Simulation of Shunt Active Filter for Aircraft Electrical System

Michael Shell, *Member, IEEE,* John Doe, *Fellow, OSA,* and Jane Doe, *Life Fellow, IEEE*

***Abstract*—Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper.**

***Keywords*—IEEEtran, journal, LaTeX, paper, template.**

I. Introduction

The increase of the aircraft operational costs associated with the fuel consumption makes this subject one of the main concern in the development of the new aircraft projects. In this scenario, the aviation market has been changed the design perception with respect of use of the electrical system. The electrical system dependency to power an increasing number of embedded systems and, in some cases, replacing the power source where it used to be powered by hydraulic and pneumatic system has increased in the past few years, creating the concept of the More Electrical Aircraft (MEA).

This context raised the relevance of the electrical system in the hole of aircraft operational safety. In this way, the electrical system needs to have a greater reliability and to operate in a way to avoid failures of the equipment connected to it. However, the rise of electrical equipment connected in the electrical system, specially the non-linear loads, has increased the harmonic distortion content being introduced in the electrical grid, diminishing the power quality and becoming a subject of study in aircraft operational safety.

To improve the power quality with the reduction of the total harmonic distortion (THD), some conditioners are applied in the equipment power input and in the electrical grid, such as filters and high power factor converters. The implementation of these conditions must consider the reliability, the weight and cost to be feasible in aircraft systems.

In this context, some topologies to rise the power quality are already use in the aircraft electrical system, such as the passive filters and multi-pulse converters []. However, its characteristics are unfavorable to extended use due to its weight and volume, making these applicable only to specific equipment.

With the increase of the number of the non-linear loads use, and the demand to ensure the good power quality, this paper presents a concept of a shunt active filter to be applied in the electrical aircraft system. This subject is being an item of recent study, considering different active filters topologies. To understand the theory evolved in the active filter operation, this paper also presents the instantaneous power theory, as well as its physical implementation. A simulation is presented to analyze the shunt active filter operation when considered its use in an aircraft electrical power system.

II. Power Qaulity in Aircraft

The power quality in aircraft electrical generation and distribution system is a concern which regards the safe airworthiness. The electrical fed equipment used in aircraft design must be qualified to ensure the proper operation and integration. Thereby, the power quality is one of the subjects considered in the qualification tests, which are specified by standard test procedures issued by aeronautical authorities. The most used standards in qualification are the MIL-STD 704, which qualifies the electrical system; and the DO-160, which qualifies the embedded equipment. To ensure the proper equipment operation when connected to the grid, the electrical power generation and distribution system (EPGDS) must comply to these standards.

The use of the EPGDS to power the high number of non-linear loads injects in the system harmonic distortion content, which degrades the power quality and decrease the power factor. Thus, means of power factor correction must be applied in the EPGDS to adequate the system to operates within the constraints of the aeronautical standards.

Some implements are already used in aircraft electrical system to reduce the power factor and increase the power quality. Some of these artifacts are the passive filters and multi-pulse converters [**?**] [1], [2] [26,27], however, despite of the good reliability, they are bulky and heavy. There are some other topologies that are useful for harmonic content reduction, but, their characteristics do not make them feasible to operate in the aircraft systems. In this scenario, the active filter, due to its features as lightweight and fast response to load variation, appears to be a feasible topology to reduce the harmonic content and increase de power factor [3]–[5] [34,39, 40]. There are some drawbacks in its use, as the high complexity and low reliability, but the advances in power electronics are making them feasible to be implemented in aircraft electrical system [6] [3].

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III. Active Filters

The active filter operates creating waveforms to interact with the voltages and currents presented in the electrical grid to establish a power factor equal to one. This is accomplished by measuring the voltage waveforms from the power source and the current waveforms from the load, and then using these parameters on the instantaneous power theory to determine the current reference as an input to be set in a compensator. The compensator injects current waveforms in the circuit with symmetrical values of the components which degrades the power factor. The typical system compounded by a non-linear load with an active filter is presented in Fig. 1.

