Hardware Implementation of Fuzzy Logic Based Active Power Filter In High Frequency Air Craft Power System

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***Abstract* -** A fuzzy controlled shunt active power filter for air craft power system has been proposed in this paper. Circuit parameter selection and control design using fuzzy remarkably enhance the performance of APF. The improvement in the control scheme using fuzzy makes APF versatile for compensation of harmonic currents and unbalance in source voltage. The simulation result gives the effectiveness of the proposed system.

***Keywords* -** *Active power filter, fuzzy logic controller, Total harmonic distortion (THD).*

I. INRODUCTION

Aircraft power systems present a unique set of power quality problems in an environment that needs the equipment being powered should be in highest level of reliability. Consequences of increasing amount of microprocessor-based flight systems, navigation and communications equipment being incorporated into today's aircraft, where power quality is of the most importance.

In aircraft system equipment designed in accordance with Federal Aviation Administration (FAA) and military standards is typically very robust, and are tolerant of most power quality anomalies. Retrofit of older aircraft, the integration of COTS equipment, or the implementation of new technology into existing aircraft can be another story.

Brief overview of the aircraft power system as well as the power quality problems which are arising frequently and their possible effects is as follows. We converse new technology available that can provide solutions to the most troublesome problems. A archetypal aircraft power system is a multiple generator based system consisting of:

During maintenance the aircraft systems is supplied by a ground based generator or inverter source, prior to departure and after arrival. An Auxiliary Power Unit (APU) generator, that supplies engine beginning power and emergency power to the primary electrical system in the event of main generator or an engine failure The main power bus supplied by these generators is a 115/200Vac, 400Hz, 3Ø bus. This bus supply power to the other power buses 115Vac, 400Hz 1Ø, 115Vac, 60Hz 1Ø, 26Vac, 400Hz, 28Vdc and 270Vdc.

The most of the utility load and dc loads in airborne systems are supplied by diode rectifiers or semi controlled rectifier, which results in a large amount of harmonics. The richness of harmonic current will lead to electromagnetic interference issues, power losses, and abnormal operation of electronic equipment.

Several techniques could be applied, to address this power quality problem in airplane, like power factor correction, multiphase transformer rectifiers, their heavy weights and bulky volume could make their use as drawback. The shunt active power filter compensates the harmonic with much lesser capacity and weight.

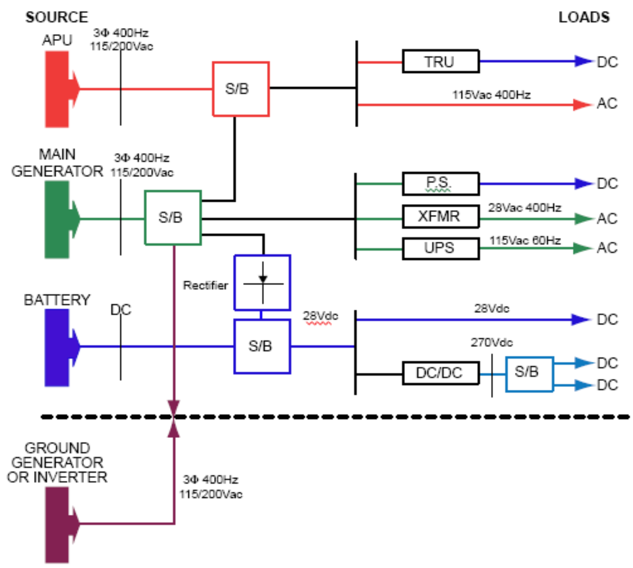


Fig.1 Structure of Aircraft Power System

Although the principle for APF applied to the 50- or 60-Hz power systems is the same as that for a 400-Hz aircraft power system, there exists a great challenge in designing a high performance 400-Hz APF due to its wider bandwidth and limited switching frequency. In this regard, there have been few publications on 400-Hz APF applied to the aircraft power systems [8]–[15]. In [8], analysis and simulation were given to illustrate the harmonic cancellation using APF. In [9]–[15], a multilevel APF was proposed to reduce the switching frequency. In [14], a novel method to detect the fundamental frequency and harmonics is proposed for variable frequency aircraft power systems. In [15], an iterative learning control is applied to improve the performance of a 400-Hz shunt active filter.

In this paper, we analyse the control strategy of fuzzy logic in the key circuit design of APF. Simulation is given to verify the control.

II. SYSTEM DESCRIPTION

The control system consists of four main functional blocks:

1. Software phase locked Loop to detect the voltage phase angle for synchronous reference frame transformation;

2. Dc bus voltage regulator to maintain the stability of the dc bus voltage;
3. Low-pass filter (LPF), which aims to filter out the current fundamental components and then extract the harmonic components to be compensated; and
4. Control loop, designed for tracking the harmonic component reference.

