Sizing of active power filters using some optimization strategies

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Abstract

Purpose – the change in the way of active power filters (APF) location can lead to overall cost reduction due to less number or less power of APFs required. The paper goal was to minimize the APF currents what is equivalent to solution with less apparent power of installed devices. The next step consists in development of new methods of APF optimal location.

Design/methodology/approach – some scripts integrating optimization and harmonic analysis methods in Matlab and PCFLO software environments have been developed in order to achieve the goal.

Findings – solution to the minimization problem determines the current spectrum of an APF connected to a selected system bus in accordance with some optimization strategies which among others enable minimization of THDV coefficients.

Research limitations/implications – the APF control algorithm defined in the frequency domain and based on given current spectrum could lead to some problems with synchronization between APF instantaneous current and compensated current waveforms.

Originality/value – there are many papers on APFs but usually systems in which an APF is connected near a nonlinear load are analyzed. Some attempts to solve the more complex problems of synchronized multipoint compensation have been already made but there is still no generally accepted and commonly used solution.

Keywords – active power filters, nonlinear loads, harmonics, THD, nonsinusoidal waveforms, optimization

Paper type – Research paper

1. Introduction

Technical problems as well as negative economic effects caused by low power quality make analysis of power quality problems more and more important. Dynamic development of modern technologies results in increased number of nonlinear loads which are the main source of higher harmonics in voltage and current waveforms. Negative consequences of higher harmonics include among others (Dugan *et al.*, 2003; Maciążek and Pasko, 2007):

1. System overloads and higher losses in resistive elements due to increased current RMS values. These effects are especially visible in the case of impulsive current waveforms which are characteristic for switched-mode power supply (PC, mobile phone chargers, etc.) and compact fluorescent lights. In spite of low average value these waveforms are characterized by high RMS value. The energy losses in supply systems could be even few times greater comparing to sinusoidal case.
2. Overloads of neutral conductor in three phase systems caused by the sum of the third order harmonics (zero sequence components). As a result the neutral current RMS value can be many times greater than for the phase currents. Many networks which are currently in use are not ready to supply such loads.
3. Overloads, too early ageing or failures of many elements of power systems, e.g. generators, transformers, motors, capacitor banks and especially components of information and communication networks.
4. Failures being a consequence of resonance phenomena caused by higher harmonics.

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The reduction of waveform distortions in power systems requires application of additional passive or active compensators, e.g. APFs (Akagi *et al.*, 2007). In the past compensators have been usually selected individually. Now the more and more distributed character of distortion sources makes the problem of spread out compensator location and sizing, which ensures achievement of desired effects (IEEE Std 519-1992; PN-EN 50160:2002/Ap1:2005) with the less possible technical and financial cost, more important. This problem can be regarded as an optimization task (Grabowski and Walczak, 2012; Keypour *et al.*, 2004; Pasko 1995; Ramos *et al.*, 2006; Wang Yan-song *et al.*, 2010).

2. Optimization strategies

General optimization task with constraints:

$$\min_{\mathbf{x}} f(\mathbf{x}) \tag{1}$$

such that:

$$\mathbf{c}(\mathbf{x}) \leq 0 \tag{2}$$

can be used for APF location and parameter determination. The first case considered in the paper consists in APF current RMS value $\left|I_w^k\right|$ minimization in W selected buses by means of the APF while harmonic voltage standard levels (IEEE Std 519-1992; PN-EN 50160:2002/Ap1:2005) and APF current constraints defined by $THDV_{wmax}$ and $\left|I_w^k\right|_{\max}$, respectively, are simultaneously observed assuming that the maximum harmonic number under consideration is equal to H:

$$\min_{\mathbf{x}} f_1(\mathbf{x}) = \min_{\left\{\mathrm{Re}(I_{wh}^k),\, \mathrm{Im}(I_{wh}^k)\right\}} \sum_{w=1}^{W} \left|I_w^k\right| = \min_{\left\{\mathrm{Re}(I_{wh}^k),\, \mathrm{Im}(I_{wh}^k)\right\}} \sum_{w=1}^{W} \sqrt{\sum_{h=2}^{H} \left|I_{wh}^k\right|^2} \tag{3}$$

such that $\mathbf{c_1}(\mathbf{x}) \leq 0$:

$$\left|I_w^k\right| - \left|I_w^k\right|_{\max} \leq 0, \quad w = 1,2,..,W \tag{4}$$

$$THDV_w - THDV_{w\max} \leq 0, \quad w = 1,2,..,W' \tag{5}$$

Minimization of the APF current and so the required nominal apparent power of devices to be installed (IEEE Working Group on Nonsinusoidal Situations, 1996) leads to cost reduction – Fig. 1 shows an exemplary relation between the APF size and its price. It can be included in the definition of the optimization problem (Grabowski and Walczak, 2012).

