POWER FACTOR AND HARMONIC DISTORTION CORRECTION OF CONSUMERS BY COMBINATION OF DETUNED FILTERS

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ABSTRACT

In this paper the results of investigation in the area of power factor and harmonic distortion correction of consumers with high current and voltage distortion are presented. The corresponding values of the voltage and current harmonics are greater than the highest admissible values for capacitors and corresponding filters reactors. The original procedure, which enables successive decreasing of harmonic distortion by switching the capacitor sections, is presented. By using the proposed method, the combination of detuned filters, the voltage distortion is decreased by two times. In such way, the corresponding voltage and current harmonics are under the highest admissible values for low- and medium- voltage networks.

INTRODUCTION

Power supply of the entire complex of ski resort on Zlatibor (Serbia) is carried on through the transformer station TS 10/0.4 kV 2×1000 kVA. DC drive of the ski lift (power 730 kW) is the only consumer connected to the transformer TR2 10/0.4 kV, 1000 kVA, while the rest of the consumption (30-100 kW) is being supplied by the transformer TR1 10/0.4 kV, 1000 kVA. Load of the DC motor goes from 80 to 500 kW and from 250 kvar to 550 kvar. Consumer takes over the amount of reactive energy, which is 2-3 times greater then the amount of active energy. Therefore, the expenses for the reactive power participate in more than 30 percent in the overall expenses for the electrical power. Measurement results indicate presence of high current and voltage distortion (THD_I = 30-60%, THD_U = 8-14%). It was necessary to design and install a power factor correction system, which would result in reactive power reduction as well as improvement of the electrical power quality.

Anti-resonant filter, in the capacitor bank, consists of serial connection of capacitors for reactive power compensation and specially added inductance. Inductance value is calculated so that the mentioned serial circuit presents an inductive reactance for the harmonics of a given order ($\nu = n$) and higher order, i.e. for the harmonics of order $\nu \geq n$. This ensures that so formed section of capacitors represents significant impedance for harmonics of order $\nu \geq n$.

In practice, anti-resonant filters for harmonics of order $\nu \geq 3$ (usually for frequency f_r = 135 Hz) or harmonics of order $\nu \geq 5$ are used. The latter are constructed for two values of resonant frequency (mostly for f_r = 189 Hz and f_r = 213 Hz). The catalogues of known manufacturers [3], [4] provide information about the characteristics of these anti-resonant filters (Table 1).

Table 1: Basic characteristics of anti-resonant filters

Set frequency f_r (Hz)	Order of set frequency ($n = f_r/f$)	Relative reactance $p = 1/n^2$ (%)
135	2.7	13.7
190 (189)	3.8 (3.78)	6.92 (7)
215 (213)	4.3	5.42 (5.5)

COMBINED ANTI-RESONANT FILTER

Manufacturers and designers of anti-resonant filters do not recommend use of capacitors with parallel sections for different resonant frequencies. It is truly justified when it comes to anti-resonant filters for harmonics of different order, for example $\nu \geq 3$ and $\nu \geq 5$, because of the possibility of parallel resonance for the third harmonic currents between the filter sections. But, there is no such danger for the capacitor bank which is formed out of anti-resonant filters for the harmonics of the same order, $\nu \geq 5$, but with different values of resonant frequency, in this case f_r = 189 Hz and f_r = 213 Hz. This way we come to the **combined anti-resonant filters within the same capacitor bank.** The essence of the proposal is a new solution for the construction and formation of the capacitor bank, which consists of anti-resonant filters. This solution is particularly useful when it comes to anti-resonant filter for harmonics of order $\nu \geq 5$, since it is possible to construct a capacitor that consists of combined anti-resonant filters instead of filter values for the same resonant frequency as is common in conventional solutions. The novelty is that instead of capacitor's anti-resonant sections for harmonics of order $\nu \geq 5$, which are set to one resonant frequency (f_r = 189 Hz), two types of anti-resonant filters (section capacitor-reactor) are used, as follows:

- for f_r = 189 Hz, and
- for f_r = 213 Hz.

