TJES
ISSN: 1813-162X
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

Study and Analysis of Multi-Pulse Converters in Modern Aircraft Electrical Power System

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ABSTRACT
In this paper a complete model of aircraft electrical system is simulated and analyzed using 24-pulse techniques in power conversion. The classical aircraft electrical system is described in this paper. The performance characteristics of 24-pulse converters are studied with different conditions of operation and the simulated model is tested with different jet engine speed which yields to different frequencies of operation from 400Hz to 1200 Hz. The simulated system is described and analyzed in two sections; Generating-Rectifying and Inverting unit. In order to match the practical condition, different types of load are considered here such as; constant power load, constant voltage load, constant current load, passive and dynamic load. The voltage and current for the generator side and inverter side are recorded and the total harmonic distortion (THD) is calculated for different conditions of operation. The obtained results are compared with conventional 6-pulse converters which are used in classical aircraft electrical power system. The proposed system is simulated and analyzed using the PSIM 9 software package with analysis completed in MATLAB 2010.

Keywords: **Aircraft Electrical Power System, 12-Pulse, 24-Pulse, Generating Unit, Rectifying Unit, Inverting Unit, 400 Hz, 270 Vdc, 115/200 Vac.**

دراسة وتحليل محولات الطاقة المتعددة النبضات المستخدمة في منظومات الطاقة الكهربائية الحديثة للطائرات

الخلاصة
في هذا البحث تم محاكاة و تحليل نموذج كامل للمنظومة الكهربائية في الطائرات باستخدام تقنية 24- نبضة في منظومات محولات الطاقة. كما تم شرح وتوضيح الية عمل المنظومات الكلاسيكية المستخدمة في الطائرات. وايضا فقد تم في هذا البحث دراسة وتحليل خصائص الاداء لمنظومات التحويل ذات الـ24- نبضة في ظروف اشتغال مختلفة. كما تم فحص المنظومة لسرع مختلفة للمحرك التوربيني والذي سيؤدي الى عمل المنظومة بترددات مختلفة تتراوح بين 400 هرتز الى 1200 هرتز. ان المنظومة التي تمت محاكاتها وصفت وحللت في مرحلتين؛ مرحلة التَوليد والتوحيد و مرحلة التحويل العاكس. وللاقتراب من الحالة العملية الفعلية لاشتغال المنظومة، فقد تم استخدام انواع مختلفة من الاحمال الكهربائية مثل الاحمال ذات الطاقة الثابتة، الاحمال ذات الفولطية الثابتة، الاحمال ذات التيار الثابت، الاحمال ذات الطبيعة الغير فعالة والاحمال الديناميكية. كما تم تسجيل وتحليل الفولتيات والتيارات الخارجة من مرحلة التوليد ومرحلة التحويل مع حساب معامل التشويه الكلي لكل موجة وفي جميع ظروف الاشتغال المختلفة. واخيرا تمت مقارنة النتائج المستحصلة من االمنظومة مع اداء منظومات الطاقة الكهربائية الكلاسيكية التي تستخدم تقنية ال 6 – نبضات. في هذا البحث تمت محاكاة وتحليل المنظومة باستخدام برنامج متخصص في مجال الكترونيات القدرة وهو الـ PSIM9وايضا تم استخدام ال MATLAB 2010 لاكمال العمليات الحسابية المستخدمة في تحليل المنظومة.

الكلمات الدالة : نظام الطاقة الكهربائية في الطائرات، 12-نبضة، 24 – نبضة، وحدة توليد، وحدة التوحيد، وحدة العاكس، 400 هرتز، 270 فولت تيار مستمر، 200/115 فولت تيار متناوب.

INTRODUCTION

In classical aircraft, the electrical power can be obtained from A.C generator or D.C generator or from both. These generators are connected directly to the shaft of aircraft jet engine through a reducer (gear box); in addition to these generators there are additional components which are necessary for the electrical system such as voltage regulation, voltage protection, fault detection and voltage control unit.[1]

Generally, the speed of the aircraft jet engine is varying from idle speed to maximum speed during the flight mission, so that a constant-speed drive (CSD) system is used inside many aircrafts system. (CSD) system is consisting of three stages regulated synchronous generator to drive the generators in a constant speed. The output frequency of such system is maintained constant by means of a hydro-mechanical system connected to the engine through a gearbox to drive the generator in a constant speed, such systems need an additional weight, cost and additional maintenance; also the complex hydro-mechanical devices are not highly reliable. [1]

Due to developments in power electronics technique and devices, these difficulties are eliminated and tend to a reduction in weight and cost and increase the reliability of the aircraft electrical power system by replacing the mechanical systems with electrical systems. The modern electrical systems are more flexible compared to the classical systems since its components can be distributed throughout the aircraft near the power consumers, in contrast to the mechanical system in which they must inevitably be located close to the engine. [2]

