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The Effect of the Design Method on Efficiency of Resonant Harmonic Filters

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Abstract—**Distribution voltage harmonics and load current harmonics other than harmonics to which a resonant harmonic filter (RHF) is tuned, deteriorate the filter efficiency in reducing harmonic distortion. The paper presents results of a study on dependence of this deterioration on the method of the filter design. The study was confined to four-branch RHFs of the 5th, 7th, 11th and 13th order harmonics, installed on buses that predominantly supply six-pulse ac/dc converters or rectifiers.**

The filters under investigation were designed according to two different approaches: a traditional approach and an approach based on an optimization procedure. In the traditional approach, the reactive power allocated to particular branches of the filter and their tuning frequencies are selected at the designer's discretion, according to recommended practices. In the optimization based approach, the reactive power allocated to particular branches and tuning frequencies are resultants of an optimization procedure that minimizes the bus voltage and the supply current THD in the system with the filter under design.

Index terms--**Resonant harmonic filters, harmonic distortion, harmonic filter design, nonsinusoidal systems**

I. INTRODUCTION

The efficiency of resonant harmonic filters in reduction of harmonic distortion is reduced by distribution voltage harmonics and the load current harmonics other than harmonics to which the filter is tuned. Harmonic amplification due to filter resonance with the distribution system inductance is the main cause of this efficiency deterioration.

Harmonic amplification caused by the filter resonance with the distribution system inductance depends on frequencies of this resonance and can be reduced by appropriate selection of the filter parameters. Harmful effects of the filter's low impedance at tuning frequencies can be reduced [1-6] by detuning the filter from frequencies of characteristic harmonics. Unfortunately, this detuning reduces the attenuation of the load current characteristic harmonics. Thus, to improve the filter efficiency, a trade off between attenuation and amplification of particular harmonics is needed. This trade off is a core of some recommended practices, commonly applied during RHF design. Also, it can be achieved by a "cut and trial" approach or by an optimization procedure.

Although the "cut and trial" approach may improve the filter performance, optimization is a better approach to such a trade off problem. A filter designed using optimization routines is referred to as an *optimized filter*. Such a procedure requires that conditions of the filter operation with respect to the load and the system parameters as well as the distribution voltage and load current harmonics are specified. Therefore, the filter can be considered as an optimized filter only for those conditions.

The most common RHFs in distribution systems are those used for reduction of harmonic distortion caused by six-pulse ac/dc converters and rectifiers. Characteristic harmonics of such devices are of the order $n = 6k \pm 1$, while their asymmetry, asymmetry of the thyristors' firing angle and other loads contribute [1-4, 7] to the presence of other current harmonics. Investigations of the filter effectiveness in this paper are confined to just such RHFs, composed of four resonant LC branches for reduction of the 5th, 7th, 11th and 13th order harmonics. Filters with high-pass branches are beyond the scope of this study.

Resonant harmonic filters are often superseded by switching compensators, commonly known as "active harmonic filters"(AHFs). Such devices have a number of advantages over RHFs. First of all, they have an adaptive capability. However, the power rating of AHFs is limited by their transistors' switching power. Moreover, high frequency switching, necessary for operation of these devices, is a source of electromagnetic interference. Therefore, RHFs, might still be an important alternative, in particular, if an optimization procedure could elevate their efficiency.

This paper does not present results of a "case study" for a particular field situation. The results are based on computer modeling of different filters operating in different conditions with respect to the short circuit power and waveform distortion. This makes it possible to draw more general conclusions on the effect of the method of the filter design on the filter efficiency.

In order to present, in the limited space of this paper, the effect of some important parameters and distortion on the filter efficiency, less important parameters are neglected or kept constant at the level that can be expected in field situations. Consequently, the results presented in this paper do not have the accuracy common for "a case study". However, at the cost of lower accuracy, these conclusions are not confined to a specific field situation, thus they are more general.

II. MEASURES OF FILTER EFFICIENCY

Installation of a RHF at a supply bus, as shown in Fig. 1, changes the bus voltage and the supply current distortion. The reduction of this distortion owing to the presence of a filter provides a quantitative measure for the filter efficiency.

