PERFORMANCE OF PASSIVE FILTERS

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***Abstract* – A study was proposed to evaluate how passive filters behave with respect to the variation of the harmonic content of the current in a low-voltage system. A model in that the non-linear load is a SCR rectifying bridge, feeding a variable load DC motor, was developed and simulated. An approach was developed for the filters design which correlates the 60 Hz reactive power of each filter with the percent contribution of the harmonics (which should be mitigated), and satisfactory results were obtained.**

KEYWORDS

Harmonics – Passive Filters – Power Quality – Matlab.

I. INTRODUCTION

There is at the present time a great concern about the harmonic content in the electric networks, since the number of non-linear loads is significant, either for home, commercial or industry consumers. These non-linear, or harmonic generating loads, cause a series of problems, for both the energy suppliers and the consumers, which can be categorized into instantaneous effects [1] and long term effects caused by the heating.

Given the gravity of the problem, an increasing effort has been made by the authorities in order to regulate the emission levels, for both the equipments and the systems.

This work is concentrated on the study of a method to reduce the harmonic content in an low-voltage industrial system, more specifically, a circuit that feeds a variable load DC motor through a SCR bridge, as depicted on figure 1.1. The circuit was created as a model, but it is important to emphasize that care has been taken to choose values coherent with reality.

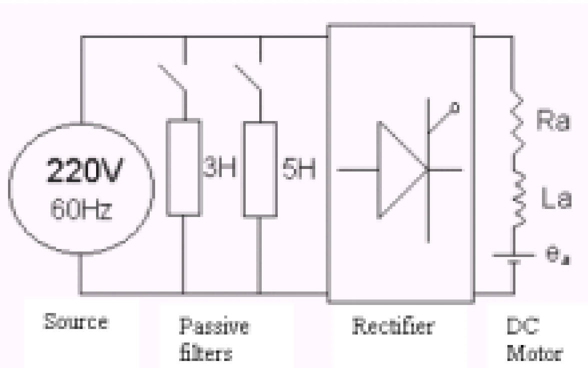

FIGURE 1.1 – The model analyzed

This is a single phase system with a full-wave bridge rectifier. The line impedance is considered.

There are two main reasons that justify the choice of the model:

1. It is an extremely common situation in industries, presenting high indexes of THD;
2. The system presents a variation of THD in the network, according to the variation of the motor load.

The objective of this study is to analyze, through computer simulations, how big this variation of THD is and how tuned passive filters behave in these conditions, verifying their range of operation, effectiveness, i.e, their applicability to the situation in debate. The advantage of reducing the THD of a system through tuned passive filters is that this technique is much cheaper and easy to implement, if compared to active filters, usually are recommended when there is variation of the harmonic content of the network.

II. GETTING THE HARMONIC SPECTRUM OF THE SYSTEM

Two software packages, Matlab and PSpice, were used to simulate the system. We can split the simulations into two different phases: the first one, when the system is modeled through equations and solved [2] through the software Matlab, obtaining its harmonic content for the different operational conditions; and a second one, using a circuit simulation software package (PSpice), to analyze the behavior of the circuit when applying passive filters.

Matlab is an integrated software environment for systems and algorithms modeling, being considered a leading product in the area of numeric and scientific computing. This program has its own programming language, however easily learned by people with programming knowledge on another languages, like C, Fortran, etc. The greatest advantage of this high level language is its easy matrix manipulation, also having a large mathematics methods and function library. Two of these functions have been extensively used in this work: the function ode45 (ordinary differential equations), for solving differential equations and the fft, for obtaining the harmonic spectrum of the current on the source.

In a first moment, the variation of the firing angle (alpha) of four SCRs which compose the bridge was set between 0° and 80°, in steps of 10°. In the sequence, the system equations were modeled according to its operating states and solved for the different conditions.

Variation of THD and main harmonics as a function of alpha is represented on figure 2.1.

Analyzing the graphic, it can be easily observed a gradual and proportional decay of the main harmonics, as well as the THD, when the firing angle of SCRs is increased, not having variation of harmonic(s) if compared to the other ones. Therefore, the worst case, or the critical case, is when the firing angle of the SCRs is zero.

