Constant Frequency Aircraft Electric Power Systems with Harmonic Reduction

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***Abstract*-The ever-increasing number of power electronic converters connected to the aircraft electric power system significantly increases harmonic levels and voltage transients in that system. Stringent limits on harmonic current distortion and perturbation of the aircraft electric power supply demands accurate simulation and development of high performance filters for the mitigation of harmonics and minimization of system transients. This paper presents the simulation, modeling, and transient analysis of conventional and advanced aircraft electric power systems with harmonic mitigation using passive harmonic filters. The aircraft electric power system is analyzed considering equivalent passive AC and DC loads under transient and steady state operating conditions. The electric power source is simulated by a controlled motor-generator set to provide a constant frequency and a constant output voltage source. The DC power is generated using 12-pulse converters. Moreover, to mitigate the harmonics generated by the converters a passive input filter is designed to meet the harmonic standards for the AC side of the aircraft electric power system.**

I. INTRODUCTION

Any conventional aircraft utilizes a combination of hydraulic, electric, pneumatic and mechanical power transfer systems. Increasing use of electric power is seen as the direction of technological opportunity for advanced aircraft power systems based on rapidly evolving technology advancements in power electronics, fault-tolerant electrical power distribution systems and electric-driven primary flight control actuator systems [1]. It is found in [2] that the advanced aircraft electrical power systems are more energy-efficient as well as more reliable than their conventional counterparts, as losses in electrical cabling are lower than those in hydraulic or pneumatic piping.

The electric systems in advanced aircraft can be designed to provide the right function at the right time. The central hydraulic lines are kept energized during the entire flight. However, the landing gear and secondary flight control require power for only a short time. Electrical systems can be switched on and off as needed, thus conserving power. The coupling between converters performance and filter values complicates the analysis and design problem, which is further compounded by the use of high frequency power supply system.

In this paper the conventional and advanced aircraft electric power systems are analyzed and simulated under transient and steady state conditions. A motor-generator set is controlled to provide the aircraft power source which has a constant frequency and voltage magnitude during all loading cases. The harmonic contents are calculated and harmonic mitigation passive filters are designed to meet the respective standards for the voltage and current waveforms on the AC side of the main aircraft power supply. The DC bus voltage is obtained and regulated from a controlled 12-pulse converter to meet the standards concerning the magnitude of the DC voltage and its ripple contents.

II. CONVENTIONAL AIRCRAFT SYSTEM

Conventional aircraft electric power system (EPS) often consists of two or more engine driven generators to supply the AC loads throughout the aircraft. While the engine driven generators are singly connected to the distribution buses in some civil configurations (i.e. each generator is responsible for a specific numbers of buses), all American and European air forces use the parallel connection configuration. All aircraft needs AC and DC power altogether. This DC power comes from rectification of the AC power using the transformer rectifier units (TRUs). These units are normally 12 pulse configuration [3].

Due to its cyclic operation of these units, it is considered as the harmonic source in the aircraft EPS. These units can increase the voltage distortion and the harmonic contents into the AC side of the aircraft EPS. Increasing harmonics may lead to malfunction of most of the sensitive instruments and circuits inside the aircraft.

A typical civil transport aircraft electrical power system is shown in Fig. 1. This is a simplified representation of the Boeing 767 aircraft EPS without including the external power system [4, 5]. The primary AC system comprises identical left and right channels. Each channel has an Integrated Drive Generator (IDG) driven from its respective engine.

Each AC generator is rated at 200V-AC, 400Hz, 90kVA and is controlled by its own generator control unit. Bus tie breakers are used to tie both buses together in the event that either generating source is lost. The bus tie breakers can also

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operate in conjunction with the external power contactor or the auxiliary power breaker to supply both main AC buses.

The 90kVA auxiliary power unit can feed the ground-handling and ground-servicing buses. It can also be used as a primary power source on flight on certain aircraft in the event that either left or right generator is lost. Each of the main AC buses feeds utility loads, galley loads, and power conversion equipments.

Some loads in aircraft needs DC power generated by using TRUs. In case of either main AC bus or TRU failure, a DC bus tie contactor closes to tie the left and right DC buses together. The main AC buses feed the aircraft galleys which is a major electrical load. That load needs 28V-DC in addition to 115V-AC and may reach a total load of 32 kVA [6, 7].

