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Bank Harmonic Filters Operation in Power Supply System – Cases Studies

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1. Introduction

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. DC and AC variable speed drives and arc furnaces are ranked among the most commonly used large power nonlinear loads.

DC drives can be a significant plant load in many industries. They are commonly used in the oil, chemical, metal and mining industries. These drives are still the most common large power type of motor speed control for applications requiring very fine control over wide speed ranges with high torques. Power factor correction is particularly important for this drives because of relatively poor power factor, especially when the motor is at reduced speeds. Additional transformer capacity is required to handle the poor power factor conditions and more utilities are charging a power factor penalty that can significantly impact the total bill for the facility. The DC drives also generate significant harmonic currents. The harmonics make power factor correction more complicated. Power factor correction capacitors can cause resonant conditions which magnify the harmonic currents and cause excessive distortion levels. For the same reasons arc furnaces are very difficult loads for a supplier and for the customer they are very difficult objects of reactive power compensation and harmonics filtering.

One of the most common methods to prevent adverse effects of nonlinear loads on the power network is the use of passive filters. However, different configurations should be considered before making the final design decision. Among the performance criteria are current and voltage ratings of the filter components, and the effect of filter and system contingency conditions. Before any filter scheme is specified, a power factor study should be done to determine if any

reactive compensation requirements are needed. If power factor correction is not necessary, then a minimum power filter can be designed; one that can handle the fundamental and harmonic currents and voltages without consideration for reactive power output. Sometimes, more than one tuned filter is needed. The filter design practice requires that the capacitor and the reactor impedance be predetermined. For engineers not knowing the appropriate initial estimates, the process has to be repeated until all the proper values are found. This trial-and-error approach can become complex as more filters are included in the systems.

While the effectiveness of a filter installation depends on the degree of harmonic suppression, it also involves consideration of alternate system configurations. As the supplying utility reconfigures its system, the impedance, looking back to the source from the plant's standpoint, will change. Similar effects will be seen with the plant running under light versus heavy loading conditions, with split-bus operation, etc. Therefore, the filtering scheme must be tested under all reasonable operating configurations.

The general procedure in analyzing any harmonic problem is to identify the worst harmonic condition, design a suppression scheme and recheck for other conditions. Analysis of impedance vs frequency dependencies for all reasonable operating contingencies is commonly used practice. A frequency scan should be made at each problem node in the system, with harmonic injection at each point where harmonic sources exist. This allows easy evaluation of the effects of system changes on the effective tuning. Of particular importance is the variability of parallel resonance points with regard to changing system parameters. This problem is illustrated by the practical example.

In a most classic cases all filter considerations are carried out under the following simplifying assumptions: (i) the harmonic source is an ideal current source; (ii) the filter inductance L_F and capacitance C_F are lumped elements and their values are constant in the considered frequency interval; (iii) the filter resistance can be sometime neglected and the filter is mainly loaded with the fundamental harmonic and the harmonic to which it is tuned e.g. [1]. 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. An example of the new approach is the use of artificial intelligence methods, among them the genetic algorithm (AG) [2 - 4]. The usefulness of this new method is illustrated by examples of designing selected filters' structures: (a) a group of single-tuned filters; (b) double-tuned filter and (c) C-type filter.

2. Single-tuned single branch filter

Many passive LC filter systems, of various structures and different operating characteristics have been already developed [4 - 9]. Nevertheless, the single-tuned single branch filter (Fig. 1) still is the dominant solution for industrial applications, and it certainly is the basis for understanding more advanced filtering structures.

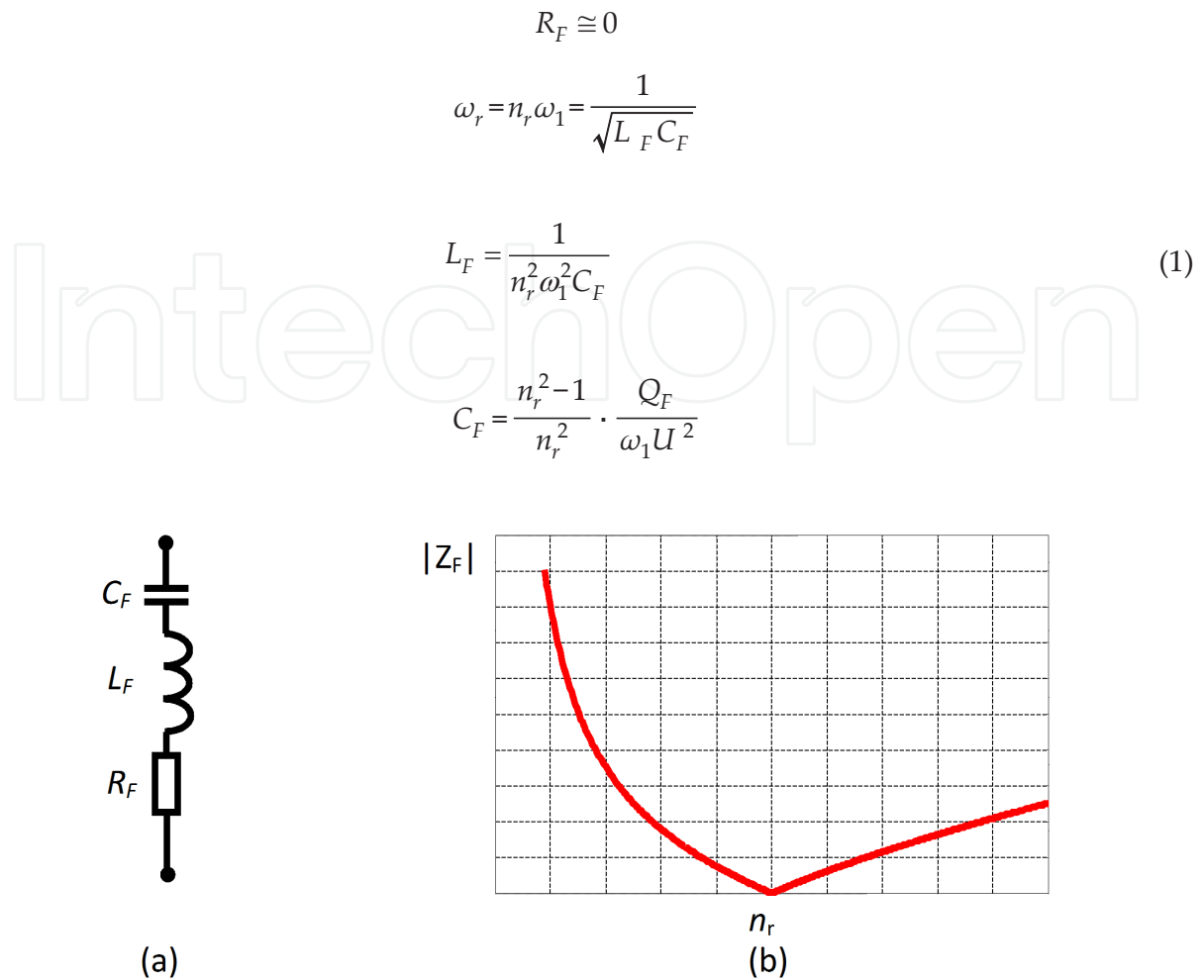


Figure 1. Single branch filter and the frequency characteristic

Where k single-tuned filters are operated in parallel in order to eliminate a larger number of harmonics then k voltage resonances (series resonances) and k current resonances (parallel resonances) occur in the system. These resonance frequencies are placed alternately and the series resonance is always the preceding one. In other words, each branch has its own resonance frequency.

The schematic diagram of an example group of filters in a large industrial installation and characteristics illustrating the line current variations and the 5th harmonic voltage variations in result of connecting ONLY the 5th harmonic filter are shown in Fig. 2. The figure also shows the 7th harmonic voltage variations prior to and after connecting the 5th harmonic filter. The 5th harmonic filter selectivity is evident — its connection has practically no influence on the 7th harmonic value.

Relations (2) allow determining parameters of a group of single-tuned filters taking into account their interaction, as well as choosing the frequencies for which the impedance frequency characteristic of the filter bank attains maxima, where (the filters' resistances $R_i \rightarrow 0$): C_i - the filters' capacitances; L_i - the filters' inductances; ω_{ri} - tuned angular frequency; n_{ri} - orders of filter tuning harmonics; m_i - orders of harmonics for which the impedance character-

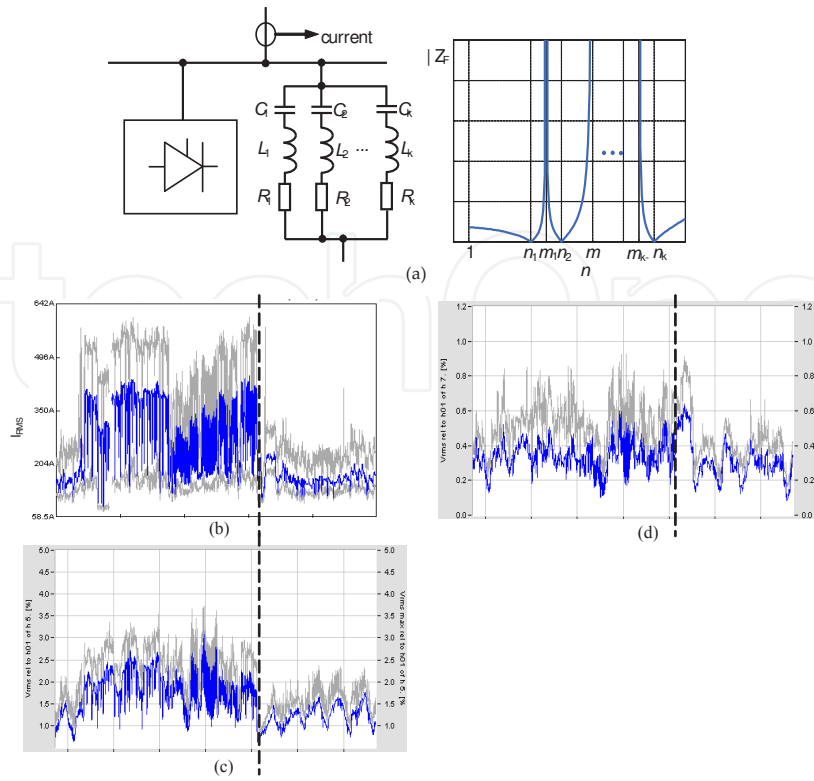


Figure 2. Groups of single branch filters: (a) schematic diagram; (b) current (I); characteristics of (c) 5th and (d) 7th voltage harmonic. The vertical line indicates the instance of the 5th harmonic filter connection

istic should attain maxima; Q_F - reactive power of the basic harmonic of the filter or group of filters and U – RMS operating voltage.

$$\begin{bmatrix} \frac{n_{r1}^2 m_1}{n_{r1}^2 - m_1^2} & \frac{n_{r2}^2 m_1}{n_{r2}^2 - m_1^2} & \dots & \frac{n_{rk}^2 m_1}{n_{rk}^2 - m_1^2} \\ \frac{n_{r1}^2 m_2}{n_{r1}^2 - m_2^2} & \dots & \dots & \frac{n_{rk}^2 m_2}{n_{rk}^2 - m_2^2} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{n_{r1}^2 m_{k-1}}{n_{r1}^2 - m_{k-1}^2} & \dots & \dots & \frac{n_{rk}^2 m_{k-1}}{n_{rk}^2 - m_{k-1}^2} \\ \frac{n_{r1}^2 \omega_1}{n_{r1}^2 - 1} & \frac{n_{r2}^2 \omega_1}{n_{r2}^2 - 1} & \dots & \frac{n_{rk}^2 \omega_1}{n_{rk}^2 - 1} \end{bmatrix} \begin{bmatrix} C_1 \\ \vdots \\ C_k \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \frac{Q_F}{U^2} \end{bmatrix} \quad (2)$$

$$L_i = \frac{1}{n_{ri}^2 \omega_1^2 C_i} \quad i = 1 \dots k$$

2.1. Example 1

An example application of the method will be the design of single-tuned filters (two single-tuned filters) for DC motor (Fig. 3). The basis for design is modelling of the whole supplying system. The system may comprise nonlinear components and analysis of 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.

