Harmonic Distortion in a Low Voltage Electrical System: Passive Filtering

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***Abstract* - This paper presents the study of the three-phase electrical system of a building with the same characteristics as a commercial one. The characterization of loads, voltage and current harmonic content are done. A procedure for harmonic distortion correction is presented through passive filtering. The results of on-site measurements and results obtained through numeric simulation for the proposed filters are provided in this paper.**

I. INTRODUCTION

Electricity is indispensable in our lives, for domestic use or trade activities: lighting, heating, and so on.

At low AC voltage electric facilities, in general, prevailed linear loads, that is, those constituted essentially by resistance, inductance and capacitance of fixed values; in other words, loads with a constant impedance. As examples of these kinds of loads, one can find induction motors, incandescent illumination and heating equipment.

The nonlinear loads, in which the current is not proportional to the voltage, represented a small percentage of the total of the usual loads and had little influence on the project and operation of the facilities.

However, in recent years, with the incorporation of electronics in electric equipment, certain problems with power quality in the facilities began to appear. With the growing use of microcomputers, UPS, variable speed drives, light dimmers, and other types of nonlinear loads, the problem of harmonic distortion has been worsening. These loads, while polluting the electrical system, are, at the same time, very sensitive to the effect caused by this distortion.

In order to overcome these problems, the study of power quality becomes more and more necessary. Some of the adverse effects of concentrated nonlinear loads upon a facility are:

- voltage distortion within the facilities;
- excessive neutral return currents;
- High level of neutral-to-ground voltage;
- overheated transformers;
- large magnetic fields emanating from transformers;
- decreased distribution capacity;
- power factor rate penalties.

The waveform not purely sinusoidal can be expressed by means of a series of sinusoidal components. These components are called harmonics:

$$v(t) = Vm_1 cos(\omega t + \Phi_{v1}) + Vm_2 cos(2\omega t + \Phi_{v2}) + \\ + Vm_3 cos(3\omega t + \Phi_{v3}) + \ldots + Vm_h cos(h\omega t + \Phi_{vh}) \quad (1)$$

$$i(t) = Im1 cos(\omega t + \Phi i1) + Im2 cos(2\omega t + \Phi i2) + \\ + Im3 cos(3\omega t + \Phi i3) + \ldots + Imh cos(h\omega t + \Phi ih) \quad (2)$$

Generally, the even order harmonics are null, because the devices work in a symmetrical and periodical way. The higher-order harmonics are small due to the attenuation imposed by the presence of system inductance.

In low voltage systems three techniques of attenuation of the harmonic distortion stand out:

1) Passive Filtering: it consists of creating a low impedance path to the harmonics by using several sections of tuned filters, usually in RLC series configuration, connected to the secondary side of the main transformer, at the PCC (Point of Common Connection);

2) Active filtering: It may be performed by static converters that "generate" appropriate harmonic components, producing the "cancellation" of the harmonic distortion seen at the PCC;

3) Special transformer configuration [5]: Harmonics are canceled by using some special connections or configurations in the transformers.

II. ON-SITE MEASUREMENTS

The electrical system of two laboratory buildings at the Federal University of Santa Catarina was chosen for the present study. Most of the loads were single-phase connected (discharge illumination, microcomputers, printers and air-conditioning equipment). In this case, microcomputer power supplies (single-phase rectifiers with a capacitive output filter) was the main source of harmonics.

The measurements were made at the PCC with a digital scope and the data were analyzed by dedicated software. Measurement was done at nominal load conditions - the worst situation of facility operation. In Fig. 1 the facility one-phase simplified diagram is shown.

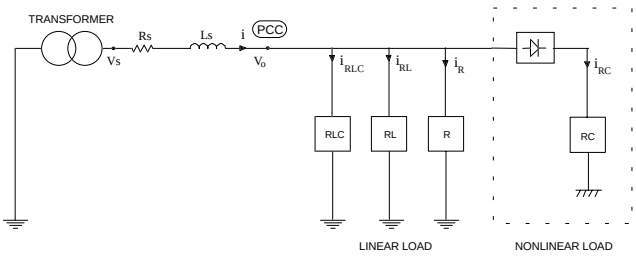

Fig. 1: Facility one-phase simplified diagram.

In Fig. 2 one can notice that the current waveform in phase A is strongly distorted due to the presence of a nonlinear load. The flattening at the peak of the voltage waveform is due to the current drained by power supplies.