AIRCRAFT ELECTRICAL POWER SYSTEM

Most of modern aircraft electric power system includes two independent channels in order to increase the reliability and to provide energy in case of emergency. The rated frequency of the aircraft power system is 400 Hz, however, the jet engine speed changes approximately from 33% (idle speed) to 100% of its maximum speed i.e. with a ratio of 1:3, resulting in a changing in the aircraft synchronous generator frequency in the range of 400 Hz to 1200 Hz (without using a CSD). Therefore it is necessary to design and built an electrical system with constant frequency and high reliability especially in fighter aircraft where engine throttle settings are changed very frequently throughout the mission. In the aircraft electrical system, different types of power consumers require power that is different from those provided by the main generators. For example, in an advanced aircraft power system having a 270 Vdc primary power supply, certain components are employed which require 28 Vdc or 115/200 Vac fixed frequency, so that aircraft power systems must employ multi-voltage level hybrid DC and AC systems. Therefore it is necessary to build a power system employs not only components which convert electrical power from one form to another, but also components which convert the supply to a higher or lower voltage level. So that in modern aircraft, different kinds of power electronic converters, such as AC-DC, DC-AC and DC-DC are required. [1], [2], [3]

IMPORTANT CONSIDERATION FOR AIRCRAFT POWER SYSTEM DESIGN

Earlier aircrafts contain DC generator and AC generator for each engine, but present aircrafts contain only AC generator and a rectifier to provide a DC voltage. Future aircrafts contain only one high voltage DC generator (270-Vdc). [4]

Because of weight constraints, the lightest power distribution systems are getting attention. The AC voltage conversions via heavy transformers are no longer a good solution but DC systems with lighter DC-DC converters are a good solution. The value of 270-Vdc is the typical intermediate output from full-wave rectification of the 3-phase 115-Vac, 400Hz AC input. This means that every subsystem on the plane has a full-wave rectifier, and there may be some overall savings if that was done in a central location and the 270-Vdc was distributed to each load. The current ratings are slightly reduced, but only 2 wires for 270-Vdc are needed instead of 3 or 4 wires for 3-Phase 115/200 Vac. [4-5]

Description of Proposed System

Aircraft electric power system consists of independent channels, depending on the number of power plant (Jet Engine) in the aircraft. A single channel of 120 KVA of the aircraft electric system is studied here and the system diagram is shown in Fig.(1).[5]

During starting mode, the constant frequency system provides power through the power converter to the electric machine which acts as a starter to the aircraft engine. In the generating mode, the variable-speed engine of the aircraft (Jet Engine) acts as the prime mover for the field-controlled synchronous generator, resulting in variable voltage and variable frequency at the generator's terminals. This power is delivered via the power converter (AC-DC) to high voltage 270-Vdc main distribution Bus. A power rectifier converts the AC voltage to a constant 270-Vdc and then converted to fixed 115/200-Vac, 400Hz through the power inverter unit. Also a (dc to dc) converter is used to supply all power consumers with required power.[2],[4],[6]

In order to attach the best performance of AC-DC and DC-AC converter, a 12-pulse rectifier and 24-pulse inverter are used in the proposed system to get high PF, low THD and low ripple. This system is considered to be more efficient than conventional methods of power generation and the amount of power conversion required is reduced with accompanying weight savings. [1], [2]

Structure of Proposed System

A complete model for a proposed aircraft electrical power system is designed as shown schematically in Fig.2, the system is divided into three stages: generating rectifying unit and inverting unit which shown below and DC-DC converter unit as illustrated later. [2]

Generating and Rectifying Unit

The main purpose of this stage is to generate and convert the variable frequency and variable amplitude of the synchronous generator to a fixed DC voltage with low ripple in the 270-Vdc bus and with low total harmonic distortion (THD) and high power factor in the generator side. This condition is done by using a 12-pulse Transformer-Rectifier Unit. Figure (3) shows parallel connection of two 6-pulse bridges to get 12-pulse operation with high power at high current application. Because of a phase shift by the input transformer, the line current (or synchronous generator current) will have a 12-level and it is closely to sinusoidal waveform. A three phase three windings transformer with (Y/Y/Δ) winding types is used, the synchronous generator is connected to the (Y) type primary winding and each of the two secondary windings is connected to a three phase, 6-pulse uncontrolled rectifiers (passive rectifier) which is normally robust and connected in parallel for high current applications. A phase shift of (30o) must be provided between the two secondary windings and the turn ratio of (Δ) secondary winding is ($\sqrt{3}$) times the (Y) secondary winding. For this system the power factor can be as high as 0.98 with a total harmonic distortion (THD) less than 15% and the output ripple frequency is (12) times that of the main frequency. In addition, L-C filter is connected as a DC filter in the output of the power converter (rectifier) to smoothing the output DC voltage-current on the 270-Vdc bus. [2], [7]

To obtain a 270-Vdc on the output of the rectifier unit, the r.m.s value of the synchronous generator must be in the proper level and equal to: - [8]

$$V_{dc} = \frac{12}{\pi}\int_{5\pi/12}^{7\pi/12} V_m \sin\theta \;\; d\theta \qquad \text{……..………... (1)}$$

$$V_{dc} = V_m \frac{12}{\pi}\frac{\sqrt{3}-1}{2\sqrt{2}} = 0.98862 \;\; V_m \qquad \text{………. (2)}$$

and the total harmonic distortion at the generator side for voltage and current is given as:

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \;\&\; THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \qquad \text{……..(3)}$$

Where (h) is the harmonic order, (V1 & I1) are the amplitudes of fundamental voltage and current, (Vh & Ih) are the amplitudes of harmonic voltage and current.

