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Optimum allocation of active power filters in large supply systems

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Abstract. Problems concerning electrical power quality and especially estimation of costs required for reduction of higher harmonics in power network voltage and current time waveforms have been considered in the paper. The application of active power filters to reduction of higher harmonics has been analysed taking into account, in particular, the necessary investment costs. Two goal functions have been used to solve the underlying optimization problem – the first one that enables direct cost minimization and the second one based on the cost-effectiveness approach used by economists. Such approach is substantially different from solutions proposed by other authors who concentrate rather on theoretical issues and do not take into consideration the economical market-based reality. In the paper, theoretical analysis has been followed by an example of optimal allocation of active power filters in a large supply system.

Key words: optimum allocation, active power filters, large supply systems.

1. Introduction

Dynamic technological development results in fast increase of the number of electrical loads with nonlinear voltage-current characteristics. Consequently, some additional components (higher harmonics) arise in current /voltage waveforms changing their shape to non-sinusoidal. Higher harmonics present in current and voltage waveforms have strong negative economic impact. In accordance with reports made by Leonardo Power Quality Initiative [1] the total costs caused by power quality (PQ) problems to European economy exceed 150 billion € with about 5% of the cost contribution from higher harmonics in voltage and current waveforms, Fig. 1, [2].

Moreover, higher harmonics are responsible for 22% of all problems caused by poor power quality and 25% of the harmonic costs are related to equipment, either in the form of repair or replacement [1]. Negative consequences of higher harmonics have been presented in Fig. 2, [2].

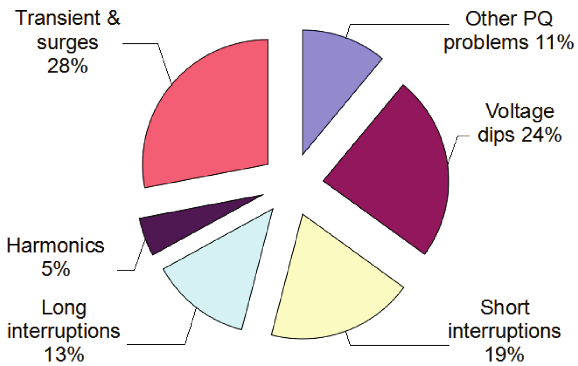

Fig. 1. Main reasons of poor power quality and their percentage in the total PQ cost in EU

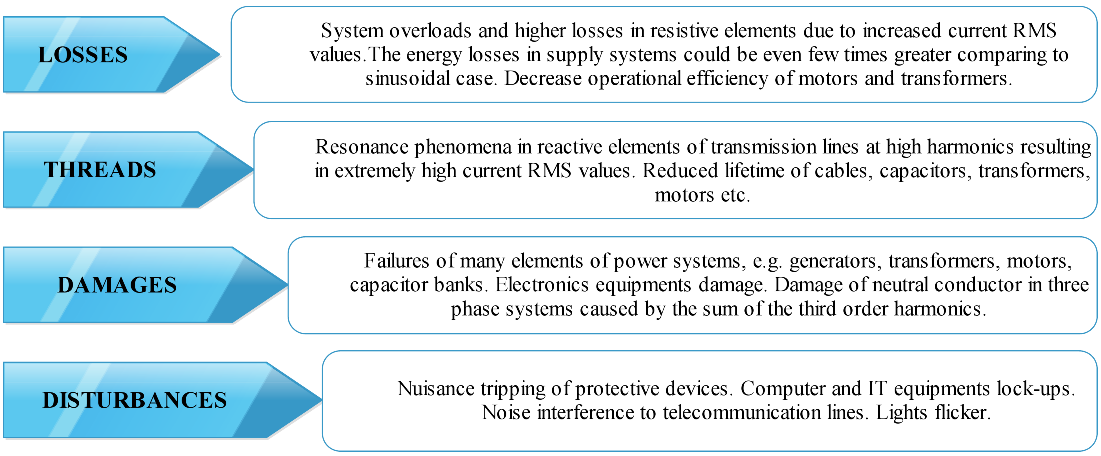

Fig. 2. Problems caused in power systems by higher harmonics

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Parallel passive filters are the simplest and the most often used method of current higher harmonic elimination. Nevertheless, this solution requires prior analysis of power system operating point followed by determination of dominant harmonics [3]. Due to dynamic changes in harmonic content caused by large number of nonlinear loads with wide spectrum of generated harmonics, superior compensation results could be obtained by application of parallel or series active power filters [3], hybrid systems or UPFCs (Unified Power Flow Controller). Only parallel active filters (APF and HAPF) have been considered in the further part of this paper. It is a consequence of the fact that current higher harmonics are usually the main cause of voltage higher harmonics due to voltage drops across line impedances which on the other hand result in distortions of power network voltages.

