AIRCRAFT ELECTRICAL EQUIPMENT

Part 1

ELECTRICAL POWER SUPPLY SYSTEM OF AIRCRAFT

2018

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

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ELECTRICAL POWER SUPPLY SYSTEM OF AIRCRAFT

Manual

Kharkiv, «Khai» 2018

УДК 629.735.33.064.5 (075.8)
Р-86

Конспект лекцій написано згідно з програмою підготовки бакалаврів і магістрів. Подано матеріал з основних властивостей електричних кіл з урахуванням їхніх особливостей і використання в системах електрообладнання літальних апаратів, а також відомості про найважливіші прилади електрообладнання, які сприяють розумінню їхнього призначення й місця на літальних апаратах.

Описано найважливіші пристрої систем електрообладнання літальних апаратів (СЕЛА) – джерела електричної енергії, перетворювачі різних типів і призначень, електродвигуни і виконуючі пристрої.

Для студентів механічних і електромеханічних спеціальностей вищих навчальних закладів з поглибленим вивченням технічної англійської мови і студентам, які навчаються англійською мовою.

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P-86 Aircraft Electrical Equipment [Text]: manual/ V.N. Postnikov, A.G. Kisly, O.N. Kosychenko, S.N. Firsov, K.F. Fomychov – Kharkiv: National Aerospace University nam. N.E. Zhukovsky “Kharkiv Aviation Institute”, Part 1, 2018. – 159 p.

The manual has been prepared to suit bachelor and master syllabus. It includes basic characteristics of electrical circuits, in particular its use in aircraft electrical equipment (AEE) and to give the most important information about electrical equipment devices for understanding their functions and location on aircraft.

There are the description main devices of AEE – electrical energy sources, different devices of transformation, electric motors actuators.

The manual can be useful for everyone in field of engineering for learning English technical terms by the students studying English.

Illustration 99.Tables 4. Bibliography 12 titl.

УДК 629.735.33.064.5 (075.8)

Abbreviation

AEA – All-Electric Aircraft
AEE – All-Electric Engine
AMB – Active Magnetic Bearings
APV – Auxiliary Power Breaker
APU – Auxiliary Power Unit Screenshot
Auto TR –Auto Transformer Regulator
BCL – Battery Charge Limiter
BPCU – Bus Power Control Unit
CB – Circuit Breaker
CF – Constant Frequency
CSD – Constant Speed Drive
ECS – Environmental Control System
EEP – Electrical Equipment of Planes
EHA – Electro-Hydrostatic Actuation
ELCU – Electronic Load Control Unit
EMA – Electromechanical Actuation
EPS – Electrical Power System
EPDS – Electrical Power Distribution System
FCS – Flight Control System
GSF – Ground Support Equipment
HP – High Pressure
HTR – High Voltage Transformer Regulator
IDG – Integrated Drive Generator
IS/G – Integrated Starter and Generator
LPG – Low Pressure
LTR – Low Voltage Transformer Regulator
MEA – More Electric Aircraft
MEE – More Electric Engine
PDMS – Power Distribution and Management System
PMC – Power Management Centre
PMG – Permanent Magnet Generator
PPDU – Primary Power Distribution Unit
PPU – Primary Power Unit
PSS – Power Supply System
RAT – Ram Air Turbine
RPDU – Remote Power Distribution Unit
SPDU – Secondary Power Distribution Unit
SPU – Secondary Power Unit
TRU – Transformer Rectify Unit
VF – Variable Frequency
VSCF – Variable Speed Constant Frequency

Introduction

On modern aircraft electricity performs many functions, including the ignition of fuels in turbine engines, the operation of communication and navigation systems, the movement of flight controls, and analysis of system performance. There are literally thousands of electrical connections controlling hundreds of electrical devices, each of which was installed and will be maintained by an aircraft technician. On large commercial or complex military aircraft there are literally kilometers wire controlling almost every facet of flight.

The enormous decrease in the use of electronic systems has made it essential to the aircraft technician to obtain a thorough understanding of electricity and electronics.

Generators were the first means of supplying electric power for aircraft.

An electric generator can be defined as a machine that changes mechanical energy into electric energy. On the aircraft mechanical energy is usually provided by the aircrafts engines.

The use of electric power to drive aircraft systems and sub-systems that had earlier been driven by hydraulic, pneumatic and mechanical systems is becoming a dominant trend in the aviation industry. Advances in the areas of power electronics are providing the technology to improve efficiency and safety of aircraft systems operation. The aircraft industry is developing the More Electric Aircraft (MEA) with an ultimate goal of distributing only electric power across the airframe. The replacement of existing systems with electric equivalents and will continue to significantly increase the electrical power requirement.

Increasing use of electrical power is seen as the direction of technological opportunity for aircraft power systems based on rapidly evolving advancements in power electronics fault tolerant power distributing systems and electrically driven actuators. The use of More Electric Architecture on aircraft offers significant cost benefits with recurring cost due to fewer parts, integration of key sub-systems, and multi-use of components.

The need for environmental sustainability, efficiency and economy in aviation is translating into a process of reducing aircraft weight and refining its systems/ Reduce aircraft weight has a direct influence on the fuel consumption of the aircraft.

Chapter 1

GENERAL QUESTIONS OF POWER SUPPLY OF PLANES

1.1. Functions of Aircraft Electric Equipment and its Basic Elements

Now electrical energy is widely applied on flying aircraft: airplanes, helicopters, missiles. It is used for operation of electric motors, starting systems, control devices for starting the electric motors and special equipment, navigating flight, radio-electronic, anti-icing and lighting equipment, air conditioning systems, for external and internal illumination, heating.

Electrical equipment of planes (EEP). EEP is a complex set of different gears, machines and devices.

The elements have great reliability, high technical indexes besides EEP ensures high quality of operation, they are convenient in service and have rather small mass and dimensions.

Different installations may be used as sources of aircraft energy: hydraulic, mechanical, pneumatic, chemical, pyrotechnic and electrical. The electrical energy is the most universal type of energy i.e. it can be used almost in every case. It enables to reduce a number of used types of energy.

Other important advantages of electrical energy application are: simplicity of electrical energy generation, possibility of its simple transmission and distribution among consumers, convenient transformation into other types of energy, convenience of automation of special operations, possibility of reducing the mass of Power Supply System (PSS) elements (absence of cables, shafts, manifolds, etc.), reservation simplicity resulting in system reliability improvement.

EEP basic elements. All EEP depending on the function of each element can be subdivided into three basic groups (Fig. 1.1):

1. Sources of electrical energy and converters, their protective and control devices.
2. System of transmission and distribution of energy.
3. Consumers of electrical energy.

The first group includes:

a) electrical generators of direct and alternating current;

b) chemical current sources;

c) converters of electrical energy of all types;

d) rectifiers, transformers, voltage multipliers;

e) the control and protective equipment, including voltages and frequency regulators;

f) devices ensuring a uniform distribution of active and reactive power between the working generators.

The second group includes:

a) an electrical network (different wires and wisps);

b) measuring devices;

c) devices for observation over mode of operation of EEP;

d) mounting and adjusting the equipment (sockets, boards, distribution devices etc.).

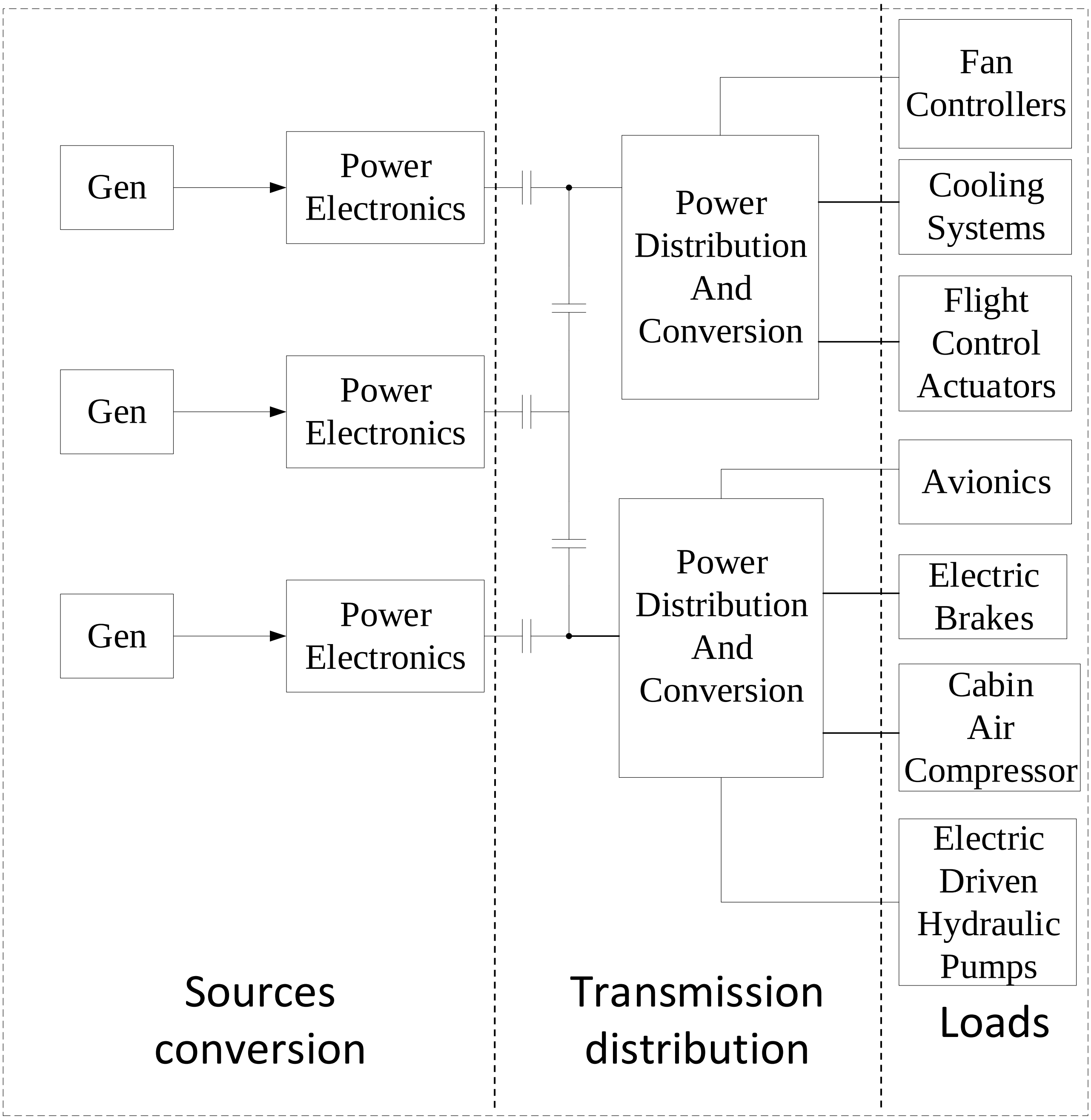


Fig. 1.1. Electrical Equipment of Planes basic elements

The third group includes:

a) electric motors, electromagnets and other devices used for actuating and control of the executive mechanisms and different airplane machines;

b) lighting and auto alarm devices (external, internal and control);

c) anti-icing and heating devices, as well as refrigerating machinery and fire-prevention system;

d) starting devices (electrical starters for engine starting etc.);

e) communication facilities and radio equipment, photography equipment ;

f) installations of automatic control, computers;

g) measuring devices based on use of electrical energy, thermometers, tachometers, fuel gauge, compasses etc.

1.2. Specific Features of Operation Conditions and Basic Requirements to EEP

It’s more difficult and complicated to compare working conditions of separate elements and all complex of EEP in comparison with conditions of the ground equipment operation. They are characterized by wide change of temperature (from ***–60ºC*** up to ***+160ºC***), pressure, damp and electric conductivity of the air, presence of mechanical forces acting on the equipment, change of equipment position in space, presence of oil and fuel steams.

With increase of flight altitude, pressure and temperature, density and damp of the air diminish. The pressure that is equal to $\boldsymbol{10^5}$ Pa of the Earth surface falls ***5*** times at the altitude of ***12000m*** and it falls ***180*** times at the altitude of ***35km***.

The air density is directly proportional to pressure and is inversely proportional to temperature.

The air humidity diminishes with altitude. At the altitude of ***9-10 km*** water steams in the atmosphere are practically absent, and on the Earth they can reach ***98%***.

The air electric conductivity increases with increase of flight altitude. It is explained by reduction of air density and increase of intensity of air ionization by cosmic and ultra-violet rays.

With increasing the flight altitude and lowering the air density the conditions of air-cooling the EEP are deteriorating, that makes it necessary to reduce loads and increase EEP weight.

The lowering of the contents of water and oxygen steams in the air with increase of altitude results in aggravation of communication and sharp increase of wearing brushes and collector. The reduction of air density resulted by increasing of altitude makes it necessary to choose the larger isolation intervals and to increase weight of products.

At low temperatures the viscosity of lubricant grows, that results in the necessity of increasing electric motor power.

Under vibrations the mechanical loads on a product increase ($f_v = 5 \ldots 2000$ ***Hz***), resulting in lowering their durability, accuracy of coal voltage regulator operation.

The operation in weightlessness conditions hampers EEP cooling (absence of natural convection).

However, despite the difficult conditions of maintenance and more rigid requirements, EEP is appreciably lighter, than ground equipment. It is achieved at the expense of shorter life expectancy that allows increasing admissible heating and loads of the equipment, due to application of better materials, more perfect technique and more perfect architecture of EEP maintenance.

1.3. Airplane Power Supply Systems. Selection of Parameters

An aircraft, as a rule, has a number of energy sources operating for a common power network. For example, to improve the reliability of a power supply system it is necessary to have several energy sources providing a self-contained starting of the aircraft engines.

Generators are the main power sources on the aircraft. But in the event of engine failure the generators don't operate either. That's why the storage battery (accumulator) is required for starting the first engine. Storage batteries also have a function of emergency power supply. They provide the power supply of vitally important equipment responsible for successful realization of the flight mission and accident-free flight completion. This equipment includes air navigation, radio communication, anti-icing, fire suppression as well as airplane control systems.

To provide the operation of electric energy services both direct and alternating current are required.

The airplane PSS parameters depend on the airplane type and purpose, total power consumed by its services, the type of the current, voltage magnitude and frequency of most of the services.

Thus, the type of current is not important for heaters, anti-icing facilities and for some other devices. But such devices as gyroscopic systems require alternating voltage of ***36 V 400 Hz***.

As the airplane size and power of the systems increased, the voltage magnitude in direct current electrical systems also increased being ***6 V, 8 V, 12 V***. In 1934 the voltage magnitude equal to ***27,5 V*** was agreed on. Further voltage increase in the direct current system under the operation conditions of high altitude makes the commutation of electrical equipment difficult. That's why the nominal voltage in the direct current system is settled to be equal to ***28,5 V*** (at the power sources terminals) and ***27,0 V*** (at the service terminals).

The electric power system of aircraft has made dramatic progress in recent years because the aircraft has depended more and more on the electricity. The twin **28 *V* DC** system was classical electric power system from **1940 s** to **1950 s**. An inverter was also adopted to provide **115 *V* AC** to the flight instruments.

Along with the increasing power requirements, especially incorporated electrically actuated landing gear on the aircraft, the type of electrical power generation system changed. Along with the time, the electrical power system has evolved in the types and power capacity (illustrated in Fig. 1.2).

For the alternating current systems the voltage magnitude is mainly limited by the conditions of safe operations. When the phase voltage exceeds ***100 … 150 V*** the network weight decreases insignificantly. However, the threat of getting the crew an electric shock greatly increases. That's why the nominal voltage in three-phase AC system is agreed to be equal to ***200/115 V*** for services and ***208/120 V*** for power supplies of modern airplanes and helicopters.

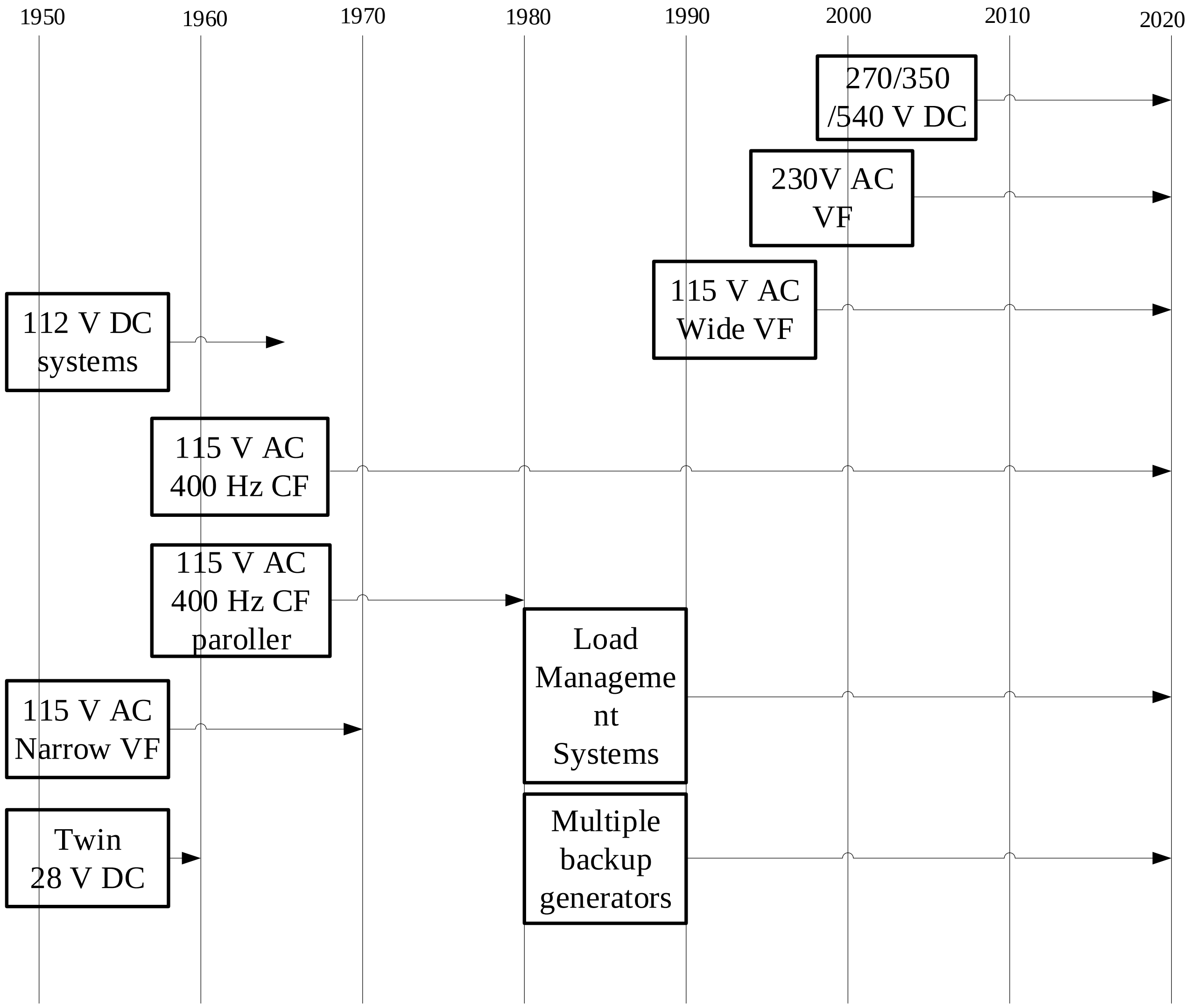


Fig. 1.2. Electrical System Evolution

In the secondary AC systems which are considered to be the systems of low power such voltage is not the best (even if the maximum weight is taken into account). That's why these systems make use of voltage equal to ***36 … 40 V*** especially for instrument system supply.

The AC system may have two variants: single-phase and three-phase systems. The three-phase system with grounded neutral is chosen as the basic one. Such system provides smaller weight of electric motors and AC - generators, improves their reliability and characteristics (compared with single-phase system).

Calculations show that the best frequency is equal to ***400... 800 Hz*** depending on the relationship between the electric equipment system's power and their weight.

In most countries the frequency of ***400 Hz*** is agreed as nominal. Thus, the nominal parameters of power supply system of alternating current and constant frequency are: the number of phases ***m=3***, linear service voltage ***200 V*** and frequency ***400 Hz*** **(*500 Hz*)**.

There are various generators utilized on a modern aircraft.

1. **Integrated Drive Generators** (IDG) is widely used in all kinds of aircraft nowadays. The techniques of it are adequately nature.
2. **Variable Speed Constant Frequency** (VSCF). The VSCF generators supply 115 V, 400 Hz constant frequency (CF) electrical power to airframe systems via the conversion of power electronics.
3. **Variable Frequency** (VF) generator can be driven by the engine directly and can supply the variable frequency (generally 320-1050 Hz) power to airframe systems without the help of complex mechanical conversion equipment's. The main advantages of the VF technology are: cost saving, weight reducing and reliability improving. Four 250 kVA VF generators have been utilized on B787 as the main electrical power sources.
4. **270 V DC**. For the sake of reducing the mass of wires and conduction loss of electrical power, the high voltage generation technology has been used to provide the electric power. The 230 V AC, 270 V DC and which is a famous MEA.

1.4. Types of Power Supply Systems

All power supply systems currently available may be divided into three types according to electric current parameters.

The first type has the primary system of direct current and low voltage. The structure of this system is illustrated in Fig. 1.3.

The main electric power supplies in the system of this type are the DC generators 2 with nominal voltage ***28,5 V***. The generator is put into operation with the help of primary engine. The generators are put in parallel connected into the general air board buses. Storage batteries 4 are usually used as the emergency source. Rotary or static converters are used as a power source for AC equipment. Thus, the air board electric network has three main buses:

– three-phase AC bus 36 V (115 V/200 V), 400 Hz;

– main DC bus: 28,5 V;
– DC emergency bus 24 V.

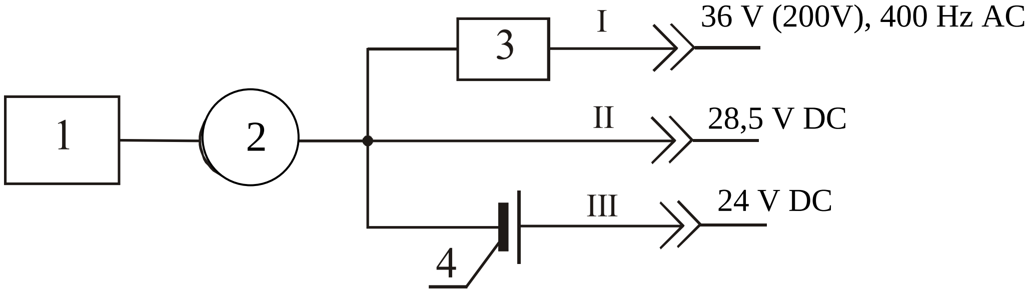


Fig. 1.3 Power supply system of the first type
1 – primary engine; 2 – generator; 3 – converter of DC into AC; 4 – storage battery; I, II, III – buses

The second type is the type with primary system of AC, step-up voltage, and stable frequency. The motor drive of the AC generators is also used to active of aircraft engines. In order to achieved the frequency stability two methods may be used (Fig. 1.4):

a) rotation of the generator shaft across the regulator with alternating gain;
b) using of static converters of alternating frequency current into fixed frequency current.

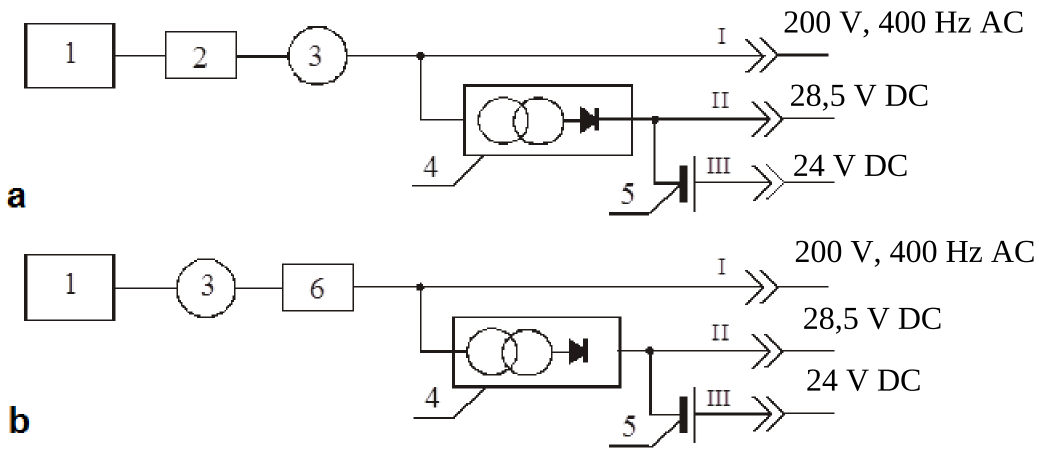


Fig. 1.4. Power supply system of the second type
a – with a drive of constant rotational speed; b – with the frequency converter;
1 – primary engine; 2 – redactor; 3 – a.c.generator;4 – rectifier;
5 – storage battery; 6 – static frequency converter

Rotation of the generator shaft across the reducer with alternating reduction ratio 2 makes possible to get the constant speed of the generator shaft at alternating angular velocity of primary engine 1 rotation. Such drive is called a drive of constant rotational speed (DCRS for short). The structure of power supply system with this type of drive is illustrated in Fig. 1.4, a.

The application of static converters does not require the use of redactor ***2*** with alternating gain. In this case the static converter 6 acts as a current frequency stabilizer.

The structure of the power supply system with static converters is shown in Fig. 1.4, b.

The air board power supply system of the second type has three buses as well:

– main three-phase bus 200 V 400 Hz;
– DC bus 28,5 V;
– emergency DC buses 24 V.

In this case the DC bus with voltage equal to ***28,5 V*** is assigned to the secondary system; voltage across bus II is generated by means of rectifier ***4***.

The emergency system (as in the power supply systems of the first type) is supplied by power due to storage batteries ***5***.

The third type is the combined or mixed power supply system.

Reducers with alternating gain and static converters of the current frequency are complex devices. Besides, there are a lot of devices and instruments onboard the aircraft that can normally operate when being supplied by unstable frequency current. It gives the possibility of designing the power supply system based on DC generators of low voltage and AC generators of unstable frequency and step-up voltage. The structural diagram of power supply system of a mixed type may be given in the following form (Fig. 1.5).

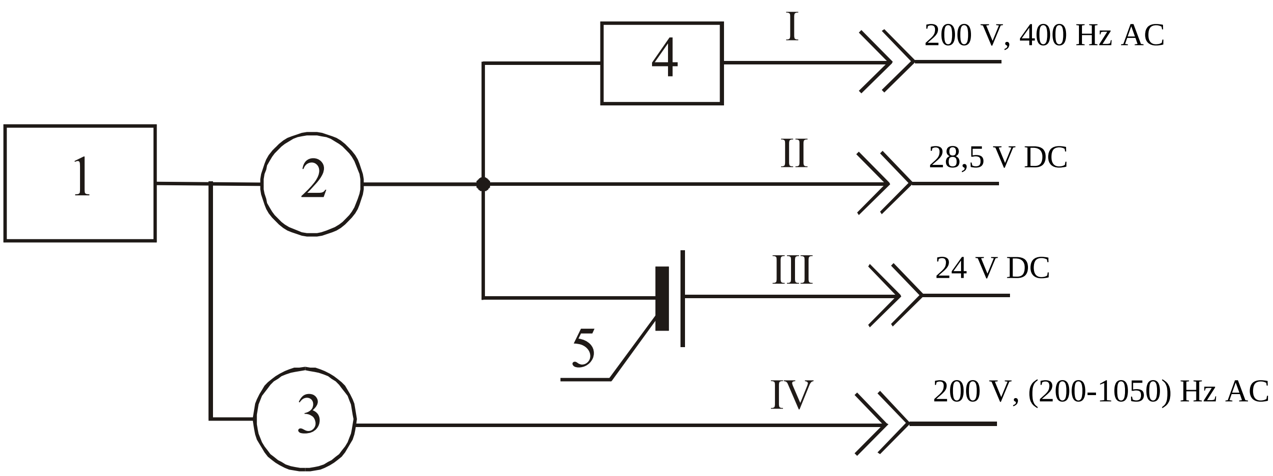


Fig. 1.5. Power supply system of the third type
1 – primary engine (aircraft engine); 2 – DC generator; 3 – AC generator of alternating frequency; 4 – converter of direct current into alternating current stable frequency; 5 – storage battery

Fig. 1.5 shows the power supply system of the third type with the following buses:

- I – three-phase AC bus with nominal voltage 200 V 400 Hz;
- II – DC bus 28,5 V;
- III – emergency DC bus 24 V;
- IV – three-phase AC bus with nominal voltage 200 V, alternating frequency (200 … 1050) Hz.

If necessary, the direct current load may be supplied from the AC buses through rectifiers. If it is required that the step-down voltage of constant frequency (e.g. ***36 V, 400 Hz***) be applied to the flight-navigational instruments the blocks (units) of step-down transformers may be used. For example, the power supply system of the AN-140 consists of:

– primary system of alternating three-phase current with nominal voltage of ***115/200 V***, alternating frequency of ***340 … 510 Hz***;

– secondary system of alternating three-phase with nominal voltage of ***115/200 V***, constant frequency of ***400 Hz***;

– secondary system of direct current with nominal voltage of ***27 V***.

The power supply system B787/A380 consists of:

– primary system of AC three - phase with nominal voltage **230/400 V**, alternating frequency of **360…800 Hz**;

– secondary system of AC three-phase with nominal voltage **115/200 V**, constant frequency of **400 Hz;**

– secondary system of DC with nominal voltage of **270 V**;

– secondary system of DC with nominal voltage of **27 V**.

1.5. Terms and Concepts

Aircraft electrical equipment is a set of various instruments, facilities and devices used in the process of aircraft operation.

Aircraft power supply system is a system of electric power generation and distributions.

Busses are systems of like priority on a common line.

Bus Bar is a primary power distribution point connect to the main power source.

Constant speed drive (CSD) is a unit used in conjunction with AC alternators to produce a constant-frequency AC voltage.

Primary power supply system is a system for conversion of any other type of energy into electric energy. It usually includes generators with their equipment and power network.

Secondary power supply system is a system for conversion of primary system electric energy into electric energy of another type current or voltage.

Split-bus electrical system is a power distribution system containing two isolated bus bars.

1.6 Control Questions

1. Name the advantages of using electric energy in aviation.
2. Explain the principle of classification of power supply system (PSS) units.
3. What are the specific features of PSS operation conditions?
4. What are the requirements imposed on PSS?
5. What are the main sources of electric energy used on aircraft?
6. How is the selection of PSS parameters performed?
7. What are the characteristics of PSS of the first type?
8. What are the characteristics of PSS of the second type?
9. What are the specific features of the mixed PSS?
10. What are the advantages of the VF technology?

Chapter 2

AIRCRAFT STORAGE BATTERIES

The battery is an essential component of almost all aircraft electrical systems. Batteries are used to start engines and auxiliary power units, to provide emergency backup power for essential avionics equipment, to assure no-break power for navigation units and fly-by-wire computers, and to provide ground power capability for maintenance preflight checkouts. Many of these functions are mission critical, so the performance and reliability of an aircraft battery is of considerable importance. Other important requirements include environmental ruggedness, a wide operating temperature range, ease of maintenance rapid recharge capability, and tolerance to abuse.

2.1. General principles

Various dissimilar metals have opposite polarities with respect to one another and when two such metals are rubbed together, one will have a positive charge and the other a negative charge. If two plates of dissimilar metals are placed in a chemical solution called **an electrolyte**, opposite electric charges will be established on the two plates. In simple terms an electrolyte is a solution of water and a chemical compound that will conduct an electric current because it contains positive and negative ions.

The action of an electrolyte will be clear if a specific case is considered. When a rod of carbon and a plate of zinc are placed in a solution of ammonium chloride, the result is an elementary **voltage cell** (Fig. 2.1).

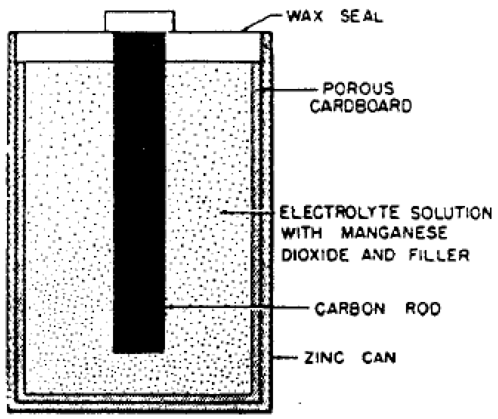


Fig. 2.1. Construction of a simple dry cell

The carbon and zinc elements are called **electrodes**. The carbon, which is a positively charged electrode, is called the **anode** and the zinc plate is called the **cathode**.

The combination of two electrodes surrounded by an electrolyte will form a **cell**.

A cell is a device that transforms chemical energy into electric energy.

The container which may be constructed of one of many different materials provides a means of holding (containing) the electrolyte. The container is also used to mount the electrodes. In the voltaic cell the container must be constructed of a material that will not be acted upon by the electrolyte.

A dry cell is so called because the electrolyte is in the form of a paste; the cell may therefore be handled without the danger of spillage. The voltage of any cell depends on the materials used as the electrodes.

In the simple galvanic cell, the electrolyte in a liquid form (so called **wet cell**).

A primary cell is one in which the chemical action eat away one of the electrodes, usually the negative electrode. When this happens, the electrode must be replaced, or the cell must be discarded, in the galvanic-type cell, the zinc electrode and the liquid electrolyte are usually replaced when this happens. In the case of the dry cell, it is usually cheaper to buy a new cell. That is primary cell cannot be recharged.

In **a secondary cell** the chemical action that produced the electric current can be reversed; in other words, secondary cells can be recharged. This is accomplished by applying a voltage higher than that of the cell to the cell terminals; this causes a current to flow through the cell in a direction opposite to that in which the current normally flows.

The positive terminal of the charging source is connected to the positive terminal of the cell, and the negative terminal of the charging source is connected to the negative terminal of the cell. Since the voltage of the charger is higher than that of the cell, electrons flow into the negative plate and out of the positive plate. This causes a chemical action to take place that is the reverse of the one that occurs during operation of the cell; the elements of the cell return to their original composition. At this time, the cell is said **to be charged**. Secondary cells can be charged and discharged many times before they deteriorate to the point at which they must be discarded.

In the secondary cell, the material of the plates does not go into solution but remains in the plates, where it undergoes a chemical change during operation.

Electrochemical Action

If a load (a device that consumes electrical power) is connected externally to the electrodes of a cell, electrons will flow under the influence of a difference in potential across the electrodes from the anode through the external conductor to the cathode. A cell is a device in which chemical energy is converted to electrical energy. This process is called **electrochemical action**.

The voltage across the electrodes depends upon the materials from which the electrodes are made and the composition of the electrolyte. The current that a cell delivers depends upon the resistance of the entire circuit including that of the cell itself. The internal resistance of the cell depends upon the size of the electrodes, the distance between them in the electrolyte and the resistance of the electrolyte. The larger the electrodes and the closer together they are in the electrolyte (without touching) the lower the internal resistance of the cell and the more current the cell is capable of supplying to the load.

Primary Cell Chemistry

When a current flows through a primary cell having carbon and zinc electrodes and a diluted solution of sulphuric acid and water (combined to form the electrolyte), the following chemical reaction takes place.

The electron flow through the load is the movement of electrons from the negative electrode of the cell (zinc) and to the positive electrode (carbon). This causes fewer electrons in the zinc and an excess of electrons in the carbon. The hydrogen ions (H_2) from the sulphuric acid are attracted to the carbon electrode. Since the hydrogen ions are positively charged, they are attracted to the negative charge on the carbon electrode.

This negative charge is caused by the excess of electrons the zinc electrode has a positive charge because it has lost electrons to the carbon electrode. This positive charge attracts the negative ions (SO_4) from the sulpuric acid. The negative ions combine with the zinc to form zinc sulphate. This action causes the zinc electrode to be eaten away. Zinc sulphate is a grey-white substance that is sometimes seen on the battery post of an automobile battery.

The process of the zinc being eaten away and the sulphuric acid changing to hydrogen and zinc sulphate is the cause of the cell discharging. When the zinc is used up the voltage of the cell is reduced to zero. In Fig. 2.1 it can be noticed that the zinc electrode is labeled negative and the carbon electrode is labeled positive. This represents the current flow outside the cell from positive to negative.

The zinc combines with the sulphuric acid to form zinc sulphate and hydrogen. The zinc sulphate dissolves in the electrolyte (sulphursc acid and water) and the hydrogen appears as gas bubles around the carbon electrode. As current continues to flow, the zinc gradually dissolves and the solution changes to zinc sulphate and water. The carbon electrode does not enter into the chemical changes taking place, but simply provides a return path for the current.

Secondary Cell Chemistry

As stated before, the differences between primary and secondary cells are, the secondary cell can be recharged and the electrodes are made of different materials. The secondary cell shown in Fig. 2.2 uses sponge lead as the anode and lead peroxide as the cathode. This is the lead-asid type cell and will be used to explain the general chemistry of the secondary cell. Later it can be seen that the materials, which make up the port of a cell are different, but that the chemical action is essentially the same.

Fig.2.2 view A shows a lead-acid secondary cell that is fully charged. The anode is pure sponge lead peroxide, and the electrolyte is a mixture of sulpharic acid and water.

Fig.2.2 view B shows the secondary cell discharging. A load is connected between the cathode and anode.

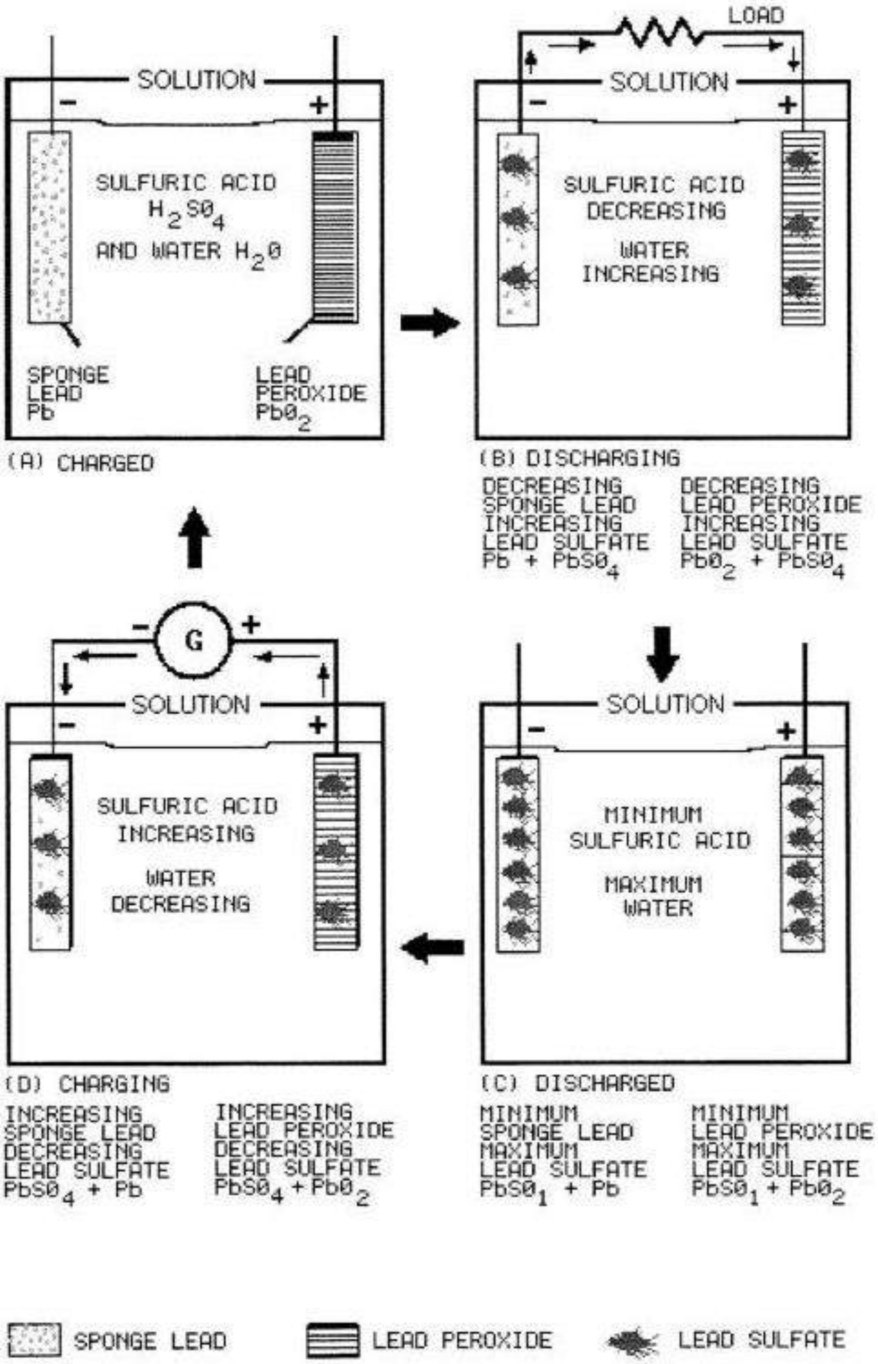


Fig. 2.2. Secondary cell

This electron flow creates the same process as was explained for the primary cell with the following exceptions:

–In the primary cell the zinc anode was eaten away by the sulphuric acid. In the secondary cell the sponge-like construction of the anode retains the lead sulphate formed by the chemical action of the sulphuric acid and the lead.

–In the primary cell the carbon cathode was not chemically acted upon by the sulphuric acid. In the secondary the lead peroxide cathode is chemically charged to lead sulphate by the sulphuric acid.

When the cell is fully discharged it will be as shown in Figure 2.2 view C/ The cathode and anode retain some lead peroxide and sponge lead but the amounts of lead sulphate in each is maximum. The electrolyte has a minimum amount of the sulphuric acid. With this condition no further chemical action can take place within the cell.

The secondary cell can be recharged. Recharging is the process of reversing the chemical action that occurs as the cell discharges. To recharge the cell, a voltage source, such as generator is connected as shown in Figure 2.2 view D. The negative terminal of the voltage source is connected to the cathode of cell and the positive terminal of the voltage source is connected to the anode of the cell. Within this arrangement the lead sulphate is chemically changed back to sponge lead in the cathode lead peroxide in the anode and sulphuric acid in the electrolyte. After all the lead sulphate is chemically changed, the cell is fully charged as show in Figure 2.2 view A. Once the cell has been charged, the discharge – charge cycle may be repeated. Notice in the above paragraph that the anode and cathode appear to have changed polarity. This is because a cell being recharged is an electrolytic cell (rather than a voltaic or galvanic cell, as it was when discharging). In an electrolytic cell, the anode is positive and the cathode is negative.

Polarization of the cell

The chemical action that occurs in the cell while the current is flowing causes hydrogen bubbles to form on the surface of the anode. This action is called **polarization**.

Some hydrogen bubbles rise to the surface of the electrolyte and escape into the air, some remain on the surface on the anode. If enough bubbles remain around the anode, the bubbles form a barrier that increases internal resistance. When the internal resistance of the cell increases, the output current is decreased and the voltage of the cell also decreases.

A cell that is heavily polarized has no useful output. There are several methods to prevent polarization or to depolarize the cell.

One method uses a vent on the cell to permit the hydrogen to escape, into the air. A disadvantage of this method is that hydrogen is not available to reform into the electrolyte during recharging. This problem is solved by adding water to the electrolyte, such as in an automobile battery. A **second method** is to use material that is rich in the oxygen, such as manganese dioxide, which supplies free oxygen to combine with the hydrogen and form water.

A **third method** is to use a material that will absorb the hydrogen, such as calcium. The calcium releases hydrogen during the charging process. All three methods removes enough hydrogen so that the cell is practically free from polarization.

Local Action

When the external circuit is removed the current ceases to flow, and, theoretically, all chemical action within the cell stops. However, commercial zinc contains many impurities, such as iron, carbon, lead and arsenic. These impurities form small electrical cells within the zinc electrode in which current flows between the zinc and its impurities. Thus the chemical action continues even though the cell itself is not connected to a load.

Local action may be prevented by using pure zinc (which is not practical), by coating the zinc with mercury to the zinc during the manufacturing process. The treatment of the zinc with mercury is called amalgamating (mixing) the zinc. Since mercury is many times heavier than an equal volume of water, small particles of impurities weighing less than mercury will float to the surface of the mercury. The removal of these impurities from the zinc prevents local action. The mercury is not readily acted upon by the acid. When the cell is delivering current to a load the mercury continues to act on the impurities in the zinc. This causes the impurities to leave the surface of the zinc electrode and float to the surface of the mercury. This process greatly increases the storage life of the cell.

2.2. Types of cell

The development of new and different types of cells in the past decade has been so rapid that it is virtually impossible to have a complete knowledge of all the various types. A few recent developments are the silver-zinc, nickel -zinc, nickel-cadmium, silver-cadmium, organic and inorganic lithium, and mercury cells.

Primary Dry Cell

The dry cell is the most popular type of primary cell. It is ideal for simple applications where an inexpensive and non - critical source of electricity is all that is needed.

The dry cell is not actually dry. The electrolyte is not in a liquid state, but is a most paste. If it should become totally dry, it would no longer be able to transform chemical energy to electrical energy.

The construction of a common type of dry cell is shown in Fig. 2.3. These dry cells are also referred to as leclanche cells. The internal parts of the cell are located in a cylindrical zinc container.

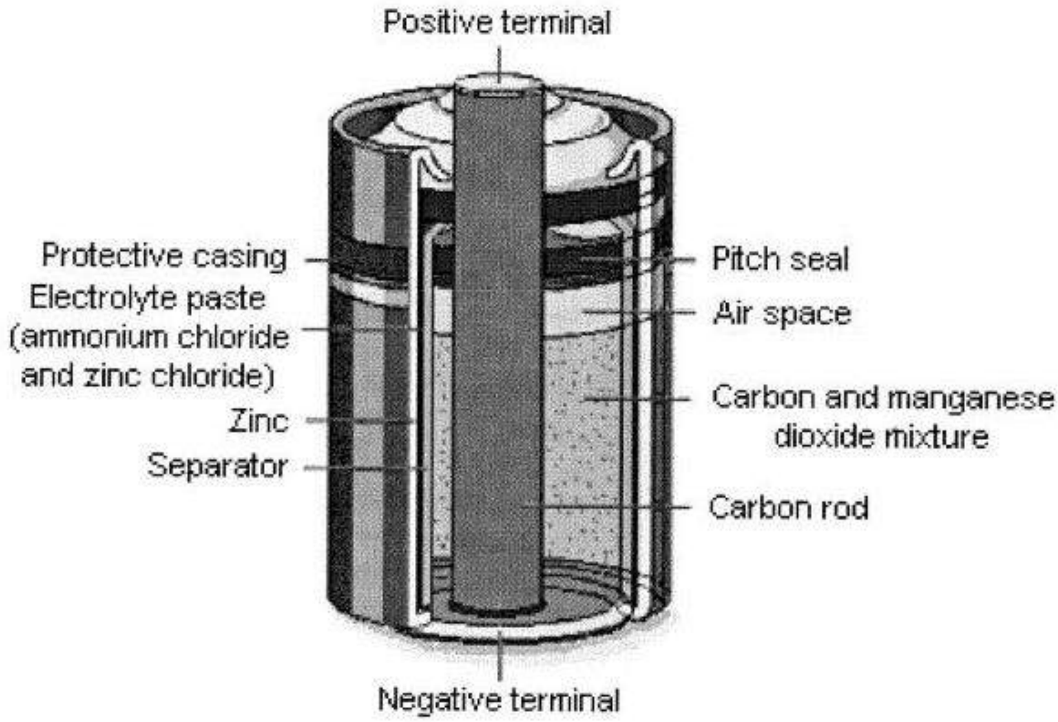


Fig 2.3. Cutaway view of the general-purpose dry cell

This zinc container serves as the negative electrode (anode) of the cell. The container is lined with a non – conducting material, such as blotting paper to separate the zinc from the paste. A carbon electrode is located in the center, and it serves as the positive terminal (cathode) of the cell. The paste is a mixture of several substances such as ammonium chloride, powdered coke, ground carbon, manganese dioxide, zinc chloride, graphite and water. This electrolyte paste also serves to hold the cathode rigid in the center of the cell. When the paste is packed in the cell, a small space is left at the top for expansion of the electrolytic paste caused by the depolarization action. The cell is then sealed with a card board or plastic seal.