The second approach consists in minimization of voltage distortions in all busses *W'* of the analyzed power system while APF current constraints are observed:

$$\min_{\mathbf{x}} f_2(\mathbf{x}) = \min_{\left\{\mathrm{Re}(I_{wh}^k),\, \mathrm{Im}(I_{wh}^k)\right\}} \sum_{w=1}^{W'} THDV_w \tag{6}$$

such that constraint $\mathbf{c_2}(\mathbf{x}) \leq 0$ defined only by (4) is fulfilled.

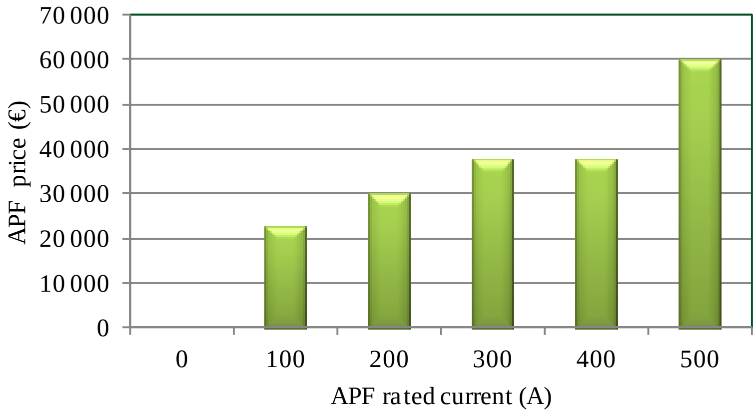

Fig. 1. Exemplary relation between APF price and size

2.1. Test system

A supply system used to test the optimization strategies presented in the beginning of chapter 2 has been shown in Fig. 2. It contains 20 buses with 8 DC distributed motors driven by 6-pulse line-commutated adjustable speed drives (ASD) which are the main harmonic sources in the system (Grady, 2006; Maciążek *et al.*, 2010). THDI for each bus is given in section 2.3 – see Tab. I.

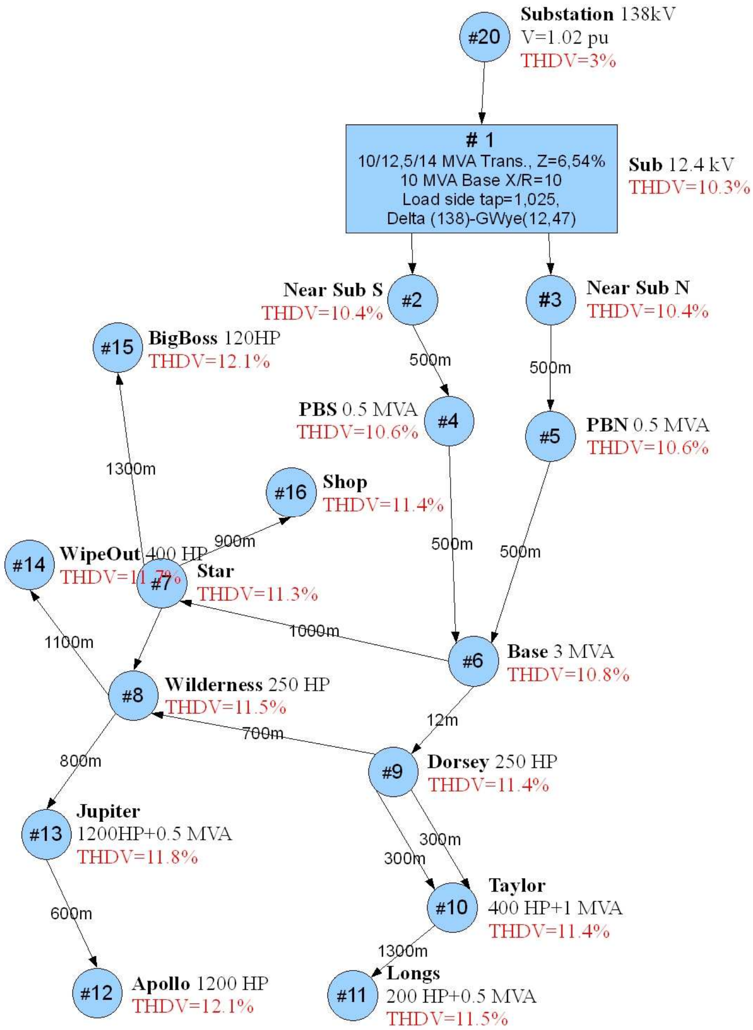

Fig. 2. Test system diagram – *THDV* values before optimization

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2.2. Software implementation