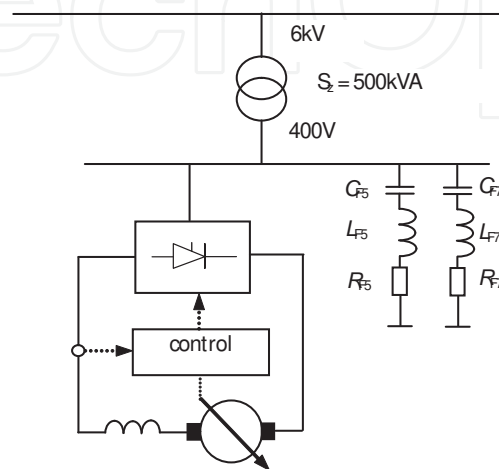


Figure 3. Diagram of the power system with the designed group of single-tuned filters for system with DC drive supplied by 6-pulse controlled rectifier: $P_N = 22\text{kW}$, $U_N = 440\text{V}$, $I_N = 56,2\text{A}$, $J = 2,7\text{kgm}^2$, $R_t = 0,465\Omega$, $L_t = 15,345\text{mH}$, $n_N = 1500\text{ r/min}$, $k = 2,62$

Parameters of the single-tuned filters group were determined by means of the Genetic Algorithm minimising the voltage harmonic distortion factor with limitation of the phase shift angle between fundamental harmonics of the current and voltage $\phi_{(1)} > 0$. Parameters of the applied Genetic Algorithm: (a) each parameter (C_{F5} , C_{F7}) is encoded into a 15-bit string; (b) range of variability from $1\mu\text{F}$ to $100\mu\text{F}$; (c) population size 100 individuals; (d) crossover probability $p_k = 0.7$; (e) mutation probability $p_m = 0.01$; (f) Genetic Algorithm termination condition – 100 generations; (g) selection method Stochastic Universal Sampling (SUS); (h) shuffling crossover (APPENDIX A).

The genetic algorithm objective is to find the capacitance values of two single-tuned filters tuned to harmonics $n_{r5} = 4.9$ and $n_{r7} = 6.9$. 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.

Basic characteristics of the power system, before and after connecting the filters, are tabulated in Fig. 4 ($C_{F5} = 30.14\mu\text{F}$; $C_{F7} = 4.11\mu\text{F}$; the phase shift angle between the voltage and current fundamental harmonics: prior to connection of filters – 11° , after connection of filters 0.2°).

In industry many of the supply systems consist of a combination of tuned filters and a capacitor bank. Depending on the system configuration the capacitor bank can lead to magni-

fication or attenuation of the filters loading. Filter detuning significantly affects this phenomenon. Therefore, specifying harmonic filters requires considerable care under analysis of possible system configurations for avoidance of harmonic problems.

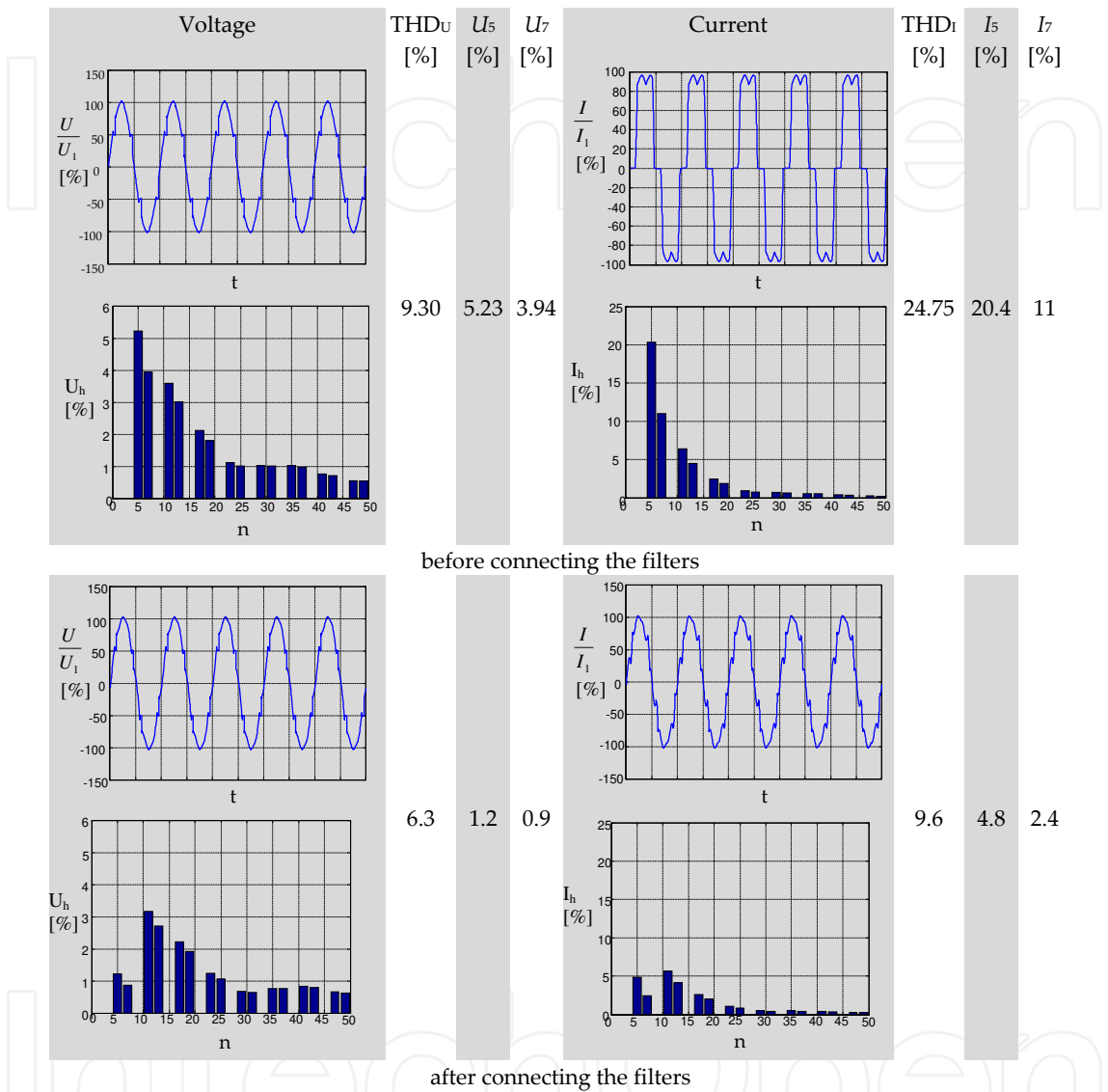


Figure 4. The voltage-current waveforms and spectrum before and after connecting the filters (U_1/I_1 – basic voltage/current harmonic; U_h/I_h – h. order voltage/current component)

3. Parallel operation of filters

3.1. Example 2 – description of the system

Fig. 5 shows a one-line diagram of a mining power supply system which will be used to analyze operation characteristics of the single tuned harmonic filters in a power supply system

including power factor correction capacitor banks. System contains two sets of powerful DC skip drives as harmonic loads connected to sections A and B. The drives are fed from six-pulse converters. As a result, there is significant harmonic current generation and the plant power factor without compensation is quite low.

