ISSN: 2395-1680 (ONLINE)
DOI: 10.21917/ijme.2020.0172

PERFORMANCE EVALUATION OF MULTILEVEL SHUNT ACTIVE POWER FILTER USING FUZZY PI CONTROL FOR AIRCRAFT POWER UTILITY

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Abstract
The implementation of electric power in aircraft system increases the use of different kinds of power electronic converters such as AC/DC rectifiers, DC/AC inverters and DC/DC choppers in the system. The incursion of numerous power electronic devices leads to complex network and also causes power quality and stability issues. The current harmonics may cause unbalance in the aircraft electric power system and severe voltage distortion. Thus, the active filters can compensate the harmonics, improves the power factor and work as a reactive power compensator, thus in turn afford power quality enhancement of the system. This work proposes the use of a five level cascaded H-bridge VSI with an improved current control and a suitably developed modulation strategy to reduce harmonics in air craft system.

Keywords:
Power Quality, Active Power Filter, Fuzzy PI controller, Harmonics Compensation

1. INTRODUCTION

Optical Recent advances in the areas of power electronics, electric devices and microprocessors have allowed fast improvements in the performance of aircraft electrical systems. This leads to the concept of the all-electric aircraft and the more electric aircraft in civil air craft systems. Thus the increasing use of electric power in the aircraft system entails power quality, and stability problems.

Shunt active filters are most effective device for the reduction of current distortion and for power quality improvement in electrical systems. Shunt active power filter compensate current harmonics and unbalances by injecting equal-but-opposite compensating current. Hence, the application of shunt active filter to solve the power quality issues of the aircraft catches increasing attention. However SAF control becomes a real challenge in modern AC-MEA power grids because the fundamental supply frequency is about 400Hz.

Several papers have been published about the APF's application in the aircraft. In [1], a complete model of an aircraft electric power system is developed and an active filtering technique is proposed using a harmonic cancellation method. In [9], the authors proposed an estimation method of fundamental frequency and harmonics for APF applications in aircraft systems. Biagini et al. [12] investigated the development of an improved deadbeat controlled shunt APF for aerospace applications working in an aircraft power system with a supply frequency of 400 Hz. In [14], a shunt APF using perfect harmonic cancellation is studied. The harmonic filtering performance of the APF in both the conventional and the advanced aircraft EPS is presented with Matlab simulation results. In [15], based on the given structure and modeling of the advanced aircraft EPS, performance characteristics of the EPS without and with APF are compared.

In this control, the DC-link voltage is sent to the voltage regulator. The output of the regulator along with the synchronous sine wave detected from the phase voltage is sent to the multiplier. The output of the multiplier is connected to the current regulator. The current regulator modulates the modulator to generate the PWM signal for the inverter.

While designing SAPF, switching power loss plays important role. When compared to other multilevel inverter (MLI), the cascaded MLI possess low switching loss. On the other hand, the dead-time effect deteriorates the current tracking performance of APF, particularly in the high switching frequency application. The dead-time effect could be attenuated by the multilevel cascaded converter with CPS PWM modulation implemented with a low switching frequency. Hence five level cascaded SAPF is selected as the power stage configuration of the Aeronautical APF (AAPF).

2. METHODOLOGY

The currents drawn from the ASF and Load system have to exactly compensate the dissipated power. Therefore the reference current for each phase may be obtained as a sinusoidal waveform in-phase with the corresponding fundamental component of the phase voltage. The reference current signal for each phase is obtained by subtracting the phase current from the previously generated current reference waveform. Such reference signals are tracked by the control algorithm.

2.1 REFERENCE CURRENT GENERATION

For the reference current generation a modified p-q theory was implemented. The efficiency of the p-q theory is very poor when the grid voltages are non-ideal. For this reason, generation of three virtual grid voltages is proposed. These virtual voltages will have the same amplitude as the fundamental harmonic voltage of the grid and are synchronized with zero phase shifting of the corresponding grid voltages.