Since the zinc container is the anode, it must be protected with some insulating material to be electrically isolated. Therefore, it is common practice for the manufacturer to enclose the cell in cardboard and metal container.

The dry cell (Fig 2.3) is basically the same as the simple voltaic cell (wet cell) described earlier, as far as its internal chemical action is concerned. The action of the water and the ammonium chloride in the paste, together with the zinc and carbon electrodes produces the voltage of the cell. Manganese dioxide is added to reduce polarization when current flows and zinc chloride reduces local action when the cell is not being used.

A cell that is not being used (sitting on the shelf) will gradually deteriorate because of slow internal chemical changes (local action). This deterioration is usually very slow if cells are properly stored. If unused cells are stored in a cool place, their shelf life will be greatly preserved. Therefore, to minimize deterioration, they should be stored in refrigerated spaces. The cell is sealed at the top to keep air from entering and drying the electrolyte. Care should be taken to prevent breaking this seal.

The leclanche Cell_was invented and patented in 1866 by Georges Leclanche. It contained a conducting solution (electrolyte) of ammonium chloride , a cathode (positive terminal) of carbon, a depolarizer of manganese dioxide, and an anode (negative terminal) of zinc. The Leclanche battery (or wet cell as it was referred to) was the forerunner of the modern dry cell zinc-carbon battery.

The Daniell Cell also called **the gravity cell** or **crow foot cell** was invented in 1836 by John Frederic Daniell, who was a British chemist and meteorologist. The Daniell cell was a great improvement over and is somewhat safer than the voltaic used in the early days of battery development. The Daniell cells theoretical voltage is 1.1 volts. The Daniell proper consists of a central zinc anode dipping into a porous earthenware pot containing zinc sulphate solution. The porous pot is in turn, immersed in a solution of cooper sulphate contained in a copper can, which acts as the cells cathode. The use of a porous barrier prevents the copper ions in the copper sulphate solution from reaching the zinc anode and undergoing reduction. This would render the cell ineffective by bringing the battery to equilibrium without driving a current.

Other Types of Cells

Voltaic cells utilizing an alkaline electrolyte are usually termed as **alkaline cells**. The electrolyte consists primarily of a potassium hydroxide solution. The electrodes of such cells can be of several different types of materials, such as manganese dioxide and zinc, silver oxide and cadmium, mercuric oxide and zinc or nickel and cadmium. These various electrode materials will determine if the alkaline cell is a rechargeable secondary cell or a non rechargeable primary cell. The different electrodes will also determine the cells voltage output. Most common alkaline cells produce approximately ***1.5 V*** without a load applied to the cell.

Mercury cells are another common type of dry cell used for a variety of applications. A mercury cell consists of a positive electrode of mercuric oxide mixed with a conductive material and a negative electrode of finely divided zinc. The electrodes and the caustic electrolyte are assembled in sealed steel cans. Some electrodes are pressed into flat circular shapes, and others are formed into hollow cylindrical shapes, depending on the type of cell for which they are made. The electrolyte is immobilized in an absorbent material between the electrodes. With the birth of the space program and the development of small transceivers and miniaturized equipment, a small cell, which is capable of delivering maximum electrical energy at constant discharge voltage. The mercury cell, which is one of the smallest cells, meets these requirements.

There are many different types of primary cells. Because of such factors as cost, size, case of replacement and voltage or current needs, many types of primary cells have been developed. The following is a brief description of some of the primary cells in use today.

The Manganese Dioxide –Alkaline – Zinc Cell is similar to the zinc – carbon cell except the electrolyte used. This type of cell offers better voltage stability and longer life than the zinc – carbon type. It also has a longer shelf life and can operate over a wide temperature range. The manganese dioxide – alkaline – zinc cell has a voltage of 1.5 volts and is available in a wide range of sizes. This cell is commonly referred to as the alkaline cell.

The Magnesium – Manganese Dioxide Cell uses magnesium as anode material. This allows a higher output capacity over an extended period of time compared to the zinc – carbon cell. This cell produces a voltage of approximately 2 volts. The disadvantage of this type of cell is the production of hydrogen during its operation.

The Lithium – Organic Cell and **Lithium – Inorganic Cell** are recent developments of a new line of high – energy cell. The main advantages of these types of cells are very high power, operation over a wide temperature range, they are lighter than most cells, and have a remarkably long shelf life of up to 20 years.

Lithium cells contain toxic materials under pressure. Do not puncture, recharge, short – circuit, expose to excessively high temperatures, or incinerate. Use these batteries/cells only in the approved equipment. Do not throw in bin.

Disposable Cells

These are not designed to be rechargeable – i.e. **primary cells**. Disposable may also imply that special disposal procedures must take place for the proper disposal according to the regulation, depending on battery type:

– **Zinc – Carbon**: mid cost, used in light drain applications.

– **Zinc – Chloride**: similar to zinc – carbon but slightly longer life.

– **Alkaline**: alkaline/manganese “long life” batteries widely used in both light – drain and heavy – drain applications.

– **Silver – Oxide**: commonly used in the hearing aids, watches, and calculators.

– **Lithium Iron Disulphide**: commonly used in digital cameras. Sometimes used in watches and computer clocks. Very long life (up to ten years in wrist watches) and capable of delivering high currents but expensive. Will operate in sub – zero temperatures.

– **Lithium – Thionyl Chloride**: used in industrial applications, including computers, electric meters and other devices which contain volable memory circuits and act as a "carryover" voltage to maintain the memory in the event of a main power failure. Other applications include providing power for wireless gas and water meters. The cells are rated at 3.6 Volts and come in 1/2AA, AA, 2/3A, A, C, D and DD sizes. They are relatively expensive, but have a long shelf life, losing less than 10% of their capacity in ten years.

– **Zinc – air**: commonly used in hearing aid.

– **Nickel Oxyhydroxide**: ideal for applications that use bursts of high current, such as digital cameras. They will last two times longer that alkaline batteries in digital cameras.

– **Paper**: in August 2007, a research team at RPI developed a paper battery with aligned carbon nanotubes, designed to function as both a lithium – ion battery and super – capacitor, using ionic liquid, essentially a liquid salt, as electrolyte. The sheets can be rolled, twisted, folded or cut into numerous charges with no loss of integrity or efficiency or stacked, like printer paper (or a voltaic pile), to boost total output. As well, they can be made in a variety of sizes, from postage stamp to broadsheet. Their light weight and low cost make them attractive for portable electronics, aircraft, and automobiles, while their ability to use electrolytes in blood make them potentially useful for medical devices such as pacemakers. In addition, they are biodegradable, unlike most other disposable cells.

Rechargeable Cells

Also known as **secondary** batteries or accumulators. The National Electrical Manufacturers Associations has estimated that US demand for rechargeable is growing twice as fast as demand for non – rechargeable. There are a few main types:

– **Nickel – Cadmium** (Ni - Cd): Best used for motorized equipment and other high – discharge, short – term devices. Ni – Cd batteries can withstand even more drain than NiMH, however, the mAh rating is not high enough to keep a device running for very long, and the memory effect is far more severe.

– **Nickel – metal hydride** (NiMH): Best used for high – tech devices. NiMH batteries can last up to four times longer than alkaline batteries because NiMH can with stand high current for a long while.

– **Rechargeable alkaline**: Uses similar chemistry as non – rechargeable alkaline batteries and are best suited for similar applications. Additionally they hold their charge for years, unlike NI – Cd and NiMH batteries.

– **Lithium ion** (Li – ion): Continuing in the tradition of modern battery chemistries, the lithium – ion battery has an increased energy density and can provide a respectable amount of current. High discharge rates don't significantly reduce its capacity nor does it lose very much capacity after each cycle, still retaining 80% of its energy capacity after 500 recharge cycles. This is a volatile technology, early versions were prone to exploding in the labs. It is the vitality nature of lithium that gives this battery its punch, though. These benefit come with a price, of course.

– **Fuel Cells**: The fuel cell isn't so much a battery as it is a catalytic chemical engine that creates electricity from hydrogen and oxygen. The fuel is typically a variation of hydrogen, such as the hydrocarbon fuels methanol, natural gas, or even gasoline. The output of the fuel cell is electricity and water. (Fig. 2.4).

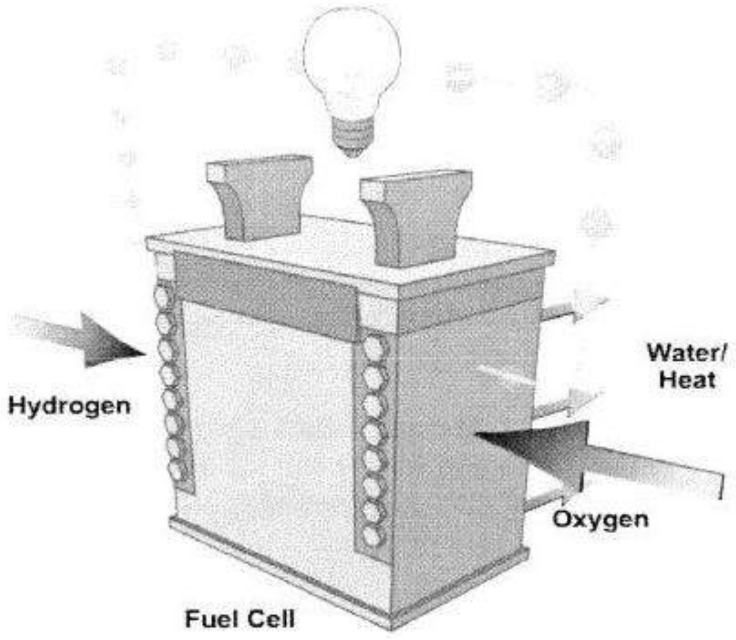


Fig.2.4. Fuel Cell

2.3. Secondary Wet Cells

Secondary cells are sometimes known as wet cells. There are four basic type of wet cells, the lead – acid, nickel – cadmium, silver – zinc, and silver – cadmium.

Lead – Acid Cell is the most widely used secondary cell. The previous explanation of the secondary cell describes exactly the manner in which, the lead – acid cell provides electric power. The discharging and charging action presented in electrochemical action describes the lead – acid cell.

The lead – acid secondary cell used in a storage battery consist of positive plates filled with lead peroxide (PbO_2); negative plates filled with pure spongy lead (Pb); and an electrolyte consisting of a mixture of 30 percent sulfuric acid and 70 percent water, by volume (H_2SO_4).

The chemical action takes place when a battery is delivering current. The sulfuric acid in the electrolyte breaks up into hydrogen ions (H_2) carrying a positive charge and sulfate ions (SO_4) carrying a negative charge. The (SO_4) ions combine with the lead plate and form lead sulfate ($PbSO_4$). At the same time, they give up their negative charge, thus creating an excess of electrons on the negative plate.

The H_2 ions go to the positive plate and combine with the oxygen of the lead peroxide (PbO_2), forming water (H_2O), and during the process they take electrons from the positive plate. The lead of the lead peroxide combines with some of the (SO_4) ions to form lead sulfate on the positive plate. The result of this action is that the positive plate has a deficiency of electrons and the negative plate has an excess of electrons.

When the plates are connected together externally by a conductor, the electrons from the negative plate flow to the positive plate. This process will continue until both plates are coated with lead sulfate and further chemical action is possible. The battery sulfate is highly resistant to flow of current, and it is chiefly this formation of lead sulfate that gradually lowers the capacity of the battery until it is discharges.

During the charging process current is passed through storage battery in a reverse direction. A do supply is applied to the battery with the positive pole connected to the positive plate of the battery and the negative pole connected to the negative plate. The voltage of the source is greater than the voltage of the battery. This causes the current to flow in the direction to charge the battery. The (SO_4) ions driven back into solution in the electrolyte, where they combine with the H_2 ions of the water, thus forming sulfuric acid. The plates then return to their original composition of lead peroxide and spongy lead. When this process is completed the battery is charged.

Nickel-Cadmium (Ni - Cd) electric cells have been developed to a degree of efficiency and dependability. They are used in small devices that formerly used carbon-zinc dry cells and in other devices where carbon-zinc cells cannot meet the load requirements. They are also being manufactured in large sizes for use in aircraft where large load requirements are present. Ni - Cd cells are made with various electrode designs, but the active elements remain the same.

In a charged state, the negative electrode consists of metallic cadmium (Cd), and the positive electrode is nickel ox hydroxide (NiOOH). During discharge the electrodes alter chemical composition.

The most common electrode designs for nickel-cadmium cells consist of perforated steels pockets to hold the active materials or perforated nickel plates or woven nickel screens into which the active materials are impregnated by sintering.

In the case of nickel-cadmium electrodes, the sintered material is nickel or nickel-carbon for the positive plates and cadmium for the negative plates.

An advantage of nickel-cadmium secondary cell is that it can stand in a discharged condition indefinitely at normal temperatures without deterioration. If a lead-acid battery is left in discharged condition for a substantial period of time sulfation of the plates occurs, and the cells lose much of their capacity.

During the discharge of a nickel-cadmium cell, electrons are released in the negative material as chemical change takes place. These electrons flow through the outer electric circuit and return to the positive electrode. Positive ions in the electrolyte remove the electrons from the positive electrode. During charge, the reverse action takes place, and the negative electrode is restored to a metallic cadmium slate.

Nickel-cadmium cells generate gas during the latter part of a charge cycle and during overcharge. Hydrogen is formed at the negative electrode, and oxygen is formed at the positive electrode. In vented-type batteries, the hydrogen and oxygen generated during overcharge are released to the atmosphere together with some electrolyte fumes. In a sealed dry cell, it is necessary to provide a means for absorbing the gases. This is accomplished by designing the cadmium electrode with excess capacity. This makes it possible for the positive electrode to become fully charged before the negative electrode. When this occurs oxygen is released at the positive electrode, while hydrogen cannot yet be generated because the negative electrode is not fully charged. The cell is so designed that the oxygen can travel to the negative electrode, where it reacts to form chemical equivalents of cadmium oxide. Thus when a cell is subject to overcharge, the cadmium electrode oxidized at the rate just sufficient to offset input energy, and the cell is kept at equilibrium at full charge.

If a cell is charged at the recommended rate, overcharging can occur for as long as 200 or 300 charge cycles without damage to the cell. If the charge rate is too high, the oxygen pressure in the cell can become so great that it will rupture the seal. For this reason, charge rates must be carefully controlled.

The nickel – cadmium and lead – acid cells have capacities that are comparable at normal discharge rates, but at high discharge rates the nickel – cadmium cell can deliver a longer amount of power. In additional the nickel – cadmium cell can:

– be charged in a shorter time;

– stay idle longer in any state of charger and keep a full charge when stored for a longer period of time;

– be charged and discharged any appreciable damage;

– due to their superior capabilities, nickel – cadmium cells are being used extensively in many aircraft applications that require a cell with a high discharge rate.

The Silver – Zinc Cells is used extensively to power emergency equipment. This type of cells is relatively expensive and can be charged and discharged fewer times than other types of cells. When compared to the lead – acid or nickel – cadmium cells, these disadvantages are over – weighed, small size, and good electrical capacity of the silver – zinc cell.

The Silver – Cadmium Cell is fairly recent development for use in storage batteries. The silver – cadmium cell combines, some of the better features of the nickel – cadmium and silver – zinc cells. It has more than twice the shelf life of the silver – zinc cell and can be recharged many more times. These disadvantages of the silver – cadmium cell are high cost and low voltage production.

The electrolyte of the cell is potassium hydroxide and water as in the nickel – cadmium and silver – zinc cell. The anode is silver oxide as in silver – zinc cell and the cathode is cadmium hydroxide as in the Ni-Cd cell/ Different combinations of materials are used to form the electrolyte, cathode and anode of different cells. These combinations provide the cells with different qualities for many varied applications.

Open and Closed-Circuit Voltages

There are two different ways to measure the voltage of a battery or cell. Voltage measured when there is no load applied to the battery is called the **open-circuit voltage** (OCV). The voltage measured while a load is applied to the battery is called the **closed-circuit voltage** (CCV).

The OCV is always higher than the CCV because a battery can maintain a higher pressure (voltage) when there is no current flow leaving the battery.

The OCV of a fully charged aircraft battery may reach ***13.2 V***; however, when even a small load is applied, the CCV will measure near ***12 V***. This battery would typically be referred to as a ***12-V*** battery. The CCV of a battery is usually a function of the load applied and the state of the charge of that battery. If a battery is connected to a heavy load, the CCV will be lower than if that battery was connected to a light load. If a battery is near the total discharge, the CCV will be lower than if that same battery was fully charged.

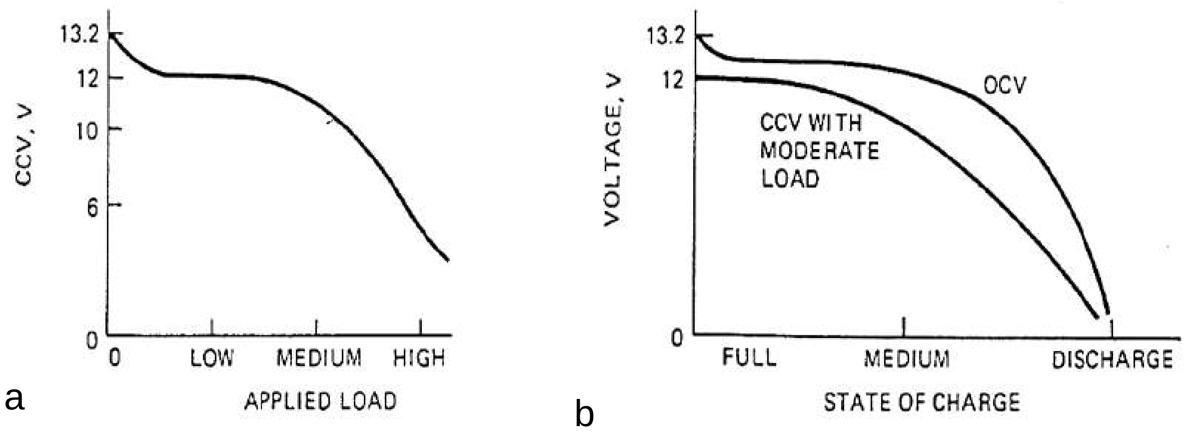


Fig. 2.5. The relationship between OCV and CCV for various loads:
a – closed-circuit voltage versus the applied load; b – open and closed-circuit voltage versus a battery state of charge

The OCV of a battery is typically affected very little by its state of charge until the battery reaches near complete discharge. Fig. 2.5 illustrates the relationships between OCV and CCV for various loads and battery states of charge.

Internal Resistance

The resistance present inside of a battery while connected to a load is called **internal resistance** (R_0). R_0 restricts the movement of current inside of any power source, including batteries. In the case of a battery, the R_0 is determined by the load applied and the battery state of charge.

A battery's R_0 is equal to the difference between the OCV and the CCV, divided by the applied load current I_l. That is $R_0 = \frac{V_{oc} - V_{cc}}{I_l}$. This equation is derived from Ohm's law. A battery internal resistance can be determined as follows. If the $V_{oc} = 14V$ and $V_{cc} = 12V$ with $I_l = 100\,A$, the R_0 is $0.02\,\Omega$. The calculation is

$$R_0 = \frac{V_{oc} - V_{cc}}{I_l} = \frac{14 - 12}{100} = 0.02\,\Omega.$$

A battery internal resistance always becomes greater as the battery becomes discharged. This is due to the lowering of a battery CCV as the battery becomes weaker. The OCV remains nearly constant while the CCV drops; therefore, the difference between these two voltages increases. Hence R_0 increases.

The R_0 of a battery becomes very significant when a power source is chosen or a delicate circuit is designed. However, for general-purpose applications, a battery internal resistance will not adversely affect an aircraft electrical system until that battery becomes over percent discharged. When the battery reaches this low state of charge, its internal resistance becomes too high and the CCV lowers. This CCV obviously affects circuit performance.

Capacity and Rating of Batteries

The capacity of a battery is measured in ampere-hours. The ampere-hours capacity is equal to the product of the current in amperes and the time in hours during which the battery will supply this current. The ampere-hour capacity varies inversely
with the discharge current. For example, a 400 ampere-hour battery will deliver 400 amperes for 1 hour or 100 amperes for 4 hours.

Storage batteries are rated according to their rate of discharge and ampere-hour capacity. Most batteries are rated according to a 20-hour rate of discharge. That is, if a fully charged battery is completely discharged during a 20-hour period, it is discarged at the 20-hour rate. Thus, if a battery can deliver 20 amperes continuously for 20 hours, the battery has a rating of 400 ampere-hours. Therefore, the 20-hour rating is equal to the average current that a battery is capable of supplying without interruption for an interval of 20 hours. (Aircraft batteries are rated according to a 1-hour rate of discharge).

All standards batteries deliver 100 percent of their available capacity if discharged in 20 hours or more, but they will deliver less than their available capacity if discharged at a faster rate. The faster they discharge, the less ampere-hour capacity they have.

The low-voltage limit as specified by the manufacturer, is the limit beyond which very little useful energy can be obtained from a battery. This low-voltage limit is normally a test used in battery shops to the determine the condition of a battery.

2.4. Lead-Acid Storage Batteries

A **storage battery** is the name for a battery of secondary cells and particularly for lead-acid and nickel-cadmium batteries. Two types of **lead-acid** batteries currently being used in aviation are the **vented cell** (1) and the **sealed (recombinant gas)** (2) battery (Fig. 2.6).

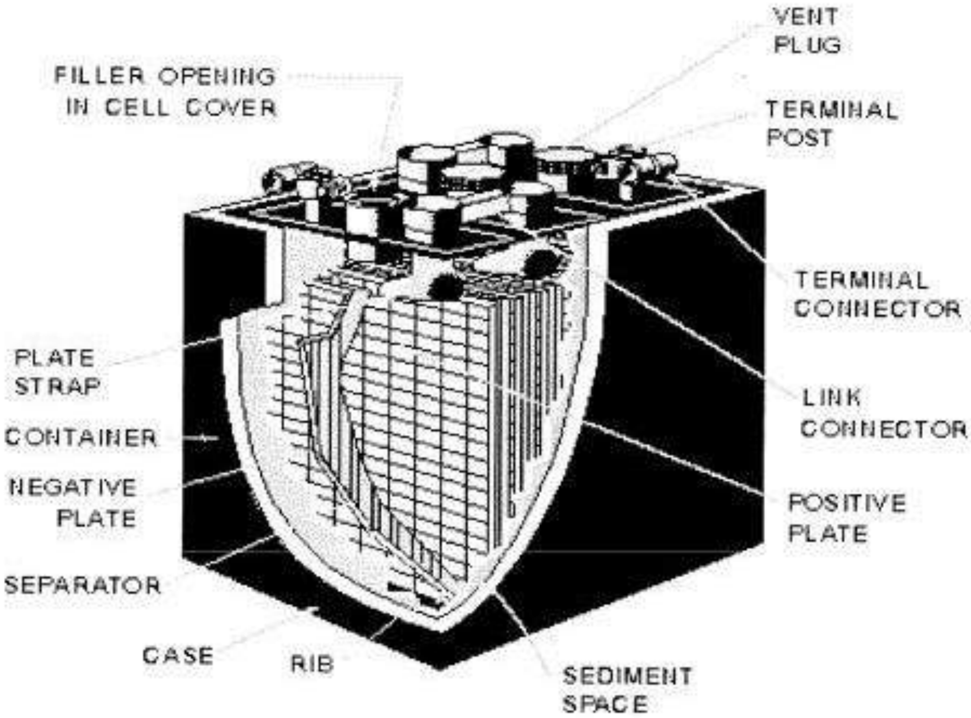


Fig. 2.6. A sealed lead-acid aircraft battery construction

The modern sealed-cell lead-acid batteries are more powerful and require less maintenance than the older vented lead-acid aircraft batteries. For this reason, lead-acid batteries are being used to replace the more expensive nickel-cadmium battery in some turbine-powered aircraft. On turbine-powered aircraft, however, the installation of lead-acid batteries typically requires that external power be readily available for engine starting and the lead-acid batteries require more frequent replacement. Despite the great strides made to improve lead-acid batteries, they are still unable to deliver the current generated by nickel-cadmium batteries; therefore, nickel-cadmium batteries will remain a practical power source for aircraft.

Lead-Acid secondary cells consist of lead-compound plates immersed in a solution of sulfuric acid and water, which is the **electrolyte**. Each cell has an OCV of approximately ***2.1 V*** when fully charged. When connected to a substantial load, the voltage is approximately ***2 V***. Aircraft storage batteries of the lead-acid type are generally rated at ***12*** or ***24 V***; that is, they have either 6 or 12 cells in series.

Schematic diagrams of cells connected in series and parallel are shown in Fig. 2.7.

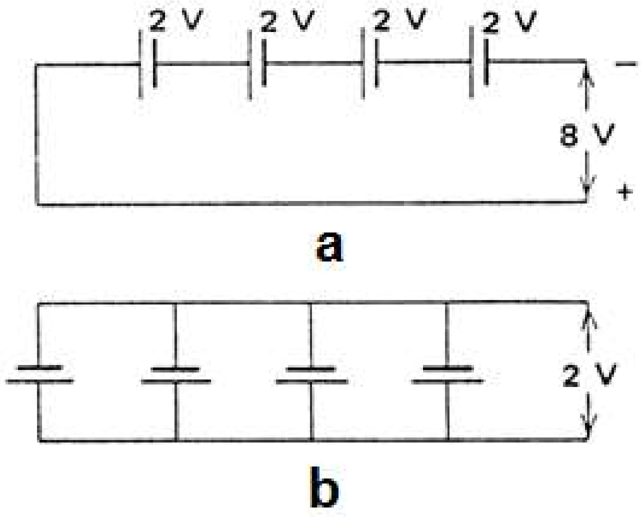


Fig. 2.7. Series (a) and parallel (b) cell connections

In the diagram four ***2-V*** cells are connected in series to produce ***8 V***. If the same four cells are connected in parallel, as shown in Fig. 2.7 (b), the total voltage is the same as that of one cell; however, the capacity of the group, in amperes, is four times the capacity of a single cell. To increase both voltage and the amperage by combining single cells, the cells are connected in a series-parallel circuit like that shown in Fig. 2.8

When 16 cells are connected in this manner the voltage is four times as great as that of a single cell, and the current capacity of the combined cells is four times as great as that of a single cell.

Storage batteries are convenient for aircraft use because their weight is not excessive for the power developed, and they can be kept in a nearly fully charged state by means of an engine-driven DC alternator. It must be remembered that the aircraft storage battery is used only when sources of electric power are not available.

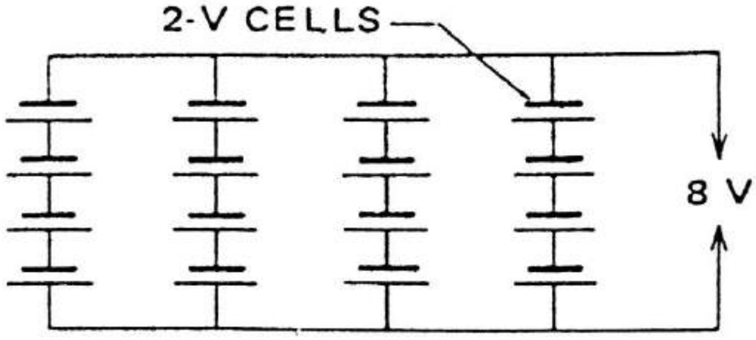


Fig. 2.8. Series-parallel cell connection

On light aircraft, the battery is used during initial engine starting, for intermittent load that exceeds alternator output, and in emergency situations (alternator failure).

Large turbine-powered aircraft typically use the storage battery only for emergency power; any current required for starting the engines is supplied by a separate ground power unit. The storage battery on most commercial jets would supply approximately 30 minutes of emergency power in the case of complete alternator system failure.

Lead-Acid Battery Construction

A storage battery consists of a group of lead-acid cells connected in series and arranged somewhat as shown in Fig. 2.9. Under moderate load the closed circuit voltage (CCV) of the 6-cell battery is approximately 12 V and that of a 12-cell battery is about 24 V. As stated earlier, CCV is the voltage of the battery when connected to a load.

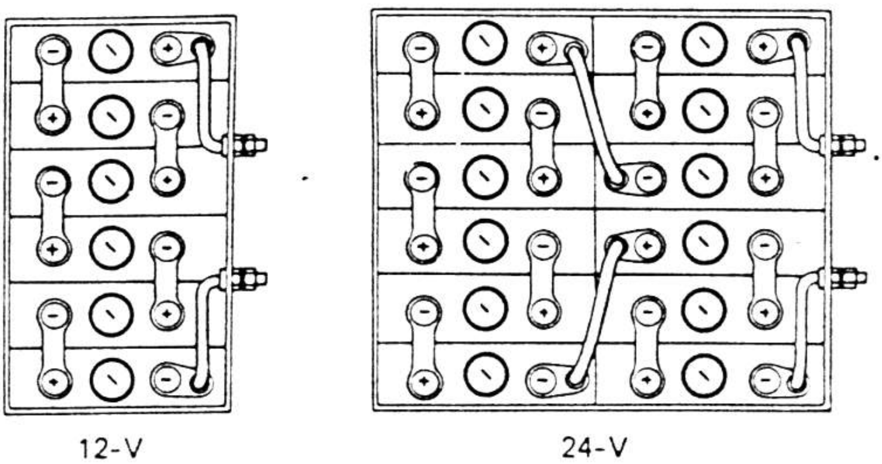
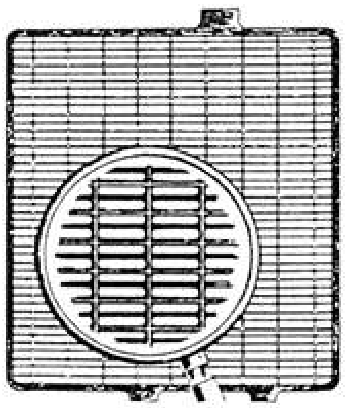


Fig. 2.9. Arrangement of cells in a lead-acid storage battery

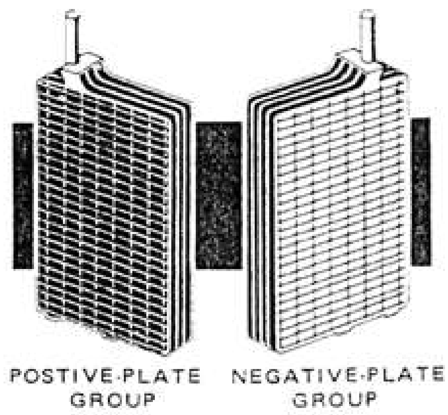
Each cell of a storage battery has positive and negative plates arranged alternately and insulated from each other by **separators**. Each plate consists of a framework, called the **grid**, and the **active material** held in the grid. A standard formula for the grid material is 90 percent lead and 10 percent antimony. The purpose of the antimony is to harden the lead and make it less susceptible to the chemical action. Other metals, such as silver, are also used in some grids to increase their durability.

A typical grid is illustrated in Fig. 2.10, a.

The plates are made by applying a lead compound to the grid. The paste is mixed to the proper consistency with diluted sulfuric acid, magnesium sulfate, or ammonium sulfate and is applied to the grid in much the same manner as plaster is applied to lath wall. The paste for the positive plates is usually made of red lead (Pb_3O_4) and a small amount of litharge (PbO). In the case of the negative plates, the mixture is essentially litharge with a small percentage of red lead. The consistency of the various materials and the manner of combining them have considerable bearing of the capacity and life of the finished battery.



a



b

Fig. 2.10. Lead-Acid cell plate group:
a – grid for a lead-acid cell plate; b – plate groups

In compounding the negative-plate paste, a material called an **expander** is added. Its purpose is to prevent the loss of porosity of the negative material during the life of the battery. Without the use of an expander, the negative material contacts until it becomes quite dense, this limiting the chemical action to the immediate surface. Typical expanding materials are lampblack, barium sulfate, graphite, fine sawdust and ground carbon. Other materials, known as hardness and porosity agents, are sometimes used to give the positive plates desired characteristics for certain applications. This adds substantially to the active life of the battery.

After forming the plates are washed and dried. They are then ready to be assembled into **plate groups**.

Plate groups are made by joining a number of similar plates to a common terminal post (Fig. 2.10, b).

The number of plates in a group is determined by the capacity desired, inasmuch as capacity is determined by the amount (area) of active material exposed to the electrolyte.

Since increasing plate area will increase a battery’s capacity, many manufactures strive for the maximum in internal battery dimensions. However, for aircraft use, we typically strive for the smallest, lightest battery with a relatively high capacity.

A positive-plate and negative-plate groups meshed together with separators between the positive and negative plates constitute a **cell element**.

The **separators** used in lead-acid storage batteries are made of fiberglass, rubber, or other insulating materials. Their purpose is to keep the plates separated and thus prevent an internal short circuit. The material of the separators must be very porous so that it will offer a minimum of resistance to the current passing through. And the separators must resist the chemical action of the electrolyte.

When the cell elements are assembled, they are placed in the **cell container**, which is made of hard rubber or a plastic composition. Cell containers are usually made in a unit with as many compartments as there are cells in the battery.

When a storage battery is on charge and approaching the full-charge point or is at the full-charge point, there is a liberal release of hydrogen and oxygen gases. It is necessary to provide a means whereby these gases can escape, and this is accomplished by placing a vent in the cell cap.

Although the majority of lead-acid storage battery are constructed with similar features there are many differences in size and detail design depending on use to which the battery is to be put.

There is a completely assembled metal-uncased battery for aircraft shown in Fig. 2.6.

A storage battery for light aircraft is made with a lightweight polystyrene case and is designed for use in an aircraft with an enclosed and ventilated battery compartment. The plates in this battery are **reinforced** with plastic fibers, and the positive plates are enclosed in micro porous pouches to provide plate separation and protection. The intercell connectors are internal and permanently sealed with an epoxy resin.

Battery Charging

Secondary cells are charged by passing a direct current through the battery in a direction opposite to that of discharge current. This means that the supply current's positive terminal must be connected to the battery's positive terminal and the negative connected to negative. Various methods of supplying the charge current are available. Onboard the aircraft, the generator or alternator will supply the charging current. Other ground-based charging equipment will convert common ***115-V*** AC. current into the DC voltage needed for battery charging. The two general types of charging equipment are **constant-current chargers** and **constant-voltage chargers**.

A constant-current battery chargers supply a consistent current to a battery for the entire charge cycle. The charging equipment monitors current flow and varies the applied voltage in order to charge the battery. As the battery begins to charge, its voltage is lower than when the battery becomes fully charged. The constant-current charger will increase its voltage supplied to the battery during charge in order to maintain the current flow set by the operator.

The proper connection of more than one battery to a constant-current charger in series connected with respect to each other and charger, thus allowing for a constant current to flow through each battery. Constant-current chargers require careful supervision while in use. Because of the risk of overcharging, most constant-current chargers will automatically turn off after a predetermined time. The exact current flow and time of charge must be known and programmed into the charging equipment to prevent over or undercharging of the batteries.

Constant-voltage chargers supply a constant voltage to the battery and allow current to change as the battery become charged. The constant-voltage charger supplies approximately ***14 V*** for charging 12-V batteries and ***28 V*** for charging ***24 V*** batteries. A higher potential at the charger is necessary to ensure the current to flow from the charger to the battery. If the battery is nearly discharged, it will offer very little opposition to the electrons flowing into the battery. As the battery becomes charged it will offer more resistance to the current supplied by the charger.

Since that charger supplies a constant voltage, a relatively high current will flow into a discharged battery and that current will slowly diminish as the battery becomes charged.

When the battery is fully charged its voltage will be almost equal to the charger voltage, hence the charging current will drop to less than ***1 A***. Because the current supplied to the battery drops to a very low value as the battery becomes charged, constant-voltage charging is usually considered the safest method of battery charging. A constant-voltage charger is, by far, the most common type of ground-based battery charger. A constant-voltage charger is also the type supplied by the aircraft generator system. If more than one battery is connected to a constant-voltage charger, all the batteries and the charger must be connected in parallel. This will ensure a constant voltage to each battery.

Voltage Rating

Storage batteries of all types are rated according to voltage and ampere-hour capacity. It has been pointed out that the voltage of a fully charged lead-acid cell is approximately 2.1 V when the cell is not connected to a load. A nickel-cadmium cell is rated at about 1.22 CCV.

Under a moderate load, the lead-acid cell will provide about 2 V. With an extremely heavy load, such as the operation of an engine starter, the voltage may drop to 1.6 A. A lead-acid cell that is partially discharged has a higher internal resistance than a fully charged cell. Hence it will have a higher voltage drop under the same load. This internal resistance is partially due to the accumulation of lead sulfate in the plates. The lead sulfate reduces the amount of active material exposed to the electrolyte. Hence it deters the chemical action and interferes with the current flow.

Fig. 2.11 shows the discharge characteristics of a typical aircraft lead-acid cell.

The OCV remains almost at ***2.1 V*** until the cell is discharged. It then drops rapidly to zero. The CCV gradually decreases from 2 to approximately ***1.8 V*** as the cells discharge. Again, the voltage drops rapidly when the cell nears discharge.

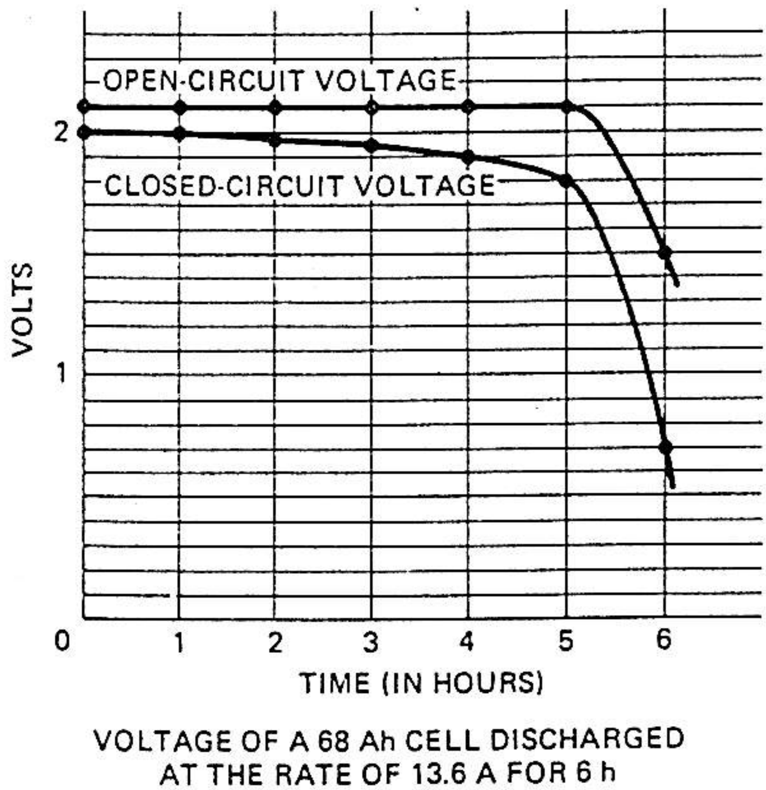


Fig. 2.11. Discharge characteristics of a lead-acid cell

Even though battery cells vary considerably in voltage under various conditions, batteries are nominally rated as ***6 V*** (3 cells), ***12 V*** (6 cells), and ***24 V*** (12 cells). In replacing a battery, the technician must ensure that the replacement battery is of the correct voltage rating.

Power Rating

As stated above under “Battery Ratings”, most storage batteries are rated in ampere-hour at a 5-h discharge rate. This means that the battery was discharged to 0 V in 5h to determine its capacity. Most 12-V batteries used for single-engine aircraft have a capacity rating between 25 and 35 Ah; however, larger capacities are available.

A direct comparison of ampere-hours alone does not indicate a battery, total power output. To determine total power, the battery voltage must be conside red, because power (wattage) is the product of voltage and amperage.

If the power desired for a specific job is not available in a single battery, often two or more batteries are connected in parallel. Connecting batteries in parallel will increase the available amperage capacity and maintain a constant voltage.

Battery Load Tester

There are various automatic **battery testers**. This machine will test not only batteries, but also the aircraft's charging system if so desired. While automatic battery load test is being performed, the load applied for ***15*** s, and the **open-circuit voltage** (OCV) and **closed-circuit voltage** (CCV) are automatically compared. The OCV is the voltage of the battery with no load applied; the CCV is the measure of battery voltage while the battery is under load.

Discharged batteries must be charged prior to testing. The high-rate discharge battery capacity test is probably the most common and practical test used. This test is designed to simulate the load typically placed on the battery during an engine start. This load can reach several hundred amps for a few minutes, definitely, the most strenuous time for any battery.

To simulate a starting load, the test equipment is connected to the battery in parallel. Then the operator applies a load approximately two or three times the battery ampere-hour rating. If the CCV is still low, the battery is defective. If the CCV remains high after the recharge, the battery is probably airworthy.

For aircraft lead-acid batteries, it is typical to use a hydrometer-test to determine the batteries' state of charge. A **hydrometer** is a tool used to measure the specific gravity or density, of a liquid. The **specific gravity** of a substance is defined as the **ratio of the weight of a given volume of that substance to the weight of an equal volume of pure water at *+4°C***. The specific gravity is taken at the fluid level on the stem of the hydrometer when it is floating freely in the electrolyte. When a battery is tested with a hydrometer, the temperature of the electrolyte must be taken into consideration because the specific gravity readings on the hydrometer will vary from the true specific gravity as the temperature goes above or below ***80°F*** (***26,7°C***). A higher or lower temperatures it is necessary to apply a correction. Some hydrometers are equipped with a correction scale inside the tube; the temperature correction then can be applied as the hydrometer reading is taken.

2.5. Nickel-Cadmium Storage Batteries

Aircraft nickel-cadmium storage batteries are constructed of wet cells. One advantage of the nickel-cadmium cell is that it contains a greater power-to-weight ratio than a lead-acid battery. Also, the CCV of a nickel-cadmium (Ni-Cd) battery remains nearly constant during the entire discharge cycle. Ni-Cd batteries are much more costly than a typical lead-acid battery and therefore they are usually found on turbine-powered aircraft. The extra capacity available from a Ni-Cd battery will help prevent a hot start of turbine engine, and thus the extra cost is justified.

Cell and Battery Construction

The Ni-Cd cell is a vented cell similar to that of a lead-acid battery. The cells are placed in an insulated metal or plastic case in proper order and then connected in series by the cell conductors. The end cells may be connected to external posts or to a quick-disconnect unit. A complete battery is illustrated in Fig. 2.12

The vents of each cell are required in case the battery becomes overcharged. Only at this time does a NC cell emit gas.

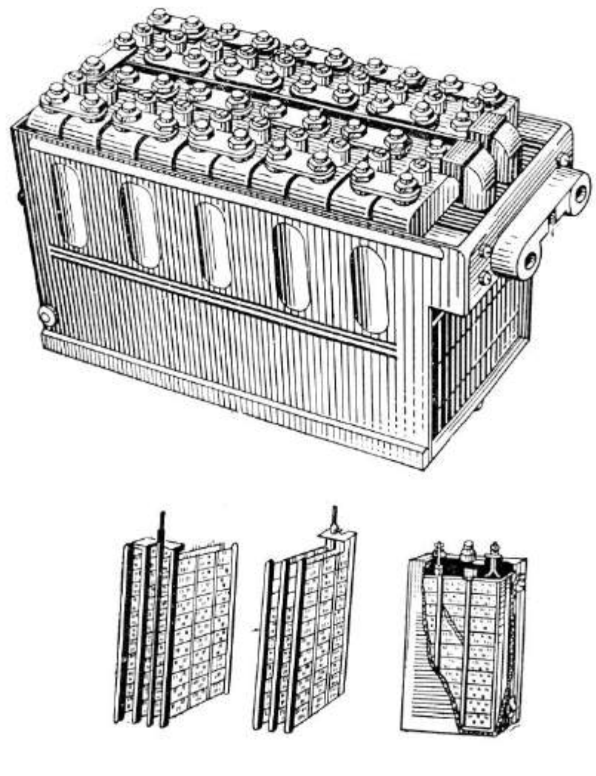


Fig. 2.12. Nickel-cadmium aircraft battery

The vents of each cell are required in case the battery becomes overcharged. Only at this time does a NC cell emit gas.

Each cell of the battery consists of negative and positive plates, separators, electrolyte, cell container, cell cover, and vent cap. A Ni-Cd cell components are shown in Fig. 2.13.

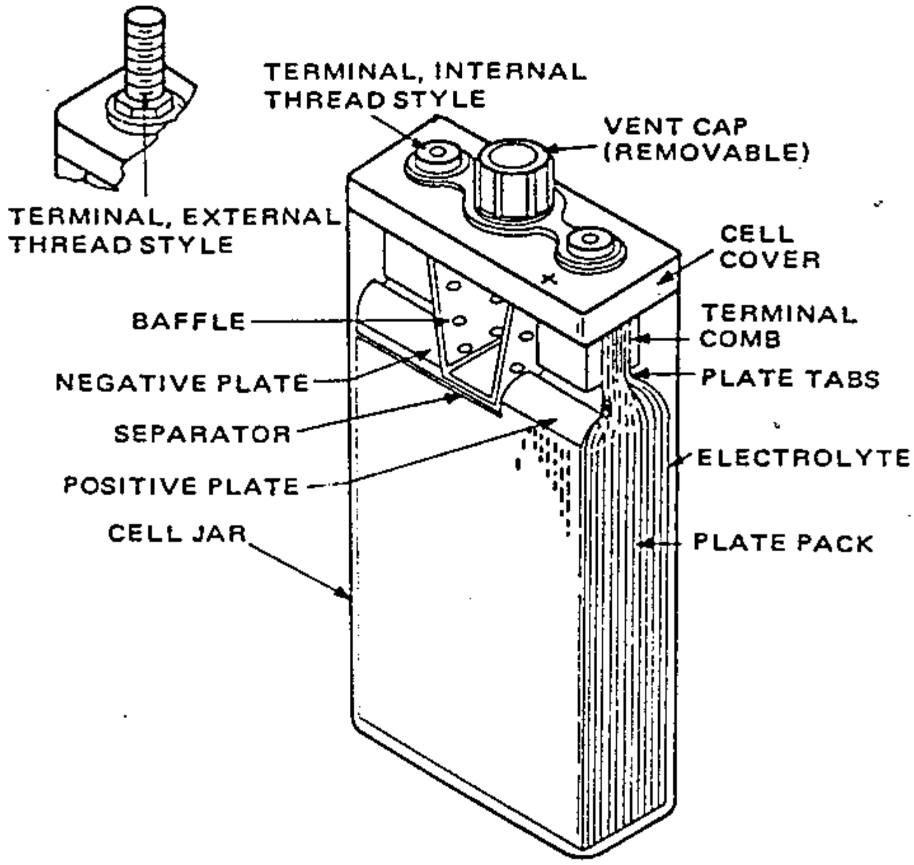


Fig. 2.13. Nickel-cadmium cell components

The plates are made from sintered metal plaques impregnated with the active materials for the negative and positive plates. The porous plaque is impregnated with nickel salts to make the positive plates and cadmium salts to make the negative plates. After the plaques have absorbed sufficient active material to provide the desired capacity, they are placed in an electrolyte and subjected to an electric current which converts the nickel and cadmium salts to the final form.

A nickel tab is welded to a corner of each plate and is the means by which the plates are joined into plate groups.

The separator in a Ni-Cd cell is a thin, porous multilaminate of woven nylon with a layer of cellophane. The separator serves to prevent contact between the negative and positive plates.

The electrolyte for a Ni-Cd battery is a solution of 70 percent distilled water and 30 percent potassium hydroxide, which gives a specific gravity of 1.3.

Specific gravities for Ni-Cd batteries may range between 1.24 and 1.32 without appreciably affecting the battery operation. **The electrolyte** in a Ni-Cd battery does not enter into the charge-discharge reaction; this is the reason you cannot determine a NC battery state of charge by testing the electrolyte specific gravity with a hydrometer.

The cell container consists of a plastic cell jar and a matching cover which are permanently joined at assembly.

The cells are assembled into a battery container and connected together with stainless conductor links. Usually, 19 or 20 cells (depending on the total voltage required) are assembled into a battery with the correct polarity so that each cell is in series.

Principles of Operation

The advantage of a Ni-Cd battery is that the active materials of the cell plates change in oxidation state only, not physical state. This means that the active material is not dissolved by the electrolyte of potassium hydroxide. As a result the cells are very stable even under a heavy load, and the chemicals last a long time before the battery requires replacement.