With the analysis accomplished through the WaveStar software (Fig. 3) it was obtained the values of THD=2.37% (THD - Total Harmonic Distortion) for the input voltage and THD=11.24% for the input current were obtained. They are very close to the maximum values admitted for this system (12%) in agreement with the IEEE 519-1992 Recommended Practices.

One can see in Fig. 3 the strong presence of the characteristic single-phase rectifier harmonics (3rd, 5th and 7th).

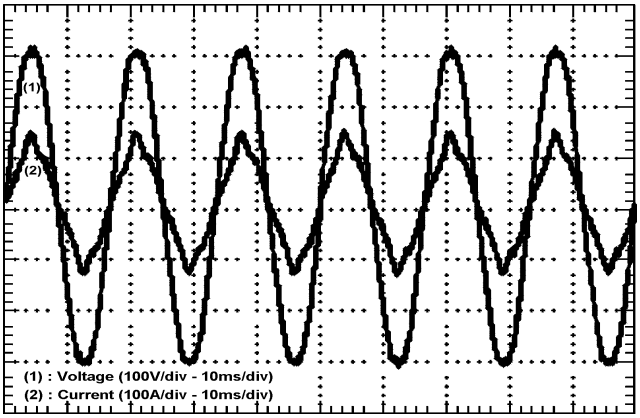

Fig. 2: Input voltage and current – phase A

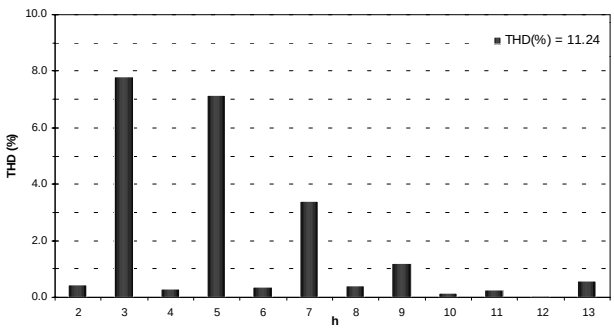

Fig. 3: Harmonic components for input current phase A

In Fig. 4, it is possible to observe higher amplitude of the input current, compared with the current in phase A shown in Fig. 2. The system presents a visible load imbalance, with voltage THD=3.24% and current THD=17.89%. It can be seen that the THD and the individual content of the 3rd harmonic are greater than the limits specified by the norm. It can be observed in Fig. 5 that the 3rd harmonic component is very high (15.2%).

The current in phase C (Fig. 6) has the same magnitude as the phase B current (Fig. 4). In fact, current imbalance is related to the current of phase A (Fig. 2). For phase C one can find voltage THD=3.22% and current THD=11.31%. These values are in agreement with IEEE 519-1992 Recommended Practices (Fig. 7).

Due to the load imbalance a high and strongly distorted neutral current appears (47.2 A rms) as shown in Fig. 8. It is important to remember that there is no cancellation of triplens harmonics in the neutral conductor [3].

Even with a high current distortion in the three phases, the power factor (PF) is high in the three phases of the system (PF_A=0.985, PF_B=0.971 and PF_C=0.984). In fact, the current and voltage are almost in phase and, as a consequence, displacement power factor is almost unity.