The first group of sections behaves as a classic anti-resonant filter, because of the reactance of filter section, which is, in units of capacitor reactance for the first harmonic (X_{C1} = 100%):

$$X_{L\text{-}C} = 5 \times 7_L\% - 100_C\%/5 = 15_L\%$$

but it has the inductive nature in order to avoid the possibility of parallel resonance. As a rule, the value of reactance $X_{L\text{-}C}$ is significantly higher than the network reactance, on the bus to which is capacitor connected. Therefore, the greater part of injected current harmonics goes to the network. This way the basic function of anti-resonant filter - protection of the capacitor against current harmonics, is achieved. However, if the values of voltage and current harmonic distortion are $THD_U > 4\%$ and $THD_I > 30\%$ respectively, it is recommended to use absorption filters [3], [4], which are much more expensive and still require much more space in the plant.

As it will be shown, a suitable choice of first section filter can be achieved so the fifth harmonic of current does not exceed the maximum permissible value for the capacitor and reactor, even when the value of harmonic voltage distortion THD_U is 10%. Further involvement of parallel sections, with a serial reactor reactance p = 7%, reduces the harmonic distortion of voltage, so the currents through each section of the compensator are proportionately reduced as well. Consequently, the current fifth harmonics which go to the network are insufficiently reduced, so harmonic distortion of voltage remains relatively high. It is difficult to reduce it enough to the secure value $THD_U < 5\%$ from the value $THD_U = 10\%$.

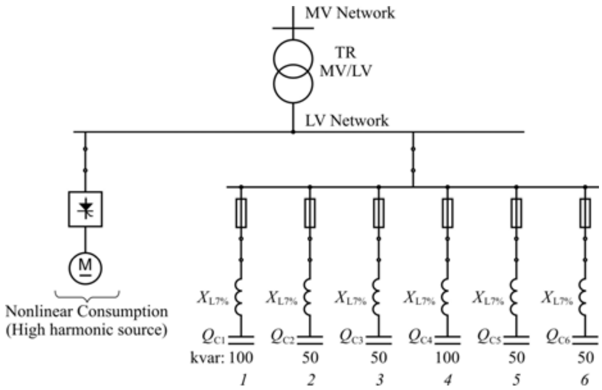
In order to make further illustrations two different versions of design and application of capacitor banks will be presented and discussed:

- common variant, which consists of uniform filters for the same values of resonant frequency, as it is common in conventional solutions, and then
- variant of the capacitor bank, which consists of combined anti-resonant filters, and which is proposed in this solution.

Capacitor banks with anti-resonant filters with same values of resonant frequency

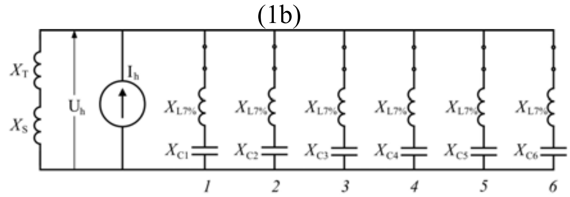
Figure 1a shows the single-line capacitor scheme of uniform anti-resonant filters with reactance of serial reactors p = 7% (and $X_{L-C} = 15_L\%$), connected to the low voltage side of MV/LV transformer, which supplies nonlinear consumers (source of higher harmonics), while in Figure 1b appropriate scheme for the calculation of harmonic currents is presented. Figure 1c shows diagrams of the dominant fifth harmonic currents for different switching modes, when turned on is: one section, sections 1-2, sections 1-3, sections 1-4, sections 1-5 and sections 1-6, respectively.

