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Fuzzy Logic Controller for Cascaded Shunt Active Power Filter

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ABSTRACT
With the increasing use of electrical power in place of hydraulic, pneumatic, and mechanical power is demanding more advanced aircraft power systems 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 and also fuzzy logic control is applied to improve the dynamic performance of the APF and for reduction of THD. The two H-bridge cascaded inverter is used for the aeronautical APF (AAPF). Justifications 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. Simulated waveforms in different load conditions indicate the good performance of the AAPF.

Keywords: cascaded multilevel inverter, close-loop control, feed forward of fundamental load current.

1. INTRODUCTION
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. 1 illustrates the next-generation electrical power system (EPS) of MEA (J. A. Rosero et al., 2007). In the variable-speed variable-frequency (VSVF)-based EPS, the "constant speed drive" is moved (A. Hamadi et al., 2010). 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. The shunt compensator

behaves as 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. 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), (A. Varschavsky et al.,2010). In this paper, a high-performance aircraft APF is proposed. Differently from traditional open-loop control strategy, the proposed aeronautical APF (AAPF) works in a close-loop way. 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.

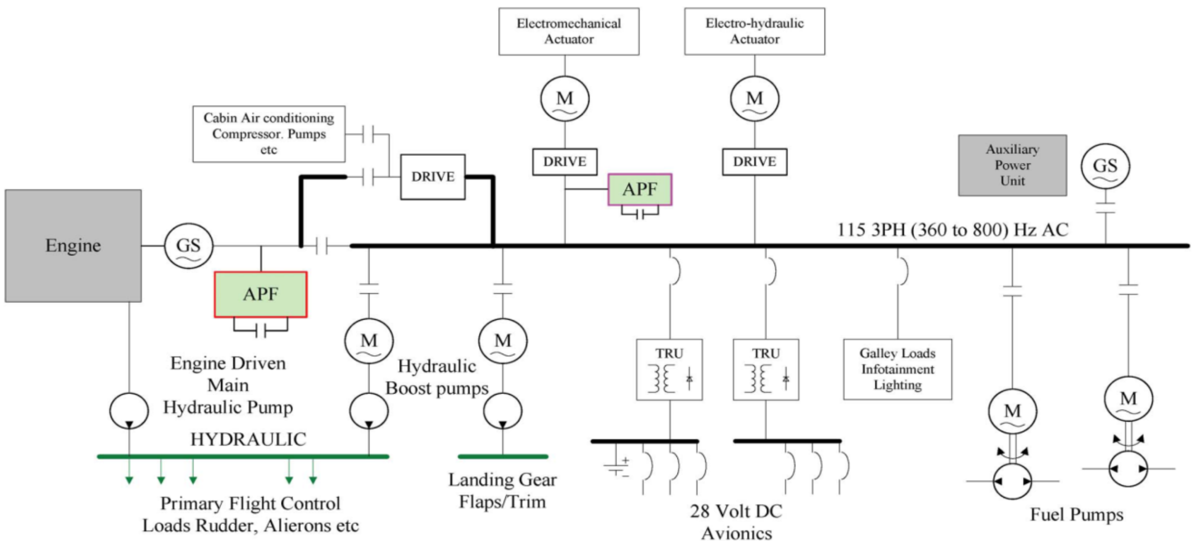

Figure 1

Next-generation electrical system of MEA

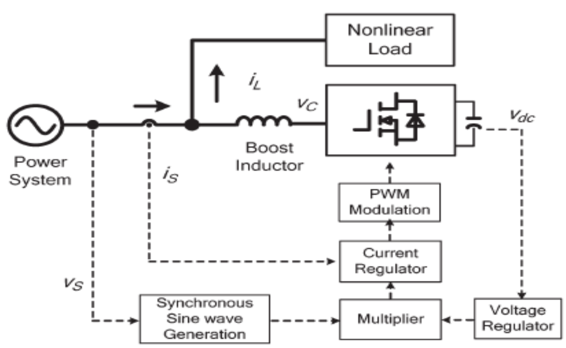

Figure 2

Control diagram of source current direct control.

2. CLOSE-LOOP CONTROL STRATEGY ANDITS 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 approaches, essentially based on feed forward open loop control, are sensitive to the parameter mismatches and rely on the ability to accurately predict the voltage-source inverter current reference and its control performance The close-loop control named as source current direct control is applied as the main control strategy of the proposed AAPF. This control strategy operates as follows: (A. Luo, X. Xu et al.,2010). 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. In the close-loop control, detection and control target is the source current (S. Rahmani et al., 2010). In the aircraft EPS, the fundamental frequency is much higher than 50-Hz power system. Furthermore, measure errors, analog to digital conversion time, digital delay, and other non ideal factors will deteriorate the open-loop compensation effect to a worse degree As we known, 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

2.2. Source Current Direct Control

In this paper, 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 in 16by Wu and Jour. The basic system diagram of the close loop control scheme is given in Fig. 2 (B. Singh et al ., 2010). 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 multipliers 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. 3 gives the equivalent control model of this compensation strategy. As shown in Fig. 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

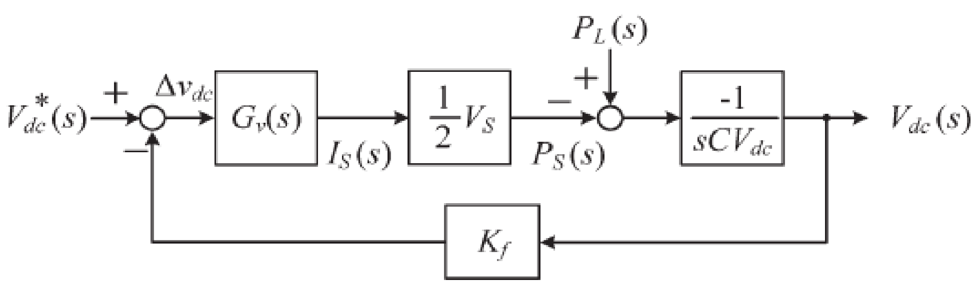

Figure 3

Model for active power analysis

3. 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. The cascaded multilevel inverter (CMLI) shown in Fig 3. Is one of the most important topology in the family of multilevel inverters).(A. Bhattacharya et al .,2011)It requires least number of components when compared to diode-clamped and flying capacitors type multilevel inverters 9. In addition it has several advantages that have made it attractive in power systems and drive applications.