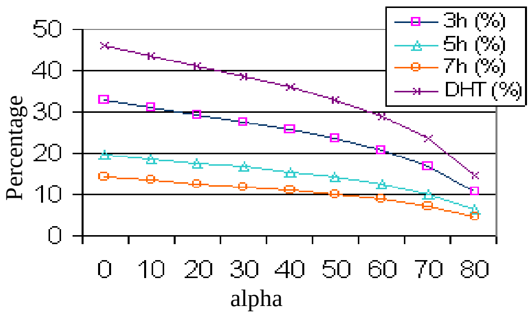

FIGURE 2.1 - Variation of THD and main harmonics as a function of alpha

We should remember that a SCR bridge with a small firing angle is equivalent to a diode rectifying bridge. Based on this simplification, we decided to use the Pspice software program to simulate the circuit with one, two and three harmonic filters.

Another important information obtained through the initial simulations refers to the variation of the reactive power of the system.

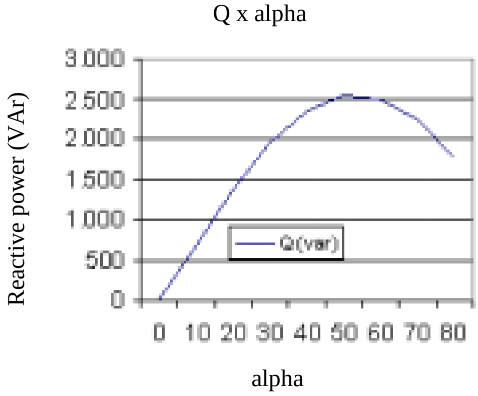

FIGURE 2.2 – Variation of the reactive power of the system as a function of alpha

III. PROJECT AND SIMULATION OF PASSIVE TUNED FILTERS

We use filters to limit harmonic current and/or voltage in the network to a specific value. There are many available filter topologies, and its choice depends on the network characteristics and its non-linear loads. Other factors should be taken into account, specially economic ones, involving initial investment costs, equipment maintenance and possible capital losses, e.g. equipment damage resulted of inadequate project, specially if caused due to parallel resonance. We should emphasize the uniqueness of each case and that there are no fixed rules applied filter projects, and the limits and potentials of the system under analysis are decisive factors that, if well considered, will optimize the design of the filter or even to lead alternative solution, eliminating it [3].

Tuned filters are series resonating circuits that, on the tuning or resonating frequency, present low impedance (in practice equal to the resistance of the circuit). For frequencies below the tuned frequency their behavior is capacitive and for frequencies above, inductive. Therefore, for the fundamental frequency, these filters act as reactive compensators.

The process for determining the tuning of a passive filter is based on the concept of series resonance, a condition that a circuit consisting of at least one capacitor and one inductor will present a purely resistive input impedance. In this case X_L will be equal X_C.

Knowing that X_L=wL and X_C=1/wC, we get the resonance condition:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (3.1)$$

where f_r is the resonance frequency (harmonic frequency to be attenuated). From (3.1):

