Volumetric Optimization of Passive Filter for Power Electronics Input Stage in the More Electrical Aircraft

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Abstract—**The increasing number of power electronic converters connected to aircraft electrical supply networks increases the harmonic levels. Conventional filter design is not well adapted to many power converters, since their behaviour is strongly coupled with filter values. This paper proposes a methodology to optimize a passive input filter and to fulfil harmonic and power factor standards. The method is applied to a diode rectifier, with capacitive load, which represents a very common Power Input Stage for actuators.**

I. INTRODUCTION

The "More Electrical Aircraft" concept (MEA) is no longer theory but reality: the new Airbus A380 aircraft already takes advantage of numerous electrical and electro-hydraulic actuators, reducing the hydraulic requirements, and therefore simplifying the power distribution.

This incurs in turn an increase of electrical power consumption. Further, the rise of In Flight Entertainment (IFE) technology also contributes: increased demands of 30 kW per passenger in three years and 50 kW in five years are expected. In the MEA, power generation will be simplified: the gearbox, ensuring constant frequency electricity supply and hydraulic power, will disappear. It is heavy and expensive, especially at these new power levels. As a consequence, the frequency of the AC electrical network will no more be constant. This will result in multiplication of the Power Electronic Input Stages, feeding electro-hydraulic actuators, or other electrical equipment (roughly 75% of the total consumption). However, the multiplication of Power Electronics must not deteriorate the power quality of the network: harmonic generation by these non-linear loads must be kept within the existing standards for the 115/200VAC, 400Hz main [1]. The electrical power network must be redesigned, in order to comply with this new requirement [2] [3].

This breakthrough is the target of the "Power Optimised Aircraft" (POA) european project. Its main objectives are to:

- Improve the efficiency of Technical Loads to reduce their power consumption
- Use load management to decrease overall commercial load power consumption.
- Examine alternative aircraft level architectures (Fig. 1 and Fig. 2) - which are not possible with conventional equipment – to reduce overall aircraft power consumption and maintain electrical power quality.

This paper proposes a methodology to optimize passive filters for Power Electronics Input Stages.

Among various possible topologies, the simplest consists of a conventional diode bridge, with capacitive load. It is presented in section II.

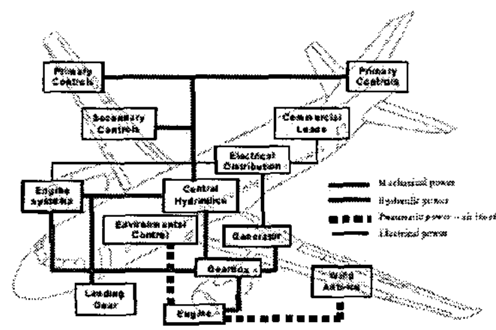


Fig. 1: Conventional Equipment systems Architecture

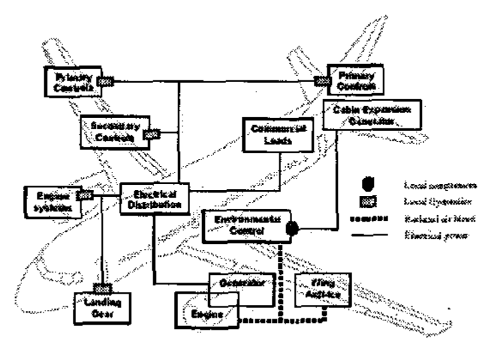


Fig. 2: Potential POA Architecture

Due to high harmonic levels created by this structure, a filter is required. A Passive filter is the most common solution. Their conventional design will be reviewed in section II. In practice the behaviour of the diode rectifier with capacitive load depends greatly on line impedance, and therefore on the input filter. Thus, it will be shown that this conventional design is not as effective as forecast. The only presently available solution is to design the filter taking into account the complete filter-diode bridge association. Since an analytical method is not possible, an implicit approach using simulation will be used. An optimisation problem will hence be created, with constraints such as harmonic content, power factor, etc. Section IV will describe this method with either one or two converters connected to the network.

A study of sensitivity to frequency variation is also undertaken and discussed.