Nowadays, the increase in the usage of non-linear loads especially the power electronic equipments leads to deterioration of the quality of voltage waveforms at the point of common coupling (PCC) of various consumers. Active power Filter (APF) has been used to mitigate the harmonic pollution in electrical networks. APF acts as an ideal current source and inject the compensating current into the ac lines by selective harmonic compensation in order to cancel the line current harmonics (D. Ganthony et al., 2007). 11A cascaded H-Bridge multilevel inverter has been used to realize the three phase shunt active filter. For the multilevel inverter a uni-polar multicarrier PWM (MCPWM) technique is proposed. Since the harmonics are the most critical factor in selecting the control technique for the active power filters, the potential impact of the MCPWM techniques on the THD is investigated. Power quality (PQ) is the key to successful delivery of quality product and operation of an industry 14. The term PQ means to maintain purely sinusoidal current waveform in phase with a purely sinusoidal voltage waveform. The deteriorating quality of electric power is mainly because of current and voltage harmonics due to wide spread application of static power converters, zero and negative sequence components originated by the use of single phase and unbalanced loads, reactive power, voltage sag, voltage swell, flicker, voltage interruption etc. 1. To improve the power quality traditional compensation methods such as passive filters used have many disadvantages such as fixed compensation, bulkiness, electromagnetic interference and possible resonance etc.,

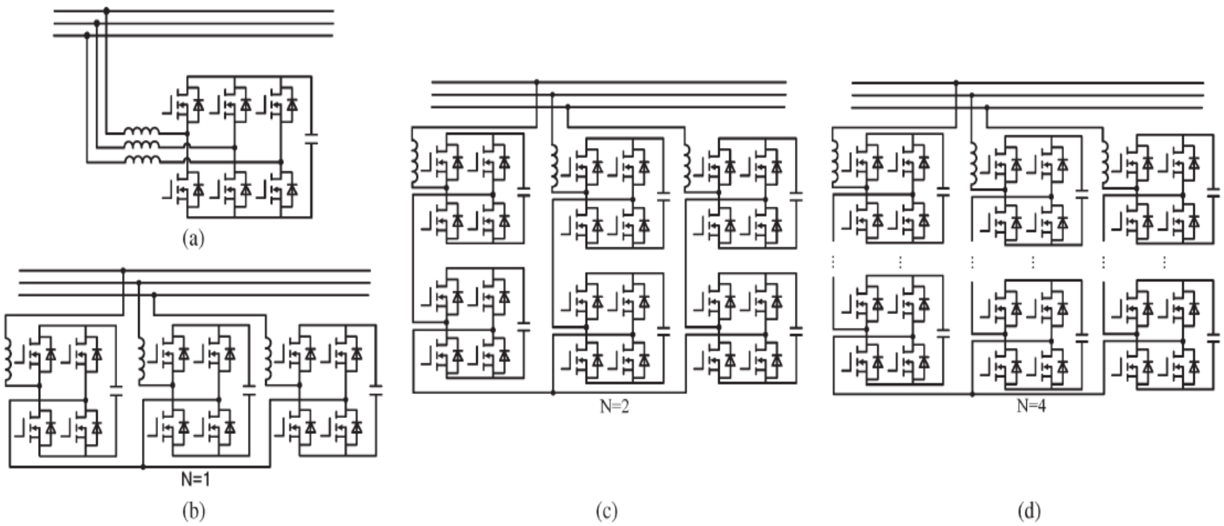

Figure 4

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

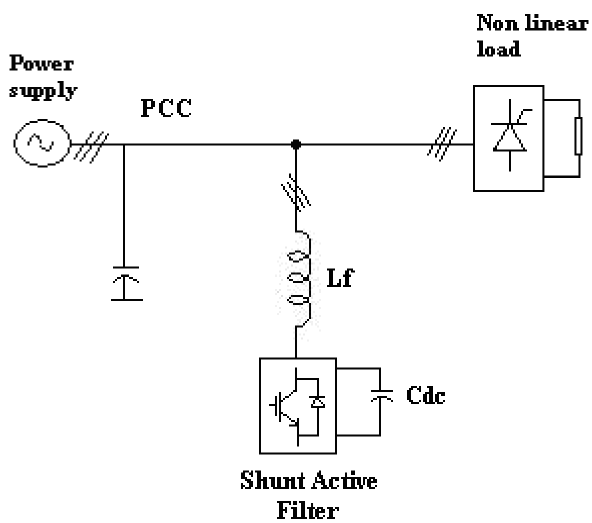

Figure 3.1

Block diagram of shunt active power filter

At low voltage levels, conventional two level inverters are used. At medium voltage levels, the conventional two level inverters either require interface transformers between the inverter terminals and the supply terminals or need active devices to be connected in series to achieve the required voltage levels. The multilevel inverters 4 are able to achieve the required voltage levels using devices of low voltage rating (E. Lavopa et al., 2007). Hence in this proposed work, the APF is realized using the cascaded H-bridge multi-level inverter. Besides, steps are taken to operate the inverter in the over modulation region. Over modulation is not intended to be a normal operating condition for a multilevel inverter, but in the case of active power filters there may be brief periods where the demanded output is sufficiently large 5, 6. The report is organized as follows:

Section II discusses the working of the APF with its schematic diagram.