The measured load phase currents (i_{La}, i_{Lb}andi_{Lc}) are transformed into the synchronous reference frame to obtain i_{Lq} andi_{Ld}. LPFs are employed to filter out the dc components in the synchronous reference frame, which represents the fundamental frequency components of the load currents. The harmonic components ($\tilde{i}_{Lq}$ and$\tilde{i}_{Ld}$) are easily obtained by a simple subtraction of the filtered components ($\bar{i}_{Lq}$ and$\bar{i}_{Ld}$) and the transformed components (i_{Lq} and i_{Ld}). Due to losses in power devices and other components, the real power is drawn by a small amount, which would result in dc voltage decrease. To keep the dc voltage constant, a dc voltage regulator is used by adding dc regulating value Δi_{Ld} to the *d*-axis filter current. All of these computations are implemented in a digital signal processor (DSP). Two paralleled PWM inverters with the same driving signals are used to expand the output capacity.

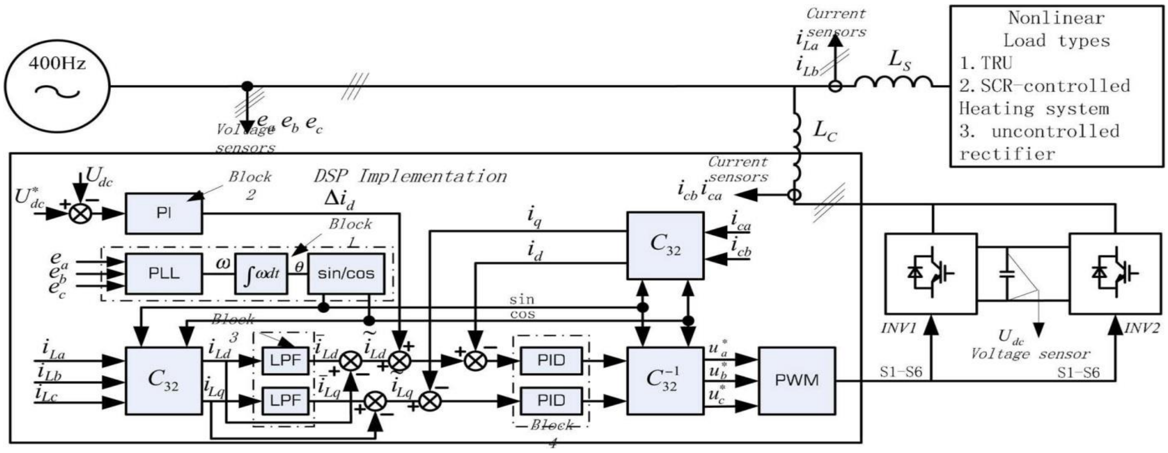


Fig.2 Structure of Active Power Filter

III. HARMONIC ANALYSIS

Total harmonic distortion is one of the methods to characterize the linearity of an amplifier (THD). Harmonic distortion is measured by applying a spectrally pure sine wave to the amplifier in a defined circuit configuration (i.e., bias conditions, output amplitude, frequency, etc.) and perceiving the output spectrum . The amount of distortion present at the output of the amplifier depends on several parameters, such as:

Small and large signal nonlinearity of the amplifier being tested, amplifier's output amplitude, amplifier's Frequency response, load applied to the output of the amplifier, amplifier's power supply voltage , circuit board layout , grounding , thermal management, etc.

Measurements based on amplitudes (e.g., voltage), need to be converted in terms of power to make the addition of harmonic distortion meaningful. For example, for a voltage signal, the ratio of the square of the RMS voltages is equivalent to the power's ratio.

Harmonic distortion can be measured by applying a spectrally clean sine wave voltage signal to the input of the amplifier under test. Next, the input power level is adjusted to the amplifier for a desired output power level and then looking at the output harmonic spectrums (second, third, and fourth harmonics, etc.) of the amplifier on a spectrum analyzer relative to the amplitude of the output fundamental signal, Another method is to measure the output waveform signal of the amplifier using a high speed/bandwidth oscilloscope. Detent the data if needed (i.e., remove offset; usually not essential for a CW signal), and then perform a FFT to get the amplifier output's harmonic content. The individual measurement harmonic values in power levels (second, third, and fourth, etc.) are usually expressed in decibel format, (dBc is relative to the fundamental carrier power level, or dBm is in absolute power). The simplest measurement unit to use for the harmonic measurement is dBm. This allows the tester to not have to keep track of the amplitude signal level. For example, when measured in dBc, before calculating the THD, one needs to convert the dBc value to dBm value for each of the harmonic values before calculating their individual power level in watts.