In aircraft electrical system as the rotational speed of the aircraft jet engine varies from idle speed to maximum speed i.e. in the range of (1:3), the output voltage of the synchronous generator will also varies in frequency as well as in magnitude, so that a feedback signal taken from the output of the rectifier and fed to the Generator Control Unit which is controlling the field current of the synchronous generator to regulate the DC level of the Rectifier Unit. The Generator Control Unit is consist of a comparator to compute the error signal by measuring the output signal and comparing it with the reference value and proportional-integral (PI) controller and exciter. [2,9]

In the proposed system, three different types of DC loads are connected to the regulated 270-Vdc bus through various dc–dc converters. All controlled dc loads employ the simplest type of dc-dc converter configurations in which only one switch is needed and hence, significantly minimizing switching losses, as shown in Fig.(4). These loads can be classified as constant power loads, constant current loads, and constant voltage loads.[2]

The dc loads are distributed throughout the aircraft and used for various purposes, including battery charging, lighting, heating services, actuation, subsystem controllers, and avionics system, which are all acts as a non-linear loads. [1], [2], [6]

The constant power load is connected to the main DC bus through a DC-DC buck converter where the load power is kept constant and it is assumed to be equal to (15KW), this done by controlling the load current using a PI controller. The reference current is calculated by dividing the magnitude of the reference power by the magnitude of the output voltage. The PI controller modulates the error signal which is compared with a carrier sawtooth signal to generate a gate signal for the switching device. Similarly, the constant current load is obtained by using a controlled DC-DC buck converter. The load current is regulated and set at (100A) by using a PI controller. The constant voltage load is regulated to have an output voltage value of (28 Vdc) which is used for the battery system and other constant voltage DC loads in the aircraft system. The detail of the DC loads are shown in Table (1), it can be seen from the table that the total power of the DC load is equals to 40KW. This power is represents approximately 34% of total capacity of the generating unit. [10]

Inverting Unit

In the inverter unit, (figure (2)), the 270-Vdc is converted to constant magnitude and frequency of 115/200-Vac 400 Hz to energize the specific loads. PWM technique is used to generate a sinusoidal output voltage and the modulation index control is used to regulate the inverter output. [6-8]

To provide 115/200-Vac, 400Hz at the main AC bus, and to further reduce the amount of harmonics injected into the supply, four 6-pulse inverters are used and fed from the 270-Vdc main bus. These multi-pulse inverters are suitable in high voltage and high power applications due to their ability to synthesize waveforms with better harmonic spectrum and higher voltages with a limited maximum device rating.[11]

In general star and delta-connected windings have a relative phase shift of (30^o) and two 6-pulse inverter bridges connected to each of these Y and Δ transformers will give an overall 12-pulse operation eliminating 5th and 7th harmonics. Similarly, two 12-pulse inverter bridges with phase shift of (15^o) will give an overall 24-pulse operation eliminating 11th and 13th harmonics.[11]

The inverters are directly connected to the primary windings of two separate three-phase transformers. The Y/Y and Δ/Y transformers are connected to the main ac bus to provide the 30o phase shift needed for a true 12-pulse inverter and the harmonic characteristic of such inverter is given as: [2,3]

$$h = kp \pm 1 \;,\; V_h = \frac{V_1}{h} \quad \text{.................... (4)}$$

Where (h) is the harmonic order, (k) is a constant = (1, 2 …), (p) is the converter pulse number. [2]

The 12-Pulse voltage source inverter gives better harmonic performance and is obtained by combining two 6-Pulse inverters. The fundamental and harmonic components of the phase-to-phase voltages and phase-to neutral voltages are phase shifted by 30^o from each other. If this phase shift is corrected, then the phase-to neutral voltage harmonics, other than those of($12k \pm 1$) would be out of phase to those of the phase-to-phase voltage and with $1/\sqrt{3}$ times the amplitude. Hence if the phase-to-phase voltages of a second converter are connected to a transformer with Δ-connected secondary and $\sqrt{3}$ times the turns compared to the Y-connected secondary, and the pulse train of one converter is shifted by (30o) with respect to the other, the combined output voltage will have a 12-pulse waveform, with harmonics of the order of ($12k \pm 1$). Thus the 12-Pulse inverter will have 11th, 13th, 23th, 25th, 35th, 37th, ..., harmonics with amplitudes of 1/11th, 1/13th, 1/23th, 1/25th, 1/35th, 1/37th, respectively of the fundamental AC voltage. [7]

In the same way, the 24-pulse inverter is obtained by combining two 12-pulse inverters. If the first one is connected to the Y side and the other is connected to Δ side with phase shift of (15^o) from each other, then, the harmonic order of other than those of $(24k \pm 1)$ would be out of phase. Thus the 24-Pulse inverter will have 23rd, 25th, 47th, 49th ..., harmonics with amplitudes of 1/23th, 1/25th, 1/47th, 1/49th, respectively of the fundamental AC voltage[7] .