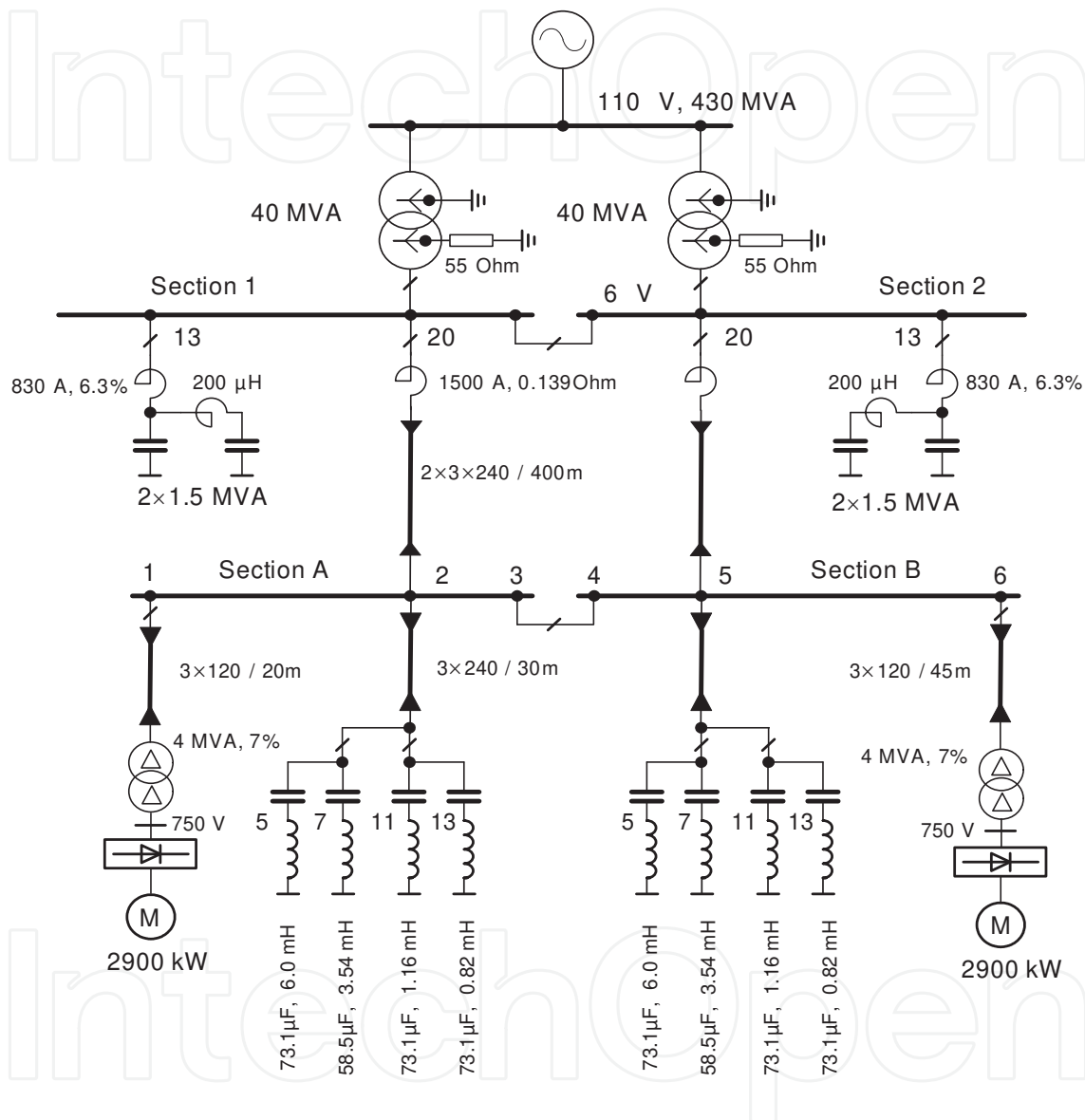


Figure 5. One-line diagram of a mining power supply system

Shunt capacitors 2x1.5 MVA connected to main sections 1 and 2 to partially correct the power factor but this can cause harmonic problems due to resonance conditions. The sections A and B can be supplying from the main section 1 or 2. Four single-tuned filters (5th, 7th, 11th, and 13th harmonic order) have been added to the sections A and B to limit harmonic problems and improve reactive compensation. Specifications of the harmonic filters are shown in the Table 1.

Allowable current limit for filter capacitors is 130% of nominal RMS value and voltage limit -110%. The iron-core reactors take up less space comparatively to air-core reactor and make use of a three-phase core. Reactors built on these cores weigh less, take up less space, have lower losses, and cost less than three single-phase reactors of equal capability. Reactors are manufactured with multi-gap cores of cold laminated steel to ensure low tuning tolerance. The primary draw back to iron-core reactors is that they saturate.

Filter, tuning		Capacitor bank		Reactor bank (three phase, iron-core)		
F5 $n_{r5} = 4.81$	Bank rating	2×500	kvar	Nominal voltage	7.2	kV
	Nominal voltage	6.6	kV	Nominal current	120.0	A
	Nominal current	87.4	A	S.c. current	14.0	kA
	Capacitance	73.1	μF	Inductance	6.0	mH
	Cap. tolerance	-5...+10	%	Inductance tolerance	± 5	%
F7 $n_{r7} = 6.98$	Bank rating	2×400	kvar	Nominal voltage	7.2	kV
	Nominal voltage	6.6	kV	Nominal current	100.0	A
	Nominal current	70.0	A	S.c. current	14.0	kA
	Capacitance	58.4	μF	Inductance	3.54	mH
	Cap. tolerance	-5...+10	%	Inductance tolerance	± 5	%
F11 $n_{r11} = 10.94$	Bank rating	2×500	kvar	Nominal voltage	7.2	kV
	Nominal voltage	6.6	kV	Nominal current	130.0	A
	Nominal current	87.4	A	S.c. current	14.0	kA
	Capacitance	73.1	μF	Inductance	1.16	mH
	Cap. tolerance	-5...+10	%	Inductance tolerance	± 5	%
F13 $n_{r13} = 13.02$	Bank rating	2×500	kvar	Nominal voltage	7.2	kV
	Nominal voltage	6.6	kV	Nominal current	130.0	A
	Nominal current	87.4	A	S.c. current	14.0	kA
	Capacitance	73.1	μF	Inductance	0.82	mH
	Cap. tolerance	-5...+10	%	Inductance tolerance	± 5	%

Table 1. Filter specifications

The saturation level is dependent upon the fundamental current and the harmonic currents that the reactor will carry. There is not standard for rating harmonic filter reactors and therefore, it is difficult to evaluate reactors from different manufacturers. For example, some reactor manufacturers base their core designs (cross sectional area of core) on RMS flux, while other will based it on peak flux (with the harmonic flux directly adding). There is a signifi-

cant difference between these two design criteria. For evaluation purposes, reactor weight and temperature rise are a primary indication of the amount of iron that is used. The second feature of the reactors is considerable frequency dependency of eddy currents loss in the winding.

Equation (1) shows that the relative resonant frequency n_r depends on the power system frequency and filter inductance and capacitance. Any variation of these parameters causes deviation of the resonant frequency. So, possible deviation from the designed value can be obtained using (1) by the equation:

$$\frac{n_d}{(1 + \Delta f_*)\sqrt{(1 + \Delta L_*)(1 + \Delta C_*)}} \leq n_r \leq \frac{n_d}{(1 - \Delta f_*)\sqrt{(1 - \Delta L_*)(1 - \Delta C_*)}} \quad (3)$$

where: Δf_* - power system frequency variation, p.u.; ΔL_* , ΔC_* -filter inductance and capacitance variations, p.u.; n_d - designed relative resonant frequency ($d = 5, 7, 11, 13$).

Assuming $\Delta f_* \approx 0$, the possible deviation of relative resonant frequency n_r from the designed value for the investigated filter circuits can be defined using values of ΔL_* , ΔC_* from the Table 1:

$$0.93n_d \leq n_r \leq 1.05n_d \quad (4)$$

This means that the analysed filter circuits have the following possible ranges of relative resonant frequency n_r :

5-thorder filter - $4.3 \leq n_r \leq 5.1$;

$$7\text{-thorder filter} - 6.5 \leq n_r \leq 7.4; \quad (5)$$

11-th order filter - $10.2 \leq n_r \leq 11.5$;

13-th order filter - $12.1 \leq n_r \leq 13.7$.

It is obvious that the detuning of higher order filter is more sensitive for the same filter capacitance or inductance drift than detuning of lower order filter, as value of resonant frequency ω_r defines its deviation:

$$\Delta \omega_r \approx \frac{d\omega_r}{dC} \Delta C = -\frac{\omega_r}{2C} \Delta C \quad (6)$$

3.2. Filter characteristics analysis

In order to demonstrate filter circuits behavior under all reasonable operating configurations and get numerical results for comparison purposes, computer simulations have been performed using frequency and time domain software.

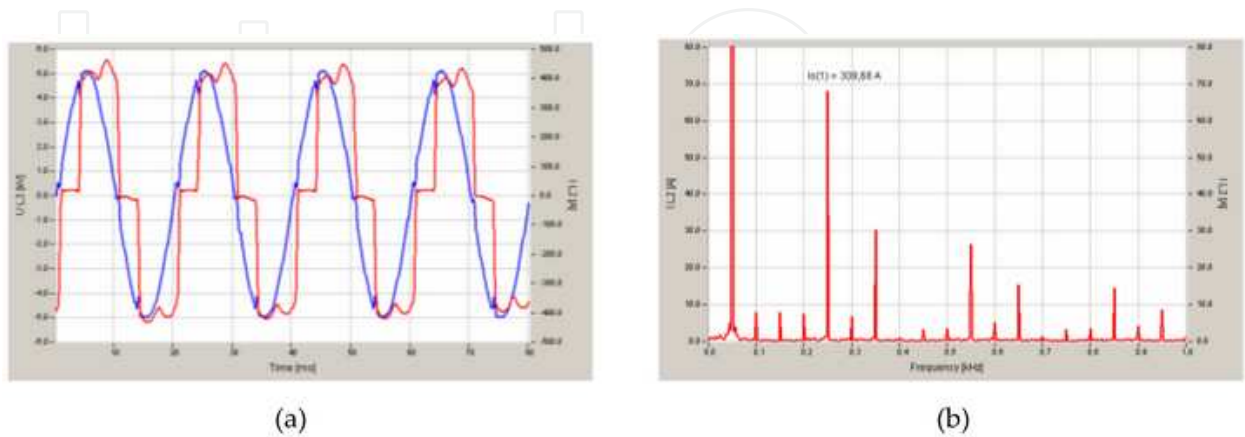


Figure 6. Current and voltage waveforms of the fully loaded DC drive (a) and the current harmonic spectrum (b)

Measurements performed at the facility were used to characterize the DC drive load and obtain true source data for computer analysis of the filter characteristics. For example, Fig. 6 shows the DC drive current and its harmonic spectrum in the supply system consisting of 5th order filter under isolated operation of the section A.

Harmonic currents in the supply system components are listed in Table 2. There are obvious important findings from these measurements: 1) noncharacteristics current harmonics are present due to irregularities in the conduction of the converter devices, unbalanced phase voltages and other reasons; 2) there is resonance condition near 4th harmonic in the system configuration with 5th filter connected. Similar measurements also provided for the system with other filter sets.

Analysis of the system response is important because the system impedance vs frequency characteristics determine the voltage distortion that will result from the DC drive harmonic currents. For the purposes of harmonic analysis, the DC drive loads can be represented as sources of harmonic currents. The system looks stiff to these loads and the current waveform is relatively independent of the voltage distortion at the drive location. This assumption of a harmonic current source permits the system response characteristics to be evaluated separately from the DC drive characteristics.

In Fig. 7 are depicted the worst case of frequency scan for system impedance looking from the section A with several filters connected as concerns 5th harmonic filter loading. These conditions occur with upper limit (see (3)) of filter reactor and capacitor rating variations. Proximity of the frequency response resonance peaks to 4th and 5th harmonics produces significant magnification the harmonic currents in the 5th filter and feeder circuits.