The complexity of power systems forces some simplification in the field of analysis as well as parameter identification. One of the most common consists in linearization of the system assuming periodic waveforms and quasi-steady state. For each harmonic equivalent impedances are determined and next amplitude and phase characteristics are calculated.

The test system (Fig. 2) has been modelled in PCFLO software which enables harmonic analysis (Grady, 2006) and uses mentioned above approach. Analysis of harmonics propagation in power systems requires information about models of nonlinear loads which are the main source of harmonics (Walczak and Świszcz, 2005). In order to solve problems considered in this paper PCFLO must be controlled by external program which is able to perform optimization and result analysis. Matlab has been chosen as master level application. Integration of Matlab and PCFLO was the first step which resulted in development of the PcfloPackage library (Lewandowski *et al.*, 2011). The next step consists in optimal parameter setting as well as optimal location of APF taking advantage of cooperation between both software environments with the help of the library.

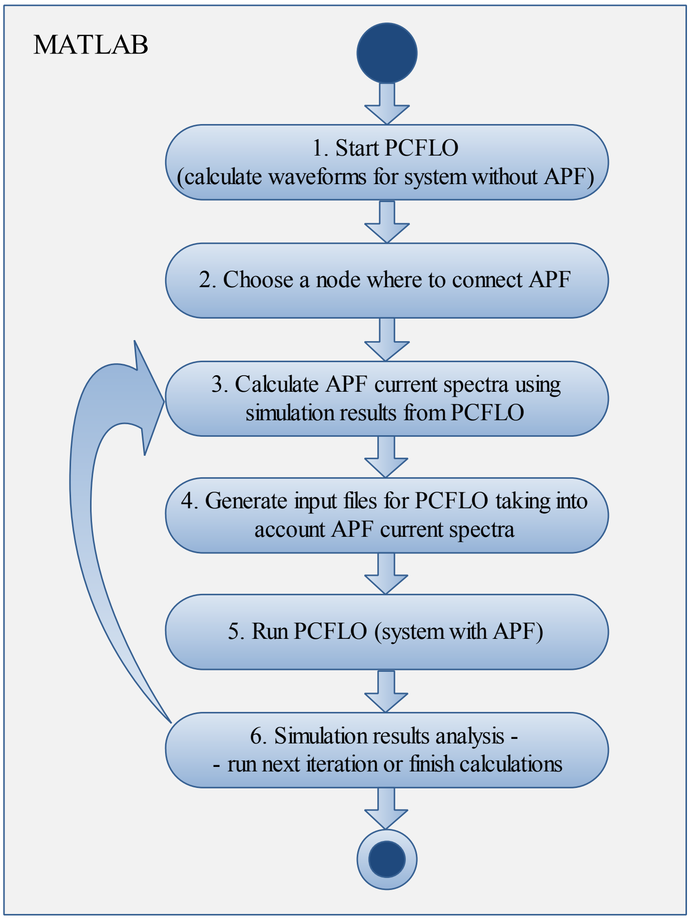

Fig. 3. Block diagram illustrating Matlab and PCFLO cooperation

The following example shows first results of optimization using goal functions (3) and (6) and assuming that a single APF is placed in the bus #12 with the highest value of total harmonic voltage distortion THDV ($W = 1$, $W' = 20$). The sequential quadratic programming (SQP) algorithm implemented in Matlab has been applied. The solution has been compared to simple compensation approach which consists in injection of a sum of higher harmonics of a nonlinear load connected to the bus under consideration (Lewandowski *et al.*, 2011) and makes the line current shape almost sinusoidal.

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2.3. Example

Application of optimization approaches presented in the beginning of chapter 2 results in APF parameters which ensure minimization of the goal function while satisfying given constraints. Fig. 4 shows the convergence of the algorithm for both optimization approaches defined by objective functions f_1 and f_2 with constraints expressed by c_1 and c_2, which should take negative values if the constraints are fulfilled.

