Simulation of Shunt Active Filter for Aircraft Electrical System

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***Abstract*—The increasing in the electrical system dependence, along with the expansion of the amount of electrical load connected in the distribution system, has raised the concern to the issues regarding power quality, which is associated to the growth of the harmonic distortion in the voltage waveforms. In this scenario, this study focuses in the power quality improvement and power factor correction by the utilization of active filtering. The instantaneous power theory, and the main theoretical basis used in comprehension and elaboration of the filters are approached in this paper. To validate its implementation in the aeronautical electrical system, a simulation is proposed with the active filter operating in a power generation and distribution system, where the filter is connected at the power input of an electro hydrostatic actuator. The models used in the simulation intent to simulate an aeronautical electrical system, and the results obtained are presented as a mean to measure the effectiveness of the active filter implementation.**

***Keywords*—Power Quality, THD, Simulation, Active Filter**

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 [1]. 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) [2].

This context raised the relevance of the electrical system in the role 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 [3], 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. The implementation of these conditions must considers the reliability, the weight and cost to be feasible in aircraft systems.

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In this context, some topologies to increase the power quality are already use in the aircraft electrical system, such as the passive filters and multi-pulse converters [4]–[6]. However, its characteristics are unfavorable to extensive use due to its weight and volume, making these applicable only to specific equipment.

With the increase in the number of the non-linear loads applied in the electrical grid, and the requirement 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 [7]–[9]. 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 with these standards.

The non-linear loads inject harmonic distortion content in the system, which degrade the power quality and decrease the power factor. Furthermore, the increase in the number of electrical equipment connected in the grid enhances the degradation of the power quality. 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 [4]–[6], 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 doable topology to reduce the harmonic content and increase de power factor [4], [9], [10]. There are some drawbacks in its use, as the high complexity and low reliability, but the advances in power electronics are making them practical to be implemented in aircraft electrical system [11].

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 [12]. 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 a shunt active filter is presented in Fig. 1.

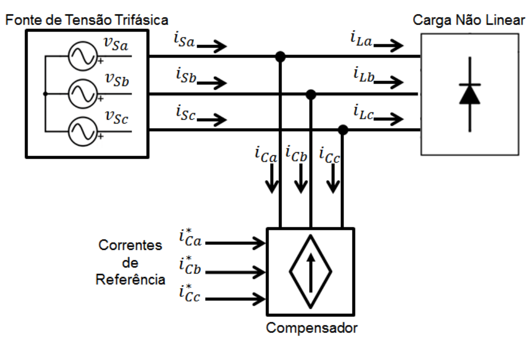

Fig. 1. Simulation Results

A. Instantaneous Power Theory

The instantaneous power theory was presented by Akagi [13], 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 [14]. 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. 1.

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

According to [14], 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 [14], [15].

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

Considering a system without zero-sequence voltage and/or current, such as the aircraft electrical system, the eq 2 can be simplified as the eq 3, where the instantaneous zero-sequence power is absent.

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

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. 4.

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

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 [13], [15]. 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. 5.

$$\begin{aligned} p &= \overline{p} + \tilde{p} \\ q &= \overline{q} + \tilde{q} \end{aligned} \tag{5}$$

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 contain 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 canceled 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.

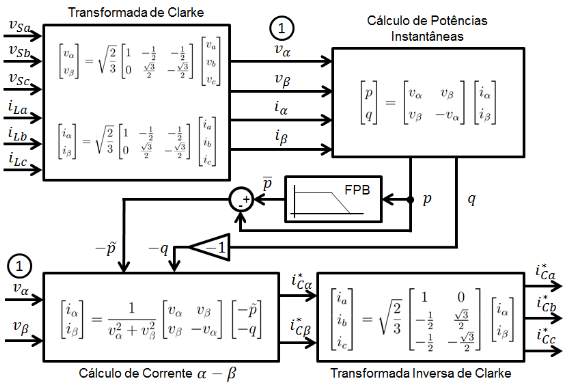

Fig. 2. Simulation Results

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 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 [14]. This happens insofar as 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 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, the filter defined as per Fig 2 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 [14].