Harmonic order	Feeder current, I_s		Drive current, I_D		5-th filter current, I_{F5}	
	A	%	A	%	A	%
1	241,49	100,0	309,68	100,0	157,87	100,0
2	8,49	3,5	8,04	2,6	0,61	0,4
3	9,75	4,0	8,03	2,6	1,77	1,1
4	41,62	17,2	7,51	2,4	39	24,7
5	27,02	11,2	68,09	22,0	42,54	26,9
6	4,31	1,8	6,75	2,2	2,42	1,5
7	25,43	10,5	30,21	9,8	5,28	3,3
8	0,74	0,3	0,85	0,3	0,28	0,2
9	2,81	1,2	3,36	1,1	0,57	0,4
10	2,92	1,2	3,49	1,1	0,57	0,4
11	22,09	9,1	26,36	8,5	4,33	2,7
12	4,16	1,7	5,04	1,6	0,89	0,6
13	12,7	5,3	15,43	5,0	2,77	1,8
14	1,21	0,5	1,49	0,5	0,27	0,2
15	2,79	1,2	3,37	1,1	0,59	0,4
16	2,84	1,2	3,41	1,1	0,59	0,4
17	12,14	5,0	14,57	4,7	2,48	1,6
18	3,52	1,5	4,28	1,4	0,73	0,5
19	7,35	3,0	8,74	2,8	1,38	0,9

Table 2. Harmonic currents for the system consisting of 5th harmonic filter

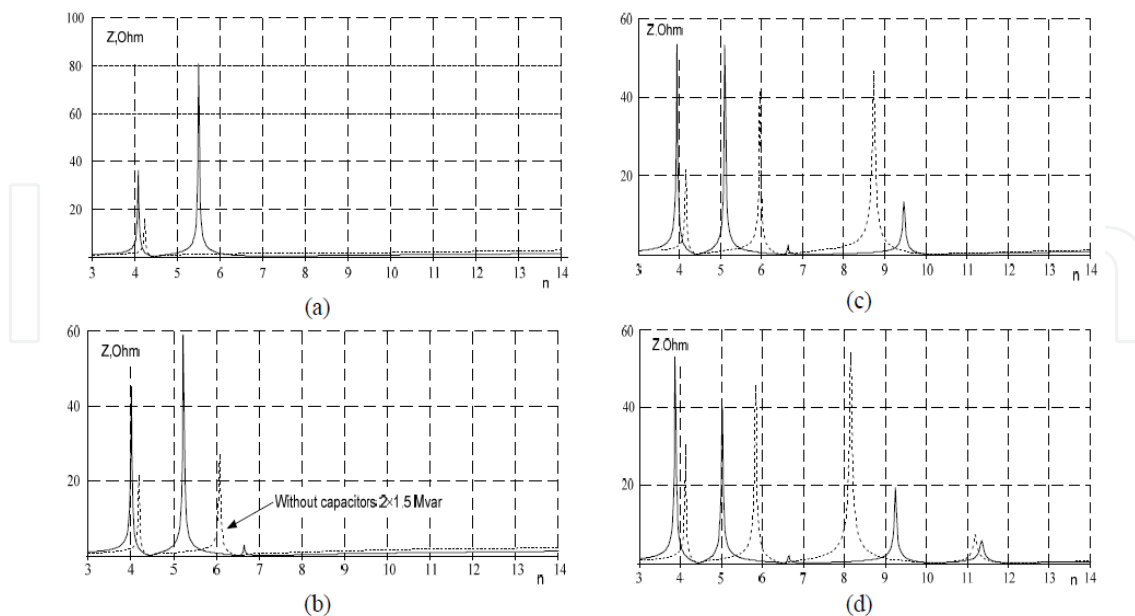


Figure 7. Frequency scans for the system impedance with 5th (a), (5+7)-th (b), (5+7+11)-th (c), (5+7+11+13)-th (d) harmonic filters

Harmonic current magnification in a filter circuit can be defined by the following factor:

$$\beta_{Fn} = \frac{|I_{Fn}|}{|I_{Dn}|} = \frac{|Z_n|}{|Z_{Fn}|} \tag{7}$$

and for the feeder circuit similarly:

$$\beta_{Sn} = \frac{|I_{Sn}|}{|I_{Dn}|} = \frac{|Z_n|}{|Z_{Sn}|} \tag{8}$$

where: I_{Dn} , I_{Sn} , I_{Fn} - the n^{th} harmonic current of the harmonic source, feeder and filter, correspondingly; Z_n , Z_{Sn} , Z_{Fn} - the n -th harmonic impedances of the system, feeder and filter at the point of common connection, correspondingly.

The harmonic magnification factor allows estimating harmonic current in a filter or feeder circuit for several system configurations relative to source harmonic current. A value less than 1.0 means that only a part of the source harmonic current flows in the circuit branch.

Calculated values of harmonic magnification factors for analyse 5-th filter loading in the several system configurations are listed in Table 3. Column “Upper deviation limits” with 2×1.5 Mvar capacitors corresponds to the Fig. 7. The significant 4-th and 5-th harmonics magnification can be observed from the Table 3 in the 5-th filter and feeder circuits in the case of 2×1.5 Mvar capacitors connected. It can cause the filter overload and allowable system voltage distortion exceeding. On the other hand when lower deviation of the filter parameters the magnification factors are considerably less. Switching off the 2×1.5 Mvar capacitors reduces 5-th harmonic magnification in the circuits to acceptable levels, but 4-th harmonic is magnificated considerably more due to close to resonant peak.

System configuration	Upper deviation limits				Lower deviation limits			
	5 th filter		Feeder		5 th filter		Feeder	
With cap. 2×1.5 Mvar	β_{F4}	β_{F5}	β_{S4}	β_{S5}	β_{F4}	β_{F5}	β_{S4}	β_{S5}
F5	4.2	0.8	9.3	1.7	0.5	1.1	2.6	0.4
F5+F7	14.4	1.4	32.2	2.8	0.6	1.0	3.3	0.4
F5+F7+F11	4.8	2.8	10.2	5.5	0.8	0.9	4.5	0.4
F5+F7+F11+F13	2.4	18.6	5.2	36.7	1.4	0.8	7.4	0.3
Without cap. 2×1.5 Mvar								
F5	0.8	0.3	1.9	0.7	0.2	1.6	1.3	0.6
F5+F7	1.1	0.4	2.4	0.8	0.3	1.5	1.4	0.6
F5+F7+F11	1.5	0.5	3.2	1.0	0.3	1.4	1.6	0.5
F5+F7+F11+F13	2.1	0.6	4.5	1.1	0.3	1.3	1.8	0.5

Table 3. Harmonic current magnification factors β in the system

The calculated harmonic current magnification factors in filter circuits in the possible filter configurations are depicted in the Table 4. It is here noted that harmonic loading of the filters in the system without 2×1.5 Mvar capacitors depends on the filter configuration and filter detuning. It is well known that the series L-C circuit has the lowest impedance at its resonant frequency. Below the resonant frequency the circuit behaves as a capacitor and above the resonant frequency as a reactor. When a filter is slightly undertuned to desired harmonic frequency it has lower harmonic absorbing as a result of the harmonic current dividing between the filter and system inductances. If the filter is slightly overtuned than parallel resonant circuit created of the filter capacitance and system inductance will magnify the source harmonic current. Regularity of the phenomena for the analyzed system with multiply filter circuits one can see in the bottom part of the Table 4 for the system configuration without capacitors 2×1.5 Mvar.

Switching in capacitors 2×1.5 Mvar to the bus section changes the filters loading due to parallel resonant circuit created of the capacitors and system impedances. The resonant frequency of the system looking from the section A with several connected filters depends on the number of the filters and specifies the filter loading.

System configuration	Deviation limits							
	5 th filter		7 th filter		11 th filter		13 th filter	
With cap. 2×1.5 Mvar	Up	Lo	Up	Lo	Up	Lo	Up	Lo
F5	0.8	1.1	-	-	-	-	-	-
F5+F7	1.4	1.0	0.1	0.1	-	-	-	-
F5+F7+F11	2.8	0.9	0.1	0.1	0.6	1.9	-	-
F5+F7+F11+F13	18.6	0.8	0.1	0.1	1.3	1.3	0.6	3.2
Without cap. 2×1.5 Mvar								
F5	0.3	1.6	-	-	-	-	-	-
F5+F7	0.4	1.5	0.5	3.0	-	-	-	-
F5+F7+F11	0.5	1.4	0.7	1.9	0.7	1.3	-	-
F5+F7+F11+F13	0.6	1.3	0.8	1.5	2.5	1.0	0.7	2.1

Table 4. Harmonic current magnification factors β_{Fn} in the filter circuits

Figure 8 shows current waveforms and its harmonic spectrums for parallel 11th and 13th harmonic filters in the analyzed system obtain from time domain computer simulation of the system. The first observation of these two cases is significant harmonic overloading of the filters. In the case in question of filter iron-core reactor the phenomenon can cause the reactor temperature rise and its failure.

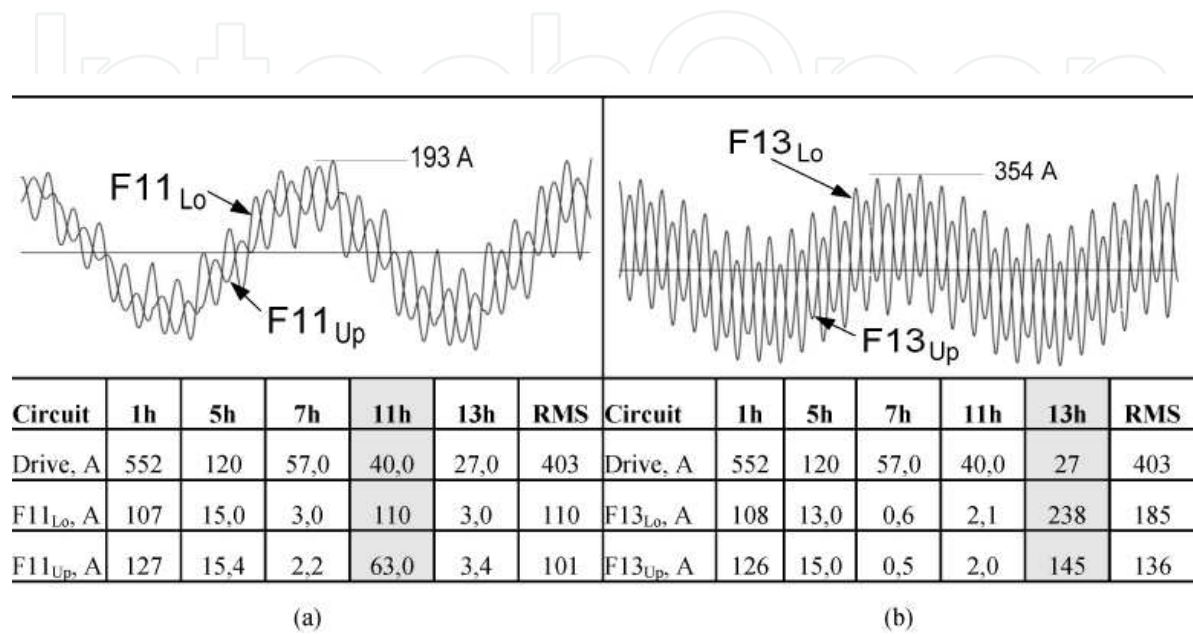


Figure 8. Current waveforms and its harmonic spectrums for parallel 11th (a) and 13th (b) filters

The most representative cases of the parallel filter configurations (e.g. when feeding sections A and B from section 1) are depicted in the Table 5. Two parallel the same order filters have opposite resonance detuning with upper and lower parameter deviation limits. From analysis of the Table 5 it is seen that opposite resonance detuning of the same order filters can cause considerable filter overload. As it has been noted earlier the higher order harmonic filters are more sensitive to filter component parameter variations from the detuning point of view. Furthermore, resonance detuning of the same order filters in the some system configurations can cause parallel system resonance peaks close to characteristic harmonic.