Both AC buses feed 26V-AC buses via autotransformer to feed certain loads. Other specific feed from the left main bus is a switched feed to the AC-standby (AC-STBY) bus. The battery can feed the essential electrical loads and the main AC buses through inverter (INV) in case of all generators failure. The utility or services loads are distributed throughout the aircraft and may be broadly subdivided into the following: motors and actuation, lighting services, heating services, subsystem controllers and avionics systems. Motors (AC and DC) in an aircraft are used for linear and rotary actuation, control valve operation, engine starting, and cooling fans.

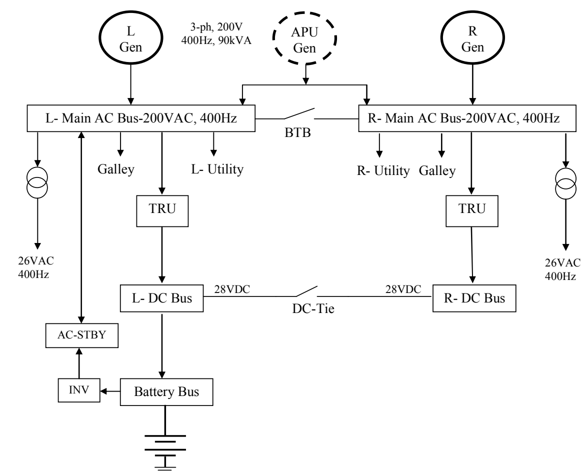

Fig. 1: Boeing 767 electric power distribution system.

Lighting systems in aircraft can be divided into external lighting (navigation, strobe, landing, taxi, inspection, logo lights) and internal lighting (cockpit/flight-deck, passenger information, emergency, bay and evacuation lighting). Lighting may be powered by 28V-DC or 26V-AC provided by auto-transformer from the main AC buses, Fig. 1.

The use of electrical power for heating purposes on aircraft can be extensive. The highest power usage relates to electrically powered anti-icing and de-icing systems which can consume many tens of kVA [5]. Windscreen heating is another important electrical heating service. Aircraft subsystems controllers are packaged into line replaceable units which permit rapid removal should a fault occur. These electronics needs ±15V-DC and +5V-DC which can be obtained using single phase AC/DC converters.

A. Transient Simulation of Conventional Aircraft System

A model for the aircraft EPS is developed to represent the actual loads as closely as possible. A single branch of the conventional aircraft EPS is shown in Fig. 2. The DC voltage is obtained by connecting two TRUs in series to obtain 12 pulse rectifications to minimize the harmonic contents in the output DC voltage [8]. The equivalent EPS for Boeing 767 aircraft is estimated from that of the C130E aircraft [8].

The appropriate phase currents, phase resistance and inductance are then calculated based on the kVA rating and the PF for each phase. The different loads rating and parameters for the simulated B767 aircraft are listed in Table I. To generate a three-phase with constant frequency and constant voltage, a motor-generator set is used as shown in Fig. 2. The frequency is regulated by regulating the DC motor speed by using proportional-integral (PI) controller.

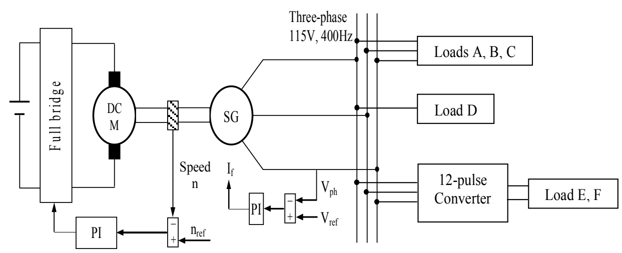

Fig. 2: Simulated branch of conventional aircraft EPS.

TABLE I
BOEING 767 AC AND DC LOAD PARAMETERS

Load	phase	S (VA)	PF	R (ohm)	L (mH)	I (A)
A	a	11645	0.74	0.84	0.304	100
	b	3670	0.67	2.41	1.065	32
	c	3500	0.66	2.49	1.129	30
B	a	833	0.90	14.28	2.752	7
	b	833	0.90	14.28	2.752	7
	c	833	0.90	14.28	2.752	7
C	a	5048	0.82	2.15	0.597	44
	b	5048	0.73	1.91	0.712	44
	c	5048	0.73	1.91	0.712	44
D	a	2925	0.96	4.34	0.504	25
	b	--	--	--	--	--
	c	--	--	--	--	--
E		11610	--	0.068	--	415
F		10300	--	0.076	--	368

The magnitude of the phase voltage of the generator, is controlled by comparing it to the reference voltage (115V-AC) using another PI controller which controls the field current of the synchronous generator. To check the system transients are within standard limits specified in [9], a combination of different AC and DC loads are considered and simulated using PSIM6 software package [10]. The severe case is considered when the motor-generator set is loaded with all AC and DC loads. The listed loads are switched on at the same time of 0.3second (which is chosen long enough to make sure that the generator output reaches its steady state value). The rms value of the generator phase voltage is shown in Fig. 3 following the sudden simultaneous application of the AC and DC loads. It is clear that the generator phase voltage during transient and steady state conditions is within the standard limits [9].

