A Low Switching Frequency High Bandwidth Current Control for Active Shunt Power Filter in Aircrafts Power Networks

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***Abstract*- A five-level active shunt power filter (ASF) structure with a predictive current controller is proposed in this paper for application in aircraft power systems with variable fundamental frequency (ranging from 360Hz to 800Hz). The tested ASF is capable of a high bandwidth current control with a low switching frequency being able to effectively track harmonic current reference signals up to 5.6 kHz. Analysis of the proposed ASF structure for the aircraft applications includes current tracking performance and harmonic spectrum of the output ASF voltage. A comparison of the proposed five-level topology is made with the two–level one.**

I. INTRODUCTION

A tendency in the today aircraft industry is to achieve “more electrical aircrafts” to gain better efficiency and reduce the cost [1, 2]. The increased number of electrical loads on-board requires different power levels and therefore more power electronics converters, pushing for careful attention on the power quality issue in the aircraft power system.

The use of active power filters (APF) in power systems represents the best solution, in terms of performance and effectiveness, for harmonic distortion elimination, power factor correction, balancing of loads, voltage regulation and flicker compensation [3]. The shunt APF, connected in parallel with the non-linear load, is commonly utilized to compensate for current disturbances while the series APF is utilized to compensate for voltage disturbances.

The control structure of the active shunt filter (ASF) includes three key elements: the dc-link voltage control, the current control system and the method to determine the current references from the sensed currents of the harmonic producing load. The main focus of this paper is the performance of the ASF current control loop.

In ASF applications, the reference for the current loop consists of harmonic components at frequency much higher than the fundamental (usually 5th and 7th in three-phase systems). In the specific case of this research work the ASF is employed for harmonic compensation in an aircraft power system with the fundamental frequency varying from 360 to 800 Hz. This makes the current controller design a quite challenging task since the main harmonics to cancel will be in the worst case scenario at 4 kHz and 5.6 kHz.

A predictive controller [4], which incorporates a method for predicting variables two sample periods ahead of their appearance, is here employed allowing the control to work in the presence of microprocessor, and actuation delays. The proposed controller is a model-based controller and therefore the knowledge of system parameters is essential for satisfactory performance. Furthermore it introduces a minimal phase error by predicting the current reference two sampling instants ahead. This prediction is based on a polynomial extrapolation technique, designed using the Genetic Algorithm (GA) optimisation tool.

Multilevel converters [5] are generally used to obtain high voltage capability, good power quality, good electromagnetic compatibility and low switching losses at the expense of to the larger number of switching devices and capacitor banks needed. Among these features the possibility of lower switching frequency operation is the most attractive for this work. The multilevel structure, chosen in this work for ASF applications in aircrafts, is a series connection of H-bridges per phase. This converter has a modular structure with a separate dc side of each module and balanced switch current. A five-level ASF structure is used in this work to obtain a low switching frequency with a high bandwidth current control loop for effective harmonics compensation in aircrafts power networks.

The second section of the paper gives a small introduction about the aircraft power system specifications. The third section presents the five-level converter structure chosen for active power filtering application in aircrafts with an appropriate pulse width modulation. In the fourth and fifth sections, the overall control structure and current controller design are presented respectively. Verification of the proposed system performance is given through the simulation results in the sixth section. A few remarks concerning harmonic spectrum issues are indicated in the seventh section and finally the proposed five-level ASF structure is compared with the two-level one in the eight and last section.

II. AIRCRAFT POWER SYSTEM

In conventional aircrafts, the main power source to power the electrical subsystems, such as engine starting system, ignition system, passenger cabin service, lighting system etc., are aircraft engine driven AC generators [1, 2]. At present most commercial aircrafts have a three-phase power system operated with fixed frequency voltage (400Hz, 115V per phase) generated by a constant speed drive system. In modern aircrafts variable speed constant frequency starter/generator systems also are used; they deliver variable frequency power supply to the power converters which provide constant frequency voltage in output. A tendency in the future commercial aircrafts is to use variable frequency (VF) generators to meet lower maintenance cost and to increase reliability (the expected variable frequency range is 360 to 800Hz).