II. POWER INPUT STAGE

A. *Electro-Hydrostatic Actuator (EHA)*

The EHA (Fig. 3) will become increasingly prevalent in aircraft of the future. The power input stage of the actuator is a three phase diode bridge. This converter is often used due to its simplicity and robustness (Fig. 4). However, from the network point of view these loads are non linear and involve significant low frequencies harmonic injection (order $6p\pm1$). A diode bridge directly connected to the network can have a THD higher than 100% if the network line impedance is small. Nonetheless, the legal limits imposed at these frequencies are stringent, in particular for fifth and seventh order harmonics (Table I) [4].

In order to analyse correctly these harmonics and the filter design, the study which follows is in steady state. For this reason, all components downstream of the diode bridge are modelled as an equivalent resistance.

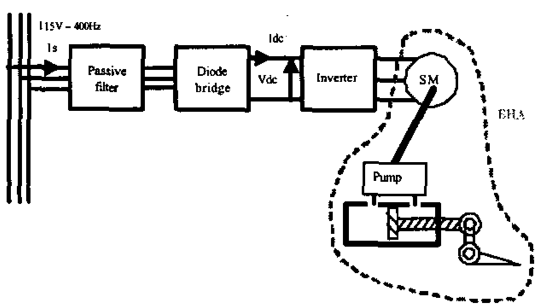


Fig. 3 : Structure of PIS +EHA

TABLE I: ABD0-100 STANDARD ON CURRENT HARMONICS LOAD CONSUMPTION

Harmonics order	Limits
3, 5 et 7	$I_3 = I_5 = I_7 = 0.02\, I_1$
n = 9, 15, 21,…, 39	$I_n = 0.1\, I_1 / n$
11	$I_{11} = 0.1\, I_1$
13	$I_{13} = 0.08\, I_1$
17 et 19	$I_{17} = I_{19} = 0.04\, I_1$
23 et 25	$I_{23} = I_{25} = 0.03\, I_1$
29, 31, 35 et 37	$I_n = 0.3\, I_1 / n$

B. *Passive input filter*

In order to meet the relevant standards, a passive filter is required. Often a smoothing inductance is added at the input. Figures 5 and 6 show power factor (PF) and total harmonic distortion (THD) as a function of this inductance. The figure shows that for an improvement in THD the PF is degraded. Consequently, it is impossible to guarantee both appropriate THD and power factor as imposed by the standards ($FP \geq 0.95$). Hence, other filter structures must be considered.

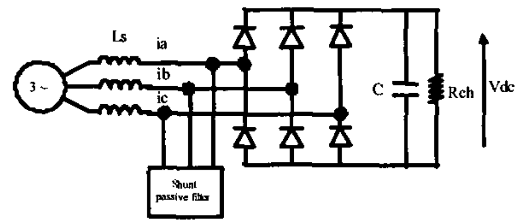


Fig. 4 : Power Input Stage of EHA

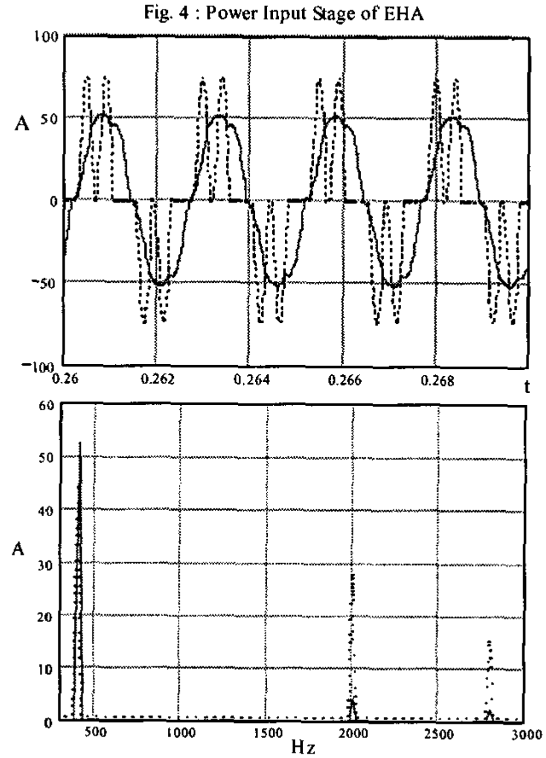


Fig. 5. Example of Input current (in time and frequency domains) for Ls = 520 μH (solid line) and 10μH (dotted line), Rch = 4.1 Ω (solid line) and R = 6.7 Ω (dotted line) – in order to conserve a constant power load of 10kW- the voltage source is 115 Vrms, 400Hz.