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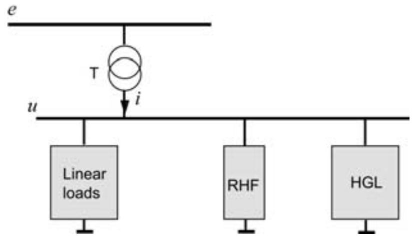

Fig. 1. Distribution system bus with harmonic generating load and resonant harmonic filter

A one phase equivalent circuit of the system in Fig. 1 is shown in Fig. 2.

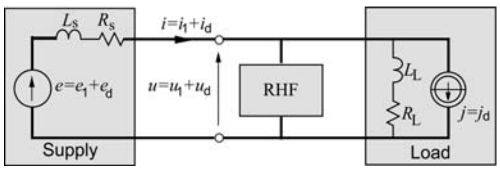

Fig. 2. One phase equivalent circuit of the system in Fig. 1.

The efficiency of RHFs in reduction of the voltage distortion differs from their efficiency in reduction of the current distortion. Therefore, the filter efficiency is specified by two different measures. One for the voltage, and one for the current.

Let u_1 denote the fundamental harmonic of the bus voltage and U_1 is its rms value. Let u_{d} denote the distorting component of this voltage, i.e., the sum of harmonics

$$u_{\mathrm{d}} = \sum_{n=2}^{\infty} u_n \tag{1}$$

and $||u_{\mathrm{d}}||$ is its rms value [8, 9]. The Total Harmonic Distortion (THD) of the bus voltage in the system with a filter is

$$\delta_u = \frac{||u_{\mathrm{d}}||}{U_1}\,. \tag{2}$$

Let us denote by δ_{u0} the THD of the bus voltage in the same system but without the filter. Thus, the filter efficiency in reduction of the bus voltage distortion, ε_u, can be expressed in terms of the this voltage THD value before and after the filter is installed:

$$\varepsilon_u \;=\; \frac{\delta_{u0}-\delta_u}{\delta_{u0}}\,. \tag{3}$$

The filter efficiency is positive when it reduces the voltage distortion and it is negative when this distortion, due to a filter resonance, increases. A filter that entirely reduces the bus voltage distortion has $\varepsilon_u = 1$; a filter that does not affect THD has efficiency $\varepsilon_u = 0$.

Similarly, a measure of the filter efficiency in reduction of the supply current distortion, ε_i, can be defined as follows.

Let i_1 denote the fundamental harmonic of the supply current and I_1 denote its rms value. Let i_{d} be the distorting component of this current and $||i_{\mathrm{d}}||$ is its rms value. Then the THD of the supply current in the system with the installed filter is

$$\delta_i = \frac{||i_{\mathrm{d}}||}{I_1}\,. \tag{4}$$

Let the THD of the supply current in the same system but without the filter be denoted by δ_{i0}. Then, the filter efficiency in reducing the supply current distortion can be defined as

$$\varepsilon_i \;=\; \frac{\delta_{i0}-\delta_i}{\delta_{i0}}\,. \tag{5}$$

The RHF efficiency does not depend only on the filter itself but also on equivalent parameters of the system at the bus where it is installed as well as on the harmonics of the distribution voltage, *e*, and the load generated current, *j*.

III. TRADITIONAL DESIGN OF RHFs

Resonant harmonic filters for the 5th, 7th, 11th and 13th order harmonics, i.e., of the structure shown in Fig. 3,

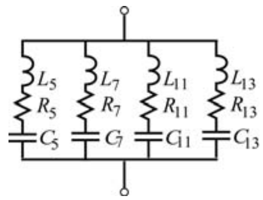

Fig. 3. Four branch RHF structure

are designed traditionally by calculating the capacitance C_k and inductance L_k, k = 5, 7, 11, 13, in such a way, that the branch has a resonance at the frequency

$$z_k = \frac{1}{\sqrt{L_k C_k}}\,, \tag{6}$$

equal to or in a vicinity of harmonic frequency, $\omega_k = k\omega_1$. The reactive power of the fundamental harmonic, Q_k, compensated by such a branch is

$$Q_k = a_k Q = B_{1k}\, U_1^2 = \frac{\omega_1 C_k}{1-\omega_1^2\, L_k C_k} U_1^2 \tag{7}$$

where Q is the load reactive power per phase, a_k is the coefficient of the reactive power allocation to the branch $L_k C_k$ and B_{1k} is the branch susceptance for the fundamental harmonic. Combining (6) and (7) gives

$$C_k = \;[1 - (\frac{\omega_1}{z_k})^2]\,\frac{a_k\, Q}{\omega_1 U_1^2}\,. \tag{8}$$

$$L_k = \frac{1}{z_k^2 C_k}\,. \tag{9}$$

The resistance R_k depends on the inductors' Q-factor, q, defined as

$$q = \frac{\omega_1 L}{R}\,. \tag{10}$$

According to Ref. [6], for high voltage applications where air-core inductors are used, the Q-factors of $50 < q < 150$ are typical, while for low voltage applications iron-core inductors are needed with $10 < q < 50$.