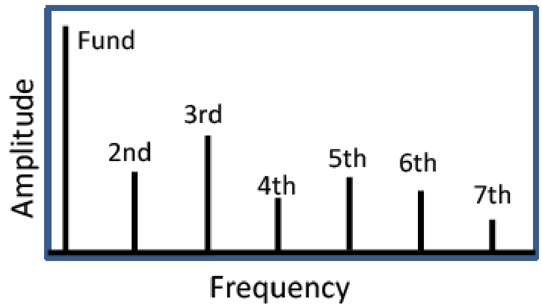


Fig.3 Typical harmonic content of an amplifier's output

Total Harmonic Distortion (THD) is expressed in Root-Sum-Square (RSS) in percentage. The THD is usually calculated by taking the root sum of the squares of the first five or six harmonics of the fundamental. In various practical situations, there is insignificant error if only the second and third harmonics are included, as long as the higher harmonics are three to five times smaller than the largest harmonic. For example, 0.10 is one harmonic value and 0.03 is additional higher harmonic value however three times smaller in amplitude:

$$\sqrt{0.102+0.032} = \sqrt{0.0109} = 0.104 \approx 0.1$$

If the measurement data is in power

$$THD(\%) = 100 \times \frac{\sqrt{P_2+P_3+P_4+\cdots+P_n}}{P_1} \quad (1)$$

Where P_n is in watts,

If the measurement data is in volt,

$$THD(\%) = 100 \times \frac{\sqrt{V_2^2+V_3^2+V_4^2+\cdots+V_n^2}}{V_1^2} \quad (2)$$

where V_n is the RMS voltage.

IV. CONTROL SCHEME

A. PID controller:

PID controllers are a family of controllers. PID gives the designer a larger number of options and those choices mean that there are more prospects for changing the dynamics of the system. If the designer works it right, the designer can get the advantages of several effects. In specific, starting with a proportional controller, and including integral and derivative terms to the control the designer can take advantage of the following effects.

An integral controller gives zero SSE for a step input. A derivative control terms often produces quicker response. A PID controller operates on the error in a feedback system and does the following: A PID controller calculates a term proportional to the error - the P term. A PID controller calculates a term proportional to the integral of the error - the I term. A PID controller calculates a term proportional to the derivative of the error - the D term. The three terms - the P, I and D terms, are added together to produce a control signal that is applied to the system being controlled. PID controllers can be viewed as three terms - a proportional term, and integral term and a derivative term - added together. PID controllers are also known as three-term controllers and three-mode controllers. Here's a block diagram representation of the PID.

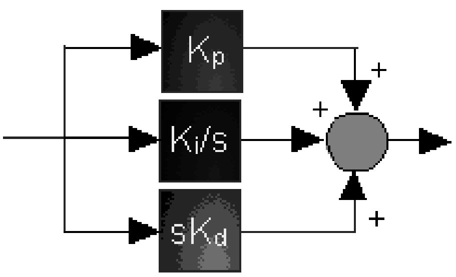


Fig.4 Representation of PID

There are three controllers acting in concert. The three controllers are:

- A proportional (top),
- An Integral (centre),
- A Derivative (bottom)

The proportional, integral and derivative outputs are added together. The PID controller transfer function can be obtained by adding the three terms.

$$PID(s) = K_p + K_i/s + sK_d$$

PID type controllers do work satisfactory, if the process under control is in a stable condition, they do not cope well in other cases: The presence of strong disturbances (non-linearity) Time-varying parameters of the process (non-linearity) Presence of dead times.

PID and bang-bang type controllers can only cope with one variable. This usually results in several independently operating control loops. These loops are not able to "talk to each other". In cases where it is desirable or necessary to exploit interdependencies of physical variables, one is enforced to set up a complete mathematical model of the process and to derive differential equations from the process which are essential for the execution of a solution, where fuzzy logic provides an elegant and extremely proficient solution to the problem. Fuzzy logic lets engineers design supervisory multi-variable controllers from operator experience and experimental results rather than from mathematical models.

B. Fuzzy control

Fuzzy controllers are very simple conceptually. They consist of an input stage, a processing stage, and an output stage. The input stage maps sensor or other inputs, such as switches, thumbwheels, and so on, to the suitable membership functions and truth values. The processing stage invokes each appropriate rule and generates a result for each, then blocs the results of the rules. In conclusion, the output stage converts the combined result back into a specific control output value.

Triangular shape is the common membership functions , although trapezoidal and bell curves are also used, but the shape is generally less important than the number of curves and their placement. From three to seven curves are generally appropriate to cover the required range of an input value, in fuzzy jargon.