Increasing number of nonlinear loads and consequently distortions of voltage and current waveforms in power systems as well as still high prices of compensation systems have encouraged researchers to work on new solutions leading to power quality improvement, e.g. [3–5]. Among papers on this topic, there are also publications closely related to the problem covered by this paper, i.e. optimization of compensator allocation in power systems. The proper allocation could help to improve compensation results and decrease the required nominal power of compensation systems. In publications on optimization of active power filter allocation [6–13] the main aim consists in such allocation of compensators which ensures minimum nominal currents (minimum nominal power is directly related to the compensation costs). If some additional factors, e.g. contents of individual harmonics or THDI coefficients, have to be included in the optimization process, then multi-objective optimization methods could be applied [14–17]. However, systems analysed in these papers include a few or at most a dozen buses. It must be stressed that the problem complexity increases substantially along with the number of busses. Thus, for practical reasons, an approach that enables finding satisfactory solution in acceptable amount of time should be worked out. Of course, all methods used in the cited above papers could be also applied for large supply systems if time is not a key factor – see for example comparison of computational times for combinatorial and genetic algorithms presented in the paper concluding chapter.

There are also some papers describing application of optimization approach directly to investment costs [10, 13, 14, 16]. However, contrary to the approach presented in this paper, a linear relation between the compensator cost and its rating has been assumed in these publications. This assumption is not realistic as the prices of power electronic devices, including APFs, rise sharply along with the nominal rating.

Main differences between solutions on APF optimal allocation presented in this paper and those known from the publications cited so far include:

- development of a goal function based on real costs of active compensation so that optimization results reflected the investment costs in the best possible way,
- development of complete optimization algorithms leading to such allocation of compensation devices in large supply systems that allows to put the assumed goals, reflected by the proposed or any other goal function, into practice [18],
- development of a software package which enables harmonic flow analysis and application of arbitrary optimization methods for allocation of active compensators including hybrid ones,
- analysis of compensation costs in a large supply system including almost 450 buses.

The proposed solutions have been verified by means of simulations, namely three variants of compensation with different constraints have been checked. The compensation costs have been verified for the following cases:

- full elimination of nonlinear load influence (THDV minimization),
- bringing THDV below the limits imposed by standards (THDV $< 5\%$) with some additional constraints (type of compensators – hybrid or active, limited compensator nominal currents),
- minimization of investment costs using a goal function developed for the cost-effectiveness approach.

Presented results prove that analysis of the system followed by deliberate allocation and sizing of active power filters could allow to cut investment costs and ensure improvement of power quality indices above the limits accepted by end-users and electricity providers.

2. Model of the test supply system

A few test systems used for the harmonic flow analysis could be found in the publications cited in the previous section. However, these systems have too low number of buses in order to evaluate optimization methods used to minimize investment costs in fairly realistic conditions. Thus, in this paper another system has been used [19]. Its main features are as follows:

- 445 buses,
- 450 lines,
- 37 nonlinear loads,
- 186 linear loads,
- widely varied distances between buses, including segments above 1000 m,
- medium voltage (MV) system,
- full data about line parameters and loads.

The block diagram of the system has been shown in Fig. 3. Its analysis has been presented in the following sections.