The modified p-q theory uses the virtual grid voltages for the reference current generation. The virtual grid voltages are transformed into α-β reference frame. The instantaneous active and reactive powers of the system are calculated via the following equation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (1)$$

Through this theory, the harmonic components of the current and the reactive power of the load can be compensated. This is achieved using a low pass filter. Therefore in order to calculate the reference compensation currents needed to compensate the harmonics, the α-β-0 coordinates is inverted as in Eq.(2).

$$\begin{bmatrix} i_{c\alpha}^{*} \\ i_{c\beta}^{*} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} - \bar{p}_0 \\ q \end{bmatrix} \tag{2}$$

where $-p_0$ is the loss caused by inverter operation. The grid should compensate the loss in order to keep the capacitor voltage constant. Conventionally *loss p* is calculated by the use of a fuzzy PI controller. Thus, the reference compensation currents in *a-b-c* coordinate is given by

$$\begin{bmatrix} i_{ca}^{*} \\ i_{cb}^{*} \\ i_{cc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{c0}^{*} \\ i_{c\alpha}^{*} \\ i_{c\beta}^{*} \end{bmatrix} \tag{3}$$

2.2 DC VOLTAGE CONTROLLER

For the dc bus voltage control an FLC PI is implemented. The error between the sensed and the reference dc bus voltage (V_{dc},V_{dcref}) and the error variation $\Delta e = e(k) - e(k-1)$ at k^{th} sampling instant are given as input to the controller. The output of the controller is considered as the active power losses of the inverter (*loss p*). The coefficients G_1, G_2 and G_3 are used to adjust the input and output control signals.

The FLC convert the crisp variables into linguistic variables uses the following seven fuzzy sets, namely NL (negative Large), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), PL (positive large). The fuzzy logic controller characterized as

- Seven fuzzy sets for each input (e, Δe) and output (Δp_{loss}) with triangular membership functions.
- Continuous universe of discourse for Fuzzification.
- Implications using Mamdani's min operator.
- Defuzzification using the centroid method

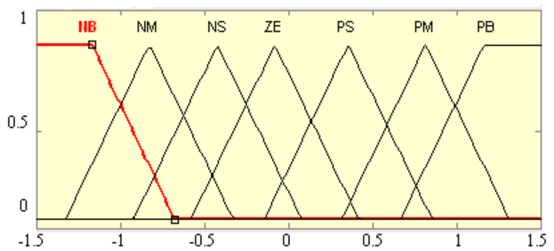

Fig.1. Membership Functions for e

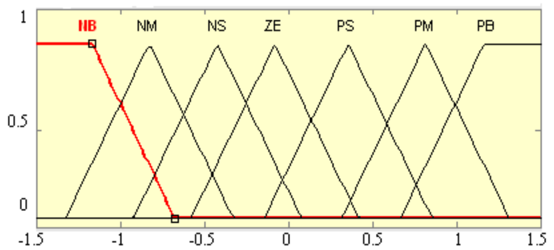

Fig.2. Membership Functions for Δe

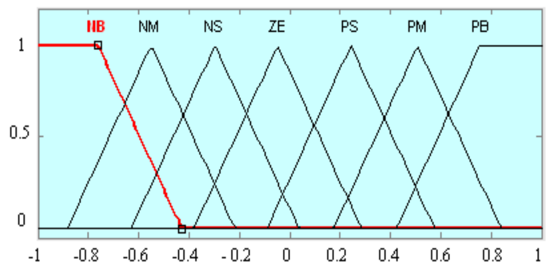

Fig.3. Membership Functions for Δu

The Fig.1-Fig.3 shows the normalized triangular membership functions for the input and output variables. In the design of the fuzzy control algorithm, the knowledge of the systems behavior is very important. This knowledge is represented in the form of rules of inference. The rule table is shown in Table.1 contains 49 rules.

The Table.1 shows the rule base of fuzzy PI controller with V_{dc} and $V_{dc\text{-}ref}$ as inputs. Output variable is change in current. The rule base consists of 49 IF-THEN rules.

Table.1. Rule base of fuzzy PI controller

$\Delta e/e$	NL	NM	NS	ZE	PS	PM	PL
NL	NB	NB	NB	NM	NM	NS	ZE
NM	NB	NB	NM	NS	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PS	PM	PB	PB
PL	ZE	PS	PM	PM	PB	PB	PB

3. CONSTANT SWITCHING FREQUENCY SUB-HARMONIC PULSE WIDTH MODULATION

Most commonly used modulation techniques for multilevel inverters are space vector PWM method and carrier based PWM methods. Due to its fast response, simple computation and its suitability for multilevel inverters, carrier based PWM method was implemented in this work. The Fig.4 gives the block diagram of the controller to generate the gating signals using CSFSHPWM method.