The concept of more electrical aircraft (MEA) includes a replacement of some mechanical, hydraulic and pneumatic loads with electrical ones. An increased number of electrical loads on board will therefore require power supplies that are different from those provided by the main generators. So MEAs will include an increased number of power converters, which are known as extremely nonlinear loads, forcing more attention to power quality issues on the weak isolated aircraft power network.

III. LOW SWITCHING FREQUENCY TOPOLOGY

To achieve the large control bandwidth required to compensate for high frequency harmonics while keeping the switching frequency low, a five-level converter with two single-phase H-bridge inverters connected in series (per phase) is employed. The five-level ASF connected to the power network is presented in Fig.1. This converter topology modulated with a phase-shifted carriers PWM strategy, gives an effective switching frequency four times the actual one of a single switch [7]. The sampling frequency must be exactly four times larger than the employed switching frequency and the modulation signal samples for each H- bridge must be taken at the peak and base of each particular (phase shifted) carrier to meet the best harmonic spectra of the output PWM voltage [8].

In this configuration, each H-bridge is modulated by a three-level carrier-based PWM. Using this modulation approach, sideband harmonics of the line output voltage of a single-phase H-bridge only exist at even carrier multiple groups (first dominant sideband harmonics are around $2\omega_c$, where ω_c is the carrier frequency in radians per second). Further harmonic cancellation for the proposed five-level converter topology is achieved by phase shifting the harmonics of the series connected H-bridges. This harmonic shifting is achieved by phase shifting the carriers of each bridge to achieve additional harmonic sideband cancellation around the even carrier multiple group. Optimum harmonic cancellation (for series of two H-bridges) is achieved by phase shifting each carrier by 90°. The first dominant sideband harmonics are in this case around $4\omega_c$.

IV. CONTROL STRUCTURE

The ASF system control structure is cascaded, with the current control as inner and the voltage control as outer control loop. The time constant of the voltage control loop is much higher then the current control loop so the design of these two loops can be independent. The output of the voltage PI controller presents the active component of the active power filter current to cover losses in the switching devices and parasitic resistance in the circuit. The active component needs to be added to the harmonic reference.

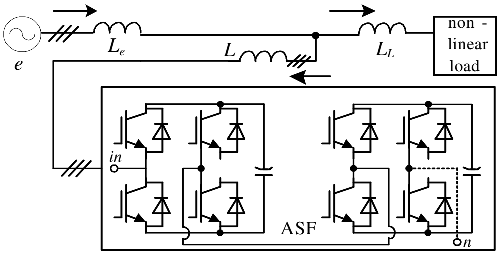

Fig.1 Five-level active shunt filter (ASF) connected to the power network

The proposed ASF current controller is derived in the fixed a-b-c reference frame to maintain flexibility for future work on an unbalanced supply; to add an active current component reference to the harmonic current components reference, the supply voltage angle needs to be calculated as shown in Fig 2.

Phase-shifted carrier PWM (PSCPWM) to modulate cascaded single-phase H-bridges is here used. The advantage of this kind oh modulation is the inherent voltage balancing of the series connected H-bridges in one phase. Including inevitable losses of the active shunt filter (semiconductor switches and inductor resistance), the voltage control loop, Fig.2, can keep the voltage level of the dc link across one phase on the desired level. To equalize the voltages of two H-bridges in one phase, caused by the difference in losses of two bridges, the voltage balancing control structure is added, Fig.2.