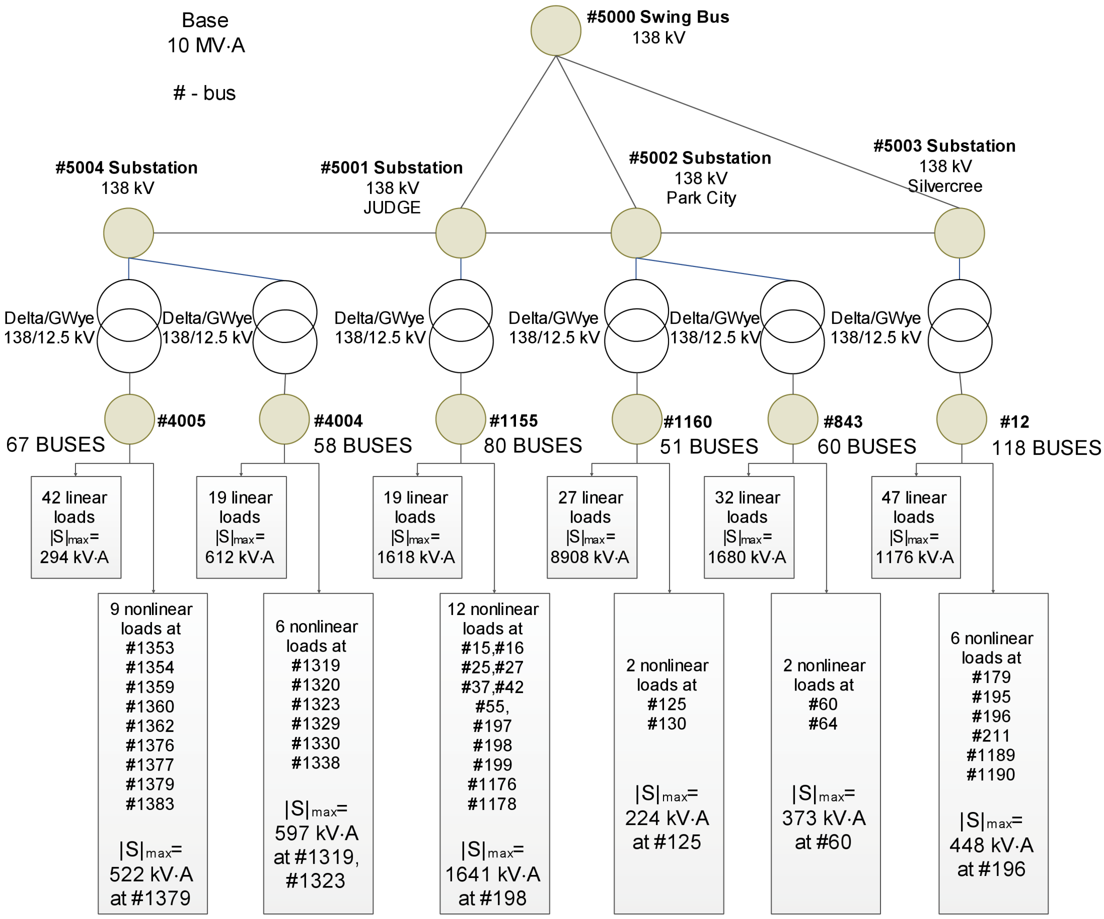

Fig. 3. Block diagram of a large supply system under consideration

3. Goal function – optimization of active compensation investment costs

Analysis of many combinations of active power filter connections to buses of a supply system is required in order to carry out optimization of compensator allocation. Results depend on the chosen goal function and the optimization algorithm used. Such algorithms as GBDT [6], combinatorial [20], genetic [7–9, 16], TABU [10] or PSO [13–15] have been used. If computation time is a key factor then global optimization methods, e.g. genetic algorithms, give the best results. On the other hand, combinatorial algorithms followed by detailed result analysis allow to achieve solutions that are best tailored to users' expectations. Because of the size of a supply system used in simulations, genetic algorithms have been applied in the paper. Furthermore, for the sake of result comparison, combinatorial approach and result analysis from the power quality and compensation cost point of view have been also used.

Goal functions which enable optimal choice with regard to compensation costs have always a form of compromise between the scale of power quality improvement and the financial costs required for this improvement.

The following goal function enables to take into consideration economic criterion through direct compensator cost minimization:

$$\underset{T[w]}{\text{minimize}}\ f = \sum_{w=1}^{W} g\left(\left|I_{T[w]}^{k}\right|\right), \tag{1}$$

where $T[\;]$ – set including numbers of buses to which APFs should be connected, w – index pointing at an element of the set of bus numbers, W – number of APFs connected to the system, $g(\cdot)$ – function relating nominal currents and costs of APFs, $|I^k|$ – RMS value of APF current.

