# STUDY AND PERFORMANCE OF MULTI LEVEL CASCADED SHUNT ACTIVE FILTER FOR AIRCRAFT APPLICATION

**Irshad Basha Shaik, G.Naveen, M.Kondalu, S.Ananthasai**

**Abstract— With the progress of "more electric aircraft," introducing active power filter (APF) technology into the aircraft power system to improve its quality and reliability catches growing interest. In this paper, based on the analysis and modeling of the shunt APF with close-loop control, a feed forward compensation path of load current is proposed to improve the dynamic performance of the APF. The two H-bridge cascaded inverter is selected for the aeronautical APF (AAPF). Justifications paper for topology choosing and corresponding system control method are given. Furthermore, the global framework and operation principle of the proposed AAPF are presented in detail. A prototype with the load power of 7.2 kVA is built and tested in the laboratory. Experimental results verify the feasibility of the proposed AAPF and the high performance of the control strategy during steady-state and dynamic operations.The increasing use of electrical power in place of hydraulic, pneumatic, and mechanical power is demanding more advanced aircraft power systems. The concept of the "all-electric aircraft" and the "more electric aircraft" (MEA) have been introduced to overcome some of the drawbacks found in conventional architectures and bring more attractive advantages, such as improved fuel consumption and lower maintenance and operation costs. This implies an increase of the electrical load and power electronic equipment, higher consumption of electrical energy, more demand for generated power, power quality, and stability problems.**

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**Irshad Basha Shaik**, Student Joginpally B.R Engineering College, Hyderabad, India

**G.Naveen**, Assoc.Prof Joginpally B.R EngineeringCollege Hyderabad, India

**M.Kondalu** , Prof &Head, Joginpally B.R Engineering College, Hyderabad, India

**S.Ananthasai**, Asst.Prof, Joginpally B.R Engineering College Hyderabad, India

***Index Terms***— APF : Active Power Filter, AAPF : Aeronautical Active Power Filter, EPS: Electric Power Supply, MEA: More Electric Aircraft ,CPS : Carrier Phase Shift, PWM : Pulse Width Modulation, IR: International Rectifier, THD: Total Harmonic Distortion.

## I. INTRODUCTION

The latest research about civil aircraft systems has moved towards the increasing use of electric power in place of other conventional sources like mechanical, hydraulic, pneumatic power. This technological trend is known as the Electric Aircraft.

Recent advances in the areas of power electronics, electric devices, control electronics devices, and microprocessors have allowed fast improvements in the performance of a aircraft electrical systems. The use of electric power brings significant advantages for the operation of the whole system. These advantages are listed here.

***Advantages of the increasing use of electric power in the aircraft system***:

- optimization of the performance
- optimization of the life cycle cost
- reduction of weight and size of the equipment
- increased reliability

Important changes are brought to the aircraft electrical system due to the increasing use of electric power. These changes are listed below. Consequences of the increasing use of electric power on the aircraft electrical system:

- more electrical loads
- more complex topology of the electrical network

These aspects have to be taken into account when designing the devices in the system. It is crucial to guarantee that not only the device itself functions properly according to the specifications, but also that the interaction with the whole system respects the required conditions. In a system like the aircraft power network, the amount of generated power cannot be considered as infinite compared to the demanded power. Strict limitations are imposed on the stability and the power quality of the aircraft power system, in

order to guarantee its optimal performance. Particularly, limitations on the voltage and current harmonics injected by the distorting loads are strictly recommended by aircraft regulations. In order to respect these conditions, the power electronic devices used on board have to be designed in order to inject the minimum amount of harmonics and the harmonics which exceed the maximum allowed level have to be eliminated or compensated. Shunt active power filters provide an elective solution for the harmonic elimination and the improvement of the power quality for this kind of a system. The shunt active filter works as a controlled current source which injects into the grid an amount of harmonic current equal to the one drawn by the distorting loads.

The control strategy is proposed for a controlled shunt APF to reduce real-time computational requirements. The harmonic filtering performance of the APF in both the conventional and

the advanced aircraft EPS is presented with matlab simulation Results. Based on the given structure and modeling of the advanced aircraft EPS, performance and its characteristics of the EPS without and with APF are compared. The power-quality characteristics of both the conventional and the advanced aircraft EPS with APF are shown. The shunt APF with close-loop control, a feed forward compensation path of load current is proposed to improve the dynamic performance of the APF.