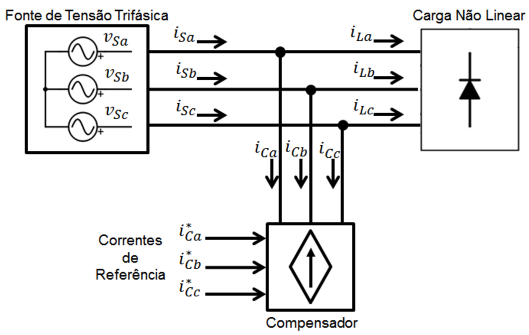

Fig. 1. Simulation Results

A. Instantaneous Power Theory

The instantaneous power theory was presented by Akagi [?], which proposed some new concepts for the instantaneous active and reactive power. This theory can be used in three phase, three or four wire system and in steady or transient state [?], [?]. In this theory, the manipulation of the active and reactive power calculations brings a tool to determine the currents that carry some content which degrade the power factor, such as harmonic distortion and phase shift. Considering a three-phase system, composed by the phases a, b and c, the instantaneous power theory is based in the coordinates transformation from the abc to $\alpha\beta 0$. This is known as the Clarke Transformation and is shown in eq. (2) 1.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix};$$
$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

According to [?], the instantaneous power is defined as shown in eq (3) 2, where the p_0, p and q are the instantaneous zero-sequence power, the active instantaneous power and the reactive instantaneous power, respectively [?], [7].

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (2)$$

Considering a system without zero-sequence voltage and/or current, such as the aircraft electrical system, the eq (3) can be simplified as the eq (4), where the instantaneous zero-sequence power is absent.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

The reverse calculation, i.e., the determination of the currents i_α and i_β when the voltages v_{alpha} and v_β and the instantaneous power p and q are known is presented in eq. (5) 4.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (4)$$

By definition, the active instantaneous power is composed by the energy that is swapped between two subsystems, whereas the reactive power is composed by the energy being swapped between the 3 phases of the system [?]. Furthermore, both p and q can be defined as a composition of an average ($\overline{p}$ and $\overline{q}$) and an oscillating ($\tilde{p}$ and $\tilde{q}$) values, as defined in eq. (6) 5.

$$\begin{aligned} p &= \overline{p} + \tilde{p} \\ q &= \overline{q} + \tilde{q} \end{aligned} \quad (5)$$

To create an active filter to coordinate a power factor equal to 1, the only permitted power flowing in the transmission lines is the average value of the instantaneous active power ($\overline{p}$). To ensure this condition, the filter must inject in the lines currents which contains the symmetrical values of the instantaneous reactive power (q) and the oscillating portion of the instantaneous active power ($\tilde{p}$) created by the non-linear load. By doing this, these powers are cancelled in the same way as the current harmonic content. Thereby, the selection of power to be compensate and processed by the filter must contains the values of the $-\tilde{p}$ and $-q$ only.

The filter full operation is defined by the instantaneous power p and q calculation, followed by the selection of the power to be compensated, i.e., $-\tilde{p}$ and $-q$. Afterwards, the currents i_α and i_β are calculated using the eq (5) 4 with the values $-\tilde{p}$ and $-q$, followed by the inverse Clarke transformation to acquire the current in abc coordinates to be applied as a reference in the compensator. The whole active filter reference definition is shown in Fig. 2.

B. Control Strategy

The active filter specified in Fig (7) 2 presents very effective to set the current reference to be applied in the compensator

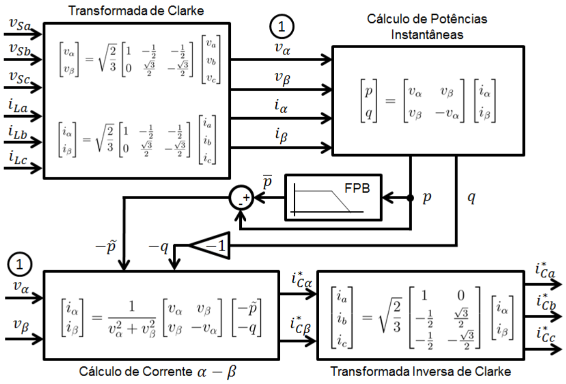

Fig. 2. Simulation Results

for mitigation of the electrical system harmonic content. However, this calculation is valid to produce sinusoidal current waveforms only when the voltages measured and used in the filter input is pure sine waves. This happens since the filter operates in such way that only the mean value of the active instantaneous power flows in the circuit. Therefore, the use of a non-sinusoidal voltage waveform in the input of the filter requires a non-sinusoidal current waveform to establish the power flow with only $\overline{p}$.

