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# Active power filters for harmonic cancellation in conventional and advanced aircraft electric power systems

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ABSTRACT

Conventional and advanced civil aircraft electric power systems are simulated and controlled to be within standards regarding the voltage magnitude and frequency everywhere in the system at different loading scenarios. Harmonics in conventional and advanced aircraft power systems are calculated and reduced using a well-designed active power filter. The control circuit of the filter is based on the perfect harmonic cancellation method. The designed filter results in bringing the harmonics in both aircraft systems down to be within the standard limits of IEEE-519 and MIL-STD-704E.



## 1. Introduction

High-current harmonics can cause severe voltage distortion, unbalance in the aircraft electric power system and can lead to interference with the aircraft communication system as well as sensitive control and navigation equipment. Compensation of the higher current harmonics generated in the aircraft electric power system, by different nonlinear loads and power electronic converters, is of great interest. Aircraft electrical power system (EPS) often consists of two or more engine-driven-generators to supply the AC loads throughout the aircraft. All aircraft systems needs AC and DC power altogether. The DC power comes from rectification of the AC power using transformer rectifier units (TRUs). These units are normally 12-pulse configuration [1]. Due to cyclic operation of these units, they are considered as harmonic sources in the aircraft EPS. These units can increase the voltage distortion and the harmonic contents into the AC side of the aircraft EPS.

### 1.1. Conventional aircraft EPS

A simplified conventional aircraft electric system was considered in [2] consisting of one motor (representing the engine) driven generator for generating a three-phase source with constant frequency and constant voltage and radial systems consisting of three-phase distribution lines and AC and DC loads (Fig. 1). The equivalent electrical loads were represented by three-phase loads (A, B and C) and single-phase load (D) as lumped resistive and inductive components (Fig. 1). The DC loads (E and F) were represented by resistive load. The DC voltage was obtained by connecting two TRUs in series to obtain 12-pulse rectifications to minimize the harmonic contents in the output DC voltage as well as in the input AC current [3].

The frequency was regulated by regulating the DC motor speed by using proportional-integral (PI) controller. Sensing the motor shaft speed and comparing it to the reference speed results in a speed error which is processed to control the full-bridge chopper which affects the input DC voltage of the DC motor. The magnitude of the phase voltage of the generator, was controlled by comparing it to the reference voltage (115 VAC) using another PI controller which controls the field current of the synchronous generator. The generator output voltage magnitude and frequency complied with the standards of MIL-STD-704F [4] and IEEE Std. 519 [5], which specify the voltage and frequency allowable limits during transient and steady-state conditions. Meeting the standard limits for 28 VDC, 115 VAC voltages and frequency were explored in detail in [2]. This simplified system does not include the external power (used for charging batteries at airport) and battery charge/discharge system.

### 1.2. Advanced aircraft EPS

The EPS consists of two independent channels, according to the number of starter/generators in the aircraft. An auxiliary/

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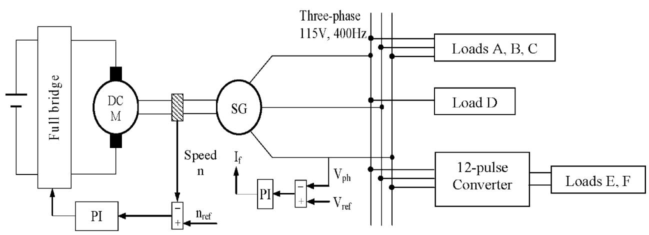


**Fig. 1.** Simulated structure for conventional aircraft electric power system.

**Table 1**
Loading scenarios

| Case No. | AC loads | DC loads |
|---|---|---|
| 1 | – | Load E |
| 2 | – | Loads E, F |
| 3 | Load A | Load E |
| 4 | Loads A, B | Load E |
| 5 | Load C | Load F |
| 6 | Loads C, D | Load F |
| 7 | All | Loads E, F |

emergency power unit contains an additional auxiliary starter/generator. Either three-phase synchronous machines or switched-reluctance machines may be used as starter/generators in a more-electric aircraft [6–8]. The power control units are used to transform the "wild frequency" AC power produced by the synchronous generators into 270 V DC power. The following reasons motivated the choice of the 270 V DC distribution bus [9]: 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 and regenerative power from electrical actuators that can be easily returned to the bus.