The system frequency and its standard limits are shown in Fig. 4 during transient condition. It should be noted that the system frequency reaches its steady state much faster than the aircraft standard limits [9]. The 28V-DC across loads E and F (see Table I and Fig. 2) is shown in Fig. 5 with the aircraft standards limits. This DC voltage has peak-to-peak ripple amplitude of 0.5V and a ripple factor of 0.6% compared to the standards of 1.5V and 3.5% [9], respectively.

B. Harmonic Contents in Conventional Aircraft System

Due to switching of the full diode bridges which feed the DC loads (load E and load F in Table I), harmonics are generated on the AC side of the converter which make perturbation for the aircraft power system. For twelve-pulse converter, as the case, the major harmonic orders are [8, 11]:

$$h = 12\,p \pm 1 \tag{1}$$

The harmonic current is related to the fundamental as:

$$I_h = I_1 / h \tag{2}$$

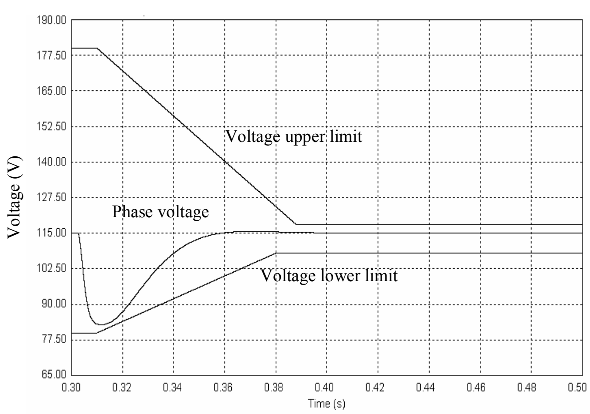

Fig. 3: Phase voltage and the standard limits [9] during transient and steady state conditions.

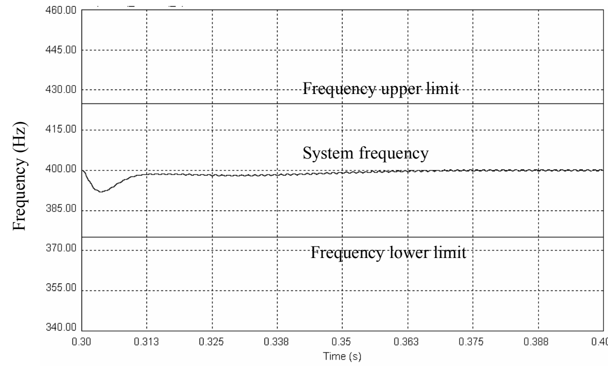

Fig. 4: System frequency and the standard limits [9] during the transient condition.

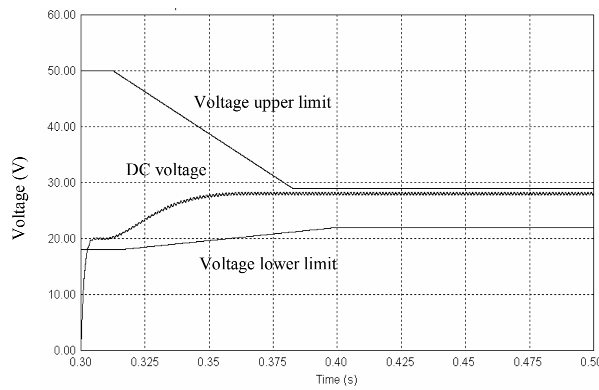

Fig. 5 DC voltage and the standard limits [9] of 28V-DC bus.

The current total harmonic distortion is given as:

$$THDi = \sqrt{I_{rms} - I_1} \Big/ I_1 \tag{3}$$

where h is the harmonic order, p is any integer, I_h is the harmonic current value, THD is the total harmonic distortion, I_{rms} is the total rms current including harmonics and I_1 is the current fundamental value.

