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Performance Analysis of AC Alternator 115/208 Volt, 400 Hz, 12 kVA of Fokker-27 Aircraft

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Abstract

Alternator (115/208 Volt, 400 Hz, 12 kVA) is a very important electrical system on Fokker-27 aircraft. The device supplies electrical current for flight equipment and other equipments on airplanes. This paper describes the performance calculation of an aircraft alternator including the power calculation and energy, fuel usage, mileage, calculating speed and frequency of the alternator, power efficiency and load analysis. In another part, it explains the alternator relationship with other tools such as: inverter (voltage converter DC to AC) which uses a voltage regulator to keep excitation and alternator rotation constant, and the battery used for special equipment or backup power source.

Keywords: Alternator, Fokker-27, inverter, aircraft, performance-analysis.

1. Introduction

There are two types of alternators commonly used in aircrafts, namely the DC alternator and the AC alternator. DC alternators are mostly found in light (small) airplanes in which the required electrical load is small. On the other hand, AC alternators are mostly found in huge commercial airplanes as well as military aircrafts. Most aircrafts require electrical energy and the use of AC system to support their weights for a particular flight. With the use of transformer, transmission from an AC electrical energy can be produced in a more effective manner using lighter equipments. The transmission of high voltage electric supply at a low current can reduce energy loss to a minimum.

In larger aircrafts, AC supply is used to enable the aircraft's electrical system to run the control system and electrical motor which supply power to the other devices. In smaller aircrafts, most of their electrical appliances operate at DC voltages of 14 V or 28 V. If a small amount of AC current is needed for certain devices, then an inverter will be used to convert DC voltage to AC voltage. The AC voltage is then used to supply power to specific devices which require AC current for operation.

Almost all alternators used for electrical generation system in aircrafts make use of the construction of a rotating field and a fixed anchor. The strength of voltage is used as the voltage generator of the aircraft's electric system, while the variation of alternator field strength depends on the electric load requirement. Thus, a voltage regulator is used to control the changing AC current flowing in rotor windings from the alternator. The voltage regulator system is also used to change the current according to need so that the alternator output voltage is constant.

Alternators and generators share some common characteristics, for example both of them are used to convert mechanical energy to electrical energy. The main differences which set them apart include the many designs available, such as: the number of anchors, all output current must be supplied through a commutator and brush. On the other hand, an alternator has a fixed anchor and can supply current through direct connection to the aircraft's electrical line. The direct connection can prevent/solve problem related to a bad connection between a rotating commutator and static brush. At high voltage levels, rotated connectors are very inefficient to use, and for this reason alternators are preferred for use in some aircrafts.

2. Alternator

Typically, three-phase alternators are used in aircrafts instead of the one-phase variant. This means that the stator

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(fixed anchor) has three windings separated at 120^0 phase angle. The rotating part is called rotor, as shown in Fig 1 which illustrates how the fixed windings are arranged, although the winding arrangement in a stator is actually quite different.

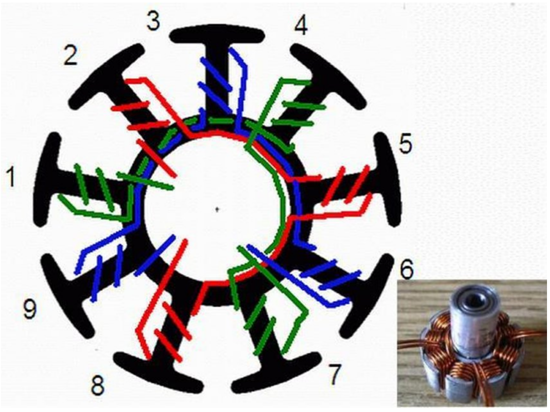

Fig 1. Star-Y Connected Stator Winding [2].

In addition, the stator windings are also connected in two types of connection, namely wye connection (*Y-connected*) and delta connection (Δ-connected), as indicated in Fig 2 and Fig 3.