As previously explained the active material of the negative plate of a charged Ni-Cd cell is of metallic cadmium (Cd), and the active material of the positive plate is nickel ox hydroxide (NiOOH). As the battery discharges, hydroxide ions (OH) from the electrolyte combine with the cadmium in the negative plates and electrons are released to the plates. The cadmium is converted into cadmium hydroxide [$Cd(OH)_2$] during the process. At the same time, hydroxide ions from the nickel ox hydroxide positive plates go into the electrolyte, carrying extra electrons with them. Thus electrons are removed from the positive plates and delivered to the negative plates during discharge. The composition of the electrolyte remains a solution of potassium hydroxide because hydroxide ions are added to the electrolyte as rapidly as they are removed. For this reason the specific gravity of the electrolyte remains essentially constant at any state of discharge.

When a NC battery is being charged, the hydroxide ions are forced to leave the negative plate and enter the electrolyte. Thus the cadmium hydroxide of the negative plate is converted back into metallic cadmium. Hydroxide ions from the electrolyte recombine with the nickel hydroxide of the positive plates and the active material is brought to a higher state of oxidization called nickel ox hydroxide.

This process continues until all the active material of the plates has been converted.

The separator acts as an electrical insulator and a gas barrier between the negative and positive plates.

Voltage Rating

The OCV of ***1.28 V*** is consistent for all Ni-Cd vented cells, regardless of the cell size. The OCV does vary slightly with temperature and elapsed time since the battery's last charge. Immediately after charge, the OCV may reach ***1.40 V***; however, it soon lowers to between ***1.35*** and ***1.28 V***. A 20-cell Ni-Cd battery would, therefore, have an OCV between 25.6 and 27 V. Near the end of the charge cycle, the same battery may reach ***28.5 V*** if the charging current is still applied. This voltage diminishes quickly after the battery is removed from the charger and will soon reach near ***25 V***.

The CCV of a vented-cell Ni-Cd battery ranges between ***1.1*** and ***1.25 V***. This voltage will vary depending on the battery temperature, the length of time since the battery's last charge, and the discharge current applied. The CCV of a Ni-Cd cell remains nearly constant under moderate load until the cell is near the completely discharged state. Fig. 2.14 illustrates the CCV of a Ni-Cd cell.

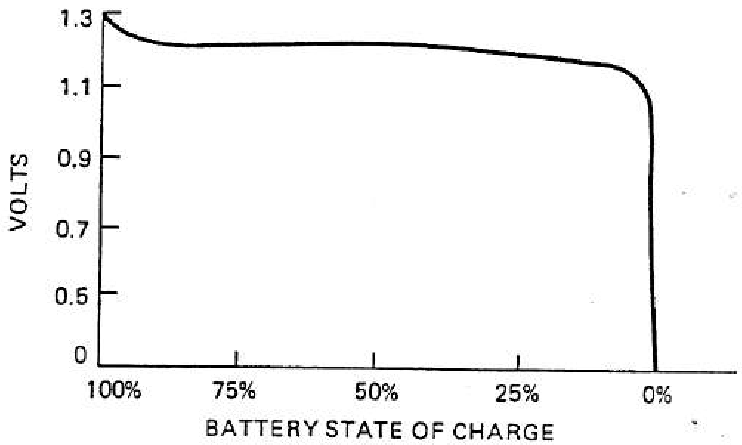


Fig. 2.14. Typical discharge voltage curve under moderate load

Capacity and Internal Resistance

A Ni-Cd battery has tremendous peak power and delivers far more power than a lead-acid battery of the same size and weight. The large amount of instantly available power produced by a Ni-Cd battery is why it is so well suited for starting turbine engines. The capacity of a Ni-Cd battery is a function of the total plate area contained inside the cells (more plate area, more capacity). Most Ni-Cd batteries are designed for 24-V systems with a capacity between 22 and 80 Ah. The ampere-hour rating is determined at a 5-h discharge rate unless otherwise denoted.

The capacitance of any battery is partially a function of that battery's internal resistance. The internal resistance of most vented Ni-Cd cells is very low (less than 1mΩ per cell), which allows these cells to maintain a high discharge current and still maintain acceptable voltage levels. The low internal resistance of a Ni-Cd battery allows it to recharge very rapidly. This resistance in part results from the large surface area of active materials made available through the use of a highly porous plate.

The output of a Ni-Cd battery is relatively constant, even in harsh operating conditions such as very cold weather. The optimum temperature range is between **+15ºC** and **+33°C**.

Also the nickel – cadmium battery has become the preferred type in today's aircraft5, there are also the nickel – iron and silver – zinc types of alkaline cell. Silver – zinc rechargeable batteries have been used in the space programmer, where size and weight factors greatly outweigh initial cost. The capacity of each cell is added together to obtain the total capacity. In effect the area of the plates has been increased. The voltage, on the other hand, does not increased

Nickel - Cadmium Battery. Maintenance. Procedures

The Ni-Cd storage battery requires specific maintenance procedures; always follow the battery manufactures recommendations during service. Every battery should have its own specific maintenance record. This will aid in the isolation of defects and will help to ensure optimum battery performance.

Every aircraft maintenance schedule will specify **a battery inspection period**. This schedule should not exceed 50 flight hours for a new batteries to ensure proper battery and aircraft compatibility and operation. After a few months, the inspection periods can be lengthened.

The reconditioning of Ni-Cd aircraft batteries is usually performed between 100 and 300 flight hours. The exact reconditioning time period depends mainly on the aircraft starting procedures, operating temperatures, and generator voltage regulator setting.

Reconditioning of the battery is necessary to prevent any **cell imbalance**, which may result in a temporary loss of battery capacity. Cell imbalances occur during recharging by an aircraft constant potential charging system.

The typical reconditioning procedures include a battery inspection as previously stated, a battery discharge disassembly, and cleaning or repairing as needed. Finally, the battery is reassembled and recharged. To correct a cell imbalance during reconditioning the battery is typically discharged to zero capacity and then recharged. This process is often called a battery **deep cycle**.

If the battery is received in a charged condition, an **electrical leak check** should be performed. Prior to discharge, that test detects current leakage from the cells to the battery case. A leakage exceeding 50 mA measured from any positive cell connection to the case is usually excessive.

Just as with lead-acid batteries, a **constant-voltage charger** will supply a constant voltage to the battery during charging. The current supplied by this type of charger is high during the start of the charge cycle and lower as the battery reaches a fully charged state. The exact current flows will be a function of the capacity of the charger, temperature, and the battery's state of discharge. The correct voltage setting is very important when using a constant-voltage charger. The charging equipment must be set and regulated to ensure a complete battery charging without battery overcharging.

Constant-current charging of Ni-Cd batteries is recommended to ensure better cell balance and total battery charge, as well as to prevent the possibility of thermal runaway. However, constant-current charging typically requires a longer charging time and creates a greater water loss during overcharge than constant-voltage charging. Unlike lead-acid batteries, Ni-Cd batteries can be stored for a long period of time in a charged or discharged state without damage.

Installation of Aircraft Batteries

The battery compartment in an airplane should be easily accessible so that battery can be serviced and inspected regularly; it should also be isolated from fuel, oil and ignition systems and from any other substance or condition that could be detrimental to its operation. Any compartment used for a storage battery that emits gases at any time during operation must be provided with a ventilation system.

Be sure both the aircraft and battery connectors have the same polarity.

Also ensure that the new battery will have proper ventilation to remove any heat that may be produced during the battery use. Always check that the battery charging specifications and the aircraft charging system voltage coincide. The Ni-Cd battery must be charged at a specific voltage for proper operation.

The electric leads to a battery in an airplane must be large enough to carry any load imposed on the battery at any time. They must be thoroughly insulated and protected from vibration or chafing and are usually attached to the airplane structure by means of rubber-lined or plastic-lined clamps or clips. Battery cables must be securely attached to the battery terminals, which must be protected from accidental shorting by means of a terminal cover.

Quick-disconnect battery connectors are found on some lead-acid batteries and practically on all Ni-Cd batteries. The quick-disconnect consist of an adapter secured to the battery case in place of the terminal cover and a plug to which the battery leads are attached. Two smooth contact prongs are screwed onto the battery terminals, and the plug is pulled into place on battery by means of a large screw attached to a hand wheel. This screw also pushes the plug off the terminals to disconnect the battery.

2.6. Terms and Concepts

Ampere-hour capacity (Ah) is quantity of electricity that has passed through a circuit when a current of 1 A has flowed for 1 h.

Battery is a group of voltaic cells connected together in series to produce a desired voltage and current capacity.

Typical batteries utilize primary, secondary, and photovoltaic cells.

Cable is a group of insulated electric conductors usually covered with rubber or plastic to form a flexible transmission line.

Capacity is a battery or cell's total available current. Typically measured in ampere-hours for aircraft storage batteries.

Cell is a combination of two electrodes surrounded by an electrolyte for the purpose of producing voltage.

Electrolyte is any solution that conducts an electric current.

Lead-acid cell is a secondary cell that produces voltage using an acidic electrolyte and lead-compound electrodes.

Primary cell is a voltaic cell whose chemical action destroys some of the active elements in the cell, thus making it impossible or impractical to recharge the cell.

2.7. Control Questions

1. Briefly describe a voltaic cell.
2. What is the difference between a primary cell and a secondary cell?
3. What voltage is developed by a carbon-zinc cell?
4. What is a dry cell?
5. What electrolyte material is used in an alkaline cell?
6. What are the active materials in a nickel-cadmium cell?
7. What are active materials in a lead-acid storage cell?
8. Describe the construction of a lead-acid storage cell.
9. Describe a plate group.
10. What electrolyte is used in a lead-acid storage cell?
11. What materials are used for separators?
12. How are aircraft storage batteries constructed to provide the elimination of explosive gases?
13. What determines the voltage of aircraft storage batteries?
14. What rating is used to describe aircraft storage batteries?
15. What is buttery efficiency? In how many ways battery efficiency is expressed?
16. How battery capacity is defined? On which factors it depends?
17. If a storage cell delivers 20 A for 5 h, what will the ampere-hour rating be?
18. What occurs with respect to ampere-hour rating when the discharge rate is increased above that used to establish the rating?
19. What is the most common method for determining the state of charge of a lead-acid battery?
20. Give the specific gravity range for a lead-acid cell.
21. Explain the difference between constant-voltage charging and constant-current charging.
22. What electrolyte is used in NC batteries?
23. What are the plate materials and electrolyte used in a Ni-Cd battery?

Chapter 3

AIRCRAFT GENERATORS OF A DIRECT CURRENT

3.1. Primary Sources of Electrical Energy

The process of obtaining electrical energy from other types of energy is referred to as generation of the electric power. Generators that are devices for conversion of mechanical energy into electrical energy are the most widely used as **the primary energy sources**. Aircraft engines of the modern aircraft as well as special (auxiliary) engines are used as the sources of mechanical energy. The engines cause the generators to rotate and they form the airboard electric station complex.

Facilities used for deriving the electrical energy from chemical energy are called chemical sources of current. Such sources are defined as accumulators. Aircraft accumulators are referred to as **secondary sources of electrical energy** as they require the continuous additional charging from other sources. Alternating and direct current generators as well as starter-generators on aeroplanes and helicopters are referred to as primary sources of electrical energy.

The generator operation is based on the principle of electromagnetic induction. This principle consists in emergence of e.m.f. in the armature windings when these windings cross the magnetic field of the inductor (stator). This field is developed in the generator poles when the direct current passes through the windings of the excitation coil. In self-excited generators these windings are fed by the current worked out by the generator itself.

Starters-generators perform two functions:

- they provide the aircraft electric network with high-quality energy,
- they start the turbojet and turboprop aircraft engines.

The operation of starter-generator at the aircraft engine-starting regime is programmed by special engine-starting equipment.

The airborne generators operate under the conditions of high mechanical, electrical and thermal loads. However, their weight is 10 times smaller compared with the ground generators. It is achieved by means of the following measures:

1) increase of rotational speed of the generator armature;
2) application of special structural and electrotechnical materials in the process of their manufacture;
3) improvement of cooling conditions.

The generator is usually cooled by expulsion of internal cavities by in-taking air. The air is forced through a ventilator mounted on an armature shaft.

3.2. Structure of the DC Aircraft Generator

For airplanes equipped with DC electrical systems, the DC generator is the regular source of electrical energy. One or more DC generators, driven by the engine, supply electrical energy for the operation of all units in the electrical system, as well as energy for charging the battery. The number of generators used is determined by the power requirement of a particular airplane.

Aircraft DC generators have for the most part been replaced by AC generators (alternators) on modern aircraft. However, there are still several DC generators currently in operation on older aircraft or the other DC generators are used on smaller light aircraft.

The typical representatives of direct current generation are the generators of a ГСР (generator aircraft expended) type. The generators of this type have the extended range of rotational speeds. The basic characteristics of generators are given in table 3.1.

Table 3.1. Basic characteristics of ГСР type generators

Type of the generator	Nominal values			Rotational speed, thousand rev/min	Efficiency
	Power, kW	Voltage, V	Current, A		
ГСР -3000	3	28,5	100	4 … 9	0,74
ГСР -6000	6	28,5	200	4 … 9	0,76
ГСР -9000	9	28,5	300	4 … 9	0,76
ГСР -12000	12	28,5	600	4 … 9	0,77
СТГ-18000	18	28,5	600	4 … 9	0,79

To have a general idea of the generator structure, we shall show its simplified construction.

Construction Features of DC Generators

Generators used on aircraft may differ somewhat in design, since they are by various manufactures. All, however, are of the same general construction and operate similarly. The major parts, or assemblies of a DC generator are a field frame (or yoke), a rotating armature, and a brush assembly. The parts of a typical aircraft generator are shown in Fig. 3.1.

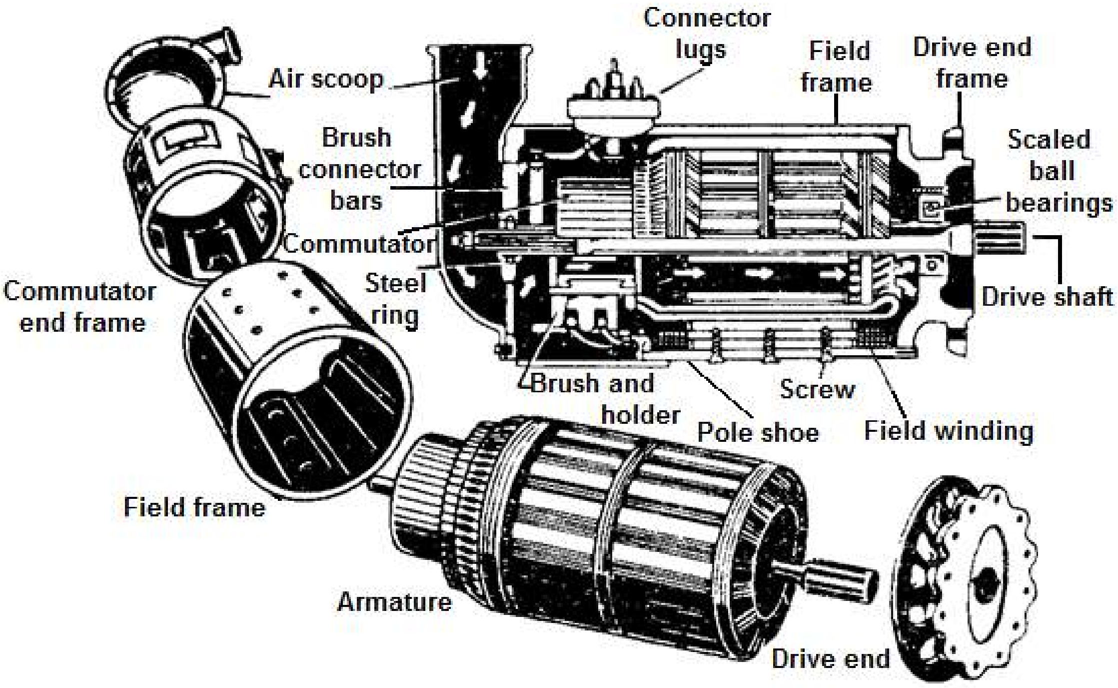


Fig. 3.1. A typical assembly of DC generator

The armature assembly consists of armature coils wound on an iron core, a commutator and associated mechanical parts mounted on a shaft. It rotates through the magnetic field produced by the field coils. The core of the armature acts as an iron conductor in the magnetic field and, for this reason; it is laminated to prevent the circulation of eddy currents.

An armature (Fig. 3.2) has coils placed in slots of the core, but there is no electrical connection between the coils and core. The use of slots increases the mechanical safety of the armature. Usually, the coils are held of place in the slots by means of wooden or fiber wedges.

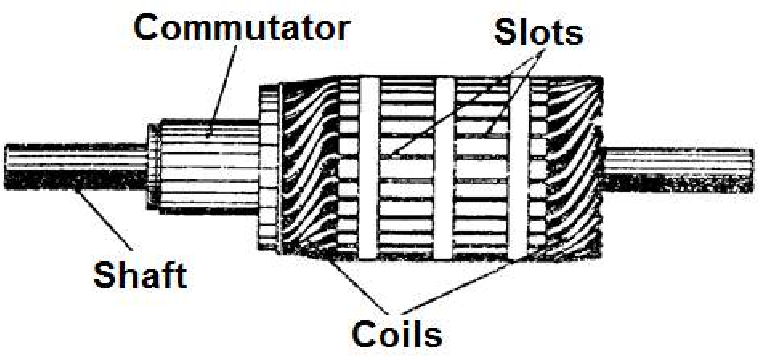


Fig. 3.2. The armature assembly

The connection of the individual coils, called coil ends, are brought out to individual segments on the commutator.

The armatures of all aircraft generators are supported in high efficiency ball or roller bearings, or in combinations of these two types. Where combinations are used in a single generator it will be found that the ball bearing is invariably fitted at the roller bearing at the commutator end. This arrangement permits lateral expansion of the armature shaft, arising from temperature increases in the generator, without exposing the bearings to risk of damage.

Field-frame assembly. The heavy iron or steel housing that supports the field poles is called the **field frame**, **field ring**, or **field housing**. It not only supports the field poles best but also forms a part of the magnetic circuit of the field. The shoes are held in place by large countersunk screws that pass through the housing and into the shoes.

Small generators usually have two or four poles mounted in the field-frame assembly and large generators can have as many as eight main poles and eight interpoles. The pole pieces are rectangular and in most instances are laminated. The main shunt field winding consists of many turns of comparatively small insulated copper wire. Series windings, such as those on the interpoles, consist of a few turns of insulated copper wire large enough to carry the entire load current without overheating. A typical field-frame assembly is shown in Fig. 3.3.

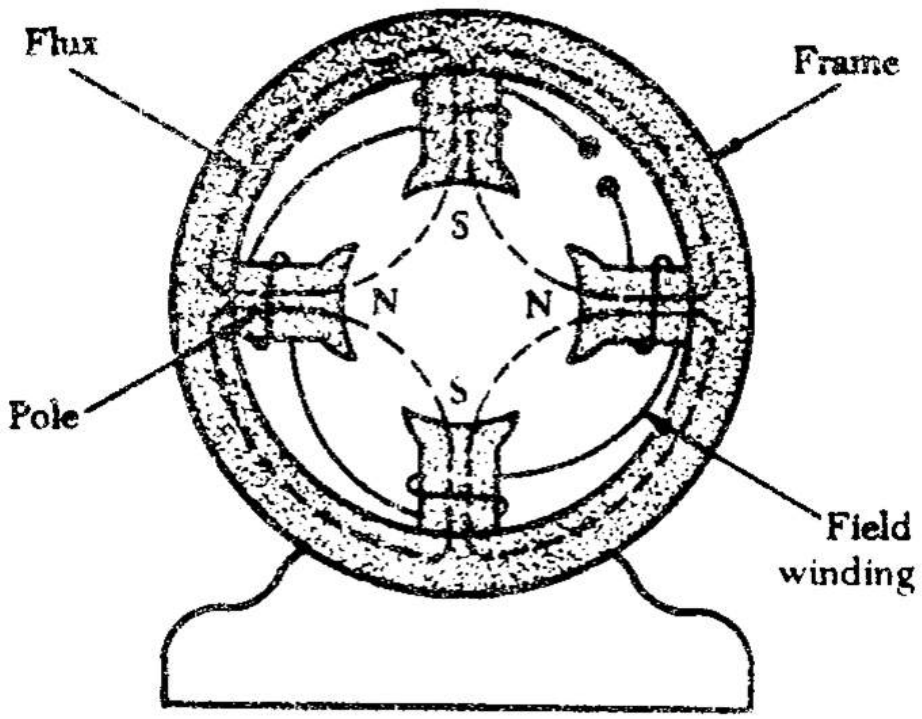


Fig. 3.3. Field-frame assembly

Interpoles and compensating windings. During operation on load, the current flowing though the armature winding of a generator creates a magnetic field, which is superimposed on the main field produced by field-winding current. Since lines of force cannot intersect the armature field distorts the main field by amount which varies with the load; such distorting effect is termed **armature reaction**.

If uncorrected armature reaction produces two additional undesirable effects:

a) it causes a shift of the magnetic neutral Axis, i.e. the axis passing through two points at which no EMF is induced in a coil, setting up reactive sparking at the commutator,

b) it weakens the main field causing a reduction in generated EMF.

The position of the brushes can be altered to minimize these effects under varying load conditions, but a more effective method is to provide additional windings in the electromagnet system, such windings being reffered to as interpole and compensating windings. Interpole windings are wound on narrow-faced auxiliary pole pieces located midway between the main poles, and are connected in series with the armature. The windings are such that an interpole has the same polarity as the next main pole in the direction of rotation, and as the fluxes are opposite in direction to the armature flux, they can be equalized at all loads by having the requisite number of turns. In order to provide true correction of armature reaction compensating windings are there for connected in series with the interpole and armature windings.

Brush rigging assembly is located at the commutator end of the generator. The brushes are small blocks of a carbon and graphite compound soft enough to give minimum commutator wear but sufficiently hard to provide long service. Special brushes have been designed for generators operating at extremely high altitudes. They are needed because arcing increases at high altitudes and will cause the rapid deterioration of ordinary brushes.

Cooling features. Since a generator operating at full capacity develops a large amount of heat, it is necessary to provide cooling. This is accomplished by means of passages leading through the generator housing between the field coils. In high-output generators there are also cooling air passages through the armature. Cooling air is forced through the passages either by a fan mounted on the generator shaft, or by pressure from a ram air duct leading into an air scoop mounted on the end of the generator or by bleed air from the compressor of a turbine engine. Openings are provided in the end frame opposite the fan or air fitting to allow the heated air to pass out of the generator housing.

3.3. Types of DC Generators

There are three types of DC generators: series-wound, shunt-wound, and shunt-series or compound wound.

The difference in type depends on the relationship of the field winding to the external circuit.

Series-Wound DC Generators

The field winding of a series generator is connected in series with the external circuit, called the load (Fig. 3.4). The field coils are composed of a few turns of large wire. The magnetic field strength depends more on the current flow rather than the number of turns in the coil. Series generators have very poor voltage regulation under changing load, since the greater the current through the field coils to the external circuit the greater the induced EMF and the greater the terminal or output voltage. Therefore, when the load is increased, the voltage increases; likewise, when the load is decreased, the voltage decreases. The output voltage of a series-wound generator may be controlled by a rheostat in parallel with the field winding.

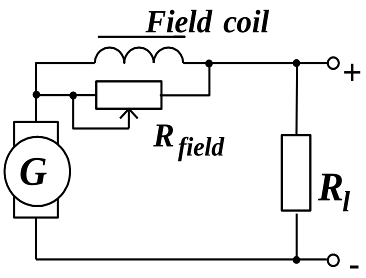


Fig. 3.4. Series-wound generator

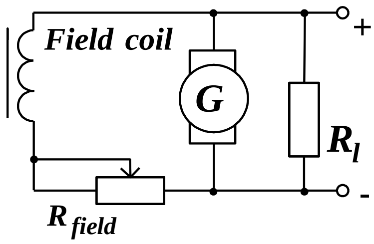


Fig. 3.5. Shunt-wound generator

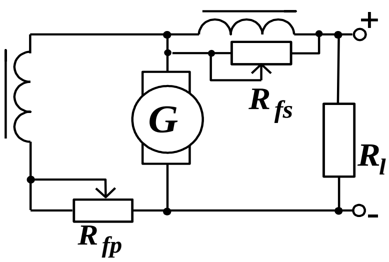


Fig. 3.6. Compound-wound generator

Since the series-wound generator has such poor regulation, it is never employed as an airplane generator. Generators in airplanes have field windings which are connected either in shunt or in compound (Fig. 3.5 and 3.6)

Shunt-Wound DC Generators

A generator having a field winding connected in parallel with the armature coil (with the external circuit) is called a shunt generator, as shown in Fig. 3.5. The field coils of a shunt generator contain many turns of small wire. The magnetic strength is derived from a large number of turns rather than the current strength through the coils. If a constant voltage is desired, the shunt-wound generator is not suitable for rapidly fluctuating loads. Any increase in load causes a decrease in the terminal or output voltage, and any decrease in load causes an increase in terminal voltage. Since the armature and the load are connected in series, all current flowing in the external circuit passes through the armature winding. Because of the resistance in the armature winding there is a voltage drop. As the load increases the armature current increases and $I_{arm}R_{arm}$ drop in the armature increases. The voltage delivered to the terminals is the difference between the induced voltage and the voltage drop; therefore, there is a decrease in terminal voltage. This decrease in voltage causes a decrease in field strength because the current in the field coils decreases in proportion to the decrease in terminal voltage; with a weaker field, the voltage further decreases.

When the load decreases, the output voltage increases accordingly, and a larger current flows in the windings. This action is cumulative, so the output voltage continues to rise to a point called field saturation, after which there is no further increase in output voltage.

The terminal voltage of a shunt generator can be controlled by means of a rheostat inserted in series with the field windings. As the resistance is increases, the field current is reduced; consequently, the generated voltage is also reduced. For a given setting of the field rheostat, the terminal voltage at the armature brushes will be approximately equal to the generated voltage minus the $I_{arm}R_{arm}$ produced by the load current in the armature; thus, the voltage at the terminals of the generator will drop as the load is applied. Certain voltage-sensitive devices are available which automatically adjust the field rheostat to compensate for variations in load. When these devices are used, the terminal voltage remains essentially constant.

Compound-Wound DC Generators

A compound-wound generator combines a series winding and a shunt winding in such way that the characteristics of each are used to advantage (Fig. 3.6). The series field coils are made of a relatively small number of turns of large cooper conductor, either circular or rectangular in cross section and are connected in series with the armature circuit. These coils are mounted on the same poles on which the shunt field coils are mounted and, therefore, contribute a magneto motive force which influxes the main field flux of the generator.

If the ampere-turns of the series field act in the same direction as those of the shunt field, the combined magneto motive force is equal to the sum of the series and shunt field components. Load is added to a compound generator in the same manner in which load is added to a shunt generator by increasing the number of parallel paths across the generator terminals. Thus the decrease in total load resistance which added load is total load resistance which added load is accompanied by an increase in armature-circuit and series-field circuit current.

The effect of the additive series field is that of increased field flux with increased load. The extent of the increased field flux depends on the degree of saturation of the field as determined by the shunt field current. Thus the terminal voltage of the generator may increase or decrease with load, depending on the influence of the series field coils. This influence is referred to as the degree of compounding.

A flat-compound generator is the one in which the no-load and full-load voltages have the same value. Whereas an under-compound generator has a full-load voltage less than the no-load value, and an over-compound generator has a full-load voltage which is higher than the no-load value. Changes in terminal voltage with increasing load depends upon the degree of compounding.

If the series field aids the shunt field, the generator is said to **be cumulative-compounded**.

If the series field opposes the shunt field, the machine is said to be **differentially compounded** or is called a differential generator.

Compound generators are usually designed to be over compounded. This feature permits varied degrees of compounding by connecting a variable shunt across the series field. Such a shunt is sometimes called a **diverter**. Compound generators are used where voltage regulation is of prime importance.

Differential generators have somewhat the same characteristics as series generators in that they are essentially constant-current generators. However, they generate rated voltage at no load, the voltage dropping materially as the load current increases. Constant current generators are ideally suited as power sources for electric arc welders and are used almost universally in electric arc welding.

If the shunt field of the compound generator is connected across both the armature and the series field, it is known as a **long-shunt connection**, but if the shunt field is connected across the armature alone, it is called a **short-shunt connection**. These connections produce essentially the same generator characteristics.

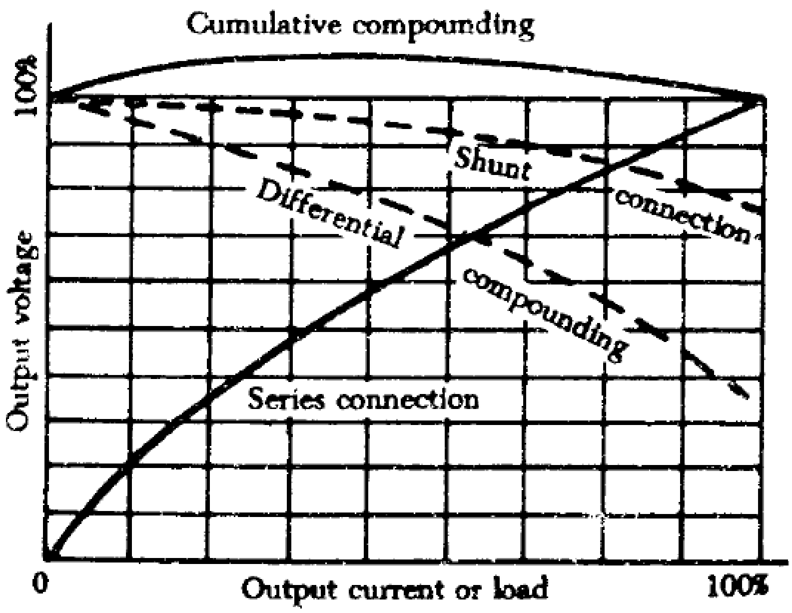


Fig. 3.7. Generator characteristics

A summary of the characteristics of the various types of generators discussed is shown graphically in Fig. 3.7.

3.4 Specific Features of DC Aircraft Generators

The operation of DC generators is determined by the following parameters: output voltage V, load current I_l, excitation current I_e, rotational speed n, temperature of its parts τ. The relation between these values for a specific generator may be written down in the form of the basic equation:

$$F\left(V, I_l, I_e, n, \tau\right) = 0 . \qquad (3.1)$$

The analytical expression of this relation makes a problem due to the non-linearity and complexity of the generator main feature, i.e. magnetization curve. That's why the equation (3.1) is usually given graphically as the relations between two values meanwhile the values of the other three are constant. These relations are called the generator performance.

The necessity of special considering the aircraft generators characteristics stems from different conditions and diverse requirements imposed on aircraft and general-purpose generators used in industry (for example, the operation at variable rotational speed).

Since all aircraft generators have shunt excitation we shall consider the main characteristics just for this case. The main characteristics include no-load, load external and control characteristics. Let's consider special features of the characteristics given above.

No-load characteristics. No-load conditions characterizes by absence of a load, i.e. these are the conditions when the external network is switched off. The generator EMF is referred to as the function of its armature rotational speed **n** and magnetic flux Φ_0

$$E = kn\Phi_0 , \qquad (3.2)$$

where k is the constant coefficient.

The magnetic flux depends on the excitation current, that is why the generator no-load characteristic is defined as the relationship between the EMF and the excitation current at the constant armature rotational speed and the absence of load:

$$E = f\left(I_e\right) \text{ at } n = const \text{ and } R_l = \infty , \qquad (3.3)$$

where R_l is the load resistance.

Let's give the general view of the no-load characteristics (Fig. 3.8).

No-load characteristics make it possible to estimate the degree of magnetic system saturation and the degree of magnetic material application. As the diagram shows, the saturation of aircraft generators is insignificant and it decreases with the increase of rotational speed $\boldsymbol{n}$. Besides, it is possible to determine those minimal armature n_{min} revolutions, taking these characteristics into account. Where the nominal output EMF $E_0 = 28.5\ V$ and the corresponding excitation current still provides.

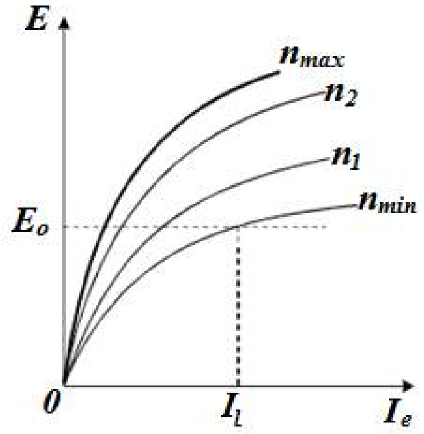


Fig. 3.8. The performance of no-load operation of the generator

Load characteristics. Load characteristic is the relationship between the voltage V_l and the excitation current at the constant rotational speed and the constant load resistance R_l

$$V_l = f\left(I_e\right) \text{ at } n = const \text{ and } R_l = const. \qquad (3.4)$$

The generator load characteristic takes the following form (Fig. 3.9).

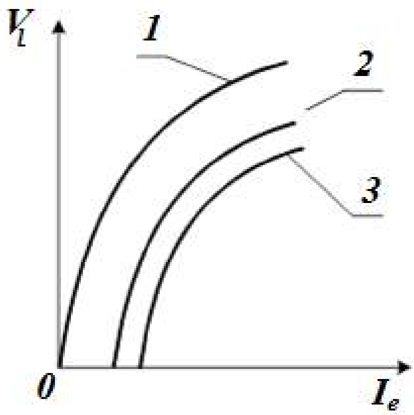


Fig. 3.9. Load characteristics

Where:

1. No-load characteristic;
2, 3. Load characteristics at the load resistance R_{l2} and R_{l3} – (R_{l3} > R_{l2}).

Load characteristics are used for estimation of magnetic circuit condition under load. As one can see from the diagrams, as the load increases, the slope of dependence $V_l = f\left(I_e\right)$ decreases. Besides, as the load increases, the losses on the armature increase and the voltage V_l on a load becomes equal:

$$V_l = E - I_a R_a , \tag{3.5}$$

where R_a, I_a are the armature resistance and current respectively.

External characteristics. External characteristic is the relationship between voltage across V_l and current through load I_l at armature constant rotational speed and constant resistance R_e of the excitation circuit:

$$V_l = f\left(I_e\right) \text{ for } n = const \text{ and } R_e = const . \tag{3.6}$$

Let's consider the diagrams of external characteristics (Fig. 3.10).

The upper characteristic in Fig. 3.10 corresponds to the maximum revolutions (n_{max}) and the lower one to the minimum revolutions (n_{min}).

External characteristics are used to determine the generator. Let’s mark a number of specific points on one of the characteristics: ***A, B, C, D***. The point ***A*** corresponds to the no-load conditions. The load current is absent ($I_l = 0$).

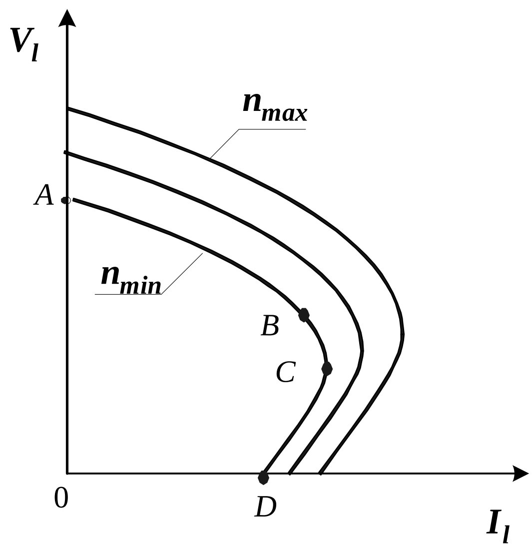


Fig. 3.10. External characteristics

The point B corresponds to the maximum permissible current for the given rotational speed at nominal voltage ($V_l = 27\ V$). The point ***C*** corresponds to the critical current. This is the maximum current at the given rotational speed. The point ***D*** corresponds to the armature short circuit, i.e. when the load resistance R_l is equal to zero ($R_l = 0$).

The values of limiting (point ***B***) and critical current (point ***C***) show the generator overload capacity. The higher these values are, the higher the generator quality is.

Control performance. Control performances shows which law is to be used for changing the generator excitation current so that the voltage value will remain constant.

A distinction is made between **the control performances by speed**, i.e. the relationship between excitation current and the armature rotational speed at the constant voltage:

$$I_e = f(n) \text{ and } V_{l\,nom} = const \quad (3.7)$$

and the control performance by load, i.e. the relationship between excitation current at constant speed and voltage on the one hand and load current on the other hand

$$I_e = f(I_l) \text{ at } n = const \text{ and } V_{l\,nom} = const\,. \quad (3.8)$$

Let's consider the **control performance of relationship** between excitation current and the armature rotational speed (Fig. 3.11).

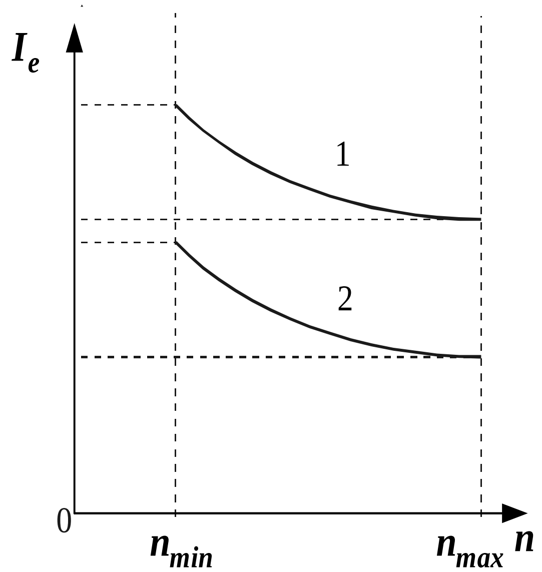


Fig. 3.11. Control performances by speed
1 – at nominal load; 2 – at smaller than nominal load.

As can be seen from the diagrams, when the rotational speed is high, only the slight change of excitation current is required to keep the voltage constant.

The control performance by load can be represented with the help of the diagram in Fig. 3.12.

This characteristic gives the idea about a range of changing of excitation current and saturation power of magnetic system.

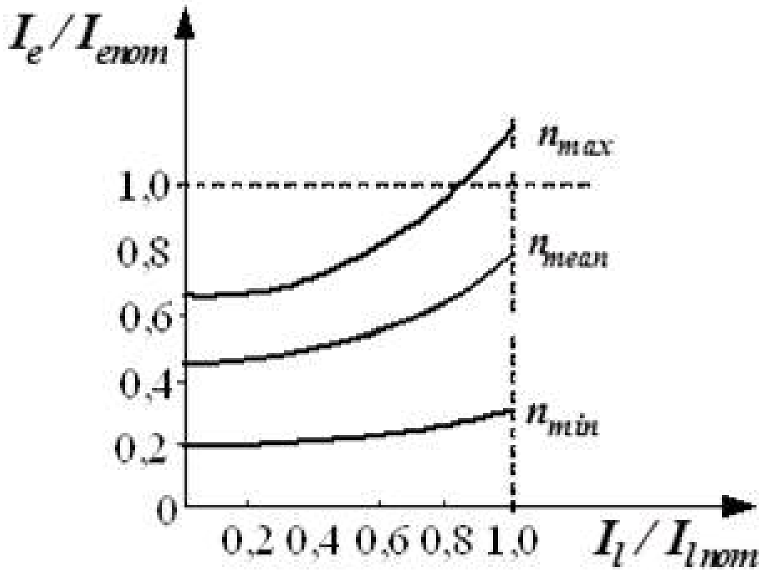


Fig. 3.12. Control performance by load

3.5. Operation of the Generator with a Storage Battery. Parallel Operation of Direct Current Generators

Generators and a storage battery (basic and auxiliary power supplies respectively) are used as the sources of electrical energy on the airplanes with direct power supply. The generators and the storage batteries are connected in parallel to the common buses. The following stages of generator and storage battery operation may be named:

1) **Operation of one storage battery (SB)**. The generator is not connected with the common buses and the services obtain power from **SB**. Such conditions occur when the generator rotational speed is lower n_{min}. In this case if the generator is connected (switched on) with the common buses, the current from **SB** (reverse current) will pass into the generator. Since $E_g < E_{ab}$ and the lower the generator rotational speed is, the greater is the reverse current value (discharge current **SB**). It can result both in the generator damage and in the excessive discharge **SB**.

In order to protect the generator from the reverse-current the use is made of reverse current relay (differential undercurrent relay) that performs two functions:

a) to switch automatically the generator for the parallel operation with **SB** as soon as its EMF becomes somewhat higher than **SB** EMF;

b) to switch off the generator from the aircraft electrical wiring system when the reverse current exceeds the predetermined value.

Numerous devices have been manufactured for the purpose of automatically disconnecting the generator, the simplest being the **reverse-current cutout relay**. Fig. 3.13 is a schematic diagram illustrating the operation of such a relay.

A voltage coil and a current coil are wound on the same soft-iron core. The voltage coil has many turns of thin wire and is connected in parallel with the generator output; that is, one end of the voltage winding is connected to the positive side of the generator output and the other end of the winding is connected to ground, which is the negative side of the generator output.

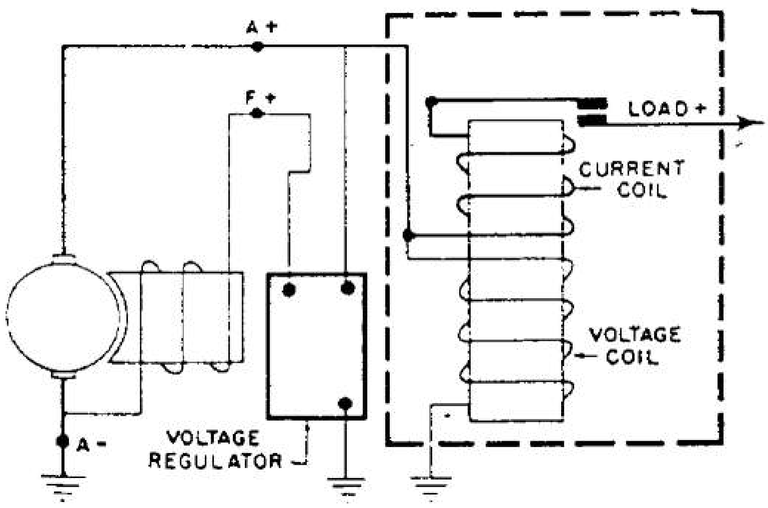


Fig. 3.13. Reverse-current cutout relay circuit

This is clearly shown in the diagram. The current coil consists of a few turns of large wire connected in series with the generator output. Hence it must carry the entire load current of the generator. A pair of heavy contacts points is placed where it will be controlled by the magnetic field of the soft-iron core. When the generator is not operating these contact points are held in an open position by a spring.

When the generator voltage reaches a value slightly above that of the battery in the system, the voltage coil in the relay magnetizes the soft-iron core sufficiently to overcome the spring tension. The magnetic field closes the contact points and thus connects the generator to the electrical system of the airplane. As long as the generator voltage remains higher than the battery voltage the current flow through the current coil will be a direction that aids the voltage coil in keeping the points closed. This means that the field of the current coil will be in the same direction as the magnetic field of the **voltage** coil and that the two will strengthen each other.

When an airplane engine is slowed down or stopped the generator voltage will decrease and fall below that of the battery. In this case the battery voltage will cause current to start flowing toward the generator through the relay current coil. When this happens the current flow will be in the direction that creates a field opposing the field of the voltage winding.

These result in weakening the total field of the relay, and the contact points are opened by the spring thus disconnecting the generator from the battery. The contact points may not open in normal operation until the reverse current has reached a value of ***5*** to ***10 A***.

Generally speaking, the tension of the spring controlling the contact points should be adjusted so that the points will close at approximately ***13.5 V*** in a ***12-V*** system and at ***26.6*** to ***27 V*** in a ***24-V*** system.

2) **The generator operation for the external network and for SB charge**. These conditions of operation occur when the generator rotational speed is in the range of n_{MIN}, n_{MAX} and when the load on the generator is lower than limiting ($I < I_{bus}$). In this case the generator not only provides services with power, but also recharges AB.

3) **Generator and SB combined operation for the external network**. At constant voltage on the buses the highest current passing from the generator to the network equals

$$I_{g\,max} = I_{bus} - I_{AB}.$$

The further load increase causes the reduction of the generator voltage and current reduction of the storage battery charge I_{AB}. When $V_g = E_{AB}$ **SB** operates in no-load conditions and the generator operates overloaded. If the load increases further, the services will obtain the electrical energy both from the generator and from **SB**.

Parallel operation of generators. Modern airplanes usually have several generators included for parallel operation. The number of generators equals the number of aircraft engines or exceeds it. The number of generators may double the number of engines. The mounting of two generators operating parallel has some advantages over one generator of increased capacity and over the isolated operation of several generators.

These advantages include the reliability of electrical energy supply in case of a generator failure or aircraft engine stop and the more efficient application of generators.

Besides, in case of DC generators parallel operation the **SB** capacity reduces, the number of **SB** reduces as well and the conditions of **SB** operation become easier.

In order to switch on these generators for parallel operation some conditions should be carried out:

1) the voltage of the connected generator should be equal to voltage on the buses;

2) the correct polarity should be observed during the process of the generator connection to the buses;

3) the external characteristics of the generators should be the same or similar so that the load will be distributed equally between the parallel operating generators and this distribution will be kept in all operating conditions.

The difference of external characteristics is caused by the following factors:

a) different rotational speed of the generators since it is impossible to achieve the complete synchronization of the aircraft engines rotational speed;

b) different level of adjustment of voltage regulators of different generators.

Current Limiter

In some generator systems a device is installed that will reduce the generator voltage whenever the maximum safe load is exceeded. This device is called **current limiter** and is designed to protect the generator from loads that will cause overheating and eventually burning the insulation and windings.

The current-limiter operates on a principle similar to that of the vibrator-type voltage regulator. Instead of having a voltage coil to regulate the resistance in the field circuit of the generator the current limiter has a current coil connected in series with the generator load circuit (see Fig. 3.14).

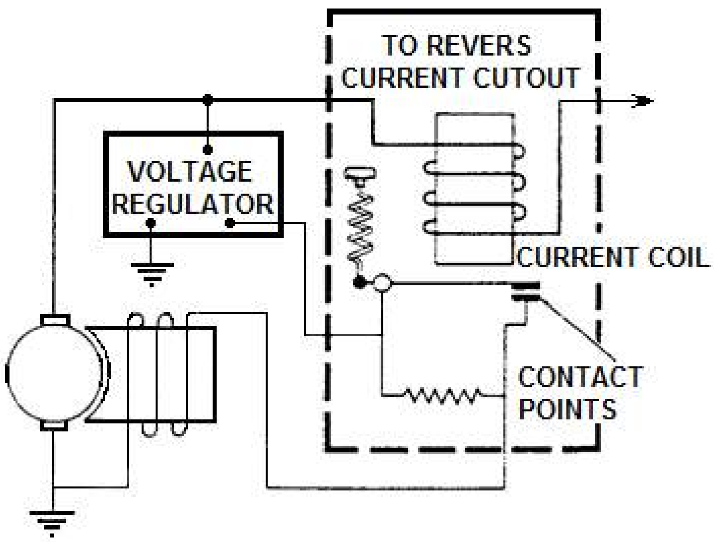


Fig. 3.14. Current-limiter circuit

When the load current becomes excessive, the current coil magnetizes the iron core sufficiently to open the contact points and a resistance to the generator field circuit. This causes the generator voltage to decrease with a corresponding decrease in generator current. Since the magnetism produced by the current-limiter coil is proportional to the current flowing through it the decrease in generator load current also weakens the magnetic field of the current coil and thus permits the contact points to close. This removes the resistance from the generator field circuit and allows the voltage to rise again. If an excessive load remains connected to the generator, the contacts of the current-limiter will continue to vibrate, thus holding the current output at or below the minimum safe limit. The contact points are usually set to open when the current flow is ***10*** percent above the rated capacity of the generator.

The current limiter described above should not be confused with the fuse-type current-limiter. The fuse-type limiter is merely a high-capacity fuse that permits a short period of overload in a circuit before the fuse link melts and breaks the circuit.