The opinions with respect to the reactive power allocation to particular branches are divided. According to Ref. [10], this allocation is irrelevant for the filter properties. Consequently, it could be assumed that each branch compensates the same reactive power, i.e., allocation coefficients have the same value. Such filters will be referred to as *Type A* filters in this paper. However, there are also other practices or recommendations. The reactive power allocation for a two branch filter of the 5th and 7th order harmonics assumed in Ref [5] is in proportion of Q_5/Q_7 = 2:1, while in Ref. [4] this proportion is

Q_5/Q_7 = 8:3. According to Ref. [11], the reactive power allocation should be "*...proportional to total harmonic current each filter will carry*". Filters designed according to this recommendation will be referred to as *Type B* filters.

In the presence of distribution voltage harmonics, the filter branches are tuned traditionally to a frequency below the harmonic frequency. It increases the branch reactance at the harmonic frequency and keeps it inductive, even if the capacitance of the capacitor bank declines in time. However, there are substantial differences in opinions on how much the branches should be detuned. Reference [5] assumes that filters are detuned by 5% below harmonic frequencies, while Ref. [1] suggests that detuning should be in the range of 3 to 10% below these frequencies. Indeed, detuning assumed in Ref. [7] amounts to 8% for all branches, i.e., the relative detuning is the same for all branches. According to Ref. [4] the branches are detuned by 18 Hz, i.e., the absolute detuning is the same. Branches are tuned to frequencies 4.7 ω_1 and 6.7 ω_1, respectively. It means that there is the lack of a clear recommendation with respect to the filter detuning. Even the degree of detuning is not related to the level of these harmonics.

When a harmonic filter is under design, the attenuation of dominating, characteristic harmonics is the subject of main concern. The ac/dc converters and other nonlinear loads supplied from the same bus, also generate other, non-characteristic harmonics. Their level is reported in numerous papers [1-5, 7, 12]. The traditional approach to filter design essentially neglects the presence of non-characteristic harmonics in the load current and the distribution voltage harmonics in the filter design process, considering them as kind of "minor" [8] harmonics. Tuning the filter branches to a frequency below harmonic frequencies is a common counter-measure to the degrading effect of distribution voltage harmonics.

IV. UPPER LIMIT OF FILTERS EFFICIENCY

The filter efficiency in the lack of harmonics other than harmonics to which the filter is tuned, could be considered as a reference for an investigation on how other harmonics affect the filter performance.

Let us consider a filter for reducing harmonic distortion caused by a load that generates current harmonics of the relative content $J_n/I_1 = 0.8 \times I_1/n$, i.e.,

$$J_5/I_1 = 16\%,\ J_7/I_1 = 11.4\%,\ J_{11}/I_1 = 7.3\%,\ J_{13}/I_1 = 6.1\%.$$

and the power factor λ = 0.8. Such a situation could be considered as typical for buses loaded with six-pulse ac/dc converters, rectifiers and some amount of linear loads. The bus voltage and the supply current THD, δ_{u0} and δ_{i0}, before the filter was installed, for a few different short circuit powers and the reactance to resistance ratio of the supply, X_s/R_s = 5, are tabulated in Table 1.

Table 1. Bus voltage and supply current THD before any filter is installed, δ_{u0} and δ_{i0}

S_{sc}/P	-	20	25	30	35	40	45	50
δ_{u0}	%	**8.4.**	**6.9**	**5.9**	**5.1**	**4.5**	**4.1**	**3.7**
δ_{i0}	%	**19.8**	**20.2**	**20.4**	**20.6**	**20.8**	**20.9**	**21.0**

The THD of the bus voltage and the supply current after a four-branch Type A or Type B filter of the 5th, 7th, 11th and 13th order harmonics is installed, δ_u and δ_i, are compiled in Tables 2 and 3. The filter branches were detuned by -12 Hz. The filter inductors' q-factor was assumed to be q = 40.