It should be quite clear from the above presented example that specifying harmonic filters and power factor correction requires considerable care and attention to detail. Main results of the investigation are follows:

- it is a bad practice to add filter circuits to existing power factor correction capacitors,
- improper design of the filter resonant point considering capacitor and reactor manufacturing tolerance and operation conditions can cause significant harmonic overloading of the filter,
- it is desirable to avoid the parallel operation of the same order filters in the system.

System configuration	Deviation limits							
	5 th filters		7 th filters		11 th filters		13 th filters	
With cap. 2×1.5 Mvar	Up	Lo	Up	Lo	Up	Lo	Up	Lo
2×(F5+F7)*	0.55	0.55	0.50	0.50	-	-	-	-
2×(F5+F7)	0.15	0.91	0.10	0.21	-	-	-	-
2×(F5+F7+F11+F13)	0.18	1.05	0.10	0.16	0.57	1.42	2.92	4.82
(F5+F7)+2×(F11+F13)	18.34	-	0.11	-	0.55	1.44	3.02	5.01
Without cap. 2×1.5 Mvar								
2×(F5+F7)*	0.41	0.41	0.50	0.50	-	-	-	-
2×(F5+F7)	0.13	0.77	5.40	9.44				
2×(F5+F7+F11+F13)	0.15	0.86	1.21	2.11	0.50	1.23	3.12	5.13
(F5+F7)+2×(F11+F13)	0.84	-	1.23	-	0.48	1.20	3.11	5.04

Note. *Both of 5th filters and 7th filters are fine-tuned.

Table 5. Harmonic current magnification factors β_{Fn} in the filter circuits (parallel operation)

4. 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 (e.g. more difficult tuning process, higher sensitivity of frequency characteristic to changes in components values) and advantages (e.g. lower power losses at fundamental frequency, reduced number of reactors across which the line voltage is maintained, compact structure, single breaker) versus single-tuned filters. 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. 9. There are also the relations used to determine its parameters.

4.1. Example 3

As an example let us design a double-tuned filter (consider alternative configurations presented in Fig. 10) with parameters: $Q_F = 1\text{Mvar}$, $U = 6\text{kV}$, $n_1 = 5$, $n_2 = 7$, $n_R = 6$. Locations of the filter frequency characteristic extrema are determined using relations as in Fig. 9, whereas the genetic algorithm (APPENDIX A) determines the values of C_1 and C_2 for which the impedance-frequency characteristic attains the least value (at chosen harmonic frequencies) for the given filter power (R_{C1} , R_{C2} , R_{L1} , R_{L2} –equivalent capacitor and reactor resistances; Fig. 9).

$$\begin{aligned}
 \omega_R &= \frac{1}{\sqrt{L_2 C_2}} \Rightarrow L_2 = \frac{1}{\omega_R^2 C_2} \\
 \omega_S &= \frac{1}{\sqrt{L_1 C_1}} \Rightarrow L_1 = \frac{1}{\omega_S^2 C_1} \\
 \omega_S &= \frac{\omega_{n1} \omega_{n2}}{\omega_R} \\
 C_2 &= \frac{\omega_S^2}{\omega_{n1}^2 + \omega_{n2}^2 - \omega_R^2 - \omega_S^2} C_1 \\
 C_1 &= \left\{ \omega_1 \left(\frac{\omega_R}{\omega_{n1} \omega_{n2}} \right)^2 - \frac{1}{\omega_1} + \frac{\omega_1 \left[(\omega_{n1}^2 + \omega_{n2}^2 - \omega_R^2) \omega_R^2 - \omega_{n1}^2 \omega_{n2}^2 \right]}{\omega_{n1}^2 \omega_{n2}^2 (\omega_R^2 - \omega_1^2)} \right\} \frac{U^2}{Q_F}
 \end{aligned} \tag{9}$$

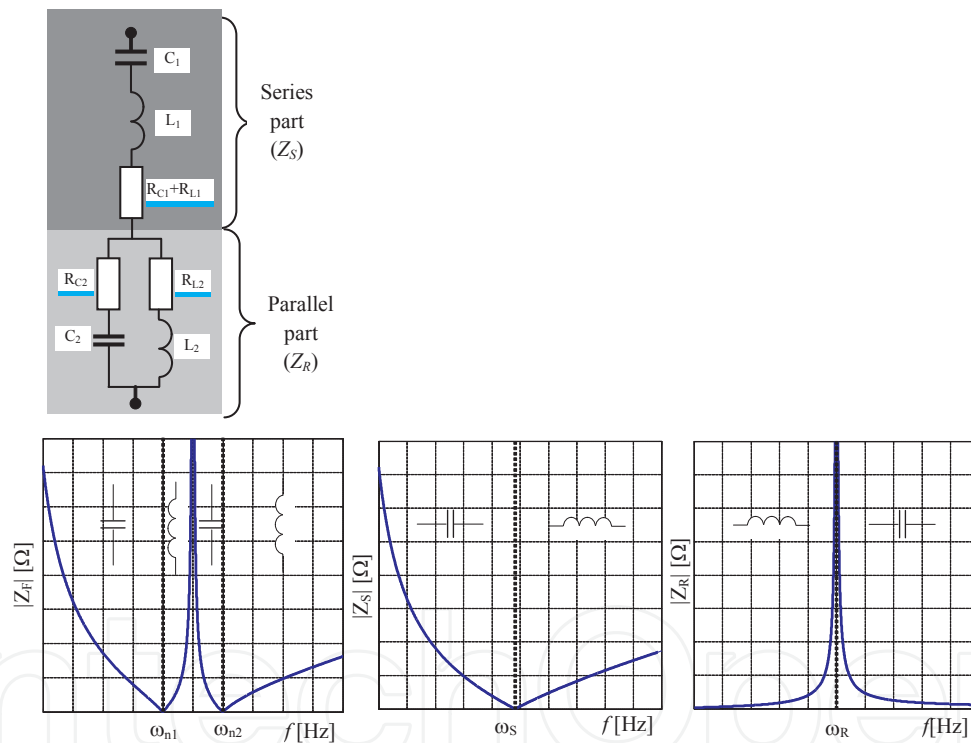


Figure 9. The double-tuned filter and its essential frequency characteristics; the basic configuration and frequency characteristics of: the series part, parallel part, and the whole filter (ω_R – angular resonance frequency of the parallel part; ω_S – angular resonance frequency of the series part; ω_{n1} , ω_{n2} – tuned angular frequencies of the double-tuned filter; equation 9 R 0).

Figure 11 shows graphic window of the programme developed by authors in the Matlab environment for optimisation of double-tuned filter. 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.

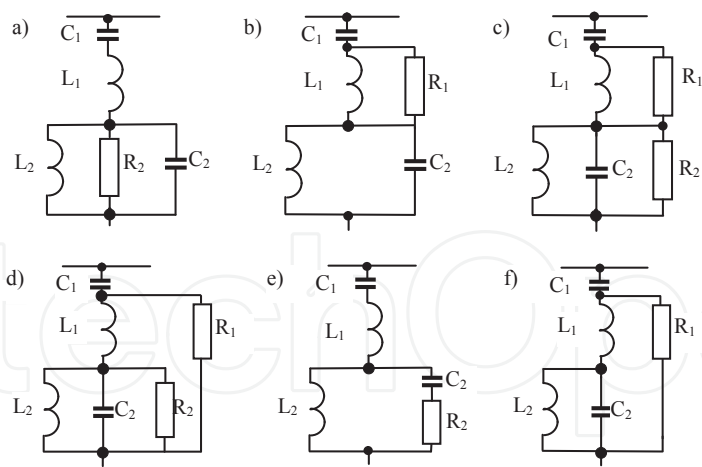


Figure 10. Alternative configurations of a double-tuned filter

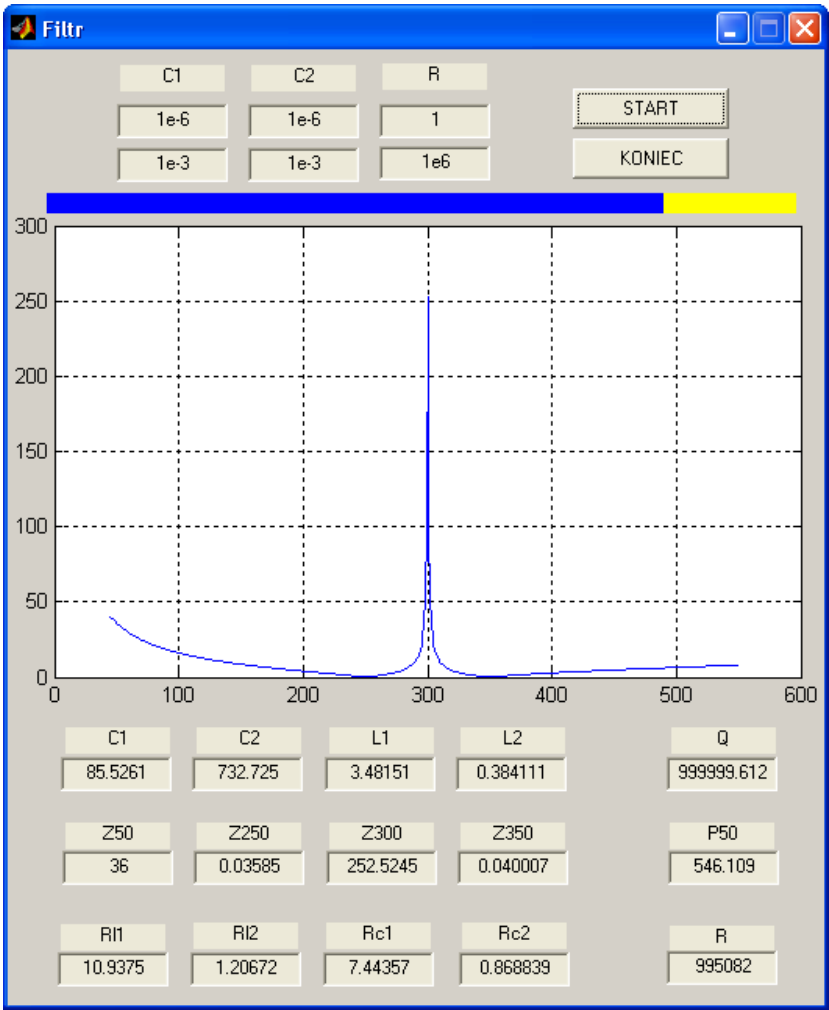


Figure 11. Graphic window of the program determining parameters one of the double-tuned filter in Fig. 10a (KONIEC = STOP)

The range of variability of decision variables: $C_1 = (10^{-6} - 10^{-3})$, $C_2 = (10^{-6} - 10^{-3})$. The Genetic Algorithm parameters: (a) each parameter is encoded into a 30-bit string, thus the chromosome length is 60 bits; (b) population size 1000 individuals; (c) crossover probability $p_k = 0.7$; (d) mutation probability $p_m = 0.01$; (e) Genetic Algorithm termination condition – 100 generations; (f) ranking coefficients $C_{\min} = 0$, $C_{\max} = 2$; (g) inverse ranking was applied in order to minimize the objective function; (h) selection method SUS and (i) shuffling crossover. The Genetic Algorithm goal was to minimize impedances for selected harmonics (n_1 and n_2) and maximize the impedance for the n_R harmonic.

