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Passive Power Filter Design Using Genetic Algorithm

***Abstract**. Continuous technological development facilitates the increase in the number of nonlinear loads that significantly affect the power quality in a power system and, consequently, the quality of the electric power delivered to other customers. One of the most common methods to prevent adverse effects of nonlinear loads on the power network is the use of passive filters. Design of such filter can be regarded as a multi-criterial optimisation task, to which genetic algorithms can be employed. Watching recent tendencies in science can be observed an increasing number of "artificial intelligence" applications to practical solutions. It has been therefore decided to apply genetic algorithms (GA) to passive power filter design as an example of GA usefulness for technical issues. The paper presents passive filter structures designed using a program developed by the author in the MATLAB environment employing genetic algorithm. Two methods of approaching the design goal are presented - traditional and GA.*

***Streszczenie.** Śledząc tendencje współczesnej nauki, można zauważyć zwiększającą się ilość zastosowań „sztucznej inteligencji" w praktycznych rozwiązaniach. Idąc w tym kierunku, zdecydowano się zastosować Algorytmy Genetyczne (AG) do projektowania pasywnych filtrów energetycznych jako przykład użyteczności AG w zagadnieniach technicznych. Projektowanie takiego filtru można potraktować jako zadanie optymalizacji wielokryterialnej, do rozwiązania, którego można użyć Algorytmy Genetyczne. Artykuł przedstawia przykładowe struktury filtrów pasywnych, zaprojektowanych za pomocą opracowanego przez autora, w środowisku Matlab, programu wykorzystującego AG. Przedstawiono dwie metody podejścia do postawionego zadania projektowego.(**Projektowanie energetycznych filtrów pasywnych z użyciem algorytmu genetycznego**)*

Keywords: passive filters, power system harmonics, genetic algorithms.
Słowa kluczowe: filtry pasywne, harmoniczne, algorytm genetyczny.

Introduction

Filtering of harmonics and reactive power compensation are an important issue in improving the power quality [1] - [4]. The essential data necessary for designing the passive filters to reduce voltage harmonic distortion and reactive power are:

- data about harmonic source, i.e. the amplitude-frequency spectrum of a nonlinear load current, reactive power of the fundamental harmonic to be compensated, etc.,
- data on the supply network, i.e. the frequency characteristic of the power system impedance at the point of the filter connection (PCC), diagrams and technical data of the nearest neighbourhoods of the considered point of connection, the spectrum of voltage distortion at this point, total voltage harmonic distortion factor (THD) and individual harmonic limits as specified in the technical conditions of connection,
- data about the filter, i.e. location of its installation, the chosen structure, technical specification of passive elements to be used, etc.

In a most classic cases all further considerations are carried out under the following simplifying assumptions:

- the harmonic source is an ideal current source
- the filter inductance L_F and capacitance C_F are lumped elements and their values are constant in the considered frequency interval,
- the filter resistance can be neglected,
- the filter is exclusively loaded with the fundamental harmonic and the harmonic to which it is tuned.

The above assumptions allow designing simple filter-compensating structures. However, if a more complex filter structures or a larger number of filters connected in parallel are designed or their mutual interaction and co-operation with the power system (the network impedance), or non-zero filter resistances should be taken into account, these may impede or even prevent an effective analysis. Thus we are looking for new ways to solve design tasks. An example of the new method is the use of Genetic Algorithms (GAs). There are numerous examples of genetic algorithms application to optimisation of passive filters parameters but they still use the above-mentioned simplifications [5], [6]. Artificial intelligence methods are becoming a popular tool for solving various technical problems [7], [8].

For these reasons a new method for passive filters design is proposed. It allows application of arbitrary filter structure, the number of filters, as well as taking into account their mutual interaction and co-operation with the power network and non-zero filter resistance. The method employs genetic algorithms and models of a power system in which the filters are to be implemented.

Genetic Algorithm

Genetic Algorithms (GA) are stochastic global search method, mimicking the natural biological evolution. Genetic Algorithms idea first introduced by J.H. Holland in the late sixties and seventies of the last century. He noted that natural evolution is done at the chromosome level, and not directly to individuals. In order to find the best individual, genetic operators apply to the population of potential solutions, the principle of survival of the fittest individual. In every generation, new solutions arise in the selection process in conjunction with the operators of crossover and mutation. This process leads to the evolution of individuals that are better suited to be the existing environment in which they live.

AG popularity is due to its features:

- they don't process the parameters of the problem directly but they use their coded form,
- they start searching not in a single point but in a group of points,
- they use only the goal function and not the derivatives or other auxiliary information,
- they use probabilistic and not deterministic rules of choice.

These five features consists in effect on the usability of Genetic Algorithms and hence their advantages over other commonly used techniques for searching the optimal solution. There is a high probability that the AG does not get bogged in a local optimum.

An important term in genetic algorithms is the objective function. The objective function is the basis of assessment of the quality of all individuals in the population and the creation of a new generation. Each iteration of the genetic algorithm creates a new generation.

Principle of operation

Genetic algorithms provide potential solutions to a given problem and the choice of final solution leaves you. Where a particular problem is not single solution as in the case of a multi-criteria optimization, the AG are potentially useful to identify those alternatives. Figure 1 shows the basic block diagram of a Genetic Algorithm.