Table 2. Bus voltage and supply current THD with Type A filter

S_{sc}/P	-	20	25	30	35	40	45	50
δ_u	%	**2.0**	**1.8**	**1.7**	**1.6**	**1.5**	**1.4**	**1.3**
δ_i	%	**7.8**	**9.0**	**9.7**	**10.8**	**11.5**	**12.2**	**12.8**

The following coefficients of the reactive power allocation, proportional to harmonic content, were chosen, according to Ref. [11], for the Type B filter

$$a_5 = 0.39,\quad a_7 = 0.28,\quad a_{11} = 0.18,\quad a_{13} = 0.15.$$

Table 3. Bus voltage and supply current THD with Type B filter

S_{sc}/P	-	20	25	30	35	40	45	50
δ_u	%	**1.3**	**1.2**	**1.2**	**1.1**	**1.1**	**1.0**	**1.0**
δ_i	%	**5.0**	**6.0**	**6.8**	**7.5**	**8.2**	**8.9**	**9.5**

The filter efficiency, ε_u and ε_i, in reducing the bus voltage and the supply current distortion, calculated according to formulae (3) and (5) for the data compiled in Tables 2 and 3, are tabulated in Table 4. Since this is efficiency of filters in the lack of other harmonics than the 5th, 7th, 11th and 13th order, therefore, this efficiency could be considered as an upper limit of the efficiency of the analyzed filters.

Table 4. Upper limit of efficiency of Type A and B filters

Filter	S_{sc}/P	20	25	30	35	40	45
A	ε_u	**0.76**	**0.74**	**0.71**	**0.69**	**0.67**	**0.66**
	ε_i	**0.61**	**0.55**	**0.52**	**0.48**	**0.45**	**0.42**
B	ε_u	**0.85**	**0.83**	**0.80**	**0.78**	**0.76**	**0.74**
	ε_i	**0.75**	**0.70**	**0.67**	**0.64**	**0.61**	**0.57**

The results compiled in this table show that the filter efficiency declines by a few percent with the short circuit power increase. Moreover, the Type B filters are more efficient than the Type A filters. Also, the filters are more efficient in suppressing the bus voltage harmonics than the supply current harmonics.

V. EFFECT OF NON-CHARACTERISTIC CURRENT HARMONICS AND DISTRIBUTION VOLTAGE DISTORTION

The load current harmonics other than those to which the filter is tuned, i.e., non-characteristic harmonics, are attenuated or amplified depending on the frequency of the filter resonances with the distribution system.

Their rough effect on the filter efficiency, without going into detail with respect to harmonic spectrum, can be obtained assuming that non-characteristic harmonics form a uniformly distributed harmonic noise, i.e., they have the same rms value. To calculate this effect more accurately, information on a true spectrum of non-characteristic harmonics is needed, but this changes from case to case.

The filters' efficiency, assuming that non-characteristic current harmonics in the range from the 2nd to the 12th order have the same rms value and their total rms value is of 1% of the fundamental harmonic, i.e., each of them amounts to J_n = 0.35% of I_1, is shown in Table 5.

Table 5. Efficiency of Type A and Type B filters at 1% of distortion by non-characteristic current harmonics

Filter	S_{sc}/P	20	25	30	35	40	45
A	ε_u	**0.75**	**0.72**	**0.69**	**0.63**	**0.64**	**0.61**
	ε_i	**0.56**	**0.54**	**0.49**	**0.39**	**0.42**	**0.39**
B	ε_u	**0.57**	**0.65**	**0.71**	**0.67**	**0.73**	**0.73**
	ε_i	**0.51**	**0.53**	**0.61**	**0.61**	**0.59**	**0.56**

The results compiled in Table 5 show that the load current distortion by non-characteristic harmonics of only 1% causes a substantial reduction of the filter efficiency.

To compare the reduction of the filter efficiency by the distribution voltage harmonics with this reduction by non-characteristic current harmonics, it was assumed that the THD of the distribution voltage amounts to 1%. Moreover, it was assumed that the distribution voltage harmonics decline as $1/n$ and, according to IEEE 519 Standard, the even order harmonics contribute only to 25% to the voltage distortion. Thus, they have the values shown in Table 6. The filter efficiency is shown in Table 7.