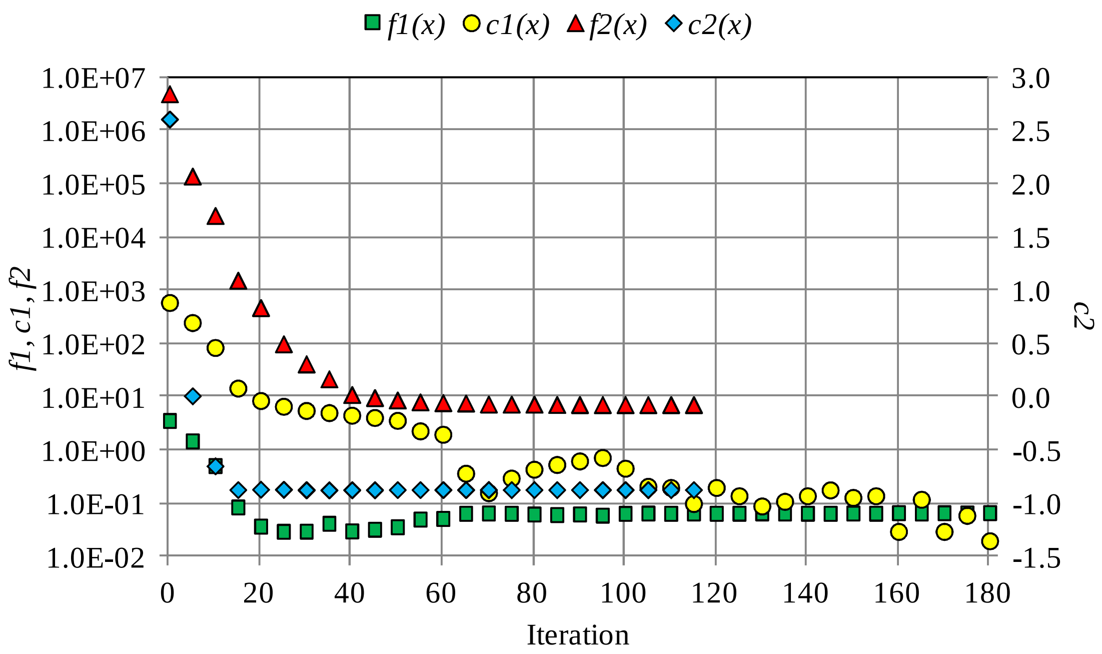

Fig. 4. Goal function and constraint values during optimization process

The original, i.e. before compensation, voltage and current waveforms for the bus #12 have been shown in Fig. 5.

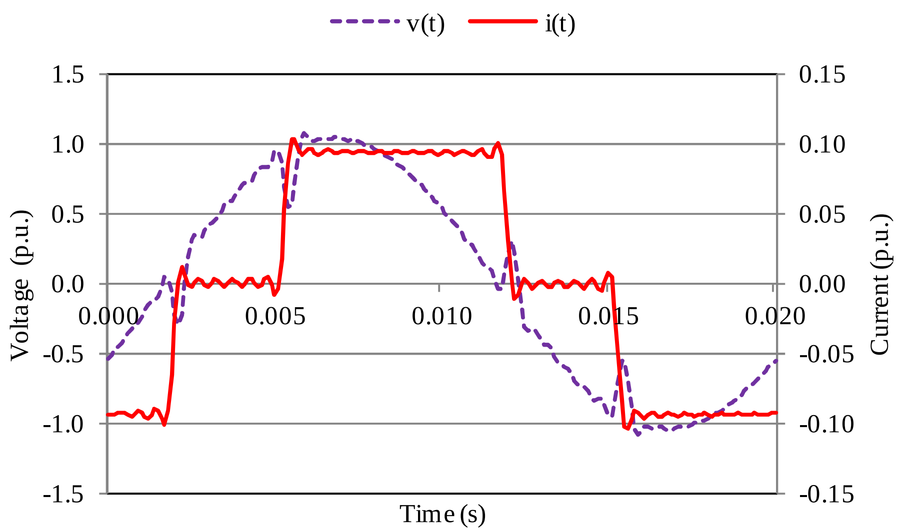

Fig. 5. Voltage and current waveforms (bus #12) before compensation

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Application of the optimization strategy (3), which aims at compensator RMS current minimization while achieving the limit values of *THDV* coefficients in all buses, leads to voltage and current waveforms shown in Fig. 6. The optimization strategy (6), which aims at *THDV* coefficients minimization while achieving the limit values of compensator RMS current, leads to voltage and current waveforms shown in Fig. 7.