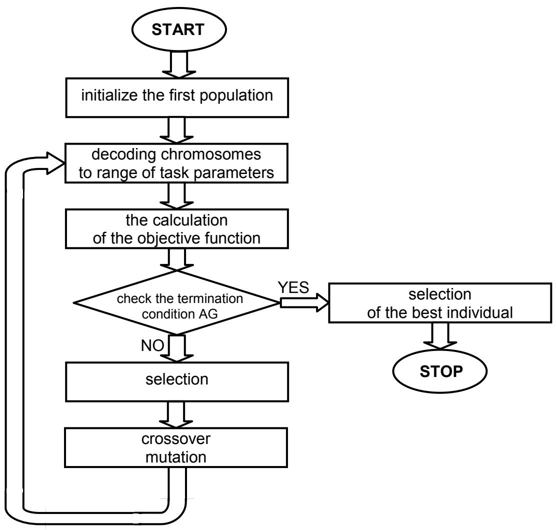

Fig. 1. Block diagram of the basic Genetic Algorithm (GA)

Since the first research on the form of genetic algorithms and components underwent modifications and the current form of the basic genetic algorithm includes:

- initialization of the first population,
- decoding the chromosomes to the task parameters,
- determine the value of the objective function for each individual,
- check the condition of ending the algorithm
- selection,
- crossing and mutation.

Initialize the first population - Genetic algorithms operate on a population of potential solutions. Each subsequent generation creates the child population, after which it is expected to make it better than their parents. The first population is generated completely randomly. But before it is created, you must specify the basic parameters of the Genetic Algorithm, such as population size (the number of individuals in the population), the number of task parameters (decision variables) and the length of the chromosome (code length of each of the decision variables).

Decoding - Genetic algorithm able to work properly it is necessary to decode genotypes (chromosomes) to phenotype, that is, the range of parameters the task. The AG is possible to use different coding methods. It is preferable to use a Gray code, as it has a fixed value in terms of Hamming distance between two consecutive values. Each two adjacent values differ by the value of one bit. Each parameter task Genetic Algorithm has allowed range of variation.

The objective function - On the basis of decoded chromosome representation it is possible to assess the fit of individual members of the population to the "environment" task. This is done by the objective function, which is characterized by the individual adjustment of the space problem. In the real world, it can be the ability to survive in a particular environment. Therefore, the objective function establishes the basis for the selection of individuals to be included in the pool of parental during reproduction. The purpose of the objective function is to estimate the usefulness of an individual to the development of the population. The higher the value of the objective function, the individual is better, better adapted, which has a greater chance of survival. It is assumed that the objective function must be non-negative.

Condition for the end of the algorithm - AG work termination condition depends on the optimization task. The algorithm can finish their work, the objective function reaches its maximum value. Another way is to count the deviation of the objective function within the population. If it is small the algorithm terminates. The algorithm may end operation as such after a period of work or after the assumed number of iterations (generations).

Selection - The most important operator of genetic algorithm is to select individuals which will participate in the creation of a new generation. This choice is based on the objective function. The most adapted individual has the greatest opportunity to participate in the creation of a new population. There are many methods of selection. The most popular method is the method of selection based on the roulette wheel. For each individual assigned to a section of the roulette wheel size proportional to the value of the objective function of an individual (Fig. 2). Thus, the higher the value of the objective function, the larger section of the roulette wheel corresponds to an individual. All the roulette wheel is the sum of the objective function value of all individuals in the population.

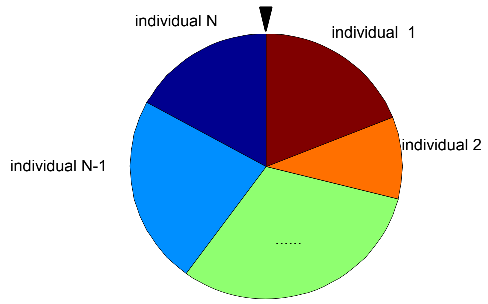

Fig. 2. Sample roulette wheel with assigned areas for the population of individuals

Crossover - This operator is used to differentiate the population by which each generation there are new individuals, different of individuals selected for the initial population. First randomly select two individuals from the pool of parents. If after checking the condition of crossover, crossing individuals are randomly selects the crossing point. The operation consists of replacing crossover of genetic material between chromosomes. This is done by taking the first part of the genes of the chromosome, and combined with the genes of the second chromosome (Fig. 3).

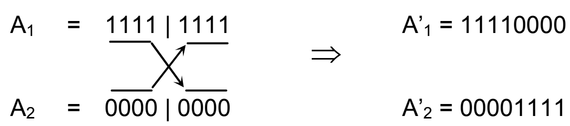

Fig. 3. Example, individuals crossover

As a result of crossover operator receives two new individuals included in the new generation of A'_1 and A'_2. This creates a new diverse individuals with the genetic material, but with the genes of their parents, who were selected in the selection process for parental pool.

Mutation - After crossover operator each individual in the population is checked and undergoes mutations. Mutation probability is low. If individual is mutated, randomized gene is subject to this process. The operator changes the value of the gene mutation to the opposite, i.e. 0 is changed to 1 and 1 to 0.

After these three genetic operators such as selection, crossover and mutation, the child population is obtained, which is better adapted than their parents, taking into account the average value of the objective function, which provides a better potential solutions to the task optimization.

Selected Filter Structures

The usefulness of the new method is illustrated by examples of designing selected filters' structures:

1. a group of single-tuned filters,
2. double-tuned filter,
3. C-type filter.

The formulas quoted later, allow to set filters parameters with the simplistic assumption that the resistance of the filters are equal to zero. This assumption does not apply in the design of filters, using Genetic Algorithms.

1. Single-tuned single branch filter

Many passive *LC* filter systems, of various structures and different operating characteristics have been already developed [9] - [15]. Nevertheless, the single-tuned single branch filter (Fig. 4a) still is the dominant solution for industrial applications, and certainly is the basis for understanding more advanced filtering structures.