$$L = \frac{1}{4\pi^2 f_r^2 C} \qquad (3.2)$$

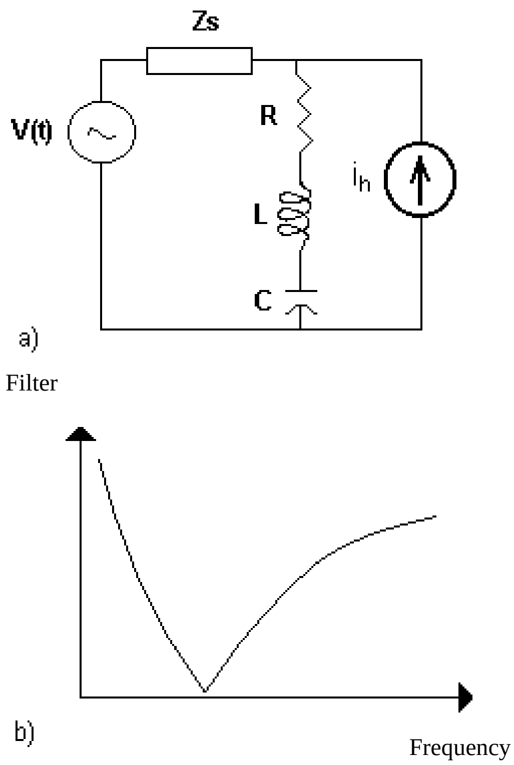

FIGURE 3.1 - (a) RLC serial filter; (b) RLC serial filter Z_Xf curve.

The value of the capacitor is calculated as a function of the desired reactive power:

$$C = \frac{Q_C}{wV^2} \qquad (3.3)$$

We can design the tuned filters from f_r and equations (3.2) e (3.3).

There is many works in literature on the design of tuned passive filters [1, 3, 4, 5], each one adequate to a specific application, or emphasizing specific system, filter or component properties. This work is unique due to the characteristic of the system and a specific methodology will be conceived for the filter design.

The priorities of this project should be emphasized: a) reduce the THD to a minimum and, if possible, be compliant with IEEE 519-1992 recommendation [6] – adopted as a reference; and b) improve to a maximum displacement factor, trying to keep it in the range between 0,92 capacitive e 0,92 inductive.

Based on data obtained on item 2, it was noticed that the current harmonics decrease in relation to the fundamental almost linearly with the increase of the firing angle of the SCRs, The minimum angle, i.e. zero, has the greatest percent harmonic content. Reducing the harmonics for this situation will solve the problem also for all other ones.

Analyzing the problem from the priority point of view b), the filter capacitors bank may be used to compensate the reactive components of the system, since the filter, for frequencies below the tuning frequency, has capacitive behavior.

In this circumstance, the maxim reactive power that can be used by the filters is the one that presents a displacement factor of 0,92 capacitive, for a firing angle of zero. On the other side, the situation that the system has a greater reactive power is for an alpha angle of 50°, with Q=2539,74VAr.

We should find a point with a reduction of the system harmonic distortion associated with the greatest reactive compensation.

The bases for dimensioning the passive filters are the equations 3.2 e 3.3, deduced on 3.1. A nominal voltage of $220V_{rms}$ is assumed for the capacitor in order to simplify the calculation. It's important to mention that the capacitor voltage will be greater than the network voltage, and it should be taken into account for dimensioning. Reference [3] states that a capacitor with a permanent 5% overvoltage has its life reduced to 69,5%.

Using the trial and error method – aiming a value of 0,92 as a maximum of 0.92 for the capacitive displacement factor –, it was found for Qc the value of 1950VAr, used to calculate the filter capacitance and inductance. The results are shown on Table 3.1, with C = 106,87uF and L = 7,3154mH. For this capacitive reactance, for comparative purposes, a 5th harmonic filter, with L = 2,634mH, was designed.

Based on the collected data the displacement factor condition was fulfilled, but the percent of the THD and the harmonic components surpasses the recommendations:

- Limit for individual components lower than the 11th harmonic = 4%;
- THD limit = 5%.

TABLE 3.1
Results obtained for the 3rd and 5th harmonic filters

	Ief (A)	3h (%)	5h (%)	7h (%)	DHT (%)	Fd
No filter	18,96	31,0	18,11	12,48	40,78	0,976i
3h filter	23,68	4,22	14,66	10,36	22,15	0,913c
5h filter	23,25	34,31	1,77	7,85	36,85	0,927c

The limits established by the recommendations refer to the measured at the connection with the distribution system, not at an independent equipment. Nevertheless it was not the case of the analysis, it was used as a reference parameter. The limits recommended by the IEEE differ, given the voltage level an the short-circuit level of the connection with the distribution system. In this study, a rate lower than 20 was adopted between the short-circuit current and the load current.

The equivalent reactive power for 3rd and 5th harmonic passive filters should be equal to the maximum power define on the previous item, therefore the sum of the generated reactive power should be equal to the defined power.