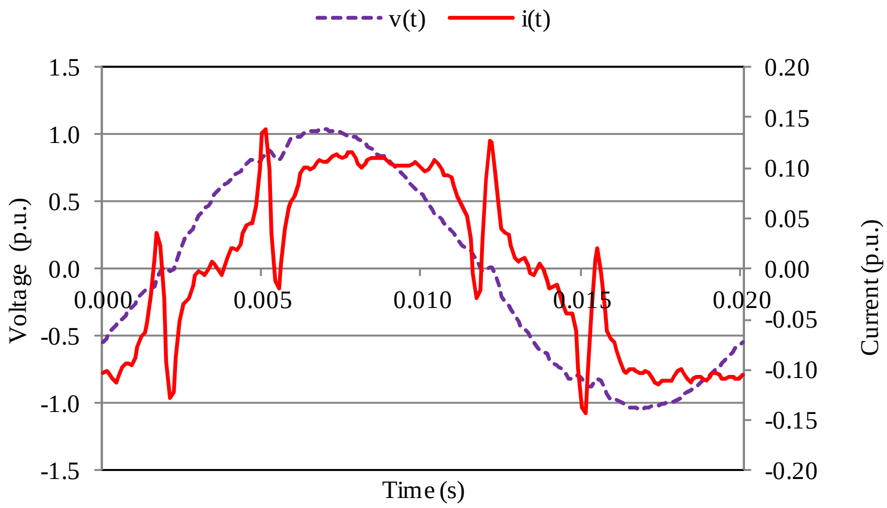

Fig. 6. Voltage and current waveforms (bus #12) after compensation based on the objective function f_1

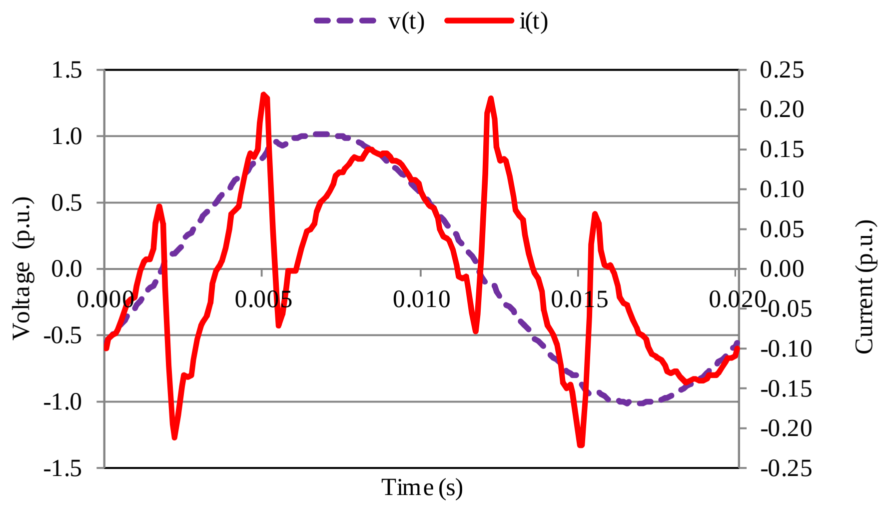

Fig. 7. Voltage and current waveforms (bus #12) after compensation based on the objective function f_2

In order to enable comparison to the simplest and the most popular control algorithm used for compensators (Lewandowski *et al.*, 2011; Pasko and Maciążek, 2006) the corresponding waveforms have been shown in Fig. 8. The current distortions are noticeably less for this approach but the *THDV* coefficients are above the limits.

It must be stressed that optimization strategies (3) and (6) lead to the determination of the APF current higher harmonics (h>1). Of course, the problem formulation can be extended including also the determination of the first harmonic. In that case the phase shift between voltage and current, which is still visible after compensation (Figs. 6, 7 and 8), could be decreased – the APF could also compensate the reactive power at the fundamental frequency (Szromba, 2004). Such approach will be investigated in future works.