Equalizing Circuit

When two or more generators are connected in parallel to a power system, the generators should share the load equally. If the voltage of one generator is slightly higher than of the other generators in parallel, that generator will assume the great part of the load. For this reason an equalizing circuit must be provided that will cause the load to be distributed evenly among the generators. An equalizing circuit includes an equalizing coil wound with the voltage coil in each of the voltage regulators, an equalizing bus to which all equalizing circuits are connected, and a low-resistance shunt in the ground lead of each generator (see Fig. 3.15).

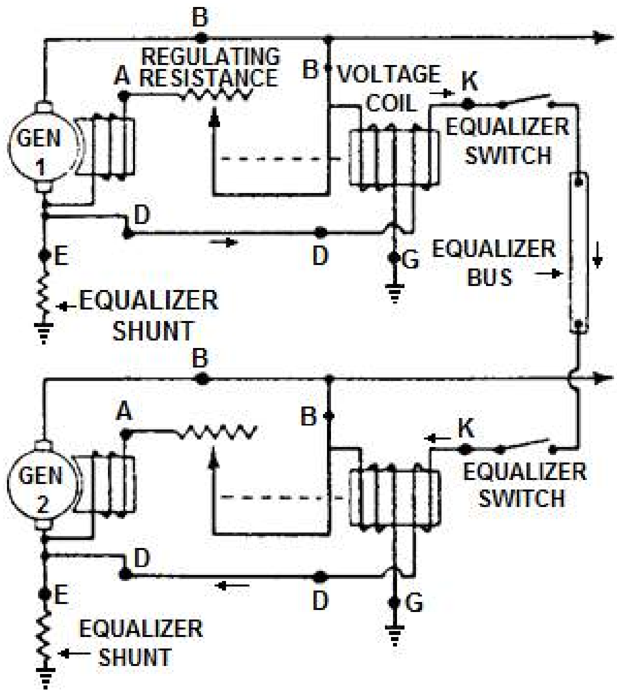


Fig. 3.15. Equalizing circuit

The equalizing coil will either strengthen or weaken the effect of the voltage coil, depending on the direction of current flow through the equalizing circuit. The low-resistance shunt in the ground lead of each generator causes a difference in potential between the negative terminals of the generators that is proportional to the difference in load current. The shunt is of such a value that there will be a potential difference of ***0.5 V*** across it at maximum generator load.

Assume the generator ***1*** in Fig. 3.15 is delivering ***200 A*** (full load) and that generator ***2*** is delivering ***100A*** (half load). Under these conditions there will be a potential difference of ***0.5 V*** across the shunt of generator ***1*** and ***0.25 V*** across the shunt of generator ***2***. This will make a net potential difference of ***0.25 V*** between the negative terminals of the generators. Since the equalizing circuit is connected between these points, a current will flow through the circuit. The current flowing through the equalizing coil of voltage regulator ***1*** will be in a direction to strengthen the effect of the voltage coil. This will cause more resistance to be placed in the field circuit of generator ***1***, thus weakening the field strength and causing the voltage to be reduced. The drop in voltage will result in the generator taking less load. The current flowing through the equalizing coil of voltage regulator ***2*** will be in a direction to oppose the effect of the voltage coil, thus causing a decrease in the resistance in the field circuit of generator ***2***. The generator voltage will increase because of increased current in the field windings, and the generator will take more of the load. To summarize, the effect of an equalizing circuit is to lower the voltage of a generator that is taking too much of the load and to increase the voltage of the generator that is not taking its share of the load.

Equalizing circuit can be correct for only small differences in generator voltage. Hence the generators should be adjusted to be as nearly equal in voltage as possible. If the generator voltages are adjusted so that there is a difference of less than 0.5 V between any of them, the equalizing circuit will maintain a satisfactory load balance. A periodic inspection of the ammeters should be made during flight to see that the generator loads are remaining properly balanced.

3.6. Starter-Generators

A starter-generator is a combination of a generator and a starter in one housing. Starter-generator are typically employed on small turboprop and turbine-powered aircraft. Most starter-generator contains at least two sets of field windings and only one armature winding. While in the start mode, the starter-generator employs a low-resistance series field. At this time a high current flows through both the field and armature windings, producing the high torque required for engine starting.

While in the generator mode, starter-generator is capable of supplying current to the aircraft electrical system. A typical starter-generator can supply a direct current of up to ***300 A*** at ***28.5 V*** while in the generator mode. To generate electric power, the shunt winding of the starter-generator is energized, and the series field is de- energized. The shunt winding is a relatively high-resistance coil that produced the magnetic field to induce voltage into the armature. The voltage produced in the armature sends current to the aircraft bus, where it is distributed to the various loads of the aircraft.

It should be noted that several types of starter-generators are currently in use. Some employ two separate field windings as stated above. Other use only one (shunt) field winding. If only one field winding is used, special circuitry is needed in the generator control unit to increase starting torque to an appropriate level. The technician should become familiar with any specific starter-generator before beginning maintenance procedures.

One advantage of the starter-generator is that only one drive gear mechanism is used for both the start and the generator modes. Therefore, the starter motor drive gear need not be engaged to or disengaged from the engine drive gear. Also the starter-generator reduces both size and weight as compared to a conventional system that employs two units: a starter and a generator. The main disadvantage of starter-generator is that they are unable to maintain full output at a low rpm. Most starter-generators therefore must be used on turbine-powered aircraft that consistently maintain a relatively high engine rpm.

3.7. Terms and concepts

Airborne power electric station is a system consisting of aircraft engines and generators.

Equalizing circuit is a circuit in a multiple-generator voltage regulator system that tends to equalize the current output of the generators by controlling the field currents of the several generators.

Primary source of energy on the airplane. There are DC generators and starter- generators.

Reverse current is the current flowing from network to the generator when $E_G<E_{AB}$. This value may be of danger for the generator operation.

Reverse current relay is a relay incorporated into generator circuit to disconnect the generator from the battery when battery voltage is greater than generator voltage.

Starter - generator is a unit that is used on turbine engines to provide starting torque and generate electric power.

3.8. Control Questions

1. Explain the electrical principle by which electricity is produced in a generator.
2. Name the essential parts of a DC generator.
3. What determines the voltage value in a generator?
4. How can commutator ripple be reduced?
5. Explain armature reaction.
6. How can armature reaction be reduced?
7. Describe the function of a stator-generator.
8. What types of aircraft typically employ starter generators?

9. Describe the armature assembly for typical aircraft generator.
10. What is the method of DC generator excitation and what kinds of excitation are used in aircraft generator design?
11. What characteristics determine the aircraft generator properties?
12. What method is to reduce the load shock on the shaft of an aircraft generator use?
13. Compare the shunt field winding in an aircraft generator with the winding.
14. Describe means for cooling aircraft generator.
15. Name the stages of combined operation of aircraft generator and SB.
16. What conditions should for switching on DC generators for parallel operation observe?
17. Describe the operation of an equalizing circuit.
18. Why is a reverse-current cutout relay required in a generator system?
19. Explain the operation of a reverse-current cutout relay.
20. Explain the operation of a current-limiter used in a vibrator-type voltage regulator.

Chapter 4

AIRCRAFT AC GENERATORS

There are two types of generators currently used on aircraft, the DC and AC generators.

A generator which produces alternating current is referred to as AC generator and, through combination of the words “alternating” and “generator” the word “alternator” has come into widespread use. In this text the word “alternator” is applied only to AC generator.

Direct-current generators have the following drawbacks:

– outside contact between brushes and armature collector isn’t reliable enough;

– arcing between brushes and collector;

– influence of arcing on radio communicative and other electronic equipment.

The alternating current generators don’t have these drawbacks. In addition, they have the following advantages:

– higher specific generated power;

– absence of brush-collector node;

– ability to work more reliably at high attitudes;

– simplicity in transforming current type and voltage value.

That’s why AC generators have been widely used as primary sources. The advantages of AC power supply system can be explained by the fact that its basic parameters such as: frequencies, voltages, number of phases and their connection were chosen correctly. These parameters influence the weight, dimensions, and electrical and mechanical characteristics of major elements of power system.

Generators and engines having rotating rate from ***6000*** up to ***12000 rev/min*** are applied to the majority of electro mechanisms. From the view point of weight, efficiency and cost, synchronous generators with the machines number of poles $p = 6...8$ have the best properties. Using the known relation between frequency f, number of pole pairs p and rotation rate n:

$$f = \frac{pn}{60},$$

it can be easily established, that optimum frequency for airplane generators ranges between ***300 … 550 Hz***.

AC three-phase system has advantages over single-phase system from the point of view of weights of electric engines and generators, and possibility of getting phase and linear voltages at once.

Optimum voltage should be chosen with taking into account network weight. Calculations show, that in order to reduce network weight, voltage should be increased up to ***120 … 200 V***. Increase of voltage up to large values isn't recommended because of mechanical strength of wires and from the point of view of safety precautions.

4.1. Characteristic Properties of Aircraft Alternators

Characteristic property of airplane alternators is their small weight (***10*** times less, than industrial DC generators have). Airplane alternators are approximately two times lighter than airplane DC generators with the same capacity.

According to the way of magnetic field formation alternators are divided into generators with electromagnetic excitation and generators with excitation from permanent magnets.

There are two types of alternators: the **rotating-field** (revolving-field) type and a **rotating armature** (revolving) armature type. Almost all alternators for aircraft power systems are constructed with a rotating field and a stationary armature (Fig. 4.1).

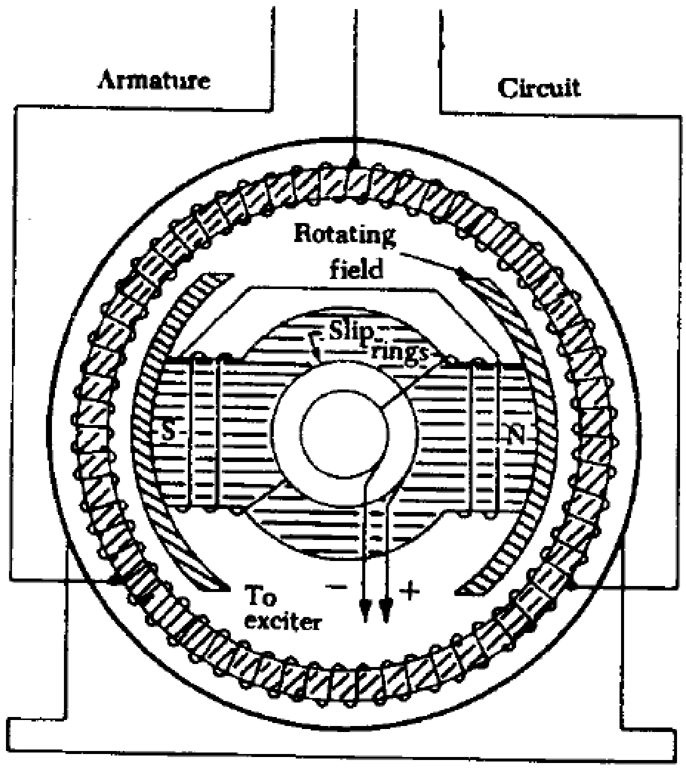


Fig. 4.1. Alternator with stationary armature and rotating field.

The advantage of having a stationary armature winding is that the armature can be connected directly to the load without having sliding contacts in the load circuit.

Three-Phase Alternator

A three-phase, or poly-phase circuit, is used in most aircraft alternators, instead of a single or two-phase alternator. The three-phase alternator has three single-phase winding spaced so that the voltage induced in each winding is $\mathbf{120^{\circ}}$ out of phase with the voltages in the other two windings. A simplified schematic diagram, showing each of three phases, is illustrated in Fig. 4.2.

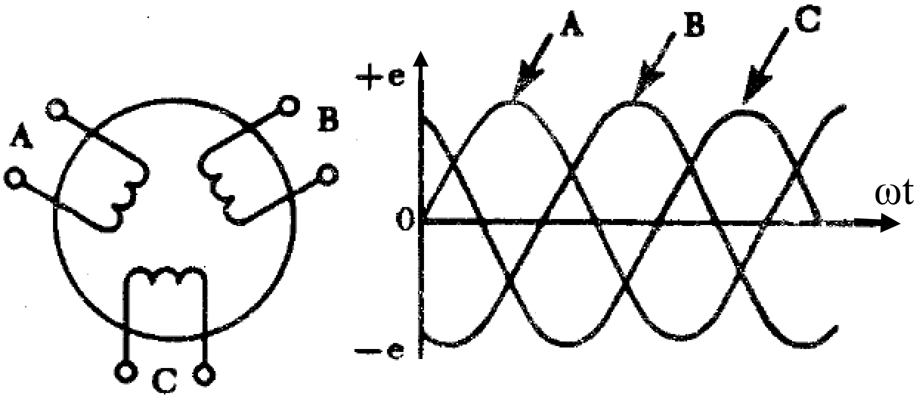


Fig. 4.2. Simplified schematic diagram of three-phase alternator with output waveforms

The rotor is omitted for simplicity. Sine voltages are shown to the right of the schematic diagram.

A three-phase stator can also be connected so that the phases are connected in wyes (A) and delta (B) as shown in Fig. 4.3.

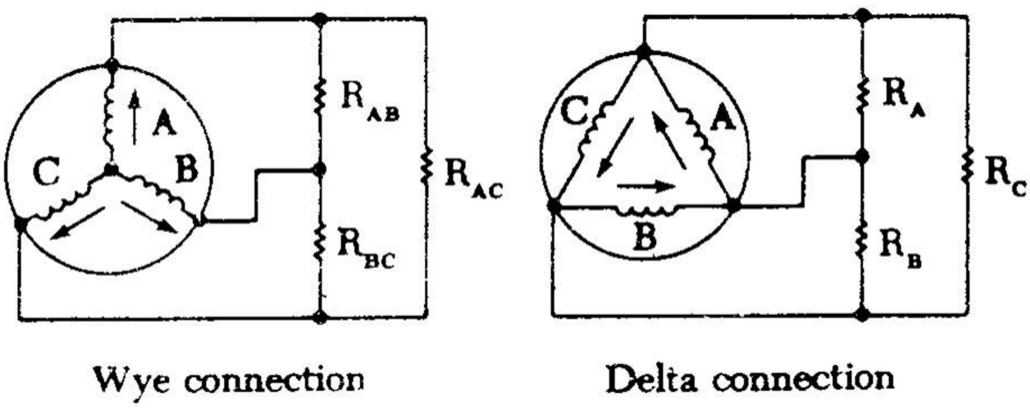


Fig. 4.3. Wye and delta connected alternators

For equal loads, the delta connection supplies increased line current at a value of line voltage equal to phase voltage, and the wye connection supplies increased line voltage at a value of line current equal to phase current.

4.2. Alternator excitation systems

AC generators used in mixed power supply systems, can have the following excitation systems:

– separate excitation from onboard DC network;

– excitation from the special exciter which is placed on the same shaft where basic generator is arranged.

Schematic diagram of excitation of AC generator when excitation winding is led off a network, has the following form (Fig. 4.4).

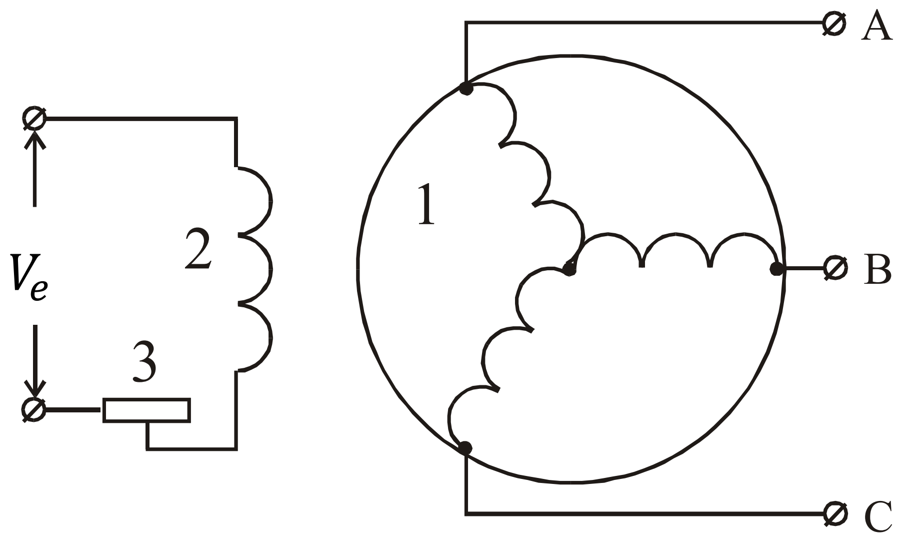


Fig. 4.4. The alternator with feeding excitation winding of onboard network

Drawbacks of the excitation system are necessity in a steady direct current; large energy expenses for output capacity control; significant increase of regulator weight, since a great number of excitation currents are subject to adjustment.

Therefore this excitation system is applied for generators of relatively small power (***7,5... 30 kVA***). For generators of capacity more than ***30 kVA***, special exciters are basically applied. Schematic diagram of excitation of AC generator when excitation winding is fed on exciter, has the following form (Fig. 4.5).

Where 1 is generator armature; 2 is excitation winding; 3 is exciter; 4 is excitation winding of exciter; 5 is resistance of voltage regulator.

The advantage of this excitation system is independence from other sources. For these purposes the exciter is made according to the diagram with separate (parallel) excitation.

The disadvantage of this system is increase in weight and dimensions.

For air power supply system's synchronous generators (alternators) of three-phase and single-phase current are made.

Three-phase generators of GSS type are issued with power of ***5, 7, 30, 40, 90, 120 kVA***, linear voltage ***120, 208 and 360 V***, variable and stabilized frequency.

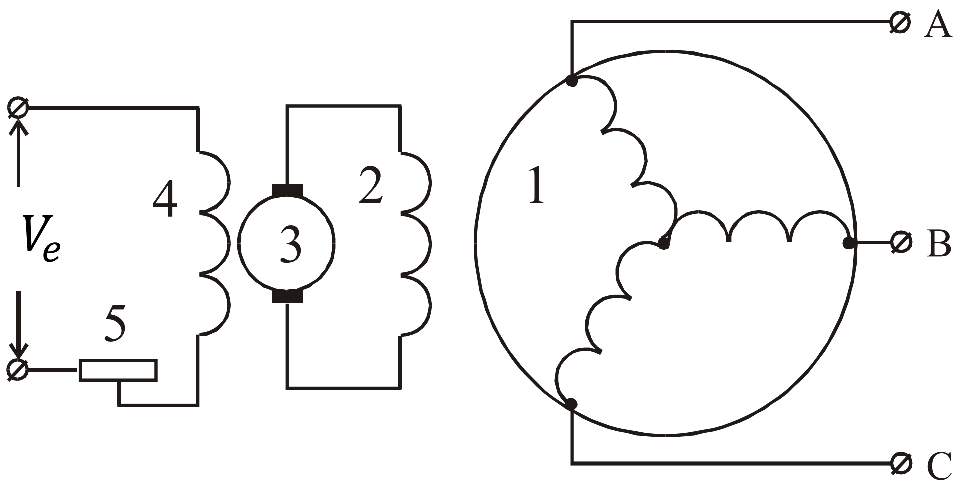


Fig. 4.5. The alternator with an exciter

Single-phase generators are made on the basis of three-phase ones. Single-phase feed is carried out from two phases by connecting loads with any two of three terminals of armature winding, as shown in Fig. 4.6. Third phase is not used.

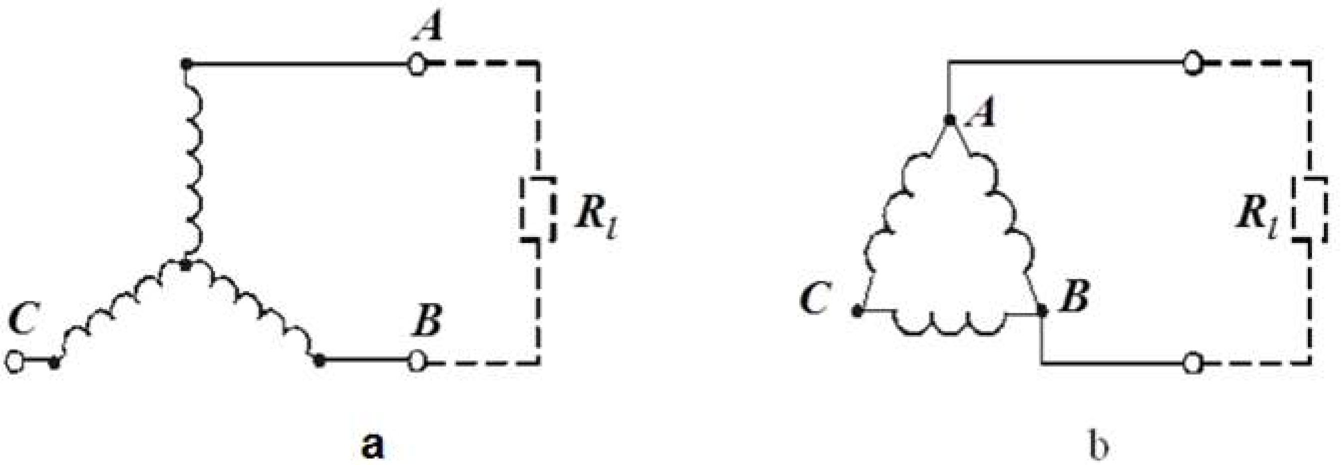


Fig. 4.6. Diagram of connections of armature winding of single-phase generators made on the basis of three-phase generators:
a – in the form of a wye; b – in the form a delta

In electric machines reliability and service life are determined by three basic factors: quality of electric insulation, quality of bearings and reliability of brush-contact devices. The first two factors depend on the level of development of branches contiguous to machine building. The third factor can be excluded by the method of developing non-contact generators.

Let's consider principle of construction of brushless alternator with rotating rectifier. Its diagram is given in Fig. 4.7.

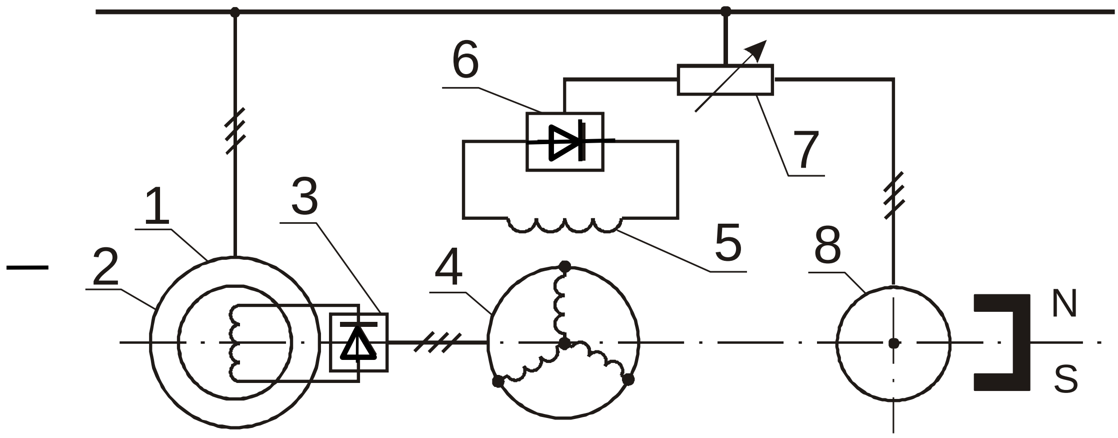


Fig. 4.7. Diagram of the alternator with rotating rectifier

Generator represents a cascade circuit consisting of three electric units: basic three-phase synchronous generator 1; three-phase synchronous exciter 4; three-phase electromagnetic pilot exciter 8.

All these three units are mounted on the same shaft.

When common shaft rotates the magnetic fields of rotor of pilot exciter 8 induce three-phase alternating current in the windings of its stator. Current from stator of pilot exciter gets in voltage regulator 7, and then on excitation winding 5 of the exciter. Thus current is rectified in rectifying unit 6. When rotor of exciter is rotated in magnetic field created by excitation winding 5, three-phase alternating current is induced in rotor. This current goes then to the following cascade. At first it is rectified in rectifying unit 3 and feeds excitation winding 2 of main generator. Excitation winding 2 is placed on rotating inductor. When inductor in armature winding 1 of main generator is rotated, three-phase alternating current of frequency ***400 Hz*** is induced. Then this current gets into aircraft onboard power network. Thus, in the considered electric machine.

4.3 Alternator Basic Characteristics

Properties of electric AC generators, as well as DC generators, are described by the characteristics. Generally characteristics are graphic dependences between basic values. These characteristics are:

– **the open-circuit characteristic** (dependence of no-load EMF on excitation current $E = f(I_e)$ at constant rotation velocity $n = const$) (Fig. 4.8);

– **the short-circuit characteristic** (dependence of short circuit current on excitation current $I_{sh} = f(I_e)$ at $V = 0$ and $n = const$) (Fig. 4.9).

Open and short-circuit characteristics are basic ones. The form of characteristics is influenced by a type of excitation system and generator rotation velocity. Each rotation velocity has corresponding characteristics.

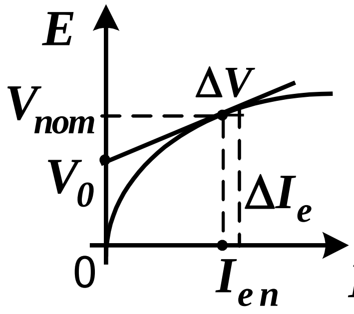


Fig. 4.8 Alternator no-load characteristic

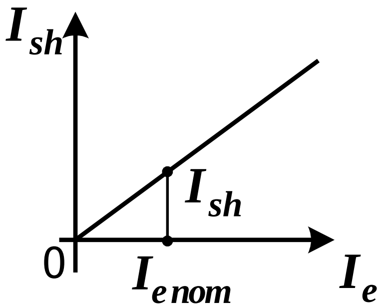


Fig. 4.9 Alternator short-circuit characteristic

Open and short-circuit characteristics give the possibility for determining main parameters of alternators.

– **external characteristic** (dependence of voltage at generator on load current $U = f(I_l)$ at $I_e = const$, $n = const$) (Fig. 4.10);

– **control performance** (dependence of excitation current on load current $I_e = f(I_l)$ at $n = const$, $V = const$) (Fig. 4.11).

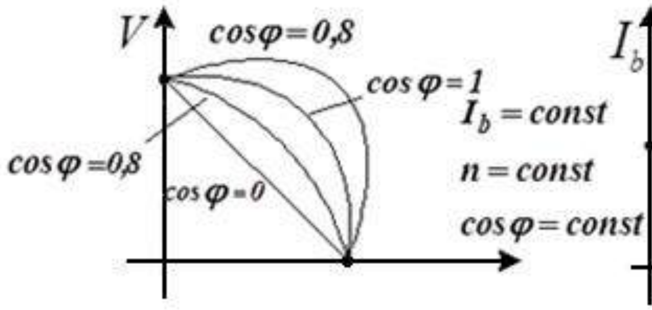


Fig. 4.10. Alternator external chracteristic

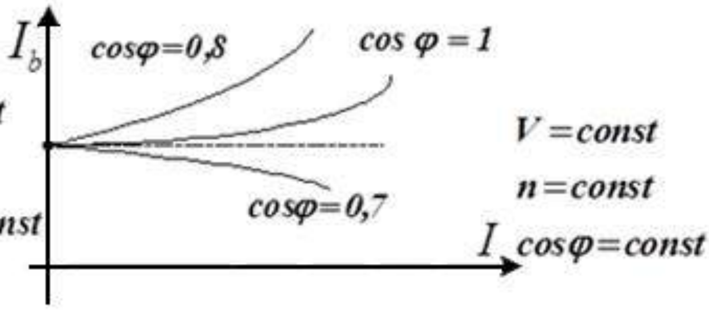


Fig. 4.11. Alternator control perfomances

The voltage of the generator can be determined for changing the value of load from nominal to open circuit:

$$\Delta V\% = \frac{V - V_{nom}}{V_{nom}} \cdot 100\%,$$

where V_{nom} is voltage across nominal load; V_0 is a voltage across $R_l = \infty$.

Using control performance a type, circuit board, construction of generators and control limits of exciting current can be determined.

4.4. Constant-Speed Drive System

In an AC system it is usually necessary to maintain a fairly constant speed in the ac generator. This is because the frequency of the AC generator is determined by the speed with which it is driven. It is especially important to maintain constant generator speed in installations in which the generators operate in parallel. In this case it is absolutely essential that generator speed be kept constant within extremely close limits.

In order to provide constant speed generator operation in modern AC electrical systems, it is common practice to use a **constant-speed drive** (CSD). CSD units are manufactured in many designs to fit a variety of applications. The principle of operation for all CSDs is essentially the same.

The complete CSD system consists of an axial gear differential (AGD), whose output speed relative to input speed is controlled by a flyweight-type governor that controls a variable-delivery hydraulic pump. The pump supplies hydraulic pressure to a hydraulic motor, which varies the ratio of input rotation per minute (rpm) to output rpm for the AGD in order to maintain a constant output rpm to drive the generator and maintain an AC frequency of ***400 Hz***.

A typical AC generator and CSD assembly is shown in Fig. 4.12.

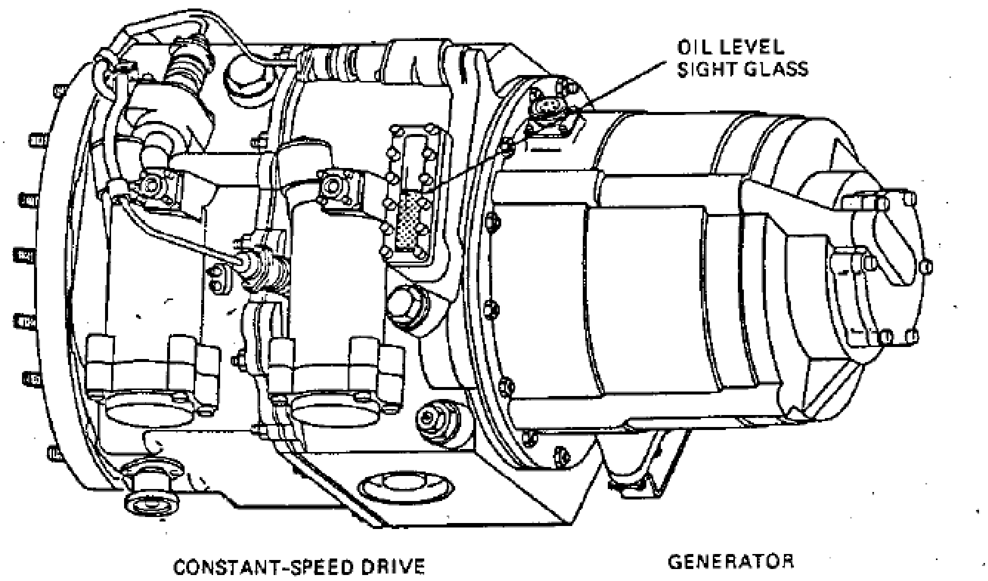


Fig. 4.12. A typical CSD and generator assembly

In this view the CSD is on the left end of the assembly, and the generator is on the right end. The generator is cooled by an oil spray delivered by the CSD section. Most CSDs are equipped with a quick attach/detach (QAD) adapter. This unit allows the technician to remove and replace a generator and CSD assembly in a matter of minutes. The QAD ring is mounted to the CSD by means of several bolts through the mounting flange.

To remove the generator from the aircraft, one must only release the QAD using one fastener.

To remove the generator from the aircraft, one must only release the QAD using one fastener aircraft that has a defective generator CSD.

A normal operating temperature for the cooling oil is approximately $94^{\circ}C$. In order to maintain the correct cooling capacity, the oil should be monitored periodically. A sight glass as shown in Fig. 4.12 is employed on most constant speed drives to allow the technician a quick check of the oil level. In the case of an in-flight oil loss or an over temperature condition, a warning indicator will light up on the flight deck. In this situation the CSD should be disengaged immediately and inspected upon landing.

Most CSD units are equipped with an electrically activated generator-drive disconnect mechanism. This disconnect mechanism couples the CSD input shaft to the CSD input spline. The CSD disconnector is operated manually from the aircraft flight deck or automatically by a generator control unit. The disconnector is activated in the event of certain generator system failures.

The **integrated drive generator** (IDG) is a state-of-the-art means of producing AC electric power. The IDG contains both the generator and the CSD in one unit. This concept helps to reduce both the weight and the size of the traditional two-unit system.

4.5. Synchronizing Alternators

Two or more alternators may be operated in parallel, with each alternator carrying the same share of the load. However, certain precaution must be taken and various conditions complied with before connecting an alternator to a bus with another alternator.

Synchronizing or paralleling the alternators is somewhat similar to paralleling DC generators, except when there are more steps with alternators. In order to synchronize (parallel) two or more alternators to the same bus, they must have the same phase sequence as well as equal voltages and frequencies.

The following steps are a general guide in synchronizing an alternator and connecting it to a bus system on which one or more alternators are already operating.

1. **Phase sequence check**. The standard phase sequence for AC, three-phase power circuits is A, B, C. The phase sequence can be determined by observing the small indicator lamps, connected as shown in Fig. 4.13.

If one lamp lights, the phase sequence is A, B, C. If the other lamp lights the phase sequence is A, C, B. If the light indicates the wrong phase sequence, reverse the two leads to the incoming alternator. To parallel or synchronize two alternators with the wrong phase sequence would be the same as short circuiting of two leads and would set up dangerous circulating currents and magnetic disturbances within the alternator system, which could overheat the conductors and losses the coil winding.

2. **Voltage check**. The voltage of the alternator to be connected to the bus

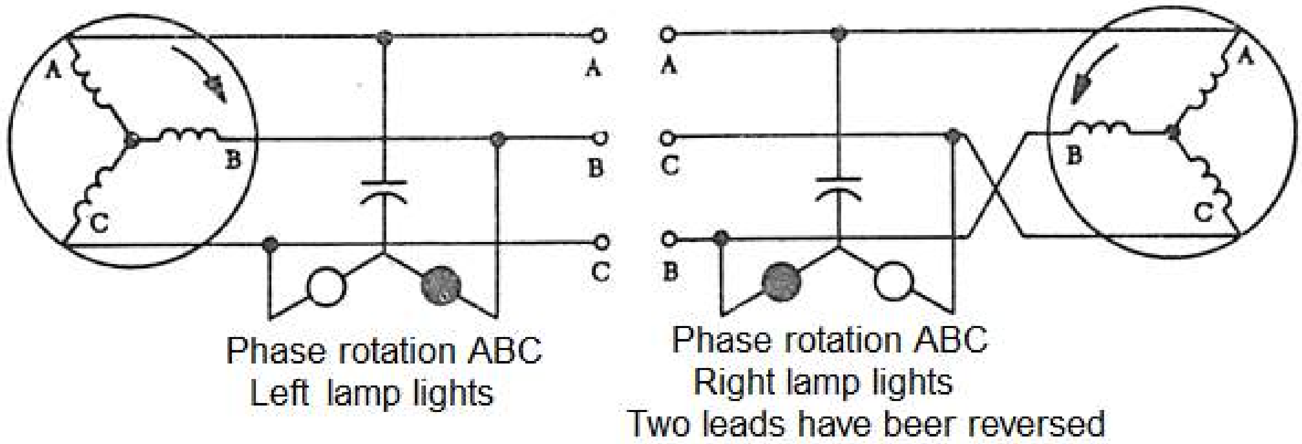


Fig. 4.13. Phase sequence indicator

must be equal to the bus voltage. It is adjusted by a control rheostat located on the switch panel. This rheostat controls the current in the voltage regulator coil and causes the alternator magnetic field to increase or decrease, controlling, in turn, the alternator voltage.

3. **Frequency check**. The frequency of an alternator is directly proportional to its speed. This means that the speed of the alternator being connected to the bus must equal the speed of the alternators already connected. By observing the frequency meter and by adjusting the rheostat on the switch panel the frequency of the incoming alternator can be brought up to the correct value.

4. **Coincidence of generator and work voltages in phase**, that is

$$\varphi_{gen} = \varphi_{bus} .$$

Alternators synchronization is a highly difficult and responsible process, therefore it automized, i.e. special synchronizers are applied.

4.6. Variable-Speed Constant-Frequency Power System

In efforts to simplify and improve the production of AC power for aircraft and to get away from the need for hydro mechanical constant-speed drives, a number of systems have been devised for producing ***400 Hz*** three-phase electric power through electronic circuitry. This has been made possible by the great advances in solid-state technology developed in recent years.

Variable-speed constant-frequency systems are typically referred to as **VSCF** systems. Basically, the systems employ a generator driven at a variable speed, thus producing a variable-frequency output. The rotational speed of the generator is a direct function of the engine rpm. No constant-speed drive (CSD) mechanism is needed for VSCF systems. The elimination of the mechanical CSD improves reliability of the systems and offers more flexibility on installation of the generator. The generator variable-frequency output current is converted to a constant-frequency ***400 Hz*** alternating current by means of solid-state circuitry. This makes the electric power suitable for aircraft use. Several military aircraft currently use VSCF systems as primary and secondary AC power sources. VSCF systems are also found on the Boeing and Airbus commercial airlines.

Utilizing state-of-the art electronic components, the VSCF systems improve reliability over the mechanical-hydraulic units of the constant-speed drive. One VSCF system can contain only two moving parts, the oil pump and the generator rotor. There are no other parts to wear or require periodic overhaul.

The VSCF systems also offer greater flexibility than the typical CSD. The generator must still be mounted to the engine drive mechanism: however, the control units of the VSCF system can be mounted virtually anywhere on the aircraft. Elimination of the CSD therefore allows for a more compact engine nacelle.

Fig. 4.14 is a block diagram showing the principal elements of a VSCF system found on the Boeing-737 aircraft.

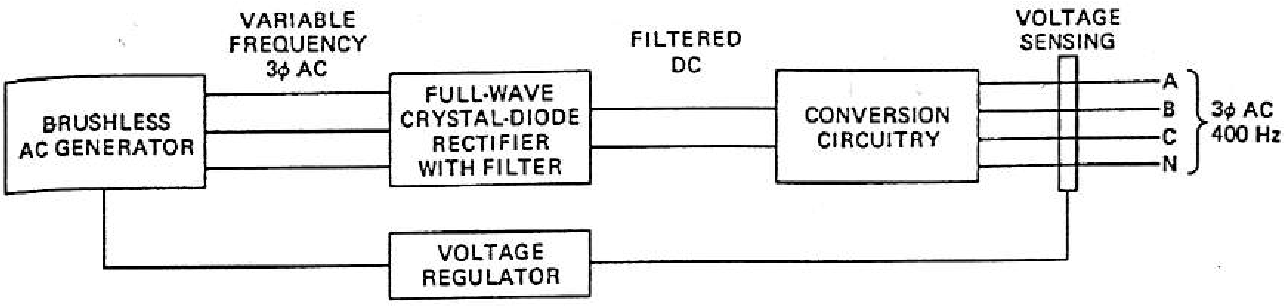


Fig. 4.14. A block diagram of a variable-speed constant-frequency power system

The brushless AC generators are similar to those described previously however, since they are driven directly by the engine, its rotational speed and output frequency will vary as engine speed varies. The variable three-phase power is fed to the full-wave rectifier within the VSCF converter, where it is changed into direct current and filtered. This direct current is fed to the inverter circuitry, where it is formed into square wave outputs that are separated and summed to produce three-phase ***400-Hz*** alternating current. The functions of the VSCF converter are similar to those of a typical static inverter. The generator converter control unit (GCCU) provides VSCF control and protection through the use of a voltage regulator and built-in test circuitry.

Currently, VSCF systems are in limited use, however, if the projected reliability and operating costs are accurate, VSCF systems will be the next-generation electric power supply systems for modern aircraft.

4.7. Terms and concepts

Clutch is a mechanical device used to connect or disconnect a motor or some other driving unit and the driven unit.

Constant-speed drive (CSD) is a unit used in conjunction with ac alternators to produce a constant-frequency ac voltage.

Contact alternator is an alternator, which has sliding contacts.

Current limiter is a device installed in a circuit to prevent current from increasing above a specified limit.

Generator control unit is a solid-state device that controls generator output parameters.

Inverter is a mechanical or electronic device that converts direct current into alternating current.

Solid-state is an adjective used to describe electric devices that use a solid material, such as silicon or germanium, to control current flow.

4.8. Control Questions

1. What are the advantages of AC generator?
2. Describe the types of AC generator construction.
3. Describe the operation of a typical aircraft alternator.
4. How is the production of a three-phase alternating current accomplished in an aircraft alternator?
5. What is a three-phase armature?
6. Describe basic systems of alternator excitation.
7. What basic characteristics has AC generator?
8. Describe the conditions of alternator connection in parallel operation.
9. Describe the differences between aircraft and auto alternator.
10. Explain how field excitation is accomplished in a brushless generator.
11. What is an integrated drive generator?
12. What is the meaning of ***kVA***?
13. What is the purpose of the solid-state GCU?
14. How is it possible to keep an alternator at a constant speed when the engine by which it is driven changes rpm?
15. Give a brief explanation of a CSD operation.
16. Explain the basic principles of a variable-speed constant-frequency electric power system.
17. What is the advantage of a VSCF system?
18. Explain the purpose of an inverter.

Chapter 5

STABILIZATION OF ALTERNATING CURRENT GENERATOR VOLTAGE AND FREQUENCY

5.1. Principle of Voltage Regulation

The main drive of the direct and alternating current generators is a drive of the main engines of the airplane. A peculiarity of this drive is a change of the engine angular velocity with a change of the flight mode. A range of the angular velocity variation, at which the generators should put out power into a power supply bus, depends on a type of the engine. It makes 2,0 … 2.5 for turboprop airplanes, and 1,2 … 1,4 for turbojet ones. The generator load is also variable. In this case, the direct current generator voltage and the alternating current generators voltage and frequency will also be variable.

The majority of the consumers are very sensitive to the voltage change, and a significant part is also sensitive to the frequency change. Hence, the stabilization of the voltage and frequency are needed; regulators of voltage and frequency are necessary.

Carbon-pile, magnetic, semi-conducting regulators or their combinations are used as voltage and frequency regulators. In addition to general requirements, the characteristic for all electric equipment, regulators of voltage (VR) and frequency (FR) should meet a number of special requirements determining the electric power quality, i.e. the specified accuracy of frequency and voltage stabilization, stability, small emissions of voltage and frequency. The increase of voltage and frequency stabilization accuracy improves conditions of the consumers operation, improves their characteristics, increases service life and reliability, and reduces mass and volume of the consumers and supple buses.

According to the norms now in use, for the airplane electric equipment the admissible voltage deviation, which the direct current consumers may have, is no more than $\pm\boldsymbol{10\%}$, and the admissible voltage deviation, which a source may have, is no more than $\pm\boldsymbol{3.5\%}$.

In the stable frequency alternating current systems the admissible voltage changes make $\pm\boldsymbol{5\%}$ at the consumers, and $\pm\boldsymbol{1.6\%}$ at a source, and admissible deviations of frequency make $\pm\boldsymbol{5\%}$**.**

Regulation of the generator voltage. Voltage of the DC generator is

$$V = E - I_a R_a = cn\Phi - I_a R_a = cnf(I_e) - I_a R_a,$$

where $\boldsymbol{E}$ is EMF of the generator;

$\Phi = f(I_e)$ is an excitation flux;

R_a is a generator series circuit resistance;

c is a proportionality factor.

At the rotation n and a load current change I, the voltage stabilization is provided at the expense of regulation of the excitation current I_e (i.e. flux) by the change of either excitation circuit resistance or the voltage on the excitation winding.

Modern voltage regulators have been developed to such a high degree of efficiency that the EMF of a generator will vary only a small fraction of a volt throughout extreme ranges of load and speed.

Voltage regulators or controls for modern aircraft are usually of the solid-state type; that is, they employ transistors and diodes as controlling elements. Because there are still many older airplanes in use that employ vibrator-type and variable-resistance voltage regulators, these shall be examined in the following sections.

5.2. Vibrator-Type Voltage Regulator

A generator system using a vibrator-type voltage regulator (VVR) is shown in Fig. 5.1.

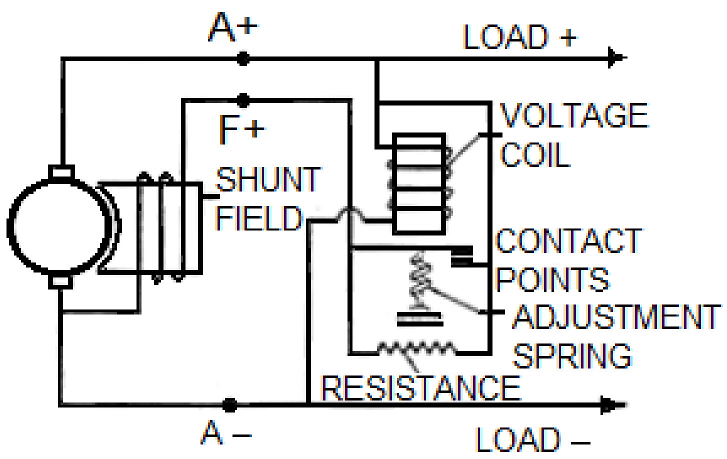


Fig. 5.1. Vibrator-type regulator circuit

A resistance that is intermittently cut in and out of the field circuit by means of vibrating contact points is placed in series with the field circuit. The contact points are controlled by a voltage coil connected in parallel with the generator output. When the generator voltage rises to the desired value, the voltage coil produces a magnetic field strong enough to open the contact points. When the points are open, the field current must pass through the resistance. This causes a substantial reduction in field current, with the result that the magnetic field in the generator is weakened. The generator voltage then drops immediately, causing the voltage coil electromagnet to lose strength so that a spring can be closed to the contact points. This allows the generator voltage to rise and the cycle is then repeated. The contact points open and close many times a second but the actual time that they are open depends on the load being carried by the generator and the generator (engine) ***rpm***. As the generator load is increased, the time that they are open decreases. Adjustment of the generator voltage is made by increasing or decreasing the tension of the spring that controls the contact points.

Because the contact points do not burn or pit appreciably VVR are satisfactory for generator that require a low field current. In a system in which the generator field requires a current as high as ***8 A***, the vibrating contact point would soon burn and probably fuse together. For this reason a different type of regulator is required for heavy-duty generator systems.

5.3. Carbon-Pile Voltage regulator

The carbon-pile voltage regulator (CVR) derives its name from the fact that the regulating element (variable resistance) consists of a stack, or pile of carbon disks (see Fig. 5.2).

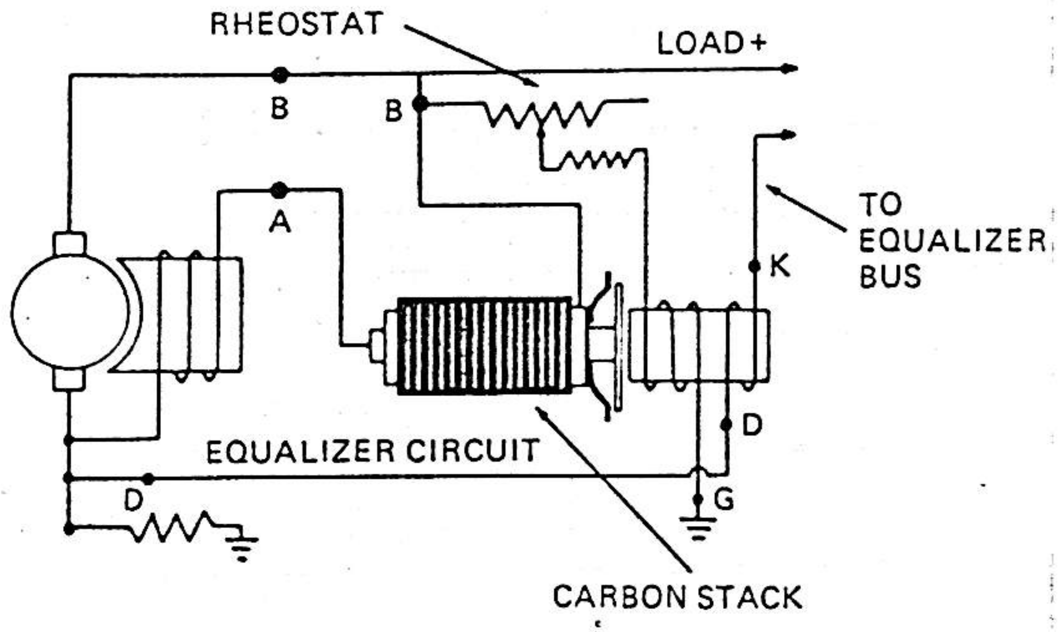


Fig. 5.2. Carbon-pile voltage regulator circuit

Usually, the carbon pile has alternate hard carbon and soft carbon (graphite) disks contained in a ceramic tube with a carbon or metal contact plug at each end. At one end of the pile, a number of radially arranged leaf springs exert pressure against the contact plug, thus keeping the disks pressed firmly together. For a long as the disks are compressed the resistance of the pile is very low. If the pressure on the carbon pile is reduced, the resistance increases. By placing an electromagnet in a position where it will release the spring pressure on the disks as the voltage rises above a predetermined value, a stable and efficient voltage regulator is obtained.