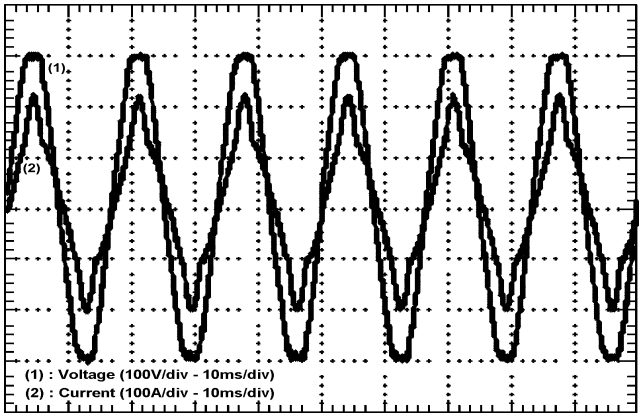

Fig. 4: Input voltage and current – phase B

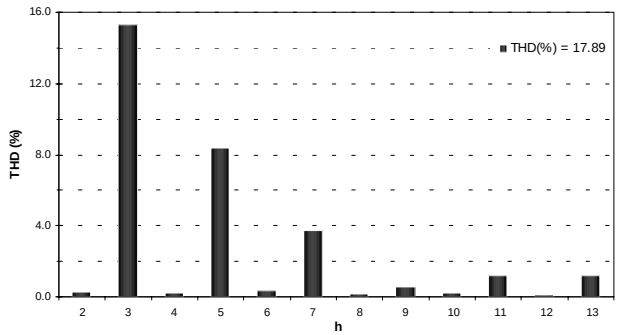

Fig. 5: Harmonic components for input current phase B

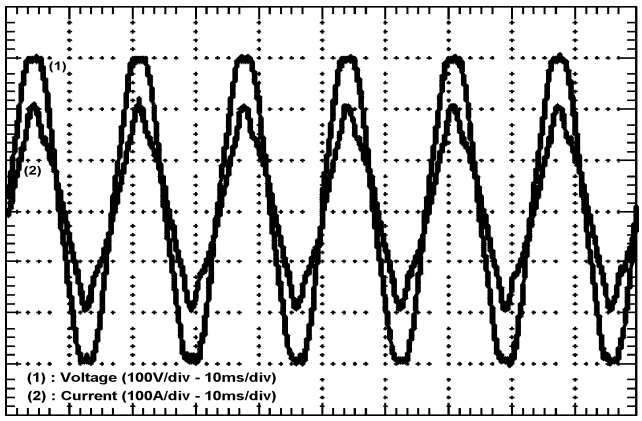

Fig. 6: Input voltage and current – phase C

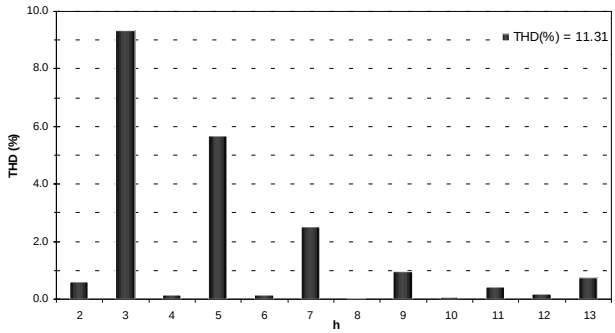

Fig. 7: Harmonic components for input current - phase C

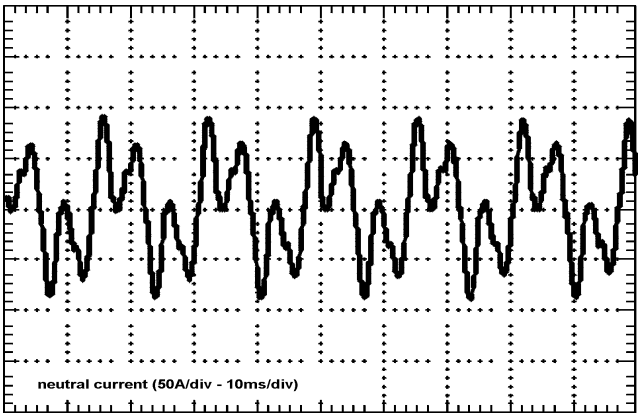

Fig. 8: neutral current of the electric installation

III. Proposal of a Method for Harmonic Distortion Correction

Some numeric simulation (PSPICE) was done and the simulated behavior of the plant had matched on-site measurements indicating that the employed model represents the facility very well. The main difficulty is to represent the nonlinear loads in order to arrive at the same harmonic content observed in on-site measurements. For this reason, current sources were employed in the plant model.

Based on simulation results, a proposal for current harmonic distortion correction was developed with the objective of complying with IEEE 519-1992 Recommended Practices. Through the data obtained from the practical measurements and the plate data of the distribution transformer, one can determine the value of the relationship $I_{SC}/I_{L.}$ This is done to verify the limits specified by the norm for THD current and also the individual limits for the current harmonic components, as shown in Table 1.

Tab. 1: Limit of current harmonic distortion for low voltage systems (120V à 69kV rms) given by IEEE 519-1992 Recommended Practices.

