Characterization and Performance Evaluation of Advanced Aircraft Electric Power Systems

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Abstract

A model of an advanced aircraft electric power system is developed and studied under variable-speed constant-frequency (VSCF) operation. The frequency of the generator's output voltage is varied from 400-Hz to 800-Hz for different loading scenarios. Power conversions are obtained using 12-pulse power converters. To reduce the harmonic contents of the generator output waveforms, two high-pass passive filters are designed and installed one at a time at the generator terminals. The performance of the two passive filters is compared according to their losses and effectiveness. The power quality characteristics of the studied VSCF aircraft electric power system are presented and the effectiveness of the proposed filter is demonstrated through compliance with the newly published aircraft electrical standards MIL-STD-704F.

Key Words: Aircraft electric power system, High-pass filters, Power quality, THD, Variable-speed constant-frequency

I. INTRODUCTION

Conventional civil aircraft architecture consists of a combination of systems dependent on mechanical, pneumatic, hydraulic and electrical sources. These systems have drawbacks such as low efficiency, difficulty in detecting leaks regarding the pneumatic system, using many gearboxes for mechanical systems, heavy inflexible piping and the potential leakage of dangerous and corrosive fluids for the hydraulic system. Electrical power is very flexible and doesn't require a heavy infrastructure. Its major drawbacks are a lower power density than hydraulic power and a higher risk of fire in the case of a short circuit [1].

The trend is to move towards more/all electric (advanced) aircraft which means that all of the power off-takes from the aircraft are electrical in nature. This requires a highly reliable, fault tolerant, autonomously controlled electrical power system to deliver higher quality power levels to the aircraft's loads. It has been found [2] that aircraft with more electric systems reduce fuel consumption and improve reliability as a result of fault-tolerant electric power distribution, flight control actuators and the elimination of the hydraulic system. Other benefits of advanced aircraft system are reduced design complexity, lower flight test hours, less tooling, shorter checkout time and elimination/reduction of the hydraulic system which has an

impact on the environment. Regarding the generating system of the aircraft there are three systems; the constant speed drive (CSD) [3], the integrated drive generator (IDG) [3], [4] and the variable-speed constant-frequency (VSCF) generating system [5].

The VSCF electrical system is more flexible than the CSD/IDG systems since its components can be distributed throughout the aircraft, in contrast to the CSD/IDG where the mechanical systems are located close to the engine. Furthermore, any electrical component can be replaced whenever failure occurs and thus the maintenance of the VSCF system is easier [5].

In aircraft electric power systems, DC power is needed and hence rectification is necessary. The rectification devices are either passive (diode) rectifiers or active elements (switches). Both rectifier circuits generate harmonics at the generator terminals which lessen the performance of the generator. The harmonics in the aircraft electric power systems are studied and eliminated using passive filters [6], [7] or active filters [8].

In this paper a complete simulation model for an advanced aircraft electric power system is investigated under the VSCF generating system. The output power of the aircraft system is equivalent to a Boeing 767's power of 90-kVA per channel. In this model, different load combinations are adopted including passive and dynamic AC loads as well as DC loads. The DC loads are constant power, constant current and constant voltage loads. Two high-pass filters (HPF); first-order and second-order filters, are designed and installed one at a time at the generator terminals to reduce the harmonics generated from

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Fig. 1. Advanced aircraft electric power system structure.

the used power conversion units.

II. COMPONENTS OF AIRCRAFT POWER SYSTEM

The electric power system of an advanced aircraft includes an internal combustion engine, electric starters/generators, integrated power units, solid-state power controllers, electric-driven flight actuators, an electric anti-icing system, a fault-tolerant solid state electrical distribution system, electric aircraft utility functions, and electric-driven environmental and engine controllers. A simplified block diagram of the electric power system of an advanced aircraft channel [9], is shown in Fig. 1. During the starting mode, the battery (or the ground power) system provides power, through the interface power converter, to the electric machine which acts as a starter for the aircraft engine.