Generally, 24-Pulse inverter has very good characteristics and it can be used without AC filters due to its high performance and low harmonic rate on the AC side due to inductive nature of aircraft electric loads, however, a passive filter is used to eliminate the switching frequency in the inverter output voltage. [7]

Fig.(5) shows in vectors the harmonics of the 6-pulse inverters, 12-pulse inverter and 24-pulse inverter. [11-13]

So that, the 24-pulse voltage source inverter is represented by the Fourier expression: [9]

$$V_{ph}(\omega t) = \frac{\pi}{3} V (\sin \omega t + \frac{1}{23} \sin 23\omega t + \frac{1}{25} \sin 25\omega t + \frac{1}{47} \sin 47\omega t + \frac{1}{49} \sin 49\omega t + ...) \quad \text{....... (5)}$$

The output voltage of 24-Pulse inverter is obtained as:

$$V_{line}(t) = 4 \sum_{h=1}^{\infty} V_m \sin(h\omega t + 22.5h + 7.5) \quad \text{.......(6)}$$

Where

and step height equal to:-

$$h = 24k \pm 1 \quad , \quad k = 1,2,3,........$$

$$\frac{\pi}{3} V_{dc} \frac{12}{\pi} \int_0^{\frac{\pi}{12}} \sin \omega t \; d\omega t = 0.134 \;\; Vdc \quad \text{.........(7)}$$

The r.m.s output voltage of a sinusoidal PWM inverter in one inverter leg (6-pulse) is given in terms of its input DC voltage and the modulation index (m) as below: [7]

$$V_{ph} = \frac{1}{2} * m * \frac{V_{dc}}{\sqrt{2}} \quad (\text{for m} \le 1) \quad \text{........(8)}$$

According to equation (8), for the single inverter (6-pulse) the output AC voltage per phase for Vdc=270 and maximum modulation index (m=1) is equal to (95V). So that for a rated r.m.s output voltage per phase of 115-Vac and a maximum modulation index (m=1), the lowest required DC voltage must be equal to (325V), therefore, 24-pulse inverter is used to avoid this problem. [2], [7]

The 24-pulse inverter is controlled by using a PI controller to control a phase voltage of 115-Vac, 400 Hz at the main AC bus. The voltage error signal is processed by the PI controller to provide the required modulation index. The appropriate gate signals are generated with required phase shift and fed to the 24-pulse inverters.

The selected AC loads are connected to the 115/200-Vac bus and it can be classified into three types; resistive loads, passive loads and dynamic loads. These loads can be represented by lighting, heating, RL load with lagging power factor equal to (0.85) as recommended by aircraft electrical standards and induction motors[14]

The AC loads are labeled A, B, and C and are shown schematically in Fig.(2) with the details shown in Table (2).

SIMULATION AND ANALYSIS

The proposed model of the aircraft electric power system shown in Fig.(2) is developed and characterized by using the PSIM 9 software package and MATLAB-2010. PSIM is a simulation software specifically designed for power electronics, motor control, and dynamic system simulation. PSIM uses a strong algorithm dedicated to electrical circuits (piecewise method, generic models and a fixed time-step). As a result, simulation times are significantly reduced, convergence problems avoided while results accuracy is saved. With fast simulation and friendly user interface, PSIM provides a powerful simulation environment to address the needed simulation.

In the model, the synchronous generator speed is controlled by using a speed governor to provide an output with a frequency range of 400 to 1200 Hz with the systems nominal frequency set at 400 Hz. Different loading condition of the aircraft power system are taken into consideration which are presented in Table (1) & (2). The system is tested with different frequencies to examine the effects of the 12-pulse uncontrolled rectifier on the system performance. The generator current and voltage are recorded and the THD values are calculated in the generator side. In the AC bus side, all passive and dynamic loads are combined to examine the performance of 24-pulse PWM inverter.

The simulation results of the generating-rectifying unit in full DC load condition are shown in Fig.(6). Generator voltage and current waveforms over the frequency range of operation are obtained and the behavior of the harmonic contents in the generator voltage and current waveforms are calculated. It is clearly that the THD values of the generator voltage increase with increasing frequency while the THD values for the generator current decrease with increasing the frequency of operation, which may be attributed to the inductive nature of the system harmonic impedance, as shown in table (3). Due to the assumed balanced conditions of the load and source, the THD values remain consistent for all phases.