Solution to the problem requires also some inequality constraints to be taken into account:

1. THDV coefficients in all system buses should not exceed the maximum assumed value $\text{THDV}_{\max}$:

$$\text{THDV}_n < \text{THDV}_{\max}; \quad n \in \langle 1, N \rangle, \tag{2}$$

   where N – total number of system buses,
2. RMS values of APF currents should not be greater than the maximum assumed value:

$$\left|I_{T[w]}^{k}\right| \le \left|I^k\right|_{\max}; \quad w \in \langle 1, W \rangle. \tag{3}$$

The goal function includes the APF cost function $g(\cdot)$, which in practice is a non-continuous step-like function – some intervals of currents (powers) correspond to the cost of single APF (it is a result of the product range available in the market). The function $g(\cdot)$, used in the paper, has been estimated on the base of price lists of APFs offered in the European market [21].

Some authors claim that standards regulating the content of higher harmonics in current and voltage waveforms are too restrictive [22] and moreover there is a discrepancy between countries in limits of distortions being up to standard, e.g. 5% and 8%. This is why in the case of combinatorial optimization another goal function has been used. Its description could be found in [21]. Some analogies of this function and the cost-effectiveness coefficient used in economic analysis could be observed. It is applied if a solution which ensures the best improvement of THDV for a given financial investment should be found. The raise of costs made by each variant of APF allocation is considered with regard to the gradient of the THDV improvement. Such approach has not been analysed so far and in our opinion it could be applied in practice because many investors, who currently prefer to use less efficient but cheaper passive filters, could be convinced to choose active compensation as an interesting alternative. Of course, the satisfactory compromise depends on a case under consideration including the sensitivity of loads in a given supply network.

4. Software system for optimization of compensation costs

Analysis of harmonic flow in power system models have been made with the help of PCFLO computer program [19]. It could be run in the batch mode using the command line instructions and reading all the configuration options as well as input data from text files prepared by the user. Matlab software, supported by a few classes written in JAVA and used to PCFLO file handling [18], has been chosen as an upper level application controlling the whole optimization process. The block diagram of the proposed optimization software system has been presented in Fig. 4.

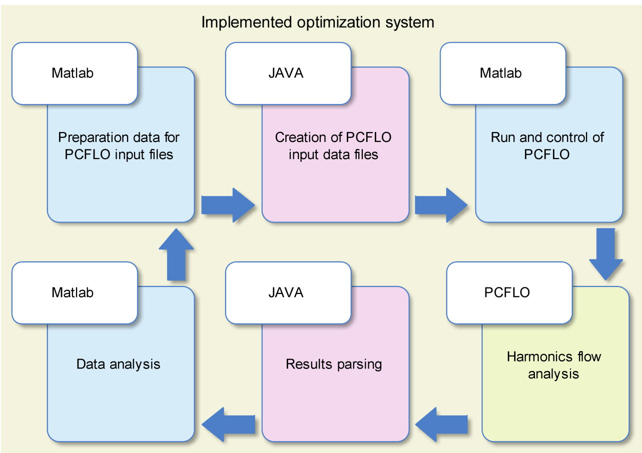

Fig. 4. Software system developed for solution of the optimization problem

Moreover, the frequency analysis has been performed assuming a linear model of the power system and treating nonlinear loads as separate current sources for each harmonic. The optimization problem has been formulated assuming that an APF being attached to one of the system buses can be treated as an ideal current source, described by a Fourier series, which enables injection of higher harmonics determined by an APF control algorithm.

5. Optimization algorithm of APF allocation

The block diagram of the developed genetic algorithm, which enables the optimum allocation of APFs in a given supply system, has been shown in Fig. 5. It includes information on which programs are responsible for realization of tasks making up the algorithm.