In the generating mode, a variable speed engine provides input power to the generator. The generator output is then delivered via the interface converter to the constant frequency system. The synchronous generator output voltage has a 400- to 800-Hz frequency range [10]. The parameters and constants of the synchronous generator have been previously reported [10]. The power converter used in an aircraft is either a passive 6-pulse [4], an active 6-pulse [2] or a passive 12-pulse [7] configuration.

In this study, a passive 12-pulse transformer rectifier unit (TRU), as shown in Fig. 2, is used in order to eliminate the low frequency input current harmonics of the synchronous generator. The TRU provides an inherent high power factor and a low total harmonic distortion (THD) of 13% [2]. No switching is required for the rectifier and hence the losses are reduced. Moreover, the diodes are normally very robust. A three-phase Y/Y/D transformer, see Fig. 2, provides the necessary phase shift for 12-pulse operation. The output voltage of the TRU (270-VDC) is regulated by controlling the field current of the synchronous generator using a feedback proportional-integral (PI) controller to meet aircraft standards [10]. The capacitor C_d at the output of the TRU in Fig. 2 is for smoothing purposes.

Three types of DC loads are connected to the regulated 270-VDC bus through different DC/DC converters as shown

Fig. 2. The 12-pulse transformer rectifier unit.

Fig. 3. Controlled DC loads connected at the 270-VDC bus: (a) CV, (b) CP, (c) CC loads.

in Fig. 3. These loads are classified as; a constant power (CP) load of 10-kW, a constant current (CC) load of 100-A, 20-kW and a constant voltage (CV) load of 28-VDC, 5.6-kW. The DC loads are regulated using PI controllers. All of the used DC/DC converters are of the conventional type which contains

TABLE I
AC LOAD PARAMETERS OF THE AIRCRAFT POWER SYSTEM

Load	S (VA)	R(Ω)	L (mH)	PF	I (A)
A	18000	2.0	0.4	0.9	52.0
B	2800	14.0	2.8	0.9	8.0
C	15500	2.3	0.5	0.87	45.0
M ₁	Load torque = 9 Nm				
M ₂	Load torque = 6 Nm				
M ₃	Load torque = 4 Nm				

only one IGBT switch, see Fig. 3.

To provide a constant frequency of 400-Hz at a 200-VAC load bus a 12-pulse sinusoidal PWM inverter is used. The 12-pulse inverter consists of two series connected 6-pulse IGBT inverters as shown in Fig. 4. The 12-pulse inverter is controlled using a PI controller to provide the required voltage magnitude, 200-V, and frequency, 400-Hz, at the AC load bus. The rms phase output voltage, V_{ph} , of a sinusoidal PWM inverter is given in terms of its DC voltage V_d and the modulation index m [11] is given as:

$$V_{ph} = 0.5 \times m \times V_d / \sqrt{2}. \quad (1)$$

The output voltage would have a 12-pulse waveform, with harmonics of the order as:

$$h = k p \pm 1, V_h = V_1 / h \quad (2)$$

where h is the characteristic harmonic order, k is a constant, p is the converter pulse number ($=12$), V_h is the harmonic voltage and V_1 is the fundamental voltage component.

One of the important methods to evaluate the power quality of a power system is to calculate the Total Harmonic Distortion (THD) factor. The THD is calculated as:

$$THD = \sqrt{v_{rms}^2 - V_1^2} / V_1 \quad (3)$$

where V_{rms} is the total rms voltage.

Two different kinds of AC loads are used in the simulated aircraft electric power system. The first type is passive AC loads consisting of a series RL load with a PF not less than 0.85 as recommended by aircraft standards [10]. These loads are named A, B, and C as shown in Fig. 5. The other type is dynamic loads consisting of three different rating induction motors of 11.2-kW, 7.5-kW and 5.0-kW, which commonly exist [12] on aircraft for electro-hydrostatic actuation and/or electro-mechanical actuation. They are connected to the 400-Hz 200-VAC bus and named M₁, M₂ and M₃, see Fig. 5. Both static and dynamic AC loads parameters are listed in Table I. The motors are loaded with a constant torque load. It is worth mentioning that the inverter-output passive filter is connected at the 200-VAC, 400-Hz load bus to mitigate the harmonics generated from the 12-pulse PWM inverter.