Section III presents a brief description of the various pulse width modulation techniques and also compares their performance.

Section IV A closed loop control scheme using synchronous reference frame (SRF) for selectively eliminating the most harmful harmonics in the line current has been developed in Section IV.

Section V Suitable simulation exercises are carried out in Section V to evaluate the performance of shunt active power filters with a variety of non-linear loads.

3.2 APF strategy

3.2.1. Active Power Filter

The increased severity of harmonic pollution in power networks has attracted the attention of power electronics and power system engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipments, generally known as active filters 7, are also called active power line conditioners. To effectively compensate the line current harmonics, the active filter controller should be designed to meet the following three goals.

3.2.2. Discussion and Demonstration on the Power Stage of AAPF

Solution	Dc-link voltage (V)	Power Device	Switching Frequency (kHz)
Three-leg inverter based APF	400	IRFP26N60L	60
			120
			240
H-bridge based APF	300	IRFP23N50L	30
			60
			120
Two H-bridge cascaded APF	150	IRFP254N	15
			30
			60
Four H-bridge cascaded APF	75	IRFP23N15D	7.5
			15
			30

- 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
- 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.

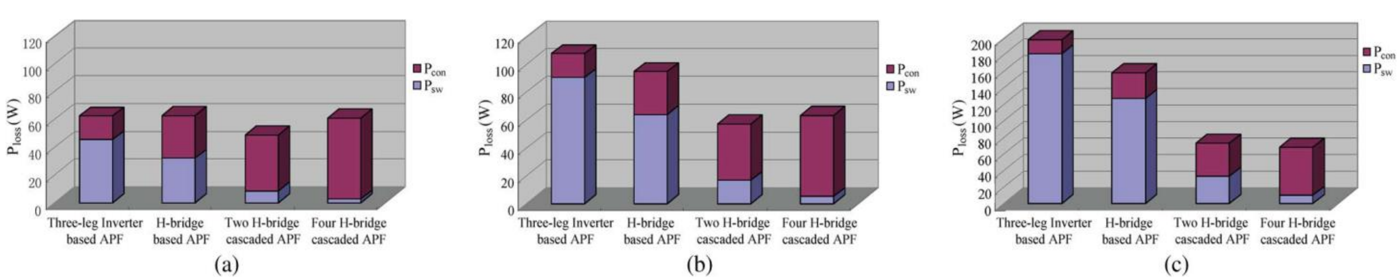

Figure 5

Power losses of different possible AAPF solutions. (a) With the equivalent switching frequency *feq* of 60 kHz. (b) With the equivalent switching frequency *feq* of 120 kHz. (c) With the equivalent switching frequency *feq* of 240 kHz

3.3. Power losses of different possible AAPF solutions

In this paper, the two H-bridge cascaded APF is selected as the power stage configuration of the AAPF, both for the accepted small power loss and reliability 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 (= 30 kHz × 2 × 2). Maintenance of the voltage balance of the capacitors is critical to the safe control of the floating dc capacitors can be divided into the following:

1) Clustered overall control

2) Balancing control

3.4. Multicarrier PWM Schemes

In this section four different control techniques as well as the proposed control scheme are discussed.

3.4.1. Phase Shifted PWM

The essential principle of PSPWM is phase shifting the carriers of each bridge to achieve additional harmonic sideband cancellation, which occur around the even carrier multiple groups .Fig. 6 shows the carrier arrangements for the three H-bridge cells connected in series in one of the phase legs of a seven level-cascaded structure.(E. Lavopa et al., 2007) Optimum harmonic cancellation is achieved by phase shifting each carrier by (k-1) /n, where k is the kth converter, n is the number of series-connected single-phase inverters per phase leg. For three cascaded H-bridges with the carrier phase shift of 60°, harmonic cancellation up to side bands around multiples of 6fc will be achieved. The cancellation is not dependent on the carrier/fundamental frequency ratio.

3.4.2. Carrier Disposition PWM

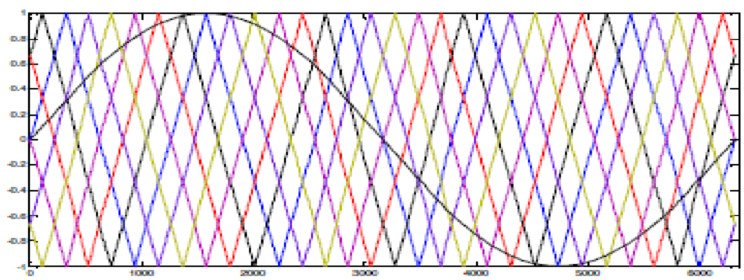

Figure 6

PSPWM Technique

In this carrier disposition PWM (CDPWM) method modulation is achieved by having L-1 triangular carriers where L is the number of voltage levels. These carriers are arranged so that they fully occupy continuous bands in the range of -(L-1) Vdc/2 to (L-1) Vdc/2 (for L odd). A single sinusoidal reference is then compared with these carriers to determine the switched voltage level. These alternative PWM strategies with differing phase relationships have been developed in the literature. The degree of freedom for these CDPWM techniques is given as:

$$Ma = \frac{2 * Ar}{(L-1) * AC}$$

where, *Ar* is the amplitude of the reference waveform. *Ac* is the amplitude of the carrier waveform. *L* is the number of levels. This CDPWM strategy includes phase disposition pulse width modulation (PDPWM), phase opposition disposition pulse width modulation (PODPWM) and alternative phase opposition disposition (APODPWM). In the PDPWM technique all the carriers are in phase across all the bands as described in Fig. 5 (E. Lavopa et al., 2009). The PODPWM is explained in the Fig. 6, in which all the carriers above the zero reference are in phase and carriers below the zero reference are also in phase but are phase shifted by 180° with respect to that above zero reference. But in APODPWM carriers in adjacent bands are phase displaced by 180°, which is shown in Fig. 6.