For a twelve pulse converter, the dominant harmonics are 11^{th}, 13^{th}, 23^{rd}, 25^{th}. The loading scenario adopted in Table II shows that THDi and THDv for some cases are exceeding the standard harmonic levels which is 5% [9, 12].

TABLE II
THD AT DIFFERENT CASES IN CONVENTIONAL AIRCRAFT

Loading scenario			Without filter		With filter	
Case	AC Loads	DC Loads	THDi %	THDv %	THDi %	THDv %
1	--	Load E	10.2	6.74	2.30	1.76
2	--	Loads E, F	8.26	9.55	3.51	3.72
3	Load A	Load E	4.43	7.07	3.19	1.02
4	Loads A, B	Load E	4.43	6.81	3.35	3.46
5	Load C	Load F	4.52	5.55	3.02	2.84
6	Loads C, D	Load F	4.32	6.07	2.43	2.28
7	All	Loads E, F	7.47	11.03	3.16	2.43

C. Passive Filter Design and Harmonic Mitigation

Several research papers [13-15] discussed the design of the passive filters. A procedure here is adopted to design the passive filter for 11th, 13th, 23rd and 25th dominant harmonics. The filter components are calculated as [13, 16]:

$$C_f = \left[1 - \left(\frac{\omega_1}{\omega_r}\right)^2\right] \frac{Q}{\omega_1 V_1^2} \quad , \quad L_f = \frac{1}{\omega_r^2 \, C_f} \qquad (4)$$

$$R_f = \omega_r \, L_f / q \quad , \quad \omega_r = h \, \omega_1 \qquad (5)$$

where C_f, L_f and R_f are the harmonic filter capacitance, inductance and resistance per phase, respectively. Q is the load reactive power per phase, V_1 is the fundamental rms phase voltage, ω_1 is the fundamental frequency (rad/s), ω_r is the filter resonant frequency and q (=20) is the inductor's q-factor.

The filter branches are tuned normally to a frequency slightly below the harmonic frequency. There are substantial differences in opinions on how much the branches should be detuned. According to [17] the branches are detuned by 18 Hz, i.e., the absolute detuning is the same. Reference [18] assumes that filters are detuned by 5% below harmonic frequencies. It means that there is the lack of a clear recommendation with respect to the filter detuning, even the degree of detuning is not related to the level of these harmonics. In the present calculation, the detuning is taken 4%, i.e. the 11th harmonic is considered $10.96\omega_1$ and the 13th harmonic is considered $12.96\ \omega_1$. After installing the designed filter, the THD for voltage and current are reduced to the standard values [9, 12] for all cases of the loading scenario as listed in Table II. Using the above design method, the filter parameters per phase are listed in Table III.

TABLE III
FILTER PARAMETERS PER PHASE

Filter	C_f (uF)	L_f (uH)	R_f (Ω)
11th	24.05	59.03	0.0814
13th	24.11	42.15	0.0689
23rd	24.22	13.41	0.0391
25th	24.23	11.35	0.0355

When static capacitors are connected to a system, there is a frequency at which the capacitors are in parallel resonance with the power system reactance. Hence, capacitors should be sized to avoid a resonance near a characteristic harmonic frequency. The parallel resonant frequency (f_p) can be calculated as [12]:

$$f_p = f_1 \sqrt{X_c / X_s} = 1 \big/ (2\pi \sqrt{L_s \, C_f}\,) \qquad (6)$$

where MVA_{sc} is the short circuit duty at the point of study, $Mvar_c$ is the capacitor rating at the system voltage, X_c is the reactance of the capacitor filter, X_s is the reactance of the power system and L_s is its inductance.

In this case, the parallel resonant frequency is much bigger than the fundamental frequency ($f_p = 6f_1$) and less than the lowest dominant harmonic frequency ($11f_1$)

ADVANCED AIRCRAFT ELECTRIC SYSTEM

An EPS of a more-electric aircraft includes the following elements [19]: internal combustion engine, electric starter/generators, integrated power units, solid-state power controllers, electric-driven flight actuators, electric-actuated brakes, electric anti-icing system, fault-tolerant solid state electrical distribution system, electric aircraft utility functions, electric-driven environmental and engine control. The EPS consists of two independent channels, according to the number of starter/generators in the aircraft.

An auxiliary/emergency power unit contains an additional auxiliary starter/generator. The generating system includes starter/generators, power control units, a generator and system control unit. Either three-phase synchronous machines [19] or switched-reluctance machines may be used as starter/generators in a more-electric aircraft. The power control units are used to transform the “wild frequency” AC power produced by the synchronous generators into 270V DC power. The system control unit controls the generators, power control units, and the DC busses.

