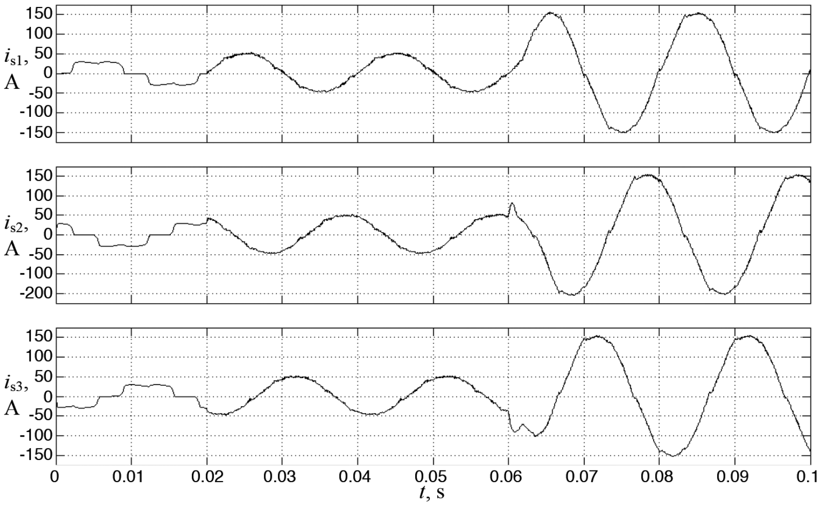

Fig. 3. Simulation results of control system with predictive voltage observer (source current waveforms) [14]

Simulation results were also confirmed by the values of the source current (after compensation) THD coefficient presented in Table 1 (THD of source current before compensation was approx. 26%).

Table 1. THD values comparison for different types of regulators [14]

Regulator type	**THDI in %**
Hysteresis	16
PI	8
Predictive with interpolation	5.5
Predictive with voltage observer	5.6

The use of the predictive controller with an observer simplifies a measurement system, reduces noise in voltage measurement and the impact of interference on the final filtration effect.

3. Sizing and placement of APFs in power networks

Problems with power quality may have very far-reaching consequences. The increasing number of nonlinear loads, which are the main cause of power quality deterioration, makes research in this field more and more important. On the other hand, the economic costs are among key factors limiting more frequent use of active power filters. Thus, methods of APF sizing and placement, which ensure required improvement of power quality along with the minimization of economic costs, are of great practical importance.

The problem of optimal APFs allocation has been considered in many papers. The aim of optimization usually consists in determination of placement of APFs with minimum nominal currents [15–19] and with still guaranteed reduction of distortions below the limits, indicated by standards [20]. The other approach consists in minimization of voltage total harmonic distortion coefficients, telephone interference factors, motor load losses or harmonic transmission line losses [21–25]. In this case the maximum acceptable APF nominal currents are defined as constraints of the optimization task. Moreover, a multi-objective optimization approach has also been used in order to simultaneously minimize several objective functions [26–30].

Since the nominal current determines the APF price, it has just been assumed in many publications that the optimization of the APF sizes leads also to the cost reduction and the economic goal is thus automatically taken into account [19, 27, 29, 31]. Our research has showed that such a simplified approach could lead to suboptimal solutions and the direct application of a cost-effective objective function gives better results. There are a few papers in which objective functions are directly based on investment costs [15, 18, 26, 28]. However, contrary to our approach, the APF cost is assumed to be a linear function of its size [15, 18, 26, 28].

In our research, it has been assumed that APFs can be controlled either by a standard or a modified algorithm. The former assumes that the APF injects currents, which cause the line currents at the point of installation to be sinusoidal and this is equivalent to local reduction of distortion. The latter requires information about voltages and currents in all network buses and enables global reduction of distortion. The second approach is similar to network-wide harmonic reduction and cooperative control presented in [19, 25] and [31]. The impact of the fixed cost of the APFs in investment costs using a fuzzy approach has been investigated in [32] and [33].

If the problem under consideration consists in placing active power filters in a network consisting of N buses, then the minimum number of the APFs is equal to 1 and the maximum possible number is equal to N – in this case there is an APF in each bus. Moreover, the APF ratings, i.e. nominal RMS currents, should be determined in order to obtain the assumed power quality indices. For a given power system, this problem may be stated as an optimization task with constraints defining the power quality as well as economical requirements. The optimization task may be defined as follows [34]:

$$\min_{\left\{\mathrm{Re}(I^k_{wh}),\ \mathrm{Im}(I^k_{wh}),\ T[w]\right\}} \sum_{w=1}^{W} g\left(\left|I^k_w\right|\right), \tag{1}$$

where:

w is the APF index, $w = 1, 2, \ldots, W$, $W \le N$,

W is the number of buses in which APFs can be placed,

$g(\cdot)$ is the nonlinear mapping between the economic cost and nominal APF current,

$\boldsymbol{T}[w]$ is the bus number for the $w^{-\mathrm{th}}$ APF,

$\left|I^k_w\right|$ is the current RMS value for the APF placed in the bus number $\boldsymbol{T}[w]$,

I^k_{wh} is the $h^{-\mathrm{th}}$ current harmonic phasor for the APF placed in the bus number $\boldsymbol{T}[w]$.