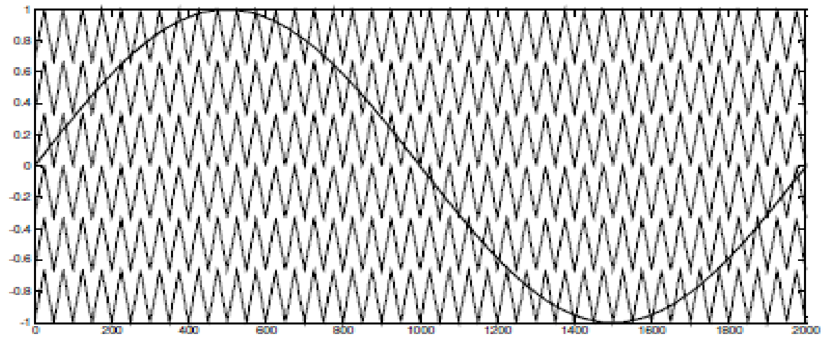

Figure 7
PDPWM technique for 3-cell bridge

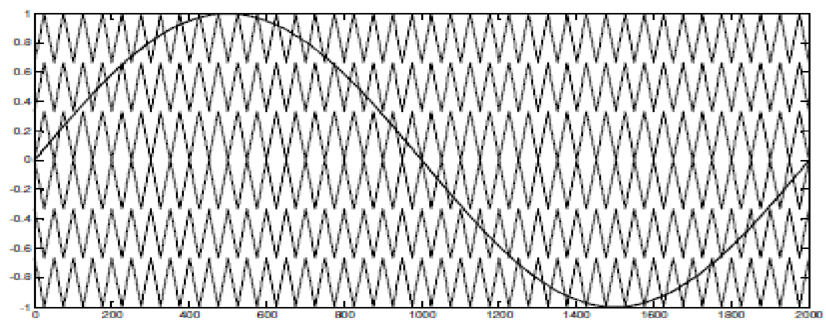

Figure 8
PODPWM Technique for 3-cell H-Bridge Inverter

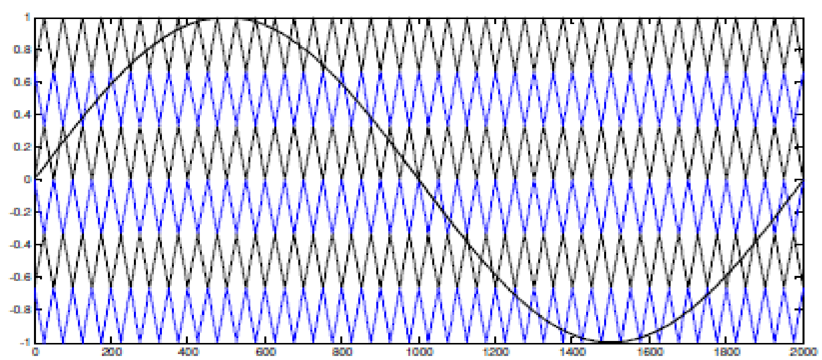

Figure 9
APODPWM Technique for 3-cell H-Bridge Inverter

3.4.3. Third Harmonic Injection PWM

The maximum modulation index of a three-phase inverter can be increased by including a common mode third-harmonic term into the target reference waveform of each phase leg 12.In this method the modulation index Ma can be increased beyond Ma=1.0 without moving into over modulation. (M. Odavic et al.,2007)Over modulation is known to produce low frequency base band distortion and is to be avoided 5. So this is an alternative topology to improve the fundamental voltage without entering into the over modulation region. The technique is clearly described in Fig .10.

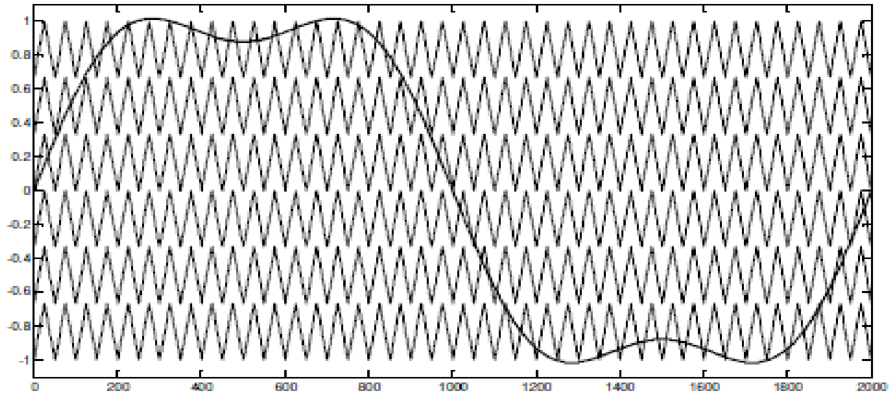

Figure 10
Third Harmonic injected-PDPWM Technique

3.3.4. Unipolar Multi-carrier PWM schemes

The unipolar multi carrier pulse width modulation scheme is obtained by comparing the rectified sinusoidal reference with multi carriers positioned above the zero level as shown in Fig. 10 (A. Eid et al., 2009) Similar to the multi-carrier PWM techniques with sinusoidal reference explained above; multi-carrier PWM techniques with unipolar reference are discussed.In the case of unipolar carrier disposition PWM scheme the carriers are positioned above the zero reference as shown in Fig. 1. In this scheme, only n carriers are required for an n-cell H-bridge inverter, unlike the above methods where 2n+1 carrier are required. In this method to obtain seven levels in the output voltage only three carriers are required but in CDPWM with sinusoidal reference six carriers are needed to attain the same number of levels.(H. Hu et al., 2010)The degree of freedom for this method is given as:

$$Ma = \frac{Ar}{N} * Ac$$

where, *Ar* is the amplitude of the reference is the amplitude of the carrier *n* is the number of H-bridge cells.

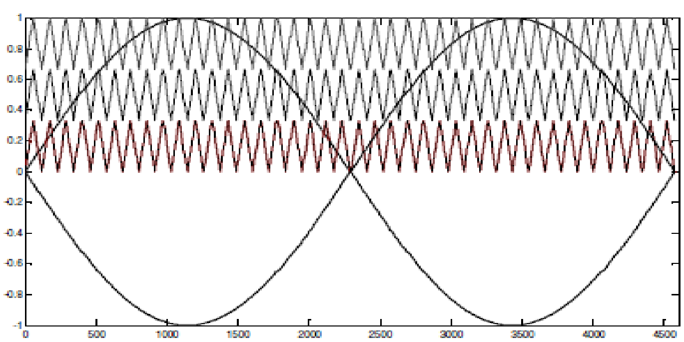

Figure 11 Unipolar –PDPWM Technique

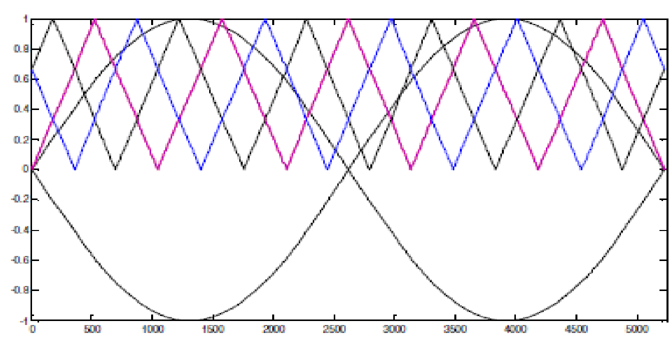

Figure 12 Unipolar –PDPWM Technique

The unipolar-phase shifted PWM is similar to the sinusoidal reference PSPWM, the carriers are phase shifted but all the carriers are arranged above the zero level as depicted in Fig. 10(V. Biagini et al., 2007)For the three cell H-bridge inverter the carriers are phase shifted by 60° to obtain seven levels. The unipolar-phase shifted PWM for seven level inverter is shown in the Fig. 11