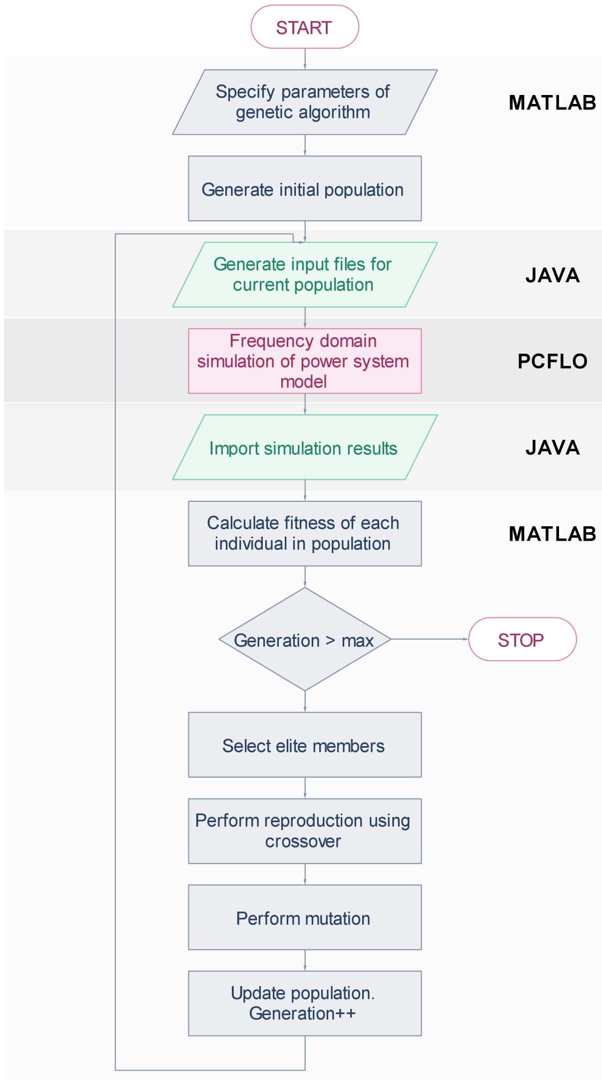

Fig. 5. Block diagram of the developed algorithm of optimum APF allocation

The algorithm presented in Fig. 5 consists of 11 basic steps. First, configuration parameters of the genetic algorithm, such as goal function, population size, elite group size and others, are set. Next, a random population of solutions (chromosomes), consisting of sets of buses to which APFs should be connected, is generated.

The third step of the algorithm comprises generation of configuration and input data files for PCFLO [19]. The information included in the chromosomes is used and in buses indicated by them virtual APFs are connected to the system. The program itself is run in the following step – it simulates the power system in the frequency domain. The PCFLO simulation results are stored in text files and include THDV and THDI coefficients as well as voltage and current spectra for all buses and lines, respectively. The fifth step of the algorithm is responsible for extraction of data from these files. It is made with the help of the library developed in JAVA. The main genetic algorithm is realized through steps 6 to 11, in which results for each individual in the current population are checked. The set of best solutions (elite members) is determined and passed on to the next generation without modifications while the other solutions undergo crossover and mutation operations before being put in the next generation. After that, the described process is repeated for the new generation.

The simulation ends if any of the conditions listed below is fulfilled:

- a maximum number of generations, assumed in configuration parameters, has been reached,
- there is no sufficient change of the fitness function during a given number of generations.

An additional problem during allocation and sizing of compensators consists in setting the right number of compensators. Two solutions of this problem have been incorporated in the proposed algorithm. The first one assumes that the number of compensators is a decision-making variable, which becomes a part of the chromosome, and it is set by the algorithm during the optimization process. The second approach consists in setting the number of compensators by the user. In this case, if the design assumptions, e.g. acceptable level of THDV or total compensation costs, have not been reached during the optimization process then the algorithm could be restarted for the number of compensators increased by 1.

6. Analysis of optimization results

Application of the proposed algorithm resulted in many solutions which have been successively analyzed. Three criterions have been used for solution evaluation. The first one has been aimed at finding a solution with minimum THDV in all buses of the system. Subsequently, this solution has been regarded as a reference point during comparison of costs obtained using different optimization strategies. The second one has been aimed at finding a solution for which the THDV coefficients do not exceed the maximum acceptable level defined in power quality standards [23] – in the paper it has been assumed that $\text{THDV}_{\text{max}} = 5\%$. The third criterion has made use of a goal function which ensures the best cost-effectiveness ratio of the obtained solution. This approach has been based on solutions achieved by means of combinatorial optimization.