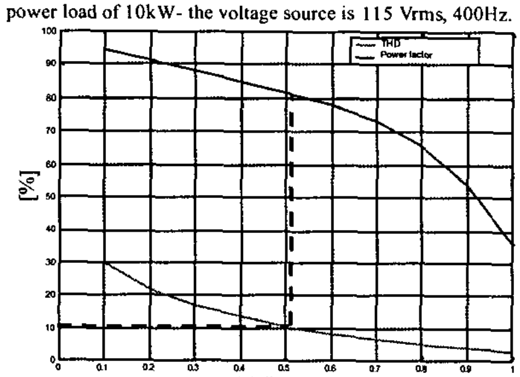
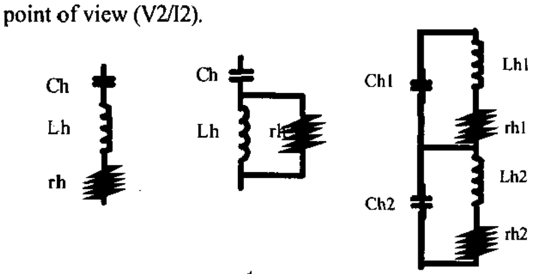


Fig. 6. THD and power factor function of Ls (P=10kW)

Several harmonic filter structures exist in the literature of which the most important are shown in Fig. 7 [5]. The impedance of each filter may be derived using the quadripole method (Fig. 8 and equation (1)). With this method it is possible to compute the gain (I2/I1) and characteristic impedance of a filter from the network (V1/I1) or diode bridge point of view (V2/I2).



(a) : series-tuned *(b) : 2nd order damped* *(c) double band-pass*

Fig. 7. Typical harmonic filters

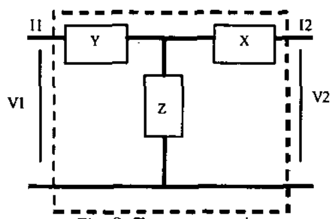


Fig. 8. T representation

$$\begin{bmatrix} V2 \\ I2 \end{bmatrix} = \begin{bmatrix} 1+\dfrac{Y}{Z} & -(X+Y+\dfrac{X\cdot Y}{Z}) \\ -\dfrac{1}{Z} & 1+\dfrac{X}{Z} \end{bmatrix} \cdot \begin{bmatrix} V1 \\ I1 \end{bmatrix} \quad (1)$$

In order to guarantee a correct response, the series tuned structure with smoothing inductance chosen is that of Fig. 9. The conventional design methodology is presented in detail in the following section.

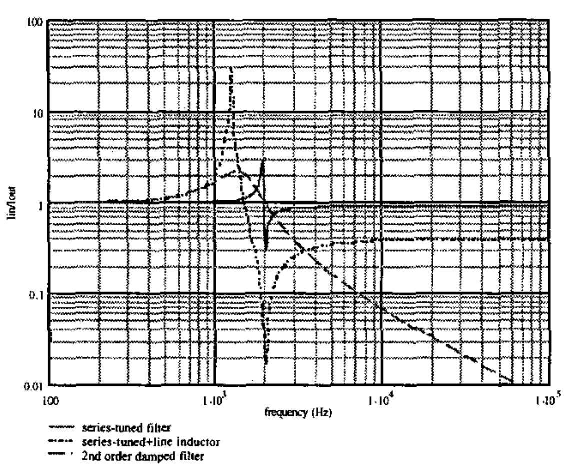


Fig. 9. Matrix representation of passive filter and transfer function of I1/I2 for typical harmonic filters

III. INPUT FILTER DESIGN

A. Conventional design procedure

In the design of the chosen filter several limits are imposed. The most important of these is a maximum voltage drop across Ls,10% of the fundamental of the supply voltage. Also to be considered is the minimisation of the unwanted harmonic (equation (2)). Ch, the series capacitance is often implemented as a capacitor bank to improve the power factor as defined by equation (3) where V is phase-neutral voltage and $?_0$ the supply frequency. Reactive power Q must be injected to provide PF = 0.95. Finally it must be verified that the current flowing in the filter at the fundamental frequency is small and hence associated losses are negligible.