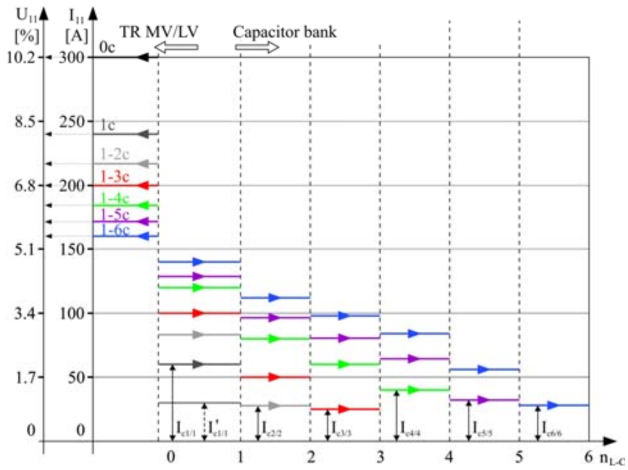
Although the application of these filters is not recommended in case of high values of voltage harmonic distortion, $THD_U \geq 5\%$, and current harmonic distortion, $THD_I \geq 30\%$, it is possible to achieve that maximum current harmonics (the 5^{th}) do not exceed the maximum permissible value for the capacitor and reactor. This is ahieved by appropriate choice of filter's first section, even when is $THD_U = 10\%$ before switching on the capacitors. Thus, the choice of the first section of capacitors with reactive power of 100 kvar (2×50 kvar), instead of 50 kvar ensures the 5^{th} harmonic current to drop from the value of 33.3 A to the value of 2×30 A (30 A on each 50 kvar section), Figure 1., With suitable choice of filter's first section (at permanently allowed values of current $I_R = 1.2\div1.3I_N$ and voltage $U_R = 1.1\div1.2U_N$), 5^{th} harmonic current does not exceed the maximum permissible value for the capacitor and reactor. Further involvement of parallel sections with $f_r = 189$ Hz, ie. with a serial reactor reactance p = 7%, gradually reduces the harmonic distortion of voltage and proportionally reduces the current through each section of the capacitor. As a consequence of this reduction, the fifth harmonic currents, which go into the network, are not reduced enough. Therefore, the harmonic distortion of voltage remains relatively high - it is difficult to reduce it from the value $THD_U = 10\%$ to the secure value $THD_U < 5\%$. So, if the values of voltage and current harmonic distortion are $THD_U > 4\%$ and $THD_I > 30\%$ respectively, it is recommended to use absorption filters [3], [4].



(1a)

(1b)





(1c)

Figure 1a, 1b and 1c

New-combined anti-resonant filters for different values of resonant frequencies

The novelty is that instead of capacitor's anti-resonant sections for harmonics of order $\nu \geq 5$, which are set to the one resonant frequency ($f_r = 189$ Hz), two types of anti-resonant filters (section capacitor-reactor) are used, as follows:

- for $f_r = 189$ Hz, i.e. with reactance of serial reactor $p = 7\%$, and
- for $f_r = 213$ Hz, i.e. with reactance of serial reactor $p = 5.5\%$.

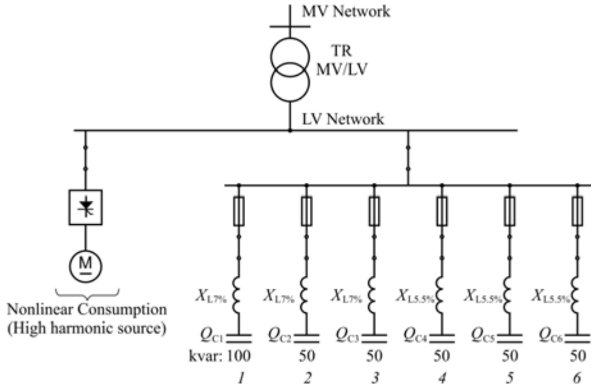
The first group consists of three sections, Figure 2, which are identical with the first three sections of the capacitor, Figure 1. First section of capacitors has power 100 kvar, which ensures that the fifth harmonic current remains within permissible limits. By the inclusion of a sufficient number of parallel sections with serial reactance p = 7% harmonic distortion of voltage drops to 5-6%, and absorption power thereof becomes relatively smaller. Because of this, even after switching on all sections of the capacitor, which led to the desired reduction of reactive loads, harmonic distortion of voltage remains above allowed limits In example given on Figure 2c, the value of distortion remained at high level $THD_U = 5.3\%$, which still represents a real danger for sensitive devices (computers, etc.). To solve this other problem as well, capacitor bank was constructed, with 4th, 5th and 6th section having the same capacitive power (50 kvar) but with reactances of serial reactors with a value of p = 5.5%, Figure 2. Thereby, anti-resonant filters were made with two times smaller reactances for 5th harmonic, i.e.:

$$X_{L\text{-}C} = 5\times5.5_L\% - 100_C\%/5 = 7.5_L\%$$

As a consequence, the current fifth harmonics which go to the network are significantly reduced, so harmonic distortion of voltage becomes lower and it is possible to reduce it from the value $THD_U = 10\%$ to the secure value $THD_U < 5\%$, Figure 2. Here we should bear in mind that a suitable choice of first section filter with a serial reactor reactance p = 5.5% (by structure, power and maximum values of current and operating voltage, $U_R = 1.1\div1.2U_N$), should achieve that fifth harmonic current does not exceed the maximum permissible value for the capacitor and reactor, for example at low (attained) harmonic voltage distortion $THD_U = 5\text{-}6\%$, before the inclusion of this section. This explains the fact that uniform application of filters, with a serial reactor reactance p = 5.5%, is not possible in networks with harmonic distortion of voltage above 5-6%.

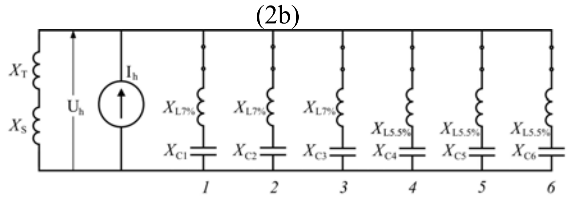
Approximate power of capacitor bank is determined by the appropriate level of compensation. Minimum power on the 1st section of a filter with a serial reactor reactance p = 7%, and the 1st section of a filter with a serial reactor reactance p = 5.5% (4th section overall), is determined by the fulfillment of the requirements that the fifth harmonic current does not exceed the maximum allowed value for the corresponding capacitors and reactors. Based on these two data, the number of sections and structure of capacitor, for reactive power compensation in a network with given (high) values of voltage harmonic distortion THD_U and current harmonic distortion THD_I, are set. In order to achieve better settings of anti-resonant filter minor changes of the capacitor's power are possible.

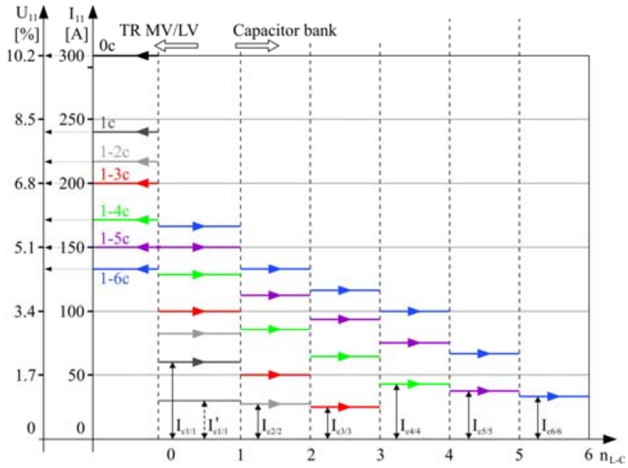
As demonstrated, it is usually possible to successfully implement the compensation of reactive power and reduce harmonic distortion of current and voltage in this way also in networks with high levels of voltage distortion up to $THD_U \leq 10\%$, and current distortion up to $THD_I = 30\text{-}50\%$.



(2a)

(2b)





(2c)

Figure 2

APPLICATION AND ANALYSIS OF THE SOLUTION

Method of application is illustrated on Figure 2, which shows principal single-line scheme of capacitor bank. This bank consists of combined anti-resonant filters (1st, 2nd and 3rd section contain a serial reactor with reactance p = 7% each, 4th, 5th and 6th section contain a serial reactor with reactance p = 5.5% each) connected to the low voltage side of MV/LV transformer from which buses nonlinear

consumers (sources of higher harmonics) are powered.
Design and structuring the capacitor is done in the usual way, but it is important to take care also about two additional facts:

- The 1st section of the capacitor, with induction reactance p = 7%, has the reactive power 100 kvar so the fifth harmonic current would not exceed the maximum allowed value for the capacitor and reactor It is also possible to implement one 50 kvar section that is constantly connected and another 50 kvar section that turns on when consumers turn on; the latter section is a part of the capacitor with sections that are in the automatic operation.
- Three more sections of capacitors with 50 kvar and reactance of serial reactor p = 5.5% are provided. After joining the 4th section with 50 kvar and reactance of serial reactor p = 7% the fifth harmonic current will not exceed maximum allowed value for this capacitor and reactor.