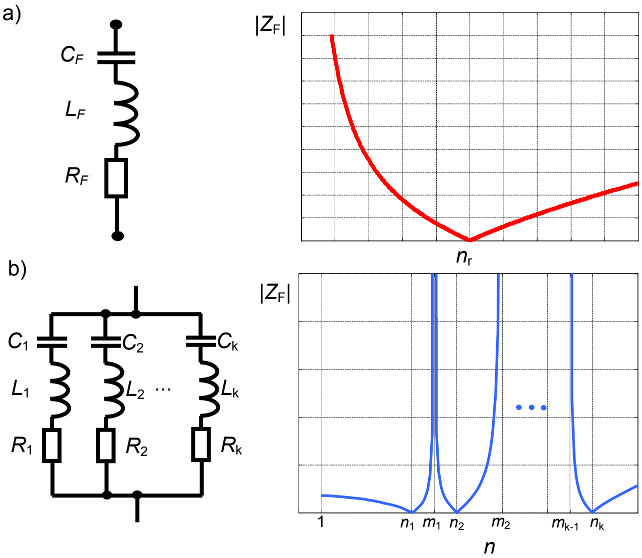

Fig. 4. Single branch filter: the frequency characteristic and formulas, a) a single filter, b) a group of filters

Single filter ($R_F = 0$):

(1) $$\omega_r = n_r\omega_1 = \frac{1}{\sqrt{L_F C_F}}$$

(2) $$L_F = \frac{1}{n_r^2\omega_1^2 C_F}$$

(3) $$C_F = \frac{n_r^2-1}{n_r^2}\cdot\frac{Q_F}{\omega_1 U^2}$$

R_F, R_j – the filters' resistances, C_F, C_j – the filters' capacitances; L_F, L_j – the filters' inductances; ω_r – tuned angular frequency; n_r, n_j, – orders of filter tuning harmonics; m_j – harmonic orders for which to design the impedance characteristics have maxima; Q_F – reactive power of the filter or group of filters; U – operating voltage.

Group of k single filters ($R_1 = \ldots = R_k = 0$) [12]:

(4) $$\begin{bmatrix} \frac{n_1^2\omega_1}{n_1^2-1} & \frac{n_2^2\omega_1}{n_2^2-1} & \cdots & \frac{n_k^2\omega_1}{n_k^2-1} \\ \frac{n_1^2 m_1}{n_1^2-m_1^2} & \frac{n_2^2 m_1}{n_2^2-m_1^2} & \cdots & \frac{n_k^2 m_1}{n_k^2-m_1^2} \\ \frac{n_1^2 m_2}{n_1^2-m_2^2} & \frac{n_2^2 m_2}{n_2^2-m_2^2} & & \frac{n_k^2 m_2}{n_k^2-m_2^2} \\ \vdots & & \ddots & \vdots \\ \frac{n_1^2 m_{k-1}}{n_1^2-m_{k-1}^2} & & \cdots & \frac{n_k^2 m_{k-1}}{n_k^2-m_{k-1}^2} \end{bmatrix} \begin{bmatrix} C_1 \\ \vdots \\ C_k \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ 0 \\ \frac{Q_F}{U^2} \end{bmatrix}$$

The solution of the matrix equation (4) is the equation (5):

(5) $$\begin{bmatrix} C_1 \\ \vdots \\ C_k \end{bmatrix} = \frac{Q_F}{\omega_1 U^2}\cdot\frac{\prod_{i=1}^{k}(n_i^2-1)}{\prod_{i=1}^{k-1}(m_i^2-1)}\cdot\begin{bmatrix} \frac{\prod_{i=1}^{k-1}(n_1^2-m_i^2)}{n_1^2\cdot\prod_{i=1,i\neq 1}^{k}(n_1^2-n_i^2)} \\ \frac{\prod_{i=1}^{k-1}(n_2^2-m_i^2)}{n_2^2\cdot\prod_{i=1,i\neq 2}^{k}(n_2^2-n_i^2)} \\ \vdots \\ \vdots \\ \frac{\prod_{i=1}^{k-1}(n_k^2-m_i^2)}{n_k^2\cdot\prod_{i=1,i\neq k}^{k}(n_k^2-n_i^2)} \end{bmatrix}$$

Hence the filter parameters can be determined:

(6) $$C_j = \frac{Q_F}{\omega_1 U^2}\cdot\frac{\prod_{i=1}^{k}(n_i^2-1)}{\prod_{i=1}^{k-1}(m_i^2-1)}\cdot\frac{\prod_{i=1}^{k-1}(n_j^2-m_i^2)}{n_j^2\cdot\prod_{i=1,i\neq j}^{k}(n_j^2-n_i^2)}$$

Taking into account that:

(7) $$1 < n_1 < m_1 < n_2 < m_2 < \cdots < m_{k-1} < n_k$$

Formulas (5) and (6) determine positive values of the capacity.

(8) $$L_j = \frac{1}{n_j^2\omega_1^2 C_j}$$

Relations (1) – (3) determine the single-tuned single branch filter parameters, relations (6) and (8) allow determining parameters of a group of single-tuned filters (Fig. 4b) taking into account their influence on the frequency impedance.

2. Double-tuned filter

Double-tuned resonant filters are sometimes used for harmonic elimination of very high power converter systems (e.g. HVDC systems). Just like any other technical solution they also have their disadvantages and advantages (versus single-tuned filters) that are listed below in table 1.

Such filters prove economically feasible exclusively for very large power installations and therefore they are not commonly used for industrial applications. There are, however, rare cases in which the use of such filter is justified. The double-tuned filter structure and its frequency characteristics are shown in Fig. 5.

Table 1. Selected disadvantages and advantages of a double-tuned filter as compared to two equivalent single-tuned filters

Disadvantages	Advantages
- more difficult tuning process - higher sensitivity of frequency characteristic to changes in components values	- lower power losses at fundamental frequency - reduced number of reactors across which the line voltage is maintained - compact structure - single breaker

The filter parameters can be determined from relations (9) – (13) [13].