C. Fuzzy Set

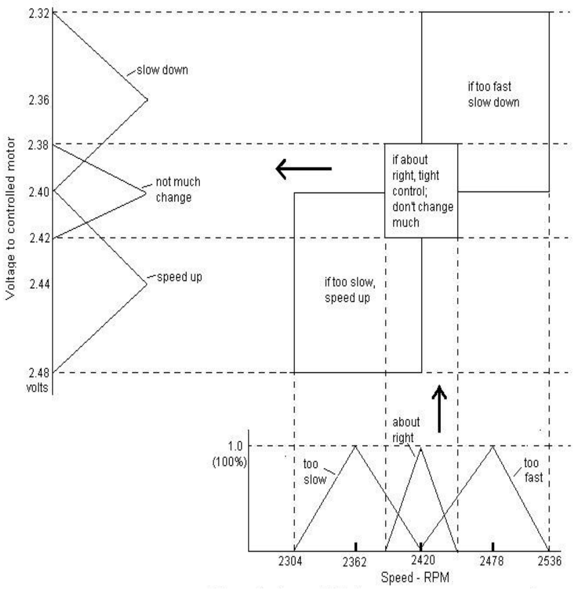
The input variables in a fuzzy control system are in general represented by sets of membership functions similar to this, known as "fuzzy sets". The converting process of a crisp input value to a fuzzy value is called "fuzzification".

A control system may also have various types of switch, or "ON-OFF", inputs along with its analog inputs, and such switch inputs of course will always have a truth value equal to either 1 or 0, but the scheme can deal with them as simplified fuzzy functions that happen to be either one value or another.

It has some advantages. In many cases, the mathematical model of the control process may not exist, or may be too "expensive" in terms of computer processing power and memory, and a system based on pragmatic rules may be more effective.

Besides, fuzzy logic is well suited to low-cost implementations based on cheap sensors, low-resolution analog-to-digital converters, and 4-bit or 8-bit one-chip microcontroller chips. Such systems can be easily upgraded by adding new rules to improve performance or add new features. In many cases, fuzzy control can be used to improve present traditional controller systems by adding an extra layer of intelligence to the current control method. Fuzzy control system design is based on empirical methods, basically a methodical approach to trial and error. The general process is as follows:

- Document the system's operational specifications and inputs and outputs.
- Document the fuzzy sets for the inputs.
- Document the rule set.
- Determine the defuzzification method.
- Run through test suite to validate system, adjust details as required.
- Complete document and release to production.



D. CONTROL CONSIDERATION

In a balanced three-phase system, the inverter model in the synchronous reference frame can be described as

$$\begin{bmatrix} L\frac{di_d}{dt} \\ L\frac{di_q}{dt}\end{bmatrix} = \begin{bmatrix} -R & wl \\ -wl & -R\end{bmatrix}\begin{bmatrix} i_d \\ i_q\end{bmatrix} - \begin{bmatrix} u_d \\ u_q\end{bmatrix} + \begin{bmatrix} e_d \\ e_q\end{bmatrix} \qquad (3)$$

$$C\frac{du_{dc}}{dt} = \frac{3e_d}{u_{dc}} i_d \qquad (4)$$

$$[e_d \quad e_q \quad e_0]^T = C_{32}[e_a \quad e_b \quad e_c]^T \qquad (5)$$

$$[i_d \quad i_q \quad i_o]^T = C_{32}[i_{ca} \quad i_{cb} \quad i_{cc}]^T \qquad (6)$$

$$[u_d \quad u_q \quad u_0]^T = C_{32}[d_a \quad d_b \quad d_c]^T{}_{U_{dc}} \qquad (7)$$

Where,

L and R	Equivalent inductance and resistance of the grid tied inductor L_c;
C	Dc bus capacitance;
ω	Angular frequency of the grid;
$[i_d \; i_q \; i_0]$	Corresponding Currents In the synchronous reference frame;
$[e_a \; e_b \; e_c]$	Three Phase Grid Voltages;
$[e_d \; e_q \; e_0]$	Voltages in the synchronous reference frame;
$[i_{ca} \; i_{cb} \; i_{cc}]$	Three phase currents from the APF;
$[d_a \; d_b \; d_c]$	Control duty cycles of three phases;
u_{dc}	dc bus voltage;
$[u_d \; u_q \; u_0]$	Voltages in synchronous reference frame;
c_{32}	Transformation matrix from the stationary frame to the synchronous reference frame which is given by

$$C_{32} = \frac{2}{3}\begin{bmatrix} \sin\omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t - \frac{4\pi}{3}\right) \\ \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t - \frac{4\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (8)$$

The inverter plant depicted in expression (3) is a nonlinear and coupling system. By assuming the grid voltages in *d-q* frame, e_d and e_q, constant and decoupling *d-q* terms, the transfer functions of the current loop can be simplified as below

$$G_{q\_c} = G_{d_c}(S) = \frac{1}{R+L_s} \qquad (9)$$

Due to the computational delay in digital control systems, a pure control delay is unavoidably introduced to the system, which has negative effect on the control bandwidth. The delay time *Td* includes the delay *Tc* caused by the current loop control