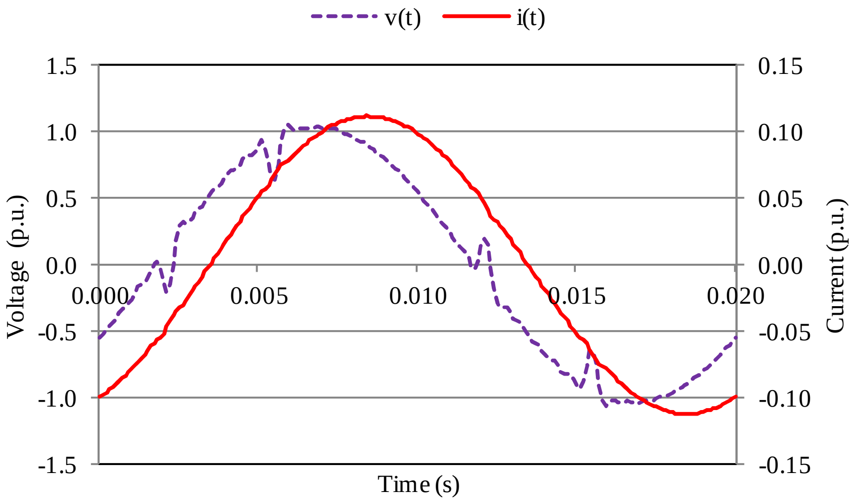

Fig. 8. Voltage and current waveforms (bus #12) after compensation (Lewandowski *et al.*, 2011)

The APF current waveforms obtained using different optimization strategies have been shown in Fig. 9. The goal function f_1 leads to the APF with lower nominal power comparing with the goal function f_2 but the final *THDV* values are lower for the function f_2 - see Tab. I.

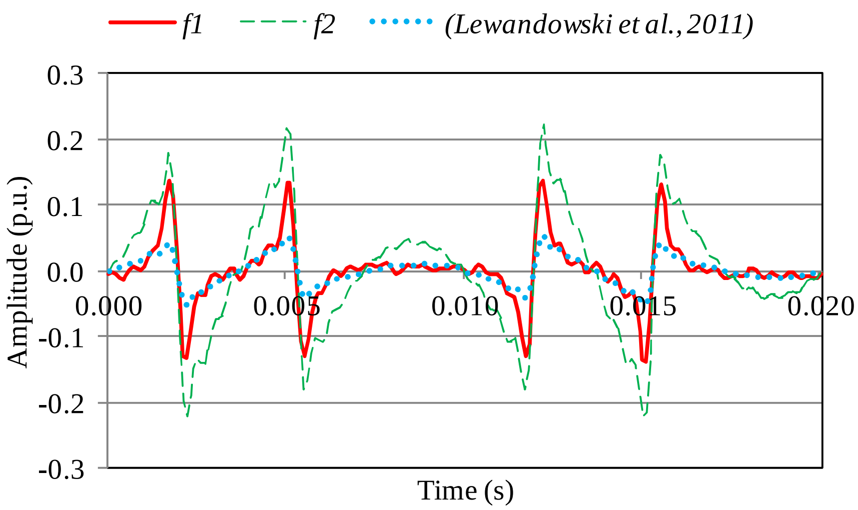

Fig. 9. APF current waveforms obtained for different optimization strategies

The goal function f_2 enables concurrent voltage distortion minimization at local and remote busses due to multi-point voltage monitoring but leads to more expensive solutions (higher APF ratings – Fig. 9) and what is more important it leads to increase of current distortion (*THDI*). The problem with high values of *THDI* coefficient consists in that *THDI* limits the true power factor of nonlinear loads (Grady, 2006). On the other hand the simplest approach (Lewandowski *et al.*, 2011) for a single APF does not allow to reach *THDV* values satisfying the standards (IEEE Std 519-1992; PN-EN 50160:2002/Ap1:2005), although it leads to the smallest APF size and reduces the current distortion in the bus to which APF is connected better than the other methods.