(9) $$\omega_R = \frac{1}{\sqrt{L_2C_2}} \Rightarrow L_2 = \frac{1}{\omega_R^2 C_2}$$

(10) $$\omega_S = \frac{1}{\sqrt{L_1C_1}} \Rightarrow L_1 = \frac{1}{\omega_S^2 C_1}$$

(11) $$\omega_S = \frac{\omega_{n1}\omega_{n2}}{\omega_R}$$

(12) $$C_2 = \frac{\omega_S^2}{\omega_{n1}^2 + \omega_{n2}^2 - \omega_R^2 - \omega_S^2} C_1$$

(13) $$C_1 = \left\{ \omega_1 \left(\frac{\omega_R}{\omega_{n1}\omega_{n2}} \right)^2 - \frac{1}{\omega_1} + \frac{\omega_1 \left[(\omega_{n1}^2 + \omega_{n2}^2 - \omega_R^2)\omega_R^2 - \omega_{n1}^2\omega_{n2}^2 \right]}{\omega_{n1}^2\omega_{n2}^2 (\omega_R^2 - \omega_1^2)} \right\} \frac{U^2}{Q_F}$$

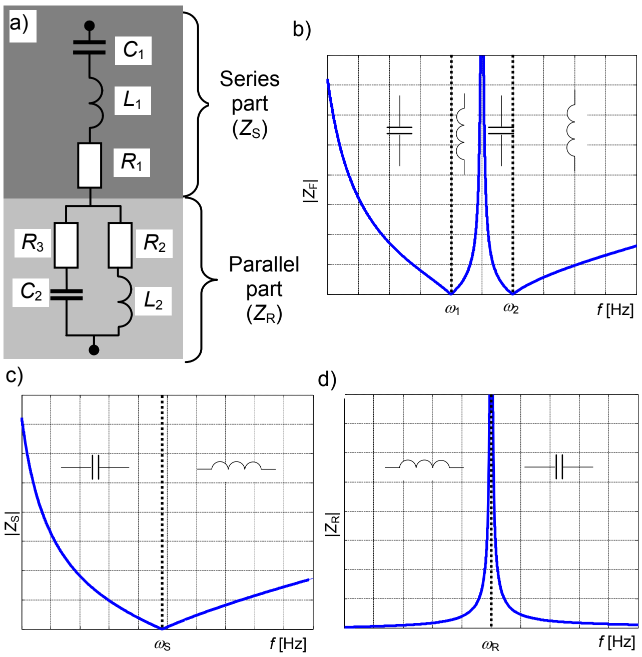

Fig. 5. The double-tuned filter and its essential frequency characteristics; (a) the basic configuration and frequency characteristics of: the series part (c), parallel part (d), and the whole filter (b)

ω_R – angular resonance frequency of the parallel part

ω_S – angular resonance frequency of the series part

ω_{h1}, ω_{h2} – tuned angular frequencies of the double-tuned filter.

3. C-type filter

The principal disadvantage of the majority of filter-compensating device structures is the poor filtering of high frequencies. To eliminate this disadvantage are usually used broadband (damped) filters of the first, second or third order; the C-type filter is included in the category of broadband filters [6], [16] - [19].

A significantly better reduction of active power losses compared to single branch filters, can be achieved in the C-type filter in which the L_2C_2 branch (Fig. 6) is tuned to the fundamental harmonic frequency. Thus the fundamental harmonic current is not passing through the resistor R_T, avoiding therefore large power losses.

The C-type filter circuit diagram and its frequency characteristic are shown in Fig. 6.

14) $$C_1 = \frac{Q_F}{\omega_1 U^2}$$

(15) $$C_2 \cong C_1(n_r^2 - 1) \quad \text{for} \quad C_1^2 R_T^2 n_r^2 \omega_1^2 >> 4$$

(16) $$L_2 = \frac{1}{\omega_1^2 C_2}$$

(17) $$k = \frac{|\underline{I}_S(n_r)|}{|\underline{I}_F(n_r)|} = \frac{|\underline{Z}_F(n_r)|}{|\underline{Z}_S(n_r)|}$$

(18) $$R_T = \frac{U^2}{n_r^3 {Q_F}^2 k \omega_1 L_S} \sqrt{U^4 - n_r^4 {Q_F}^2 k^2 \omega_1^2 L_S^2}$$

n_r – orders of filter tuning harmonics; $\underline{I}_S(n_r)$ –current harmonic (complex) of the order n_r (filter tuned harmonic) flowing to the network; $\underline{I}_F(n_r)$ – current harmonic (complex) of the order n_r (filter tuned harmonic) flowing through the filter; k – the factor that indicates distribution of the harmonic to which the filter is tuned; L_S – the network equivalent inductance; $\underline{Z}_S(n_r)$ – the network equivalent impedance (complex) for n_r harmonic.

$\underline{Z}_F(n_r)$ – the filter impedance (complex) for n_r harmonic.

Relations (14) – (16) [16] and (17) – (18) [18] allow determining the C-type filter parameters in a traditional way.

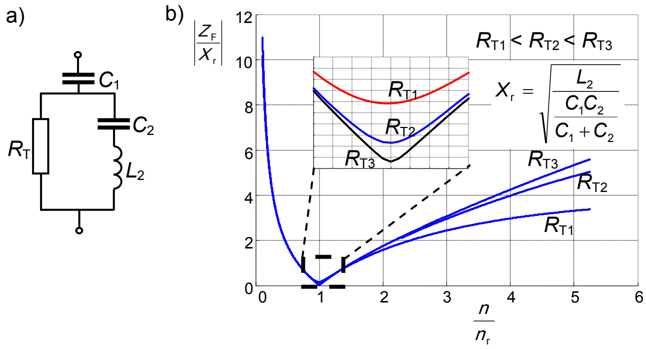

Fig. 6. The C-type filter: a) structure, b) frequency characteristic

Filter Design Using Genetic Algorithm

Complex passive filters are more and more often designed using artificial intelligence methods, like genetic algorithms [20], [21] that can also be effective in solving other problems e.g. location of filters in a power system or optimisation of the filters' power.