In aircraft electrical power system, the voltage waveforms stated in the point of common connection (PCC) are presented as non-sinusoidal, however, they are still limited by the aeronautical standards. As the voltages used in the active filter are measured at the PCC or beyond this point, its operation is not optimal for power quality purposes, and, in some cases, it may decrease the power quality and operates unstably depending the levels of harmonic distortion presented in the voltages waveforms.

According to [8], the p-q theory proves insufficient to satisfy the condition to create a current sine wave and an active instantaneous power flow consisted of only the its mean value, at the same time the voltage waveforms measured and presented on the PCC are previously distorted. To overcome this situation, a control strategy based on the use of a positive-sequence voltage detector is employed to ensure a sinusoidal current control. With this, the power flow between the load and the source is not defined as the mean value of the active instantaneous power, however, the control strategy relays on the appropriate sine wave current insertion in order to establish the proper power quality at the system.

This control is designed by the use of the positive-sequence voltage detector, which operates to extract the fundamental positive-sequence component from the distorted voltages. This component is required by the active filter to define the current shape to be applied in the electrical grid to create a sinusoidal waveform.

The positive-sequence voltage detector operates based on the p-q dual theory where it is used a phase locked loop (PLL) and the p-q theory to extract the fundamental frequency and amplitude of the distorted voltages. The PLL is show in Fig. 3 and operates defining the fundamental frequency and phase. The scheme shown in Fig. 4 uses the p-q theory and the information coming from the PLL to define the amplitude of the fundamental component to be used in the active filter calculations.

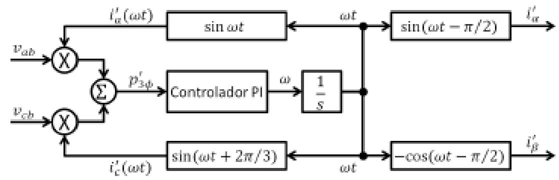

Fig. 3. Phase locked loop

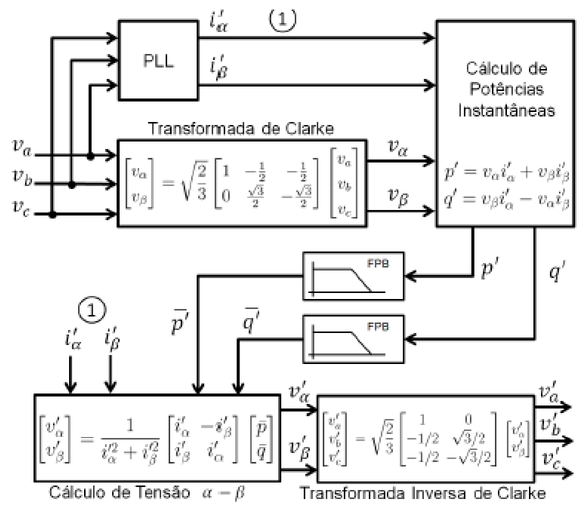

Fig. 4. Positive-sequence detector

In the operation of the active filter, some loss is presented in the circuit, mainly due to the VSC switching devices, which cause the voltage of the capacitor, locate in the converter DC side, to decrease. To avoid this voltage drop, a closed-loop design with a PI controller is applied in the active filter to define the power to compensate the system power loss. This closed-loop error signal is processed by the compensator, causing this to manage the power flow in the VSC to hold the capacitor voltage to specifically reference.

IV. Simulation of the Shunt Active Filter Operating with an Electrohidraulic Actuator

A simulation is proposed to evaluate the shunt active filter operating in an aircraft electrical system. The system is composed by the generation and distribution system and some loads constituted by electrohydraulic actuators with shunt active filter connected to its respective inputs.