4. MATLAB/SIMULATION RESULTS

4.1. Cascaded Shunt Active Power Filter

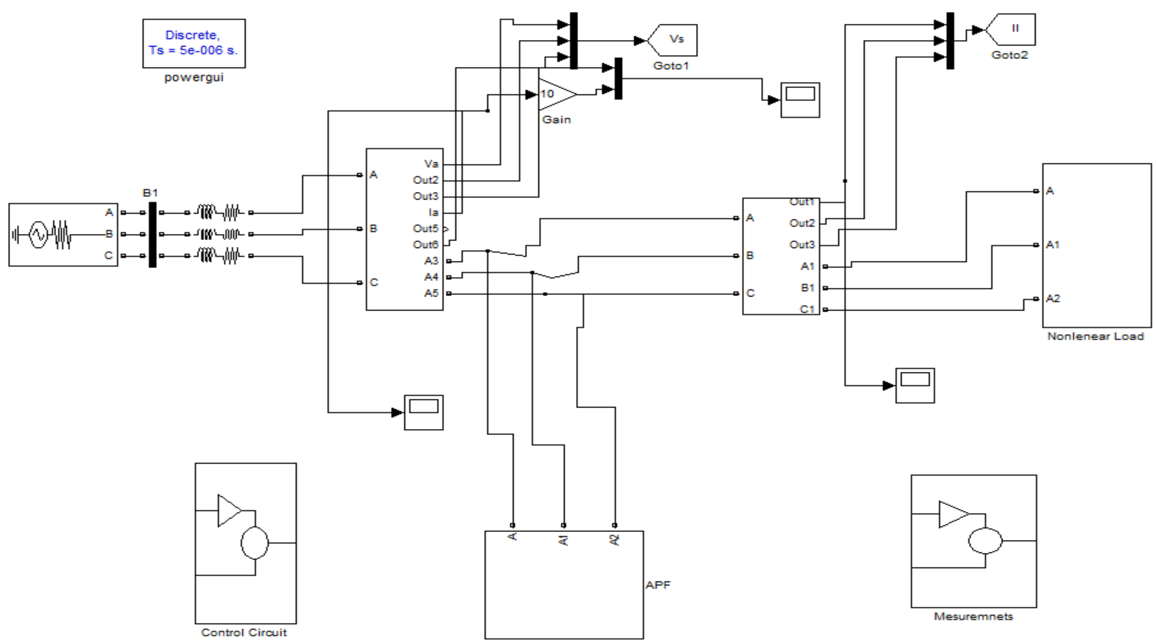

Figure 13

Cascaded Shunt Active Power Filter

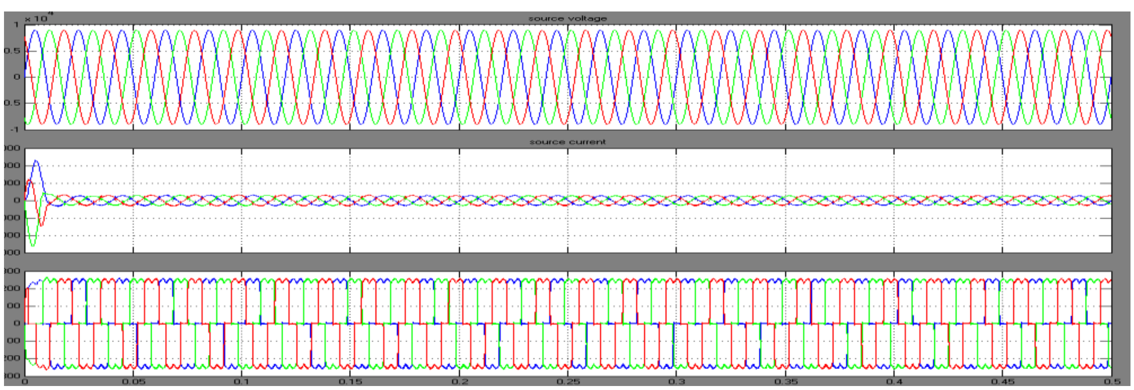

Figure 14

Simulation waveforms of AAPF under variable-frequency EPS

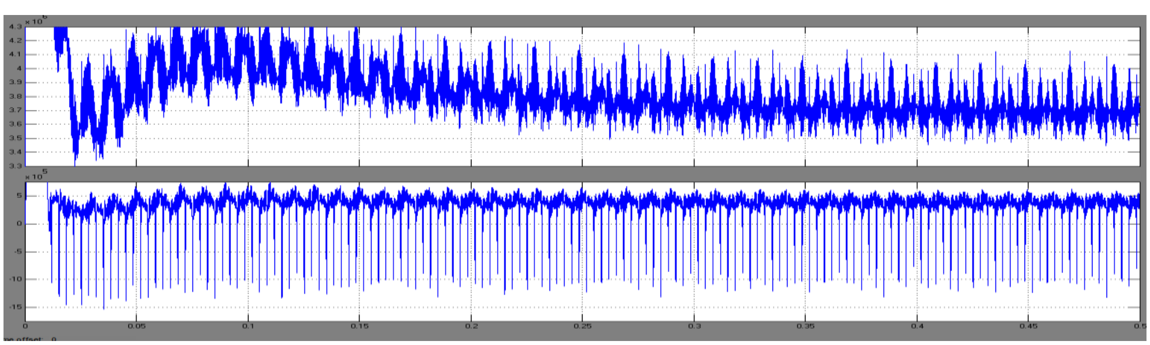

Figure 15

Simulation waveforms of AAPF under variable-frequency voltage and current