At the 115-V/200-V main AC load bus, a sinusoidal PWM 24-pulse inverter converts the DC voltage into AC voltage to feed all AC loads. The inverter output L-C filter as shown in Fig.(2) is tuned to eliminate the generated harmonics of the PWM switching, and the inductive nature of the AC loads helps to eliminate current harmonics with the passive filter. The inverter output filter consists of a series inductor along with a shunt capacitor each having a small series resistance.

The simulation result of the inverting unit in full load condition at the AC bus side is shown in Fig.(7). This figure observes the voltage waveform and current waveform of 24-pulse sinusoidal PWM inverter with L-C filter. The voltage step height of the 24-pulse inverter is shown in Fig.(8). Table (4) shows The THD for voltage and current waveforms in the 115/200Vac bus side for different load conditions as detailed in Table (2). It is clearly that 24-pulse PWM inverter has a very low THD, and that what is needed in aircraft power system. The total power of the AC loads is approximately equal to 63 kVA and this amount of power is equal to approximately 50 % of the total capacity of the synchronous generating unit. [2], [13], [15]

The modeled aircraft electrical power system parameters are illustrated in Table (5)

CONCLUSIONS

Modern aircraft electrical power system developed toward to be more electrical aircraft, therefore classical aircraft system does not sufficient for the requirement of modern aircrafts, increasing electrical devices yield to more transmission and distribution system, so that low voltage with high power loads will increase the currents drawn by the loads, and hence increases the electrical losses which produce a heat in order to dissipate this power. On the other hand 3-phase transmission system contains a three or four wires and such system tend to increase the weight and size. So that high 270-Vdc is generated and transmitted through 2-wire transmission system will be the best solution for modern aircraft system. This power will convert to any form and level in separated devices mounted near the electrical loads. To insure the power quality and low total harmonic distortion (THD), a 12-pulse rectifier and 24-pulse sinusoidal PWM inverter are used. A comparison between the 12-pulse rectifier and 6-pulse rectifiers will explain the advantages of 12-pulse rectifier technique as shown in table (6). Also figures (9) shows the comparison of the voltage THD and current THD between 6-pulse sinusoidal PWM and 24-pulse sinusoidal PWM technique.

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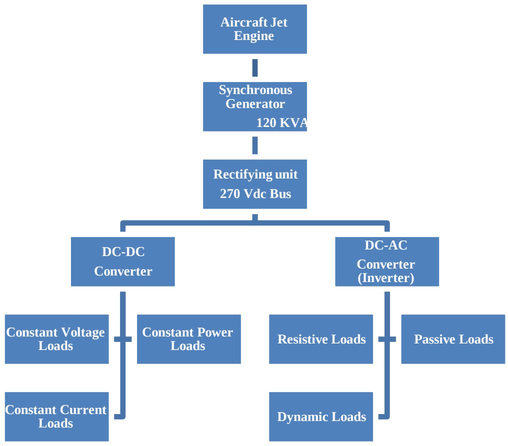