For all three cases compensation costs using APFs and HAPFs have been compared. In HAPF based compensation systems, designers have made an effort to combine advantages of passive and active filters. A power electronic part of the HAPF has substantially lower rating comparing to the APF and so it is usually a cheaper solution but it does not allow for power factor correction.

Analysis of the results for the first criterion leads to an obvious conclusion that the best solution consists in full compensation. In this case APFs are connected to all buses with nonlinear loads and as a results all unwanted current components flow only in the circuit APF-nonlinear load. Of course, the cost of such solution is very high. For the sake of further solution comparison, this cost has been set as a reference level (100%).

The results have been put together in Table 1.

Table 1
Comparison of optimization results for APF/HAPF compensators

Label	Algorithm Compensator	Constraints	HH	PFC	Numbers of buses with compensators	Max (THDV)	Relative costs
GA1	GA APF	$\text{THDV}_{\text{max}} = 5\%$ $W = 6$	X	X	42, 198, 1354, 1360, 1376, 1383	4.61%	30.12%
GA2	GA HAPF	$\text{THDV}_{\text{max}} = 5\%$ $W = 7$	X		42, 195, 198, 1359, 1360, 1376, 1383	4.82%	12.97%
GA3	GA APF	$\text{THDV}_{\text{max}} = 5\%$ $W = 12$ $I^k_{\text{max}} = 200$ A	X	X	37, 55, 64, 199, 1320, 1323, 1329, 1354, 1360, 1376, 1379, 1383	4.98%	34.36%
GA4	GA HAPF	$\text{THDV}_{\text{max}} = 5\%$ $W = 12$ $I^k_{\text{max}} = 200$ A	X		27, 42, 197, 199, 211, 1329, 1338, 1353, 1354, 1360, 1376, 1383	4.43%	22.24%
GA5	GA APF	$\text{THDV}_{\text{max}} = 5\%$ $W = \text{auto}$	X	X	37, 42, 64, 199, 211, 1354, 1360, 1376, 1379	4.86%	34.75%
GA6	GA HAPF	$\text{THDV}_{\text{max}} = 5\%$ $W = \text{auto}$	X		42, 195, 198, 1329, 1353, 1354, 1362, 1376, 1379, 1383	4.68%	18.53%
CA1	CA APF	$\text{THDV}_{\text{max}} = 7\%$ cost-effectiveness	X	X	42, 60, 196, 1354, 1376, 1383	6.61%	17.76%
CA2	CA HAPF	$\text{THDV}_{\text{max}} = 7\%$ cost-effectiveness	X		42, 60, 196, 1354, 1376, 1383	6.68%	11.12%

where GA – genetic algorithm, CA – combinatorial algorithm, APF – active power filter, HAPF – hybrid active power filter, HH – elimination of higher harmonics, PFC – power factor correction.