Table 6. Distribution voltage harmonics at THD δ_e = 1%

Odd:	E_3	E_5	E_7	E_9	E_{11}	E_{13}
%	**0.72**	**0.44**	**0.31**	**0.24**	**0.20**	**0.17**
Even:	E_2	E_4	E_6	E_8	E_{10}	E_{12}
%	**0.20**	**0.13**	**0.07**	**0.05**	**0.04**	**0.03**

Table 7. Efficiency of Type A and Type B filters at 1% of distribution voltage distortion

Filter	S_{sc}/P	20	25	30	35	40	45
A	ε_u	**0.70**	**0.70**	**0.66**	**0.57**	**0.56**	**0.39**
	ε_i	**0.50**	**0.51**	**0.46**	**0.36**	**0.36**	**0.21**
B	ε_u	**0.46**	**0.67**	**0.69**	**0.69**	**0.67**	**0.63**
	ε_i	**0.38**	**0.53**	**0.59**	**0.58**	**0.56**	**0.53**

The results tabulated above show how the distribution voltage harmonics, of an almost negligible value, can substantially degrade the efficiency of resonant harmonic filters. Their harmful effect is much stronger than the effect of non-characteristic current harmonics.

The measures of the filter efficiency, defined by formulae (3) and (5), in the presence of both load current non-characteristic harmonics and distribution voltage harmonics are no longer unique. It is for the following reason. The distorting component of the supply current is composed of two components

$$i_{\mathrm{d}} = i_{\mathrm{d}}(e) + i_{\mathrm{d}}(j) \tag{11}$$

where $i_{\mathrm{d}}(e)$ denotes the distorting component caused by distribution voltage harmonics and $i_{\mathrm{d}}(j)$ denotes the distorting component caused by the load generated current harmonics. Harmonics of the same order of these two components, depending on their phase, may add up or subtract. In general, they may have any value between their sum and their difference. If the phases of harmonics of e and j are random and mutually independent and we are not looking for the worst case scenario, than statistically the most probable rms value of the distorting current can be calculated as

$$||i_{\mathrm{d}}|| = \sqrt{||i_{\mathrm{d}}(e)||^2 + ||i_{\mathrm{d}}(j)||^2} \tag{12}$$

The same applies to the distorting component of the bus voltage, i.e.,

$$||u_{\mathrm{d}}|| = \sqrt{||u_{\mathrm{d}}(e)||^2 + ||u_{\mathrm{d}}(j)||^2} \tag{13}$$

where $u_{\mathrm{d}}(e)$ denotes the voltage distorting component caused by distribution voltage harmonics and $u_{\mathrm{d}}(j)$ denotes the distorting component caused by the load generated current harmonics. However, when a worst case scenario is a matter of concern, the rms values of distorting components should be added arithmetically.

Assuming that the THD of the supply current and the load voltage are calculated according to (12) and (13), the filter efficiency in the conditions specified in Sections V and VI are compiled in Table 8.

Table 8. Efficiency of Type A and B filters at 1 % of distribution voltage THD and 1 % of current distortion by non-characteristic harmonics

Filter	S_{sc}/P	20	25	30	35	40	45
A	ε_u	**0.69**	**0.68**	**0.64**	**0.53**	**0.53**	**0.37**
	ε_i	**0.46**	**0.50**	**0.44**	**0.29**	**0.34**	**0.19**
B	ε_u	**0.33**	**0.55**	**0.63**	**0.65**	**0.64**	**0.63**
	ε_i	**0.25**	**0.41**	**0.54**	**0.56**	**0.54**	**0.52**

The comparison of the filter efficiency compiled in Table 4 with this efficiency in the presence relatively low distortion of the distribution voltage and the presence of non-characteristic harmonics in the load current, compiled above, show how strongly these harmonics degrade the filter performance. This efficiency declines drastically with the increase of the distribution voltage distortion. Tables 9 and 10 show this efficiency for the distribution voltage THD 2.5% and 4%, respectively.