4.1.1. Fuzzy Logic Controller for Cascaded Shunt Active Power Filter

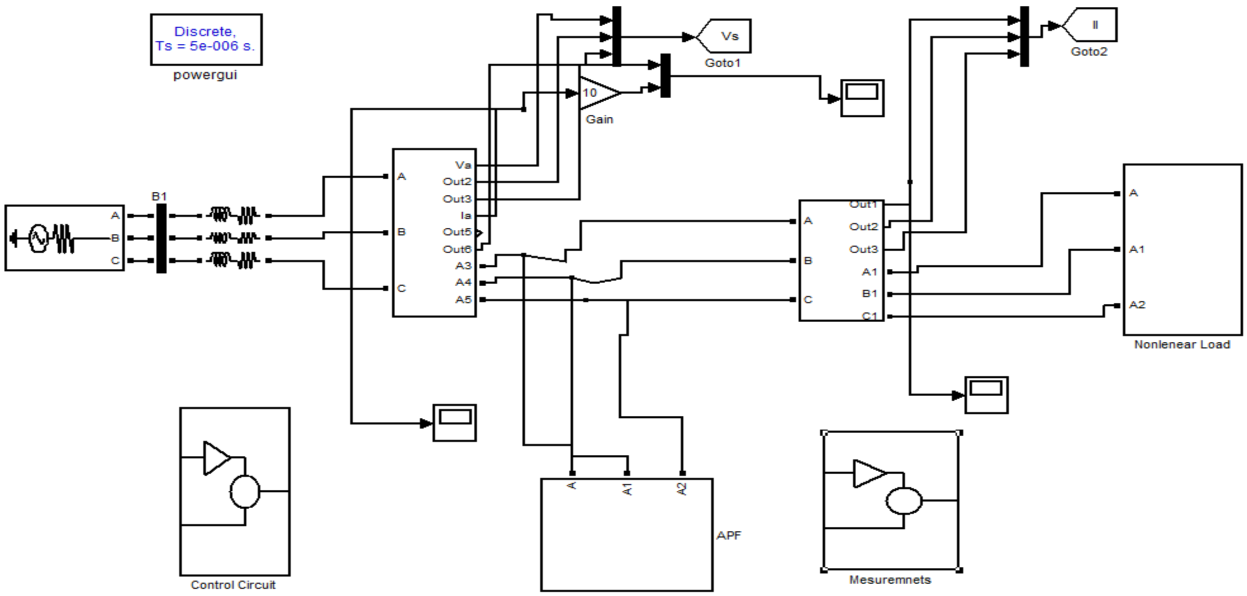

Figure 16
Fuzzy Logic Controller for Cascaded Shunt Active Power Filter

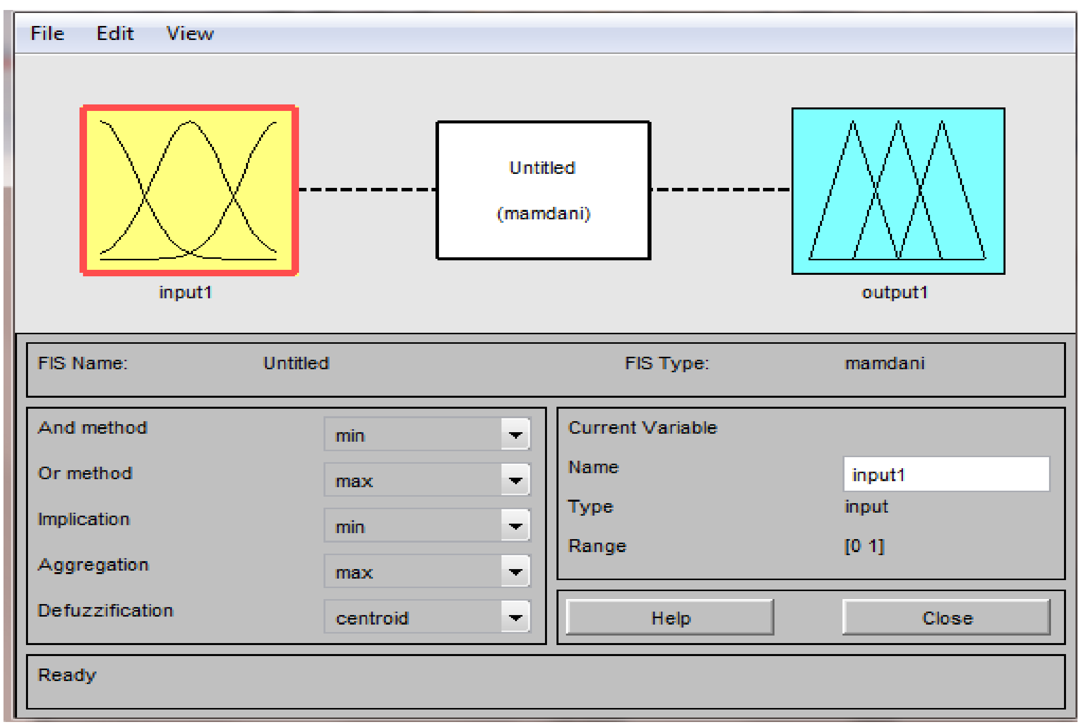

Figure 17
Mamdani controlled using Cascaded Shunt Active Power Filter

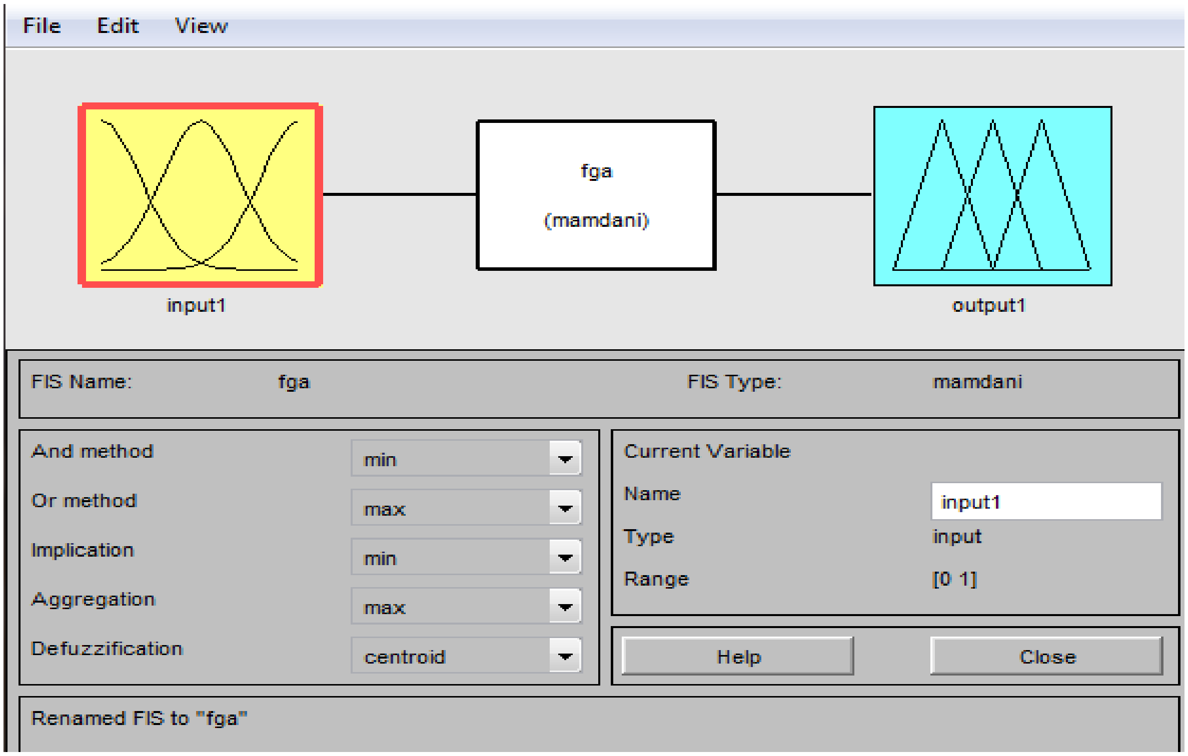

Figure 18

Mamdani controlled by using Fuzzy Logic Controller Cascaded Shunt Active Power Filter