III. AIRCRAFT ELECTRIC POWER SYSTEM SIMULATION WITHOUT HARMONIC FILTERS

The aircraft electric power system shown in Fig. 1 is simulated using the PSIM8 software package. The generator speed is controlled to provide a continuous frequency range

Fig. 4. The 12-pulse inverter configuration.

Fig. 5. Considered static and dynamic AC loads connected at the 200-VAC load bus.

from 360-800-Hz. The aircraft generating system is loaded with different loading scenarios as listed in Table II at different percentages of full load. The passive (A, B, C), dynamic (M₁, M₂, M₃) and DC (CP, CC, CV) loads are switched according to each case-study. For each case-study the THD values of the voltage and current are calculated at the generator terminals and at the AC load bus.

Fig. 6 and 7 show the THDv and THDi of the generator voltage and current for case-study 1 to case-study 7 (cs1-cs7) as influenced by the operation frequencies. The THDv is always greater than 5% for all cases over the entire frequency range and goes as high as 12% for case-study 7, see Fig. 6. For higher loads (cs4-cs7), the THDv is higher than it is for light

TABLE II
LOADING SCENARIOS

Case No.	Passive loads	Dynamic loads	DC loads	% of full load
1		x		25%
2	x			35%
3			x	40%
4	x	x		60%
5		x	x	65%
6	x		x	75%
7	x	x	x	100%

loads (cs1-cs3). The opposite is true for the generator current THDi. For larger loads, the THDi reaches the standard limit of 5%, see Fig. 7. At higher loads cases, the THDi values comply with standards.

The power factor (PF) at the generator terminals of the aircraft electric power system for case-study No. 1 to case-study No. 7 are shown in Fig. 8 as determined by the operation frequency. Higher PF values are recorded for case-study No. 3 where only DC loads are applied to the system. The lowest PF values are for case-study No. 4 where the AC passive and dynamic loads are applied and case-study No. 7 where all of the loads are applied. For all of the case-studies the PF of the generator is higher than the standard limit of 0.85 [10].

IV. PASSIVE POWER FILTER DESIGN

When static capacitors are connected to a system for voltage or reactive power control, there is a frequency at which the capacitors are in parallel resonance with the power system inductive reactance. It is found that the filter capacitance C_f should be less than 90- μ F to avoid resonance with the aircraft electric system. The parallel resonant frequency (f_p) can be calculated as [13]:

$$f_p = f_1 \sqrt{\frac{MVA_{sc}}{Mvar_c}} = f_1 \sqrt{\frac{X_c}{X_s}} = \frac{1}{2\pi} \sqrt{\frac{1}{L_s C_f}} \quad (4)$$

where MVA_{sc} is the short circuit level at the point of study, $Mvar_c$ and X_c are the capacitor filter rating and its reactance, X_s is the reactance of the power system up to the filter location, L_s is the corresponding inductance and f_1 is the fundamental operation frequency which changes from 400-to 800-Hz.

The HPF design is based on an iterative routine which chooses the filter parameters based on two criteria; the filter losses which are to be kept at a minimum at the fundamental frequency and the THD values of the generator waveforms which are reasonable and comparable to the standard values. Three different passive filters, as shown in Fig. 9, are used to improve the aircraft power quality. Two of them will be connected at the generator terminals one at a time, Fig. 9 (a) and (b), and the other will be connected all the time at the output of the 12-pulse inverter at the 200-VAC load bus, Fig. 9(c).

A. First-Order High-Pass Filter (RC Type)

The first-order HPF is the simplest high-pass harmonic filter. It consists of a capacitor with a series resistance per phase as shown in Fig. 9 (a). The value of the capacitance is chosen

Fig. 6. Generator voltage THDv as function of the operation frequency for different case studies.

Fig. 7. Generator current THDi as function of the operation frequency for different case studies.

Fig. 8. Generator PF as a function of operation frequency for different case-studies.

to avoid a parallel resonance with the aircraft power system on the one hand and to keep the THD values at the generator terminals as low as possible on the other. The series resistance is calculated from the filter corner frequency and chosen to keep the filter losses at a minimum in the fundamental frequency range (400-800-Hz). Three different corner frequencies are chosen and the THD for the generator voltage and current as well as the filter losses at the fundamental frequency are calculated and compared to choose the best design.