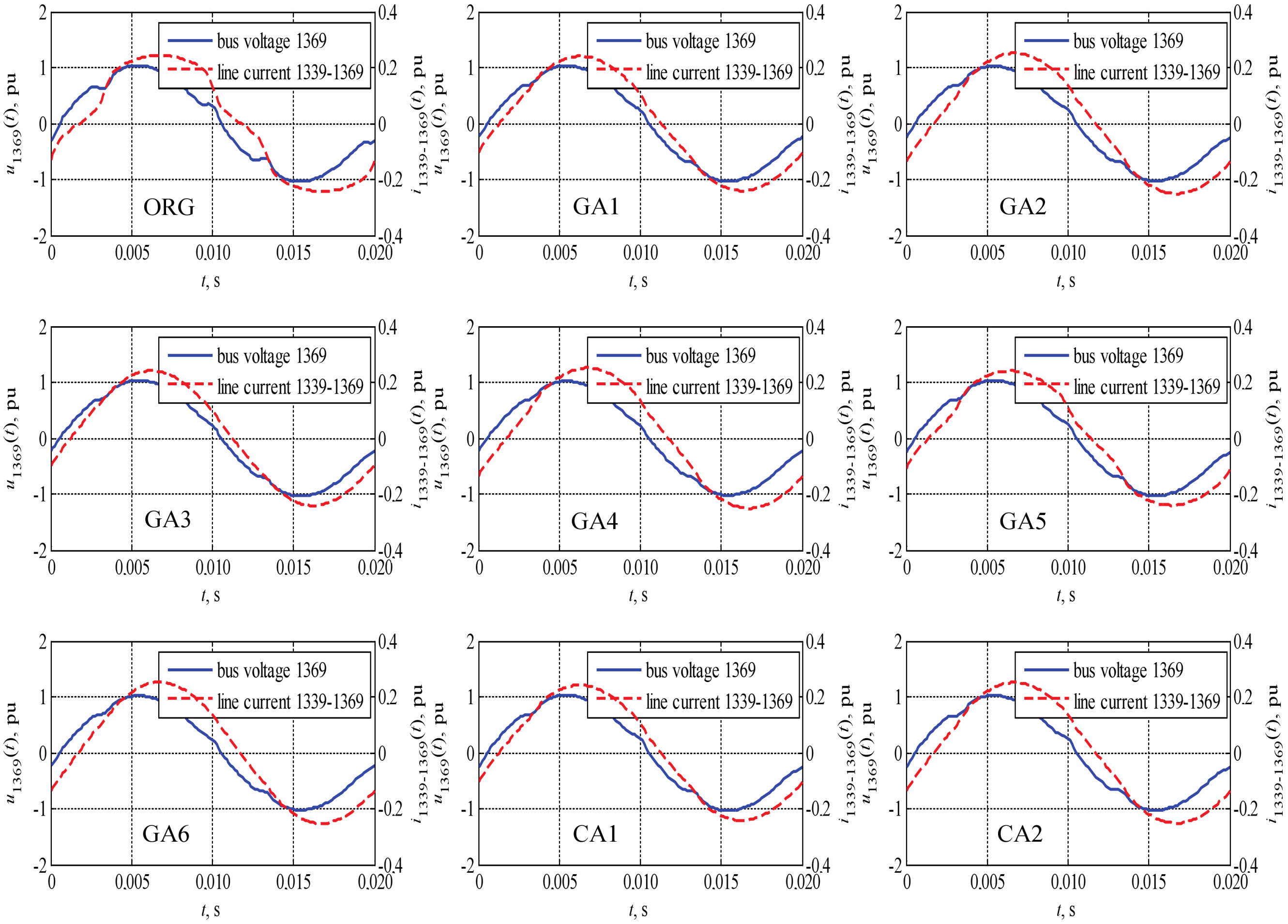

Fig. 6. Comparison of current and voltage waveforms for an exemplary bus and line

The result analysis shows that for both automatic and fixed by the user setting of the number of APFs the cost reduction of almost 70% is possible. Of course, it concerns cases for which the level of higher harmonics in voltage waveforms has been reduced below the threshold defined by standards, i.e. less than 5%.

Similar cost reduction has been also reached if a constraint on the maximum RMS value of the APF nominal current was set. Of course, in this case the required number of APFs is higher, but due to nonlinear relation between APF size and price sometimes such approach could lead to cheaper solutions. Moreover, there are often other restrictions which make application of APFs with higher ratings impossible, e.g. the available space. In such cases, the constraint on the maximum RMS value of the APF nominal current could help to decrease the investment costs even more. Application of HAPF compensators is more profitable in all cases if reduction of higher harmonics is the only aim. The results obtained for combinatorial optimization and using the goal function based on the cost-effectiveness approach have been also included in Table 1. In this case, the solution is a kind of compromise between the compensation costs and the effectiveness of higher harmonic elimination. The determination if such compromise is reasonable depends on types of loads in the power system under consideration and especially their sensitivity to higher harmonics. Thus, the decision must be made individually.

Exemplary set of voltage waveforms for a given bus as well as current waveforms through a line connected to this bus have been presented in Fig. 6. The same labels as in Table 1 have been used to indicate waveforms obtained for different approaches. The label ORG denotes current and voltage waveforms before compensation, the other labels are exactly the same as in Table 1.

Differences in the shape of waveforms as well as in the content of reactive power for the fundamental frequency can be easily noticed in Fig. 6. Of course, these waveforms are just examples for a given bus and line but on the other hand they illustrate quite well changes obtained through different optimization strategies proposed in this paper.