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 advanced aircraft system used for simulation is shown in Fig. 2. The motor-generator set is the same as the conventional case to provide the 115 VAC at 400 Hz generator bus under the same AC and DC loads. In advanced aircraft EPS, the 270 VDC voltage is usually obtained by using 12-pulse converter to reduce the characteristic harmonics, the same as in conventional EPS. In this case, two 6-pulse thyristor bridges are connected in series to obtain the 12-pulse rectification, similar to the conventional aircraft EPS. A PI controller is used to drive the 12-pulse converter to regulate the DC voltage at 270 V.

The peak-to-peak ripple voltage is 3.7 V and the ripple factor is 0.28% at the 270 VDC bus, which are lower than the standard values of 6 V and 1.5% [4], respectively. The DC loads are connected to the 270 VDC bus through DC/DC forward chopper to provide the required 28 VDC feeding the DC loads. 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. For this system, the aircraft standard limits for the 270 VDC bus voltage, 115 VAC voltage, the AC system frequency and 28 VDC ripple voltage are met. The 28 VDC bus has peak-to-peak ripple amplitude of 0.79 V and a ripple factor of 0.46% compared to the standards of 1.5 V and 3.5% [4], respectively. Meeting the standard limits for 270, 28, and 115 VAC voltages and generator frequency were explored in detail in Ref. [2].

The equivalent EPS for Boeing 767 aircraft either conventional or advanced was estimated from that of the C130E aircraft [2,3]. The loading kVA of the B767 aircraft is 2.25 times that of C130E aircraft.

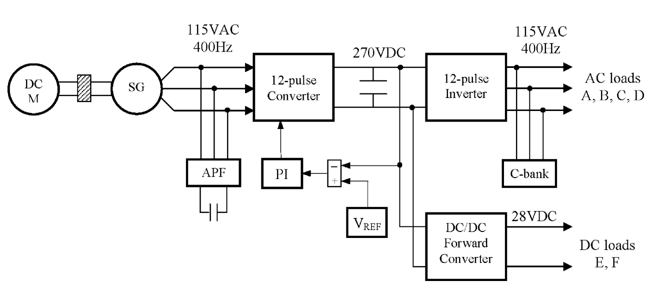


**Fig. 2.** Simulated structure for advanced aircraft electric power system.

The appropriate phase currents, phase resistance and inductance were then calculated based on the kVA rating and the fixed PF for each phase. The different loads rating and parameters for the simulated B767 aircraft were listed in Ref. [2].

### *1.3. Harmonics level mitigation in aircraft EPS*

The compensation of harmonic and reactive currents becomes increasingly important owing to the wide use of power electronic equipments in aircraft EPS. Traditionally, passive LC tuned shunt filters have been used [10–15] to eliminate line current harmonics due to nonlinear loads and to increase the power factor. However, in practical applications these passive filters showed many drawbacks [16], such as aging and tuning problems, series and parallel resonances, bulk passive components and fixed compensation characteristics.

The active power filter (APF) is considered a feasible solution to the problems created by nonlinear loads. The APF is used to eliminate the undesired harmonics and improve power factor (PF) by injecting equal but opposite compensation currents. Therefore, an APF looks like a controlled current source, connected in parallel with the nonlinear load to generate the required compensation currents. Thus, the supply (mains) only needs to feed the fundamental currents. The APF can also keep the power system balanced even with unbalanced and nonlinear loads as the case in the aircraft power system. In this case, the APF supplies harmonic, reactive, fundamental negative sequence and zero sequence current components.

### *1.4. Paper objectives*

In this paper, the performance of the conventional and advanced aircraft power systems are investigated under conditions of constant-voltage, constant-frequency source and lumped DC and AC loads. An efficient controlled APF is shunt connected to mitigate harmonics, improving PF and removing imbalance in conventional and advanced aircraft EPSs.

## 2. Simulation of conventional aircraft EPS

### *2.1. Harmonics levels*

Using of a 12-pulse converter to obtain the DC voltage generates dominant harmonics of the order 11th, 13th, 23rd and 25th. A loading scenario (Table 1) is adopted from various combinations of the AC and DC loads to study the harmonic contents in each case. The total harmonic distortion of current and voltage, THDi and THDv for some cases exceeded the standard harmonic levels which is 5% [4,17]. Due to load unbalance, neutral generator current flows. This is in addition to drawbacks resulting from loads of low power factor for some cases in Table 1. An APF is designed to: (i) compensate the reactive power components, (ii) make the PF near to unity and (iii) balance the generator phases' currents.