$L_h \cdot C_h \cdot \omega_h^2 = 1$ with $\omega_h = 2\cdot\pi\cdot5\cdot f$ to eliminate the 5th harmonics (2)

$$Q = 3\cdot\frac{V^2}{X_{LC}} = \frac{3\cdot V^2}{\left(L_h\cdot\omega_0 - \dfrac{1}{C_h\cdot\omega_0}\right)} = \frac{3\cdot V^2}{\left(\dfrac{\omega_0}{\omega_h^2\cdot C_h} - \dfrac{1}{C_h\cdot\omega_0}\right)} \quad (3)$$

In response to the low-weight requirements of the aviation industry, meeting the relevant electronic standards is insufficient. It must be established whether the filter volume, and indirectly its weight, is minimised.

B. Volumetric optimization

To be of use, passive component volume calculations must take into account the technology of realization.

For inductors, the design process starts from the computation of the area product [6] (core cross section * winding area). This depends on the working conditions of the component:

The following parameters are used to compute the area product:

- Inductor value (L)
- Peak current (Ip)
- RMS current (Irms)
- Wiring factor coefficient (Kb)
- Current density (J)
- Peak induction (Bp)

It should be noted that the area product A (equation (5)) does not depend on the number of turns.

Since A is linked to the inductor design, via the core area and the winding area, it must also be linked to its volume. This relation depends also on implementation technology. For instance, a toric inductor differs from a simple "E"core.

The link between the area product A and the inductor volume *Vl* is expressed in equation (4), where K depends on the core shape (dimensionless) [7]. For cores such as "E" cores, K can be computed and / or measured. K = 20.

Usual values for Kb, J and Bp are:

- Kb = 3
- $J = 5\ A/mm^2$
- Bp = 0.1 T (depending on the magnetic material used and on core losses permitted)

Therefore, inductor volume is a function of inductance, peak current and rms current.

$$Vl = K \cdot A^{3/4} \tag{4}$$

$$A = Sb \cdot Sf = \frac{Kb \cdot L \cdot Ip \cdot Irms}{J \cdot Bp} \tag{5}$$

For the capacitor, there are fewer design requirements.. Two methods are available to compute capacitor volume. Either an extrapolation from existing capacitors, or a simple calculation based on parallel plate capacitor formula is used. Equation 6 is obtained by combining capacitance and maximum field strength expressions in the case of two infinite plates.

- Um is the maximum capacitor voltage
- ε is the permittivity of the dielectric
- E is the electric field for the considered dielectric

$$Vc = \frac{Um^2}{\varepsilon \cdot E^2} \cdot C \tag{6}$$

Values used in this work are as follows:

- $Um = 450$ V
- $\varepsilon = 2.2.\varepsilon_0$ F/m
- $E = 45.10^6$ V/m

Fig. 10 shows the comparison between manufacturers' data and formula (6) in the case of 50 Hz capacitors. The strong correlation validates the assumption of a linear relation between capacitor volume and capacitance.

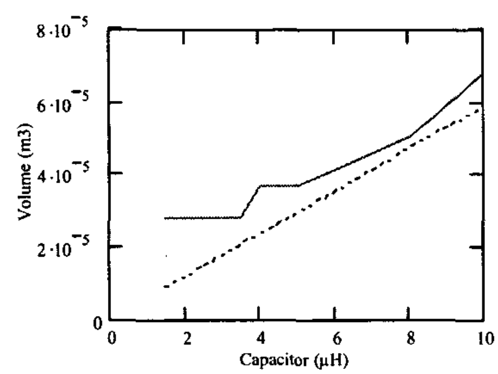


Fig. 10. Capacitor volume as a function of capacitor value. Manufacturer interpolation (solid line), parallel plate capacitor formula (dotted line)

The objective function to be minimised is therefore defined as the sum of all volumes.

$$Fobj = 3 \cdot Vc(C) + 3 \cdot Vl(L, Ip, Irms) + 3 \cdot Vs(L, Ip, Irms) \tag{7}$$

To optimise the filter a complete filter/diode bridge model must be developed. It is not acceptable to assume that these two components are independent. Fig. 11 illustrates the consequences of making this incorrect assumption. Considering the frequency spectrum of current absorbed by a diode bridge without filtering, assuming decoupled systems, it is possible to calculate the line current with a filter added by multiplying the current by the transfer function I2/I1. Comparing this to a PSpice time simulation it appears that the 5th order harmonic is removed in both cases. By contrast, the 7th order harmonic behaves differently (cf Fig. 11 and table III). It is for this reason that the optimisation model used is implemented using the SimPowerSystems tools of Matlab which undertakes time simulation of the entire structure. From this simulation the FFT of each current in Ls and Lh is calculated (in order to calculate the individual inductor volumes later) as well as the PF. The constraints chosen are :

- $Fp>0.95$
- $Ih5<2\%$

The Matlab function 'fmincon' is used as, in this case, all variables are continuous and the gradients method is most appropriate (Fig. 12).