If the level of voltage across one capacitor is higher then the desired level, the level of voltage across the other capacitor is lower. The current direction and the switch combination define charging or discharging of the each particular capacitor of the dc link. Depending on the current direction and needed charging/discharging process, the offset (offset1/offset2 in Fig.2 for upper/down H-bridge) should be added or subtracted to/from the modulating signal. Voltage balancing is achieved through a proportional control of the error between the voltage levels across the capacitors of two H-bridges in one phase, Fig.2. Once the offset for the upper H-bridge (offset1) is defined by the output of P controller, the offset for the bottom H-bridge (offset2) is given by the following equation [9]:

$$offset2 = {(-offset1 \cdot vdc1)}\Big/{vdc2} \tag{1}$$

where $vdc1$ and $vdc2$ are respectively dc voltages across the capacitors of upper and bottom H-bridges in one phase.

V. CURRENT CONTROLLER

This section is focused on the development of an efficient current controller for the aircraft active shunt power filter. This controller must be able to operate in the conditions of the aircraft power system frequency variations (variable frequency range from 360Hz to 800Hz). Most commonly, active power filters need to compensate for the dominant current harmonics which are represented by the 5th and the 7th, as well as reactive current harmonic components of the non-linear load at the point of connection.

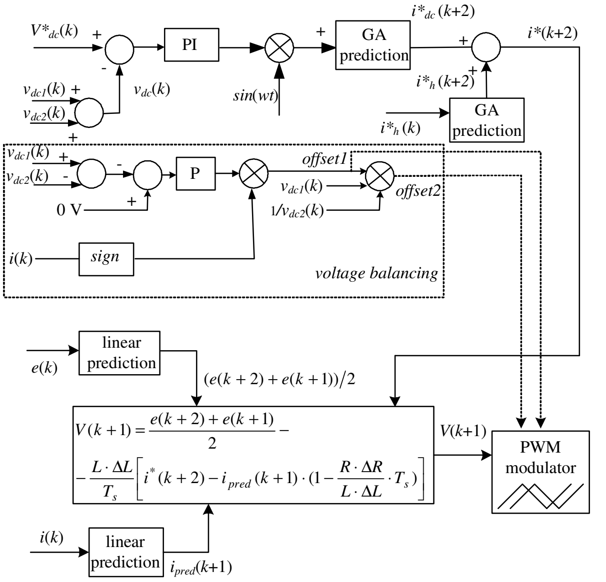

Fig. 2 The proposed control strategy (single phase representation)

In aerospace applications, if the power network works at the maximum fundamental frequency of 800Hz the active shunt power filters have to be able to inject current harmonic components with the frequency of 4kHz and 5.6kHz, corresponding to the 5th and the 7th harmonics respectively.

A "two steps ahead" predictive current controller [4], that is able to deal with unavoidable system delays in order to minimize current reference tracking errors, is here employed.

To simplify the control law, the delay caused by the computational time required for the ASF voltage reference calculation, is kept constant and equal to one sampling period. The aim of the proposed current controller is to predict the active shunt filter voltage reference for the next sampling period to eliminate the current error at the sampling instant two steps ahead. The proposed current control strategy can be summarized in the following equation:

$$V(k+1)=\frac{E(k+2)+E(k+1)}{2}-\frac{L\cdot\Delta L}{T_s}\left[i^*(k+2)-i_p(k+1)\cdot(1-\frac{R\cdot\Delta R}{L\cdot\Delta L}\cdot T_s)\right] \quad (2)$$

where $V(k)$ and $E(k)$ are respectively the active shunt filter voltage and power supply voltage, k is an instant of measurement, T_s is a sampling period, $i(k)$ is the active shunt current, $i^*(k)$ is the reference shunt filter current, $i_p(k+1)$ is the predicted active shunt filter current at sampling instant k+1, the modeled input impedance is denoted by $R\Delta R$ and $L\Delta L$ where R and L present the actual values of the input impedance and ΔR and ΔL represent the inaccuracy of the input resistance and the input inductance respectively.

It should be noted that at the instant of measurement k, current and voltage values for the next sampling period are not available and need to be predicted. The prediction of the supply voltage at the time instant k+1, and k+2 is made using available voltage values at the instant of measurement and at the previous sampling instant. A linear-type prediction is then applied.