7. Conclusions

The routine used for compensator allocation in the power system influences both the power quality improvement and the compensation costs. Algorithms proposed to solve this optimization task have brought about the expected effects. The results point out the importance of proper selection of buses to which compensators should be connected in order to avoid

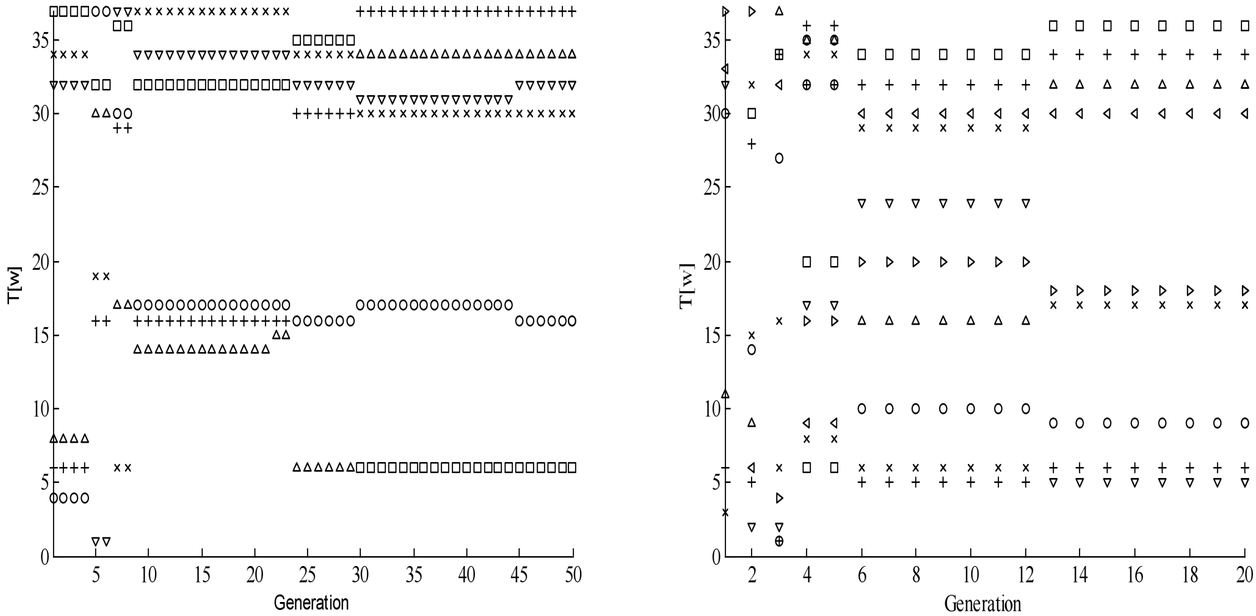

Fig. 7. Illustration of the APF bus selection process for GA1 and GA5

unnecessary investment cost increase. The combinatorial algorithms allow for more precise analysis and extensive result interpretation leading to the final solution selection. The main drawback of this approach consists in calculation times which raise sharply along with the number of buses. In the paper, despite limiting the number of buses to which compensators could be attached ($W \leq 16$), the calculation time was much more longer than for optimization with the help of genetic algorithms. Moreover, combinatorial algorithms require an additional time for post-processing of a large dataset. On the other hand, the calculation times for genetic algorithms depend strongly on the population size and the number of generations. For example, the bus selection process for the first 20 generations has been illustrated in Fig. 7. The calculation times for different algorithms and compensator types have been put together in Table 2.

Table 2
Comparison of calculation times

Label	Algorithm	Compensator type	Calculation time
GA1	GA	EFA	2 h 15 m
GA2	GA	HEFA	2 h 16 m
GA3	GA	EFA	3 h 27 m
GA4	GA	HEFA	3 h 25 m
GA5	GA	EFA	1 h 28 m
GA6	GA	HEFA	1 h 26 m
CA1	CA	EFA	145 h 36 m (6 days!)
CA2	CA	HEFA	140 h 10 m

In conclusion, the solutions proposed in the paper can lead to considerable reduction of active compensation costs and so in the future such an approach could cause increased investors' interest in the proposed method of power quality improvement.

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