The carbon-pile voltage regulator is connected in generator system in the same way any other regulator is connected, that is with a resistance in the field circuit and electromagnet to control the resistance. The carbon-pile is in series with the generator field, and the voltage coil is shunted across the generator output. A small manually operated rheostat is connected in series with the voltage coil to provide for a limited amount of adjustment, which is necessary when two or more generators are connected in parallel to the same electrical system.

Carbon-pile voltage regulator construction can be considered using Fig. 5.3.

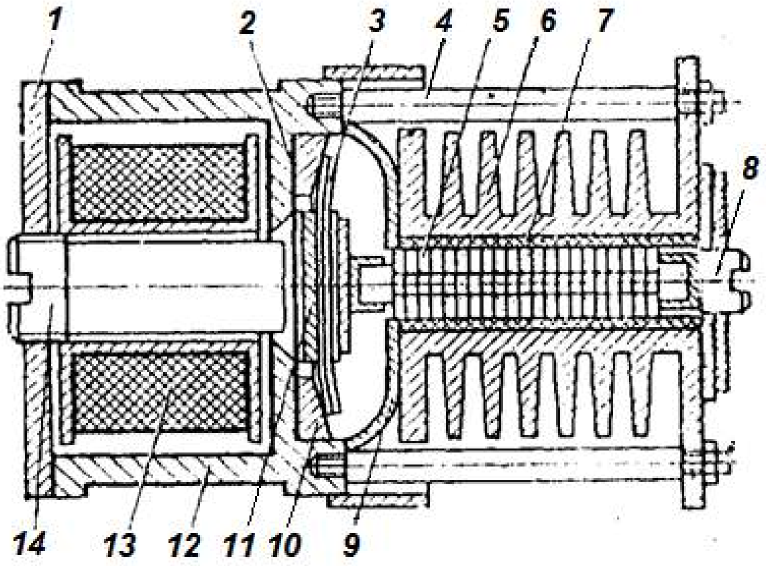


Fig. 5.3. Carbon-pile voltage regulator construction

The CVR consists of a carbon pole 5 placed into a duralumin tube 7, with oxide-varnish coating, fixed in the finned case of radiator 6, electromagnet with a core 14 and mobile armature 11 fixed on a spring 3, adjusting screw 8. A winding 13 is located on the electromagnet core. The electromagnet case 12 is designed as a glass with a cover 1. The spring 9 with the armature bears against a ring 10. The brass gasket 2 prevents the armature from adhering to the core.

The carbon-pile voltage regulators (CVR) are also widely used for alternating current generators. The schematic electrical circuit of CVR connection for three-phase synchronous generator with excitation from the onboard direct current supple line is represented in Fig. 5.4.

In this circuit the main CVR winding W_e is connected through the three-phase bridge rectifier R_c to three phases of the synchronous generator SG, therefore at the asymmetrical load the regulator maintains the average value of the voltage between all three phases.

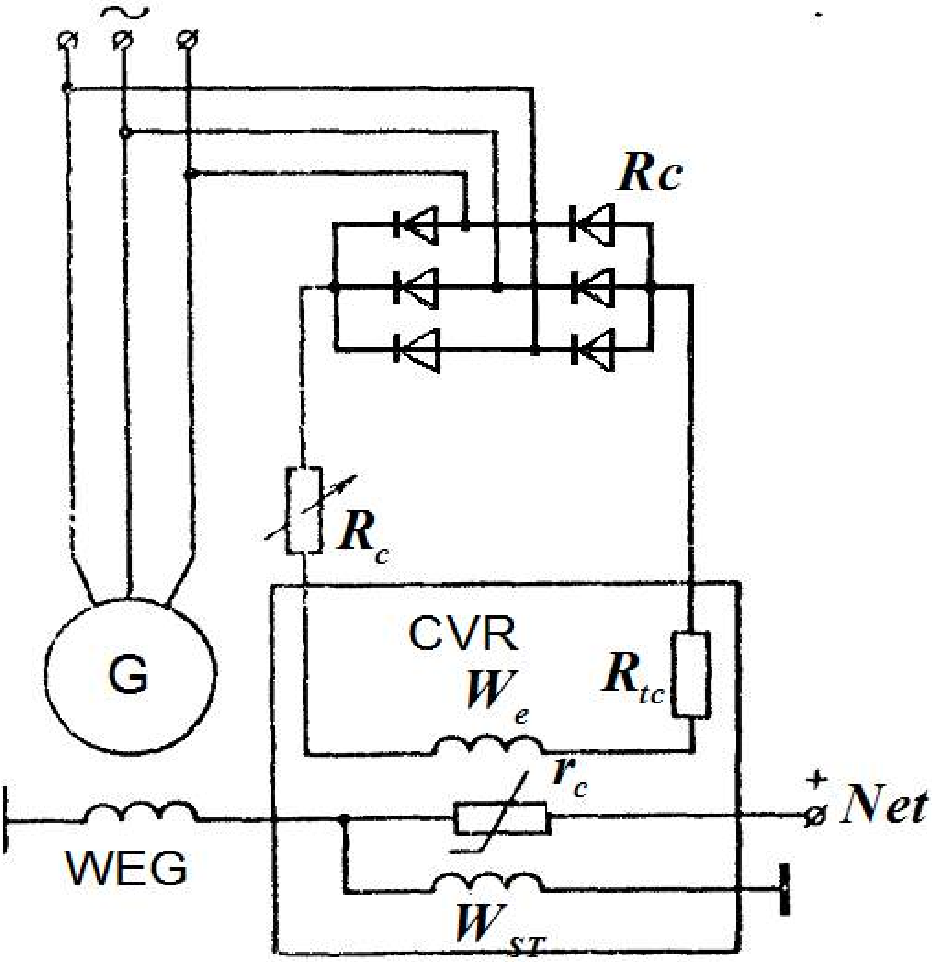


Fig. 5.4. The circuit of CVR connection for synchronous generator

Unlike CVR of the direct current a stabilizing winding of the regulator W_{st} is applied here, which is connected in parallel to the generator excitation winding.

5.4. Voltage Regulator with Application of Magnetic Amplifiers

Voltage regulator with application of contactless regulating elements - magnetic amplifiers (MA) are more accurate, reliable and convenient in operation, as CVR cannot ensure high accuracy of voltage regulation, have low stability (due to carbon washers wear) and low reliability (due to the presence of the contact device - a carbon pile).

In Fig. 5.5 an electrical circuit of VR of brushless synchronous generator (SG) with the use of single-cascade MA is shown.

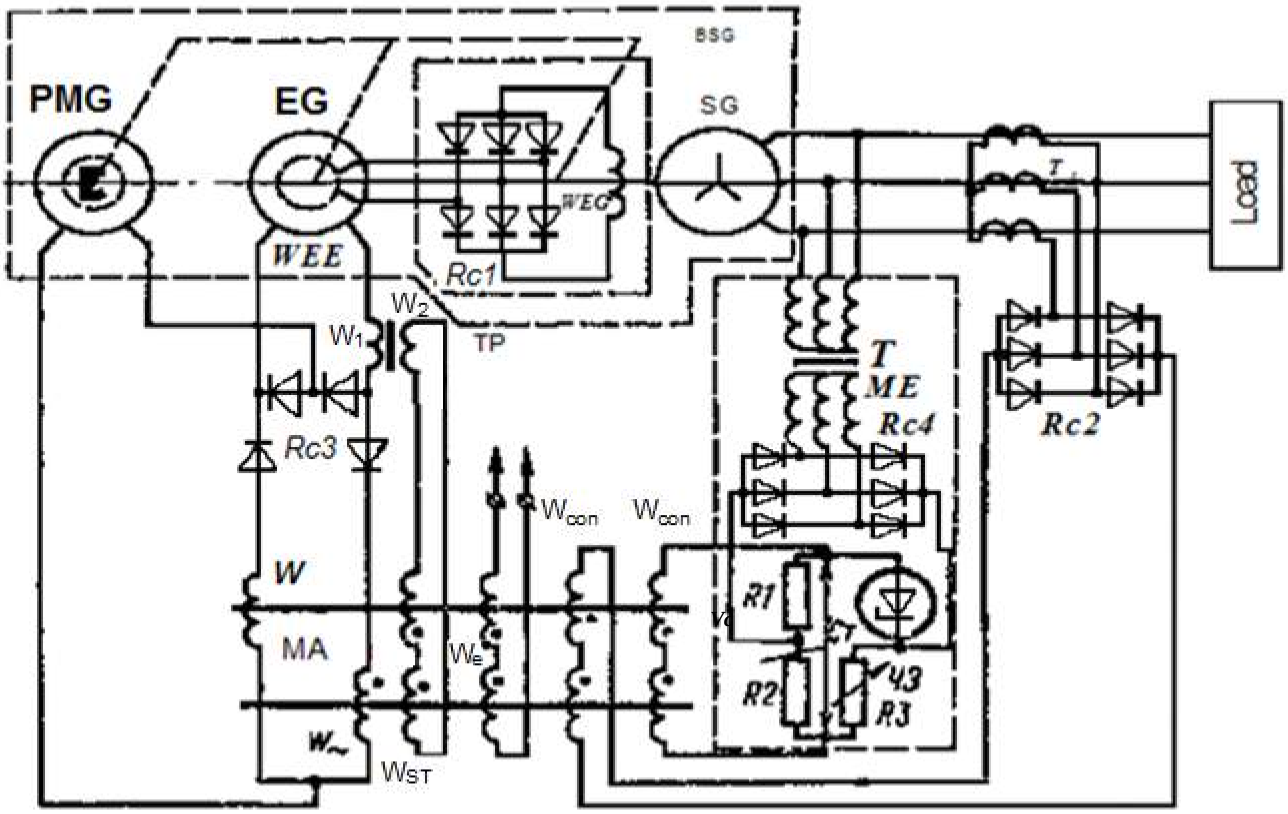


Fig 5.5. The electrical circuit of the VR block:

Main elements of the circuit are:

– Permanent Magnet generator (PMG);

– Exciter generator with rotating three phase rectifier R_c1 (EG).

– object of regulation (SG);

– regulating element (single-cascade of magnetic amplifier, mA);

– measuring element, ME (non-linear bridge with a zener diode fed from three-phase voltage of SG through the transformer *T* and rectifier R_c4;

– stabilizing devices (***T*** and a current transformer T_t, connected to the appropriate winding of MA – W_{ST} and W_{con}.

This automatic control system of the regulatory type carries out the combined regulation on the voltage deviation with the help of the non-linear bridge and control winding W_{con}, as well as on the load current I with the help of the current transformer, rectifier and winding W_{con}. Such regulation makes a system more accurate in the established modes.

Nowadays voltage regulators constructed on semi-conducting devices are applied more and more widely. The block diagram of a standard automatic control system of the aircraft generator voltage, constructed on semi-conductor devices is shown in Fig. 5.6.

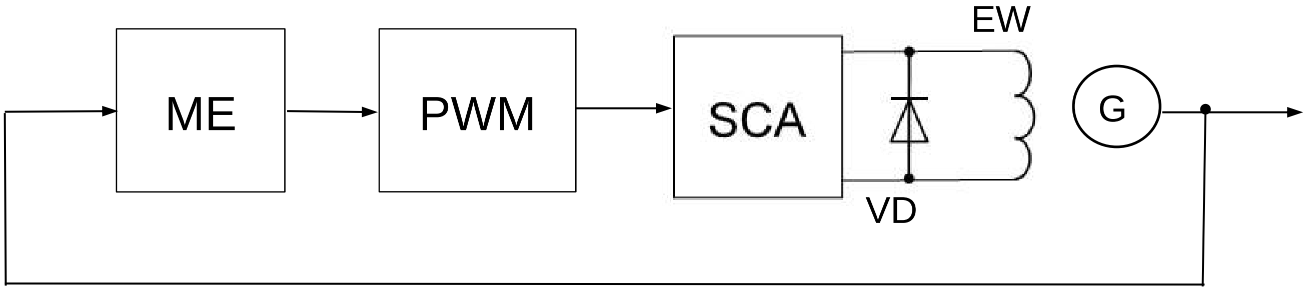


Fig. 5.6. The block diagram of semi-conducting VR

The circuit includes a measuring element (ME); pulse-width modulator (PWM), with the help of which relative pulse duration is changed depending on the adjustable voltage value; semi-conducting amplifier (SCA), excitation winding (EW), which in combination with the rectifier valve (VD) serves as a demodulator transforming a series of pulses into a current, the average value of which depends on the relative pulse duration.

5.5. Alternator Voltage Regulators

There are two major types of alternating generators (alternators) currently used on aircraft, the **DC alternator** and **AC alternator**. DC alternators are most often found on light aircraft, where the electric load is relatively small.

AC alternators are found on large commercial airliners and many military aircrafts. Since these aircrafts require large amounts of electric power the use of AC systems creates a valuable weight saving. Through the use of transformers, the transmission of AC electric power can be accomplished more efficiently and therefore with lighter equipment. With the transmission of electric power at relatively high voltages and low current, the power loss is kept to a minimum.

In large aircraft, AC power is used directly to perform the majority of power functions for the operation of control systems and electric motors for a variety of purposes. On light aircraft, most electric devices operate at ***14*** or ***28 V*** DC power.

Unlike DC generators and DC alternators require only two means of control for a voltage regulator and current limiter. The reverse-current cutout relay is not needed, because the alternator’s rectifier resists any current flow into the armature. The current limiter for most DC alternators is a simple circuit breaker. **The voltage regulator** may be a vibrator-type or carbon-type, as discussed with regards to generators, or a transistorized unit. In either case, the voltage regulator controls alternator output by varying the alternator’s input. Specifically, the voltage regulator increases the field circuit’s resistance to decrease the alternator’s output. Conversely, a decrease of the field circuit’s resistance will increase the alternator’s output.

Transistorized Voltage Regulators

One type of **transistorized voltage regulator** (TVR) contains a field relay that supplies current to the transistor; the transistor controls the current to the field. A transistor contains no moving parts; therefore, there are no contact points to fail and (or) change resistance. As the contact points of a vibrating-type regulator become pitted the accuracy of the regulator decreases and the unit eventually fails; therefore, transistorized regulators are generally considered more accurate and reliable.

Some VR contain a field relay to "turn on" the regulator and use a transistor to regulate the alternator output voltage. One example of this type of regulator consists of a field relay, a transistor, a voltage regulator winding, a diode, and resistors.

The field relay is similar to relays previously discussed. Essentially, the relay is an electromagnetically controlled switch used to connect the alternator output to one terminal of the alternator field. The other side of the field circuit is controlled by the transistor and the VR coil.

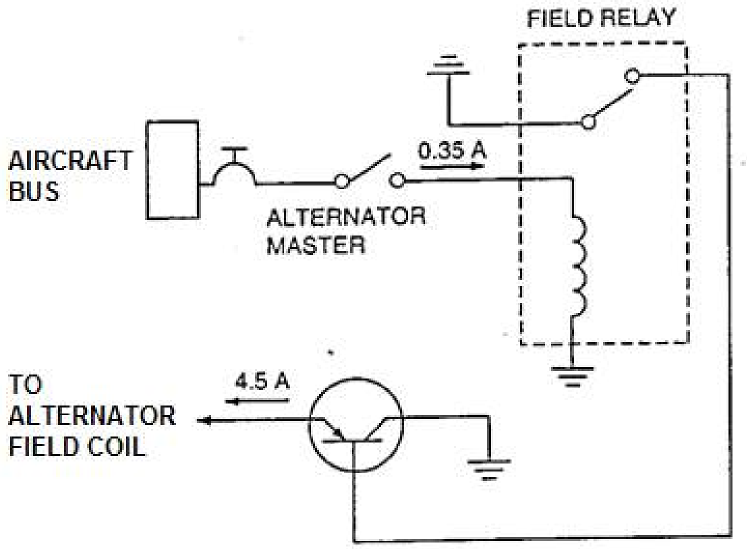


Fig. 5.7. Simplified schematic of a transistorized VR

The field control circuit of the transistorized VR is shown in a simplified form in Fig. 5.7.

In this circuit the field relay is controlled by the alternator master switch. The alternator master switch is often one-half of a dual master switch. The other half of the switch controls a solenoid, which connects the aircraft battery to the bus. When the alternator master switch is closed, the field relay closes and connects the transistor base connection to the aircraft ground (negative connection). In a typical system this will allow about ***4.5 A*** to flow through the field winding.

A p-n-p transistor becomes a good conductor through the emitter-collector section when the base circuit has negative bias. In the case of the regulator under discussion, the base circuit carries approximately ***0.35 A*** when the VR contact points are closed.

When the alternator voltage attains the value for which the regulator is adjusted the regulator contact points are opened by the magnetic force of the voltage relay thus cutting off the base current to the transistor. The emitter-collector section then becomes nonconductive, and the field current is blocked. The alternator voltage then drops, and the regulator points close again to provide bias for the transistor-base circuit. Field current can then flow through the transistor, and the voltage rises to the regulated value. This cycle continues with the regulator contact points vibrating rapidly (about ***2000*** times per second) to maintain the alternator voltage at required value.

In this type of VR, the transistor carries the field current (***4.5 A***), while the contact points a much lower current (***0.35 A***). By applying a relatively low current through the contact points, the reliability of the VR is significantly increased.

A more complete schematic diagram of VR and alternator circuits is shown in Fig. 5.8.

The diagram of the alternator shows the stator in which the alternating current is generated; the field coil and slip rings, through which current flows to the field coil; and the six diode of the rectifier. When the alternator master switch is closed the battery and alternator are connected to the field-relay coil to produce a magnetic field that closes the relay contacts. When this happens current flows from ground through the emitter-collector circuit to the control transistor and the F_1 terminal of the regulator and to the F_1 terminal of the alternator. After passing through the alternator field, the current enters the F_2 terminal of the regulator and passes through the closed field-relay contact points and out of the BAT battery terminal of the regulator. From this point it flows to the positive (+) terminal of the alternator, through the rectifier network, and to ground.

When the field winding of the alternator is energized, a DC voltage will be delivered to the system by the alternator, provided of course, that the alternator is running. As alternator voltage increases current flow through the two winding of VR coil will increase. When the voltage reaches the value for which the regulator is adjusted the contact points in the regulator section open. This lowers the emitter-base current in the transistor, and the transistor lowers the current to the alternator field.

With the contact points open, the alternator field winding receives less current, and the alternator voltage immediately decreases. With the low alternator output, the spring at the end of contact arm closes the points, and cycle repeats as previously explained. The high rate of vibration of the contact points provides a steady voltage for all practical purposes. Since the VR contact points are held closed by a spring when the voltage is below the desired value, and the points are opened as a result of alternator voltage reaching this value an increase of spring tension will cause the alternator voltage to increase. Voltage adjustments are therefore made by turning the screw that controls the spring tension.

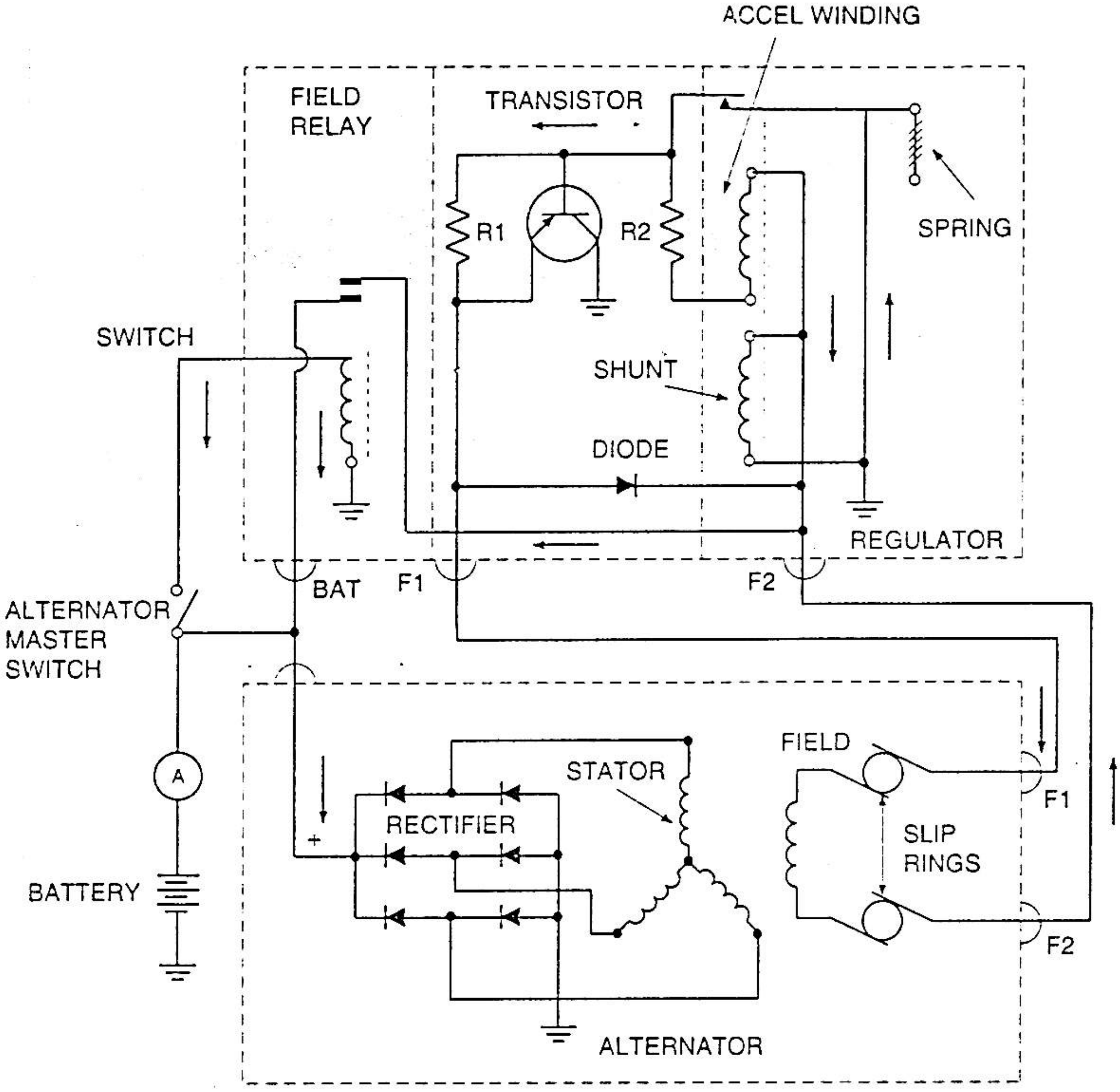


Fig. 5.8. Transistorized voltage regulator and alternator schematic diagram.

It is important to note that VR contact point carry only about ***0.35 A*** when the alternator field current is over ***4 A***. On regulators without transistor control, full generator field current must pass through the regulator contact points. Since vibrating contact points are burned by higher amperages, the use of a transistor makes it possible to increase the life of the contact points because of the lower current through the points.

In the diagram in Fig. 5.8, observe that the **accelerator winding** on the VR is connected to the regulator's F_2 terminal (a positive voltage point) and through a resistor and the contact points to ground. This winding will therefore carry less current when the contact points are open. The effect of this arrangement is to reduce the magnetic pull on the contacts as soon as contact points open, thus making the spring more effective in closing them again. When the contact points are closed the magnetic effect of the accelerator winding is added to the total magnetic force again, and the points reopen very quickly. The effect of the accelerator winding thus causes the contact points to vibrate (open and close) much more rapidly than they would with the shunt coil only. This is the reason for the term **accelerator winding**.

The diode in the regulator is connected directly across the field winding. If the voltage contacts opened without a diode in this circuit the interruption of field current and the resulting high voltage induced in the field winding would damage or destroy the power transistor. The diode is connected in such a manner to offer a high resistance to any applied voltage and a low resistance to any voltage of reversed polarity. The high voltage induced in the field relay, as the contact points open, is a reverse-polarity voltage. Thus the diode will short any current produced in this manner. The shorted current is therefore unable to the transistor.

In the use of transistors, it is important to note that high temperatures can cause improper functioning and permanent damage of the transistors. For this reason the transistors used with VRs or in any other circuits must be kept at safe operating temperatures. The transistors used with VRs usually have heavy metal bases, which act as heat sinks to carry the heat away from the active elements. In any installation the maximum safe operating temperature for the transistor must be known, and provision must be made to assure that this temperature is not exceeded.

Solid-State Voltage Regulator

A circuit diagram to illustrate the operation of a completely solid-state VR is shown in Fig. 5.9.

This regulator has no moving parts and is generally considered more reliable. In the description that follows, each item will be explained in terms of actual current flow from negative to positive. For example, when the battery is furnishing current to the circuit, current flows from the negative terminal (ground) through the circuit into the positive terminal of the battery. When the battery is being charged, current is flowing to negative terminal of the battery and out of the positive terminal.

In the circuit, when the alternator master switch is closed, the battery and alternator are connected to the relay and through relay to the positive terminal (A) of the regulator.

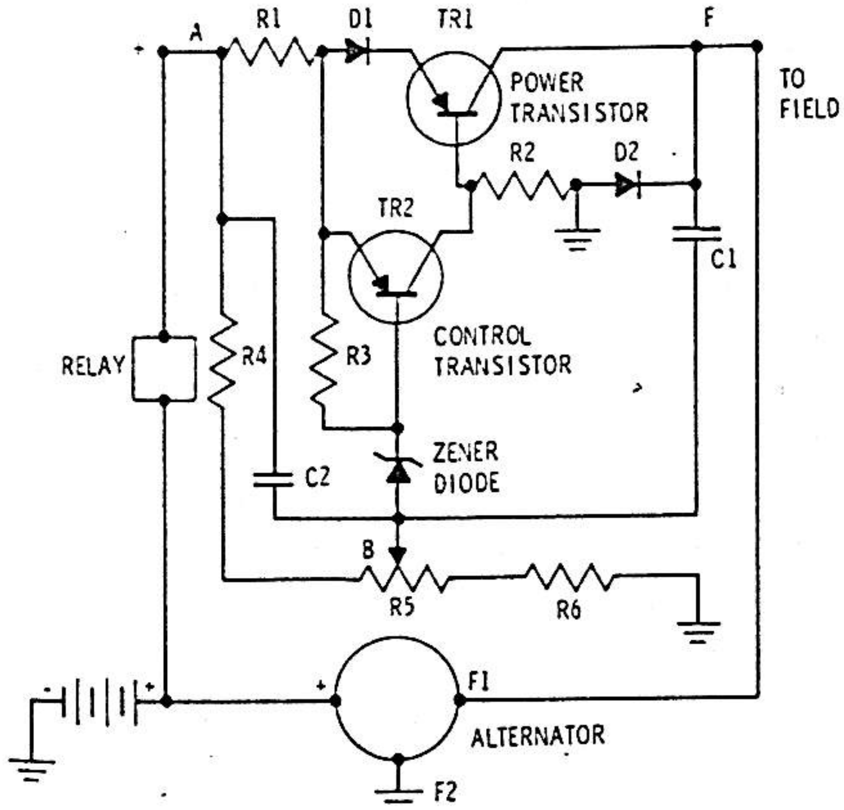


Fig. 5.9. Solid-State Voltage Regulator

There is then a complete circuit from ground through the resistor R_2, the base of the **power transistor** TR_1, the diode D_1, and the resistor R_1 and back to the battery and the positive terminal of the alternator. If the output of the alternator is below the voltage for which the regulator is set, transistor TR_1 will have forward bias, and current will flow from the F_1 terminal of the alternator to the F terminal of the regulator and through the emitter-collector circuit of TR_1. The circuit is completed through D_1, R_1, and the relay to the alternator. This current flow excites the field of the alternator, and the output of the alternator quickly rises to the desired level. In the circuit in Fig. 5.9, it can be seen that there is a circuit from ground through R_6, R_5, the **zener diode**, R_3 and R_1 to ***A***. There is also a circuit from the zener diode through the emitter-base circuit of the **control transistor** TR_2 and through R_1 to terminal ***A*** of the regulator. The zener diode blocks the flow of current from R_5 until the voltage between ground and ***A*** reaches approximately ***14.5 V***. At this point the zener diode begins to conduct current and applies a forward bias through the emitter-base circuit of TR_2, the control transistor. TR_2 then becomes conductive, and current flows through the emitter-collector section from ground. This current flow is from ground through R_2, TR_2, and R_1 and out ***A***. The effect of this is to short-circuit the emitter-base circuit of TR_1, and this causes TR_1 to stop conducting field current for the alternator. The alternator voltage immediately drops, and the zener diode stops conducting thus removing the forward bias from TR_2, which also stops conducting. This returns the forward bias to TR_1, which starts conducting field current again, and the cycle repeats. This cycle repeats about 2000 times per second, thus producing a reasonably steady voltage of approximately ***14.5 V*** from the alternator.

Transistorized Voltage Regulator Operating Theory

The two key points to understand with respect to operation of the transistorized VR are the zener diode operation and the control of the power transistor by the control transistor. The zener diode can be compared to a relief value that opens at a given pressure in a hydraulic system.

When the zener diode conducts current it causes the control transistor to shut off the power transistor. The reason that the control transistor can stop the flow of current through the emitter-base circuit of the power transistor is that there is a difference in the voltage drops across the emitter-base circuit of the two transistors when the control transistor's emitter-base circuit is conducting. The diode D_1 causes approximately a ***1 V*** drop in potentional across the emitter-base circuit of the power transistor when the circuit is conducting. When the emitter-collector circuit of the control transistor conducts current, there is no appreciable voltage drop across the control transistor; hence a ***1 V*** reverse bias becomes effective across the emitter-base circuit of the power transistor. This of course, stops the emitter-base current in the power transistor.

Adjustment of alternator voltage output is accomplished through the variable resistor R_5. A change in the resistance of this resistor will change the voltage level across the zener diode, thus raising or lowering the level of alternator output voltage required to cause the zener diode to conduct.

The resistor R_1 and capacitor C_1 act to reduce the time required for the field voltage to change between maximum and minimum values. This prevents overheating the transistor. The capacitor C_2 reduces the voltage variations that appear across the resistors R_4 and R_5, thus making the regulator more accurate. Resistor R_3 prevents leakage current from the emitter to the collector in the control transistor. Resistors R_4 is of special temperature-sensitive type that acts to increase the alternator voltage slightly at a low temperature. This aids in maintaining adequate charge current low-temperature operation. Diode D_2 aids in controlling field current flow as the power transistor rapidly turns the field current on and off.

There are many modern VRs that also monitor system voltage for any improper values. This **alternator control unit** (ACU) not only regulates alternator output voltage but also turns off the charging system if an overvoltage condition exists. The ACU also controls a low-voltage light, which illuminates in the event of a charging system failure.

5.6. Stabilization of alternating current generator frequency

At the direct connection of synchronous generators to the aircraft engine, with the change of its rotation frequency the generator frequency will also change. The stabilization of aircraft generator frequency can be carried out either by stabilization of the generator rotation frequency by means of installation of a regulating device called a constant speed drive (CSD), between the primary engine and generator; either by using cascades of adjustable electrical machines or by application of frequency converters.

Auxiliary engines for generator drives also have a wide range of rotation frequency changes. In this case, engine rotation frequency stabilization is used most often.

Classification of synchronous generator constant speed drives

The constant speed drive represents a device converting the energy of the aircraft engine into the mechanical energy of the generator shaft rotation with constant frequency.

By a type of energy used in CSD they are subdivided into mechanical, pneumatic and electromechanical drives.

By a way of energy conveyance to the output shaft CSD are divided into drives with complete energy conversion and drives of a differential type.

In drives with complete energy conversion all the energy taken off from the engine is transformed.

In drives of a differential type only a part of the energy is converted, and the other part, as a rule, the greater one, is conveyed to the generator G from the aircraft engine AE shaft through a differential reduction gear (DRG) (Fig. 5.10).

The reduction gear has rather high efficiency. (***95%*** and more), and therefore the differential drive efficiency will be greater than the efficiency of the drive with the complete energy conversion.

The summation of two flows of energy is carried out with the help of a differential reduction gear, which allows to receive resulting movement of its output shaft as a sum or difference of movements of the aircraft engine shaft and the shaft of the intermediate energy converter. In this case, the generator shaft velocity is

$$\omega_G = \omega_{ae} \pm \omega_a ,$$

where ω_{ae} is the aircraft engine angular velocity referred to the generator shaft;

ω_a is the adjustable angular velocity of the output shaft of the intermediate energy converter CE.

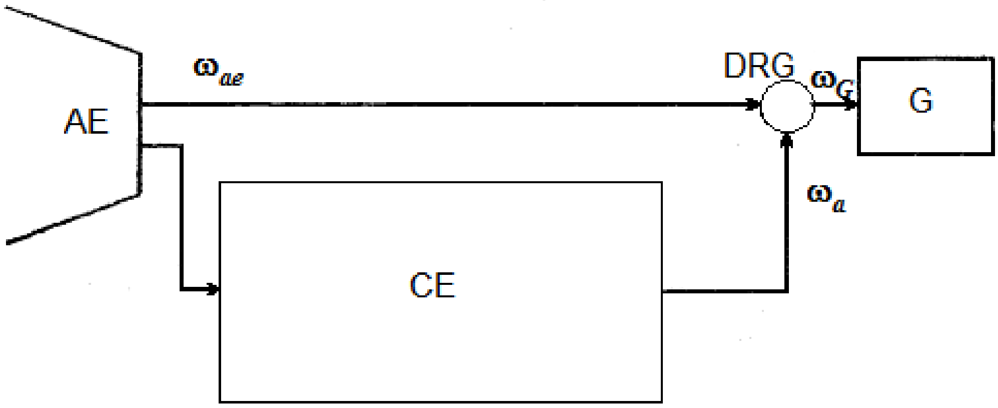


Fig. 5.10. The scheme of the differential CSD

At the change of the aircraft engine shaft angular velocity the system of CSD regulation changes the output shaft angular velocity ω_a in such a way that $\omega_G = const$.

In order to reduce overall dimensions and specific weight, the generator and CSD are united in a uniform structure – a drive of an integrated type.

A schematic diagram of the generator shaft rotation frequency adjuster is shown in Fig. 5.11.

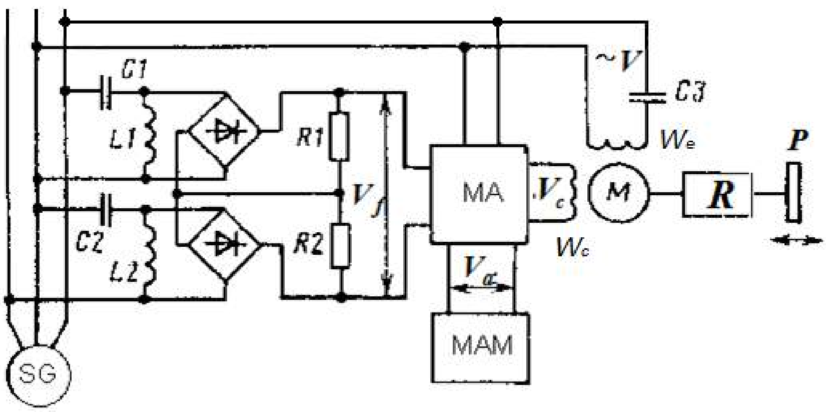


Fig. 5.11. The rotation frequency adjuster

The measuring element of the adjuster consists of two resonant circuits: L_1C_1 and L_2C_2. The resonant frequency of adjustment of the first circuit is a little bit higher than the rating value of the frequency being stabilized f_a, and the frequency of adjustment of the second circuit is a little lower than the rating value (Fig. 5.12).

$$V_f = K_f \Delta f.$$

The voltage on inductive elements L_1 and L_2 are proportional to the currents I_1 and I_2 flowing over the resonant circuits, and, hence, the voltage removed from identical resistors R_1 and R_2 will be proportional to a difference of the currents I_1 and I_2. At small deviations from f_n the difference of the currents linearly depends on frequency, therefore the voltage at the output of the measuring element will be proportional to the generator frequency deviation Δf.

The signal V_f goes to the magnetic amplifier (MA). MA output is connected to the control winding with W_c of the capacitor asynchronous engine M, the second winding of which is fed from the synchronous generator SG through the phase-shifting capacitor C_3.

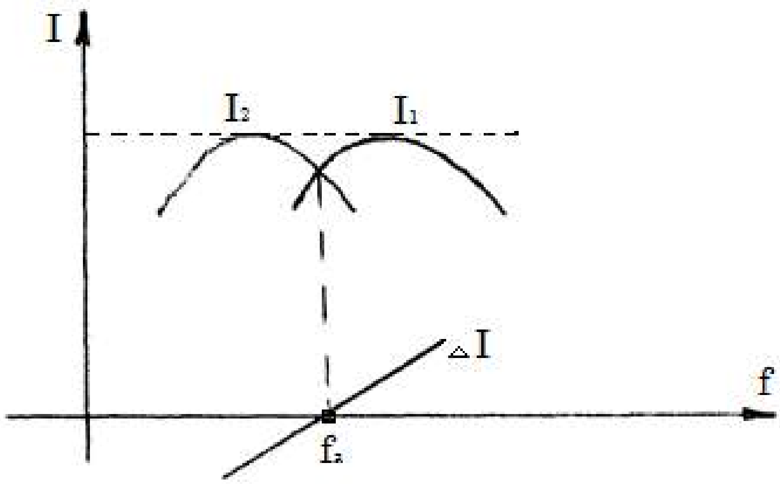


Fig. 5.12. Characteristics of the resonant circuits of the adjuster

The capacitor engine influences a platform P through a worm reduction gear R, changing a degree of the centrifugal regulator spring compression.

5.7 Regulation of frequency and voltage of electric machine converters

The electric machine converters are used as sources of the stable frequency alternating current. On the airplane, where the primary system of the stable frequency alternating current power supply is applied, the electric machine converter serves as an emergency source, which is switched on at a failure of the primary system of electric power supply.

The electric machine converters convert the energy of the direct current with a voltage of ***27 V*** into an alternating single-phase current with a voltage of ***115 V*** or into a three-phase current with a linear voltage of ***36 V*** and frequency of ***400 Hz***. The converters are made for power of up to ***6000 W***. Each converter consists of an electric machine unit and control box. The electric machine unit represents two electric machines on the common shaft in the uniform case: a direct current motor and an alternating current generator. The control box contains equipment for start-up and stabilization of the converter frequency and voltage.

Disadvantages of the electric machine converters are presence of a brush-commutator unit, low efficiency (***0,45*** … ***0,6***), great specific weight. Therefore at present electric machine converters are forced out by static ones having higher efficiency, longer service life.

5.8. Terms and concepts

1. **Accelerator winding** causes the contact points to vibrate (open and close) much more rapidly than they would with the shunt coil only.
2. **Alternator control unit is a solid-state voltage regulator containing current and voltage sensor**
3. **Automatic frequency control (AFC) is a circuit arrangement that maintains the frequency of the system within specified limits.**
4. **Bias is a voltage applied to the control element of a transistor to establish the correct operating point.**
5. **Carbon pile voltage regulator is a regulator which operation is based on the change of resistance of carbon pile or stack of carbon disks.**
6. **Master switch is a switch designed to control all electric power to all circuits in a system.**
7. **Magnetic amplifier is an electromagnetic circuit that produces amplification.**
8. **Pile (stack or carbon disks) is a carbon stack used for voltage stabilization.**
9. **Voltage regulator is a circuit that maintains a constant level voltage supply (CVS) despite changes in input voltage or load.**

5.9. Control Questions

1. What kind of drives of direct and alternating current generators are used on airplanes?
2. What are the causes of instability of the airplane generator voltage and frequency value?

3. For voltage regulation, which of the following is varied: rpm, field strength, or turn numbers of armature winding?
4. Describe the action of a vibrator-type voltage regulator.
5. What is the function of the carbon-pile in a carbon-pile VR?
6. Describe the operation of a carbon-pile voltage regulator.
7. What is advantage of using a transistorized VR?
8. What are the two key points that describe the operation of a transistorized VR?
9. How is voltage adjusted when a transistorized VR is used?
10. What is the function of the zener diode in a transistorized VR?
11. What units are used in a transistorized VR to regulate alternator voltage?
12. Describe the function of the alternator master switch?

Chapter 6

SECONDARY SOURCES OF THE ELECTRIC POWER

6.1. Classification of Electric Power Converters

The secondary systems of electric power supply are intended for feeding such aircraft consumers, for which either sort of current, or voltage value and frequency can not be used for ensuring their normal functioning. So, for example, gyroscopic devices require 36 V 400 Hz (500, 1000), devices on semi-conductor elements require 12 V, 5 V etc.

Due to a variety of consumers in the secondary circuits of electric supply the electric power is produced for them as a result of primary source energy transformation by type of current, voltage and frequency. These transformations are carried out with the help of electric machine and static converters.

Typical examples of power conversion are:

– conversion from DC to AC power – this conversion uses units called **inverters** to convert 28 V DC to 115 V AC single phase or three-phase power;

– conversion from 115 V AC to 28 V DC power – this is a much used conversion using units called **Transformer Rectifier Units** (TRUs);

– conversion from on AC voltage level to another; a typical conversion would be from 115 V AC to 28 V DC;

– battery charging – as previously out lined it is necessary to maintain the state of charge of the aircraft battery by converting 115 V AC to a 28 V DC battery charge voltage;

– in more recent military and commercial airplanes utilizing 270 V DC is required to power legacy equipment's originally designed to operate using these voltages.

The equipment required for the conversion of main power supplies can be broadly divided into two main parts: **rotating and static**, and the fundamentals of construction and operation of typical devices and machines are described under these headings.

6.2. Rotary Converting Equipment (Inverters)

The most commonly used item to be included this heading is the machine which converts DC into AC and is variously called a «rotary converter», «motor-generator» and an «inverter». All three terms can understandably, cause some confusion regarding their definition with the result that they tend to be loosely applied to machines which, although performing the same function, have quite different constructional and electrical circuit features.

Inverters consist of speed-governed DC motor, an armature and brush assembly, and a permanent magnet inductor – type AC generator, in one unit.

As an example the structure of the electric machine converter of the DC into AC is shown in Fig.6.1. In most inverters, the DC armature and the AC generating field windings are on the same rotor shaft. The DC motor field and generator output (armature) winding are on the stator. A control box on the inverter contains the necessary devices to control the inverters operation. These devices consist of the operating relays, voltage regulator and rectifier, filtering units, and smaller circuit components.

The DC motor of most aircraft inverters is essentially a shunt-wound motor. High starting current and a low rate of acceleration (due to low torque at starting) are characteristic of shunt-wound inverters.

The speed of a DC motor is inversely proportional to the strength of the field, so as the motor speed up, more current flows in the shunt windings, reducing the speed.

The generator AC voltage is proportional to the speed of the rotor and the strength of the generator rotor field flux. The controlled frequency of the AC output is usually 400 Hz. This frequency is a function of the number of poles in the generator field and the speed of the motor. Some inverters supply both three-phase and single-phase outputs.

For transformation of the low voltage direct current into the high voltage direct current or the stable frequency alternating current electric machine converters of an engine-generator type (converters) have received application on aircraft. Such converters represent a combination of the low voltage electric engine and the constant or alternating voltage generator in one machine. The generator and engine have a common body. The engine armature and the generator armature (rotor) have a common rotary shaft. As an example, the structure of the electric machine converter of the direct current into the alternating one is shown in Fig. 6.1. As we see from this figure, an engine of the constant current with parallel excitation is used as the engine. The engine operates on the supply line with the voltage of 27 V of the direct current. At the generator rotor spinning a three-phase voltage of 36 V 400 Hz is induced on its stator winding.

The difference of the low voltage direct current electric machine converter into the high voltage constant current from the considered one consists in the following. The engine and generator have one armature with two windings, two collectors and a common polar system. One winding is powered from 27 V supply line, the other is the generating one. The generating winding has a large number of coils and high output voltage (up to 1500 V).

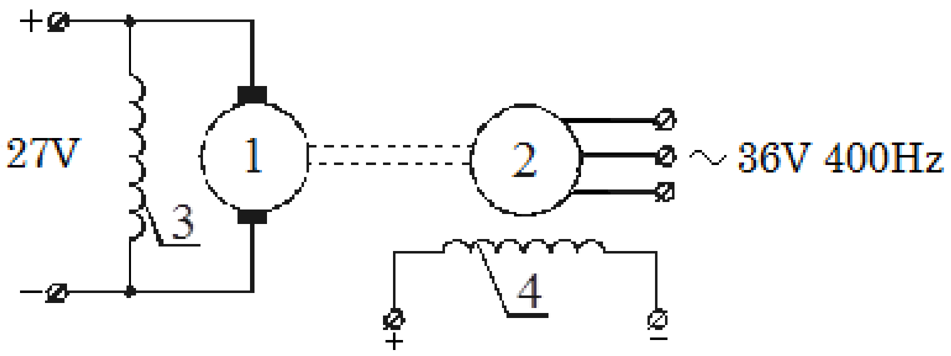


Fig. 6.1. The electric machine converter of the direct current into the alternating one:
1 – direct current engine; 2 – alternating current generator;
3 – motor excitation winding; 4 – generator excitation winding

The structural scheme and electrical circuit of the converter are shown in Fig. 6.2.

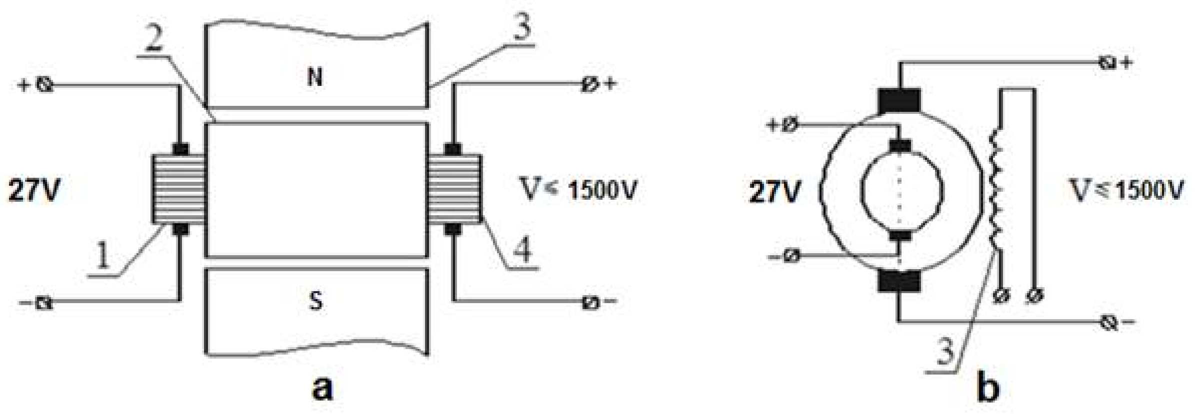


Fig. 6.2. The low voltage direct current electric machine converter into the high voltage direct current:
a – structural scheme; b - electrical circuit;
1 – collector of the engine; 2 – common armature; 3 – common polar system;
4 – collector of the generator; 5 – (common) drive winding

The electric machine converters have low efficiency (0,4... 0,55), relatively large weight and sound at operation. Therefore they are gradually replaced by so-called static converters.

6.3. Static Inverters

This inverters perform the same conversion function as the rotary machines described earlier, but by means of solid-state or static circuit principles. They are employed in a member of types of aircraft in some cases as a normal source of AC power to certain essential systems when a failure of the normal 115-volts source has occurred. The function of an inverter used for the conversion of battery supply to single-phase 115-volts source AC is shown in the block diagram of Fig.6.3.

The DC is supplied transistorized circuit of a filter network, a pulse shaper, a constant current generator, power driver and the output stage. After any variations in the input have been filtered or smoothed out DC is supplied to a square-wave generator which provides first-stage conversion of the DC into square-wave form AC and also establishes the required operating frequency of 400Hz. This output is then supplied to a pulse shaper circuit which controls the pulse width of the signal and changes its wave form before it is passed on to the power driver stage. It will be noted from the diagram that the DC required for pulse shaper operation is supplied via a turn-on delay circuit. The reason for this to cause the pulse shaper to delay its output to the power driver stage until the voltage has stabilized. The power driver supplies a pulse-width modulated symmetrical output to control the output stage the signal having a square-wave form. The power driver also short itself out each time the voltage falls to zero i.e. during “notch time”.