Table 9. Efficiency of Type A and B filters at 2.5 % of distribution voltage THD and 1 % of current distortion by non-characteristic harmonics

Filter	S_{sc}/P	20	25	30	35	40	45
A	ε_u	**0.46**	**0.51**	**0.37**	**0.16**	**0.16**	**-0.32**
	ε_i	**0.11**	**0.33**	**0.23**	**-0.10**	**0.02**	**-0.47**
B	ε_u	**-0.26**	**0.20**	**0.36**	**0.37**	**0.33**	**0.32**
	ε_i	**-0.50**	**-0.03**	**0.29**	**0.36**	**0.36**	**0.34**

Table 10. Efficiency of Type A and B filters at 4 % of distribution voltage THD and 1 % of current distortion by non-characteristic harmonics

Filter	S_{sc}/P	20	25	30	35	40	45
A	ε_u	**0.21**	**0.28**	**0.15**	**-0.24**	**-0.27**	**-1.07**
	ε_i	**-0.30**	**0.09**	**-0.05**	**-0.56**	**-0.39**	**-1.23**
B	ε_u	**-1.08**	**-0.19**	**0.03**	**0.08**	**0**	**-0.05**
	ε_i	**-1.31**	**-0.53**	**-0.01**	**0.10**	**0.12**	**0.11**

At 4% and in some cases at 2.5% of the distribution voltage THD, the filter efficiency declines to such a degree that the filter is almost not capable of reducing the bus voltage and the supply current distortion or even, when ε_u or ε_i becomes negative, the filter increases harmonic distortion. Thus, installation of such a filter might be useless or even harmful with respect to the waveform distortion.

VI. OPTIMIZATION OF FILTER EFFICIENCY

The filter efficiency might be improved if the fixed rules with respect to the reactive power allocation, i.e., selection of allocation coefficients, a_k, to the filter branches and their tuning frequencies, ω_k, are abandoned for a selection of these parameters that minimizes the voltage and current distortion.

However, a difficulty occurs when using such an approach. The set of a_k, and z_k, parameters that minimizes the THD of the supply current is different from the set of these parameters that minimizes the THD of the bus voltage. Only one of them could be minimized at the cost of another. Another option is to minimize a *weighted* THD, defined for a four-branch filter that should suppress the 5^{th}, 7^{th}, 11^{th} and 13^{th} order harmonics as

$$\delta = W_i\ \delta_i + W_u\ \delta_u = f(a_5,\ldots a_{13}, z_5,\ldots z_{13}) \qquad (14)$$

where W_i is the weighting factor of the supply current THD and W_u is the weighting factor of the bus voltage THD. It is up to the filter designer to decide which distortion is more crucial, the bus voltage distortion or the supply current distortion. If the HGL is the only high power load supplied from the bus, then the reduction of harmonics injected by such a load is the primary objective of the filter. However, when voltage quality sensitive loads are supplied from the same bus then, keeping a low THD of the bus voltage might be more crucial.

A filter with a set of parameters a_k, and z_k, and consequently, C_k,and L_k, that minimizes the weighted THD is referred to as an optimized filter. Such a filter is optimized, of course, for fixed parameters of the load and the supply source and fixed spectra of distribution voltage and the load current as well as for fixed weighted factors.

The filter efficiency of an optimized filter is calculated for its comparison with the efficiency of the Type A and Type B filters. It is assumed that the supply current contains 1 % of harmonics other than the 5^{th}, 7^{th}, 11^{th} and 13^{th} order and 2.5 % of distribution voltage harmonics. The results for an optimized filters are compiled in Table 11. Comparison of these results with those compiled in Table 9 for Type A and Type B filters installed in similar situations, shows that the filter optimization enables a substantial improvement of the filter efficiency.

Table 11. Optimized filter efficiency for 2.5% of distribution voltage THD and 1% of non-characteristic current harmonics

S_{sc}/P	-	20	25	30	35	40	45
ε_u	%	**0.67**	**0.62**	**0.58**	**0.53**	**0.49**	**0.44**
ε_i	%	**0.57**	**0.54**	**0.52**	**0.48**	**0.44**	**0.39**

Details of the optimization procedure applied for this study are not discussed here because there is a great variety of optimization procedures and the authors of this paper are not sufficiently experienced in this area to suggest that the method we applied should be recommended. Optimization procedures usually result in a number of local minima and there is no proof that a lowest local minimum is a global minimum. A better solution can be found. Nonetheless, even if better parameters of the filter might be found using another optimization procedure, the filters obtained in this study have much higher efficiency than the Type A and Type B filters.