Table 6 provides results of a double-tuned filter (Fig. 9 and 10) 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. 9. 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.

Parameter	Filter configuration						
	Fig. 10a	Fig. 10b	Fig. 10c	Fig. 10d	Fig. 10e	Fig. 10f	Fig. 9
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 [MVA _r]	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	-	-

Table 6. Basic parameters of filters from Fig. 10, designed using the genetic algorithm

5. 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 [1, 2, 10]. Broadband filters have one more advantage, substantial for their co-operation with power electronic converters: they damp commutation notches more effectively than single branch filters - they have a much broader bandwidth. They also more effectively eliminate interharmonic components (in sidebands adjacent to characteristic harmonics) generated by static frequency converters. In the C-type filter in which the L_2C_2 branch (Fig. 12) is tuned to the fundamental harmonic frequency can be also achieved a significantly better reduction of active power losses compared to single branch filters. Thus the fundamental harmonic current is not passing through the resistor R_T , avoiding therefore large power losses.

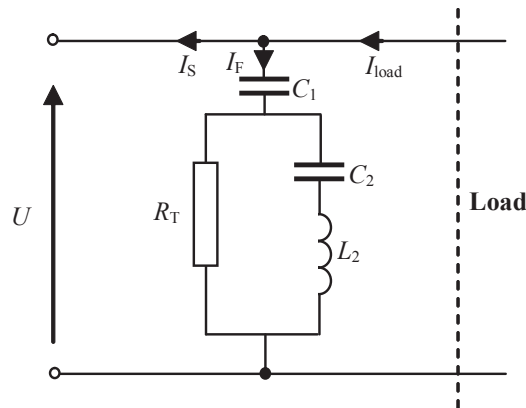


Figure 12. The C-type filter circuit

5.1. Example 4

In result of the arc furnace modernization (Fig. 13.) 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. Prior to the modernization the system comprised two parallel, single-tuned 3rd harmonic filters that were the cause of a slight increase in the voltage 2nd harmonic.

Considering the system expansion the designed C-type filter should be tuned to the 2nd harmonic. Although currently the 2nd harmonic level in the existing system does not exceed the limit, connection of new loads may increase the 2nd harmonic to an unacceptable level.

5.1.1. Traditional approach

The filter impedance is given by (Fig. 12) [1]:

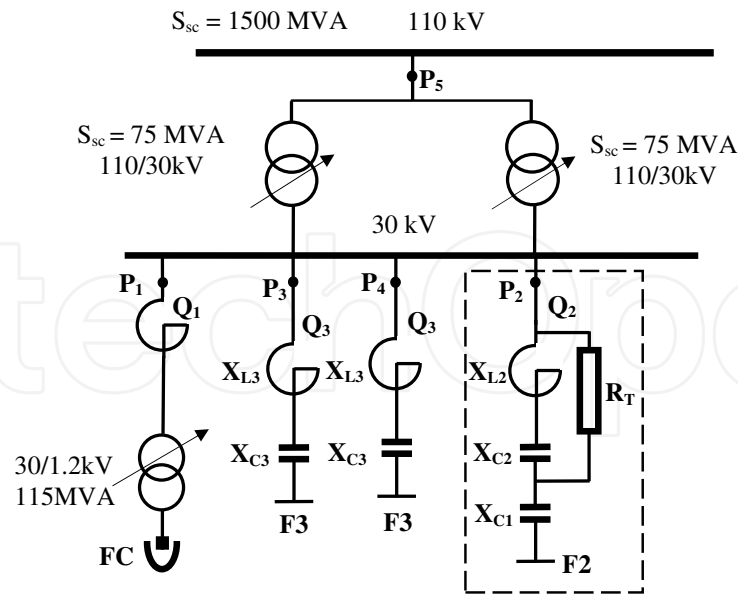


Figure 13. Single line diagram of the arc furnace power supply system

$$Z_F = \frac{\left(j\omega L_2 - j\frac{1}{\omega C_2} \right) R_T}{R_T + j\omega L_2 - j\frac{1}{\omega C_2}} - j\frac{1}{\omega C_1} \quad (10)$$

The L_2 and C_2 components are tuned to the fundamental frequency ω_1 :

$$L_2 = \frac{1}{\omega_1^2 C_2} \quad (11)$$

hence

$$Z_F = \frac{jR_T(\omega^2 - \omega_1^2)}{R_T\omega\omega_1^2 C_2 + j(\omega^2 - \omega_1^2)} - j\frac{1}{\omega C_1} \quad (12)$$

The C-type filter is tuned to the resonance angular frequency $\omega_r = n_r \omega_1$

$$\omega_r \cong \frac{1}{\sqrt{L_2 \frac{C_1 C_2}{C_1 + C_2}}} \Rightarrow C_2 = C_1 (n_r^2 - 1) \quad (13)$$

hence

$$Z_F = \frac{jR_T(\omega^2 - \omega_1^2)}{R_T\omega\omega_1^2C_1(n_r^2 - 1) + j(\omega^2 - \omega_1^2)} - j\frac{1}{\omega C_1} \quad (14)$$

The filter reactive power (Q_F) for the fundamental harmonic is given by the relation:

$$Q_F = -\frac{U^2}{\text{Im}(Z_F(\omega_1))} \Rightarrow C_1 = \frac{Q_F}{\omega_1 U^2} \quad (15)$$

that is:

$$Z_F = \frac{jR_T U^2(\omega^2 - \omega_1^2)}{R_T\omega\omega_1 Q_F(n_r^2 - 1) + jU^2(\omega^2 - \omega_1^2)} - j\frac{\omega_1 U^2}{\omega Q_F} \quad (16)$$

Distribution of the load-generated harmonic current between the filter tuned to that harmonic and the system is:

$$\frac{|I_S(n_r)|}{|I_F(n_r)|} = k = \frac{|Z_F(n_r)|}{|Z_S(n_r)|} \Rightarrow R_T = \frac{U^2}{n_r^3 Q_F^2 k \omega_1 L_S} \sqrt{U^4 - n_r^4 Q_F^2 k^2 \omega_1^2 L_S^2} \quad (17)$$

Summarizing, the C-type filter parameters can be determined from above formulas. For the arc furnace power supply system (Fig. 13) and the design requirements:

Network	3rd harmonic filters	C-type filter
$U = 30 \text{ kV}$	$Q_F = 20 \text{ Mvar}$	$Q_F = 20 \text{ Mvar}$
$S_{sc} = 1500 \text{ MVA}$	$L_3 = 18.48 \text{ mH}$	$n_r = 1.9$
$L_S = 3.129 \text{ mH}$ (supply network)	$C_3 = 63 \text{ } \mu\text{F}$	$q_{F2} = 10$ (filter quality factor)
$R_S = 30.0 \text{ m}\Omega$ (supply network)	$R_3 = 30.0 \text{ m}\Omega$	$k = 1$
	$n_r = 2.95$	

The C-type filter parameters are: $C_1 = 70.736 \mu\text{F}$, $C_2 = 198.24 \mu\text{F}$, $L_2 = 51.11 \text{ mH}$, $R_T = 276.86 \Omega$.

Figure 14a shows frequency-impedance characteristics of: the power network, the resultant impedance of two single-tuned 3rd harmonic filters, and the C-type filter impedance. Fig. 14b shows frequency-impedance characteristics of: the network, the resultant impedance of the network and two 3rd harmonic filters, and the resultant impedance of the network, two 3rd harmonic filters and the C-type filter.

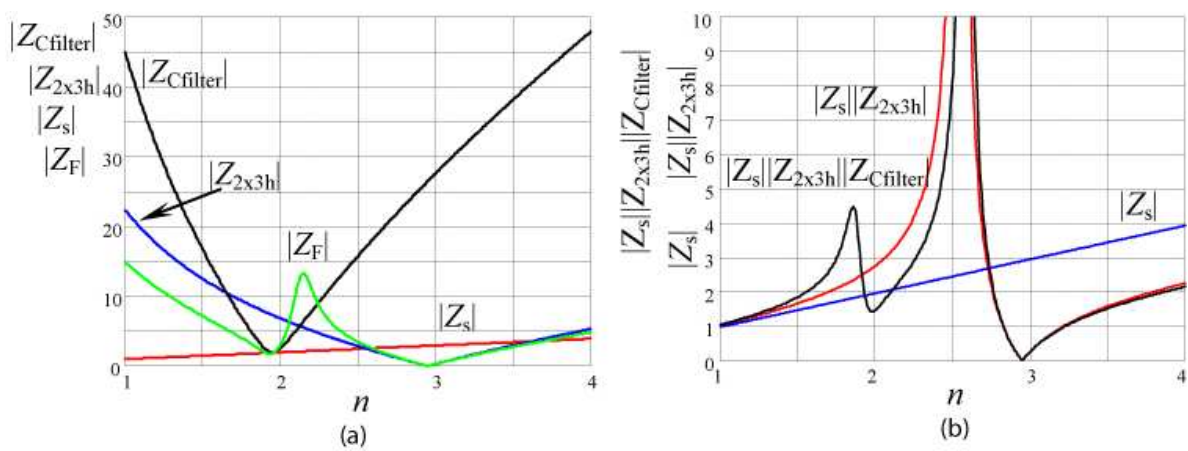


Figure 14. Frequency-impedance characteristics of: a) the power network equivalent impedance (Z_s), the resultant impedance of two 3rd harmonic filters (Z_{2x3h}), the C-type filter impedance ($Z_{Cfilter}$), the resultant impedance of two 3rd harmonic filters and the C-type filter (Z_F); b) the impedance seen from the load terminals: without filters (Z_s), the network equivalent impedance and two 3rd harmonic filters impedance connected in parallel ($Z_s||Z_{2x3h}$), and parallel connection of the network equivalent impedance, two 3rd harmonic filters and the C-type filter impedances ($Z_s||Z_{2x3h}||Z_{Cfilter}$)

Data listed in Table 7 demonstrate that connecting the C-type filter results in the expected reduction of the 2nd voltage harmonic in the supply system, whereas other harmonics are reduced to a small extent. Further reduction of the second harmonic can be achieved by improving the C-type filter quality factor q_{F2} and, consequently, reduction of the filter impedance for the filter resonant frequency and increasing the impedance for higher harmonics.