An auxiliary power unit and battery system provides power for starting the engines and emergency back-up. The following reasons motivated the choice of the 270V DC distribution bus [20]: It is a good voltage source for inverters that power motor loads of the aircraft, it is easy to provide uninterruptible power on the bus by using a battery back-up, regenerative power from electrical actuators can be easily returned to the bus. A simplified of the electric power distribution system of the advanced aircraft [5, 19, 21] is shown in Fig. 6.

A. Transient Simulation of Advanced Aircraft System

The advanced aircraft EPS is more sophisticated than the conventional one. To simulate the advanced aircraft electrical system, the battery and the external power system are neglected as the case for the conventional system. The simplified system used for simulation is shown in Fig. 7. The motor-generator set is the same as the conventional case to provide the 115V-AC at 400Hz generator bus under the same AC and DC loads.

In advanced aircraft EPS, the 270V-DC voltage is usually obtained by using 12 pulse converter to reduce the characteristic harmonics. In this case a two 6-pulse thyristor bridges are connected in series to obtain a controlled 12-pulse rectifier using PI controller. The peak-to-peak ripple voltage is 3.7V and the ripple factor is 0.28% for the 270V-DC bus, which are lower than the standard values of 6V and 1.5% [9], respectively.

The DC loads are connected to the 270V-DC bus through DC/DC forward chopper to provide the required 28V-DC feeding the DC loads.

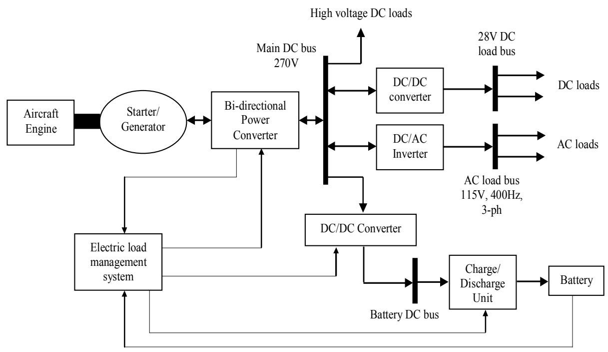

Fig. 6: Advanced aircraft electric power system structure.

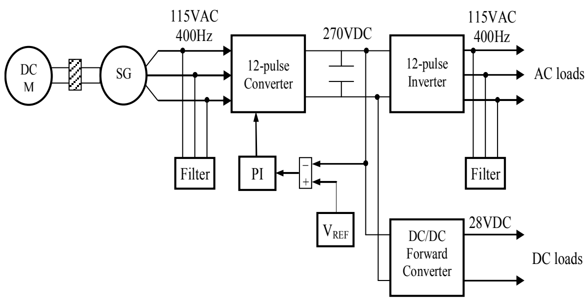

Fig. 7: Simulated system structure of advanced aircraft.

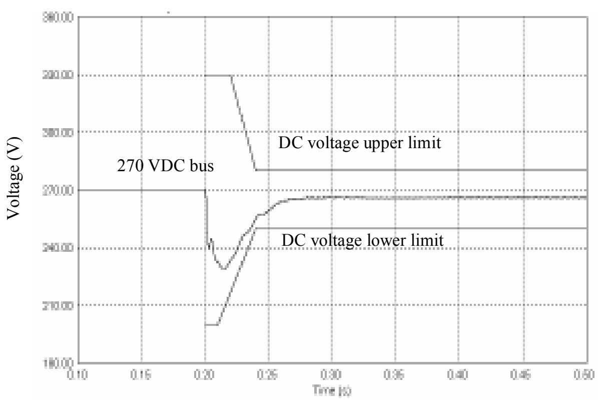

Fig. 8: DC 270V bus voltage and the standard limits [9] during transient and steady state conditions.

For supplying the same AC loads as in conventional case, two 6-pulse PWM inverters are connected in parallel to provide a smoothed 12-pulse voltage waveform. The 270V-DC bus voltage is shown in Fig. 8 with its standard limits [9] for the most severe loading case. The waveforms of the phase voltage and 28V-DC voltage are the same as in the conventional case and they are within their standard limits. The 28V-DC bus has peak-to-peak ripple amplitude of 0.79V and a ripple factor of 0.46% compared to the standards of 1.5V and 3.5% [9], respectively.