The filter capacitance C_f is calculated from the filter-injected reactive power per phase, Q_c as [14]:

$$C_f = G_c / (\omega_1 V_1^2) \quad (5)$$

where ω_1 is the fundamental frequency (rad/s).

The filter provides a low impedance above a corner frequency to filter out the high-frequency harmonics. The filter

Fig. 9. Designed passive filters: (a) first-order, (b) second-order and (c) inverter-output filter.

TABLE III
FIRST-ORDER HPF CHARACTERISTIC AND PARAMETERS

Filter parameter	Corner frequency		
	f_{c1} (4400 Hz)	f_{c2} (6600 Hz)	f_{c3} (8800 Hz)
R_f	1.0Ω	0.7Ω	0.5Ω
C_f	35 μF		
Q_c	3.5 kvar		

resistance R_f can be calculated from the corner frequency f_c equation [15]:

$$f_c = 1/(2\pi C_f R_f). \quad (6)$$

The filter loss (P_{loss}) in the fundamental frequency range is calculated as:

$$P_{loss} = 3I_f^2 R_f \quad (7)$$

where I_f is the filter fundamental current component per phase.

A computer routine is used to choose the filter parameters. The routine is shown in Fig. 10. The design parameters of the high pass RC filter are listed in Table III for the three selected corner frequencies.

The filter losses dependent on the operation frequency are shown in Fig. 11 for the selected three corner frequencies (f_{c1} , f_{c2} , f_{c3}). To improve system efficiency, the filter losses should be at the minimum values that conform to the filter design corresponding to f_{c3} . For this design, the losses at 400-Hz are equal to 460-W (0.5% of the generator power) compared with 1900-W (2.0% of the generator power) at 800-Hz.

The THDv values of the generator voltage at different frequencies for the three selected corner frequencies are shown

Fig. 10. Flow chart of the filter design procedure steps.

Fig. 11. First-order harmonic filter losses as function of operation frequency at different corner Frequencies.

in Fig. 12. The THDv value at 400-Hz is slightly larger for f_{c3} and lower for most of the frequency range when compared to f_{c1} and f_{c2} . The normal operation of an aircraft is at 400-Hz and it only goes to higher speeds under abnormal conditions such as faults, the changing/replacing of a load supply or cruising operation. Therefore a first-order HPF is rarely used due to its large power losses at the fundamental frequency, Fig. 11.

Fig. 12. Generator THDv values as function of the frequency at different corner frequencies for RC filter case.

B. Second-Order High-Pass Filter (RLC Type)

The second-order HPF is the simplest to apply while providing good filtering action and reduced losses at the fundamental frequency. Typical values of the quality factor, Q for a high pass filter, vary from 0.5 to 2.0. With a high Q , the filtering action is more pronounced at the corner frequency, while at higher frequencies the filter impedance rises steadily. For lower values of Q , the response at the corner frequency is not noticeable, and as the frequency increases, the impedance is roughly constant. The configuration of a second-order HPF is shown in Fig. 9 (b). The same procedure as the first-order filter is adopted here for determining the second-order filter parameters. Assuming the quality factor equals unity, the filter inductance, L_f and the filter resistance R_f of the second-order HPF are calculated as [16]:

$$Q = R_f / (\omega_c L_f) \quad (8)$$

where ω_c is the corner frequency in rad/s. The filter inductance is calculated from:

$$\omega_c = 1 / \sqrt{L_f C_f} \quad (9)$$

where the filter capacitance C_f is calculated in the same way as the first-order filter using (5). With the filter inductor core losses taken to be approximately equal to the winding copper losses and ignoring any capacitor leakage losses, the total filter losses can be calculated as:

$$P_{loss} = 3I_r^2 R_f \quad (10)$$

where I_r is the current through the equivalent filter resistance R_f , see Fig. 9 (b).