According to [14], the p-q theory proves insufficient to satisfy the condition to create a current sine wave and a flow consisted of the mean value of the active instantaneous power, at the same time the voltage waveforms measured 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 to establish the proper power quality at the system.

This control is designed using 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 voltages component to be used in the active filter calculations.

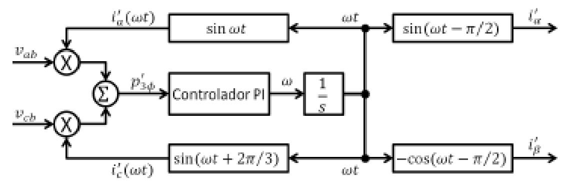

Fig. 3. Phase locked loop

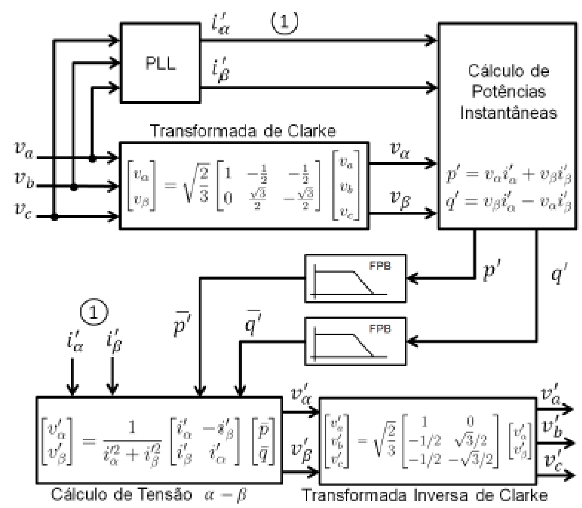

Fig. 4. Positive-sequence detector

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 VSC 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 a specifically reference.

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

A simulation was used 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 (EHAs) with shunt active filters connected to its respective inputs.

A. Active Filter Model

The shunt active filter is given by the current reference calculator and the compensator, as shown in the diagram presented in Fig. 5. This figure shows the points where the voltages and currents measurement probes are connected in the electrical grid; the calculation algorithm, where each sub-block presents its respective signals inputs and outputs; and the compensator, which consists of the VSC.

The reference calculator block defines the proper reference to be applied in the compensator. Its inputs are the load currents and the grid voltages measurements, while its output is the reference applied to the compensator. The compensator block consists of a VSC with its capacitor DC voltage regulated by a closed-loop controller. The compensator also has the hysteresis controller, which creates the commands applied to 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 [14]. Due to high switching commutation frequency, the passive filter is 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, inductors may be applied in the lines to compensate the reactive power flow.

B. Electrical System Model

The aircraft electrical system model considers the operation of the generation and distribution system with its respective non-idealities, which affect the power quality due to voltage drop. The simulation has a generator system, a power distribution system and three EHAs connected in parallel as the loads. The electrical system model is shown in Fig. 6.

The generator system consists 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. Probes in the PCC 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 controls the latero-directional and longitudinal aerodynamics surfaces. This equipment is a non-linear load, since its input has a 3-phase diode bridge. The EHAs model has a 3 phase Graetz diode bridge with a controlled current 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 simulation of the distorted current waveforms generated by the EHA in real operation.

C. Results

The simulation results show the voltages and currents waveforms measured in the PCC, the voltage frequency spectrum, the amplitude constraints defined by the MIL-STD 704F, and the calculated value of the voltage THD and IHC.

The test is divided in two conditions: the EHAs without operating and the EHAs starting their operation (maximum load). The results also show the cases where the active filters are connected and disconnected from the EHAs power input.

For the condition where the EHAs are not operating, Fig. 7 and Fig. **??** show the waveforms when the system has no active filters connected in the EHAs power inputs. For the same period, Fig. **??** and Fig. **??** show the waveforms when the active filters are connected to the EHAs power input. During this time 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 condition where the EHAs are requiring maximum current, Fig. **??** and Fig. **??** show the waveform when the active filters are not connected in the grid. In the same time interval, Fig. **??** and Fig. **??** show the waveforms when the active filters are connected to the EHAs power input. In this interval, it is clear the active filter enhancement in the system power quality. Considering these results, the active filter mitigates the harmonic content and set it within the limits of the MIL-STD 704F.