The increasing use of electrical power in place of hydraulic, pneumatic, and mechanical power is demanding more advanced aircraft power systems. The concept of the "all-electric aircraft" and the "more electric aircraft" (MEA) have been introduced to overcome some of the drawbacks found in conventional architectures and bring more attractive advantages, such as improved fuel consumption and lower maintenance and operation costs[1]. This implies an increase of the electrical load and power electronic equipment, higher consumption of electrical energy, more demand for generated power, power quality, and stability problems. Fig. 2.1 illustrates the next-generation electrical power system (EPS) of MEA. In the variable-speed variable-frequency (VSVF)-based EPS, the "constant speed drive" is moved. Harmonic current compensation by means of active power filter (APF) is a well-known effective solution for the reduction of current distortion and for power quality improvement in electrical systems[2]. The shunt compensator behaves as a controlled current source that can draw any chosen current references which is usually the harmonic components of the load currents. Meanwhile, more and more APFs are applied not only in harmonic current and reactive power compensation but also in the neutral line current compensation, harmonic damping application, and power flow control. As Fig. 2.1 shows, in the aircraft EPS, the APF could be installed in the source side (such as the aircraft generator) or near the load side, and it could even be integrated into the load-front converter (such as the input stage converter of variable-speed drives). Good power quality of the EPS is achieved by using the novel AAPF. Furthermore, in order to improve the dynamic performance of the load response, a feed forward path of the load.current is added. Based on the modeling and analysis of the close-loop system, the operation principle of the feed forward compensation path is revealed. Meanwhile, the control method of the cascaded-inverter-based AAPF is proposed. The operation principle containing the overall voltage control and voltage-balance control is given. Simulation results under different fundamental frequencies and load conditions are taken.

## II. CLOSE-LOOP CONTROL STRATEGY AND ITS FEEDFORWARD COMPENSATION

### 2.1. Close-Loop Control Strategy

In the traditional control of APF, the current reference is usually the harmonic and reactive components of the load currents. However, the approach, essentially based on feed forward open loop control, is sensitive to the parameter mismatches and relies on the ability to accurately predict the voltage-source inverter current reference and its control performance [5][6][7]. In the aircraft EPS, the fundamental frequency is much higher than 50-Hz power system. To measure errors in analog to digital conversion time, digital delay, and other non ideal factors will deteriorate the open-loop compensation effect to a worse degree. The feedback control has the following merits: It could reduce the transfer function from disturbances to the output, and it causes the transfer function from the reference input to the output to be insensitive to variations in the gains in the forward path. Therefore, compared with open-loop control, close-loop control is more suitable for the aeronautical application.

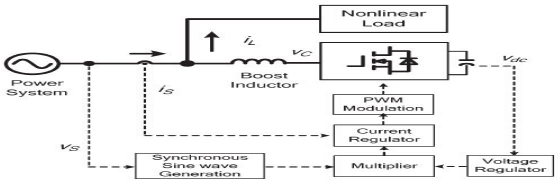



Fig. 2.1. Control diagram of source current direct control.

### 2.2. Source Current Direct Control

The close-loop control named as source current direct control is applied as the main control strategy of the proposed AAPF. The source current direct control is proposed by Wu and Jou. The basic system diagram of the close loop control scheme is given in Fig. 2.2. This control strategy operates as follows: The dc-link voltage is sent to the voltage regulator, and the output

of the regulator is sent to the multiplier as well as a synchronous sine wave which is detected from the phase voltage. The output of the multiplier is sent to the current regulator, being the source current reference. The output of the current regulator will be sent to the modulator to generate the pulse width modulation waveforms. Fig. 2.3 gives the equivalent control model of this compensation strategy. As shown in Fig. 2.3, the source current reference of the source current direct control comes from the variation of the dc-link voltage. Here, *Gv*(*s*) corresponds to the transfer function of the voltage controller; *Kf* is the dc-link voltage detection coefficient.