Example 1 – double-tuned filters

One of the methods employing GAs for passive filters design is optimisation of the filter frequency characteristic.

As an example let us design a double-tuned filter (Consider known [13], [22] alternative configurations with additional resistances, whose task is to reduce voltages or currents in the filter – Fig. 7) with parameters: Q_F = 1 Mvar, U = 6 kV, n_1 = 5, n_2 = 7, n_R = 6.

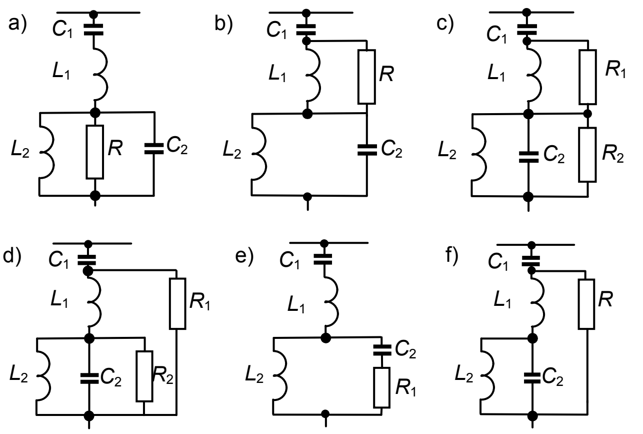

Fig. 7. Alternative configurations of a double-tuned filter

Locations the filter frequency characteristic extrema are determined using relations (9) – (11), whereas the genetic algorithm determines the values of C_1 and C_2 and the resistance value (R, R_1, R_2 – Fig. 7) for which the impedance-frequency characteristic attains the extremes (two minimums and one maximum at chosen harmonic frequencies) for the given filter power. The resistances of LC elements values are determined based on the assumed that the $q_L = X_L/R_L = 100$, $q_C = X_C/R_C = 5000$.

Range of variation of decision variables under the terms of the task: $C_1 = (10^{-6} - 10^{-3})$, $C_2 = (10^{-6} - 10^{-3})$

Genetic Algorithm parameters:

- Each parameter is coded in a string of 30 bits,
- populations of 1000 individuals,
- crossing probability $p_k = 0.7$,
- mutation probability $p_m = 0.01$,
- condition of termination of work AG - 100 generations,
- ranking with the factors: $C_{min} = 0$, $C_{max} = 2$,
- stochastic universal sampling (SUS) selection method,
- crossing the shuffle.

Each individual is assessed according to the relationship:

$$f = 500 \cdot \left(\left| Z_F\left(\omega_{(5)}\right) \right| + \left| Z_F\left(\omega_{(7)}\right) \right| \right) + \frac{100000}{\left| Z_F\left(\omega_{(6)}\right) \right|} \tag{19}$$

$$F_{goal} = \min \begin{cases} f^{\frac{10^6}{Q_F}} & Q_F < 1\,\text{Mvar} \\ f & Q_F = 1\,\text{Mvar} \\ f^{\frac{Q_F}{10^5}} & Q_F > 1\,\text{Mvar} \end{cases} \tag{20}$$

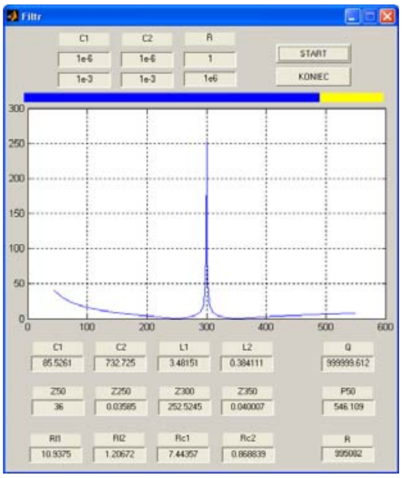

Fig. 8.Graphic window of the program determining parameters of the double-tuned filter in Fig. 7f.

Figure 8 shows graphic window of the programme developed in the Matlab environment for optimisation of double-tuned filter from Fig. 7f.

Ranges of filter parameters seeking are visible in the upper part of the window, below the found characteristic is displayed, and basic parameters of the found solution are shown in the lowest part.

Table 2 provides results of a double-tuned filter (Fig. 7a-f and Fig. 5) optimisation. The solutions are similar to each other (in terms of their values). It is noticeable that genetic algorithm is aiming to minimize the influence of additional resistances, that is to make the filter structures similar to the basic structure from Fig. 5. It means that additional resistances worsen the quality of filtering.

The obtained result ensues from the applied optimisation method, i.e. optimisation of the frequency characteristic shape.

Example 2 – group of single-tuned filters

The advantage of artificial intelligence methods is that in the early phase of design they allow to take into account the equivalent resistances of capacitors and reactors, resistances of connections, and other components values that influence filters' parameters, as well as the power network structure (the network environment) in which the designed filter will be operated. It therefore becomes possible to take into account mutual influences of the power network and the designed filter parameters.

An example application of the method will be the design two single-tuned filters for a power supply and control system for separately excited DC motor (Fig. 9). The basis for design is modelling of the whole system. The system may comprise nonlinear components and the filters can take into account their own resistance, which depends on the selected components values. Generally speaking, the model can be detailed without simplifications required by the classic design method.

The genetic algorithm objective is to find the capacitance values of two single-tuned filters tuned to component with frequency order $n_{r5} = 4.9$ and $n_{r7} = 6.9$. The filters inductances will be determined from the relation (2). It is worth pointing out that the genetic algorithm itself solves the problem of reactive power distribution between the filters. The voltage total harmonic distortion will be minimized and therefore power distribution between the filters will be achieved.