If it is assessed that the latter was not achieved, then the corresponding section should be predicted to has larger power, 100 kvar (eg. simultaneous inclusion of 4th and 5th section). Thereby, the fifth harmonic current through these capacitors with reactors p = 5.5% are reduced. To eliminate the potential for excessive current through the 4th capacitor section, $I_{C4/4}$, one can get straight down to the regime with 5 sections and with less 5th harmonic current through the 4th and 5th capacitor section, Figure 2c:

$$I_{C5/5} = I_{C4/5} < I_{C4/4}.$$

Since the reactance for fifth harmonic is two times lower when it comes to anti-resonant capacitor sections with reactor's reactance p = 5.5%, the absorption power of these filters and overall bank is increased. As a consequence, the fifth harmonic currents, which go to the network, are significantly reduced and therefore harmonic distortion of voltage becomes lower. In this case, after switching on the last section, distortion of voltage is reduced from the value THD_U = 10.2% to the safe value $THD_U \approx$ 4%. This is the biggest advantage of capacitors, which consist of anti-resonant filters combined in proposed manner.

ANALYSIS OF MEASUREMENTS

Table 1 presents the results of measuring total harmonic distortion of line voltage (THD_U) and phase voltage harmonics of order h = 1, 3, 5, 7,... 45, 47 and 49, for two specific modes:

- P = 88 kW, Q = 371 kvar, Q_C = 58 kvar (mode with one filter sections for compensation), and
- P = 84 kW, Q = 110 kvar, Q_C = 290 kvar (mode with five combined filter sections switched on).

The measurement results show that very high harmonic distortion of voltage (9.7-10.6%) is reduced to the permissible level (5.9-6.4%). For the mode when combined filter sections are all switched on, the measurement results are just slightly different from the values that are calculated and shown graphically in Figure 2c.

Table 2: Measurements results for:
(1) mode with one filter sections for compensation, and
(2) mode with five combined filter sections switched on

	(1)			(2)		
	Phase 1 [%]	Phase 2 [%]	Phase 3 [%]	Phase 1 [%]	Phase 2 [%]	Phase 3 [%]
V_{h1}	100	100	100	100.0	100.0	100.0
V_{h3}	0.2	0.2	0.1	0.7	0.4	0.2
V_{h5}	7.4	7.4	7.8	4.1	4.1	4
V_{h7}	4	3.8	3.3	3.7	3.6	3.4
V_{h9}	0.1	0	0.1	0.3	0	0.2
V_{h11}	2.4	2.2	3.1	0.9	0.8	1.1
V_{h13}	2.3	2.3	1.9	2.3	2.2	2.2
V_{h15}	0.4	0	0.3	0.3	0	0.2
V_{h17}	2.9	2.8	3.2	0.4	0.1	0.5
V_{h19}	1.6	1.7	0.7	1.5	1.6	1
V_{h21}	0	0.1	0	0	0	0
V_{h23}	0	0.3	0.6	0	0.1	0.1
V_{h25}	0.4	0.2	0.3	0.1	0	0.1
V_{h27}	0	0.1	0.1	0	0	0
V_{h29}	0.3	0.3	0.6	0.2	0.2	0.2
V_{h31}	0.3	0.2	0.3	0	0	0
V_{h33}	0	0	0.1	0	0	0
V_{h35}	0.3	0.3	0.6	0.3	0.2	0.3
V_{h37}	0.2	0.2	0.3	0	0.2	0
V_{h39}	0	0	0.1	0	0	0
V_{h41}	0.3	0.3	0.6	0.3	0.2	0.2
V_{h43}	0.2	0.2	0.2	0.1	0.2	0.1
V_{h45}	0	0	0.1	0.1	0	0
V_{h47}	0.3	0.2	0.5	0.1	0	0.2
V_{h49}	0.1	0.3	0.2	0.2	0.2	0.1
THD_U (phase to phase)	9.8	9.7	10.6	6.2	5.9	6.4

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