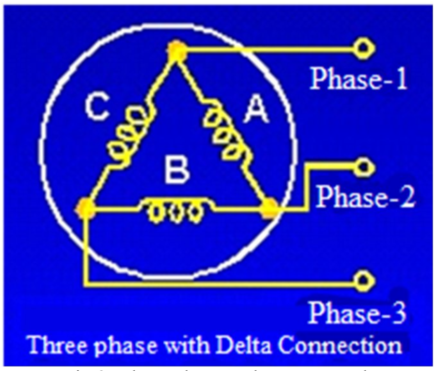

Fig 2. Three phase Delta-connected stator circuit (Δ)

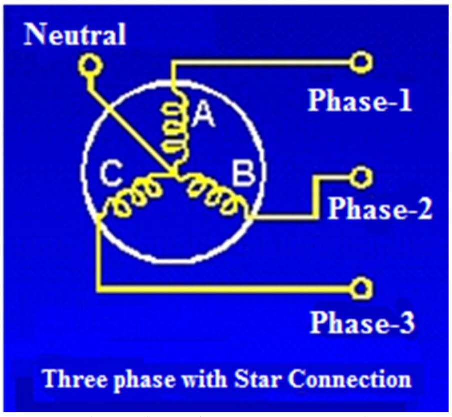

Fig 3. Three phase Star-connected circuit (Y)

The output of a three-phase alternator is a sinusoidal wave (Fig 4). Notice that there are three parts of separate 120V voltages, and each voltage reaches its maximum value on the same path at 120V point. As long as the alternator's rotor remains rotating, each phase makes a complete rotation at 360^0 in which each voltage reaches a maximum at a single direction. The wave also intercepts zero to reach a maximum in the opposite direction, and then returns to its starting point at 360^0.

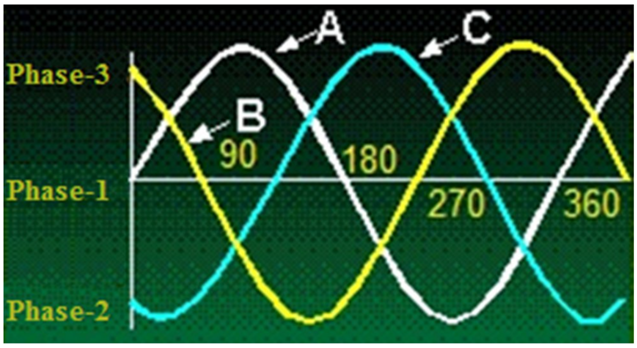

Fig 4. Output from a three-phase alternator

3. Circuit Breaker

A circuit breaker is used for breaking or connecting a network with or without load; it will also break the circuit in case of a current surge or short circuit current. This sets it apart from a normal switch, since a circuit breaker can become a switch under normal conditions and prevent excessive current in case of a short circuit. Excess current as well as short circuit current can destroy equipments in a power supply if it is allowed to flow for some time. Instant circuit breaking can reduce the risk of sparks during breaking or connecting. Sparks during switching, if not damped, will cause damage especially on circuit breaker components. Apart from functioning as a circuit breaker in closed circuits, the circuit breaker can also be designed to work manually (that is, to work with a human operator, by using a crank) and can also work automatically at the moment of interruption after receiving instruction from safety relay system. Thus, safety equipments can function normally or otherwise, automatically or manually.

Total safety equipment value is determined by :

a. Total current value (capacity of current carrier) from *bus-bar* conductor material, that is, the electrical conductor which connects a few circuits.
b. Total voltage value and frequency of phase.
c. Total interrupting current value, which is the total current which can be broken by the circuit breaker the moment the breaker's pole separates at the moment of breaking.
d. Total instantaneous working current value, which is the total maximum current at the time of short.
e. Total breaking capacity power limit is determined based on the amount of interrupting current as well as the total equivalent impedance of the line where the interruption occurs. Circuit breaker capacity is calculated based on the equation :

$$P = \sqrt{3}\, k\, I_{SW}\, V \tag{1}$$

where :

P is circuit breaker capacity.
k is substitution constant. (1.1 – 1.2).
I_{SW} is initial short circuit current.
V is voltage line.

f. Timing of circuit breaker.
g. Voltage isolation level value.

One problem with the use of Alternator 115/208 Volt, 400 Hz, 12 kVA in Fokker-27 aircraft is how the Alternator supplies electrical power to the other equipments as well as working as an electric source so that the usage time is longer and optimized.