Maxim Harmonic Distortion of the current in percent of the I_L				
h: Order of the odd harmonics				
I_{sc}/I_L	**<11**	**11≤h<17**	**17≤h<35**	**THD**
<20*	4.0	2.0	1.5	5.0
20<50	7.0	3.5	2.5	8.0
50<100	10.0	4.5	4.0	12.0
100<1000	12.0	5.5	5.0	15.0
>1000	15.0	7.0	6.0	20.0
The even harmonic are limited to 25% of the limit of the immediately superior odd harmonic				

Where:
I_{SC}: Current of short circuit at the PCC;
I_L: Maximum load current at fundamental frequency, at the PCC.

For this case, the relationship I_{SC}/I_L results in: phase A ≅ 85, phase B ≅ 59 and phase C ≅ 57. Therefore the limits specified by the norm are those highlighted in Table 1.

Passive filtering is proposed for harmonic distortion correction. The one-phase diagram of the whole system, including the passive filter, is presented in Fig. 9.

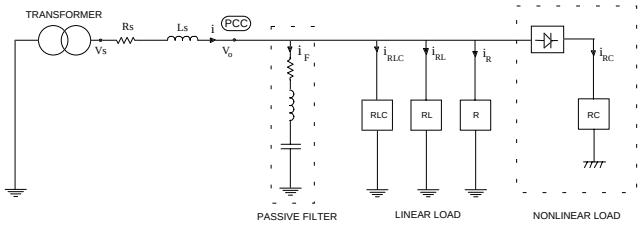

Fig. 9: One-phase diagram of the whole system, including the passive filter

In the present work the configuration RLC was used for the tuned in filter, and procedure of design is presented in reference [1].

$$R_h = \frac{K_h I_1}{i_h^2 - K_h^2 I_1^2}\left[R_S K_h I_1 \pm \sqrt{\left[(R_S I_1)^2 + (h\omega L_S)^2 \left(I_h^2 - K_h^2 I_1^2\right)\right]}\right] \quad (3)$$

$$L_h = \frac{R_h \overline{Q}}{h\omega} \quad (4)$$

$$C_h = \frac{1}{h^2 \omega^2 L_h} \quad (5)$$

where:

- R_h: series equivalent resistance of the filter (for harmonic order h);
- K_h: maximum value allowed for harmonic order h, according to table 1;
- I_1: fundamental component of the input current (rms);
- ih: h^{th} order harmonic of the input current (rms);
- h: harmonic order to be filtered;
- R_S: input series equivalent resistance;
- L_S: input series equivalent inductance;
- ω: fundamental angular frequency (rad/s);
- Q: factor of quality of the reactor (20 ≤ Q ≤ 50).

Due to the load unbalance, three single-phase tuned filters were designed for the third and fifth harmonics, in order to comply with technical standards.

Figures 10 to 13 show the simulated behavior of the electrical system operating with the third and fifth harmonic passive filters. One can notice a great improvement in voltage and current waveforms as well as a significant reduction of the neutral current.