The solution to basic problem (1) as well as to its modifications for different APF control algorithms and constraints has been presented in [34–38]. The main constraints taken into account include:

- required level of voltage THD coefficients in all system buses,
- required level of RMS values of voltage harmonics in all system buses,
- maximum nominal RMS current value of the applied APFs,
- maximum RMS values of successive APF current harmonics.

The solution to problem (1) requires power flow as well as optimization calculations. They have been carried out using PCFLO and Matlab software, respectively. A library called PcfloPackage has been developed in order to synchronize calculations in both software tools [34] – see Fig. 4.

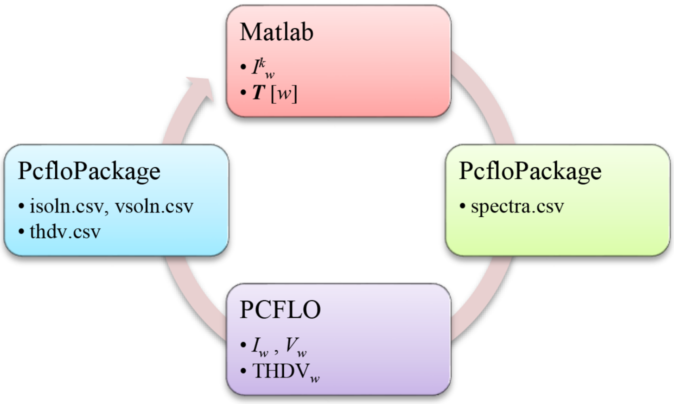

Fig. 4. Information exchange between software used to solve the problem of APF sizing and placement

The proposed algorithms of APF sizing and placement have been verified using two test systems of different size. The first one contains 20 buses with 8 DC distributed motors driven by 6-pulse line-commutated adjustable speed drives (ASD) which are main harmonic sources in the system. It is presented in Fig. 5 and its detailed description can be found in [39]. The second one contains 445 buses with 37 nonlinear and 186 linear loads and its detailed description can be found in [40].

Exemplary results of the APF placement in the system shown in Fig. 5 for $W = 2$ are presented in Fig. 6. It can be noticed that the final allocation of the APFs is defined by $\boldsymbol{T}[6]$ and $\boldsymbol{T}[13]$, which, in this case, represent buses number #8 and #15, respectively. The voltage THD coefficients have been decreased to less than 5% in all buses (the coefficients before compensation have been presented in Fig. 5) – see Table 2. The compensation cost in this case is equal to 9.1% in relation to the cost of full compensation, i.e. the APF placed in each bus with a nonlinear load. Results for $W = 1$, i.e. only 1 APF is placed, and $W = 3$, i.e. 3 APFs are placed are also shown in Table 2. However, the relative costs in these cases are higher than for $W = 2$.