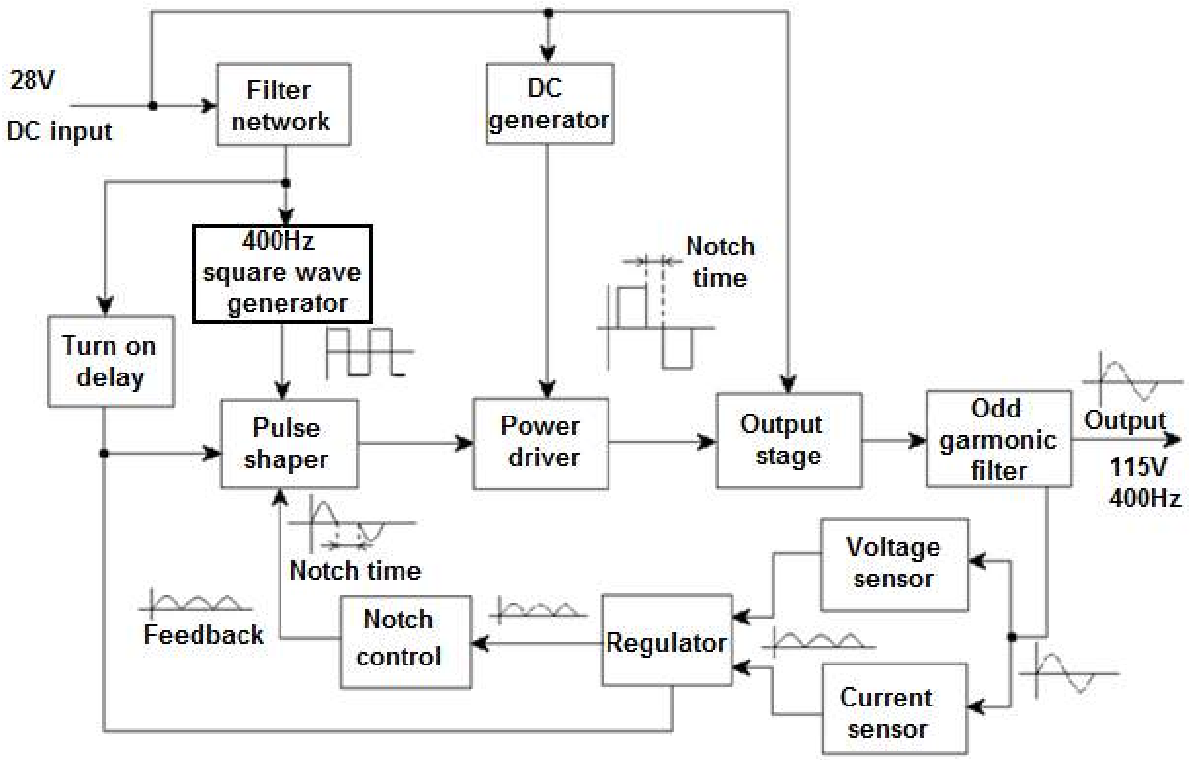


Fig.6.3. Static inverter principle

The output stage also produces a square-wave output but of variable pulse width. This output is finally fed to a filter circuit which reduces the total odd harmonics to produce a sine wave output at the voltage and frequency required for operating the system connected to the inverter.

As in the case of other types of generators, the output of static inverter must also be maintained within certain limits. In the example illustrated, this is done by means of a voltage sensor and a current sensor, both of which produce a rectified AC feedback signal which controls the "notch time" of the pulse shaper output through the medium of a regulator circuit and a notch control circuit.

A typical inverter used in a large commercial aircraft can produce 1 kVA. Static inverters are located in an electrical equipment bay; a remote on/off switch in the flight compartment is used to isolate the inverter if required.

6.4. Static converters of alternating current into the constant one

Let us consider the structure and operation principle of the static converter of the alternating current in the constant one.

The static converters of the alternating current in the constant one are intended for the alternating current transformation, for example, 115 V 400 Hz, into the constant current with a voltage of 28,5 V. In general, by means of such converters it is possible to transform practically any alternating voltage into any constant voltage. The base of such a converter are transformer-rectifier units and smoothing filters.

The most widespread rectifier devices are full-wave or half-wave multiphase circuits of rectification. Silicon semi-conductor diodes are mainly used as rectifier elements.

Transformer-rectifier units with silicon rectifiers have efficiency, high reliability, small weight (approximately from 1,8 up to 1,4 kg / kVA).

Let us consider the most widespread circuits of rectifiers connection:

1. The circuit of a **single-phase half-wave rectifier** and the output voltage oscillogram are shown in Fig. 6.4.

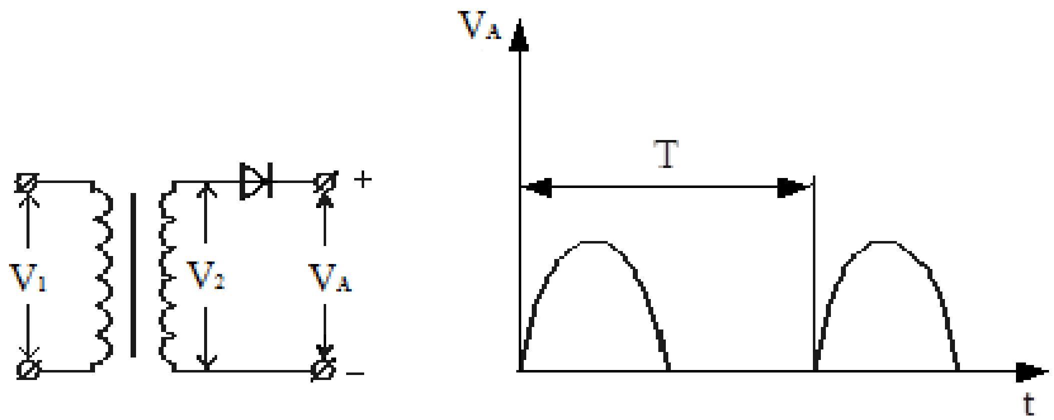


Fig. 6.4. Single-phase half-wave rectifier

1. The circuit of a **single-phase full-wave rectifier** with a midpoint and the output voltage oscillogram are shown in Fig. 6.5.

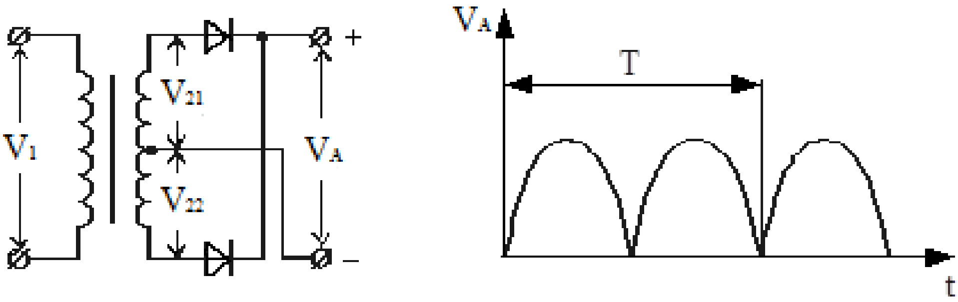


Fig. 6.5. Single-phase full-wave rectifier

3 The **bridge circuit of full-wave rectifier** and the output voltage oscillogram are shown in Fig. 6.6.

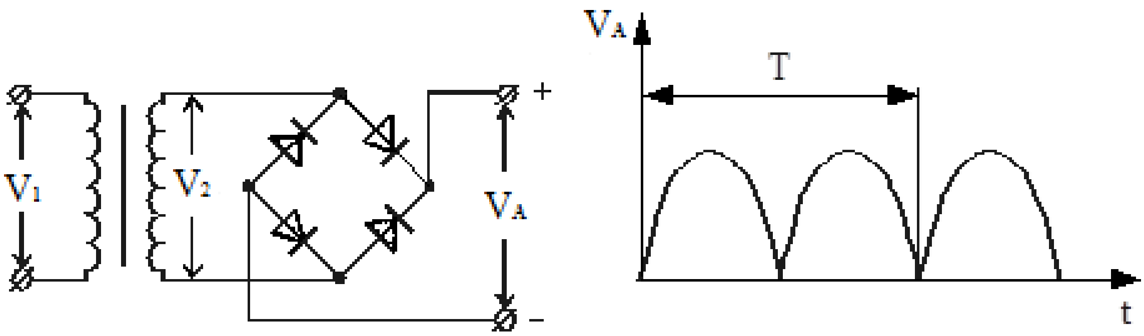


Fig. 6.6. Bridge circuit of full-wave rectifier

4. The circuit of a **three-phase half-wave rectifier** and the output voltage oscillogram are shown in Fig. 6.7.

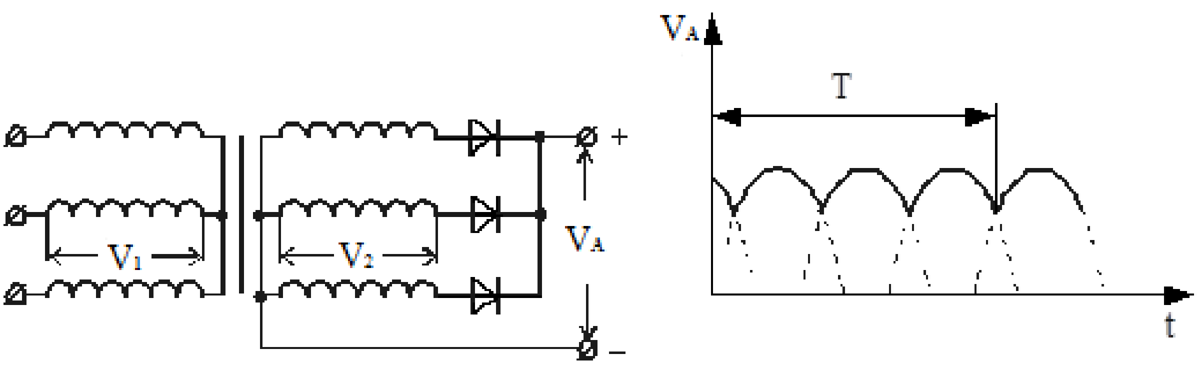


Fig. 6.7. Three-phase half-wave rectifier

5. The **bridge circuit of a three-phase half-wave rectifier** and the output voltage oscillogram are shown in Fig. 6.8.

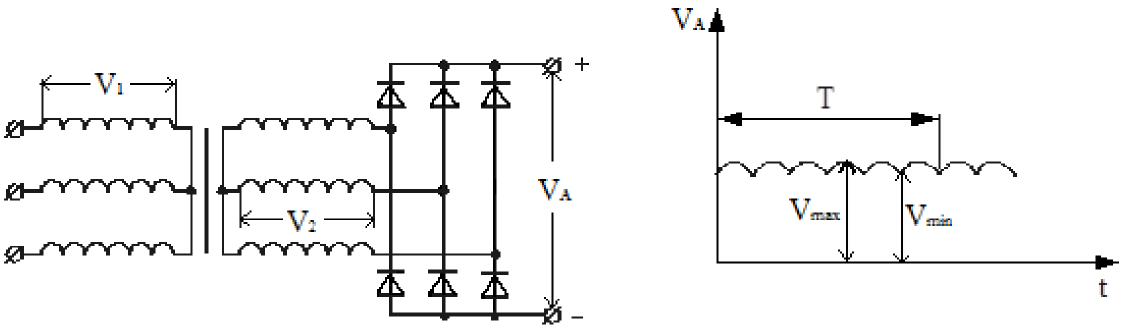


Fig. 6.8. Bridge circuit of a three-phase half-wave rectifier

Characteristics of the considered rectifiers are shown in table 6.1.

Table 6.1. The comparative characteristics of rectifiers

#	Designation of a circuit	Fig.	Basic correlations				
			$\frac{V_A}{V_2}$	$\frac{I_2}{I_A}$	K_p	$\frac{V_{INV}}{V_A}$	$\frac{P_{TR}}{P_A}$
1	2	3	4	5	6	7	8
1	Single-phase half-wave	16.4	0.45	1.57	1.57	3.14	3.1
2	Single-phase full-wave with an average point	16.5	0.9	0.78	0.67	3.14	1.48
3	Bridge single-phase full-wave	16.6	0.9	0.78	0.67	1.57	1.21
4	Three-phase half-wave (Mitkevich circuit)	16.7	1.17	0.58	0.25	2.1	1.35
5	Bridge three-phase full-wave (Larionov circuit)	16.8	2.34	0.58	0.057	1.05	1.05

For comparison of the rectifier circuits shown in Fig. 6.4...6.8 we shall introduce the following notations:

– V_1 is voltage on a primary winding of the transformer;
– V_2 is voltage on a secondary winding of the transformer;
– V_A is rectified average voltage on the rectifier output;
– V_{INV} is a value of the reverse voltage coming on the arm of the rectifier system (the reverse on the diode);

– I_W is a value of the operating current in a secondary winding of the transformer;

– I_A is average current through the rectifier valve;

– $K_P = \frac{V_{max} - V_{min}}{V_A}$ is a voltage ripple factor,

where V_{max}, V_{min} are maximal and minimal values of voltage at the rectifier output (see Fig. 6.8).

The relation of the standard transformer capacity P_{TR} to the available capacity of the rectifier $\boldsymbol{P_A=U_AI_A}$ is shown in column 8 of table 6.1 for orientation of the standard transformer selection.

As we see from tab. 6.1, the rectified voltage ripple amplitude reduction is achieved due to the increase of the phase number of the transformer secondary windings. Besides, the ripple amplitude reduction is additionally carried out at the expense of application of smoothing filters, parallel switching on of the storage battery or voltage stabilizers.

6.5. Transformers

A transformer is a device for converting AC at one frequency and voltage to AC at the same frequency but at another voltage. There are two classes of transformers, **voltage of power transformers and current transformers.**

The main parameter of a transformer is called the turns or transformation ratio K and it is expressed by the equation

$$K = \frac{W_2}{W_1} = \frac{E_2}{E_1},$$

where E_1 and E_2 are the respective EMFS of the two windings.

When the transformation ratio is such that the transformer delivers a higher secondary voltage than the primary voltage it is said to be of the **"step up"** type. Conversely, a **"step down"** transformer is one which lowers the secondary voltage.

Voltage transformer are connected so that the primary windings are in parallel with the supply voltage; the primary windings of current transformers are connected in series. A single-phase transformer as a name suggests is for the transformation of voltage from a single-phase supply or from any one phase of a three-phase supply. Transformation of three-phase AC can be carried out by means of three separate single-phase transformers, or by a single three-phase transformer. Transformer's winding for three-phase circuits can be connected in one of several combinations of the wye (star) and delta connections, depending on the requirements for transformer.

Current transformers are used in many AC generator regulation and protection systems and also in conjunction with AC ammeters. This transformers have an input/output current relationship which is inversely proportional to the turns ratio of the primary and secondary windings.

In circuit application normally requiring only a small step-up or step-down of voltage, a special variant of transformer design is employed and this is known as **auto-transformer.**

Its circuit arrangement is shown in Fig. 6.9 and from this it will be noted that its most notable feature is that it consist of a single winding tapped to form primary and secondary parts. In the example illustrated the tappings provide a stepped-up voltage output, since the number of primary turns is less than that of the secondary turns.

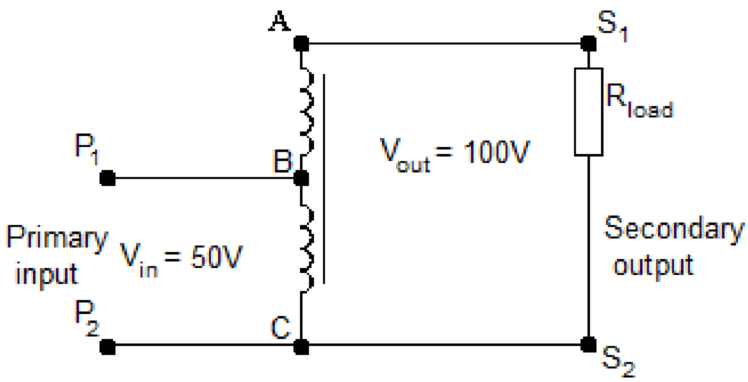


Fig. 6.9. Circuit arrangement of an auto-transformer.

Auto-transformer may also be designed for use in consumer circuits requiring three-phase voltage at varying levels.

There are many different uses for autotransformers. An autotransformer with a continuous variable tap, called a variac, is used where a continuous control from zero to full (or ever above) line voltage is necessary.

Transformers are usually rated in volt-amperes or kilovolt-amperes. The difference between the output terminal voltages at full-load and no-load, with a constant input voltage, is called **the regulation** of the transformer.

As in the case of an AC generator, regulation is expressed as a percentage of the full-load voltage, and depends not only on actual losses (hysteresis, eddy current and magnetic leakage) but also on the power factor of the load.

Transformer-Rectifier Units

Transformer-rectifier units (TRU) are combination of static transformers and rectifiers, and are utilized in some AC systems as secondary supply units, and also as the main conversion units in aircraft having rectified AC power systems. TRU’s have no moving parts other than a cooling fan.

The circuit shown schematically in Fig. 6.10. The unit consists of a transformer and two three – phase bridge rectifier assemblies mounted in separate sections of the casing. The transformer has a conventional star – wound primary winding and secondary windings wound in star and delta. Each secondary winding is connected to individual bridge rectifier assemblies made up of six silicon diodes, and connected in parallel.

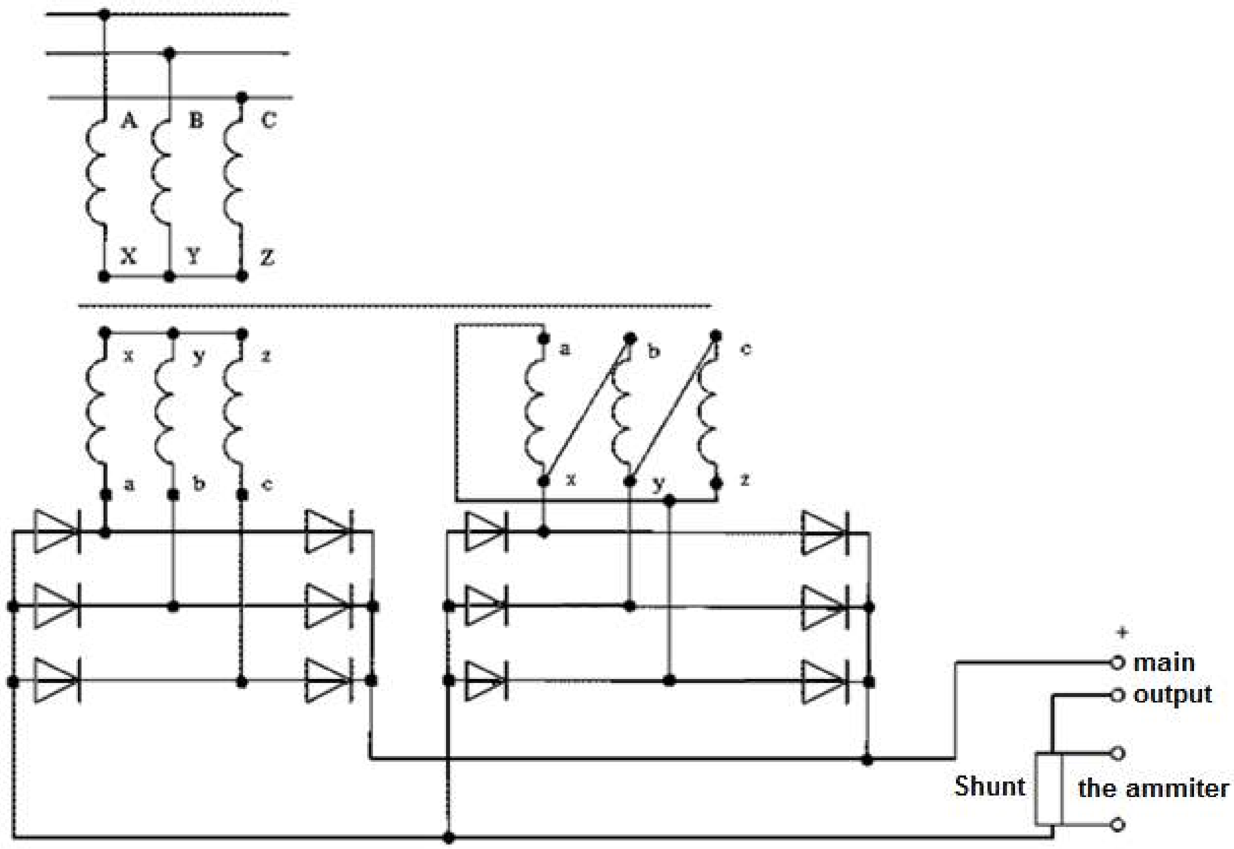


Fig. 6.10. Transfer-Rectifier Units

An ammeter shunt (dropping 50 mV at 100 A) is connected in the output side of the rectifiers to enable current taken from the main DC output terminals to be measured at ammeter auxiliary terminals. These terminals together with all others associated with input and output circuits, are grouped on a panel at one end of the unit.

Colling of the unit is by natural convection through gauze – covered ventilation panels and in order to give warning of overheating conditions, thermal switches are provided at the transformer and rectifier assemblies, and are connected to independent warning light. The switches are supplied with DC from an external source (normally one of the bus bars) and their contacts close when temperature conditions at their respective locations rise to approximately 150˚C and 200˚C.

6.6. Terms and concepts

Auto Transformer– has only one winding that is common to both primary and secondary winding.

Current Transformer has an input/output current relationship, which is inversely proportional to the turn's ratio of the primary and secondary windings.

Inverter is an emergency source of AC power when normal AC power fails.

Rotary Converter is the machine, which converts DC into AC. The unit essentially comprises to electrically separate machines mechanically coupled.

Static converter - performs the same conversion function as the rotary but by means of solid state or static circuit principle.

Transformer Rectifier Unit (TRU) convert AC into DC.

Variac – is a transformer with a continuous variable tap, which is used where a continuous control from zero to full (or even above) line voltage is necessary.

6.7. Control Questions

1. In what groups is it possible to divide electric power converters?
2. What are inverters?
3. What is the purpose of a transformer?
4. What is the function of a transformer rectifier?
5. What is the difference between an autotransformer and an ordinary transformer?
6. What functions does variac transformer provide?
7. Explain operating principle of the electric machine.
8. Draw and explain the most widespread circuits of rectifier's connection.
9. Basic parameters of the rectification circuit.
10. Describe the fundamental principle on which rectification based.
11. What is transformation ratio and how is it applied to "step up" and "step-down" transformers?
12. For what purpose is a current transformer use?
13. Describe the operation principle of a typical transformer rectifier unit with the aid of a circuit diagram.

Chapter 7

PROTECTION OF POWER SUPPLY SYSTEMS

7.1. Purpose and Main Requirements

Protection of power supply system (PSS) has two main functions:

– not to allow the services operation over extended period if the electric energy has inadequate quality;

– to prevent the emergencies in case of PSS failure.

The inadequate quality of electric energy in the direct current system is defined as the voltage deviation beyond the permissible limits or the voltage pulsation above the predetermined values; in the alternating current system inadequate quality of electric energy means the voltage and frequency deviation beyond the permissible limits, occurrence of intolerable modulations of voltage and frequency, distortion of phase voltages.

The protection scheme purpose is to protect the PSS operations against harmful effects in case of its units failure. The system consists of some subsystems (devices). Each of them provides the protection only against specific types of failure results. The protection system switches off the damaged unit (element) and re-arranges the PSS structure so that the electrical energy of the desired quality can be received either by all services or only by those responsible for flight safety.

The obligatory types of electrical energy sources protection schemes which are practically used of all kinds of airplanes are:

a) protection of direct current PSS against:

– excitation loss or voltage reduction;
– switching on the generator with wrong polarity;
– voltage increase;
-short circuits.

b) protection of alternating current PSS with constant frequency against:

– voltage increase and reduction;
– non-uniform load distribution;
– generator racing and constant frequency driver (CFD);
– short circuits;
– -increased moment at CFD input shaft.

The essential features required of airplane PSS protection schemes are:

– prevention against false operation of protection system;
– necessary to ensure the operation of protection system only of the damaged unit (element);
– speed of protection system response in order to reduce the destruction volume of individual devices.

7.2. PSS Protection in the Direct Current Systems

Protection against voltage reduction (against reverse current). The airplane generators are connected parallel to each other. If the generator is connected to the bus-bar, when its EMF is lower then the bus-bar voltage, the current flowing from the bus to the generator will equal:

$$\boldsymbol{I_2=(V_B\text{-}E_G)/\sum R_a}\ ,$$

where V_B – battery voltage; E_G **–** EMF of generator; R_a – armature resistance.

The magnitude of reverse current flowing from the bus-bar, where the generator is determined by the difference (V_B-E_G) and if may be great enough to cause the damage of generator armature and collector. Protection against voltage reduction is achieved by means of reverse current cut out relay (RCR). This relay has the following functions:

– to automatically switch the generator on when its voltage is approximately equal to the bus voltage;

– to provide the protection against voltage reduction by automatic disconnecting of the generator responsible for his reduction;

– not to allow the connection of the generator with wrong polarity;

– to make possible the forced switching on of the generator.

Fig. 7.1 shows the principle diagram of the **reverse current cut-out relay** (differential undervoltage) **relay** arrangement of five individual relays and a contactor.

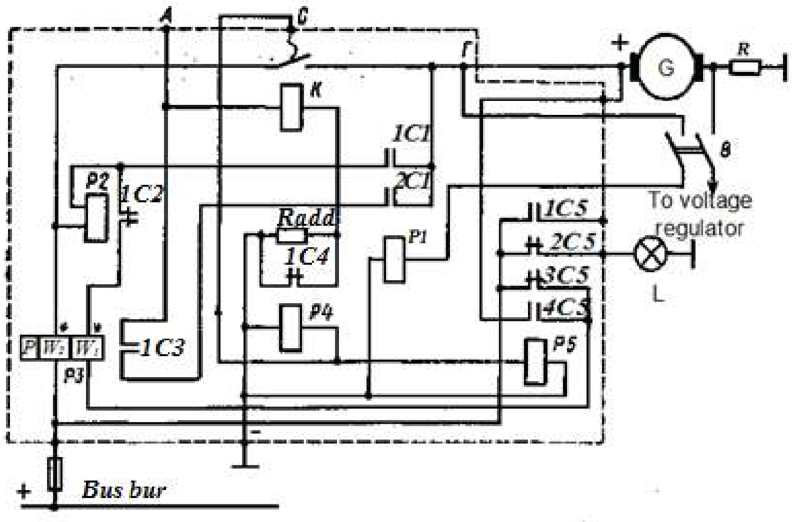


Fig. 7.1. Reverse current cut-out relay principle diagram

The polarized relay R_3 has the function of measuring and discriminating element. It has two windings energized for voltage difference between the generator and the bus-bar. Relay R_3 does not have the opposing spring and the armature it kept in the end positions by means of polarizing magnets. When the current in the windings flows from the generator to the bus-bar the relay contacts are closed, when the current flows in the opposite direction the relay contacts are open. The energizing of relay R_3 is caused by the action of winding w_1 and de-energizing is caused by the action of winding w_2 or w_1. The relay is energized when the generator voltage exceeds the bus voltage by (0,2-1,0) V and if is de-energized in case the reverse current in winding w_2 equals -(15…35) A or the voltage in winding w_1, equals (0,2…1,0)V. To protect winding $w_1$against overheating the voltage relay R_2 is introduced. Its winding is connected for the difference (E_G-V_B). Relay R_2 has the energizing voltage equals (12…16) V and the release voltage equals (3…5) V. The energizing voltage relay R_1 has two pairs of closing contacts (1C1 and 2C1) and it is intended for RCR control. In order to reduce the heating of the contactor and the contactor size, the additional resistance R_{add} is included in series with the contactor winding. This series resistance is shunted before the contactor is switched on by the contacts of the blocking relay R_4. Relay R_5 serves for indication of RCR state (on, off) and for switching the relay off in case the feeder between the RCR and the generator breakage loose.

Protection against voltage rise. The system of protection against voltage rise should switch off the faulty generator from other CSG if the voltage in the check point exceeds the predetermined value. But this protection system should not respond to the short-time voltage rises that occur in the transient conditions when a high load or the short circuit is switched off. The protection system should have a time delay either constant or depending on voltage magnitude. The prolonged overvoltage is a threat both for the services and for the generator itself. That`s why when the faulty generator is switched off its excitation field is suppressed by means of adding the damping resistance into the excitation circuit.

The principle diagram of automatic circuit breaker (ACB) as a protection against overvoltage is given in Fig. 7.2.

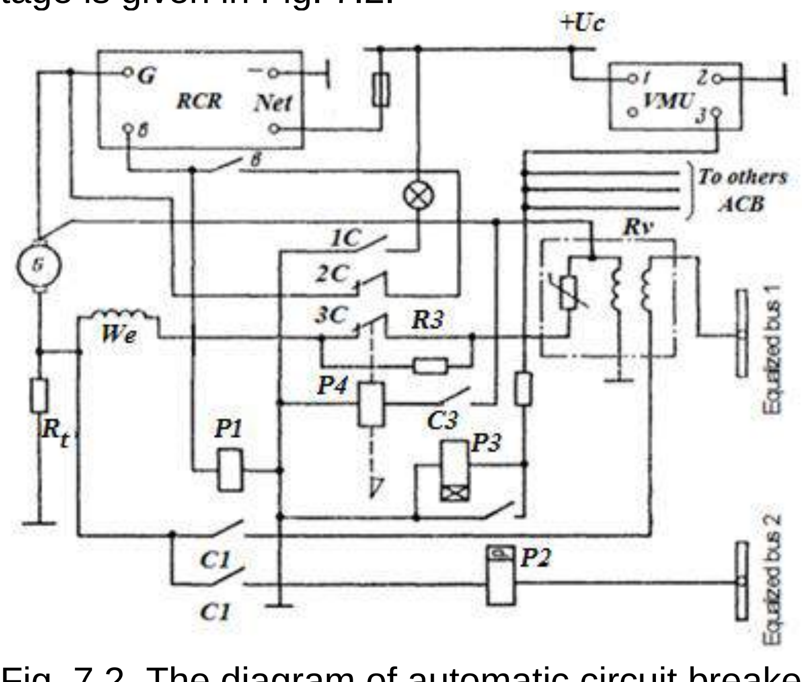


Fig. 7.2. The diagram of automatic circuit breaker

The ACB disconnects the generator if the voltage in the check point exceeds (32±1) V and the time delay is decreasing when the voltage is raising.

Voltage meter unit (VMU) shown on (Fig. 7.3).

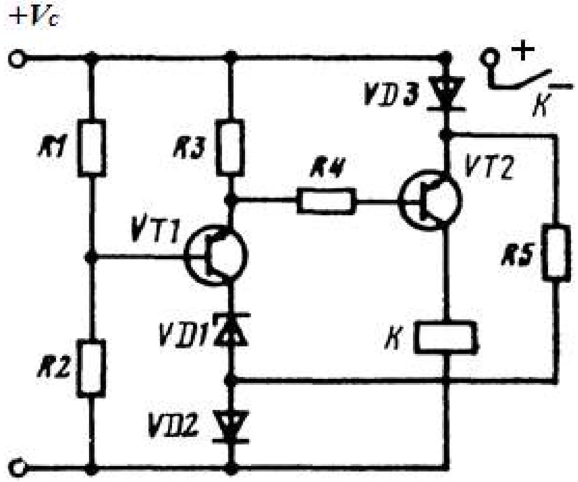


Fig. 7.3. Voltage meter unit

This unit (block) consists of voltage divider R_1 and R_2, two transistors $VT1$ and $VT2$, stabilizer diode $VD1$, load resistance R_3 and relay K. Resistor R_4 and diode $VD3$ are used for reliable $VT2$ locking, resistor R_5 provides the basic regime of transistor operation. Diode $VD2$ fulfils the functions of temperature compensation. The diagram parameters are chosen in such a way that in the event of normal bus bar voltage the transistor $VT1$ is closed and stabilizer diode $VD1$ is not broken through. When voltage equals 32 V the stabilizer diode $VD1$ is broken through, transistors $VT1$ and $VT2$ are opened and relay K comes into operation and its normally open contacts switch on the ACB of all the generators.

7.3. Protection Against Frequency Increase and Decrease

The electric supply systems operating at alternating current with voltage of 200/115 V and constant frequency of 400 Hz are provided with protection system against frequency increase and decrease. The protection should irreversibly disconnect the faulty generator from the airborne network at frequency exceeding (425±5) Hz with the time delay of not more than (4±0,6) s, and at frequency (465-480) Hz - without time delay.

When the frequency up to (375±5) Hz the disconnection should occur with time delay not more than (4±0,6) s, at frequency equal to (335-320) Hz – without any time delay.

With generators paralleled, the protection in case of frequency increase or decrease should be discriminative, i.e. only the faulty generator should be disconnected.

In most electric power supply systems the protection system has a special device for measuring the frequency of AC generator in the event of frequency deviation from the predetermined limits. With generators paralleled, in case of the damages accompanied by frequency deviations the measuring protection devices of all the generators take one and the some frequency value since the generators rotors have the same rotational speed due to the action of synchronizing moments.

In order to achieve the discrimination of frequency protection system operation the same principle is used at that in protection scheme against voltage rise and reduction, that is the introduction of discrimination into the circuit. Discrimination are measuring device responding to the sign and value of the generator active current imbalance

$$\Delta I = I_a\text{-}I_{am}.$$

At the damages resulting in the frequency increase occur, the imbalance of the healthy generators active currents is negative, and the protection systems of these generators will take the signal keeping the generators brow operation in the event of frequency increase. But for the faulty generator the imbalance of the active currents is positive and its protection system does not receive the inhibit signal. If the damages resulting into the frequency decrease occur, the inhibit signals arrive at the protection systems of healthy generators at positive imbalance of active currents. When the protection system against frequency increase and decrease comes into operation the faulty generator is disconnected from the load buses and from the buses of parallel operation. The automatic field killer is switched on and CFD is disconnected as well (if it is possible).

7.4. Generator Short Circuits Protection

If the short circuit occurs in the generator armature circuit or in its feeder, the generator should be disconnected from the network. The power supply of the short circuit point is cut off without any time delay. The protection system must come into operation not later than within 80 ms after the short circuit emerges. That`s why in order to protect generators and their feeders against short circuit the use is made of longitudinal differential protection system, which swiftly disconnect the generator in case of short circuit occurrence in the protection area. Besides, his system possesses discrimination as it does not respond to the short circuit beyond this area.

The principle of operation is based on the comparison of current values of phases at the beginning and at the end of the protected section.

The use is made of two fundamentally different circuit designs of longitudinal differential protection: with circulating currents (Fig. 7.4 (a)) and with balancing voltage (Fig. 7.4 (b)).

The current transformers are included in each phase at the beginning and at the end of protection area. Let’s consider the circuit design with circulating currents, the transformers secondary windings are connected in such a way that its EMF are directed and the currents in connecting wires have the same direction in the event of the generator normal operation and when short circuit occurs beyond the protection area. The measuring device (relay $K1$) is connected parallelly with the transformer secondary windings and the current in the relay winding is proportional to the imbalance current I_{IB}=I_1-I_2.

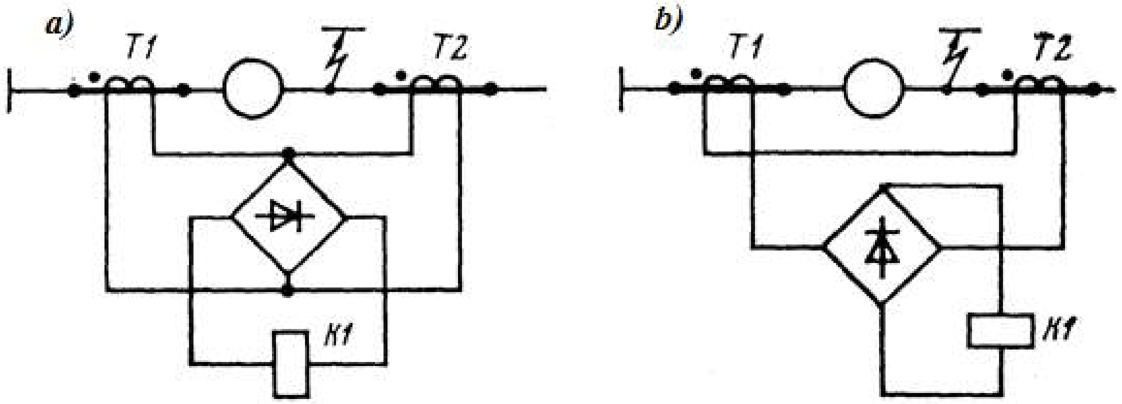


Fig. 7.4. Circuit designs of longitudinal differential protection

The imbalance current mainly occurs due to non-identity of transformers magnetization characteristics.

In order to achieve the protection selectivity in case of external short circuit the current of differential protection relay operation should exceed the maximum value of the imbalance rectified current. If the short circuit occurs within the protection area the primary currents are directed opposite to each other (in case of isolated generator operation current I_2 =0) and the current across the relay is proportional to the sum of currents flowing to the point of short circuit. This current acts on the protection servo devices and makes the relay come into operation.

The main disadvantage of the circuit design of longitudinal differential protection with circulating lies in the fact that the opens in their secondary circuits result in false protection operation.

The airborne power supply systems use the design of longitudinal differential protection with balancing voltages, the transformers secondary windings are connected in such a way (Fig.7.4 (b)) that their EMF are directed opposite to each other in normal conditions and when the short circuits occurs beyond the protection area, relay is connected in series in the connecting wires circuit. In this case the resulting EMF is equal to: $\dot{E}_r$=$\dot{E}_1$-$\dot{E}_2$, where $\dot{E}_1$ is the EMF induced in the secondary winding of the current transformer $T1$. $\dot{E}_2$ is the EMF induced in the secondary winding of the current transformer $T2$.

No current flows across the transformer secondary winding and across the relay. In the event of short circuit the secondary EMF are added $\dot{E}_r$=$\dot{E}_1$+$\dot{E}_2$.
This resulting EMF causes the current flow and the relay K_1 comes into operation.

Relay K_1 acts on the controlling devices. The devices irreversibly disconnect the generator from the network and switch on the automatic circuit breaker (ACB).

7.5. Circuit Protection Devices

The current-carrying capacity of a wire or cable is determined by its length and cross sectional area; heat dissipation is determined by I^2R losses. When the circuit or system is designed, the wire size is selected to safety carry this current. Wires and cables are subjected to abrasion during the normal service life of the aircraft; this can lead to the conductor being exposed. This exposure could lead to a low resistance path between the conductor and airframe and/or an adjacent conductor. Faulty equipment low resistance paths or over loading from additional circuits will cause the current to increase and this might exceed the current-carrying limit of the conductor. Heat will build up in the wire leading to fumes, smoke and ultimately fire. It is vital we protect against this whilst allowing for transients; the methods used in aircraft are selected from the following devices: fuse; circuit-breaker; limited resistor.

Fuses

Fuses are links of wire that are connected in series with the circuit. Their current-carrying capacity is predetermined and they will heat up and melt when this is exceeded thereby interrupting and isolating the circuit. Materials used for the **fusible link** include lead, tin-bismuth allow, cooper or silver allows. The fuse wire is contained with a grass or ceramic cartridge to prevent any particles of hot metal escaping which could cause secondary damage.

End-caps provide a connection for the fuse wire and make contact with the circuit wiring. Fuse holders consist of terminals and panel clamp-nut. Some fuse holders have an indication of the fuse condition, i.e. if the fuse has blown.

The indicating cap is black with an integrated colored light. When the fuse has blown, the cap illuminates; different colors indicate different power supply voltages. Heavy-duty fuses (typically protecting circuits with up to 50A current) are constructed with a ceramic body and terminals. Fuses are either clipped into position on a terminal board or screwed into a panel.

Fuses are relatively low cost items, but they can only be used once. In some applications, the fuse material and physical construction is design to have a time delay; the so-called **slow-blow** fuse or **current limiter**. This is made from copper allow that has a higher melting point than load/tin. It has a single strip of material waited into a narrow cross-section to provide the fusing point. Heavy-duty fuses are used at power distribution points. They have multi-strands of parallel elements and are rated up to 500A.

This type of fuse is fitted with a packing medium to contain the debris following rupture. Materials used include quartz, magnesium oxide, kieselguhr or calcium carbonate (chalk).

Fuses have a rating that determines the maximum current it can carry without melting. The fuse will also have a minimum fusing current that is affected by ageing; a process that occurs when the fuse is operated at the minimum fuse rating for prolonged periods of time. Ambient temperature affects the current rating and response time of a fuse. They must be located close to power source to minimize the length of unprotected wire; at the same time they have to be accessible for replacement.

Spare fuses must be carried on the aircraft and be accessible to the flight crew. Typical requirements are to carry 50% of each rating as spares, e.g. if the aircraft is fitted with four 10A and five 15A fuses, then two 10A and three 15A fuses should be carried as spares.

Circuit-breakers

Unlike fuses, circuit breakers can be reset (assuming that the fault condition has cleared). There are two circuit-breaker principles: electromagnetic and thermal.

An electromagnetic circuit-breaker is essentially a relay with current flowing through a coil; the resulting magnetic field attracts on armature mechanism. The current is normally a proportional of the main load current. These contacts are opened when the current through the coil exceeds a certain limit.

Thermal-type circuit-breakers consist of a bimetallic thermal element, switch contacts and mechanical latch. The thermal element is a bimetallic spring that heats up as current passes through it; this eventually distorts and trips the mechanism when the rated level is exceeded. The mechanism is linked to the main switch contacts, where the circuit-breaker **"trips"** the contacts open, thereby disconnecting power from the circuit. When the contacts open, **a button** is pushed out of the circuit-breaker. This button is used to manually reset the contacts; **a white collar** just below the button provides visual indication that the circuit-breaker is closed or tripped.

Some circuit-breakers use a large collar grip to identify specific system. They can be locked open if required e.g. if the system is installed but not certified for operation. As with fuses, the circuit-breaker should be located as close as possible to source of power; they are often arranged on the panels in groups. Circuit-breakers can also be used to conveniently isolate circuits, e.g. during maintenance. Certain circuit-breakers are fitted with removable collars so that they can be readably identified. Circuit-breakers can be single or multi-pole devices (poles are defined as the number of links that a switching device contains). Multi-pole devices are used in three phase AC circuits.

Various configurations of circuit-breaker are installed on aircraft, including:

1) automatic reset;
2) automatic trip/push to rest;
3) switch types;
4) trip free.

The circuit symbols for each of these types is illustrated in Fig. 7.5.

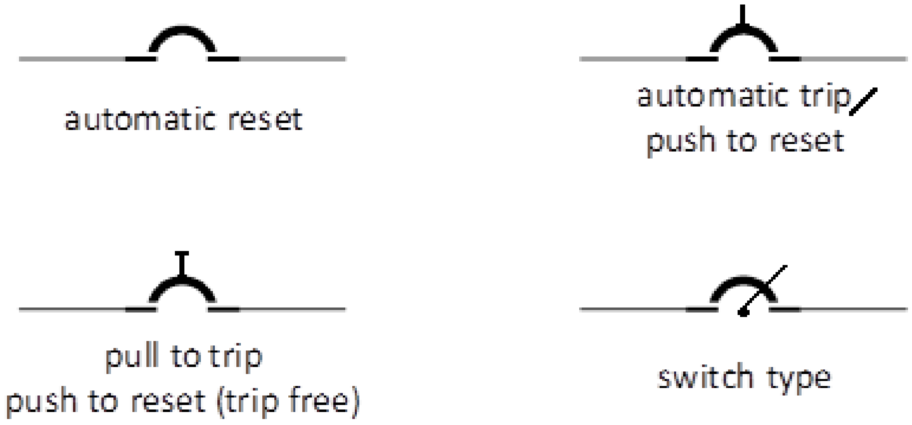


Fig. 7.5. Circuit-breaker symbols/type

Trip-free circuit-breaker contacts cannot be closed whilst a fault exists. This is the preferred type of circuit-breaker on aircraft, especially on new installations.

Limiting Resistors

There are used to limit current surges, primarily in DC circuits, where the initial current surge is large when these circuits are switched they create large current flows that can be harmful to other components and reduce the power supply voltage for a period of time (determined by the time constants of the circuit). Limiting resistors are connected in series with such circuits and then automatically shorted out once the circuit current has stabilized. Typical applications of limiting resistors are found in engine starting circuits and voltage regulators. Limiting resistors are also used in fire extinguishing systems. Fire extinguishers are activated by applying DC through current-limiting resistors to the associated squib; this ruptures a disc that allows extinguishing agent to be expelled under pressure. The limiting resistors prevent inadvertent operation of the squib. In electronics, limiting resistors are used to protect devices such as diodes.

7.6. Terms and Concepts

Circuit-breakers are electromechanical devices that interrupt and isolate a circuit in the events of excessive current.

Current limiter (slow-blow fuse) is a fuse having a time delay.

Feeder fault system protects again short circuit.

Fuse is a thermal device designed primarily to protect the cables of a circuit against the flow of short-circuit and overload currents.

Limiting resistors are used to limit current surges, primarily in DC circuits, where the initial current surge is large.

Reverse current cut-out relay is used principally in a DC generated systems either as a separate unit or as part of a voltage regulator.

7.7. Control Questions

1. What factors characterize the inadequate quality of airplane PSS operation?
2. What are the main functions of PSS protection?
3. Name the essential features required of PSS protection.
4. What are the functions of reverse current cut-out relay?
5. What methods ensure the discrimination of under-voltage and frequency protective scheme?
6. Describe reverse current cut-out relay operation.
7. Why do conductors must have low insulation resistance?
8. In what way are limiting resistors connected?
9. Determine the reason that caused the fuse to blow before replacing.
10. What are the principal differences between a fuse and current limiter.
11. What is meant by the term “Trip free” when applied to a thermal circuit breaker?
12. What do you understand by the term “reverse current”?

Chapter 8

POWER DISTRIBUTION SYSTEMS

Modern aircraft requires a consistent and reliable supply of electric power. There are four common sources of electric power used during normal aircraft operations. These sources are DC alternators, DC generators, AC alternators (generators) and the aircrafts storage batteries11 as considered earlier, the aircraft's battery is typically used for emergency operations and any intermittent system overloads. DC alternators are typically used on piston engine aircraft. DC starter – generators are used on medium-sized turbine – powered aircraft. AC alternators are used on transport-category (large) aircraft and some military aircraft.

On almost all aircraft the bus bar is connected to the positive output terminal of the generator and/or battery. The negative voltage is distributed through the metal structure of the aircraft. The metal aircraft (negative side of the voltage) is often referred to as the ground; hence thus type of distribution is often called a negative ground system. Since only one wire (and the ground) is needed to operate electrical equipment this is known as single wire system (when airframe is constructed from a conductive material. On composite aircraft, some type of ground (negative) conductor is required. Larger, more complex aircraft typically contain several bus-bars. Each bus has the specific task of distributing electric power to a given group of electric loads. Bus-bars are often categorized as AC and DC, left and right and essential and non-essential distribution buses.

Some form of electrical distribution system must be employed on every aircraft containing an electrical system. A simple power distribution system (Fig. 8.1) (PDS) consists of a basic copper conductor, called a bus bar or bus. The bus is a conductor designed to carry the entire electrical load and distribute that load to the individual power users. Each electric power user is connected to the bus through a fuse or circuit breaker (Fig 8.1).