The time taken for one simulation is approximately 10s and the optimisation function takes about 200 iterations to converge. Thus the optimization takes on average between 30 and 40 minutes.

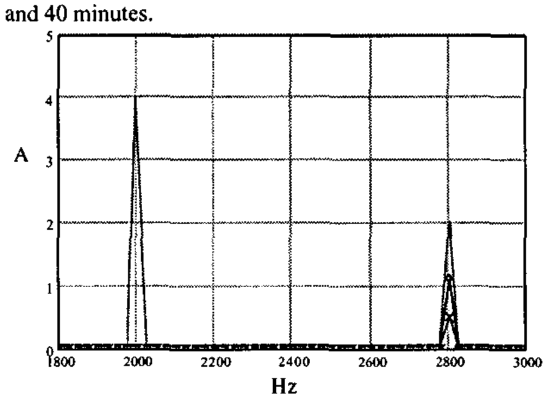


Fig. 11. Comparison of input line current spectrum without filter (solid line), after filtering with independent filter interaction assumption (X), and after filtering with time simulation (O). Table II gives harmonic magnitudes.

TABLE III
HARMONIC MAGNITUDE OF INPUT LINE CURRENT

	IH7 magnitude (A)
Diode rectifier alone	2.04
Theoretical prediction with filter (source independent of filter X)	0.51
Time simulation with filter (O)	1.12

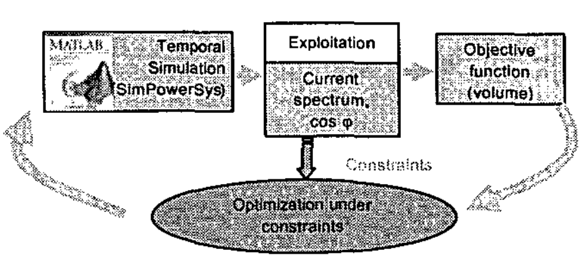


Fig. 12. Principle of optimization

IV. RESULTS AND DISCUSSION

A. Filter optimization for one converter

Table IV compares the results of conventional design and those of optimization. Two different power levels have been used. It is important to remember that in the optimization, the line voltage drop is not constrained, whereas the conventional method assumes 10% drop.

The immediate conclusion is that both strategies result in very similar values. Since the main design parameter is series inductance Ls (as mentioned in section II-B), a value of Ls leading to a 10% voltage drop is the most appropriate, when filter volume is considered. This conclusion is confirmed in Fig. 13, where all volumes of passive filters are plotted as a function of Ls. The optimum is not very pronounced, but is located around 140 µH for a 10 kW power.

Another conclusion from Table IV is that the filter volume does not vary linearly with power consumption. This will have important consequences when several converters are to be filtered. This point will be addressed in the following section.

TABLE IV
OPTIMIZATION RESULTS FOR TWO POWER LOAD

	Conventional sizing		Optimization	
	10kW	5kW	10kW	5kW
L_s (µH)	140	300	138	299
C_h (µF)	2.58	1.37	2.5	1.38
L_h (µH)	2445	4600	2440	4612
Ih5 (% of Ih1)	1.8	0.7	1.94	1.9
Ih7 (% of Ih1)	9.5	9.4	9.2	8.8
FP	0.97	0.97	0.97	0.97
Total volume (cm^3)	**696**	**635**	**694**	**631**