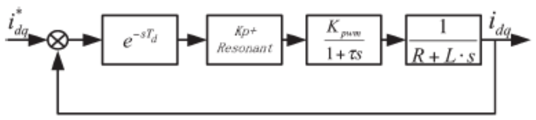


Fig.5 Diagram of the current loop with pure delay time *Td*

V. DETERMINATION OF THE KEY PARAMETERS

Since the characteristics of electric loads in the airplane varied greatly, in this research stage, it is difficult to emulate the load operating condition during normal flight. Referring to the loads for the simulated B767 aircraft, we decided to use a centralized uncontrolled diode rectifier with LCR connection as a nonlinear load to mimic the load operations, whose parameters are 0.1 mH, 330 μF, and 3.6 Ω, respectively. The switching frequency and dc voltage are designed as 50 kHz and 400 V, respectively. To reduce the EMI issue caused by high ripple currents, we limit the current ripple under 8 A. The phase voltage and frequency of the three-phase ac source are 110 V and 400 Hz.

A. Inductance $\mathbf{L_s}$

To meet the design requirements, the inductance L_s should fall in the range of [0.093 mH, 1.3 mH]. For APF, the smaller the grid-connected inductance, the wider the bandwidth, and thus, the APF can achieve a better compensating performance. In this design, we choose the grid connected inductance as 0.1 mH.

B. Line Inductance $\mathbf{L_c}$

The inductance $\mathbf{L_c}$ should be greater than 0.075 mH. To simplify the power stage design, we choose the line inductance as 0.1 mH as well.

C. DC Capacitance

It would be very complex to calculate the real power through the convolution. In this paper, we take advantage of the MATLAB simulation tool to calculate the energy transferred during the transient state. In this method, it is easy to calculate the energy transferred during transient state, and then we can calculate the required capacitance. We limit the dc bus voltage overshoot under 50 V, and a three-order Chebyshev I filter with a bandwidth of 300 Hz is designed as an LPF. Based on the simulation result, the capacitance should be greater than 0.98 mF. In this design, we choose 1 mF.

D. Control Frequency Selection

The next step is to determine the control frequency. For a digital control system, the delay time *Td*, whose effect on the compensating performance is discussed in [17], is determined by the control frequency.

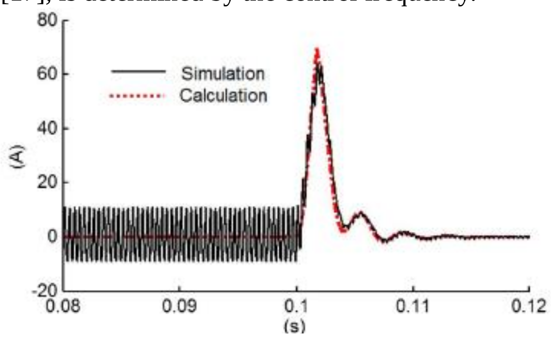


Fig.6 Harmonic extraction during load transients

As shown in Fig.6, where the load change happens at 0.1s ,the load current curve(in the d-axis) from the simulation agrees with that in calculation very well, except the high frequency ripples that are not considered in calculation ,which verifies the effectiveness of the calculation method.

VI. SIMULATION

The MATLAB software is used to design, simulate, and test the fuzzy control based APF. Simulation diagram of proposed system is shown in the Fig.7. It has 3 phase source connected to the non-linear load through a line consists of transmission line parameter. Considering current stress on power devices, two inverters were paralleled with a common D.C bus voltage. To avoid current circulating between two inverter modules, identical PWM driver signals are used to drive the corresponding switches..

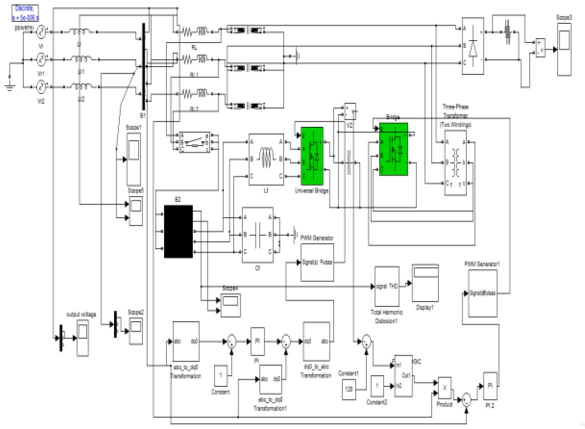


Fig.7 Simulation circuit of APF with fuzzy logic based control

A nonlinear load can be a uncontrolled rectifier. APF is designed using fuzzy logic controller. The simulation results clearly demonstrate the scheme is able to reduce the significant amount of THD in source current and voltage within limits.