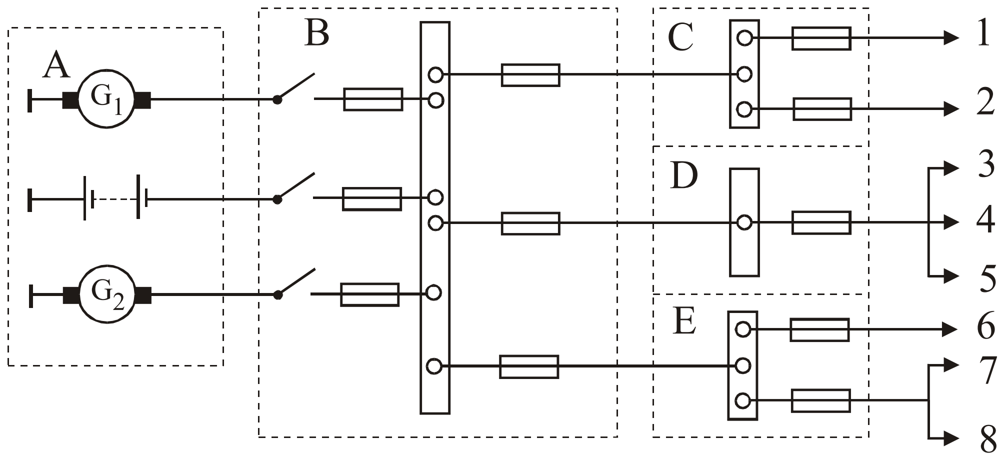


Fig. 8.1. The block diagram of the plane electric power supply distribution system

Where A – power supply sources; B – central bus bar; C, D, E – buses; 1…8 – feeders; fuse (circuit breaker) – they are made from heavy gauge wire. They will remove the power from that system if overload condition arises.

PDS can be closed and opened. For increasing reliability of the power transfer in open supply lines the power can be transferred over several parallel channels (Fig. 8.2, a). The closed PDS reliability is increased, because feeding of separate buses is carried out, at least, from two sides (Fig. 8.2, b).

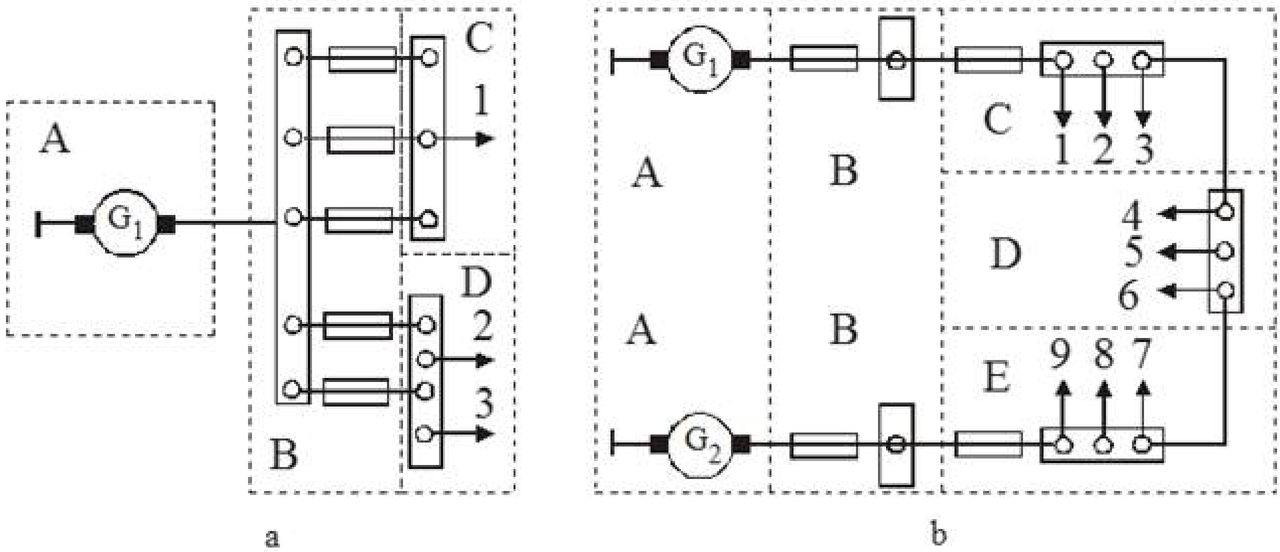


Fig. 8.2. Types of distribution power systems:

a – open supply line with parallel channels; b – closed supply line; A – power supply sources; B – central bus-bar; C, D, E – buses; 1…9 – feeders

8.1. Requirements for Power Distribution Systems

The electric power system is one of the most critical systems found on modern aircraft. A complete electrical system failure would be catastrophic.

Electric power sources must function properly when connected in combination or independently expect that generators may depend on a battery for initial excitation or for stabilization. No failure or malfunction of any electric power source may impair the ability of any remaining source to supply load circuits essential for safe operation of the aircraft, expect that a generator that depends on a battery for initial excitation or for stabilization may be stopped by failure of that battery.

Each electric power source control must allow for independent operation of each source.

There must be a least one generator in an electrical system supplies power to circuits that are essential for save operation of the aircraft. Each generator must be able to the deliver its continuous rated power. If the design of the generator and its associated circuit is such that a reverse current could flow from the battery to the generator, a reverse current cutout relay must be provided in the circuit to disconnect the generator from the other generators and the battery when enough reverse current exists to damage the system.

The requirements for electrical systems in large category aircraft specify that the generating capacity for the system and the number and kinds of power sources must be determined by a load analyses. The generating system includes electric power sources, main power buses, transmission cables, and associated control, regulation and protective devices. The system must be designed so that power sources function properly when independent and when connected in combination with other sources. No failure or malfunction of any power source can create a hazard or impair the ability of remaining sources to supply essential loads.

Electric Load

The electric load of an aircraft is determined by the load requirements of the electric units or systems that can be operated simultaneously. It is essential that the electrical load of any aircraft be known by the owner or operator, or at least by the person responsible for maintenance of the aircraft. No electric equipment can be added to an aircraft's electrical system until or unless the total load is computed, and it is found that the electric power source for the aircraft has sufficient capacity to operate the additional equipment to determine the electrical load of an aircraft**, an electrical – load analyses** is made.

One way to do this by adding all the possible loads that can be operating of any one time. Loads may be **continuous** or **intermittent**, depending on the nature of the operation. Examples of continuous loads are navigation lights, the radio receiver, the radio navigation equipment electric instruments, electric fuel pumps, electric vacuum pumps, and the air-conditioning system. These as units and systems that can be operated continuously during flight.

Intermittent loads are those that are operated for two minutes or less and are then turned off. Examples of intermittent loads are landing gear, flaps, emergency hydraulic pumps, trim motors and landing lights. These units and circuits for other electrically operated devices are normally operated for a very short period of time.

In computing the electrical load for an aircraft, all circuits that can or may be operated at any one time must be considered. The total probable continuous load is the basic for selecting the capacity of the power source. It is recommended that the probable continuous load be not more that 80 percent of the generator capacity on aircraft where special placards or monitoring devices are not installed. This permits the generator and alternator to supply the load and also keep the battery charged.

A Simple Electrical System

A simple electrical system for a light aircraft consists of a battery circuit, a generator circuit with associated controls, an engine starter circuit, a bus bar with circuit breakers, control switches an ammeter, lighting circuits, and radio circuits.

A schematic diagram of the basic power distribution system is shown in Fig. 8.3.

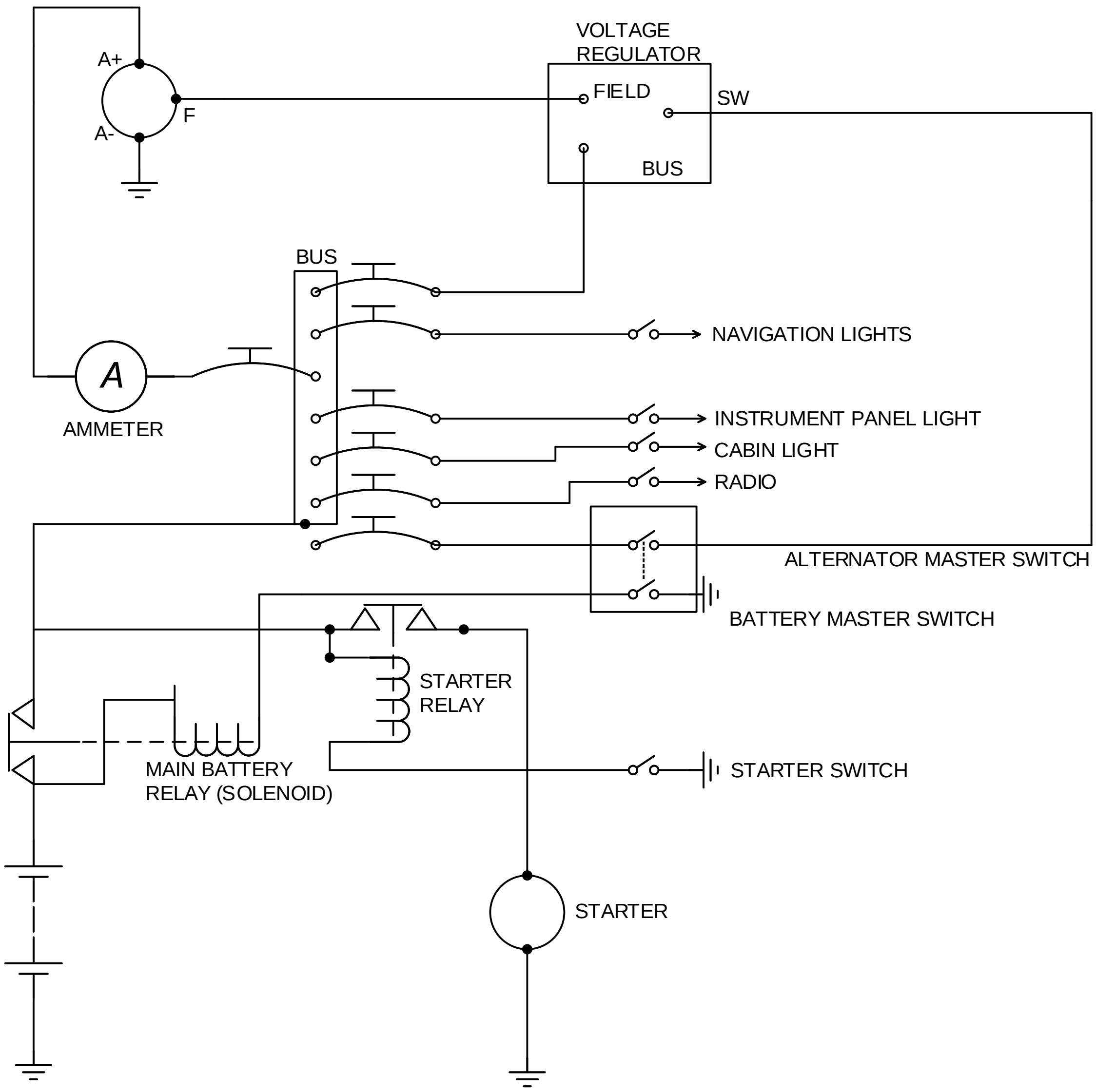


Fig. 8.3. Basic power distribution system

The high-current-carrying cables in this system are connected from the battery to the main battery relay; from the battery relay to the starter relay and from the starter relay to the starter. The ground leads for the starter and the battery are also of heavy cable.

The main alternator power cables are also considerably larger than the normal circuit wiring; however they are usually smaller than the cables required to carry full battery current. This is because the battery is used for starting the engine, and the starting current is very large. During operation of the aircraft, the battery is connected to the system but is not supplying power. Instead, it is taking power from the generator in order to maintain a charge. All the normal load currents are supplied by the generator during flight. The distribution bus receives power from the generator and/or battery during different operating modes. The bus then distributes the electric current through the individual circuit breakers to their respective loads. As shown in the schematic (Fig 8.3), the circuit breakers are connected directly to the distribution bus. This is done to prevent any accidental short to ground of an unprotected wire. It is always desirable to protect as much wiring as possible. Any wires that are not protected by a fuse or circuit breaker must be as short as practical and protected by insulated covers or 'boots' at terminal connections.

8.2. Large Aircraft Electrical System

Large aircraft electrical system have many similarities to those systems found on small aircraft. On large aircraft there is typically one battery and two or more AC generators which supply power to several distribution buses.

The AC generators are connected to the AC buses.

The DC battery is connected directly to the battery or emergency bus.

The AC power produced by generators is converted to DC where needed for special application.

All loads are connected onto specific bus bars that fulfil a specific function. These can be categorized into a hierarchy are illustrated in Fig 8.4.

Connection between bus bars are via heavy-duty contacts or breakers.

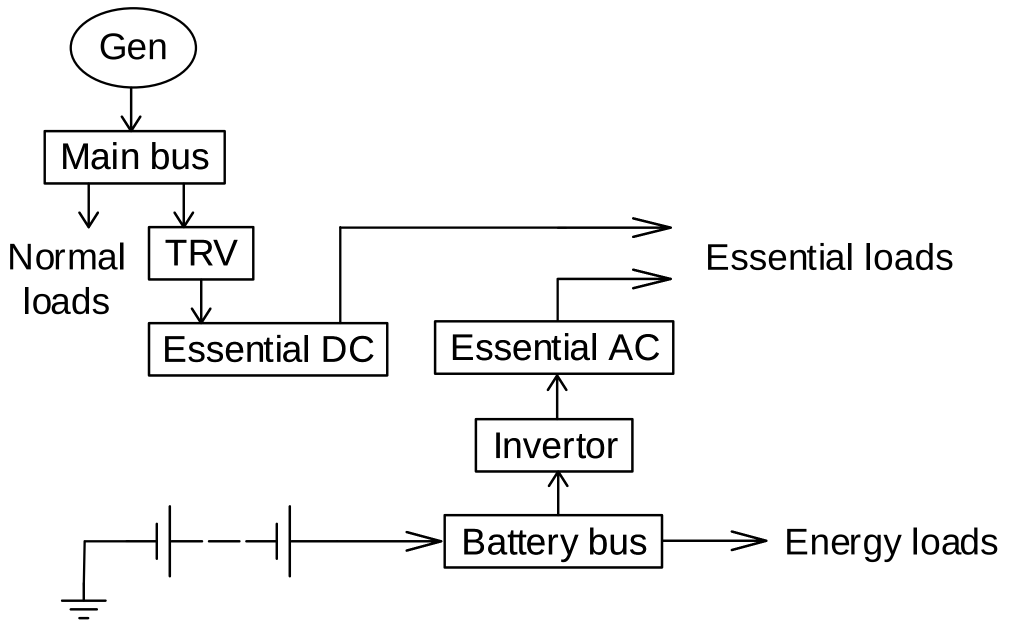


Fig 8.4. Large aircraft types electrical power hierarchy

Aircraft types vary however the following categories are typical for many installations.

Main bus: this is sometimes called the non-essential generator or load bus. It will include loads such as the galleys, in-flight entertainment and main cabin lights. This loads can be disconnected and isolated in flight without affecting the safe operation of the aircraft.

Essential bus: this is sometimes called the vital or safety bus. It will be include equipment and instruments required for the continued safe operation of the aircraft.

Battery bus: this is sometimes called the standby or emergency bus it supplies the equipment required for the safe landing of the aircraft, e.g. radios, fuel control, landing gear and fire protection.

Although the schematic diagram (Fig. 8.4) shows an entire aircraft electrical system, this is not typical. Most manufactures prefer to divide aircraft schematic into individual systems. This becomes a necessity when dealing with large complex aircraft.

Essential lighting, flight control systems and communication and navigation radios are high-priority electric systems. Galley power, non-essential lighting and various other comfort systems are considered low-priority electric systems. These non-essential systems are usually turned off during a partial generator system failure. In the case of complete generator failure, the battery will supply power for all essential electric equipment. A fully charged battery will normally supply approximately 20 to 30 min of energy power.

8.3. Power Distribution Systems

Modern large aircraft use both AC and DC. The output of a typical generator is three-phase 115V AC; this is converted by transformer-rectifier units (TRU), where DC power is needed. A TRU incorporated a step-down transformer and full-ware rectifier. Its output is 28V DC.

Most large aircraft contains two or more static inverters, which are used for emergency situations (generator failure). Each convertor is capable of converting DC supplied by the battery into AC power, which is distributed by the essential AC bus.

There are two basic configurations that are used to distribute electric power:

– the split-bus systems (B737, B757, 777, A-300, A-310, A-320);
– parallel systems (B727, B747).

In **split bus system** the engine-driver generators can never be connected to the same distribution bus. Simultaneously under normal conditions each generator supplies power only to its associated loads.

In **parallel system**, the entire electrical loads is equally shared by the working generators. Parallel AC power distribution systems are typically found on commercial aircraft containing there four or more engines.

All four generators are not necessarily paralleled in this systems. Right-side generators and the left-side generators can be connected, or they can be isolated from each other by means split system breaker.

The Split-Bus Systems (simplified schematic)

The split-bus electrical system (Fig. 8.5) contains two completely isolate power generating systems. Each system the left and right, contains its own AC generator, transformer-rectifier and distribution buses. The right and left generators power their respective loads independently of other system operations.

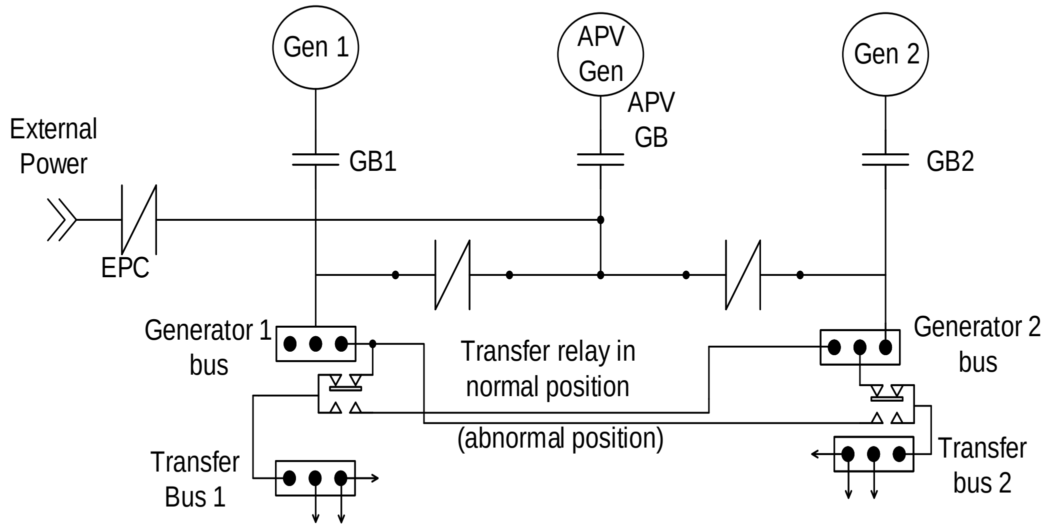


Fig 8.5. A split-bus system

In the event of generator failure, the operating generator is connected in such manner as to feed all the essential loads, or the APU generator may be employed to carry the electrical load of the inoperative generator.

This schematic shows the external power contactor (EPC) closed and ground power supply connected to the aircraft. The bus tie breakers (BTBs) 1 and 2, are closed. Connecting external power to both transfer buses and their respective electrical loads. In this configuration the generator breakers (GBs) are opened, thus disconnecting the generator from the electric system. In the case where the APU would be used to supply electric power to the entire aircraft, the EPC would be opened and the APU generator breaker would close.

Although the schematic diagram (Fig. 8.5) shows and entire aircraft electrical system, this is not typical. Most manufacturers prefer to divide aircraft schematics into individual systems. This becomes a necessity when dealing with large complex aircraft.

The major advantage of a split-bus system is that the generator operated independently that is, generator output frequency and phase relationships need not be so closely regulated. Parallel systems require strict operating limits.

Parallel Electrical Systems

This type of system maintains equal load sharing for three or more AC generators. Since the generators are connected in parallel to a common bus, all generator voltages, frequencies, and their phase sequence must be within very strict limits to ensure proper system operation. Block-diagram (Fig. 8.6) represents a typical four-generator parallel system.

In parallel electric systems power distribution system, all generators are connected to one distribution bus (Fig. 8.6).

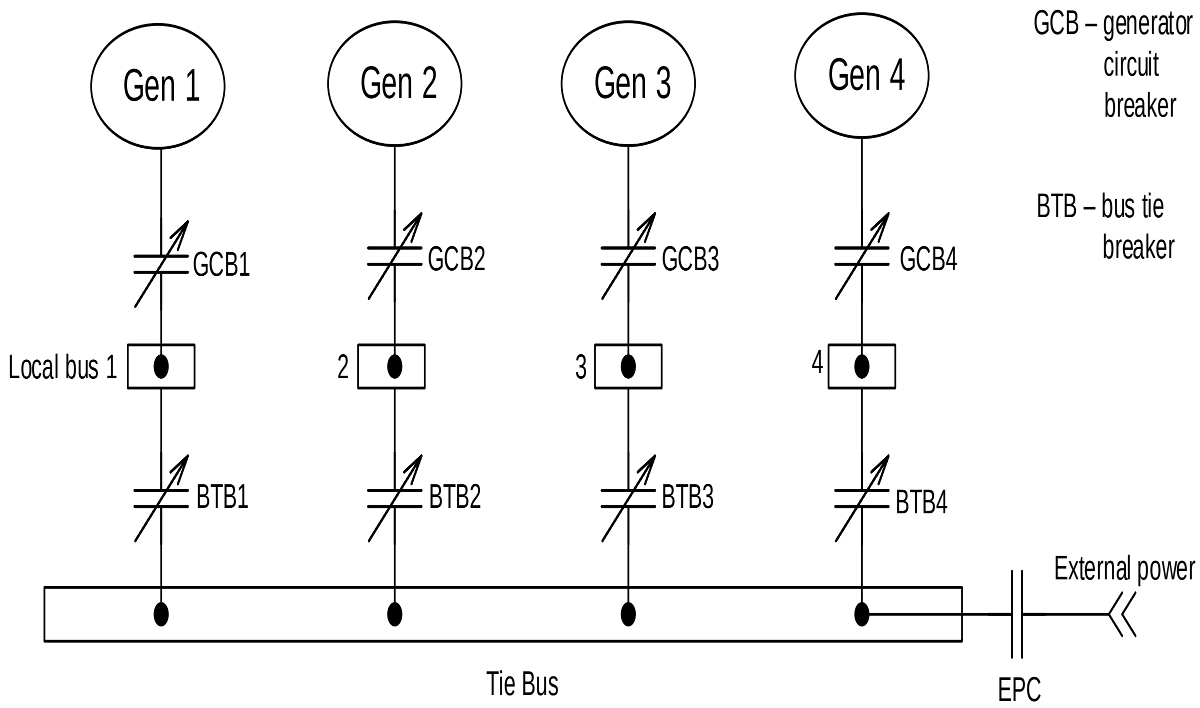


Fig. 8.6. Parallel Electrical System

All GCB and BTB are closed. All generators are synchronizing and connected in parallel by the tie bus (synchronizing bus). Its purpose is to connect the output of all operating generators. The **load buses** are used to distribute the generator current to the various electrical loads. When one generator fails, its GCB opens. However, that load bus still continues to receive power while connected to the tie bus.

If two or more generators fail, nonessential electrical loads are automatically disconnected from the system.

Split-Parallel System

Split-parallel System (SPS) is illustrated in such diagram (Fig. 8.7).

This system allow for flexibility in load distribution and get maintains isolation between systems when needed.

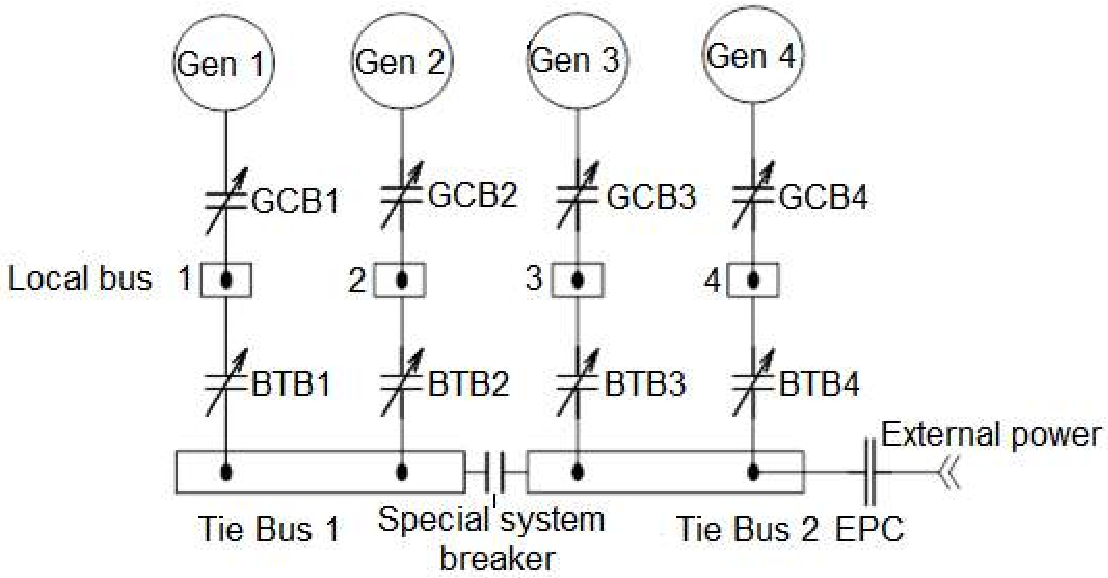


Fig. 8.7. Split-parallel system

When closed the split system breaker connects all generators together they paralleling the system when open the split system breaker isolates the right and left hand systems thus creating a more flexible parallel system. (Such system is used on Boing 747-400).

Battery Charging

The battery charger on a large aircraft operates from 115-volt, three-phase, 400 Hz AC power supplied by AC ground service bus. A completely discharged nickel-cadmium battery can be recharged in approximately 60-90 minutes. The battery charger operates in one or two modes depending on whether the aircraft in being supplied by external ground power or not.

With the aircraft on the ground, the charged battery is powered from the ground services bus and provides a constant current to the battery. When the battery terminal voltage reaches a pre-defined level (adjusted for battery temperature), charging is automatically disconnected. When external power is not available, the battery is charged from a transformer rectifier units (TRU) that provides 28VDC to maintain battery charge and supply loads on the battery bus. The battery's temperature sensor forms part of the charging system to prevent battery damage. If the battery temperature is outside a predefined range (typically -18°C to 60°C), the charging circuit is disconnected.

8.4. Control of the Power Distribution Systems

On modern aircraft employing a parallel or split-bus system, are centralized mean of controlling the power distribution between individual load buses is essential. For example, if a generator fails or a bus shorts to ground, the appropriate bus ties and generator circuit breakers must be set to the correct position or in the event of s system overload, the control unit must reduce the electrical load to an acceptable level. This is called **load shedding**. The aircraft's galley power is usually the first nonessential load to be disconnected. Also the control unit must automatically reconnect any essential loads to an operable bus. This power manipulation must take place within a fraction of a second to ensure an uninterrupted flight. To achieve this goal, modern aircraft employ a solid-state **bus power control unit** (BPCU).

The BPCU also receives input information concerning system loads from **load controllers**. Load controllers are electric circuits that sense real system current and provide control signals for the generators constant-speed drive rpm governor. The constant-speed drive output rpm in turn affects generator, output frequency. Load controllers receive their input signals from current transformers.

Current transformer consists of three inductive pickup coils that provide current-sensing signal. The electrical signal from the current transformer in conjunction with the generator control unit (CCU) and BPCU, are used to control protection circuitry and supply signals to load meters in the cockpit.

The BPCU is the main control computer for all generator and electrical power distribution. It defects an abnormal condition, opens and/or closes the appropriate bus tie and/or circuit breaker. Circuit breakers operate automatically according to GCU and BPCI signals or manually via cockpit controls. Bus tie breakers are another type of unit used to connect or disconnect main electrical distribution points. A bus tie breaker (BTB) is similar to an electric solenoid in that it is used as remote control switch. Each BTB is usually controlled by the BPCU.

On modern commercial passenger jets the BPCU performs control, test, protection, and fault identification functions.

On some aircraft the automated power distribution system provides for **a no-break power transfer** (NBPT). NBPT means that the automated system can change the AC power source without a monetary interruption of electric power. For example, when external power is being used and the aircraft is preparing to depart the gate, the engines are brought on line. During on NBTP the generator control units monitor the power source currently online (external power) and the power source requested by the flight crew (main generators). If the power requested is within specifications both power supplies are paralleled for a split second, and no power interruption occurs. If the requested power is out of limits, the GCU try to adjust the system and then connect the requested power to the buses. Is the power system cannot be adjusted to the source will be rejected, or there will be a momentary power interruption.

General Aviation Aircraft

In small general aviation GA aircraft, pilots need to be familiar with the electric systems of their aircraft. Most light GA aircraft are only concerned about an alternator failure. This type of aircraft is normally fitted with an ammeter and/or a voltmeter. On some light GA aircraft an over-voltage light and ammeter can be used to determine the natural of electrical malfunctions. Some aircraft are also fitted with a light that comes on in the event of generator failure, where the battery alone is being used to supply the avionic bus. The aircraft battery has a finite capacity, the pilot has to make decisions on the use of the aircraft power consumption in order to be able to make a safe landing.

8.5 Terms and Conception

Bus power control unit must automatically reconnect any essential loads to an operable bus (main control computer).

Load bus is used to distribute the generator current to the various electrical loads.

Load controller is an electrical circuit that sense real system current and provide control signals for CSD governor.

Load shedding is the process of switching loads of the bus.

Master switch makes it possible to disconnect all power sources from the distribution system.

Split-Bus System contains two completely isolated power generating systems. In the event of generator failure, the operating generator is connected to feed all the essential loads.

Load shedding is the process of switching loads of the bus.

Tie bus connects and synchronizes in parallel all generators.

8.6. Control Questions

1. What is the purpose of a bus bar?
2. What is the minimum time an emergency battery system must supply power?
3. Discuss the need for protective devices in aircraft electrical system.
4. What is the purpose of a master switch?
5. What must be done before adding electric equipment to an aircraft system?
6. What is a trip-free circuit breaker?
7. Describe the difference between a power distribution system on a single-engine aircraft and one in a twin-engine aircraft.
8. What is the function of a transformer rectifier unit?
9. Describe the basic operation of a split bus power distribution system.

10. What are the disadvantages of a parallel power distribution system?
11. When are parallel systems used?
12. What is the purpose of the hot battery bus?
13. Explain the difference between main, essential and battery bus bars.

Chapter 9

ADVANCED ELECTRICAL POWER SUPPLY SYSTEMS OF AIRCRAFTS

Introduction

The conventional aircraft utilized a combination of hydraulic, pneumatic and mechanics 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 system and electric driven primary flight control actuator systems.

The concept of More Electric Aircraft (MEA) implies increasing use of electrical power to drive aircraft subsystems that in conventional aircraft have been driven by a combination of mechanical, hydraulic and pneumatic systems. The objective of the MEA is to completely replace non-electrical power in the aircraft with electricity. This idea was first applied to meet the military the less overall weight of the aircraft, low maintenance cost, higher reliability and better performance. With increasing capacity and rating of the civil aircraft, the idea of MEA is also applied. The MEA concept is seen as the direction of aircraft power system technology in the future. The future aircraft power system will employ multi-voltage level hybrid DC and AC systems. Thus MEA electrical distribution systems are mainly in the form of multi-converted power systems. The electrical system of modern aircraft is a mixed voltages system which consist of the four types of voltage: 405 V AC (variable frequency), 200V AC, 28V DC and 270V DC.

Aircraft electrical power system often consist 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. Due to cyclic operator of these units, they are considered as harmonic source in the aircraft electric power system. These units can increase the voltage distortion and the harmonic contents into the AC side of the aircraft electric power system.

The constant-speed drive (CSD) generating system found onboard many aircrafts is comprised of a three-stage regulated synchronous generator, the output frequency of which is maintained constant by means of a hydro-mechanical CSD connecting it to the engine via a gearbox. A reduction in weight of the system is brought about by a combination of the driven and the generator integrated into a single unit there by providing the integrated driven generator (IDG). However, continuing developments in power electronics and microprocessor technology have led to the DC-link variable-speed constant frequency (VSCF) generating system, becoming a viable alternative to the CSD and IDG systems. The VSCF electrical system is more flexible compared to the CSD/IDG systems since its components can be distributed throughout the aircraft, in contrast to the CSD/IDG mechanical system in which they must inevitably be located close to the engine.

9.1 Power Generation Source of Aircrafts

The electrical power systems of aircrafts have made much progress in recent years because the aircrafts depend more and more on electricity as shown in Fig. 9.1.

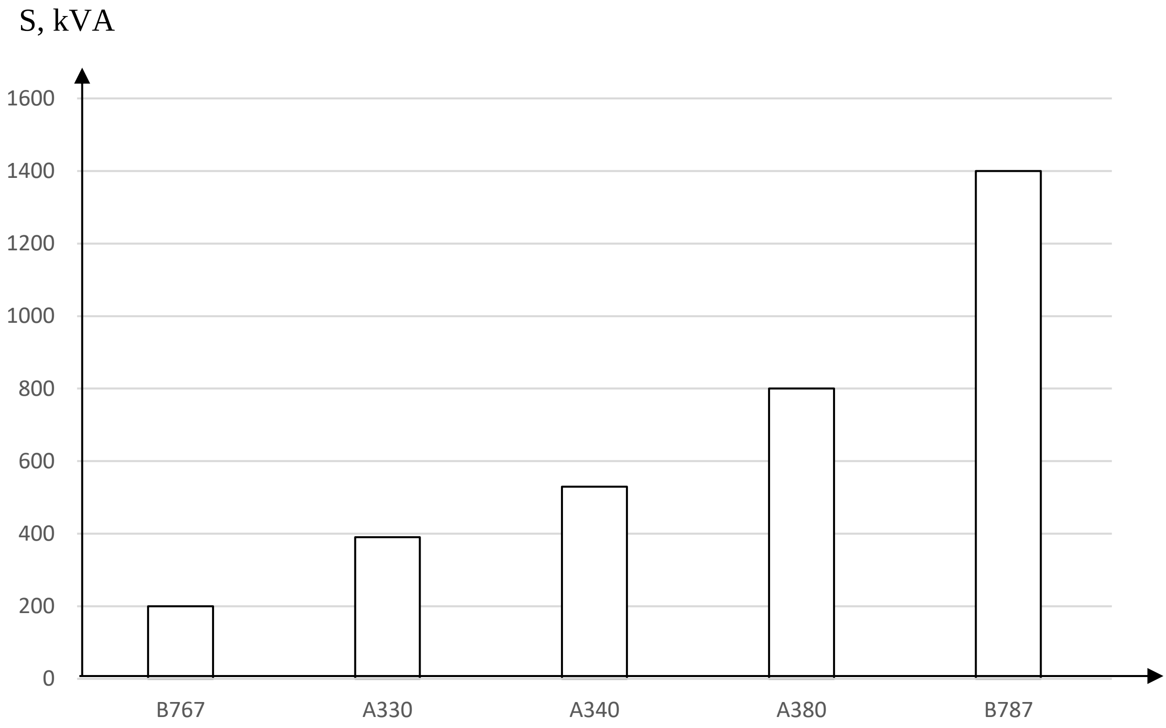


Fig. 9.1. Power rating of famous aircrafts

Different aircraft power rating with their used technologies are listed in Table 9.1.

Table 9.1. Generation, Power Rating and Application of different Aircrafts

Generation type	Civil application		Military application
IDG/CF (115 V AC/400 Hz)	B 777	2 x 120 kVA	Eurofighter Typhoon
	A 340	4 x 90 kVA	
	B 737 NG	2 x 90 kVA	
	MD – 12	4 x 120 kVA	
	B 747	4 x 120 kVA	
	B 717	2 x 40 kVA	
	B 767-400	2 x 120 kVA	

The end of table 9.1

Generation type	Civil application		Military application	
VSCF(Cycloconverter) (115 V AC/ 400 Hz)			F 18 C/D	2 x 40/45 kVA
			F 18 E/F	2 x 60/65 kVA
VSCF(DC-link) (115 V AC/ 400 Hz)	B777(Backup)	2 x 20 kVA		
	MD – 90	2 x 75 kVA		
VF (115 V AC/ 380-760 Hz)	Gobal Ex	4 x 40 kVA	Boeing JSF	2 x 50 kVA
	Horizon	4 x 25 kVA		
	A 380	4 x 150 kVA		
VF(230 V AC)	B 787	4 x 250 kVA		

These aircraft systems are highlighted as follows.

Engine Driven AC Electrical Generators

In conventional aircraft electrical systems as well as in MEA concept the aircraft electrical components operate on many different voltages both AC and DC. There are several different power sources on large aircraft to be able to handle excessive loads, for redundancy and for emergency situations, which include:

- engine driven AC electrical generators (mains);
- auxiliary Power Unit (APU);
- ram Air Turbine (RAT);
- batteries;
- external power, i.e. Ground Power Unit (GPU).

The power used in normal flight conditions by the entire aircraft is generated by AC generators driven by the main engines through an appropriate accessory gearbox. During the ground maintenance and for the engine starting, the power is provided by the APU. Most aircrafts can use the APU during the normal flight conditions as backup power source. Otherwise, in case of generators or APU failure, RATs are used as emergency power source. Obviously, external power may only be used with the aircraft on the ground. In this case a GPU (portable or stationary unit) provides AC power through an external plug on to the aircraft.

Nowadays, as typical today aircraft generator is the three-stage synchronous generator with wound field brushless exciter. It is usually realized with laminated stator core with three-phase armature winding distributed in slots and a wound rotor with salient pole. This is a high performance machine and is inherently safe, because the field excitation can be removed, de-energizing the machine. In Fig. 9.2, a, and in Fig. 9.2, b the operating principle and the electrical schematic of the conventional AC generator are depicted. It can be subdivided in:

- a permanent magnet generator;
- an excitation stator surrounding an excitation rotor containing rotating diodes;
- a power rotor encompassed by a power stator.

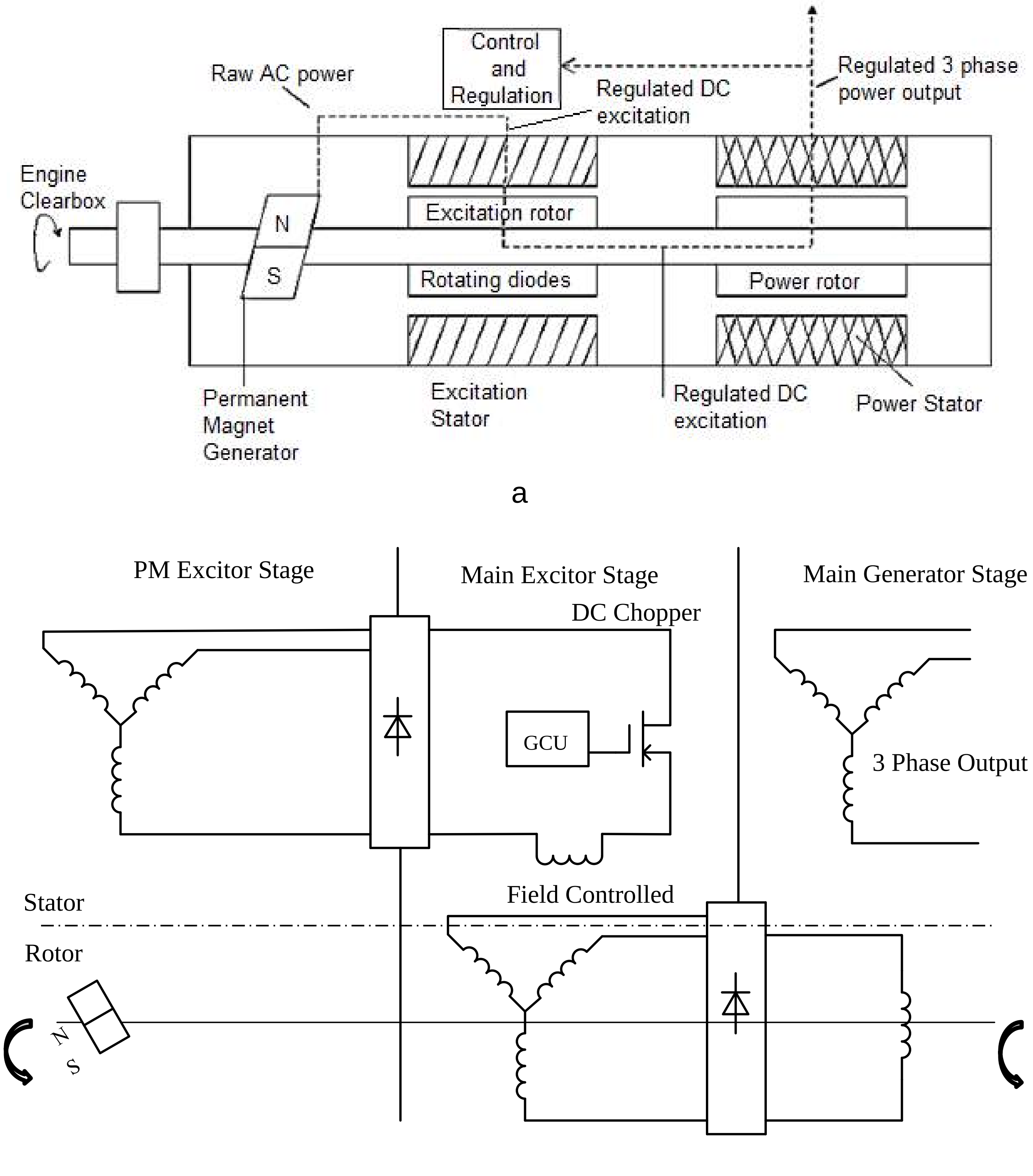


Fig 9.2. Operating principle and electrical schematic of conventional AC generator:
a – operating principle; b – electrical schematic.

The excitation system of the brushless exciter is stationary, i.e. PMs or DC electromagnets are fixed to the stator facing the exciter armature winding. In the case of DC electromagnets, the DC current can be supplied from the external DC source main armature winding via rectifier, or from a small PM generator (sub-exciter) with stationary armature winding and rotating PMs. Rotating PMs are located on the shaft of main generator. The rotation of the excitation rotor within the field produced be the excitation stator winding is rectified by means of diodes contained with the rotor. These rotating diodes supplies a regulated and controlled DC voltage to excite the power rotor windings. The rotation field generated by the power rotor induces on AC voltage in the power stator. The speed of contemporary aircraft generators is typically from 7,000 up to 24,000 rpm and output power from 30 up to 250 kW. The mechanical shaft speed and the output frequency can be both constant or variable, subdividing the generators in the following three main categories:

- constant speed constant frequency (CSCF) generators;
- variable speed constant frequency (VSCF) generators;
- variable frequency (VF) generators.

9.2. Generator Topologies

The anticipated increase in electrical power generation requirements on MEA suggests that high power generators should be attached directly to the engine, mounted on the engine shaft and used for the engine start in Integral Starter/Generator (IS/G) scheme. The harsh operating conditions and the high ambient temperatures push most materials close to or even beyond their limits requiring more innovations in materials, processes and thermal management system design.

Consequently, Introduction, Switched Reluctance, Synchronous and Permanent Magnet machine types have been considered for application in MEA due to their robust features.

Introduction Generator

Introduction Generators (IGs) are characterized by their robustness, reduced cost and ability to withstand harsh environment. However, the IG requires complex power electronics and is considered unlikely to have the power density of the other machines.

Synchronous Generator

The current generator technology employed on most commercial and military aircraft is the three-stage wound field synchronous generator. This machine is reliable and inherently safe; as field excitation can be removed de-energizing the machine. Therefore, the rating of the three-stage synchronous generator has increased over the years reaching to 150 kV on the Airbus A 380. The synchronous machine has the ability to absorb/generate reactive power, which enhances the stability of the aircraft power system. However, this machine requires external DC excitation, which unfortunately decreases the reliability and the efficiency.

Switched Reluctance Generator

Most primary electrical AC power generators today are based upon the compound generator. For example, in conventional constant frequency applications the generator is combined with a Constant Speed Drive unit, which has reliability and maintenance limitation.

Alternatively, the generator may be combine with Variable Speed Constant Frequency (VSCF) electronics or may act as a variable frequency (VF) machine, with power electronics or motor controllers downstream to control specific loads.

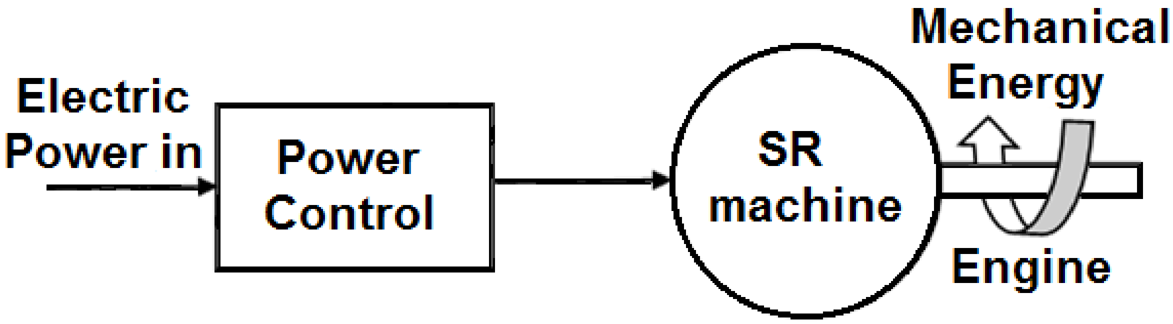
The compound generator is complex, being effectively three generators on the same shaft and multiple sets of winding and rotating diode packs mean that there are limits to carrying the technology further. Compound machines effectively have an upper speed limit as there comes a point where it is not practicable to package the rotating elements within speed or weight constants. Furthermore, as the used starter/generator becomes a realistic option for large system and more electrics system generation demands increase so there is a need to consider other options.

A likely solution to these issues is Switched Reluctance (SR) machine. The SR machine has a solid rotor so has none of the encumbrances of the compound generator; the stator is robust and has the only windings within the machine. The machine is therefore easy to manufacture and is robust. In the example shown there are four pairs of poles on the stator and four of he rotor. As the rotor pole is driven past the stator pole there is magnetic coupling between the two if a winding is placed round the stator pole then this may be used to generate electrical power. This winding will be associated with another winding diametrically opposite. AC power will be generated. This power will be multi-phase.

Power electronics is needed to condition this power and turn it into electrical power of a suitable quality for use in aircraft application. It is relatively easy to convert the power into 270 V DC or ± 270 V DC or even 540 DC. These are the typical voltages being explored is some of the advanced more-electric aircraft and engine technology demonstration programs presently under way. The simplicity and robustness of the SR machine allows it to be considered for use within the engine as opposed-to being located on an aircraft accessory gearbox.

The fact that the SR machine is relatively simple in operation and that power electronics is available allows the machine’s flexibility to be used to the full. Fig. 9.3 illustrates how a SR machine may be configured to act both as a starter and a generator.

SR Machine - Starter. The top half of the diagram shown power being applied to a power controller embracing power switching electronics. If the power is sequentially fed to the various stator windings, then the induced magnetic field will cause SR machine to motor. This mechanical energy may be harnessed to the engine shaft during the engine start cycle and cause the engine to spool up to a speed where the combustion ignites and the engine becomes self-sustaining.



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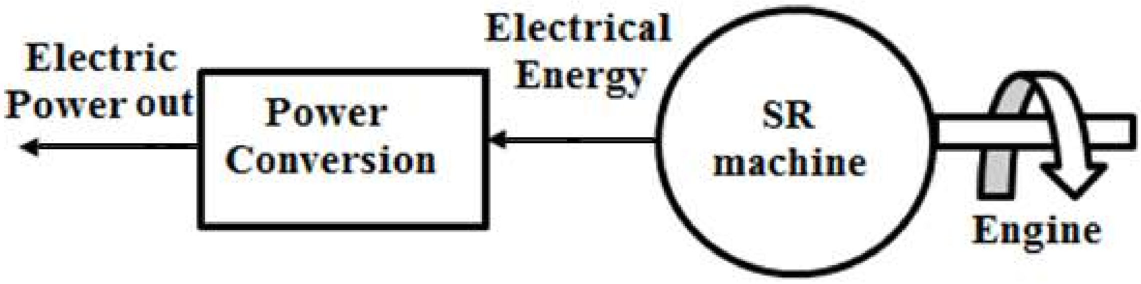

b

Fig. 9.3. Switched Reluctance machine-modes of operation:
a – motor mode, b – generator mode

SR Machine-Generator. In the SR machine generation mode, the converse is true. Mechanical energy from the engine is extracted and by switching and conditioning the winding outputs the power conversion electronics can supply high quality electrical power for the aircraft electrical system. The same switching power electronics used for SR start can be reconfigured to be used for power generation. A 270 V DC SR starter generator was demonstrated and incorporated to F-35 Lightning II electrical system.

Permanent Magnet Generators (PMGs). The fault-tolerant Permanent Magnet (PM) generator is considered to be one of the most attractive option for the MEA. It has a high kW/mass ratio and good efficiency throughout a wide speed range. Additionally, the reliability, ruggedness, and easy of cooling are also positive features.