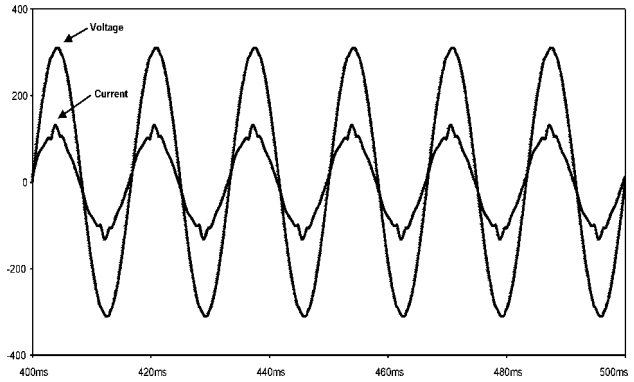

Fig. 10: Input voltage and current (numerical simulation) – phase A

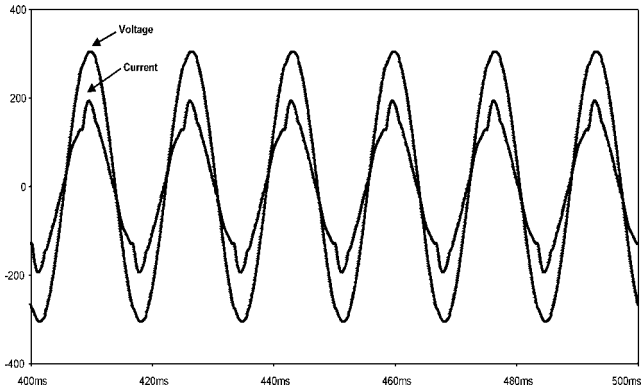

Fig. 11: Input voltage and current (numerical simulation) – phase B

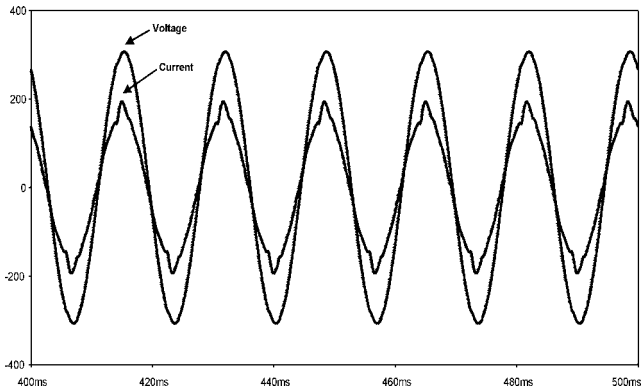

Fig. 12: Input voltage and current (numerical simulation)– phase C

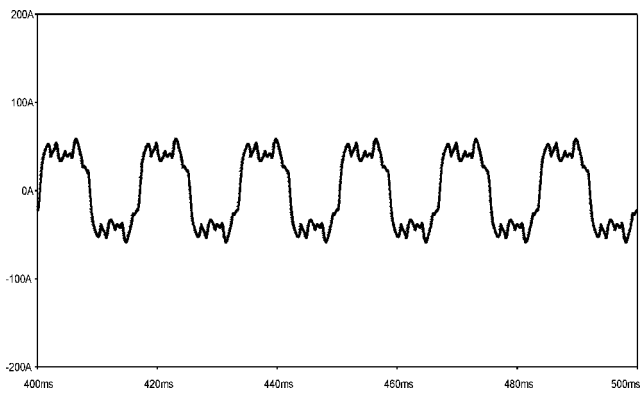

Fig. 13: neutral current (numerical simulation)

IV. Analysis of Simulation Results

Figures 14 to 16 present the effects on the input current harmonic content due to the presence of passive filters. It is possible to observe that individual component limits of the input current are in agreement with the norm. Fig. 17 shows that input current THD is lower than the limit (12%) specified by IEEE 519-1992 Recommended Practices.