B. Harmonic Levels and Mitigation in Advanced Aircraft

Existing both AC/DC and DC/AC converters in the advanced aircraft EPS as shown in Fig. 7 produces harmonics at AC load bus and at the generator terminals as well. To reduce harmonics at the AC load terminal bus, single tuned filters for 11^{th}, 13^{th}, 23^{rd} and 25^{th} are installed with values listed in table IV. This filter at AC load terminal works well for the voltage and current harmonics at the AC load side. It is found that harmonics at the generator terminals still exceeding the standards [12] because of the DC/DC and AC/DC conversions.

Another tuned filter is installed at the generator terminals for the 11^{th}, 13^{th} and a high pass filter starting from harmonic order of 23^{rd} parameters are listed in Table V. The single tuned filters are calculated as before using (4)-(6). Another branch for blocking the high frequency components is calculated as [22-24]:

$$f_d = 1/2\pi C_h R_h \quad (7)$$

and

$$m = L_h / R_h^2 C_h \quad (8)$$

where f_d is the damped frequency, m is the damped coefficient, typical values for m between 0.5 and 1.5. C_h, L_h and R_h are the high pass (damped) filter capacitance, inductance and resistance per phase, respectively.

For single tuned filters, the resistance is very small and is neglected during the simulation. In this case, m is taken 1, and f_d equals 9200Hz. THDi and THDv at the generator terminals are listed in Table VI, while for the AC load terminals are listed in Table VII. Note that THD values are within the standard limits [12].

Comparing Table II and Table VII regarding the THD for both current and voltage, it is found that THDi and THDv are much lower at the AC load bus than those of conventional system. In this case, the parallel resonant frequency at generator bus is $4f_1$-$5f_1$ for capacitance of 82uF-60uF, respectively.

TABLE IV
AC LOAD BUS FILTER PARAMETERS

Filter	C_f (uF)	L_f (uH)	R_f (Ω)
11^{th}	248.60	5.371	0.0814
13^{th}	249.20	3.835	0.0689
23^{rd}	250.23	1.220	0.0391
25^{th}	250.31	1.032	0.0355

TABLE V
GENERATOR BUS FILTER PARAMETERS

Filter	C_f (uF)	L_f (uH)	R_f (Ω)
11^{th}	82.373	15.915	0.0
13^{th}	58.977	15.915	0.0
23^{hp}	60.172	7.46	0.2875

TABLE VI
HARMONIC CONTENT AT THE GENERATOR BUS

Loading scenario	Without filter		With filter	
Case	THDi %	THDv %	THDi %	THDv %
1	19.26	19.00	3.68	2.06
2	33.95	20.24	2.10	2.17
3	28.58	21.04	1.06	3.47
4	16.91	18.51	2.42	2.55
5	22.00	20.78	1.12	1.59
6	20.76	30.68	2.90	2.58
7	26.83	18.38	1.10	2.60

TABLE VII
HARMONIC CONTENT AT THE AC LOAD BUS

Loading scenario	Without filter		With filter	
Case	THDi %	THDv %	THDi %	THDv %
3	2.39	17.97	1.65	1.37
4	1.77	19.33	0.56	0.46
5	0.84	17.32	1.76	1.64
6	1.32	18.29	1.31	1.71
7	2.52	22.31	1.04	0.78
8 (AC loads only)	1.72	21.47	1.14	1.02

Although the advanced aircraft electrical power system is heavy in weight when compared to that of the conventional case (because of presence of the rectification and inversion), the THDi and THDv for the advanced aircraft electrical power system are much lower than that for the aircraft conventional electrical power system.

CONCLUSIONS

Both conventional and advanced aircraft electrical power systems are simulated and analyzed considering equivalent passive AC and DC loads under transient and steady state operating conditions for all types of loads. Passive AC filters are proposed for the mitigation of harmonics and minimization of voltage transients in both conventional as well as advanced aircraft electric power systems. The THD for both current and voltage are calculated for both conventional and advanced aircraft EPS and it is found that the harmonic contents is much lower for the advanced aircraft electric system.

The advanced aircraft electric system is more reliable, efficient, and energy saving system. In conventional aircraft electrical system, one harmonic filter is required, while for the advanced aircraft electrical system, two filters (at the generator and AC load buses) are required. For both aircraft systems the time taken to reach steady state condition is almost the same for both conventional and advanced aircraft EPS and it's within the aircraft standard limits. The passive filters are designed such that to avoid resonance for both aircraft electrical power systems.

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