A. UNCOMPENSATED SYSTEM

After simulation without APF, it has been observed that the THD of source voltage was found as high. By viewing the graphical form it can be seen that source voltage is distorted. The Fig.8 shows the simulation result obtained at the uncontrolled rectifier acting as a nonlinear load, in which x-axis and y-axis represent the voltage magnitude and time respectively. The magnitude of voltage varies from 80v to 12v which is pulsating.

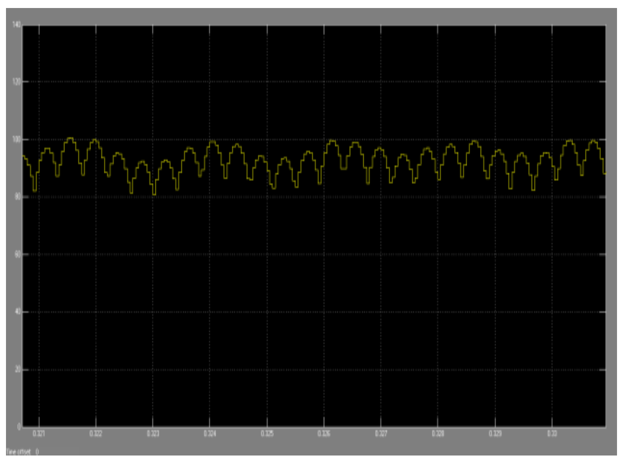


Fig.8 Non-linear load voltage

The source current waveform in 3 phase high frequency(400Hz) air craft power is mentioned in Fig.9 Important distortions are noticed in these, with each phase gets unbalanced to each other, in which x-axis and y-axis represent the time and current magnitude respectively at 0.001sec magnitude of phase-a(red) is 0 ,magnitude of phase-b(yellow)is 11amp, magnitude of phase-c(blue) is -11amps. It dictates that the current is imbalanced and gets distorted, the magnitude of each phase varies from positive to negative over a wide range.

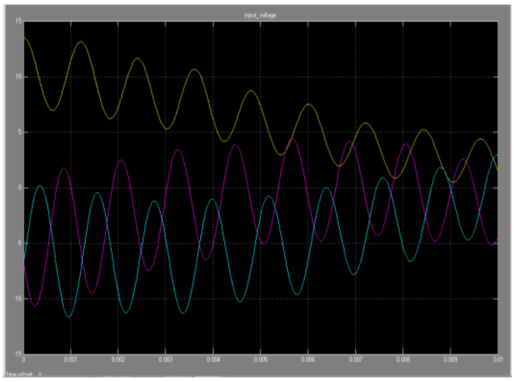


Fig.9 Source Current Without Active Power Filter

B. COMPENSATED SYSTEM.

After the application of shunt active power filtering based on fuzzy logic controller, we obtain the curves as mentioned in Fig.10 presenting the supply's current waveform in 3 phase high frequency(400Hz) air craft power system. In Graphical representation of compensated system with x-axis and y-axis, represents time and magnitude of current respectively, the Fig.10 shows two axis representation one on per unit values and another with Rms value. It describes that three phases are balanced and they attain their maximum magnitude 400amp at regular intervals.

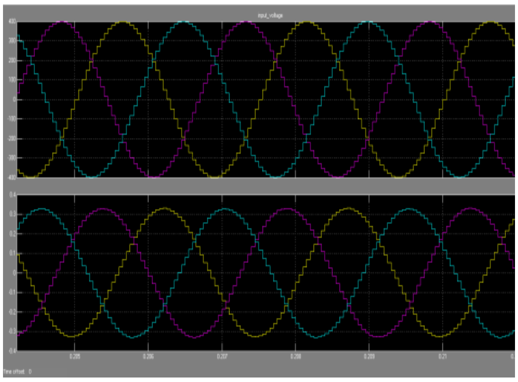


Fig.10 Source current of aircraft system with fuzzy based APF.

C. FFT ANALYSIS OF UNCOMPENSATED ACPS

Harmonic Analysis can be done using FFT analysis, the harmonic spectrum of source side current without the application Of Shunt active power filter in high frequency(400Hz) is determined .