The ASF current reference calculation, which is not the subject of this paper, can be performed using any of the algorithms presented in literature. A "two steps ahead" prediction of the current reference needs furthermore to be applied for the phase error minimization of the proposed current control method. To predict current reference values two samples ahead, an extrapolation technique here is applied. The extrapolation uses values from a few previous sampling instants to approximate a value in one or more sampling instants ahead. The employed "two steps ahead" current reference prediction method can be expressed in the form [4]:

$$i_p^*(k+2)=a\_h\cdot i^*(k)+b\_h\cdot i^*(k-1)+c\_h\cdot i^*(k-2) \quad (3)$$

where a_h, b_h and c_h are the prediction coefficients to be determined. Equation (3) is applied to each particular harmonic h present in the active filter reference current and previously identified with the chosen reference calculation algorithm. Those parameters have been selected using a Genetic Algorithm (GA) optimisation routine, Fig.2.

At the instant of measurement, the value of the ASF current at the sampling instant k+1 is not available and need to be predicted as well. This prediction uses the predicted current reference value for the following sampling instant and the values of actual and reference currents at the instant of measurement [4].

VI. CURRENT TRACKING SIMULATION RESULTS

Tab. 1 Main parameters of the proposed five-level ASF for aircraft power network

Analyzed system main parameters	
power network	115V/(360Hz-800 Hz)
dc voltage reference per converter leg:	500 V
dc capacitor	1200μF
filter input inductor	0.5 mH
switching frequency	9.6 kHz
sampling frequency	38.4 kHz

An accurate simulation model of the three-phase five-level ASF connected to the network has been developed in MATLAB/SIMULINK environment. This model includes real switches, capacitors and inductors from SimPowerSystems library. The main parameters of the proposed five-level active shunt power filter for aircrafts applications are given in Tab.1.

A Phase-shifted carrier PWM is applied with switching frequency of 9.6 kHz. To get the best harmonic contents of output ASF voltage, two triangle carrier waveforms for each H-bridge in one phase, shifted by 90º, are used. The samples of the modulation signal, obtained with the previously described control algorithm, must be taken at the peaks and bases of the particular carrier for one H-bridge. The resultant sampling frequency is four times larger then the applied switching frequency (38.4 kHz). It must be assured though that all calculations are completed inside one sampling period. Using this kind of modulation, asymmetrical PWM of each H-bridge is achieved eliminating the need for analogue anti-aliasing filters. This approach excludes additional hardware delays on the control loop, which can be a critical factor to achieve good current tracking performance for demanding aircraft ASF applications.

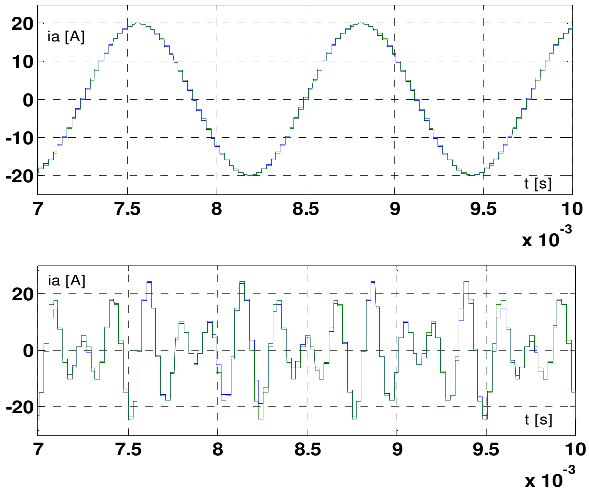

Fig. 3 Five-level active shunt filter phase current tracking performance (power network fundamental frequency of 800 Hz)
a) reactive current component, b) 5th and 7th harmonic current combination