Table 2. Basic parameters of filters from Fig. 7, designed using the genetic algorithm

Parameter	Filter configuration						
	7a	7b	7c	7d	7e	7f	5a
C_1 [μF]	85.52	85.52	85.52	85.53	85.53	85.53	85.53
C_2 [μF]	732.21	732.73	732.72	732.71	732.71	732.72	731.90
L_1 [mH]	3.481	3.481	3.482	3.482	3.482	3.482	3.482
L_2 [mH]	0.384	0.384	0.384	0.384	0.384	0.384	0.385
R_{L1} [mΩ]	10.93	10.94	10.94	10.93	10.94	10.94	10.94
R_{L2} [mΩ]	1.207	1.207	1.207	1.207	1.207	1.207	1.208
R_{C1} [mΩ]	7.44	7.44	7.44	7.44	7.44	7.44	7.44
R_{C2} [mΩ]	0.869	0.868	0.868	0.868	0.868	0.868	0.870
Z_{50} [Ω]	36	36	36	36	36	36	36
Z_{250} [mΩ]	35.82	35.8	35.83	35.85	35.79	35,85	35.86
Z_{300} [Ω]	252.76	252.58	252.53	252.47	252.59	252.53	252.87
Z_{350} [mΩ]	40	40	40.04	40.01	40	40.01	40
Q_F [Mvar]	1	1	1	1	1	1	1
P_{50} [W]	546.09	546.06	546.10	546,11	546.07	546.11	546.11
R_1 [MΩ]	-	1	1	1	-	1	-
R_2 [MΩ]	1	-	1	1	0	-	-

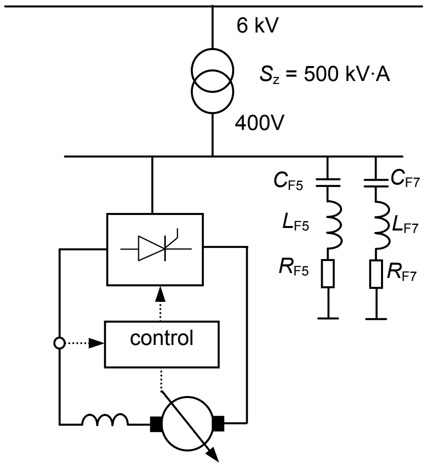

Fig. 9. Diagram of the power system with the designed group of single-tuned filters

Parameters of the single-tuned filters group were determined by means of the Genetic Algorithm minimising the voltage harmonic distortion factor while limiting the maximum value of reactive power filters 1Mvar (21).
Range of variation capacity C_{min} = 1 μF, C_{max} = 100 μF.
Parameters AG:
- population of 100 individuals,
- each of the parameters is coded in a string of 8 bits,
- crossing probability p_k = 0.8,
- mutation probability p_m = 0.01,
- crossing the shuffling,
- Selection SUS
- condition of termination of work AG - 100 generations.

$$F_{goal} = \min \begin{cases} THD_U & \text{for} \quad Q_F \le 1\,\text{Mvar} \\ Q_F & \text{for} \quad Q_F > 1\,\text{Mvar} \end{cases} \tag{21}$$

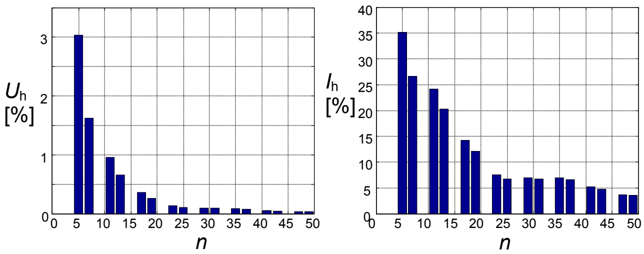

Fig. 10. The voltage and current spectrum before connecting the filters

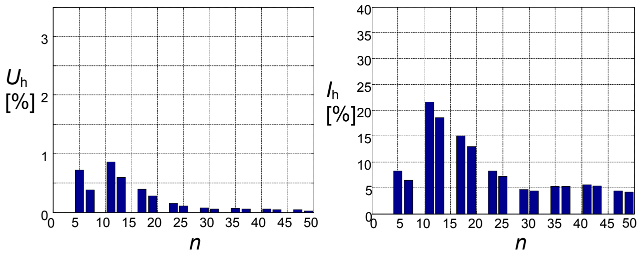

Fig. 11. The voltage and current spectrum after connecting the filters

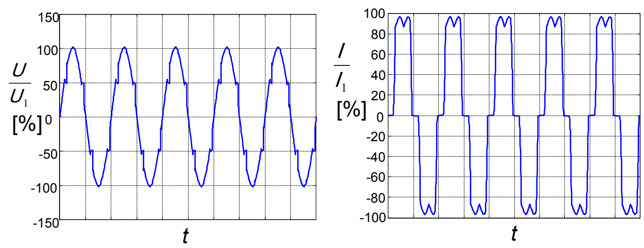

Fig. 12. The voltage and current waveforms before connecting the filters

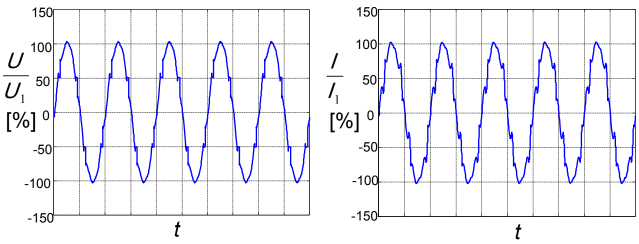

Fig. 13. The voltage and current waveforms after connecting the filters

The effectiveness of this solution is illustrated in figures 10-13. Figures 10 and 11 show voltage and current harmonics in the power system before and after connecting the designed filters. Figures 12 and 13 show voltage and current waveforms in the power system before and after connecting the filters.
Basic parameters of the power system, before and after connecting the filters, are tabulated in table 3.