Fig.1 Aircraft Electrical Power System

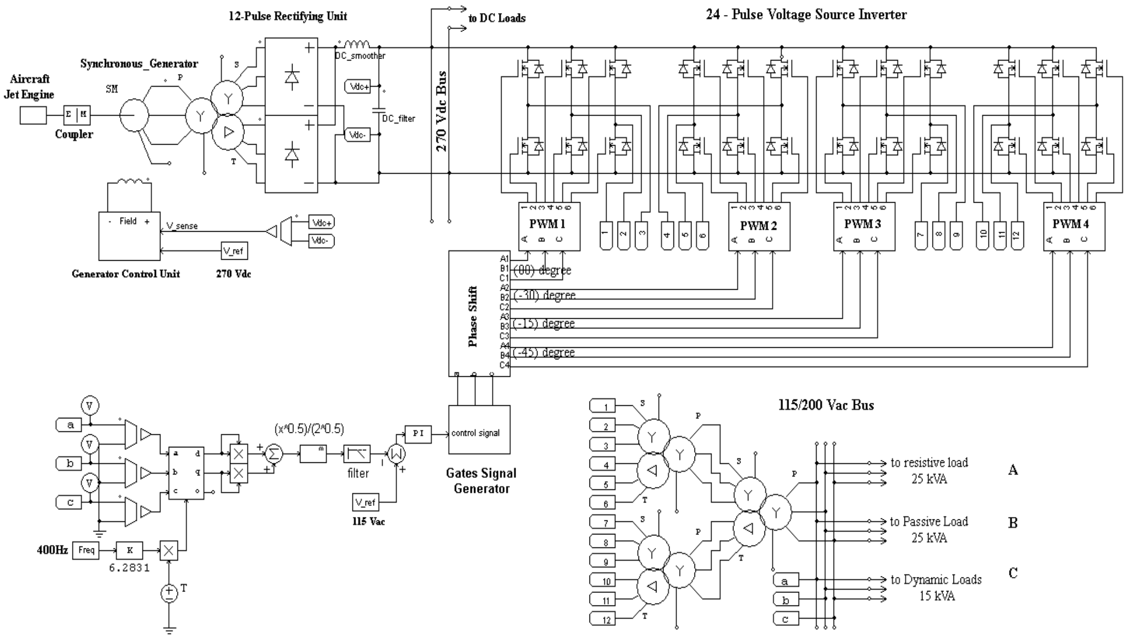

Fig.2 Schematic diagram of aircraft power system

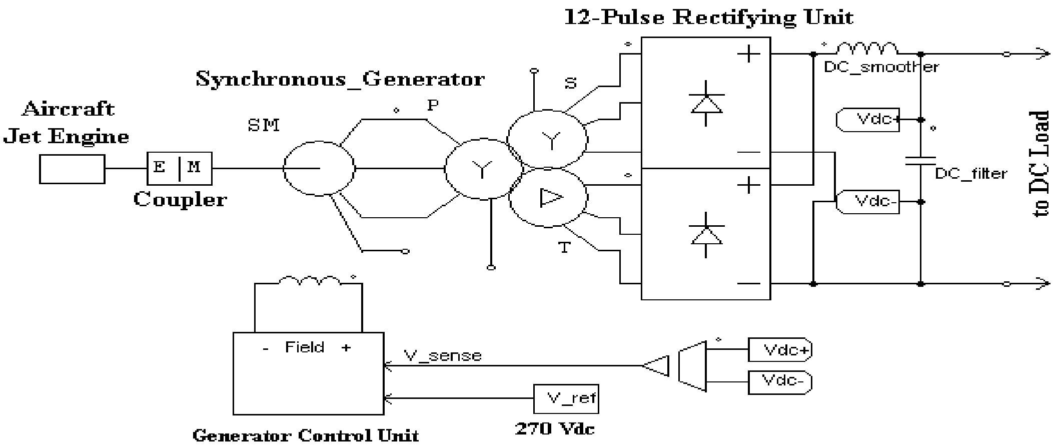

Fig.3 12-pulse parallel bridge Generating-Rectifying-Unit

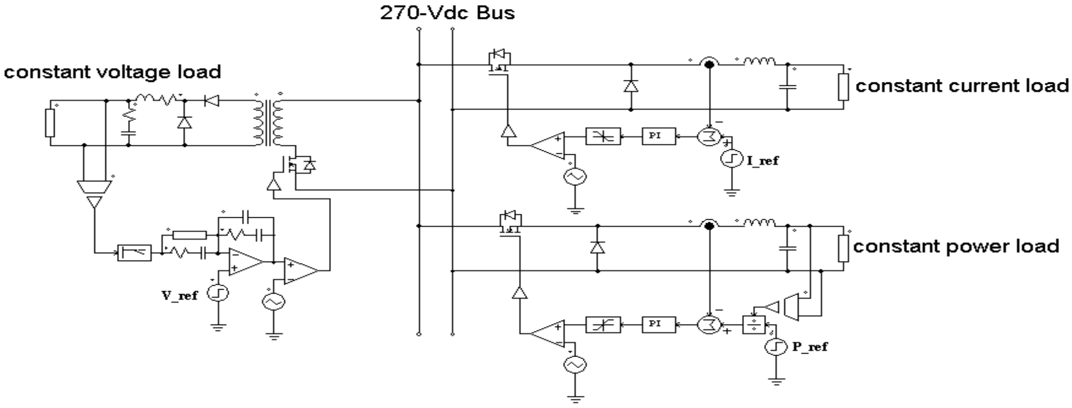

Fig.4 Types of DC Load

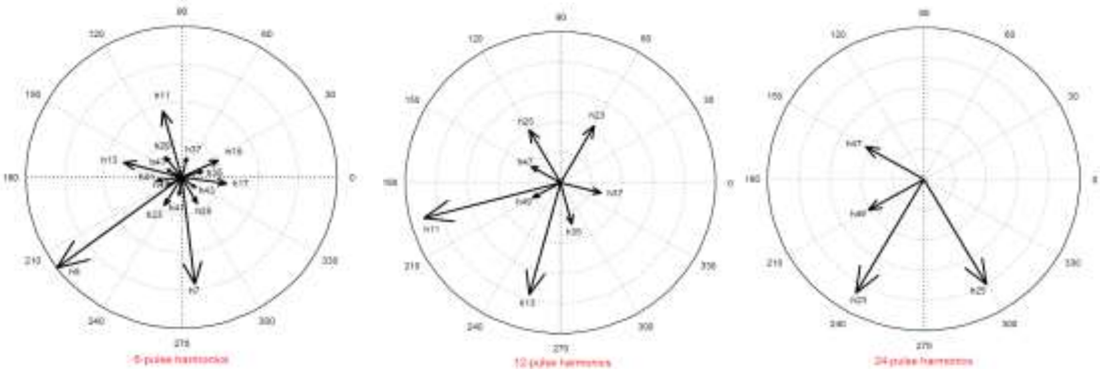