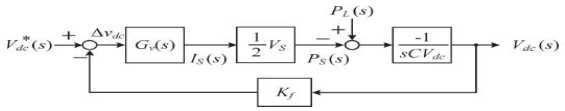


Fig. 2.2. Model for active power analysis

### 2.3. Load Current Feed forward Compensation

As Fig. 2.1 illustrates, load power *PL*(*s*) works as a disturbance factor on the APF system. The transfer function between *PL*(*s*) and Δ*Vdc*(*s*) is

$$\varphi_{en}(S) = \frac{\Delta V_{dc}(s)}{P_L(s)} = \frac{\frac{1}{sCV_{dc}}K_f}{1+G_v(s).\frac{1}{2}V_s.\frac{1}{sCV_{dc}}K_f} \qquad (2.1)$$

The transfer function between *IL*(*s*) and *IS*(*s*) is

$$H_{iL}(s) = \frac{I_S^*(s)}{I_L(s)} = \frac{\Delta V_{dc}(s)G_V(s)}{P_L(s)} \Big/ \frac{1}{2}V_s - \varphi_{en}(s).\frac{G_V(s)}{\frac{1}{2}V_s}$$

$$= \frac{G_V(s).\frac{1}{2}V_s\frac{1}{CV_{dc}}K_f}{s+G_V(s).\frac{1}{2}V_s\frac{1}{CV_{dc}}K_f} = \frac{A.G_V(s)}{s+A.G_V(s)} \qquad (2.2)$$

Where *A* = *VsKf* /(2*CVdc*).

*HiL*(*s*)|f=50 shows the dynamic speed of the current reference responding to the load power's change at fundamental frequency. Generally speaking, high dynamic respond is required for an APF system, meaning that a higher value of *HiL*(*s*)|f=50 is desired. However, *HiL*(*s*) is sensitive to many other factors, i.e., voltage controller, line voltage, dc-link voltage, dc-link capacitor, and voltage detection coefficient. Fig. 3.4 shows the bode diagram of *HiL*(*s*) in different voltage controller and coefficient A. For an APF system applied in a 220-V/50-Hz application, coefficient A corresponds to 0.14 when the dc-link voltage is 800 V, dc-link voltage detection coefficient *Kf* is 0.005, and the dc-link capacitor is 6800 $\mu$F. It is hard to design a voltage controller to derive a high value for *HiL*(*s*)|f=50 at 50 Hz in such a low value of A. In the aircraft EPS, the phase voltage is only 115 V, leading A to be 0.2 when the dc-link voltage is 600 V, dc-link voltage detection coefficient *Kf* is 0.005, and the dc-link capacitor is 3300 $\mu$F. It means that poor dynamic respond is derived in both applications. In order to improve the dynamic speed responding to the load's change, A feed forward compensation path is added to weaken the disturbance effect of the load current. Here, *F*(*s*) is the transfer function of the low-pass filter (LPF) which extracts the fundamental components of the load Currents.

$$F(S) = \frac{\omega_o^2}{S^2+\sqrt{2}\omega_o s+\omega_o^2} \qquad (2.3)$$

Here, $\omega 0 = 2\pi fc$ is the cutoff angular frequency of the LPF. After the fundamental of the load current is feed forward, the transfer function between *IL*(*s*) and *IS*(*s*) becomes[12]

$$H_{iL}(S) = \frac{A.G_v(s)}{s+A.G_v(s)} + \frac{\omega_o^2}{s^2+\sqrt{2}\omega_o s+\omega_o^2} \qquad (2.4)$$

Fig. 2.2 shows the bode diagram of *HiL*(*s*) with feed forward compensation and different cutoff frequencies[11]. After the load current is feed forward, the magnitude of *HiL*(*s*)|f=50 gets increased. However, the selection of *fc* plays an important role to *HiL*(*s*); usually, *fc* should be larger than the fundamental frequency.

## III. CONTROL METHOD OF THE CASCADED-INVERTER-BASED AAPF

### 3.1. Discussion and Demonstration on the Power Stage of AAPF

A shunt APF acts as a controlled harmonic current source, injecting current which is inverse equivalent to the load harmonic. In the 400-Hz aircraft EPS, frequencies of the 11th and 13th harmonics reach as high as 4.4 and 5.2 kHz. How to draw a high-frequency harmonic current accurately is a key issue of developing AAPF [3].