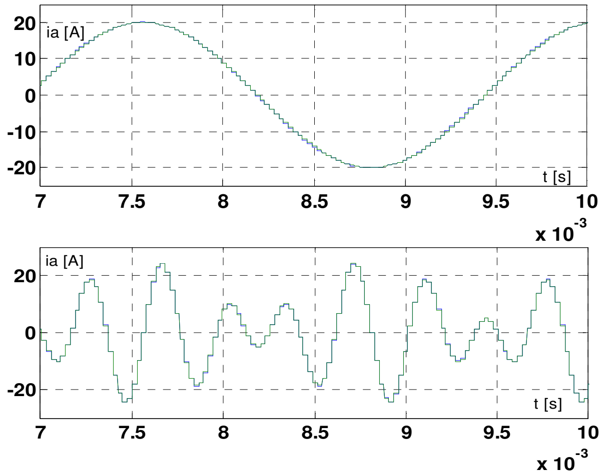

Fig. 4 Five-level active shunt filter phase current tracking performance (power network fundamental frequency of 400 Hz)
a) reactive current component, b) 5th and 7th harmonic current combination

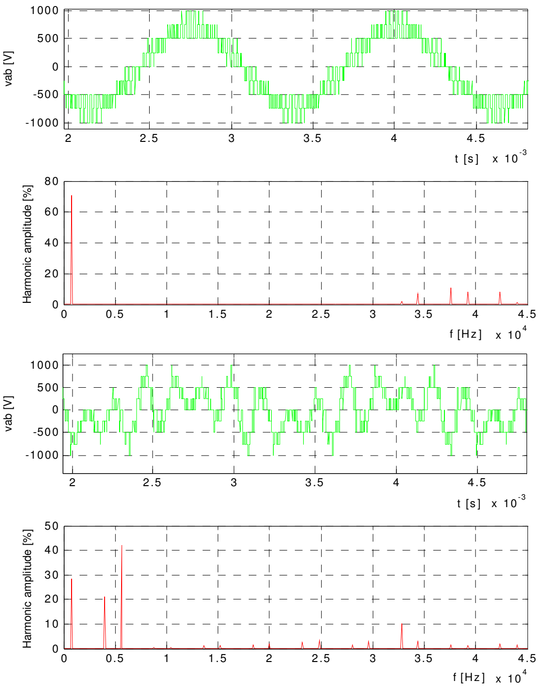

Fig. 5 Harmonic spectrum of the five level line-line output voltage PWM; switching frequency 9.6kHz, sampling frequency 38,4kHz (fundamental frequency is 800 Hz)
a) only reactive current component is injected, b) 5th and 7th harmonic current injected

The proposed five-level ASF topology with the predictive current controller has been tested for a simulated aircraft power network (115V per phase and 800Hz) in the condition of wide frequency variation. Figure 3. and Figure 4. show the current tracking performance of the proposed ASF system for a reference current consisting of a combination of the 5th and 7th harmonic components; those components are at 2 kHz and 2.8 kHz respectively for the 400Hz case of fig. 4 and at 4 kHz and 5.6 kHz respectively for the 800 Hz case of fig. 3. Simulation results confirm an excellent current reference tracking performance.

VII. HARMONIC SPECTRUM

In active shunt power filter applications, the modulating waveform of the carrier-based PWM techniques consists not only of the fundamental frequency component but also of the higher frequency components (most usually the 5th and the 7th harmonic components). The frequency spectrum of the PWM output voltage for the case in which the modulating waveform is more complex than pure sinusoidal one, is the same and defined by the general analytical expression given in [7]. However the amplitude spectrum is quite different. The harmonic energy of the sidebands of the multiple carrier groups is redistributed. This issue is particularly emphasized for the lower carrier/fundamental ratios, common in high frequency aerospace applications. In the case of a sinusoidal modulating waveform, dominant sideband harmonics are the 1st and the 5th around the 4th carrier group for the proposed five-level topology as in Fig.5a. If the modulating waveform consists of the 7th, 5th and reactive components (respectively 40%, 20% and 30% of the peak current value) the harmonic energy is more spread around multiple carrier groups, with significant harmonics till the 19th sidebands as in Fig. 5b. The triple harmonics are cancelled in line-to-line voltage for both the sinusoidal and non-sinusoidal modulating wave, as expected.