A. Active Filter Model

The shunt active filter model is composed by the current reference calculator and the compensator blocks. The reference

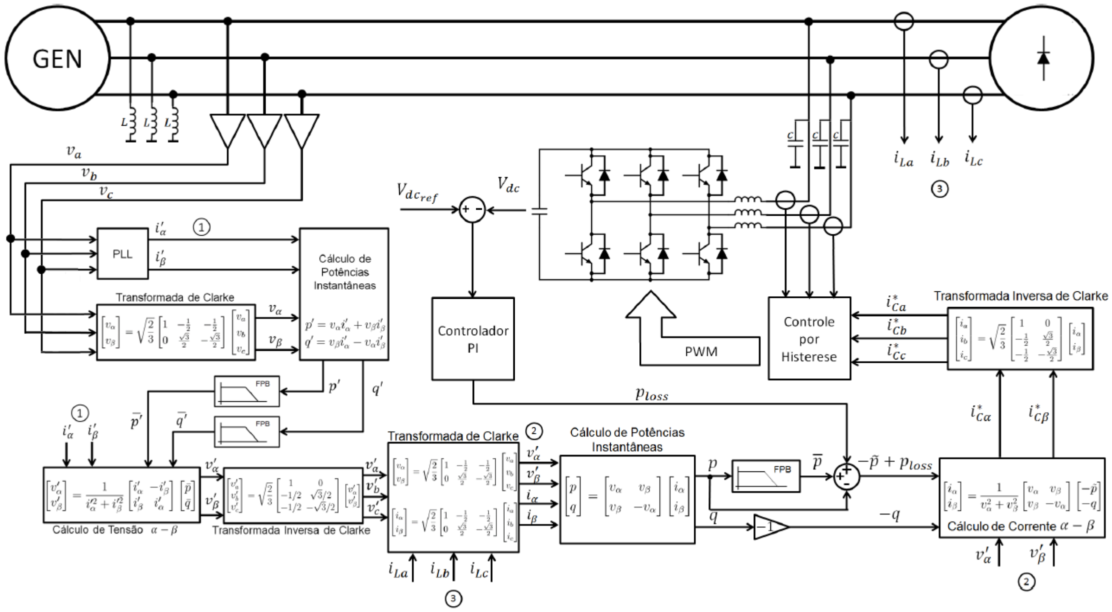

Fig. 5. Shunt active filter scheme

calculator block is given by the procedure which uses the instantaneous power theory to define the proper reference to be applied in the compensator input. The compensator block consists of a voltage source converter (VSC), with its respective capacitor DC voltage regulated by a closed-loop controller. The compensator also has the hysteresis controller which creates the commands that are applied in the VSC switching devices.

The active filter operation requires a passive capacitor filter applied in the transmission lines to eliminate the high frequency content injected in the system by the switching commutation []. As the switching commutation is set at high frequency, this passive filter might be lightweight and does not impact significantly in the aircraft system. However, the presence of capacitors in the transmission lines may decrease the power factor due to current phase shift. To eliminate this problem some inductor may be applied in the lines to compensate the reactive power flow.

The shunt active filter diagram is presented in Fig. 5. This figure shows the blocks where each calculation step is accomplished, and the points where the active filter with its respective voltage and current measurement probes are connected to the electrical grid.

B. Electrical System Model

The aircraft electrical system was modeled based on the operation of the generation and distribution system with it respective non-idealities, which affect the power quality due to voltage drop. The simulation presents a generator system, a power distribution system and three EHAs connected in parallel as the loads, as shown in Fig. 6.

The generator system is compound of a synchronous machine and a generator control unit (GCU). The GCU works as a field excitation controller to set the proper voltage in the PCC. The synchronous machine also has resistive and inductive reactance connected in series with the voltage source to model the resistance and the inductance presented in the generator coils.

The power distribution system is composed by the transmission lines between the generator and the PCC and between the PCC and EHAs. In the PCC, it is located the probes which measure the system voltages levels to be sent as the reference input to the GCU. The power transmission lines are modeled as resistive and inductive reactance in series for each of the 3 phase lines.

The EHA is an equipment used in the aircraft aerodynamic surfaces for latero-directional and longitudinal control. This equipment is a non-linear load, since in its input has a 3-phase diode bridge. The EHAs modeled has a 3 phase Graetz diode bridge with a current controlled source placed in its respective DC side. The controlled current source is defined to operate in such way to recreates the apparent power consumption of a real EHA. Thereby, this guarantees the application of the distorted current waveforms generated by the EHA in real operation.