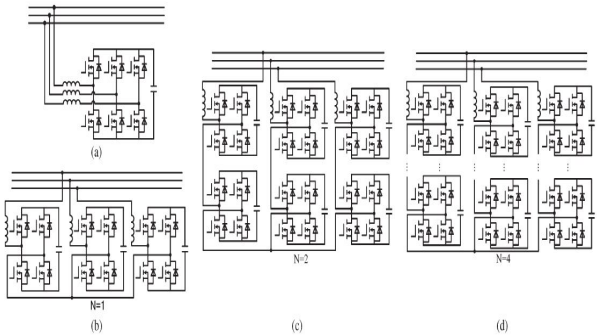



Fig. 3.1. Four possible solutions of AAPF. (a) Three-leg-inverter-based APF. (b) H-bridge-based APF. (c) Two H-bridge cascaded APF. (d) Four H-bridge cascaded APF

$$P_{con} = I_{RMS}^2 R_{ds(on)} D + V_{DF} I_D (1-D).$$

TABLE PARAMETERS OF FOUR POSSIBLE AAPF SOLUTIONS

| Solution | Dc-link Voltage (V) | Switching Frequency(KHz) |
|---|---|---|
| Three leg inverter based APF | 400 | 60 |
| | | 120 |
| | | 240 |
| H-bridge based APF | 300 | 30 |
| | | 60 |
| | | 120 |
| Two H-bridge cascaded APF | 150 | 15 |
| | | 30 |
| | | 60 |
| Four H-bridge cascaded APF | 75 | 7.5 |
| | | 15 |
| | | 30 |

Table 3.1 shows four possible solutions of APF

the three leg-inverter-based APF, the H-bridge-based APF, the two H-bridge cascaded APF, and the four H-bridge cascaded APF. Comparative study of these solutions is taken as follows. For the first solution, in order to achieve good current tracking performance in 400-Hz system, the switching frequencies of APF are selected as 30, 60, 120, and 240 kHz, and the dc-link voltage is adopted as 400 V. For the second solution, considering the "double equivalent switching frequency effect" of the carrier phase shift PWM modulation the switching frequencies of AAPF are selected as 30, 60, and 120 kHz, and the dc-link voltage is adopted as 300 V. Meanwhile, the same equivalent switching frequency means almost the same current tracking performance and almost the same bandwidth of AAPF. The switching frequencies and dc-link voltage of the other two solutions are given in Table 3.1. The power switches in Table 3.1 are all from International Rectifier (IR) Corporations with the current rating near 24 A. The switching losses and conductive losses of the power MOSFET could be evaluated by using the switching loss estimation method used .Here, *PSW* and *Pcon* correspond to switching loss and conductive loss, and *ID*, *VD*, and *fsw* are the drain current, bus voltage, and switching frequency, while *tON* and *tOFF* are the power MOSFET turn-on and turnoff times, respectively. *COSS Rds*(*on*) are the output capacitance and the on-resistance of the power MOSFET while *VDF* is the forward voltage drop of the reverse parallel diode of the power MOSFET. Power loss distributions of the four different AAPF solutions are given in Fig. 3.1.2.

1) Compared with the last two solutions, switching power loss plays important roles for the first two solutions. Un negligible switching power losses make the first two solutions less competitive when the switching frequency increases.

2) Negligible switching power losses in the last two solutions make the total power

losses smaller in a wide range of switching frequency. Meanwhile, power losses of the last two solutions are nearly in the same level. On the other hand, the "dead-time effect" deteriorates the current tracking performance of APF The switching frequency is selected as 30 kHz, so the ac voltage of each cluster becomes a five-level line-to neutral PWM waveform with the lowest harmonic sideband centered at 120 kHz Maintenance of the voltage balance of the capacitors is critical to the safe operation of the H-bridge-based AAPF. The voltage-balance control of the floating dc capacitors can be divided into the following:

1) Clustered overall control;
2) Balancing control.

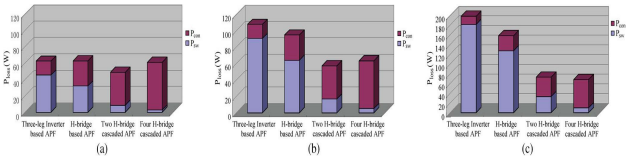



Fig. 3.1.1 Power losses of different possible AAPF

solutions (a) with the equivalent switching frequency freq. of 60 kHz (b) With the equivalent switching frequency freq. of 120 kHz (c) With the equivalent switching frequency freq. of 240 kHz.