This redistribution of the harmonic energy due to the modulation should therefore be taken into account in choosing an appropriate input filter. Sizing of the input filter, in fact, always include a compromise between the values of the input inductors and switching frequency.

The harmonic spectrum of the tested five-level ASF phase current consisting of the 5th and 7th harmonic components, (Fig.6) shows the concentration of the dominant harmonics around the 4th carrier harmonics group. These results justify the values chosen for the switching frequency (9.6 kHz) and the input filtering inductance (0.5 mH).

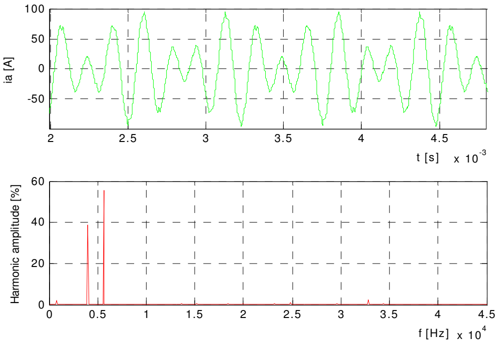

Fig. 6 Harmonic spectrum of the five-level active shunt filter phase current (fundamental frequency is 800Hz)

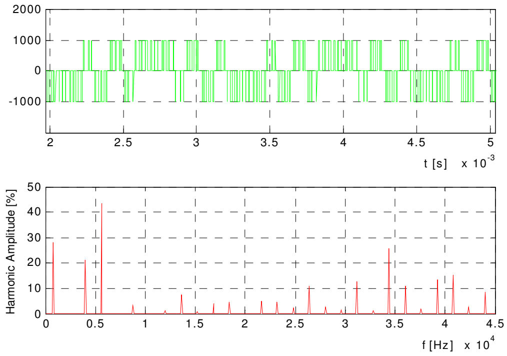

Fig. 7 Harmonic spectrum of the two-level line to line output PWM voltage (5th and 7th harmonic component injected); switching frequency 20 kHz, sampling frequency 40 kHz

VIII. COMPARISON WITH TWO-LEVEL CIRCUIT TOPOLOGY

The proposed three-phase five-level converter output PWM voltage is compared with the three-phase two-level one. The main parameters of the two-level system are given in Tab.1 excluding the switching and sampling frequency. The same predictive controller, described in section V, is applied for a two-level converter, as well. For the two-level topology, to track a current signal of 5,6 kHz, a switching frequency of at least 20 kHz must be employed. To get an optimum output harmonic spectrum, an asymmetrical PWM technique is used (two samples per switching period leading to a sampling frequency of 40 kHz). The harmonic spectrum of the line-line PWM output voltage is shown in Fig. 7. The first dominant harmonics are around the first carrier group and due to the injected 5th and the 7th harmonic components, the sidebands are more spread and filtering the unwanted harmonics from the PWM waveform is very difficult. So this confirm the superiority of the proposed five-level topology compared to the two-level one.

IX. CONCLUSIONS

A five-level H-bridges cascaded structure is proposed for active shunt filtering applications in aircraft power system networks where the fundamental frequency is expected to vary between 360 Hz and 800 Hz.

The proposed high bandwidth, two-steps ahead predictive current controller gives excellent current reference tracking performance with reduced switching frequency. The system is tested in simulation for the fundamental, 5th and 7th harmonic current components compensation.

In the environment of the fundamental frequency varying, of future aircraft power network, the proposed strategy gives very good results without any need for additional controller parameters adjusting. The employed five-level structure in combination with the phase-shifted carrier pulse width modulation strategy ensures low switching frequency, concerning a single switch, giving four times bigger effective switching frequency on the output of converter.

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