The parameters of the designed second-order HPF are listed in Table IV. The second-order HPF losses as influenced by the fundamental frequency are shown in Fig. 13. Comparing Figs. 11 and 13, the losses of the second-order HPF are much smaller than those of the first-order filter. The maximum filter loss at 800-Hz is less than 0.06% of the generator's output power. Over the entire frequency range, the impedance of the filter inductor is approximately one-tenth of the filter resistance. Therefore, most of the shunt current passes through

TABLE IV
SECOND-ORDER HPF DESIGN PARAMETERS

R_f	L_f	C_f	f_c	Q
0.9Ω	$32.7\mu\text{H}$	$40.0\mu\text{F}$	4400 Hz	1.0

Fig. 13. The second-order harmonic filter losses at variable frequency operation.

Fig. 14. THD values of generator voltage and current with RC and RLC filters for cs4 and cs7.

the inductance with a subsequent decrease in the losses when compared with the first-order filter, see Fig. 9 (b). The choice between first and second order harmonic filters is based solely on technical merits as well as cost and sophistication.

C. Inverter-Output Filter Design

The design of an output filter for a sinusoidal pulse width modulation (SPWM) inverter can be an extensive process that often involves an analysis of the inverter output voltage and the load current considering nonlinear loads [17],[18]. The proper design of a 12-pulse SPWM inverter output filter is crucial in order to supply near sinusoidal voltage to sensitive loads connected to an aircraft electric power system. A major design criterion is the selection of a filter cut-off frequency. The cut-off frequency has to fall between the highest fundamental frequency of the SPWM inverter switching frequency with a significant attenuation at the high frequency and a minimum

attenuation as well as a minimum phase-lag within the operating range of the frequency.

The inverter output passive filter simulated in this study is an ordinary LC high pass filter connected between the three phases and the neutral. The filter parameters are selected to provide a minimum attenuation and phase lag within the frequency range of operation and a maximum attenuation at the high frequency near the inverter switching frequency. The filter inductor has an inductance of 40- μ H with a series resistance of 0.04- Ω and the shunt capacitor has capacitance of 0.2-mF with a series resistance of 0.02- Ω , see Fig. 9 (c). The filter proved to be efficient in mitigating the harmonics generated from the 12-pulse sinusoidal PWM inverter to within the values required by the harmonics standards.

V. AIRCRAFT POWER SYSTEM PERFORMANCE WITH HARMONIC FILTERS

To study the effectiveness of the first-order (RC) and second-order (RLC) passive filters, either of the two filters is connected at the generator terminals and each time the THD of the voltage and current for case-studies No. 4 and 7 are calculated at different operation frequencies and plotted in Fig. 14. The THD of the generator current for both cases is always less than 5%. At higher frequency values, the THD of the generator voltage is less than 5% for RC filter while the THD values are almost constant for RLC filter and greater than 5% for case-study No. 7.

Comparing Figs. 6 and 7 with Fig. 14, the THD values of the generator voltage and the current are lower and reach the standard values for most case studies with the installation of either RC or RLC filters at the generator terminals under variable speed conditions. The THDv and the THDi of the 200-VAC bus with the installation of either the RC or RLC filters at the generator terminals are always less than 5% as shown in Fig. 15 for case-studies No. 4 and 7. The inverter-output filter reduces the 12-pulse inverter harmonics to less than the standard limit of 5%.

The PF at the generator terminals being dependent on the operation frequency after the installation of either the RC or RLC filters is shown in Fig. 16 for case-studies No. 4 and 7. With the RC filter the PF is slightly higher than that of the RLC filter. With the RC filter, the capacitor works as a power factor correction in addition to its filtering action. In the RLC filter the inductance equalizes some of the capacitive reactance. Compared with Fig. 8, the PF is higher for both filters than the case without them. From Fig. 16, one should note that the increase in the PF with the increase in the operation frequency is attributed to the decrease of the capacitive reactance of the filter capacitor.

Time waveforms for the aircraft electric power system are shown in Fig. 17 for the RC passive filter case at 400-Hz operation and the full load condition. In this figure, the generator voltage (V_G) and current (I_G) waveforms, the main AC load bus voltage (V_L) and current (I_L) waveforms, the RC filter current (I_f) waveform, and the main 270-VDC bus regulated voltage (V_d) are demonstrated. For the RLC passive filter case, the time waveforms are shown in Fig. 18. The new

Fig. 15. THD values of the AC load bus voltage and current with RC and RLC filters for case-studies No. 4 and 7.