%	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	THD _u *
Busbars voltage harmonics without filters	1,76	3.01	1.66	2.88	1.12	1.75	1.00	1,12	5.87
Busbars voltage harmonics with two 3rd harmonic filters	2.47	0,27	0.95	1.87	0.78	1.24	0.72	0.81	4.07
Busbars voltage harmonics with two 3rd harmonic filters and the C-type filter	1.32	0.27	0.91	1.78	0.74	1.18	0.69	0.78	3.37

*Total harmonic voltage distortion factor THD_u determined from components up to 15th order.

Table 7. Voltage harmonics (at the 30kV side) without filters, with two 3rd harmonic filters, and with two 3rd harmonic filters and the C-type filter

Figure 15a shows the C-type filter frequency characteristics for different filter quality factors, figure 15b illustrates the relation between the resistance R_T and the coefficient k that indicates the distribution of the current harmonic to which the filter is tuned (Table 8).

Seemingly, the most advantageous solution is to increase the filter resistance R_T in order to ensure the largest possible part of the eliminated harmonic current flow through the filter

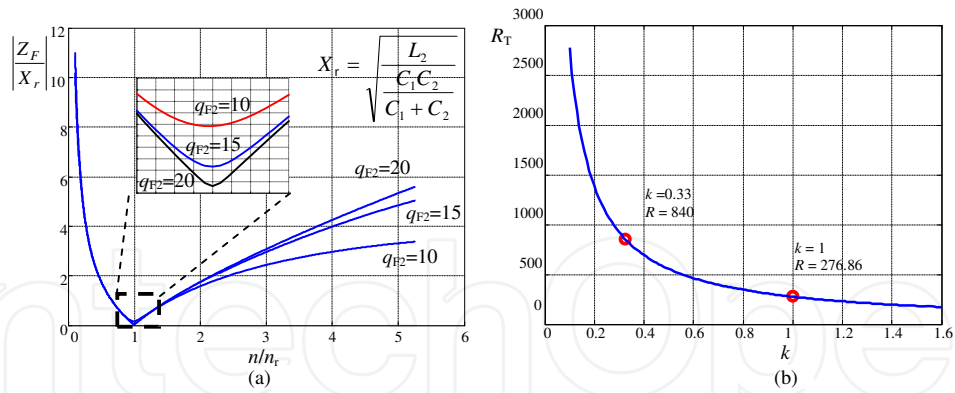


Figure 15. a) The C-type filter frequency characteristics for various quality factors $q_F = R_T/X_r$, b) the resistance R_T vs. the coefficient k

I_F [%]	38.5	44.4	50.0	51.9	57.1	66.6	75.0	83.3	91.0
I_s [%]	61.5	55.6	50.0	48.1	42.9	33.3	25.0	16.7	9.0
k	1.60	1.25	1.00	0.93	0.75	0.50	0.33	0.25	0.10
R_T [Ω]	172	221	276.86	300	350	555	840	1111	2778

Table 8. The percentage distribution of the harmonic current between the filter tuned to that harmonic and the supply network; the corresponding R_T values and the designed filter quality factor.

instead of the supply network. But the increase in the resistance will reduce high harmonic currents through the filter. Thus a compromise between the filter ability to take over the harmonic the filter is tuned to, and its capability to mitigate other harmonics should found. Increasing the R_T resistance makes the C-type filter frequency characteristic similar to that of a single-branch filter.

5.1.2. Genetic approach

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 filter parameters were computed by means of the Genetic Algorithm using the model from Fig. 13 in the Matlab environment. The arc furnace is regarded as an ideal harmonic current source and as a load for the fundamental harmonic with given active power (P) and reactive power (Q).

The range of variability of decision variables: $C_1 = (10^{-6} - 10^{-4}\text{F})$, $R_T = (1 - 10000)$. The Genetic Algorithm parameters: (a) parameter C_1 is encoded into 8-bit strings, and parameter R_T into a 12-bit string; (b) population size 200 individuals; (c) crossover probability $p_k = 0.8$; (d) mutation probability $p_m = 0.01$; (e) Genetic Algorithm termination condition – 30 generations; (f) ranking coefficients $C_{\min} = 0$, $C_{\max} = 2$; (g) inverse ranking was applied in order to minimize the objective function; (h) selection method SUS and (i) shuffling crossover. The optimiza-

tion goal was to minimize total harmonic distortion of the supply network current THD_I and reduce the angle between fundamental voltage and current harmonics $\varphi(I_{(1)}, U_{(1)})$ - (18).

$$F_{goal} = \begin{cases} THD_I + \sin\left(\varphi\left(I_{(1)}, U_{(1)}\right)\right) & Q_F \leq 20\text{Mvar} \\ 100 \cdot \left(THD_I + \sin\left(\varphi\left(I_{(1)}, U_{(1)}\right)\right)\right) & Q_F > 20\text{Mvar} \end{cases} \quad (18)$$

According with the achieved results the total capacitance $C_1 = 70.75\mu\text{F}$ and total capacitance $C_2 = 196.8\mu\text{F}$. The reactor L_2 inductance is 51.48mH . The resistor resistance is $R_T = 300\Omega \pm 10\%$.

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 (fig. 13): 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 110kV side. Essential results of measurements are provided in Table 9.

Figures 16 – 18 illustrate voltage and current waveforms recorded at the 110kV side, the arc furnace supply voltage the arc furnace and the C-type filter currents and total harmonic voltage distortion factor THD_U at both: the 30kV and 110kV 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.

6. Conclusion

This chapter presents several selected cases of power electronic systems analysis with respect to high harmonics occurrence and reactive power compensation. For these cases are proposed classical solutions, i.e. power passive filters which still are a basic and the simplest method for high harmonics mitigation. Analytical formulas that enable to determine basic parameters of various filters' structures and a group of single-tuned filters are provided.

Also a method for passive filters' design employing artificial intelligence, which incorporates genetic algorithms, is presented. It has been proved that this method can be the attractive tool to solve some kinds of power quality problems. The results obtained using GA are very close to those obtained with the analytical method. Hence the conclusion that genetic algorithms can be an efficient tool for passive filters design. The advantage of the method employing genetic algorithms is the possibility of multi-criterial optimisation and taking into account at the design stage different (e.g. voltage or current) constraints. It also can be applied to filters of various structures and degrees of complexity and can account for filters' resistance that may influence the filter resonance frequency. In other words, genetic algorithm can be a useful design tool in cases where the system analysis is too complex or even not possible.

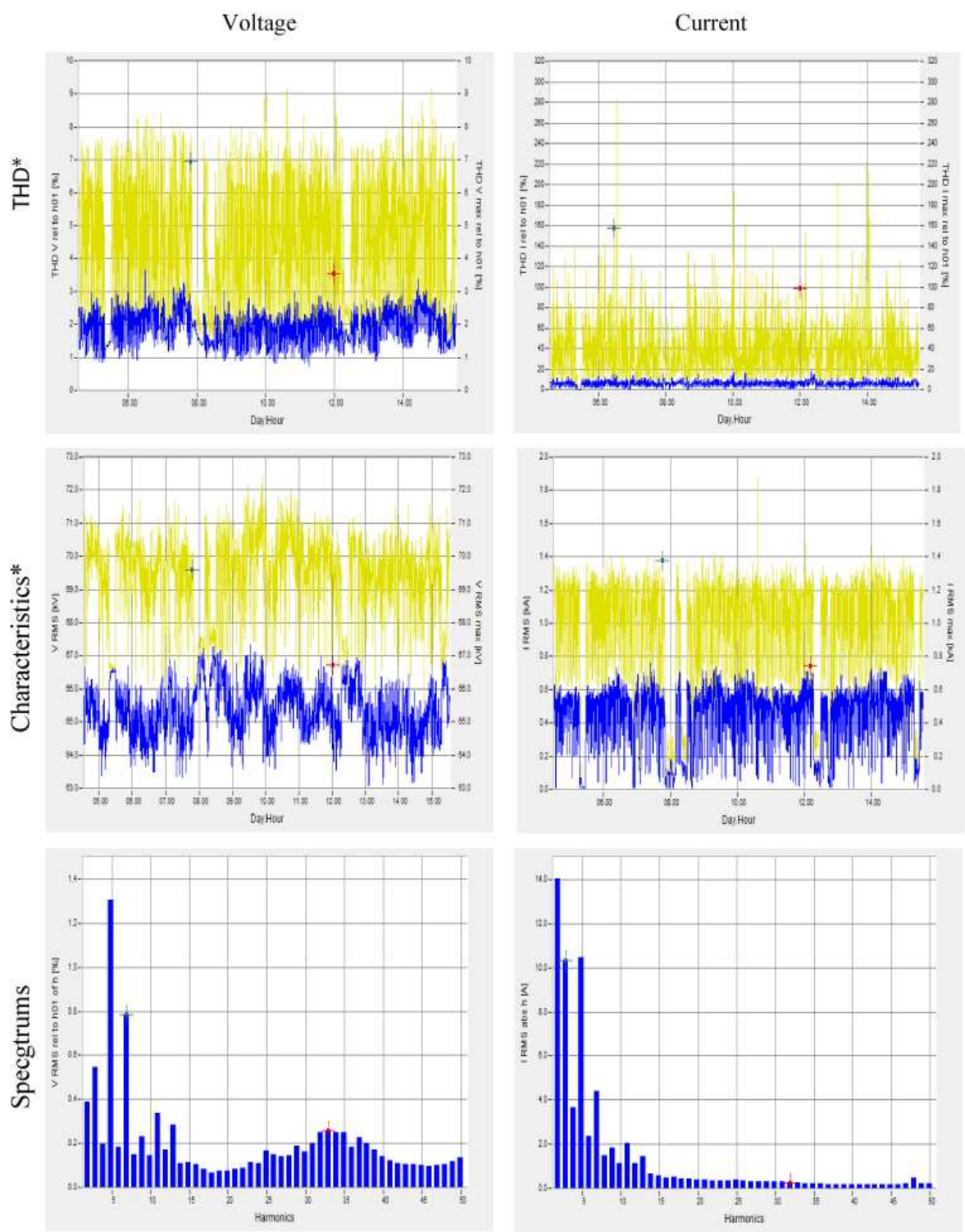


Figure 16. Voltage and current characteristics, spectrums and THD factors at 110 kV side. The graphs show two time characteristics: 10 min. averaged values (blue) and 10 ms maximum values (yellow)