4. Fokker-27 Aircraft Electrical System

Electrical energy in the AC wire line of Fokker-27 aircraft is supplied from three different sources: two engine controls with 208 Volt voltage, 3-phase, variable frequency alternator supplying main energy for electric heater. The alternators are not operated in parallel but separately. Two main alternators which are controlled by a DC motor with voltage supply of 115 Volt, 3-phase, fixed inverter and fundamental frequency of 400 Hz are installed to operate the aircraft's battery. Two AC voltage converter powers supplied with voltage at 115 Volt, 400 Hz single phase are used as lighting.

The 208 Volt alternator is an AC generator, brushless, 120/208 Volt and 3-phase to provide 12 kVA with power factor of 0.9 lagging at speed range of 6700 – 1000 RPM (10000 – 15000 RPM Engine). Output voltage frequency is 400 Hz at 8000 RPM (12000 RPM Engine). General output voltage of the alternator will be reduced at the minimum speed, which is 4020 RPM (6000 RPM Engine). Highest fan efficiency is set to anti-drive condition or air inlet end from generator. Cooling air is blown into or forced in through the generator. Therefore, the fan can run more efficiently with plenty of cooling inlet air compared to air heated by the engine [4].

A thermostat is used to send out warning in case of intense heat as well as excessive generator winding temperature. The thermostat used is a normal open circuit switch which will be closed when the air temperature reaches a critical point, which is 374±10 F (190±6 ^{0}C). Sensor is used to run the overheated light indicator on the left-hand side of the upper panel. These loads are actually not reactive loads, so frequency supply is not controlled. The supply is provided by two alternators which are designed for use with each hand – left and right. Each alternator consists of a main controller, switch controller, various measuring instruments and indicator lights to warn of any dysfunctional equipment, isolated transformer and a 3-phase circuit breaker.

A. Alternator.

In this paper, the alternator used in the Fokker-27 aircraft is an AC generator of 120/208 Volt, 3-phase, 12 kVA brushless, installed in the extra gear box connected to the engine. This alternator is relatively lighter compared to other types of alternators with similar dimensions and capacity (minimum weight of alternator is 158 kg). This equipment basically consists of three parts : fixed magnet generator (FMG) and main generator. FMG provides energy supply to control system and excitation generator produces regulated exciter for the main generator. The excitation generator is excited by an overheated thermostat and produces 3-phase AC output voltage for devices which require 208 Volt voltage supply.

B. Control Unit.

The control unit is equipped with a transistor placed in the front left-hand side of the cabin roof. The control unit consists of an alternator with a voltage regulator and overvoltage indicator. Internal power supply for the control unit is obtained from the FMG. An overvoltage test switch is provided as a precaution and is equipped with a test panel to test for excess circuit voltage.

C. Control Switch.

On/off switch of a single pole alternator is located in the left-hand side overhead panel. This switch controls the internal power supply on the control unit.

D. 3-Phase Circuit Breaker.

The feeder line of the alternator is protected with 50 Ampere current per phase using a 3-phase circuit breaker. The circuit breaker is placed in the additional gear box of the related engine.

E. Isolated Transformer

An isolated transformer is provided to protect the voltage levels of the control unit using a wave circuit from busbar voltage. The converter is wye-to-wye connected similar to the installation ratio consisting of a resistance-capacitance circuit grounded to the neutral point of the alternator connection. This converter is placed near the control unit.

The warning indicator on the aircraft will be activated due to certain reasons, which are :

a. Alternator fails to function properly.

Warning light which shows Alternator INOP (not operating) is a red sign "Press To Test" which is located on the left-hand side upper panel. The panel is controlled by an alternator transformer which is placed in the 208 Volt AC voltage panel.

b. Excess heat.

This warning indicator is shown by a red light, HEAT "Press To Test". The warning light is placed on the left-hand side upper panel. The panel is triggered by overheated alternator thermostat.

c. Excess voltage.

This warning indicator is provided by a magnetic indicator which is placed on a test and maintenance panel, and is controlled by an overvoltage controller circuit unit.

Under normal conditions, the indicator is black in color but in case of excess voltage, a red indicator will be seen on the indicator panel.

Measuring equipments installed on Fokker-27 panel (Fig 5) are :

a. Voltmeter.