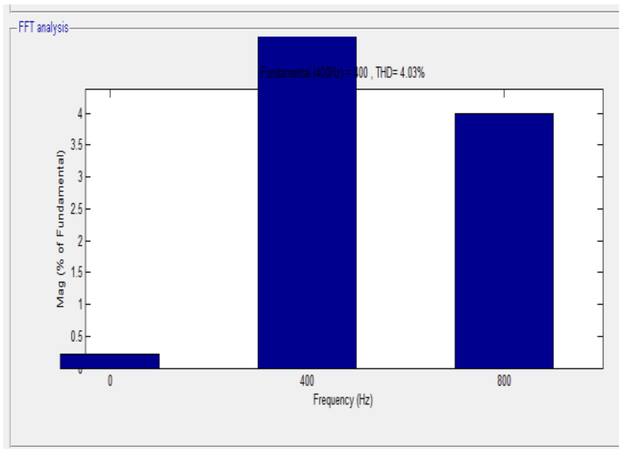


Fig.11 Harmonic Spectrum Of Source Current Without APF

The Fig.11 represent the harmonic distortion content in the source current in which x-axis and y-axis represent the frequency and Magnitude of Percentage of fundamental respectively ,it shows that at 400Hz the total harmonic distortion is about 4.03% without the application of active power .Harmonic Analysis can be done using FFT analysis.

D. FFT ANALYSIS OF COMPENSATED ACPS

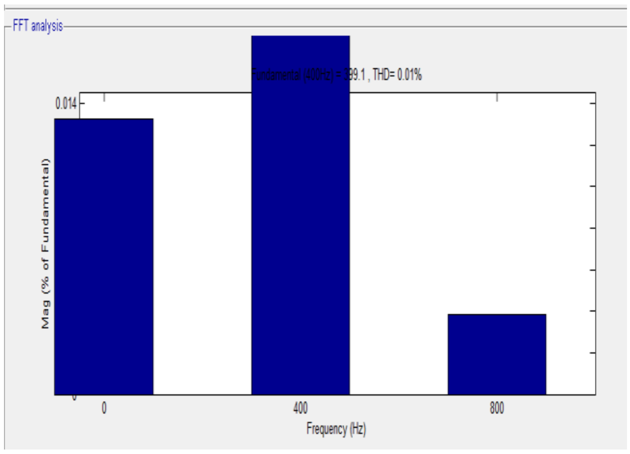


Fig.12 Harmonic Spectrum Of Source Current With fuzzy based APF

Total harmonic distortion in fuzzy based APF used in ACPS has significantly reduced to greater extent as shown in Fig.12. It represents the harmonic distortion content in which x-axis and y-axis represent the frequency and Magnitude of Percentage of fundamental respectively. It's clear that distortion was attenuated at a satisfying level seen that the THD decreased to 0.01%. The Total Harmonics Distortion of nonlinear load before using Shunt APF is about to 4.03%. but after using shunt APF with fuzzy logic is about to 0.01%.

VII. HARDWARE IMPLEMENTATION

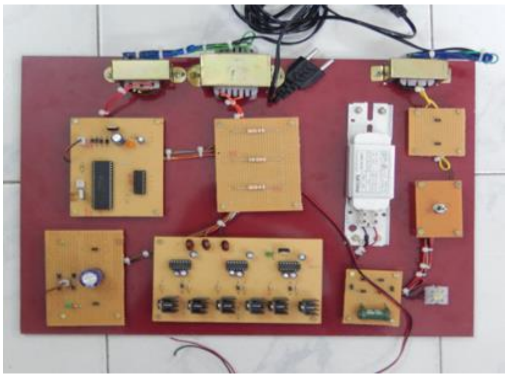


Fig.14 230V,50Hz Prototype.

The figure shown here is APF method harmonic reduction prototype. It has light weight due to transformer less prototype. It consists of power circuit which supplies a nonlinear load. The control circuit comprises of pic controller which is programmed with fuzzy logic based in order to provide signals to the inverter circuit.

PROTOTYPE WITH NORMAL VOLTAGE

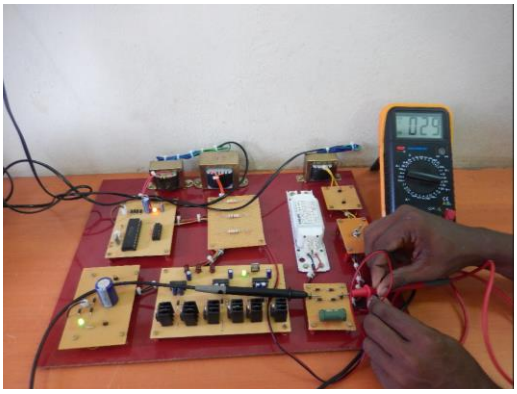


Fig.15: Hardware with normal voltage.

Fig.15 shows that the non-linear load is supplied by the secondary of single phase step down transformer. Under the normal condition supplied voltage is available at the nonlinear load Fig.16 Shows the Digital CRO waveform of normal voltage 23v.