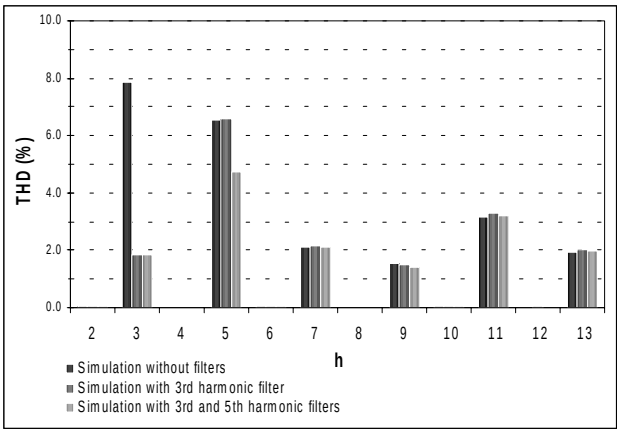

Fig. 14: Harmonic components of the input current – phase A

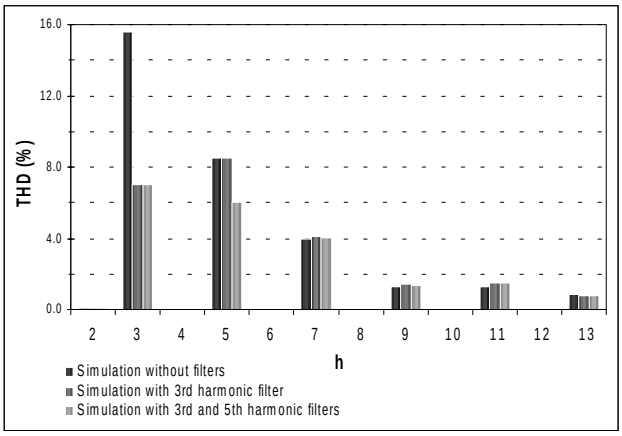

Fig. 15: Harmonic components of the input current – phase B

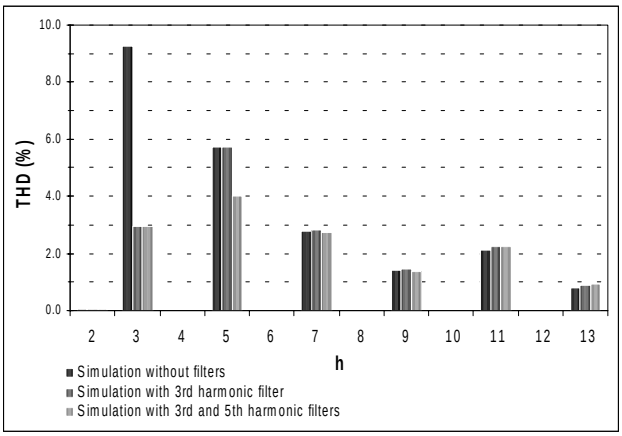

Fig. 16: Harmonic components of the input current – phase C

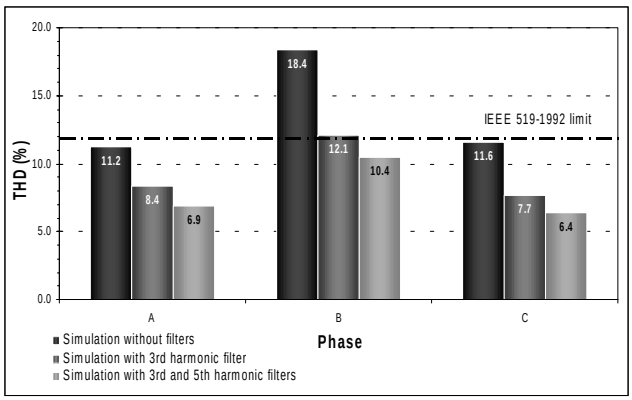

Fig. 17: Total harmonic distortion of the input current

The final results are shown in table 2:

Tab. 2: Final Results

	PHASE A	*PHASE B*	*PHASE C*
Input Voltage [V]	**221.0**	**218.0**	**216.0**
	219.3	**218.8**	**216.3**
	220.5	**219.2**	**216.7**
Input Current [A]	**83.6**	**120.0**	**123.0**
	82.7	**120.2**	**123.2**
	82.1	**118.4**	**122.4**
Voltage THD [%]	**2.37**	**3.24**	**3.22**
	0.88	**1.33**	**1.03**
	0.55	**0.81**	**0.65**
Current THD [%]	**11.24**	**17.89**	**11.31**
	11.23	**18.36**	**11.56**
	6.91	**10.43**	**6.37**
Power Factor	**0.99**$_{ind.}$	**0.97**$_{ind.}$	**0.98**$_{ind.}$
	0.98$_{ind.}$	**0.96**$_{ind.}$	**0.98**$_{ind.}$
	0.99$_{capac.}$	**0.99**$_{capac.}$	**0.99**$_{capac.}$

- Measurements

- Simulation without filters

- Simulation with Filters

The specifications of the components of the filters designed using expression (3), (4) and (5) are shown in table 3.

Tab. 3: Specifications of 3rd and 5th harmonic filters

3rd harmonic filter			
	PHASE A	*PHASE B*	*PHASE C*
Ch	183.6μF	244.8μF	244.8μF
Lh	4.3 mH	3.2 mH	3.2 mH
Frequency	180 Hz	180 Hz	180 Hz
Q	50	50	50
5th harmonic filter			
Ch	107.4μF	76.7μF	91.8μF
Lh	2.6 mH	3.7 mH	3.1 mH
Frequency	300 Hz	300 Hz	300 Hz
Q	50	50	50

V. CONCLUSION

Harmonic distortion in low voltage electric systems is increasing due to the growing number of nonlinear loads.

Even for a three-phase electric system with single-phase nonlinear loads and strong unbalances among the phases, passive filtering can be employed to correct power factor. Simulation results show that it is possible to reduce current and voltage THD with passive filtering.

In the case under analysis, the factor of displacement is almost unity requiring low capacitance and high inductance values for the filters, increasing the cost.

Passive filtering seems to be, even today, a very attractive and cost-effective solution for THD reduction due to the robustness presented by the use of passive components.

VI. REFERENCES

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