Alternator value is 120 Volt line-to-neutral (L-N) and 208 Volt line-to-line (L-L), on the alternator's main terminal. In case of a voltage drop in the feeder line, the terminal will produce a voltage of 115 Volt L-N and 200 Volt L-L on the regulator point. The 115 Volt L-N potential is monitored by a voltmeter which is installed on each alternator, respectively. Both voltmeters are placed on the left-hand side upper panel.

b. Ampere-meter.

The alternator's load current is displayed by an ampere-meter placed in the left-hand side upper panel. This device is used by connecting two poles or a two-way switch and is placed near the ampere-meter. The two available switch conditions are TOTAL and POWER UNIT. In the TOTAL condition, the ampere-meter is connected in series with a current converter which is connected with phase A of the alternator output circuit. In the POWER UNIT condition, the ampere-meter is connected in series with the current converter in the de-icing input circuit from the power unit. The TOTAL current converter is placed on an AC panel of 208 Volt.

c. Test Point.

This test point is provided on the test and maintenance panel to sustain the Line-to-Neutral and Phase-to-Phase output voltage of the alternator.

d. Alternator Load Distribution.

Each alternator is assigned separated loads. Alternators work independently of each other, and in case one of the alternators fails, the other alternators cannot be used to supply the affected load (load of the failed alternator).

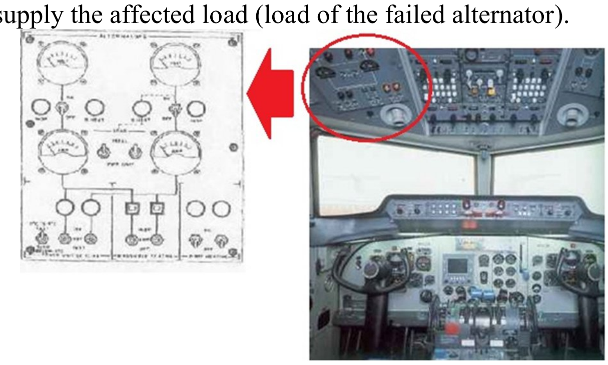

Fig 5. Location of components in the Aircraft [6].

5. Calculation of Power and Engine Energy of Fokker-27 Aircraft

In this research, calculation is done for the use of a single engine. Therefore the engine power value is:

If power is 1835 HP. 1 HP is equivalent to 746 Watt, thus :

$$Engine\ Power = 1835 \times 746\ Watt \qquad (2)$$
$$Engine\ Power = 1369\ KW$$

The energy of a single engine can be calculated using the equation,

$$Engine\ Power\ (WATT) = \frac{Energy\ (KILOWATT\ Hour)}{Time\ (Hour)} \qquad (3)$$

Thus energy value is found to be,

$$Energy\ (KILOWATT\ Hour) = Engine\ Power\ (WATT) \times Time\ (Hour)$$
$$Energy\ (KILOWATT\ Hour) = 1369\ KW \times 1\ Hour = 1369\ KWHour$$

For the use of SFC (Specification Fuel Consumption) fuel of 0.728 Lb/HP/Hour. Thus, the equation used is,

$$\text{Fuel for a single engine} = \text{Power (HP)} \times \text{SFC (Lb/HP/Hour)}$$
$$= 1835\ \text{HP} \times 0.728 \frac{\text{Lb}}{\text{HP Hour}}$$
$$= 1335.88 \frac{\text{Lb}}{\text{Hour}}$$
$$= 1335.88 \times 0.4536 \frac{\text{Kg}}{\text{Hour}}$$
$$= 606 \frac{\text{Kg}}{\text{Hour}}$$

If 1 liter = 0.91 Kg, then the calculation of fuel consumption is,

$$\text{Fuel consumption of each engine} = \frac{606 \frac{\text{Kg}}{\text{Hour}}}{0.91 \frac{\text{Kg}}{\text{Hour}}} = 666 \frac{\text{Liter}}{\text{Hour}}$$

$$\text{Fuel consumed for each KWH} = \frac{666 \frac{\text{Liter}}{\text{Hour}}}{1369\text{KWH}} = 0.486 \frac{\frac{\text{Liter}}{\text{KWH}}}{\text{Hour}}$$