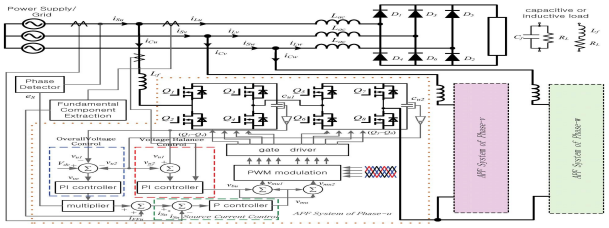



Fig. 3.1.2. System diagram of the proposed AAPF

### 3.2 Clustered Overall Control

In the cluster overall voltage control loop, sums of the capacitor voltages in each cluster (for example: *vu*1 and *vu*2 for phase-*u*) are the control target. This cluster overall control yields the *u*-phase clustered overall voltage signal *vou* from the dc capacitor voltage reference *vdc*, the dc capacitor voltages of the *u*-phase cluster *vu*1, *vu*2, and the synchronous sine wave *eSu* (as shown in Fig. 3.2.) The remaining cascaded units would share the dc-link voltage of the fault one.

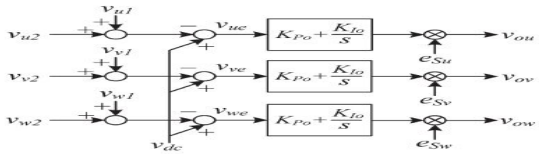


Fig. 3.2.1 Control diagram of the cluster overall control.

This voltage control scheme can increase the fault toleration and reliability of the AAPF system[5].

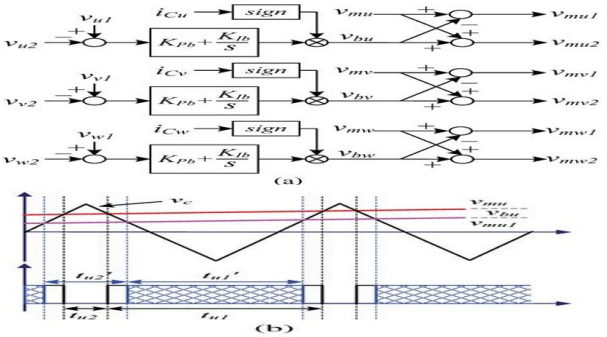


Fig. 3.2.2. Operation principle of voltage-balance control. (a) Control diagram.(b) Regulation procedure.

### 3.3. Balancing Control

The balancing control yields a balance control signal vbn (n = u, v, w) to make the voltage of the capacitors in each cluster balanced. The individual balance control yields two modulation waves vmn1 and $vmn_2$ from the origin modulation wave vm and the dc capacitor voltages of each cluster $vn_1$, $vn_2$. In the CPS PWM modulation, PWM signals for $Q_1$,$Q_2$ and $Q_3$,$Q_4$ are modulated by vmn1, while PWM signals for $Q_5$,$Q_6$ and $Q_7$,$Q_8$ are modulated by vmn2 as shown in fig 3.3.1. The current direction and the switch combination define the charging or discharging of the each particular capacitor of the dc link. Depending on the current direction and needed charging or discharging process, the voltage signal v should be added or subtracted to/from the modulating signal. For the upper cascaded unit, the input power decreases when the duty cycles of $Q_1$ and $Q_4$ decrease, resulting in the dc-link voltage vu1 being reduced. Similarly, the dc-link voltage of the lower cascaded unit $vu_2$ will get increased. The voltage balance is therefore achieved. Take the phase-u cluster for example to show the regulation procedure of voltage-balance control. In the steady state, the modulation wave of bridge 1 (composed of Q1 and $Q_2$) is vmu, and the conduct times of $Q_1$ and $Q_2$ are $tu_1$ and $tu_2$, respectively. When the situation vu1 > $vu_2$ happens, a positive balance control voltage signal vbu is obtained under the regulator's action. The final modulation wave for $Q_1$ and $Q_2$ is the sum of vmu and −vbu, which becomes vmu1 after regulation[10]. Therefore, the conduction times of $Q_1$ and $Q_2$ turn tobe $tu_1$ and $tu_2$. We could find that $tu_1 < tu_1$ and $tu_2 > tu_2$, which means that the duty cycle of $Q_1$ decreased but the duty cycle of $Q_2$ increased[4][9]. Meanwhile, the duty cycle of $Q_3$ increased, and the duty cycle of $Q_4$ decreased.