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TABLE I
VOLTAGE AND CURRENT DISTORTIONS
FOR SOME SELECTED BUSES OF THE TEST SYSTEM WITH AND WITHOUT APF

#	bus name	*THDV* (%) No APF	*THDI* (%) No APF	*THDV* (%) 1 APF*	*THDI* (%) 1 APF*	*THDV* (%) 1 APF-f_1	*THDI* (%) 1 APF-f_1	*THDV* (%) 1 APF - f_2	*THDI* (%) 1 APF - f_2
1	Sub 12.5 kV	10.4	11.0	7.9	8.4	4.2	6.5	0.4	0.3
8	Wilderness	11.5	29.7	8.8	29.7	4.7	29.7	0.4	29.7
10	Taylor	11.4	29.7	8.7	29.7	4.6	29.7	0.4	29.7
11	Longs	11.5	29.7	8.8	29.7	4.7	29.7	0.5	29.7
12	Apollo	12.1	29.7	9.0	1.6	4.7	39.0	1.8	95.7
13	Jupiter	11.8	29.7	9.0	29.7	4.7	29.7	0.6	29.7
15	BigBoss	12.1	29.7	9.4	29.7	5.2	29.7	1.2	29.7
20	Sub 138 kV	3.0	11.0	2.3	8.4	1.2	6.5	0.1	0.3

* (Lewandowski *et al.*, 2011)

In order to compare shapes of current and voltage waveforms before and after compensation using different strategies the waveforms have been collected in Figs. 10 and 11.

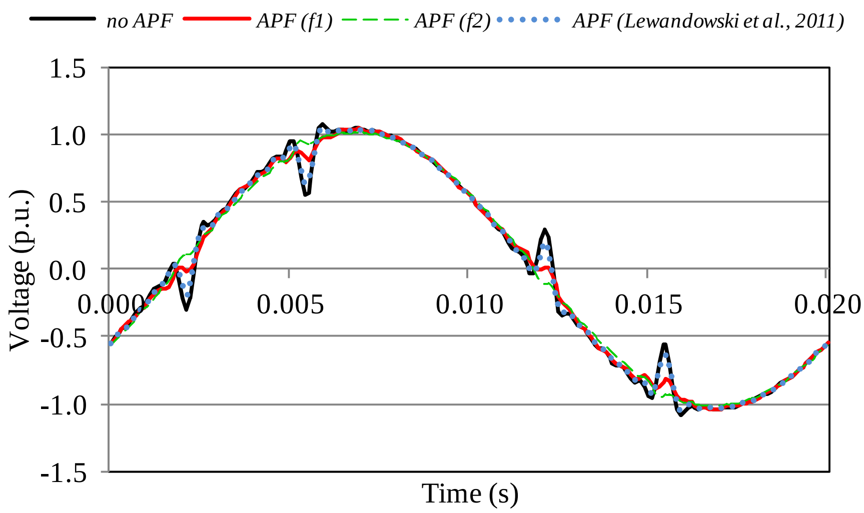

Fig. 10. Phase voltage waveforms (bus #12) before and after compensation using different strategies

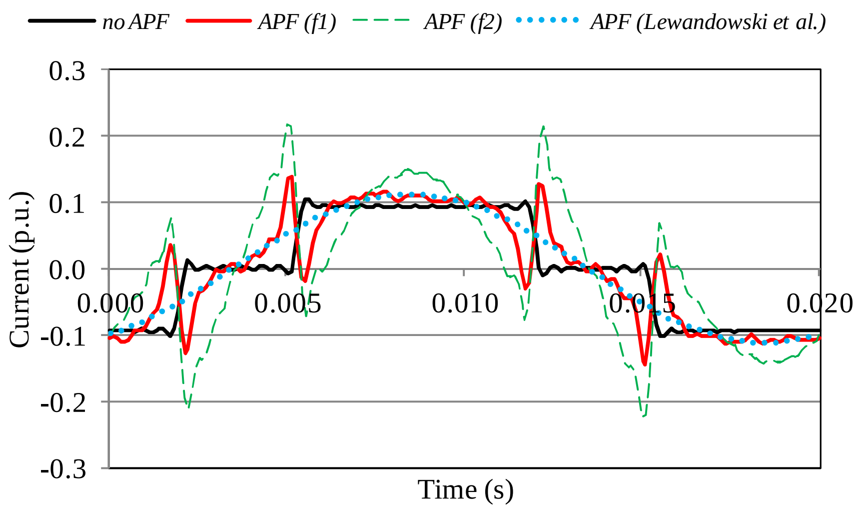

Fig. 11. Phase current waveforms (bus #12) before and after compensation using different strategies

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Line-to-line voltages can be calculated on the base of phase voltages obtained in PCFLO assuming symmetrical loads. Exemplary time waveforms and magnitude spectra of line-to-line voltages have been presented in Figs. 12 and 13.