C. Results

The results obtained by the simulation of the system are presented below. These results show the voltages and currents waveforms measured in the PCC, as well as the frequency spectrum with the amplitude limits defined by the MIL-STD 704F together with the calculated value of the voltage THD and IHC.

The test is divide in two portions: The first part is given with the EHAs not requiring any load, and the second part is given when EHAs are starting their operation, where it is observed the maximum load consumption. The results also show the

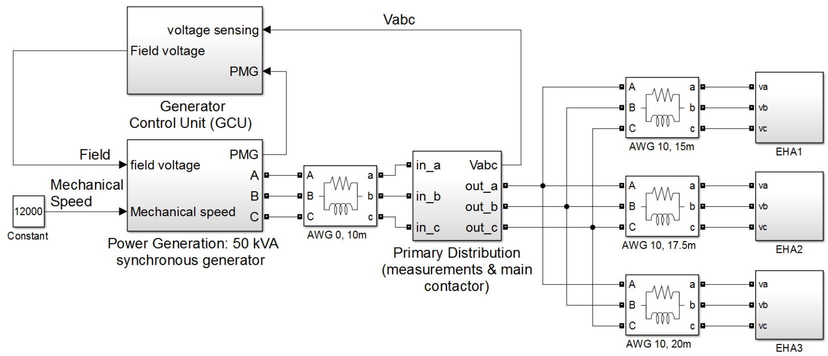

Fig. 6. Electrical generation and distribution model

cases where the active filters are connected and disconnected from the EHAs power input.

For the portion where the EHAs are not operating, Fig. 7 and Fig. 8 show the waveforms when the system has no active filters operating. For the same period, Fig. 9 and Fig. 10 show the waveforms when the active filters are connected in the EHAs power input. For this interval, the presence of the active filters degrades the power quality, since the THD increases, and the frequency spectrum presents more harmonic content. This noise is inserted in the system due to the commutation of the VSC switching devices. Thus, even with the presence of the capacitor filter in the lines, it was observed some high frequency content injected in the grid. However, despite of this adversity, the results are still inside the limits defined by aeronautical standards.

For the portion where the EHA is requiring maximum load, Fig. 11 and Fig. 12 show the waveform when the active filters are not connected in the grid. In the same period, Fig. 13 and Fig. 14 show the waveforms when the active filters are connected in the EHAs power input. In this interval, it is clear the enhancement that the active filter implies in the system power quality. Considering these results, the active filters operate to mitigate the harmonic content and set it inside the limits of the MIL-STD 704F.

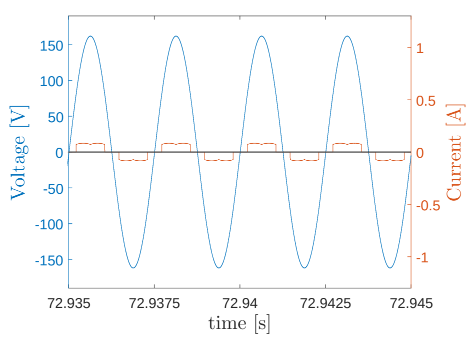

Fig. 7. Voltage and current waveforms for the system without load and filter

V. Conclusions

The shunt active filter showed propitious for use in aircraft electrical system to enhance the power quality. The simulation

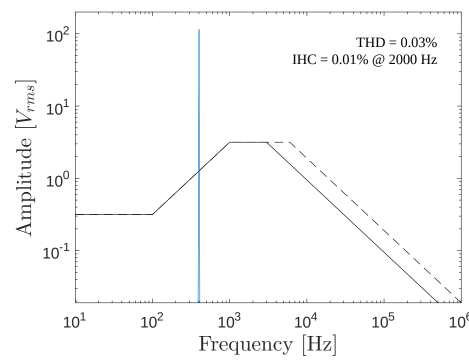

Fig. 8. Voltage spectrum for the system without load and filter

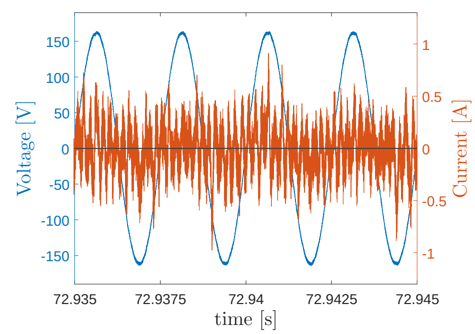

Fig. 9. Voltage and current waveforms for the system without load and with filter