V. Conclusions

The simulation results showed a correct active filter response under high load variation, keeping the voltage within the limits defined by the aeronautical standards in terms of harmonic content.

There are some drawbacks when 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 loss in the filter operation, mainly due to the non-idealities of

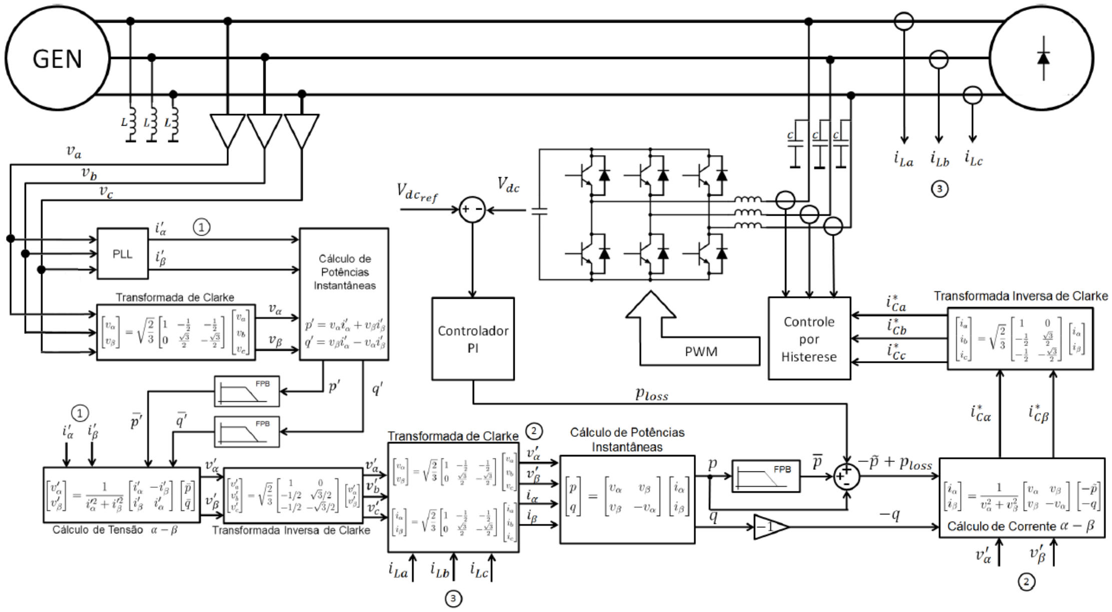

Fig. 5. Shunt active filter scheme

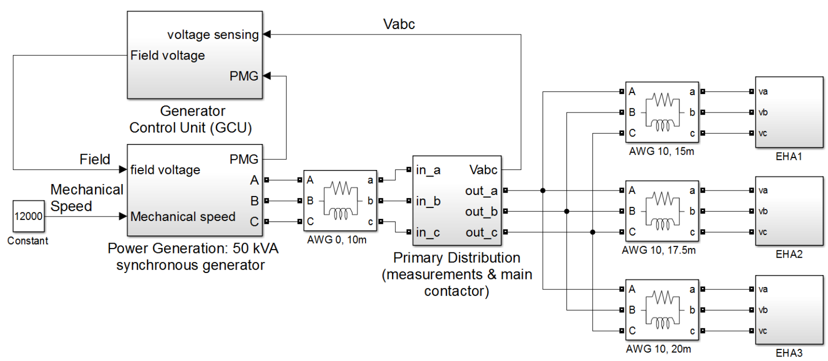

Fig. 6. Electrical generation and distribution model

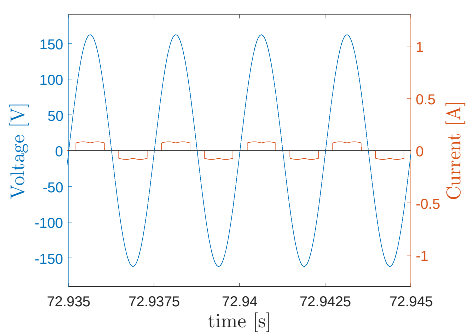

Fig. 7. Voltage and current waveforms for the system without load and filter

the switching devices, which is considerable when compared to energy drawn by the load operating with low consumption.

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