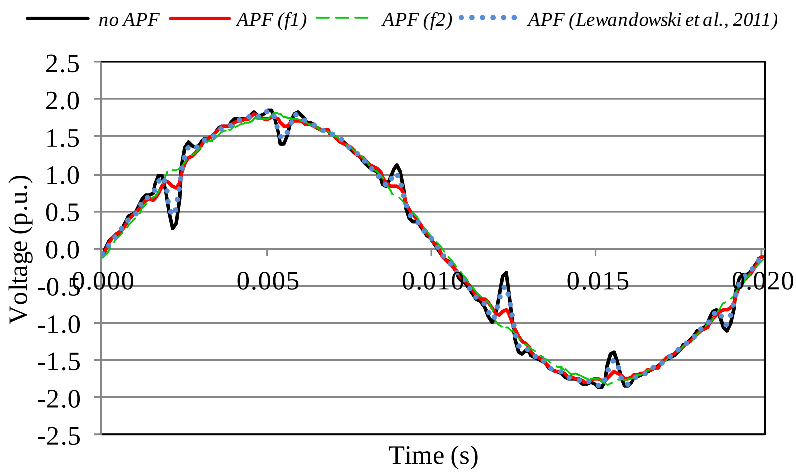

Fig. 12. Line-to-line voltage waveforms (bus #12) before and after compensation using different strategies

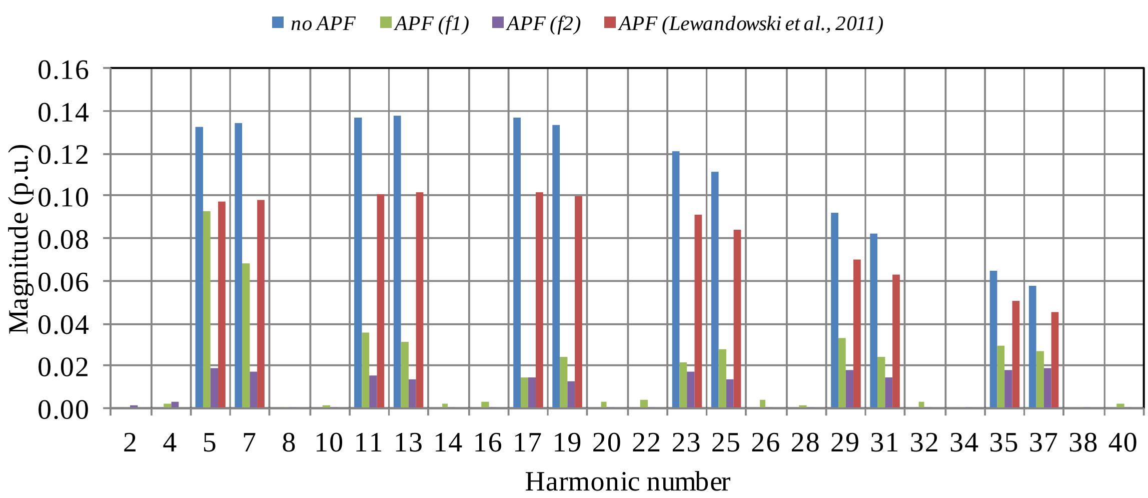

Fig. 13. Line-to-line voltage magnitude spectrum (bus #12) before and after compensation using different strategies

The THDV coefficients for the line-to-line and the phase voltages are the same (see Tab. I) because phase voltages do not contain harmonics of the third order and the magnitude spectra of both voltages can be obtained one from another just by multiplication or division by √3.

3. Conclusions

Application and first results of some optimization strategies for determination of location and sizes of active power filters carried out in Matlab and PCFLO software linked by the PcfloPackage library have been presented in the paper. Numerical verification of the proposed approach has been started with relatively simple case of single APF sizing. Simulations show a very strong link between the chosen goal function and the results.

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Application of a single APF in a supply system with several nonlinear loads can enable fulfilment of total harmonic voltage distortion limits imposed by standards in all buses of the system. However, the current distortions could be even greater than in the system without APF. More compensators are needed to decrease both current and voltage distortions. In such case the problem of optimal APF allocation as well as cost reduction rises. Optimization of APF location for fixed and variable load structures and parameters will be covered by future works.

4. Acknowledgements

This work was supported by Polish Ministry of Science and Higher Education under the project number N N510 257338.

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