In this technique triangular signals each of 2 kHz frequency (f_c) and magnitude (A_c) of 0.66 are used as carrier signals and the sinusoidal voltage wave form obtained from compensating reference current estimator is used as modulating signal. The reference modulating and carrier signals are compared constantly. When the modulating signal is greater than carrier, the output pulse is low and switches off active device corresponding to it.

4. SIMULATION RESULT AND ANALYSIS

The simulation validation of the proposed technique has been obtained by modeling the system using the software Matlab

Simulink with the toolbox SimPower System. The Table.2 presents the values of the simulation model parameters.

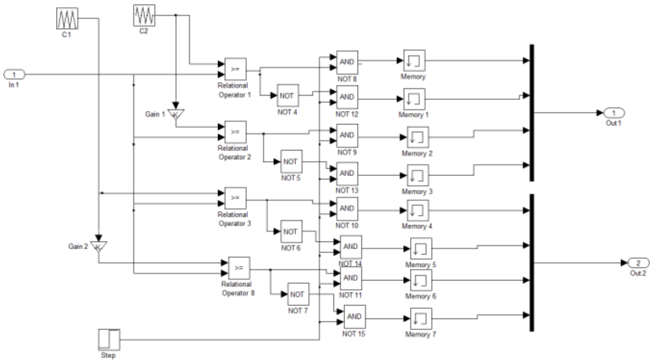

Fig.4. Gating Signal Generation by CPS-PWM

Table.2. System parameters

System Parameters	Value
Source Voltage (Vs)	115V, 40050Hz
DC Capacitor	4700uf
Reference voltage	400V
Filter Inductance (LF)	3e^{-3}mf
Filter Capacitance (CF)	10e^{-6}mH
Switching Frequency	1kHz

The proposed SAPF is simulated and investigated under diode/thyristor-rectifier load. The Fig.5 shows the instantaneous supply voltage and indicates the three-phase voltages are balanced. The Fig.6 shows source current before compensation which consists of fundamental as well as harmonic components due to the non-linear load. The source currents after compensation are presented in Fig.7 indicates when the SAPF is ON, the source currents become sinusoidal. Thus the source currents in-phase with the respective voltages is depicted in Fig.8.