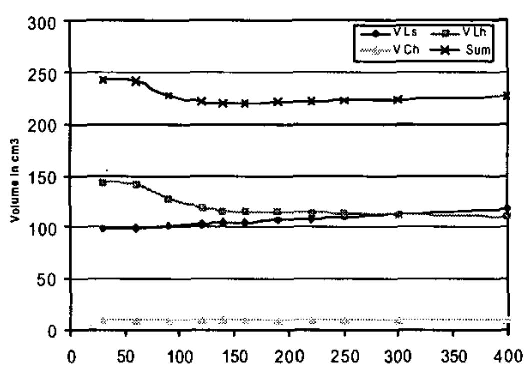


Fig. 13. Volume of passive element (for one phase) function of Ls

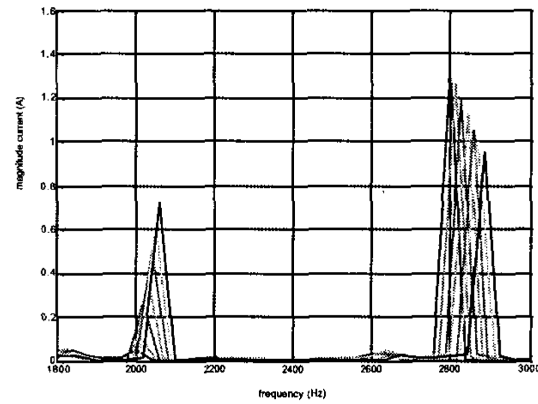


Fig. 14. Frequency sensibility analysis

After optimization, the correct behaviour of the filter must be verified under working conditions of the converter and the network. Care must be taken of the fact that in modern aircraft, a variable frequency will be used. A sensibility study has been undertaken on the network frequency, between 360 Hz and 800 Hz.

Fig. 14 shows the amplitude of harmonics 5 and 7. Obviously, the tuned filter becomes less effective as frequency varies, since it has only a narrow bandwidth.

A solution is to associate several tuned filters, to reduce the levels of both 5^{th} and 7^{th} harmonics. Another idea would be to use a different filter topology, with a wider bandwidth. The conventional design of either multiple tuned filters or more complex structures is rather more difficult than the one presented in section II-B. This shows the great interest of the method presented in this paper: a global optimization can be achieved for any filter structure, the only limitations being the number of variables and the time allowed for simulation.

B. Filter design for two converters

The comment on the non linearity of filter volume with power (TABLE IV) has interesting consequences when dealing with several converters. The filter position can be studied. Fig. 12 illustrates two different configurations for the case of two 5 kW rectifiers. In configuration 1, each converter has its own filter, whereas in configuration 2, a unique filter (designed for 10 kW) is used.

TABLE V gives the results of this comparison. Since the conventional design method is close to optimal, it has been used to design the filters in both configurations. The volume of configuration 1 is nearly twice that of the 5 kW filter in TABLE IV. The difference comes from the various line inductances (Ls1 and Ls2 in Fig.12). The volume of configuration 2 is nearly that of a 10 kW converter (once again, the difference is due to Ls2).

It is obvious that a simple filter is smaller than two independent ones. However, the harmonic level between the two converters is not reduced. This will be a drawback if other equipment is connected to this line.

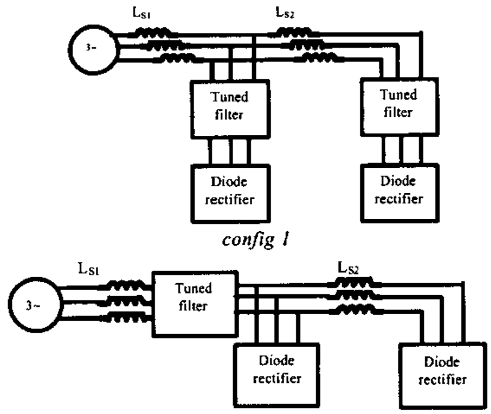


Fig. 15. Network configuration analysis

TABLE V
OPTIMIZATION RESULTS FOR TWO POWER LOAD

	Config 1	Config 2
I_{LS1_h5} %	1	2
I_{LS1_h7} %	9.8	10
FP	0.97	0.97
Volume (cm^3)	**1248**	**733**

V. CONCLUSION

This paper illustrates how to optimize a passive filter with respect to its volume for a typical power input stage: a three phase diode bridge with capacitive load. The main difficulty arises because the behaviour of the converter depends greatly on network impedance, and thus on filter values. Therefore, time simulation is used in the optimization process. This is implemented with standard MATLAB functions (fmincon, Sim Power System, ...).

The volumes of passive components are computed by taking into account the technological parameters involved in their design. The constraints are the individual current harmonic levels, and the power factor. The optimization method is compared to a conventional design method. Results are similar in the simple case of a tuned filter. However, the method is general and may apply to more complicated filter structures. This is particularly important as a simple tuned filter is not sufficient to meet all aircraft standards, especially as network operating frequency will no longer be constant in future. Therefore, several tuned filters or higher bandwidth filters should be used. In this case, conventional design is far harder and a generic optimization should be a great help for the designer.

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