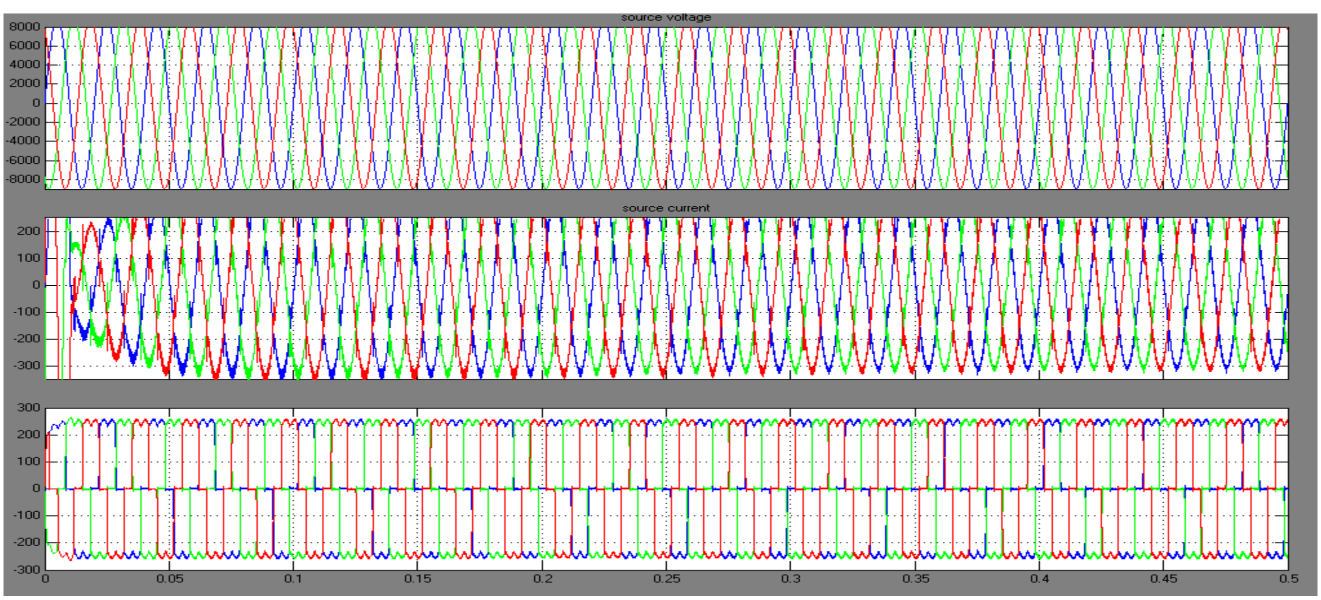

Figure 19

Simulation waveforms of AAPF under variable-frequency EPS

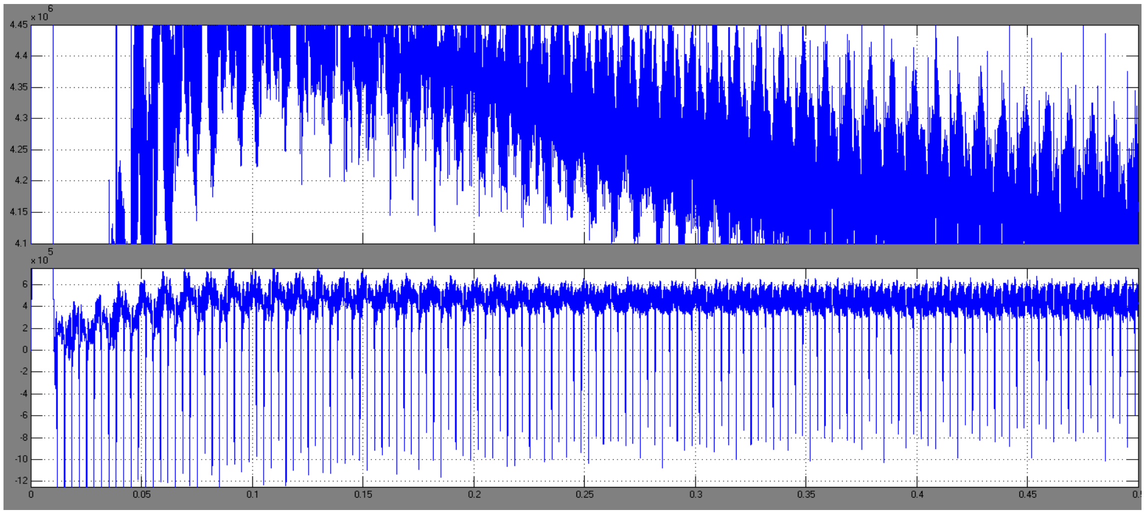

Figure 20

Simulation waveforms of AAPF under variable-frequency voltage and current

5. CONCLUSION

For elimination of power quality problems in modern aircraft EPS systems a new APF is used. In this paper, a load current feed forward compensation method for the source current direct control and fuzzy controller based AAPF has been proposed. The corresponding system control strategy of the cascaded-inverter based active filter system is shown. The cascaded H-bridge inverter has been used for active power filter. The deterioration of power quality and increase of harmonic pollution due to the increase in the usage of non-linear loads especially the power electronic equipment's has been highlighted. Then the role of APF in compensating the line current harmonics has been demonstrated by considering certain non-linear loads. Simulation results show that the dominant harmonics in the line current and total harmonic distortion have been reduced significantly. Hence there is an improvement in the power quality.

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