The filter efficiency compiled in Table 11 was calculated with the assumptions, as discussed in Section V, that non-characteristic harmonics of the load current have the same value and the distribution voltage harmonics decline as $1/n$. While the first assumption is justified in the case when non-characteristic harmonics occur because of rectifier or ac/dc six-pulse converter asymmetry, the second assumption is more artificial. However, there is no general rule with respect to harmonic spectrum of the distribution voltage, valid in all field situations. Therefore, a specific spectrum was selected to compare efficiency of filters designed using different methods. Numerical results will be different for a different spectrum and filter detuning.

The values of the reactive power allocation coefficients, a_k, and tuning frequencies, z_k, found in optimization procedure for conditions specified previously, are compiled in Table 12.

Table 12. Allocation coefficients and tuning frequencies for an optimized filter (2.5% of distribution voltage THD and 1% of non-characteristic current harmonics)

S_{sc}/P	20	25	30	35	40	45
a_5	**0.09**	**0.11**	**0.11**	**0.12**	**0.15**	**0.09**
a_7	**0.11**	**0.30**	**0.61**	**0.55**	**0.73**	**0.69**
a_{11}	**0.60**	**0.46**	**0.21**	**0.14**	**0.08**	**0.10**
a_{13}	**0.20**	**0.14**	**0.07**	**0.20**	**0.04**	**0.13**
z_5/ω_1	**5.0**	**4.99**	**4.99**	**4.99**	**4.99**	**4.99**
z_7/ω_1	**6.99**	**7.00**	**7.02**	**6.95**	**6.88**	**6.86**
z_{11}/ω_1	**11.3**	**10.8**	**10.9**	**10.9**	**11.0**	**11.0**
z_{13}/ω_1	**13.00**	**13.0**	**13.0**	**12.7**	**13.0**	**13.0**

The values of design parameters, i.e., a_k, and z_k, compiled in Table 12 for the optimized filter show that there is no general rule with respect to their selection. They strongly depend on the short circuit power of the bus where the filter is to be installed. It is easy to predict that they also depend on the voltage and current harmonic spectra.

Unfortunately, a strong dependence of the filter efficiency on the distribution voltage harmonics is also visible even when a filter is optimized. This is illustrated with the filter efficiency compiled in Table 13, of optimized filters operating at 4% the distribution voltage THD. As it is shown in Table 11 and 13, this efficiency declines with an increase of the short circuit power of the bus.

Table 13. Optimized filter efficiency for 4 % of distribution voltage THD and 1% of non-characteristic current harmonics

S_{sc}/P	-	20	25	30	35	40	45
ε_u	%	**0.46**	**0.39**	**0.34**	**0.25**	**0.18**	**0.10**
ε_i	%	**0.32**	**0.30**	**0.25**	**0.20**	**0.16**	**0.10**

VII. CONCLUSIONS

The results of this study show that when a filter is designed according to traditional methods, as are the Type A or Type B filter, then there is a substantial margin for improving its efficiency. Recommended practices with respect to the reactive power allocation and detuning do not provide reliable grounds for the design of effective filters.

At low distortion, on the level of approximately 1%, the filer effectiveness is more degraded by distribution voltage harmonics than by non-characteristic current harmonics. There is no clear regularity as to the effect of the short circuit power on the filter effectiveness and which type of filter, A or B, is more preferable. This irregularity increases with the voltage distortion. Moreover, this effectiveness approaches zero or can be even negative, i.e., the filter can increase the harmonic distortion. It may happen even if the voltage distortion is within limits recommended by Standard 519.

It is rather unlikely, though possible, that the filter efficiency could be elevated to an upper limit by a 'cut and trial' method. Optimization methods are much more appropriate. However, the Reader should be aware that even an optimized filter, after it is built and installed, does not operate with a maximum efficiency. This is because of the tolerance of filter's elements and change of their parameters with temperature and time. Also, the distribution and the load parameters as well as voltage and current harmonic spectra are known with limited accuracy and they change with time.

The efficiency obtained from the optimization procedure is only the upper limit that can be achieved for the assumed values of the distribution voltage and load current harmonics. The question of how a change in the system parameters and limited accuracy of the filter LC parameters degrade the filter efficiency cannot be answered without a separate study. However, this question also applies to filters that are not opimized.

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