PROTOTYPE WIH SAG VOLTAGE

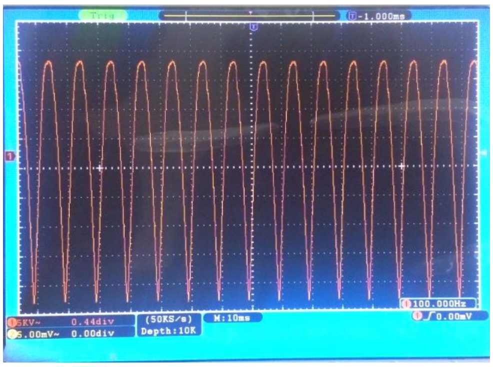


Fig 16 Digital CRO waveform of normal voltage

PROTOTYPE WIH SAG VOLTAGE

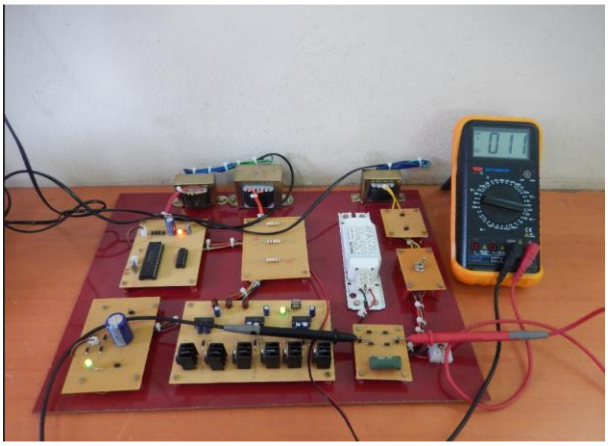


Fig.17 Prototype with the Sag voltage

Fig.17 shows that the non-linear load is supplied by the secondary of single phase step down transformer. The inductive load is connected through a switch in order to create a sag. Since the load is in excess there is dip in voltage called sag. Voltage value is reduced from 29v to 11v as shown. Fig.18 gives the Digital CRO waveform of Sag voltage reduced to11v.

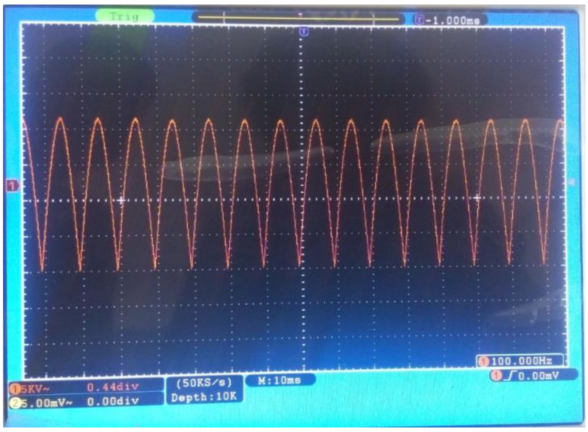


Fig.18 Digital CRO waveform of Sag voltage.

PROTOTYPE WIH COMPENSATED VOLTAGE

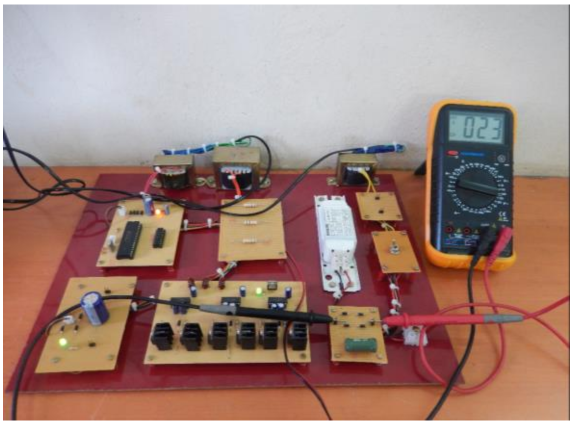


Fig.19 Prototype with the compensated voltage

Fig.6.7 shows that the non-linear load is supplied by the secondary of single phase step down transformer. The inductive load is connected through a switch. Since the load is in excess there is dip in voltage called sag. PIC controller, in which fuzzy logic was implemented, will compensate the voltage sag through Active power filter. The compensated voltage is applied through two pin connector. Thus the compensated voltage raised to 23v. Fig. 20 gives the Digital CRO waveform of Compensated Voltage 23v

Fig.20: Digital CRO waveform of Compensated voltage.

VIII. CONCLUSION

The harmonic distortion problems and their impacts on electric PQ are given. The conventional mitigation methods using passive filters have some drawback. A shunt active power filter for the high frequency air craft power system with fuzzy control based has been designed and tested. Fuzzy logic control is implemented to enhance the performance of the APF. It has been proposed to eliminate the harmonics generated by onboard nonlinear loads. This method is simpler to implement because it is only required to compensate harmonic and to generate a sinusoidal current, in phase with main voltage, the amplitude of which is controlled through the error in the load voltage. By using shunt active power filter we observed that the THD reduced below 1% at the source side with fuzzy logic. Fuzzy logic based designed APF has good harmonic current compensating effect than PI, in addition to exhibiting a good dynamic response.

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