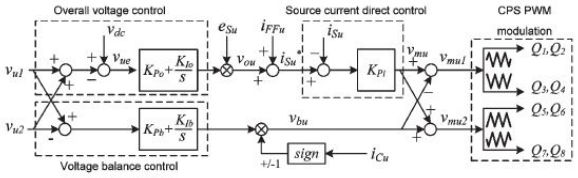
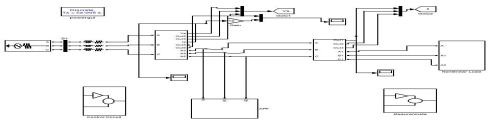


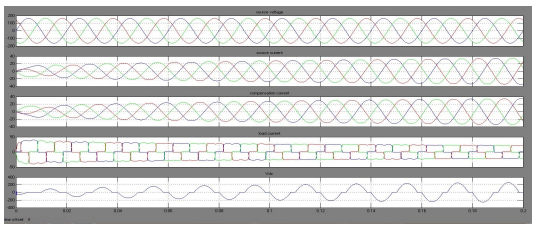

Fig. 3.3.1. Control diagram for phase-u of the proposed AAPF.

## IV. MATLAB/SIMULATION RESULTS

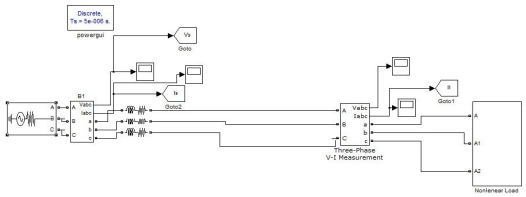
Simulation results with APF for inductive Load



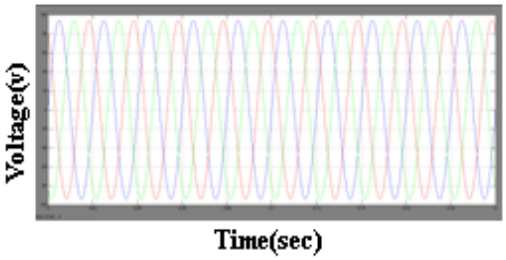
Simulated waveforms for 50-Hz EPS application with Inductive load



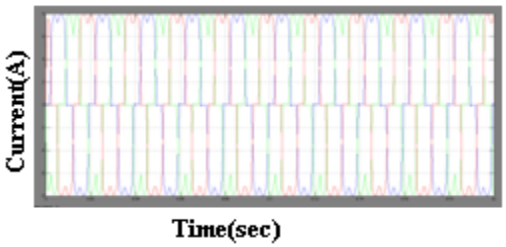
Simulation for without APF



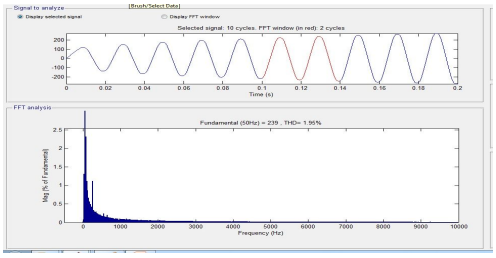
SOURCE VOLTAGE



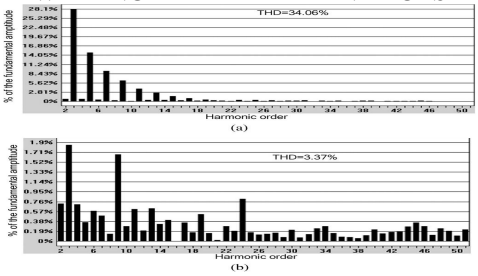

LOAD CURRENT




**With CASCADED SAPF the THD results**

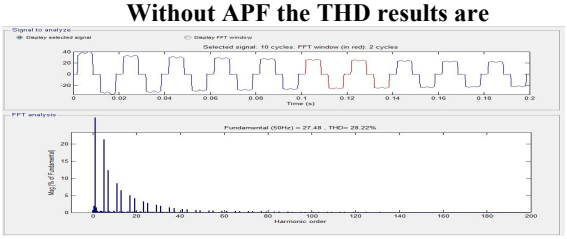


**WITH NORMAL APF THD VALUES**




Current THD. (a) Load current. (b) Source current.

**Without APF the THD results are**




## V. CONCLUSION

APF technology is a useful method to resolve the power quality issues of the modern aircraft EPS. In this paper, a load current feed forward compensation method for the source current direct control-based AAPF has been proposed. The corresponding system control strategy of the cascaded-inverter based active filter system is shown. behavior for various kinds of nonlinear load condition and the excellent dynamic performance of the proposed control method

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