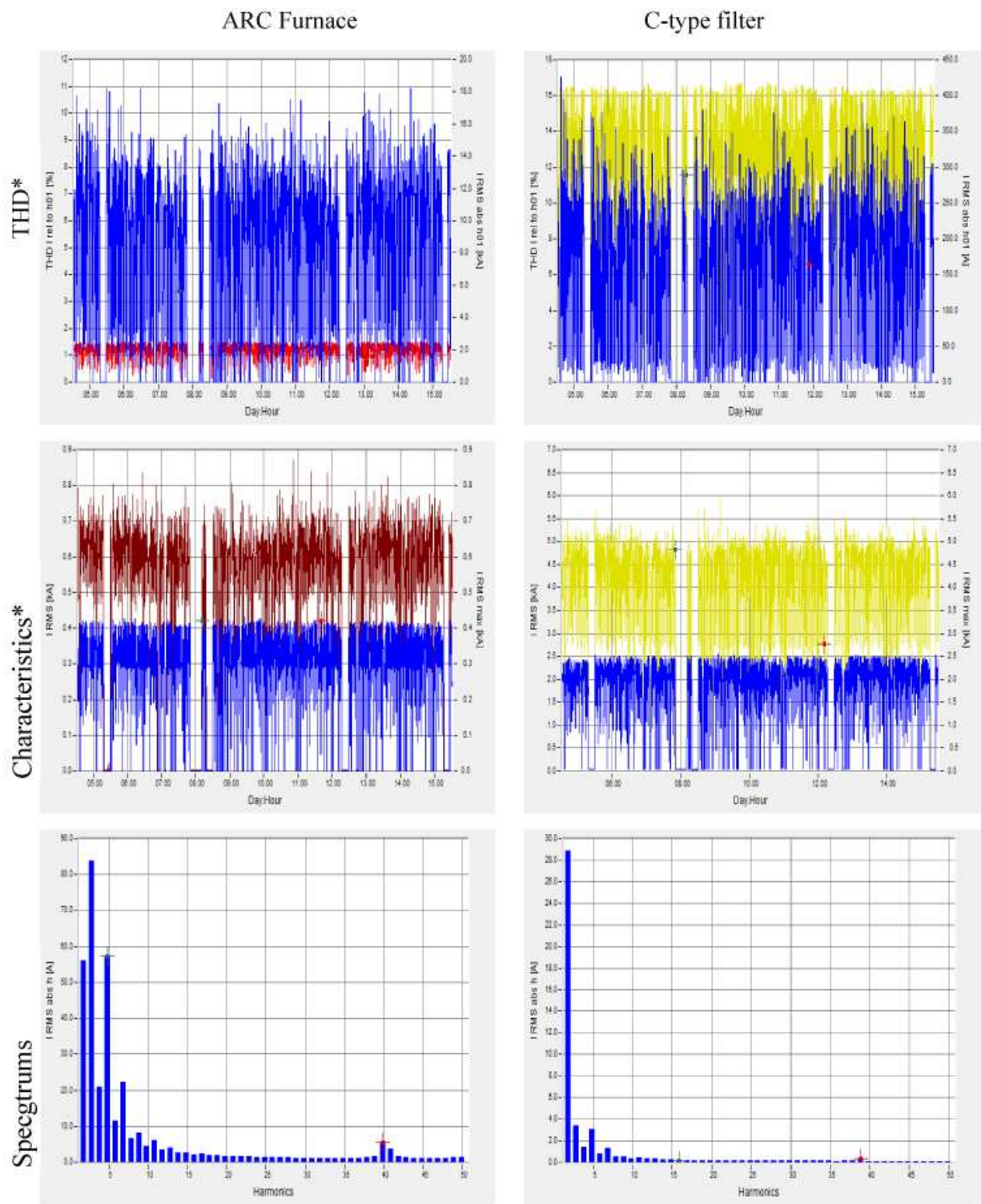


Figure 17. Current characteristics, spectrums and THD_i factors of Arc-furnace and C-type filter. The graphs show two time characteristics: 10 min. averaged values (blue) and 10 ms maximum values (yellow)

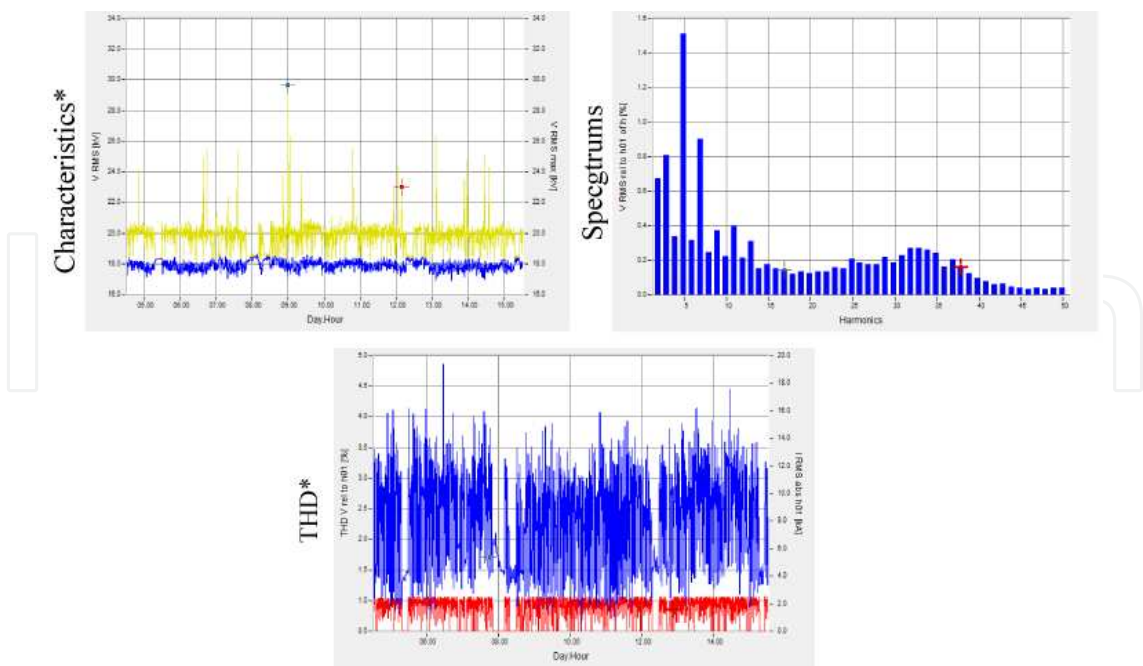


Figure 18. Current characteristics, spectrums and THD_U factors at 30 kV side. The graphs show two time characteristics: 10 min. averaged values (blue) and 10 ms maximum values (yellow)

Measurement point	P ₁ (Furnace)	P ₁ (Furnace)	P ₂ (Filter C)	P ₃ (3 rd harm. Filter)	P ₄ (3 rd harm. Filter)	P ₅ (110kV)	P ₅ (110kV)
Furnace and filters in operation	off	on	on	on	on	on	off
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 [MVA]	-	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

Table 9. The Measurement results obtained over a period of 7 days

Appendix A - Genetic Algorithms

Genetic Algorithms (GA) are stochastic global search method, mimicking the natural biological evolution. It has been 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.

GA popularity is due to its features. They: (i) don't process the parameters of the problem directly but they use their coded form; (ii) start searching not in a single point but in a group of points; (iii) they use only the goal function and not the derivatives or other auxiliary information; (iv) use probabilistic and not deterministic rules of choice. These features consists in effect on the usability of Genetic Algorithms and hence their advantages over other commonly used techniques for searching for 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. It is on the basis of all the individuals in the population are evaluated and on the basis of a new generation of solutions is created. Each iteration of the genetic algorithm creates a new generation. Figure 20. shows the basic block diagram of a Genetic Algorithm.

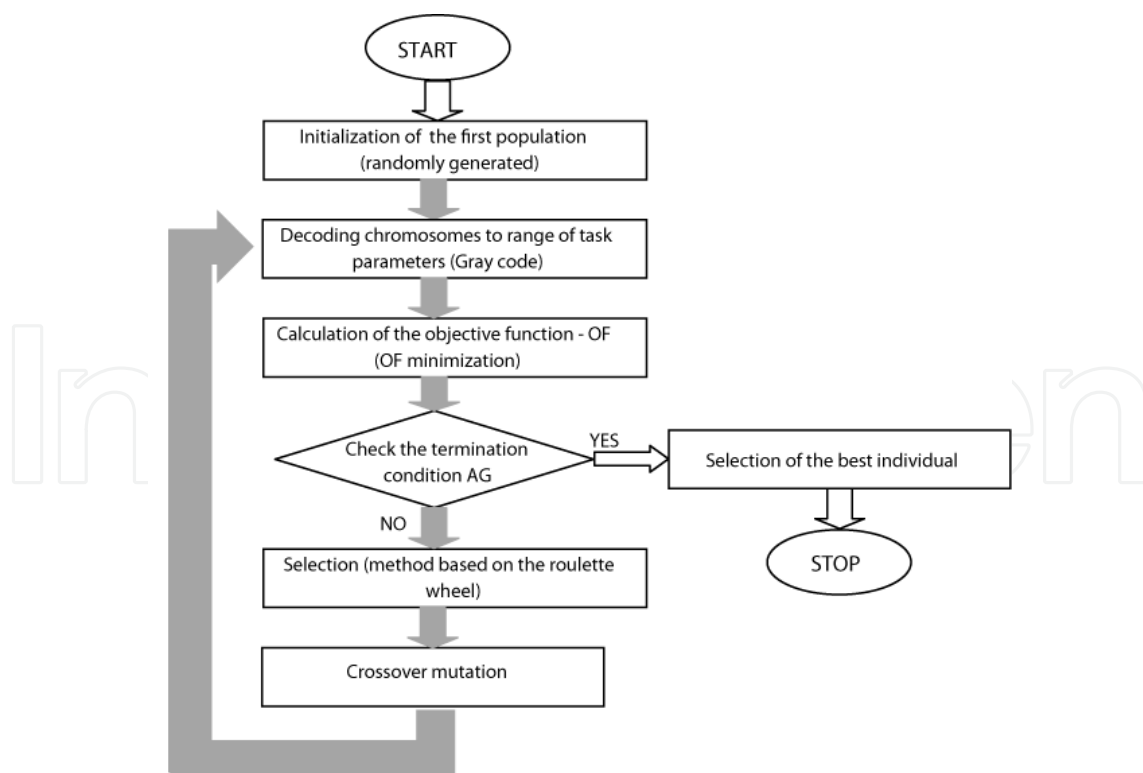


Figure 19. Block diagram of the basic Genetic Algorithm (GA)

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