Table 3. Basic parameters of the power system before and after connecting the filters

	Before	After
THD_U [%]	9.30	6.30
THD_I [%]	24.71	9.73
I_5/I_1 [%]	35.17	8.30
I_7/I_1 [%]	26.58	6.46
U_5/U_1 [%]	3.10	0.72
U_7/U_1 [%]	1.62	0.39
$c_{5(before/after)}$	4.23	
$c_{7(before/after)}$	4.11	
φ [°]	11	0.2

Example 3 - C-type filter
A major impact on power quality parameters in energy distribution networks have mines and steelworks [23], [24].
In result of the arc furnace modernization (fig. 14.) its power and, consequently, the level of load-generated harmonics have increased. It was, therefore, decided to expand the existing reactive power compensation and harmonic mitigation system. Considering the system expansion the designed C-type filter should be tuned to the 2nd harmonic due to the fact that this harmonic, though present in the system, it is not reduced whereas the 3rd harmonic filters are already installed. Although currently the 2nd harmonic level in the existing system does not exceed the limit, change loads may increase the 2nd harmonic to an unacceptable level.

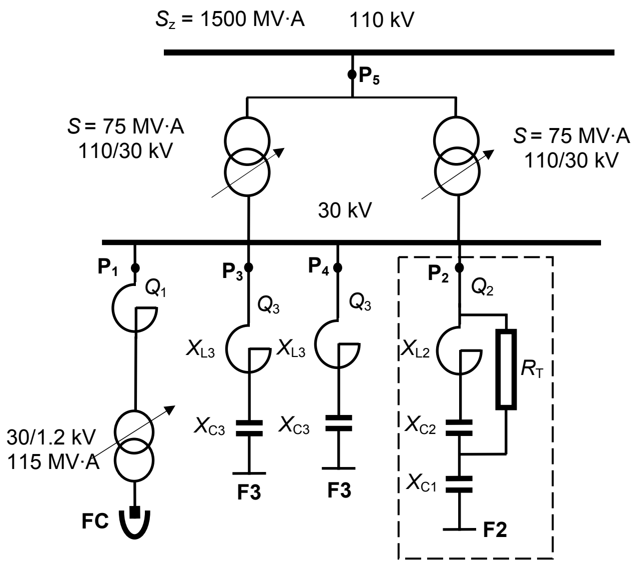

Fig. 14. Single line diagram of the arc furnace power supply system

Design objectives: for the arc furnace power supply system with parameters: $U = 30$ kV, $S_z = 1500$ MV·A, $L_S = 3.129$ mH, $R_S = 30.0$ mΩ, and two single-tuned 3rd harmonic filters: $Q_3 = 20$ Mvar, $L_3 = 18.48$ mH; $C_3 = 63$ μF; $R_3 = 30.0$ mΩ; $n = 2.95$; $q_{F3} = 110$, design the C-type filter with parameters: $Q_2 = 20$ Mvar, $n_r = 1.9$; $q_2 = 10$, $k = 1$ (the percentage distribution of the 2nd harmonic current between the designed filter and the power supply system shall be 50%:50%. A better effectiveness of the second harmonic filtering may worsen the third harmonic filtering).

Table 4. The Measurement Results Obtained over a Period of 7 Days [18]

Measurement point	P_1 Furnace	P_1 Furnace	P_2 Filter C	P_3 3rd harm. filter	P_4 3rd harm. filter	P_5 110kV	P_5 110kV
Furnace and filters in operation	No	Yes					No
U_{RMS} [kV]	18.29	17.59				65.04	66.58
I_{RMS} [A]	-	2383	391	398	385	602	86.5
P [MW]	-	93.75	0.083	0.234	0.198	105	12.14
Q [Mvar]	-	71.19	19.55	19.84	19.68	28.2	6.52
S [MV·A]	-	125.7	20.65	21.0	20.34	117.5	17.25
PF	-	0.744	0.0043	0.011	0.001	0.89	0.57
THD_U [%]	1.56	2.45				1.92	1.58
THD_I [%]	-	6.44	8.04	12.04	10.62	4.64	6.61
$I_{(1)RMS}$ [A]	-	2357	387	376	373	594	85.46
$U_{(1)RMS}$ [kV]	18.29	17.57				65.0	66.57
$U_{(2)RMS}$ [%]	0.06	0.73				0.42	0.07
$U_{(3)RMS}$ [%]	0.57	0.61				0.43	0.43
$U_{(4)RMS}$ [%]	0.04	0.34				0.19	0.04
$U_{(5)RMS}$ [%]	1.15	1.51				1.22	1.25
$I_{(2)RMS}$ [A]	-	58.7	32	10.8	9.8	15	2.21
$I_{(3)RMS}$ [A]	-	97.3	3.5	44.3	38.8	9	4.8
$I_{(4)RMS}$ [A]	-	23.1	1.5	5.1	4.5	3.7	0.6
$I_{(5)RMS}$ [A]	-	71.2	3.7	11.9	11.2	12.5	3.5
Pst [%]	1	16.66				9.17	1.02

The arc furnace is regarded as an harmonic current source and as a load for the fundamental harmonic with given active power (P) and reactive power (Q). These parameters were previously measured.

The goal of genetic algorithm is to seek the C-type filter capacitance (C_1) in order to compensate the system's reactive power, and determine the resistance value (R_T) to ensure a required distribution of the 2nd harmonic current. The C_2 and L_2 values will be determined from relations (15) and (16). Diagrams of filter circuits take into account the filters resultant equivalent resistances. The filter parameters were computed by means of the Genetic Algorithm using the model from Fig. 14 in the Matlab environment.