results presented that the active filter response was adequate for high load variation, at the same time its operation maintain the voltage inside the limits defined by the aeronautical standards in terms of harmonic content.

There are some drawbacks when the non-linear loads, connected with their respective active filters, require low power consumption. In this case, the power quality is slightly degraded, however, not substantially to make the system operate infringing the aeronautical standards.

It should be noticed that even when the loads do not consume power, the set composed by the loads and the filters draw current from the source. This is caused by the energy

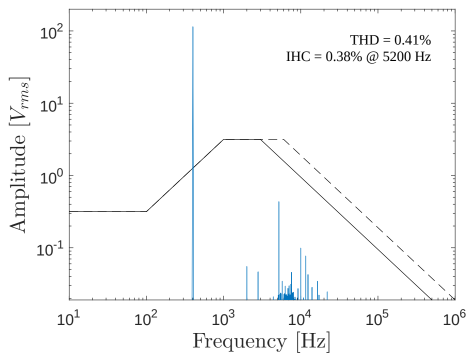

Fig. 10. Voltage spectrum for the system without load and with filter

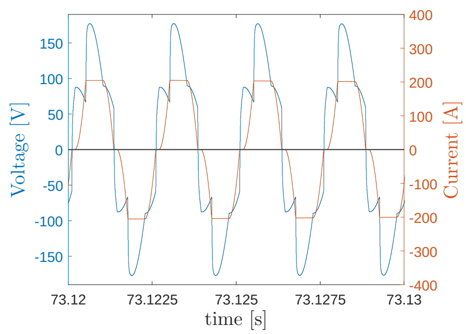

Fig. 11. Voltage and current waveforms for the system with load and without filter

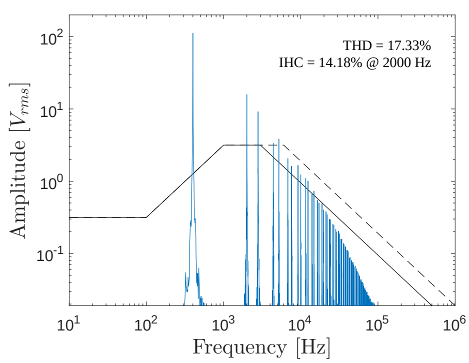

Fig. 12. Voltage spectrum for the system with load and without filter

loss in the filter operation, mainly due to the non-idealities of the switching devices, which is considerable when compared to energy drawn by the load operating with low consumption.

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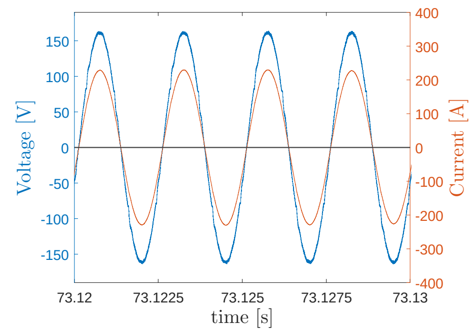

Fig. 13. Voltage and current waveforms for the system with load and filter

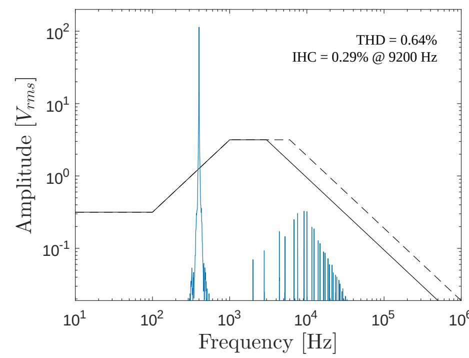

Fig. 14. Voltage spectrum for the system with load and filter

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