Fig. 16. Power factor at generator terminals as function of the frequency for cs4 and cs7 when installing RC or RLC filters.

waveform is for the filter resistance current (I_r), see Fig. 9 (b). The passive HPFs help in reducing the THD values to the standard values.

VI. MEETING AIRCRAFT ELECTRIC STANDARDS

The aircraft electric standards [20] establish the requirements and characteristics of aircraft electric power systems provided at the input terminals of electric utilization equipment. The three phase 200V-AC line voltage at load terminals should comply with the aircraft standards regarding its steady state, unbalance, modulation, phase difference, crest factor and DC component.

These parameters are listed in Table V with the simulation results of the studied aircraft system under the most severe load (case-study No. 7) for different values of the operation frequency. Table V confirms that the studied aircraft electric system characteristics are within the standards limits for all of the frequency range. The 12-pulse sinusoidal PWM

TABLE V
AIRCRAFT 200-VAC NORMAL OPERATION CHARACTERISTICS

parameter	Standard [10]	Frequency (Hz)				
		400	500	600	700	800
Steady state voltage	108-118V	115.5	115.1	115.3	114.7	114.9
Voltage unbalance	3V	1.35	0.13	0.09	0.51	0.14
Voltage modulation	2.5V	1.16	1.76	1.13	1.25	1.50
Phase voltage difference	116°-124°	120.5	120.8	120.2	120.1	119.5
Crest factor	1.31-1.51	1.44	1.46	1.43	1.44	1.46
DC component	±0.1V	0.02	0.02	0.04	0.03	0.06

TABLE VI
AIRCRAFT 28-VDC NORMAL OPERATION CHARACTERISTICS

parameter	Standard [10]	Frequency (Hz)				
		400	500	600	700	800
Steady state voltage	22.0-29.0V	28.0	28.0	28.0	28.0	28.0
Distortion factor	0.035 max	0.0032	0.003	0.0032	0.0034	0.0032
Ripple amplitude	1.5V max	0.050	0.032	0.035	0.037	0.032

TABLE VII
AIRCRAFT 270V-DC NORMAL OPERATION CHARACTERISTICS

parameter	Standard [10]	Frequency (Hz)				
		400	500	600	700	800
Steady state voltage	250-280V	270.3	270.3	270.4	270.6	270.9
Distortion factor	0.015	0.004	0.004	0.003	0.004	0.003
Ripple amplitude	6.0V	3.70	3.90	3.60	4.16	3.38

inverter along with the inverter output passive filter reduces the harmonics to a minimum at the 200-VAC bus. The aircraft standards [10] define the required parameters for the 28-VDC bus. These characteristics are listed in Table VI with the simulation results of the studied aircraft system at different frequencies. The 270-VDC bus characteristic parameters are listed in Table VII with the simulation results at different frequencies.

VII. CONCLUSIONS

The VSCF aircraft electric power system is modeled and analyzed under variable-speed constant-frequency operation.

Fig. 17. Generator voltage and current, AC load voltage and current, filter current and 270-VDC bus voltage at 400-Hz with RC filter for case-study No. 7.

The modeled aircraft system is studied in the frequency range of 400-800-Hz for different loading scenarios including passive and dynamic AC loads in addition to nonlinear DC loads of constant power, constant current, and constant voltage. The power quality characteristics of the modeled system are generated and analyzed. First-order and second-order high-pass filters are designed to reduce the harmonics at the generator terminals so that they are lower than the standard values. The power quality of the studied aircraft

Fig. 18. Generator, AC load voltages and currents, total filter current, filter resistive current and 270-VDC bus voltage at 400-Hz with RLC filter for case-study No. 7.

electric system complies with the rigorous aircraft electrical standard MIL-STD-704F for 200-VAC systems in regards to the steady state magnitude, the unbalance, the modulation, the crest factor and DC component. Moreover, the power quality of the modeled aircraft system complies with the established standards for both 28-VDC and 270-VDC voltage systems in regards to the steady state magnitude, the distortion factor, and the ripple amplitudes.

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