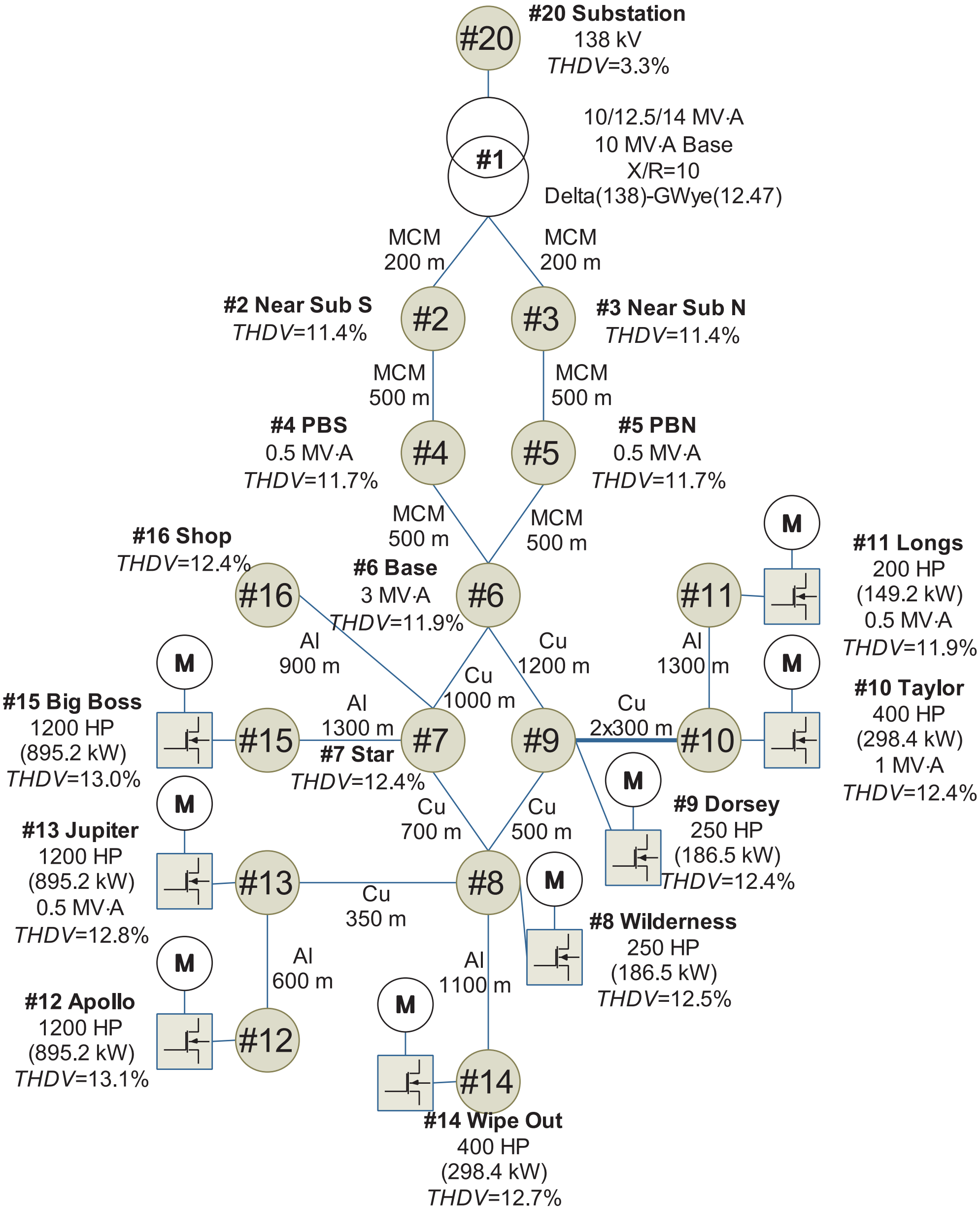

Fig. 5. Test power system [39]

It must be stressed that such result can be obtained if the control algorithm input data for each APF includes currents and voltages in all system buses. Results for the other control algorithms and different goal functions or constraints have been described in monograph [34].

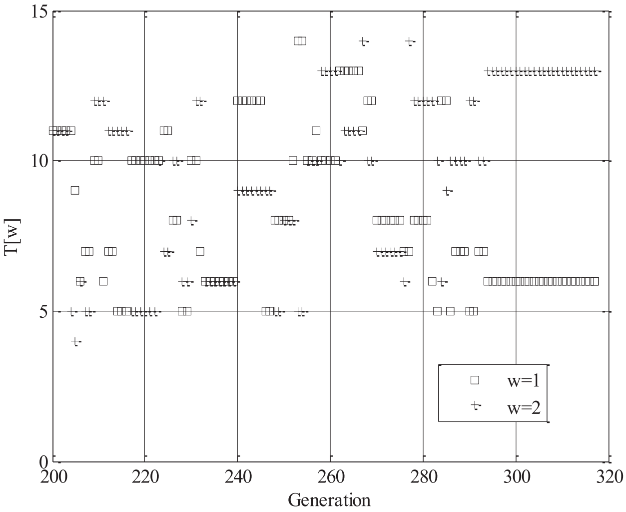

Fig. 6. Indices of buses in which APFs are placed in successive iterations of the algorithm for $W = 2$

Table 2. THDV coefficients in the system shown in Fig. 5 after APF placement

Bus index *w*	**THDV, % for**		
	***W* = 1**	***W* = 2**	***W* = 3**
1	4.0	4.0	3.9
8	4.4	4.5	4.4
10	4.4	4.4	4.4
11	4.5	4.5	4.4
12	4.5	5.0	4.8
13	4.5	4.7	4.6
15	5.0	4.8	4.8
20	1.2	1.2	1.2
Relative cost	20.5%	9.1%	10.2%
APF placement	#12	#8, #15	#13, #14, #15

4. Conclusions

This paper constitutes the first 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 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. Theoretical analysis and verification of 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 JCR list, as well as 6 monographs have been published.

Application of predictive controllers in active power filters enables enhancement of their dynamic properties as well as further reduction of a current THD coefficient. It has been shown in this paper that not only the sizing but also the APF placement is a key factor on the way to power quality improvement. Taking into account the results of team research, software solution which allows optimal APF placement and sizing based on Matlab and PCFLO has been developed. A nonlinear relation between the costs and APF nominal parameters has been implemented for the first time. The obtained results for some test power systems have confirmed that it is possible to considerably reduce the costs of power quality improvement by means of APFs. It must be stressed that so far the high costs have obstructed wider application of the APFs.

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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