Fig.5 Harmonics vector diagram of (6-pulse, 12-pulse and 24-pulse) inverters

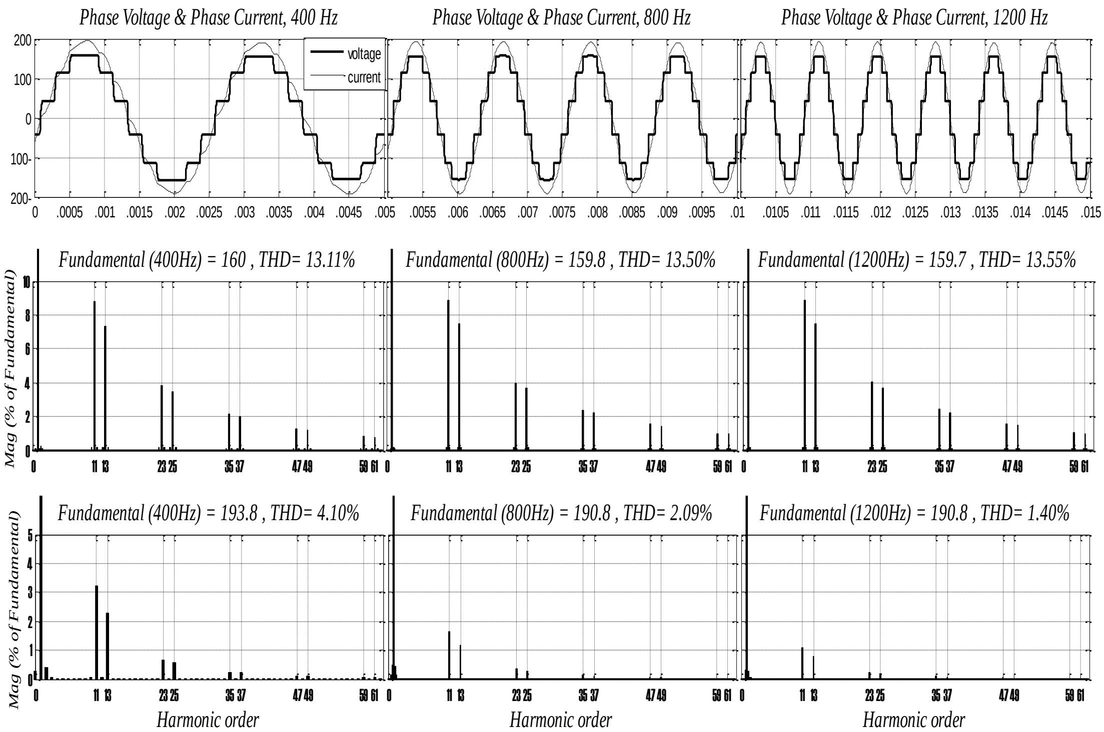

Fig.6 Generator voltage and current waveforms with FFT spectrum for different frequencies

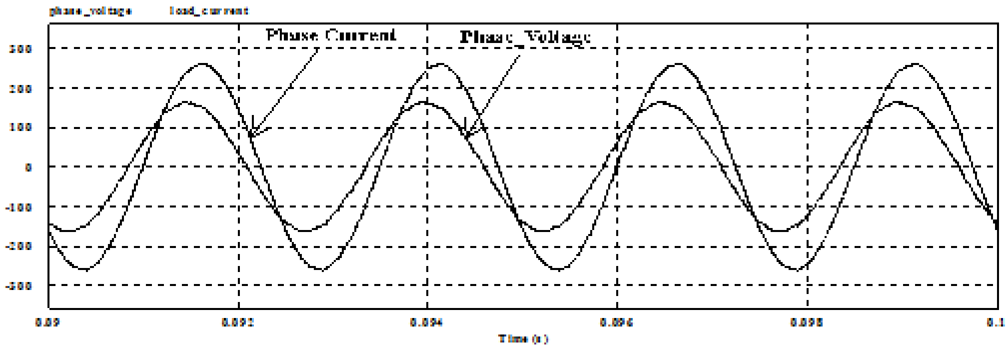

Fig.7 Voltage and current waveforms of inverting-unit at full load condition with L-C filter