The range of variation of the decision variables: C_1 = (1 μF – 100 μF), R_T = (1 Ω – 10 kΩ).

Genetic Algorithm parameters:

- C_1 and R_T parameters are properly coded in sequences of 8 and 12 bits,
- populations of 200 individuals,
- crossing probability $p_k = 0.8$,
- mutation probability $p_m = 0.01$,
- a condition end of work Genetic Algorithm - 30 generations,
- ranking with the factors $C_{min} = 0$, $C_{max} = 2$,
- SUS selection method,
- crossing the shuffle.

(22) $$F_{goal} = \min \begin{cases} THD_I & Q_F \le 20\ \text{Mvar} \\ 1000 \cdot THD_I & Q_F > 20\ \text{Mvar} \end{cases}$$

The designed C-type filter by GA has been installed in the arc furnace power supply system. The capacitance C_1 is composed of 60 capacitors (20 per phase) with capacitance 14.15 μF each, which gives total capacitance C_1 = 70.75 μF. The capacitance C_2 is composed of 24 capacitors (8 per phase) with capacitances 24.6 μF each, which gives total capacitance C_2 = 196.8 μF. The reactor L_2 inductance is 51.48 mH. The resistor resistance is R_T = 300 Ω ± 10%. Per-phase diagram of the actual single-phase filter is shown in Fig. 15.

Measurements in the power system, configured according to the above specification, were carried out in order to check the correctness of the system operation. The instruments locations were: P_1 – arc furnace, P_2 – C-type filter, P_3 – first filter of the 3rd harmonic, P_4 – second filter of the 3rd harmonic, and P_5 – at the 110 kV side.

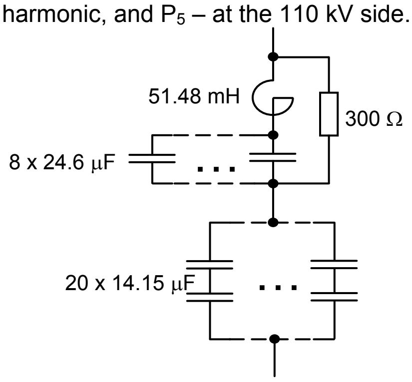

Fig. 15. Per-phase diagram of the actual C-type filter circuit

Measurements in the power system, configured according to the above specification, were carried out in order to check the correctness of the system operation. The instruments locations were: P_1 – arc furnace, P_2 – C-type filter, P_3 – first filter of the 3rd harmonic, P_4 – second filter of the 3rd harmonic, and P_5 – at the 110 kV side.

The measurements have demonstrated that the C-type filter performance has met the requirements, i.e. it attains the expected reduction of reactive power, ensures the second harmonic reduction in the power system and harmonic distortion THD_U reduction by means of high harmonics mitigation. The measurements verified the proposed method and the C-type filter designed using this method operates according to the requirements. Spectra of the voltage (fig. 16) and currents of the arc furnace (fig. 17), 3rd harmonic filter (fig. 18) and C-type filter (fig. 19) illustrate the effectiveness of performance designed C-type filter. Table 4 presents the basic parameters of the power system [22].

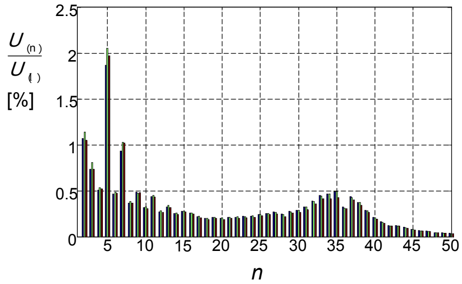

Fig. 16. Voltage spectrum (30 kV)

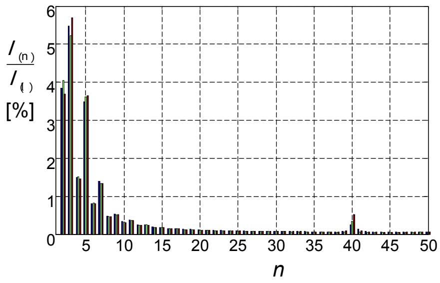

Fig. 17. Spectrum of the arc furnace current

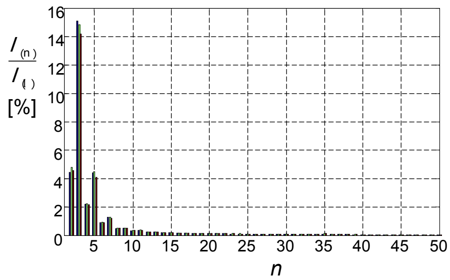

Fig. 18. Current spectrum of the 3rd harmonic filter

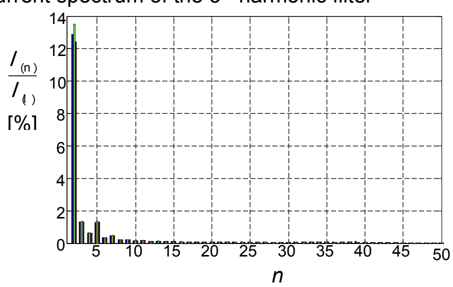

Fig. 19. Current spectrum of the C-type filter

Conclusion

The presented examples of group single-tuned, single branch passive filters, double-tuned filter and the C-type filter design, demonstrate the genetic algorithm usefulness as a tool for optimisation and seeking for filters' parameters without the need for unnecessary simplifications that may lead to erroneous solutions. The use of genetic algorithm allows imposing constraints on the optimisation task, such as the maximum filter current and maximum voltages across the filter components, and enables the multi-criterial optimisation.

All the above demonstrates the usefulness of this optimisation tool, particularly for extensive power systems.

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