6. Fokker-27 Aircraft Electrical System

In this paper, the author takes the calculation of distance between Kuala Lumpur and Palembang, which is ± 900 km. Flight time taken is ± 2.5 hours.

$$\text{Fuel usage of two engines per hour} = 666 \frac{\text{Liter}}{\text{Hour}} \times 2\ \text{engines}$$
$$= 1332 \frac{\text{Liter}}{\text{Hour}}$$

Thus, the fuel usage according to flight time taken can be calculated using the equation,

$$\text{Total usage} = \text{Fuel usage per hour} \times \text{Flight time taken} \qquad (4)$$
$$\text{Total usage} = 1332 \frac{\text{Liter}}{\text{Hour}} \times 2.5\ \text{Hour} = 3330\ \text{Liter}$$

For usage value per kilometer,

$$\text{usage per kilometer} = \frac{\text{Total usage}}{\text{Distance}} = \frac{3330\ \text{Liter}}{900\ \text{Km}} = 3.7\frac{\text{Liter}}{\text{Km}} \quad (5)$$

7. Aircraft's Mileage

It is estimated that the capacity of the SFC tank is 5000 Liter. Thus the furthest travelling distance of Fokker-27 aircraft is [8] :

$$\text{Mileage} = \frac{\text{Tank Capacity}}{\text{Usage per kilometer}} = \frac{5000\ \text{Liter}}{3.7\frac{\text{Liter}}{\text{Km}}} = 1351\ \text{Km} \quad (6)$$

The duration of flight is,

$$\text{Flight duration} = \frac{\text{Tank capacity}}{\text{Usage per hour}} = \frac{5000\ \text{Liter}}{1332\frac{\text{Liter}}{\text{Hour}}} = 3.75\ \text{Hour} \quad (7)$$

8. Calculation Of Alternator Frequency

Fokker-27 alternator frequency can be calculated using the equation [3]:

$$f = \frac{p.n}{60} \quad (8)$$

where,

- f is frequency in Hertz (Hz).
- p is total alternator pole pairs
- n is the alternator's rotation speed in revolutions per minute (RPM).

Since the aircraft's alternator has 6 poles and the engine rotation speed is 8000 RPM, the alternator frequency generated is,

$$f = \frac{3\ \text{poles} \times 8000\ \text{RPM}}{60} = 400\ \text{Hz}$$

9. Alternator Speed

The ratio of engine rotation to alternator's is [9] :

$$\text{Machine} : \text{Alternator} = 1 : 0.672$$

If engine rotation speed is 12000RPM, then :

$$\text{Alternator} = 12000\ \text{RPM} \times 0.672 = 8064\ \text{RM}$$

Engine torsion force compared to alternator is,

$$\text{Engine Torsion Force} = \frac{\text{Power}}{\left(\frac{2\pi \times \text{rotation}}{60}\right)} \quad (9)$$

Thus,

$$\text{Engine Torsion Force} = \frac{1369\ \text{KW}}{\left(\frac{2\pi \times 12000\ \text{RPM}}{60}\right)} = 1089.4\ \text{Newton}$$

$$\text{Alternator Torsion Force} = \frac{\left(\frac{12\ \text{VA}}{0.9}\right)}{\left(\frac{2\pi \times 8064\ \text{RPM}}{60}\right)} = 15.79\ \text{Newton}$$

Thus, the ratio of the two torsion forces,

$$\text{Engine Torsion Force} : \text{Alternator Torsion Force} = 1089.4\ \text{Newton} : 15.79\ \text{Newton}$$

Percentage of usage to run the alternator is [10],

$$\%\text{usage} = \left(\frac{15.79}{1089.4}\right) \times 100\% = 1.45\%$$

Power required to run the alternator,

$$P_{\text{alternator}} = 1.45\% \times 1369\ \text{KW} = 19.85\ \text{KW}$$

The above calculations are appropriate for the capacity of the installed generator which is 12 kVA.