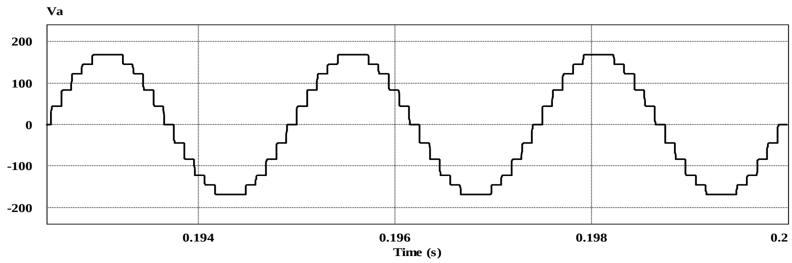

Fig.8 The voltage step height of the 24-pulse inverter

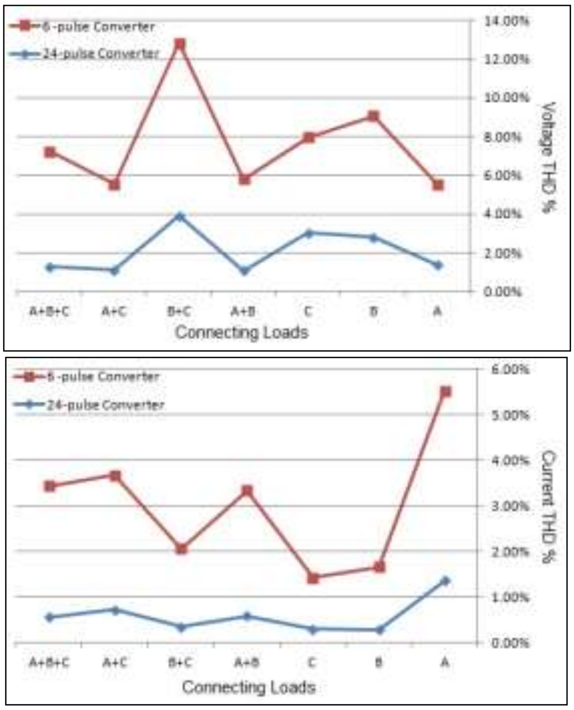

Fig.9 Voltage THD & Current THD of 6-pulse and 24-pulse

Table 1. Represent the Details of DC Loads

Dc load	Current (A)	Voltage (V)	Power (W)
Constant Current	100	150	15000
Constant Voltage	357	28	10000
Constant Power	173	87	15000

Table 2. Represents the detail of AC Loads

Load label	AC load	Load type	P.F	S (KVA)
A	Passive load	R	1	25
B	Passive load	R-L	0.85	25
C	Dynamic load	Induction motors	-	15

Table 3. THD of voltage and current waveforms of 12- pulse rectifier

Frequency (Hz)	Fundamental voltage (V)	Fundamental Current (A)	Voltage THD	Current THD
400	160.00	193.80	13.11 %	4.10 %
800	159.80	190.80	13.50 %	2.09 %
1200	159.70	190.80	13.55 %	1.40 %

Table 4. THD for the inverter output voltage and current

Loads	Voltage r.m.s (V)	Current r.m.s (A)	3-ф Power VA	Fundamental voltage (V)	Fundamental Current (A)	Voltage THD	Current THD	Power Factor
A	115.02	71.89	24.79 k	162.65	101.66	1.36 %	1.36 %	1.000
B	115.02	72.43	24.98 k	162.6	102.43	2.8 %	0.28 %	0.8498
C	115.03	47.37	16.33 k	162.6	67.00	3.02 %	0.296%	0.772
A+B	114.82	138.58	47.87 k	162.37	195.98	1.08 %	0.58 %	0.961
B+C	115.15	119.63	41.23 k	162.71	169.18	3.89 %	0.353%	0.82
A+C	115.13	112.69	38.82 k	162.81	159.37	1.11 %	0.723%	0.964
A+B+C	115.26	183.64	63.18 k	163.00	259.7	1.283%	0.558%	0.928

Table 5. Aircraft Electrical Power System Parameters

Synchronous Generator Parameters		Generator control unit	
(R(stator)) stator winding resistance	0.01 Ω	Proportional gain	0.01
(L(stator)) stator winding leakage inductance	18 µH	Integral time constant	0.01
(R(field)) Field winding resistance	0.012Ω	Low pass filter gain	1
(L(field)) Field winding leakage inductance	0.01 m	Low pass filter cut off frequency	100
(Ldm) d-axis magnetizing inductance	0.442m	Exciter gain	20
(Lqm) q-axis magnetizing inductance	0.411m	Gates signal control	
Rotor damping cage d-axis resistance	0.01	Proportional gain	0.01
Rotor damping cage q-axis resistance	0.01	Integral time constant	0.01
Rotor damping cage d-axis leakage inductance	50 µH	DC bus	
Rotor damping cage q-axis leakage inductance	50 µH	DC - smoother	0.005 mH
Number of poles	4	DC - filter	4700µf
Moment of inertia	0.01	AC bus	
Normal speed (r.p.m)	12000	L – C filter inductance	10µH
Normal frequency	400Hz	L – C filter capacitor	10µf

Table 6. : 6-pulse rectifier vs. 12-pulse rectifier

Parameters	6-pulse rectifier	12-pulse rectifier
DC output voltage	0.955 Vm	0.955 Vm
RMS output voltage	0.955 Vm	0.955 Vm
Ripple voltage	0.0408 Vm	0.019545 Vm
Voltage ripple factor	4.27%	1.023%
Form factor	1.0009	1.00005
THD	30.5 %	14.3 %