As an initial criteria, the capacitive reactive power of each filter will be made proportional to the percent contribution of the harmonic current to be reduced by the filter. If all the THD would be generated by these two components only, from table 6.2 we have that the 3rd harmonic would contribute with 63% an the 5th with 37%. Calculating the values we get Q_{3h}=1228.5VAr and Q_{5h}=721.5VAr.

From these values:

- C_3 = 67,328 μF; L_3 = 11,612 mH
- C_5 = 39,542 μF; L_5 = 7,118 mH

TABLE 3.2
Results obtained for 3rd e 5th harmonic filters.

	Ief (A)	3h (%)	5h (%)	7h (%)	DHT (%)	Fd
No filter	18,96	31,0	18,11	12,48	40,78	0,976i
3h, 5h filter	23,93	4,709	3,441	9,245	15,99	0,916c
test1	23,90	4,942	3,598	9,385	16,22	0,917c
test2	23,86	5,607	2,743	8,889	15,67	0,919c

As to 3rd harmonic it is a little above the recommendation and for 5th a little below, a test was made (test1 in Table 3.2) increasing a little the reactive power of the filter of 3rd harmonic filter, with a proportional decrease of the reactive power of the 5th harmonic filter, but it was verified that both the individual harmonic components and the THD of the system presented a small increase. Another accomplished test (test2 in Table 3.2), with the identical capacitive reactive power for the two filters, shows that the proportion of 3^{rd} harmonica increases and the other components decrease, with the THD being kept constant. This result is not satisfactory since the mitigation priority will always be for the harmonicas of inferior order.

The values obtained by the initial criteria are considered optimum and therefore valid. Since the values of the 3^{rd} and 7^{th} harmonicas besides THD are above the adopted reference, an additional 7^{th} harmonic filter will be added.

Using the same approach described on the previous item, we noticed that the 3^{rd} harmonic has a 50,33% percent contribution to the current distortion, the 5^{th} has 29,4% and the 7^{th} has 20,26%, not forgetting to mention that the total capacitive reactive power should be 1950VAr.

From these values we obtain:

- Q_{3h}=981,435VAr, Q_{5h}=573,378Var and Q_{7h}=395,07;
- C_3=53,788uF, C_5=31,424uF and C_7=21,652uF;
- L_3=14,535mH, L_5=8,956mH and L_7=6,632mH.

Table 3.3 shows that the 3^{rd} harmonic and the THD are still out of the defined range, but there was a significant reduction in the harmonic components and the current THD. According to the predefined criteria, the values are considered optimum.

TABLE 3.3
Results obtained for the 3 rd, 5 th and 7 th harmonic filter.

	Ief (A)	3h (%)	5h (%)	7h (%)	DHT (%)	Fd
No filter	18,96	31,0	18,11	12,48	40,78	0,976i
3h, 5h and 7h filter	24,1	5,556	3,62	3,446	13,04	0,918c

IV. CONCLUSION

The first result in this work was the observation that the content of the main harmonics, as well as the THD, gradually decay with the increase of the firing angle of the SCRs, being the behavior practically linear (see Figure 2.1).

Another aspect to be mentioned is that, since the chosen system was the only load of a feeder in a low voltage supply, that harmonic components were quite significant in comparison to the total source current (odd harmonics till the 15^{th} present percent value greater than 4% of the fundamental); therefore it is not a surprise that the THD was 40,7%. Considering this characteristic, one could not expect that only passive filters would be enough to make the system comply to the recommendations. However the results obtained with the filters designed in the item 3 were quite satisfactory, since the main harmonic components practically comply to the norm and the THD remained at 13%

The methodology to reduce the harmonics applied to the filter design was efficient and satisfactory. It also presented the dependence of the percent relation of the harmonics among themselves and the proportionality of the capacitive reactive power of the tuned filters. For the system presented in this article, the passive filter design criteria was valid, not being enough however to conclude that it is universally valid, or even valid for another system under different conditions. Therefore, a proposal for future studies would be a deeper analysis of the observed relations.

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