10. Battery

The battery used for this aircraft is of the Nickel-Cadmium type with current per hour capacity of 40 Ampere-Hour. Battery charging required is 140% of capacity per hour with charging time of 5 hours. Thus, the charging current needed is [1],

$$I_{\text{charge}} = \frac{\text{Capacity per Hour (Ampere Hour)}}{\text{Charging Time (Hour)}} \quad (10)$$

then,

$$I_{\text{charge}} = \frac{40\ \text{(Ampere Hour)}}{5\ \text{(Hour)}} = 8\ \text{Ampere}$$

To reach 140% of capacity per hour,

$$140\%\ \text{Capacity} = 140\% \times 40\ \text{Ampere Hour} = 56\ \text{Ampere Hour}$$

Total charging time of aircraft battery is [7],

$$T_{\text{charge}} = \frac{140\%\ \text{Capacity}}{I_{\text{charge}}} = \frac{56\ \text{Ampere Hour}}{8\ \text{Ampere}} = 7\ \text{Hour}$$

11. Power And Efficiency Of Alternator

Power yield by the inverter is given by,

$$P = V \times I \quad (11)$$

From the above equation

- P is power in VA (Volt Ampere).
- V is voltage in VOLT.
- I is current in Ampere.

For the power generated by a 1-phase alternator,

$$P_{in} = 106\ \text{Volt} \times 27.5\ \text{A} = 2915\ \text{VA}$$
$$P_{in} = 115\ \text{Volt} \times 13.1\ \text{A} = 1506.5\ \text{VA}$$

Power efficiency percentage,

$$\eta_{Power} = \frac{P_{out}}{P_{in}} \times 100\% \qquad (12)$$

then,

$$\eta_{Power} = \frac{1506.5\ \text{VA}}{2915\ \text{VA}} \times 100\% = 51.68\ \%$$

Power generated for 3-phase alternator is obtained from each phase current generated by a 9.1 Ampere 3-phase selector. Thus, the current flowing in each phase is,

$$I_{3\text{-phase}} = \sqrt{3} \times 9.1\ \text{A} = 15.76\ \text{A}$$

Power generated for 3-phase,

$$P_{in} = 106\ \text{Volt} \times 27.5\ \text{A} = 2915\ \text{VA}$$
$$P_{out} = 115\ \text{Volt} \times 15.76\ \text{A} = 1812.4\ \text{VA}$$

Power efficiency percentage,

$$\eta_{power\ 3\text{-phase}} = \frac{1812.4\ \text{VA}}{2915\ \text{VA}} \times 100\% = 62.17\%$$

12. Load Analysis

Fokker-27 alternator is used for heating equipments including [5]:

Extra cockpit heating of 5.5 Ampere.
Defrost windshield of 7.5 Ampere.
Defrost power division consists of:
Continuous air vacuum of 3.5 Ampere.
Air vacuum cycle of 19.7 Ampere.
Fan blade and rotation cycle of 24.2 Ampere

This load is used as the safety value installed on the device. For air suction cycle load and fan blade, the calculation will take the value of the largest load which is the fan blade. Thus total current usage is 40.7 Ampere. Maximum current produced by the alternator is:

$$P = \sqrt{3} \times V \times I$$
$$I = \frac{P}{\sqrt{3} \times V} = \frac{12000\ \text{KVA}}{\sqrt{3}\ \text{x}\ 208\ \text{Volt}} = 33.3\ \text{Ampere}$$

In this analysis, it is found that the alternator currently in use is insufficient to cater for the load. This variation is due to the difference between the load listing in the maintenance manual and the repairing and troubleshooting manual. This is due to the fact that the Fokker-27 aircraft in this research uses an outdated alternator (12 kVA), while the manual has been edited by the aircraft's manufacturers to use the new 15 kVA alternator. It is the user's responsibility to make adjustments and modifications to match with calculation specifications, but since the aircraft is not yet considered to fulfil flight eligibilty standards, modifications are not a requirement.

13. Conclusion

From the results of Fokker-27 aircraft Alternator 115/208 Volt, 400 Hz, 12 kVA performance calculation and analysis, it can be concluded that the alternator used in Fokker-27 aircraft is designed as small as possible with huge power (12 kVA). This can be achieved through a high frequency (400 Hz), until a small actual measurement is obtained.

A 15 kVA alternator is supposed to be used in the aircraft (according to the manual). Currently a 12 kVA alternator with 0.9 lagging power factor is used, thus it is now the time to upgrade the alternator according to the new load in order to improve the aircraft's performance.

Acknowledgement

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