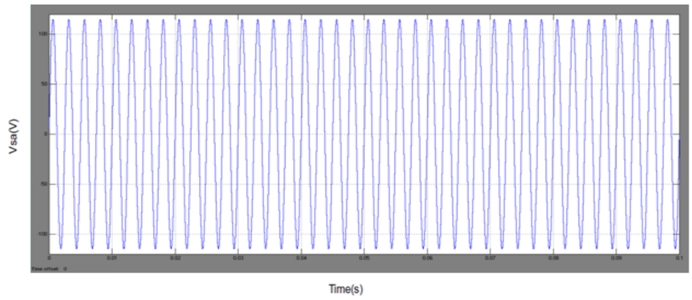

Fig.5. Source voltage for nonlinear load

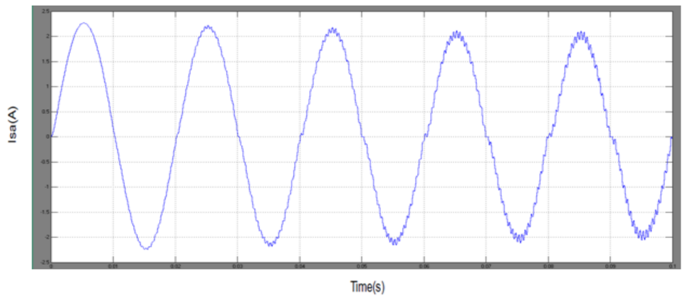

Fig.6. Source current for nonlinear load before compensation

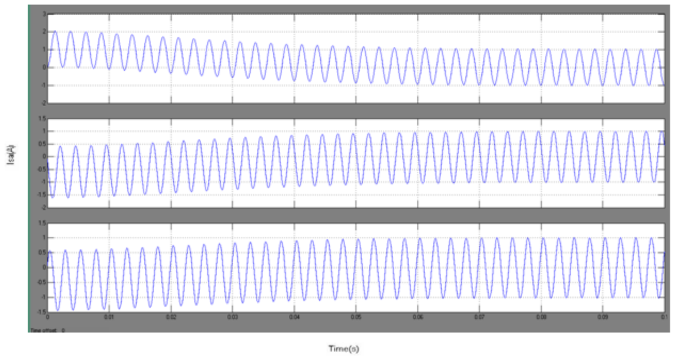

Fig.7. Source current for nonlinear load after compensation

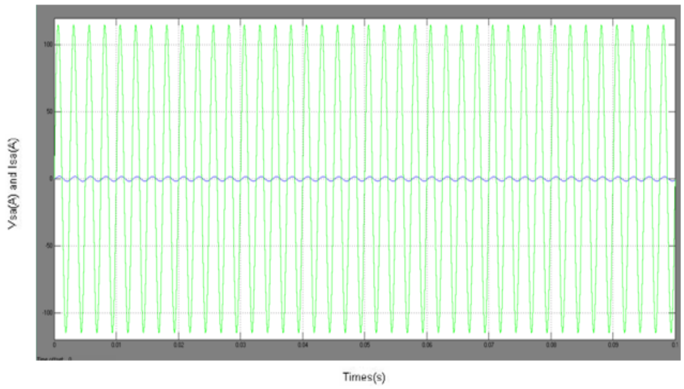

Fig.8. Source voltage and current of aircraft system after compensation

The Fig.9 illustrate plots of the order of harmonics versus magnitude in source current with SAPF. With SAPF, the order of harmonics is reduced to less than 5%. The FFT is used to measure the order of harmonics.

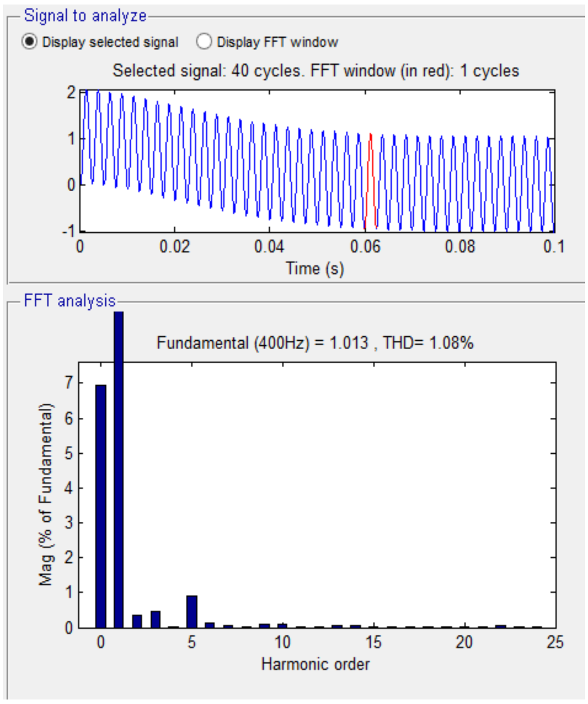

Fig.9. Harmonic Spectrum of Source Current of aircraft system with SAPF

From the Fig.9, it is concluded that the total harmonic distortion (THD) of the source current is improved to 1.08% after compensation which is within the acceptable limit of IEEE 519 standard for current distortions in distribution system. Thus from the simulation results, it is evident that this method can be can be efficiently used for reactive power compensation and current harmonics reduction in aircraft system. Thus the performance analysis of SAPF measured in terms of order of harmonic and power factor are presented in Table.3.

Table.3. Performance analysis of SAPF

Load	Condition	THD (%)	Power Factor
Diode rectifier with RL load	Without SAPF	15.04	0.92
	With SAPF	2.50	0.9999

4.1 COMPARATIVE RESULTS

In Table.4 the THD of the proposed SAPF is compared with those approaches proposed in [4] [7] and [10] for aircraft power system application.

Table.4. THD comparison

Contribution	**THD**
Biagini et al. [4]	3.7%
Odavic et al. [7]	3.3%
Chintharedi and Srinivas [10]	3.3%
Proposed work with conventional controller	3.27%
Proposed work with fuzzy PI controller	1.08%

From Table.4, it is revealed that proposed SAPF yields better THD than the existing approaches.

5. CONCLUSION

In this work, 5-level cascaded multilevel inverter based shunt active power filter was designed for aircraft system. The SAPF topology consists of five level cascaded multilevel inverter with a fuzzy PI controller to regulate the dc side voltage. Instantaneous theory is implemented for the reference current computation of SAPF and constant switching frequency sub-harmonic pulse width modulation was implemented to generate switching pulses for voltage source inverter. Simulation results analysis has shown that the proposed controller has fast response, high accuracy of tracking the DC-voltage reference, and strong robustness to load sudden variations.

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