The used of PMG to provide emergency power has become prominent over the last time. PMG may be single - phase or multi-phase devices. Fig. 9.4 shows a three-phase PMG with converter, obviously within reason the more phase used the easier the task to convert the power to regulated 28 V DC.

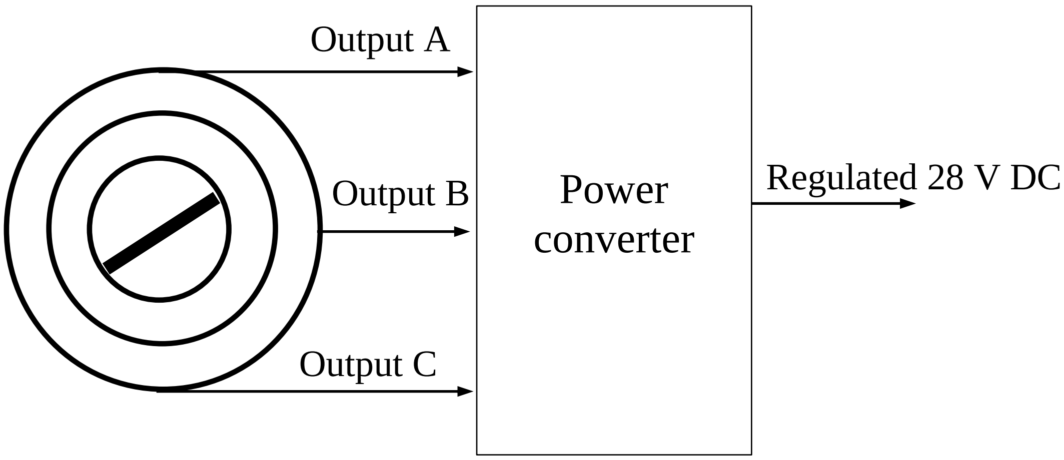

Fig. 9.4. Three-phase PMG with converter

The backup converter hosts PMGs which may supply several hundred watts of dependent generated power to the flight control DC system where the necessary conversion to 28 V DC is undertaken. It was already explained earlier when considered AC generators include a PMG to bootstrap the excitation system. Also PMGs – also called Permanent Magnet Alternators (PMAs) – are used to provide duel independent on-engine supplies. As an indication of future trends it can therefore be seen that on an aircraft such as the B 777 there are a total of 13 PGMs/PMAs across the aircraft critical control system – flight control, engine control and electrical systems.

9.3. Main Categories of Generator Systems

CSD/IDG Generating System

The electrical generator is mechanically driven by an interpose constant speed drive (CSD), which maintains constant the rotational speed of the generator shaft, allowing in this way constant frequency generator. If the CSD is directly integrated inside the generator, it can be named Integrated Driven Generator (IDG). The constant speed is obtained with an epicyclical differential a variable displacement hydraulic unit and a fixed one the drive the generator. This system can therefore provide constant output speed while the input speed (e.g. engine shaft speed) can vary depending on engine throttle. This is achieved by using hydraulic devices to add or subtract speed to or from one arm of the differential. The main features of CSD/IDG power are shown in Fig. 9.5.

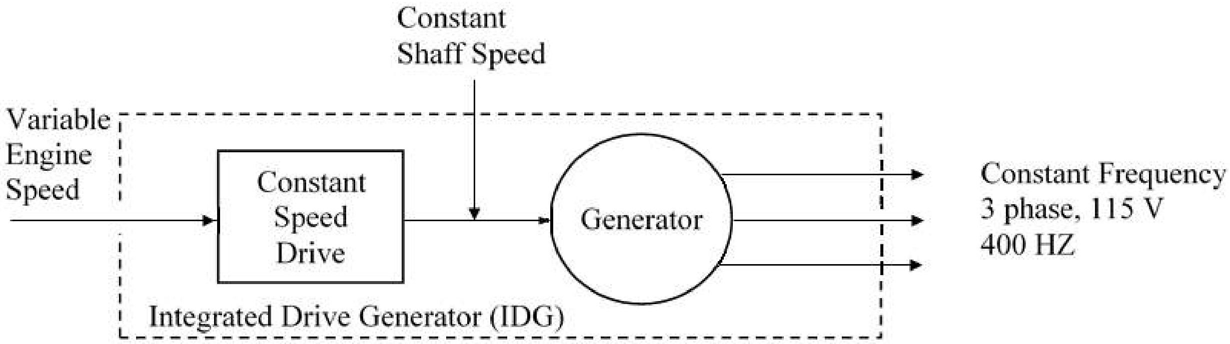

Fig. 9.5. Constant frequency/IDG generation

In common with all the other power generation types this has to cater for a 2:1 ratio in engine speed between maximum power and ground idle. The CSD in effect acts as an automatic gearbox, maintaining the generator shaft speed at constant rpm which result is constant frequency output of 400 Hz, usually within approximate by 10 Hz or less. The IDG used to power the majority of civil transport aircraft today, as shown in Table 9.1.

Considering the MEA concept, the use of this system appears not to be the best constant maintenance, particularly for the lubrication system.

VSCF Generating System

Fig. 9.6 shows the concept of the VSCF converter. In this technique the variable frequency power produced by the generator is electrically converted by solid state power switching devices to constant frequency 400 Hz, 115 V AC power.

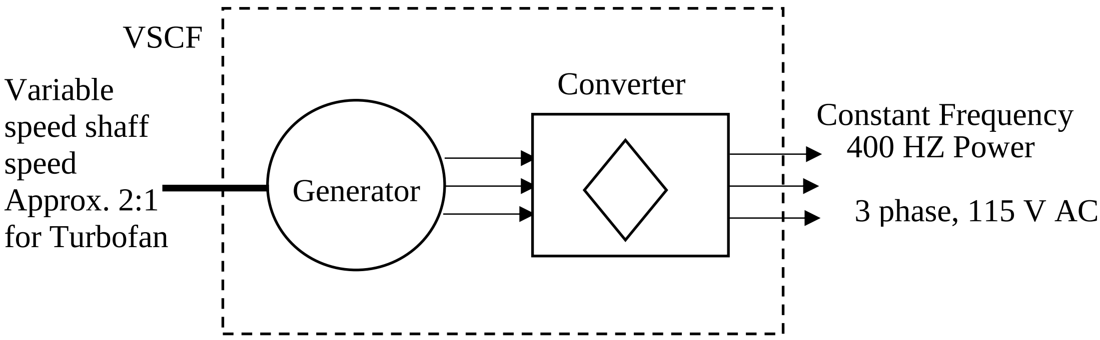

Fig 9.6. VSCF Power Generation

Two options exist:

1) **VSCF DC Link.** In the DC link the raw power is converted to an intermediate DC power stage the DC link – before being electronically converted to three-phase AC power. This system is now the preferred option for the most new military aircraft application and some commercial aircraft (B 737, MD – 90,

B 777). VSCF DC-link option is generally characterized by simplicity and reliability. The DC-link provides additional benefit for feeding high voltage loads and charging batteries.

2) **Cycloconverter.** The Cycloconverter (AC/AC converter) uses a different principle. Six phases are generated at relatively high frequency in excess of 3000 Hz and the solid state devices switch between these multiple phases in a predetermined and carefully controlled manner. The effect is to electronically commutate the input and provide three phases of constant frequency 400 Hz power. Through this appear to be a complex technique it is in fact quite elegant and cycloconverter systems have been successfully used on military aircraft in the US: F-18, U-2 and the F-117 Steal Fighter. As yet no civil applications have been used. A simplified block diagram for the such VSCF system is shown in Fig. 9.7.

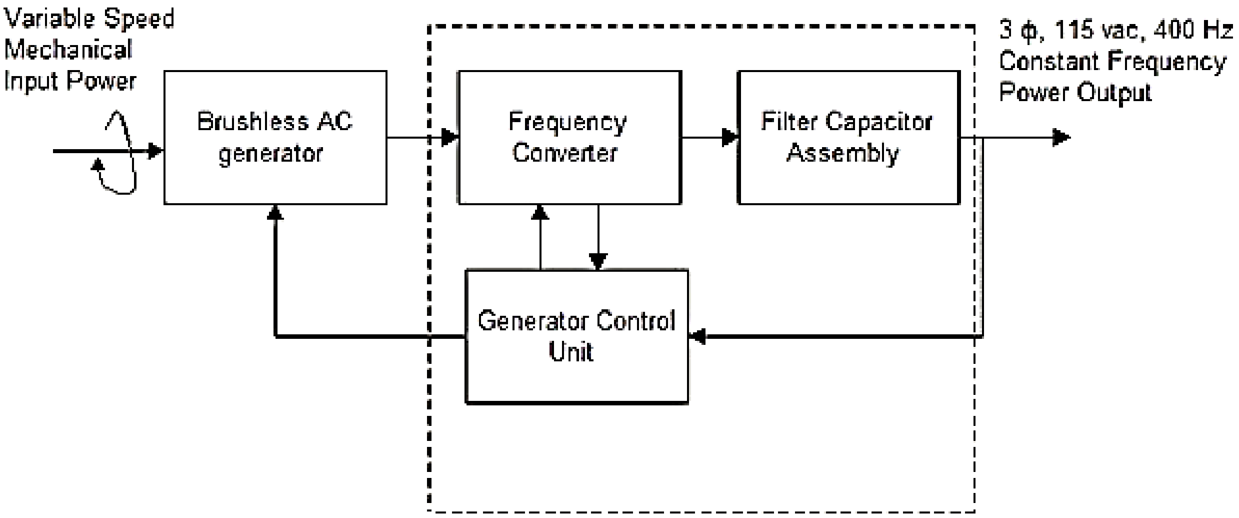

Fig. 9.7. Simplified VSCF cycloconverter system diagram.

The generator is driven by the accessory gearbox and produced AC output voltage at variable frequency proportional to the gearbox speed. The converter converts the variable frequency into constant 400 Hz, three-phase power by using an SCR-based cycloconverter. The filter assembly filters out high frequency ripple in the output voltage. The GCU regulates the output voltage and provides protection to the system.

VF Generating System

Variable frequency (VF), typified frequency wild as shown in Fig. 9.8 is the simplest and most reliable form of power generation. In this technique no attempt is made to nullify the effect of the 2:1 engine speed ratio and the power output, through regulated to 115 V AC, suffers a frequency variation typically from 360 to 800 Hz. The promising features of VF are the small size, weight, volume and cost as compared with other aircraft electrical power generation options. This wide band VF power has an effect on frequency sensitive aircraft loads, the most obvious being the effect on AC electric motors that are used in many aircraft systems.

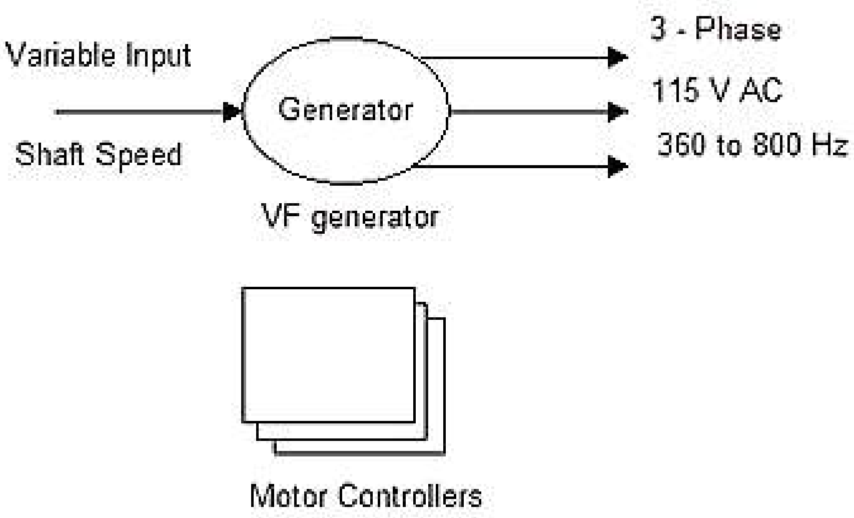

Fig. 9.8. VF Generator

There can therefore be a penalty to be paid in the performance of other aircraft systems such as fuel, ECS and hydraulic. In many cases variations in motor/pump performance may be needed to restore an easier control situation. Major airframe manufactures such as Boeing and Airbus place the burden upon equipment suppliers to ensure that major electrical components perform the specification throughout the anticipated frequency range the aircraft power quality (such as power factor) is not adversely affected.

VF is being widely adopted in the business jet community as their power requirements take them above the 28 V DC/12 kW limits of twin 28 V DC systems. Aircraft such as Global Express had designed in from the beginning. Other recent VF power users are the Airbus A 380 and Boeing 787.

The main features of different types of power generation were in Table 9.2.

Table 9.2. Types of power generation features

CSD/IDG	VSCF	VF
1. Constant frequency AC power is most commonly used on turbofan today.	1. Conversion of VF electric power to CF is accomplished by electronic controlled power switching	1. Simplest form of generation power cheapest and mass reliable.
2. System is expensive to purchase and maintain, primarily due to complexity of CSD.	2. DC-link and cycloconverter option available	2. Variable frequency has impact upon other aircraft subsystems

The end of table 9.2

CSD/IDG	VSCF	VF
3. Single company monopoly on supply of CSD/IDG.	3. Not all implementations have proved to be robust/reliable-cycloconverter shows most promise	3. Motor controllers may be needed for certain aircraft loads
4. Alternative methods of power generation are under consideration.	4. Still unproven in transport market	4. Beginning to be adopted for new programmers: gains outweigh disadvantages

9.4. Auxiliary Power Unit

Many of today's aircraft are designed so that if necessary, they may be independent of ground support equipment. This is achieved by the incorporation of an auxiliary power unit (APU) which, after being started by the aircraft's battery system, provides power for engine starting, ground air conditioning and other electrical devices. In some installations, the APU is also used for supplying power in flight in the event of an engine-driven generator failure and for supplementing the delivery of air to the cabin during take off and climb.

An external view of a typical unit and location in an aircraft is shown if Fig. 9.9.

In general, an APU consists of a small gas turbine engine, a bleed-air control and supply system, and an accessory gearbox. The gas turbine comprises a two-stage centrifugal compressor connected to a single- stage turbine. The bleed- air control supply system automatically regulates the amount of air bleed from the compressor for delivery to the cabin air condition system. In addition to those accessories essential for engine operation, e.g. fuel pump control unit and oil pumps, the accessory gearbox drives a generator which, depending on the type required for a specific aircraft, may supply either DC or AC.

A motor for starting the APU is also secured to the gearbox and is operated by the aircraft battery system or, when available, from a ground power unit.

In some types of APU the functions of engine starting and power generation are combined in a starter/generator unit. For example, the Boeing 777 is equipped with a two 120 kVA, 115 V AC, 400 Hz engine driven generator and one 120 kVA, 115 V AC, 400 Hz APU driven generator. The "more electric" Boeing 787 is equipped with a two 250 kVA, 230 V AC VF generators per engine and two 225 kVA, 230 V AC VF APU driven generators. The Airbus A 380 is equipped with four 150 kVA VF main engine driven generators and two 120 kVA, 400 Hz CF APU driven generators.

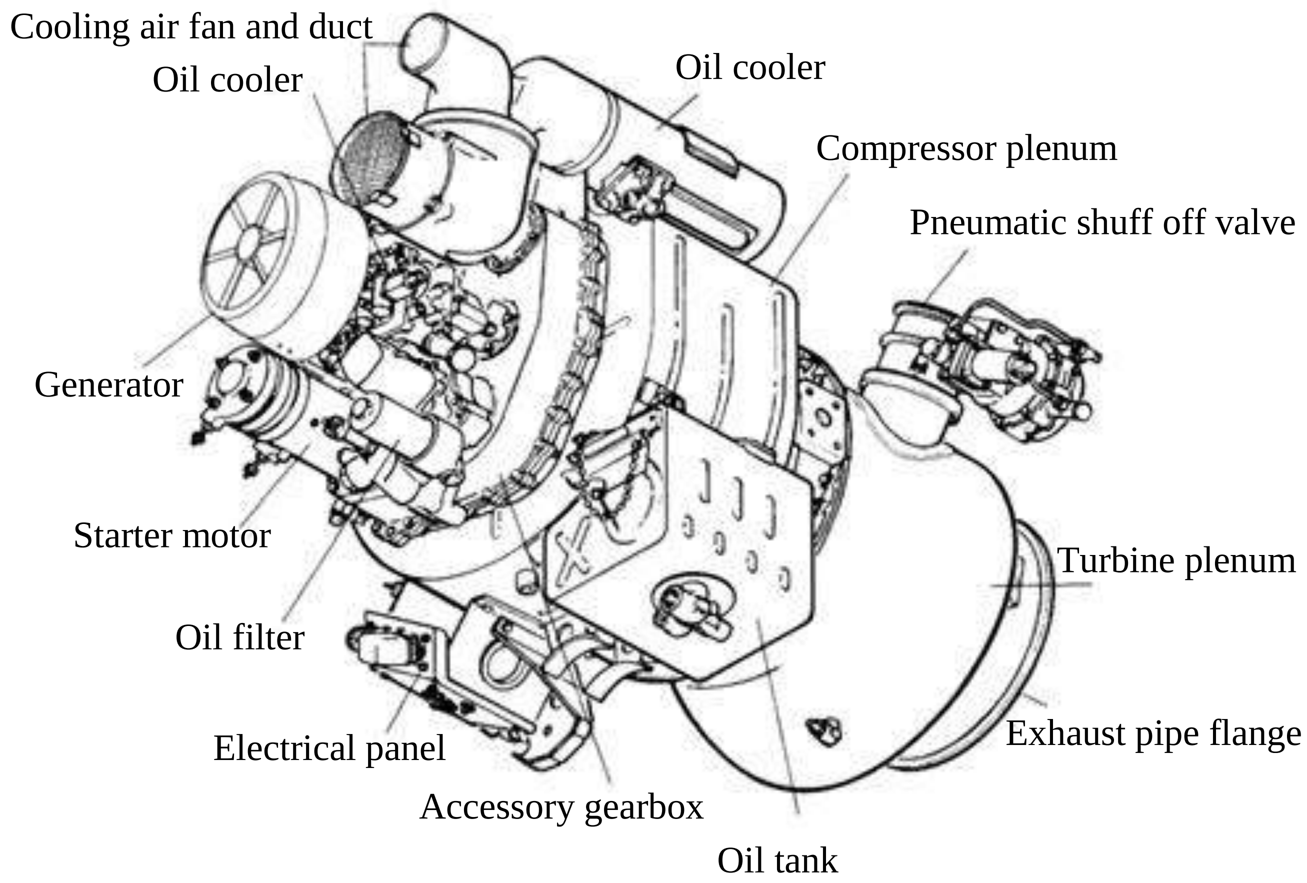

Fig. 9.9. Auxiliary Power Unit

9.5. Emergency Power Sources

In the case of the generators or APU failure, Ram Air Turbine (RAT) or fuel cell are used as emergency power sources.

RAT is a constant speed generator with three-phase power of 200 V AC and 400 Hz. It has a small propeller installed in the aircraft and used as power source. The passage of air over the turbine is used to power a small emergency generator of limited capacity usually enough to power the crew's essential flight instruments and a few other critical services (Fig. 9.10). Typical RAT generator sizing may vary from 5 to 15 kVA depending upon the aircraft.

The RAT also powers a small hydraulic power generator for similar hydraulic system emergency power provision. Once deployed then the RAT remains extended for the duration of the flight and cannot be restored without maintenance action on the ground. The RAT is intended to furnish the crew with sufficient power to fly the aircraft while attempting to restore the primary generators or carry out a diversion to the nearest airfield. It is not intended to provide significant amounts of power for a lengthy period of operation.

Today the largest RAT propeller is adopted by the Airbus A 380, which has a 1.63 m of diameter, but around 80 cm is more common. The propellers started to be realized as two bladed of four-bladed models but military (and increasingly commercial) models use ducted multi-blade fans today. Obviously the RAT are able to generate emergency power only in flight condition. Once deployed, the RAT remains extend for the duration of the flight and cannot be retreated without maintenance action on the ground.

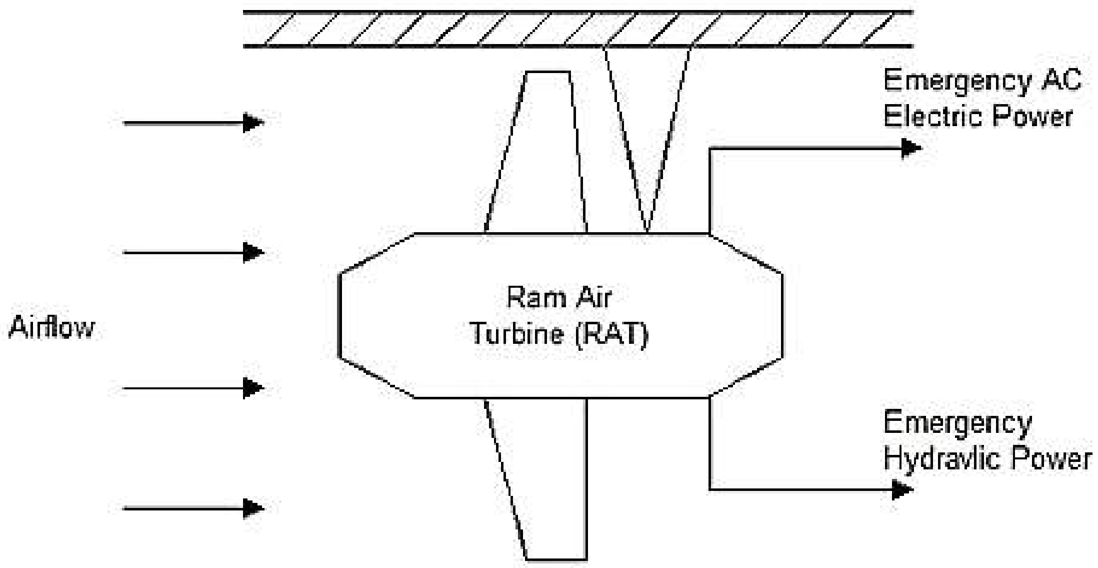

Fig. 9.10. Ram Air Turbine

9.6. Batteries

In each aircraft are present batteries as DC electrical power source. They provide an electrical storage medium independent from the primary generation sources. Their main purposes are:

- to assist in damping transient load in the DC system;
- to provide power in system startup modes when no other source is available;
- to provide short- term high- integrity source during emergency conditions.

Most modern aircraft systems utilized battery charge to maintain the battery at moderately high energy levels during normal system operation. To preserve battery health, it is usual to monitor its temperature which gives a useful indication of over-charging and if thermal runaway is likely to occur. The most commonly used battery is the nickel-cadmium (Ni-Cd) type; lead-acid batteries are usually avoided in modern applications due to corrosive effects. In modern civil aircraft typical batteries capacity are within 30-50 Ah, in a number varying from two to four plus that used the APU.

9.7. Ground power Units

For much of the period of aircraft operation on the ground a supply of power is needed. Ground power may be generated by means of a motor-generator set where a prime motor drives a dedicated generator supplying electrical power to the aircraft power receptacle.

The usual standard for ground power 115 V AC three-phase 400 Hz, which is the same as the power supplied by the aircraft AC generators. In some cases, and this is more the case at major airports, an electrical conversion set adjacent to the aircraft gate supplies 115 V AC three-phase power that has been derived and converted from the national electric grid.

The aircraft system is protected from substandard ground power supplies by means of a ground power monitor. This ensures that certain essential parameters are met before enabling the EPC to close. In this way the ground power monitor performs a similar function to a main generator GCU. Typical parameters which are checked are under voltage, over voltage, frequency and correct phase rotation.

The noise is eliminated along with saving fuel cost and dispersing any type of emission.

9.8. Terms and Contents

1. **More Electric Aircraft (MEA)**. The concept of MEA implies increasing use of electrical power in aircraft systems.
2. **Full Electric Aircraft (FEA)**. The objective of FEA is to completely replace non – electrical power in the aircraft with electricity.
3. **Engine driven AC electric Generator**. The power used in normal flight conditions by entire aircraft is generated by AC generators driven by the main engines through an appropriate accessory gearbox.
4. **Auxiliary POWER UNIT (APV)**. The power is provided by APV during the ground maintenance and for the engine starting. APV can be used during the normal flight conditions as backup power source.
5. **Ram air Turbine (RAT)** is used as emergency power source.
6. **Ground Power Unit (GPV)** is a stationary unit which provides AC power through an external plug on to the aircraft.

9.9. Control Questions

1. What do you understand by terms variable frequency system?
2. State the factors upon which the output frequency system?
3. Describe the construction of a typical aircraft generators.
4. Describe how the speed of constant frequency generator is maintained.
5. What are advantages of brushless aircraft generator?

6. In which way does an auto transformer differ from a conventional transformer?
7. What function does a variac transformer provide?
8. Why are APVs particularly useful in aircraft?
9. How is the emergency generator driven?

Chapter 10

ADVANCED DISTRIBUTION POWER SYSTEMS OF AIRCRAFTS

10.1 Convention Aircraft

Conventional aircraft electric power System (AEPS) often consist of two or more engine-drive generators to supply AC loads throughout the aircraft. While engine driven generators are single connected to the distribution buses in some civil aircraft configurations (i. e. each generator is responsible for a specific numbers of buses) almost all American and European air forces use the parallel connection configuration.

AC/DC rectifiers are used to convert the AC voltage with fixed frequency at the main AC bus to multi-level DC voltages at the secondary buses which supply electrical power to DC loads as shown at Fig. 10.1.

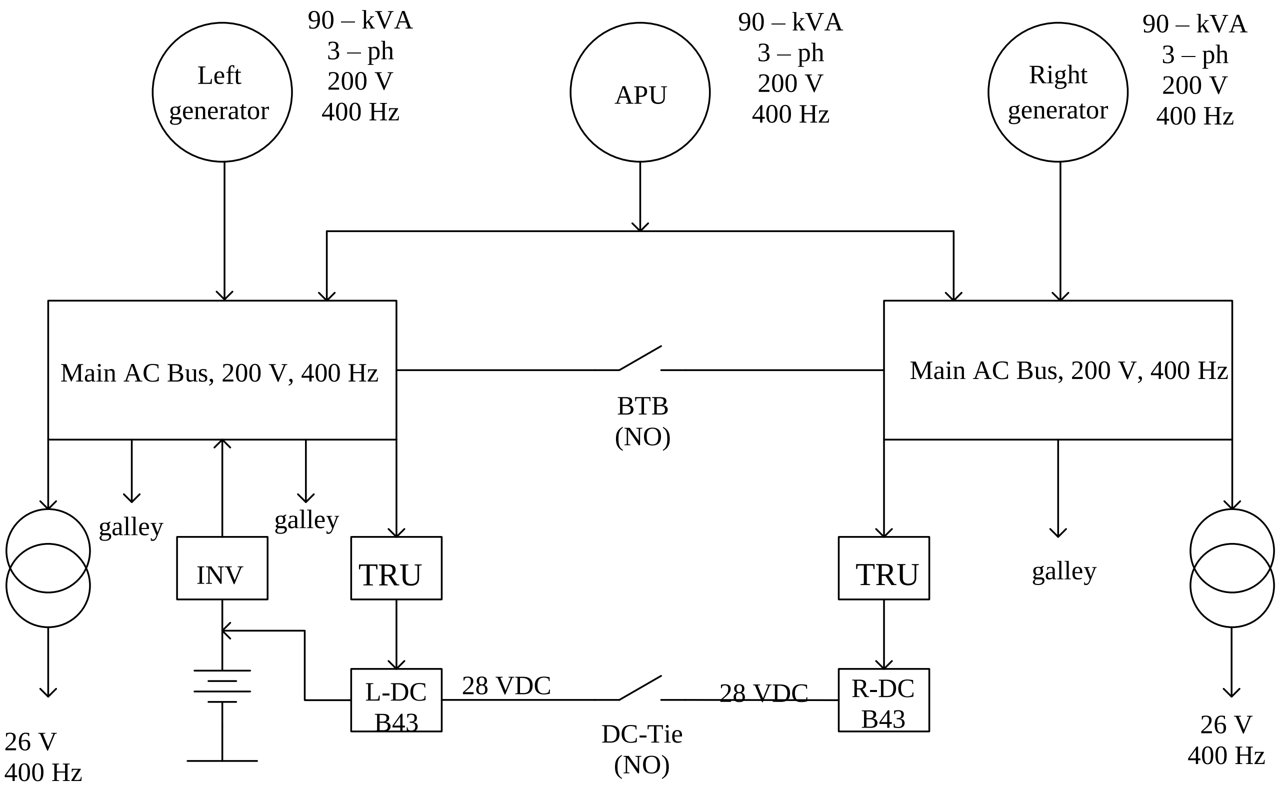

Fig. 10.1. Conventional B 767 aircraft power distribution system.

In this configuration, the main generators bus bars are connected together through Bus-Tie Breaker (BTB). In the event that one generator should fail it is automatically isolated it's from respective bus bar and all bus bar loads are then take over by the operative generators. Should both generators fail however, nonessential loads can no longer be supplied, but the batteries will automatically supply power the essential services and keep them operating for a predetermined period depending on load requirements and battery of change.

In conventional aircrafts system, the synchronous generator supplies AC voltage at constant frequency to the AC loads in the aircraft power system.

10.2. More Electric Aircraft

Advanced in power electronics, control systems, motor drives, and electric machines helped in developing new technologies of the VSCF system. The main advantages of this system is that it provides better starter/generator systems. Other advantage are: higher reliability, low recurring costs, and shorter mission cycle times. VSCF system employ on AC three-phase synchronous generator and solid state converters. Each solid state converter consists of (a) a rectifier unit which converts a variable frequency AC voltage into DC (b) an intermediate circuit and (c) an inverter which then converts the DC into three-phase AC constant frequency voltage.

The schematic of a typical variable-speed constant-frequency starter/generator system is shown in Fig. 10.2.

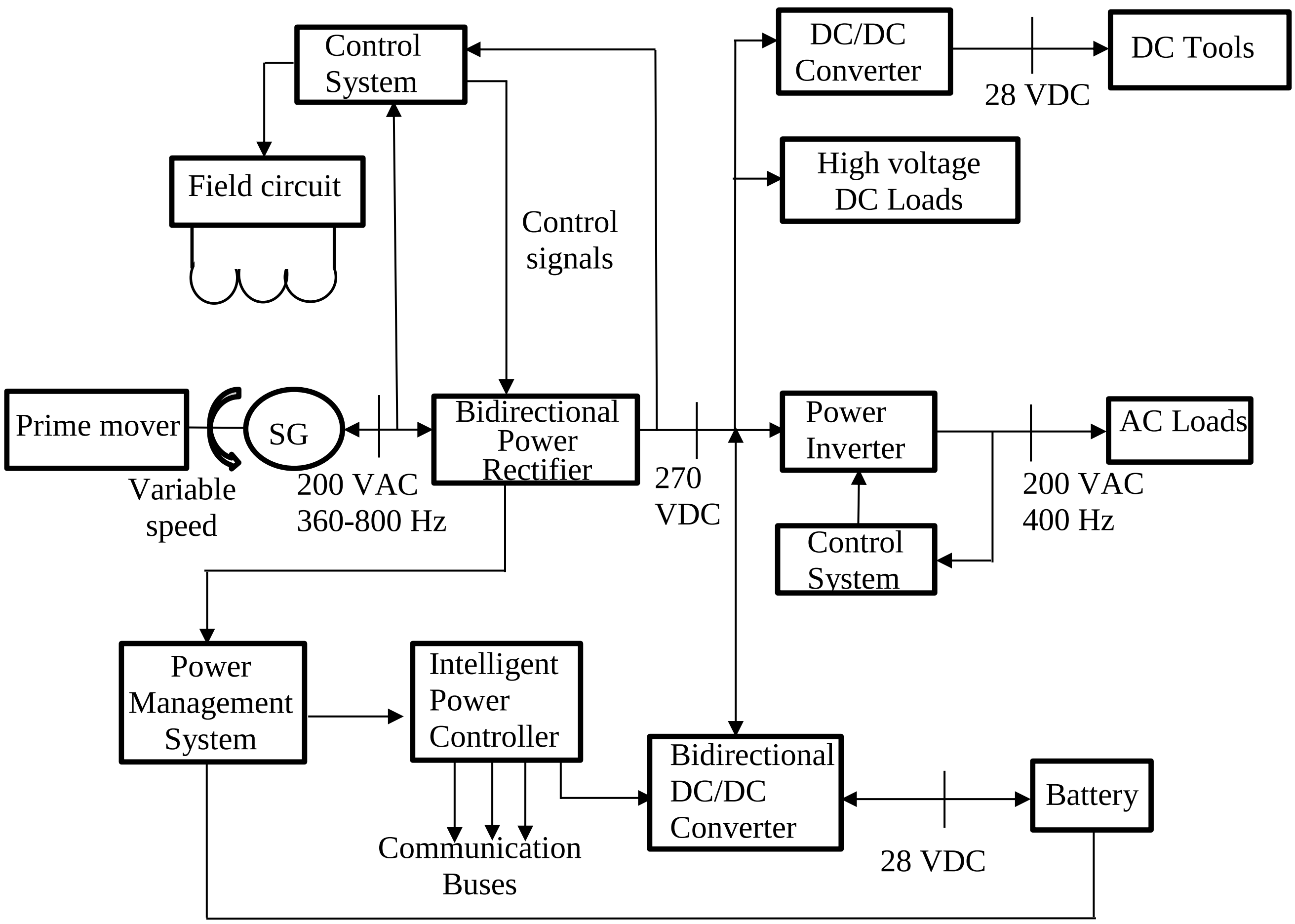

Fig. 10.2. More electric aircraft power distribution system

In the generating mode of VSCF system, aircraft engine, which has variable speed, provides mechanical input power to the electric generator. The electric generator then supplies variable frequency AC power to a (bi-directional) power converter, which provides AC constant frequency voltage to the main bus. In the motoring mode, the constant frequency AC system, via the bi-directional power converter, provides input electric power to the electric machine, which acts as a starter to aircraft engine. Synchronous, induction and switched reluctance are competing candidates for VSCF starter /generator systems. Comparison of these machines for aircraft power system applications is mainly based on the weight, power density, efficiency, control complexity and features, complexity of design and fabrication, reliability and thermal robustness, as well as economics.

10.3. Latest MEA Aircrafts

The latest aircrafts power system distribution for B 787/A 380 is shown in Fig. 10.3.

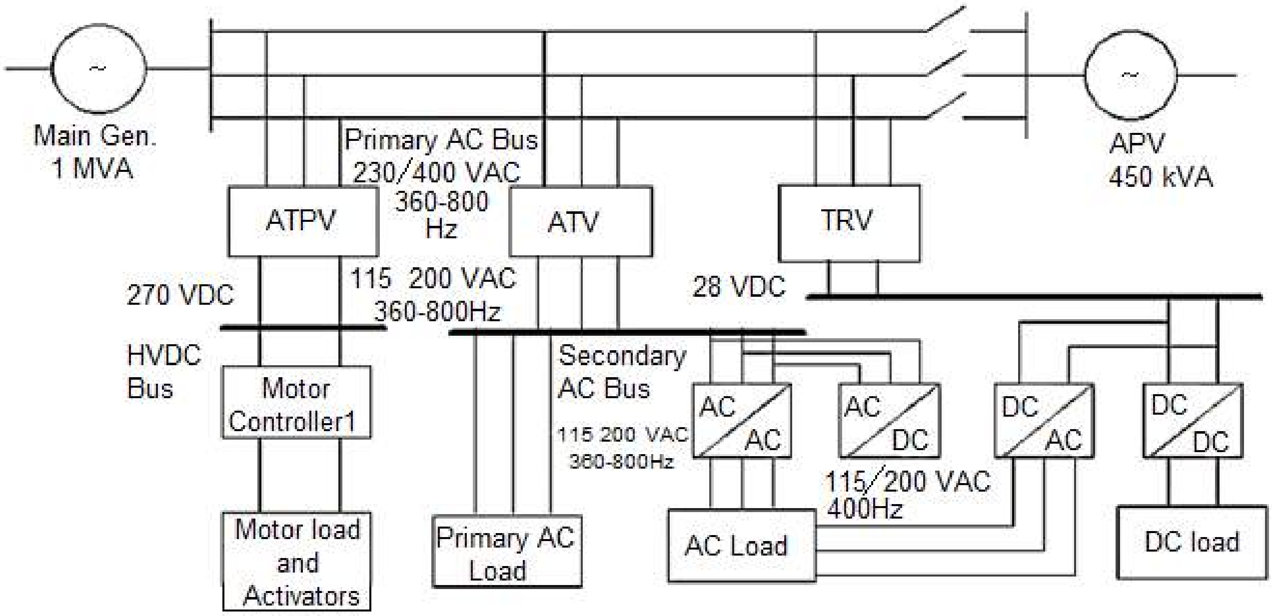

Fig. 10.3. B 787/A 380 aircrafts distribution system

The power rating of the main generator may reach 1 MVA, while, the APV generator rating may reach 450 kVA. Here the primary AC bus is characterized by its higher rating voltage of 400 V with frequency range of 380-800 Hz, instead of 200 V as previous systems.

The primary AC power bus feed the 270 V HVDC through Auto-Transformer Rectifier Unit (ATRU), secondary AC bus of 200 V and frequency of 380-800 Hz through Autotransformer Unit (ATU), the 28 VDC bus through Transformer Rectifier Unit (TRU) and primary AC loads.

The primary power distribution system consolidates the aircraft electric power inputs and it can accept power from the main aircraft generator, APU generator, ground power and/or RAT generator when deployed by the emergency electrical system.

The secondary AC bus has a lower voltage of 200 V then the primary bus with variable frequency 380-800 Hz. Both variable frequency and fixed frequency of 400 Hz of AC loads are fed from the secondary bus at the same voltage rating of 200 V. This bus can supply critical DC loads in case of failure in DC bus by AC/DC power converts.

The 270 HVDC bus is found in MEA and latest version of B787 and/or A380. The ATRU is used to convert the 400 V of primary AC bus to the 270 V DC. The HVDC bus feeds only the large motor such as action motors and hydraulic pumps.

The 28 V DC bus exists in all aircraft systems. The TRU is used to convert the high voltage of primary AC bus to the 28 VDC. The 28 V DC bus feeds the low voltage DC loads as well as charging the batteries onboard. It can also feed the critical AC loads in case of secondary AC bus failure through using DC/AC power converters. In case of emergency, the most important AC or DC loads are fed from RAT, fuel cell stacks and from the 28V DC bus by using DC/AC converters.

10.4. Recent Electrical System Developments

Three major aircraft programmers under way illustrate in different ways the architectures and concepts that have involved since the turn of the millennium. This project are: Airbus A 380, Airbus 400 M, Boeing 787. Each of these systems is described.

Airbus A380 Electrical System

The A380 was the first large civil aircraft in recent times to re-adopt variable frequency (VF), or ‘frequency wild’ as it was formerly called, since some of the turboprop airlines airliners of 1950’s and early 1960’s.

AC power generation. The key characteristics of the A380 electrical power generation systems are as follows:

- 4 x 150 kVA VF Generators (370-770 Hz). VF generators are reliable but do not offer a no break power capability;
- 2 x 120 kVA CF APU generators (nominal 400 Hz)
- 4 x External Power Connections (400 Hz) for ground power;
- 1 x 70 kVA Ram Air Turbine for emergency use.

The 150 kVA per primary power channel represented in increase over previous civil aircraft. Hitherto the most powerful had been the Boing 777 with 120 kVA plus 20 kVA (VSCF Backup) representing 140 kVA per channel.

The AC power system architecture is shown in Fig. 10.4.

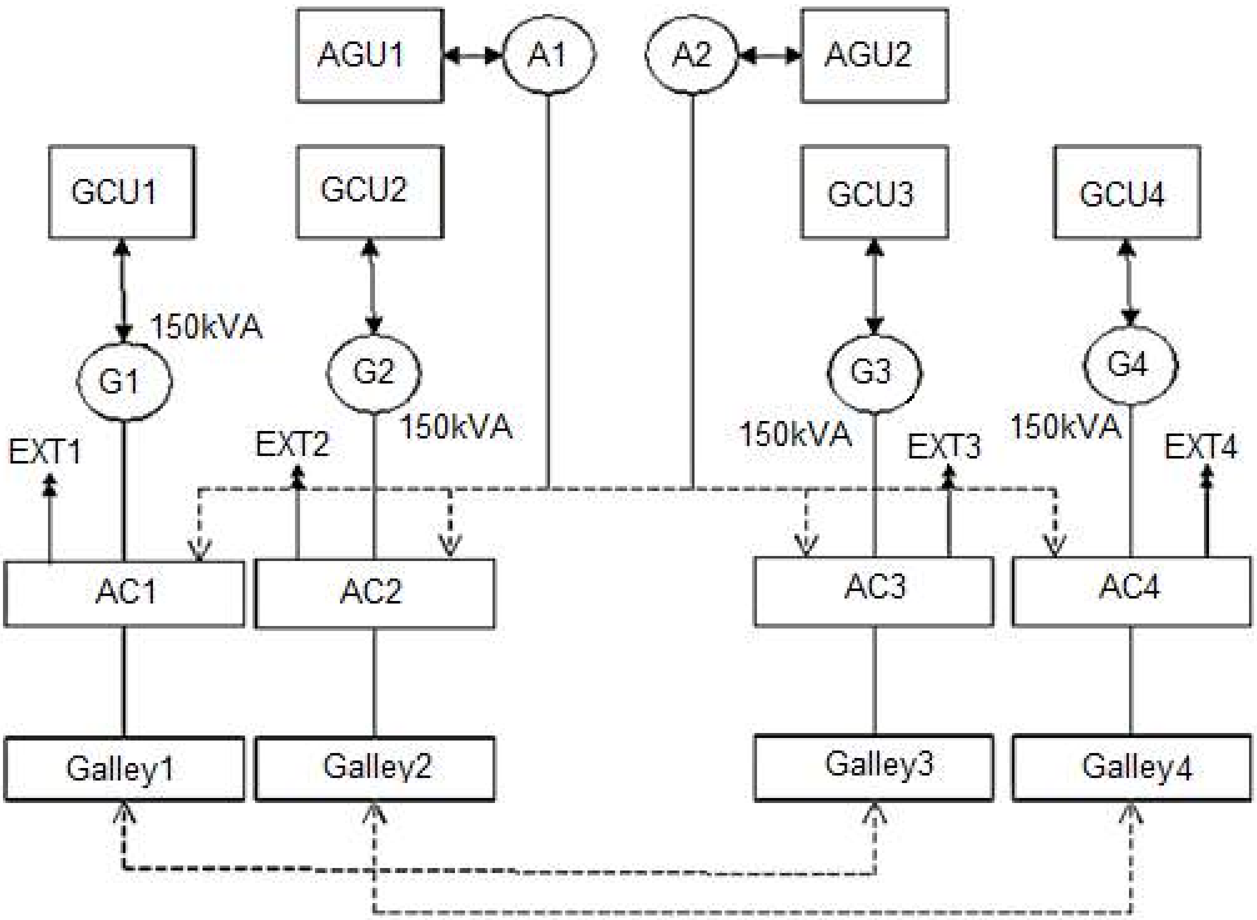

Fig 10.4. A380 AC electrical power architecture

Where GCU – generator control unit; AGCU – auxiliary generator control unit.

Each of the main 150 kVA AC generators is driven by the associated engine. The two APU generators are driven by the respective Auxiliary Power Unit (APU). Each main generator supplies power to the appropriate AC bus under the control of the GCU. Each main AC bus can also accept a ground power input for servicing and support activities on the ground. Because the aircraft generators are variable frequency (VF) and the frequency of the AC power depends upon the speed of the appropriate engine, the primary AC buses cannot be parallel.

The aircraft galley which from a large proportion of the aircraft load are split between each of the four AC buses as shown.

DC System. The key characteristics of the A380 DC power conversion and energy storage system are outlined below:

– 3 x 300 A Battery Charger Regulator Unit (BCRU); these are regulated TRUs;

– 1 x 300 A TRU;

– 3 x 50 Ah Batteries;
– 1 x Static Inverter.

The DC system provides no-break power capability there by permitting key aircraft system to operate without power interruption during changes in system configuration. Most control computers or IMA cabinets are DC powered and the use of DC paralleling techniques facilitates the provision of no-break power for these crucial elements. See Fig 10.5.

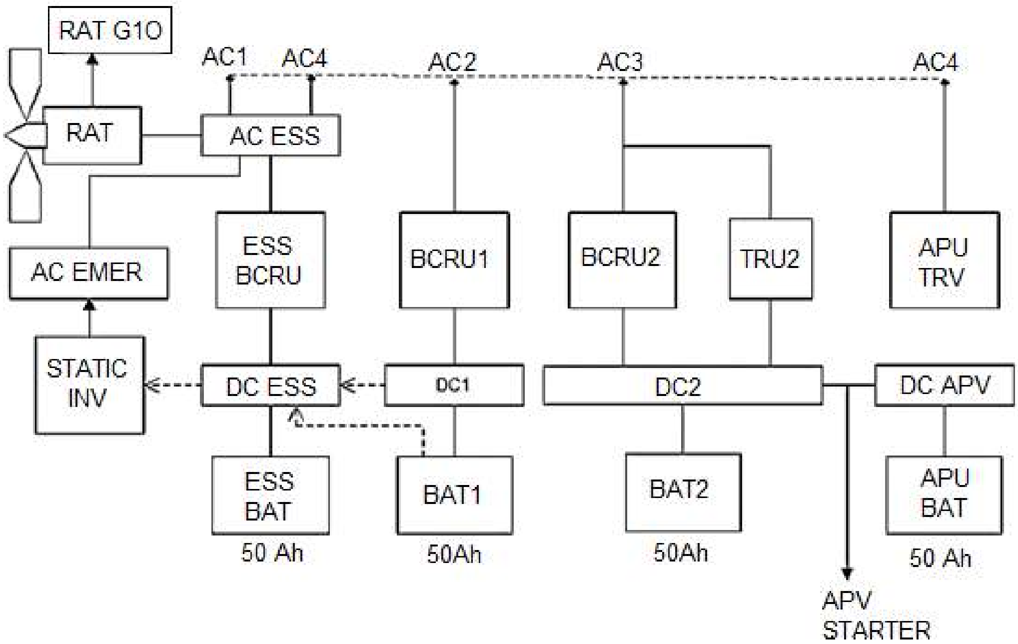

Fig. 10.5. A380 DC electrical power architecture

The figure showed how the AC buses 1 to 4 (AC1 to AC4) feed the main DC system power conversion unit. The Ram Air Turbine (RAT) feeds the AC Ess bus as do main AC buses AC1 and AC4. The AC Ess bus in turn feeds an AC E mer bus which can also be powered from the DC Ess bus through a static inverter. AC1/AC4, AC2 and AC3 respectively feed the DC Ess, DC1 and DC2 buses that are regulated to 28 V DC since the BCRUs are effectively regulated TRUs. Each of those buses has an associated 50 Ah battery whose charge is maintained by the charging function of the BCRU.

For APU starting the following dedicated subsystem is provided:

- 1 x 300 A APU TRU;
- 1 x 50 Ah TRU Battery.

Airbus 400M Power Generation System

The A 400M is a European joint project to develop a military transport to replace the number of platforms. The A 400M barrows much of the electrical power technology from the A380 and also uses the common avionics architecture.

The key point of the A400 AC architecture are:

- 4 x 75 kVA VF generators operating over 390-620 Hz frequency range;
- 1 x 90 kVA APU generator operating at a nominal 400 Hz;
- 1 x 43 kVA RAT;
- 1 x 90 kVA ground power connection.

The DC system has almost identical features to the A380 system:

- 3 x 300 A Battery Charger Regulator Unit (BCRU); rated at 400A ;
- 1 x 300 A TRU which also supports APU starting;
- 3 x 40 Ah NiCd Batteries.

The higher rating of BCRUs (400A versus 300A) result from the higher DC loads on the military platform. DC paralleling technologies provide DC no- break power as for the A380.

Boing 787 Power Generation System

The B787 now in the late stages of prototype build has many novel more-electric aircraft features. The aircraft is a large step toward the all-electric airplane one in which all system are run by electricity. Bleed air from the engines has essentially been eliminated and while hydraulic actuators are still use the major of their power comes from electricity.

In breaking with five decades of practice, Boing claims that electric compressors are better suited for the cabin that engine bleed and had many savings.

The B 787 (Dream liner) electrical power system is portrayed at a top level in Fig 10.6.

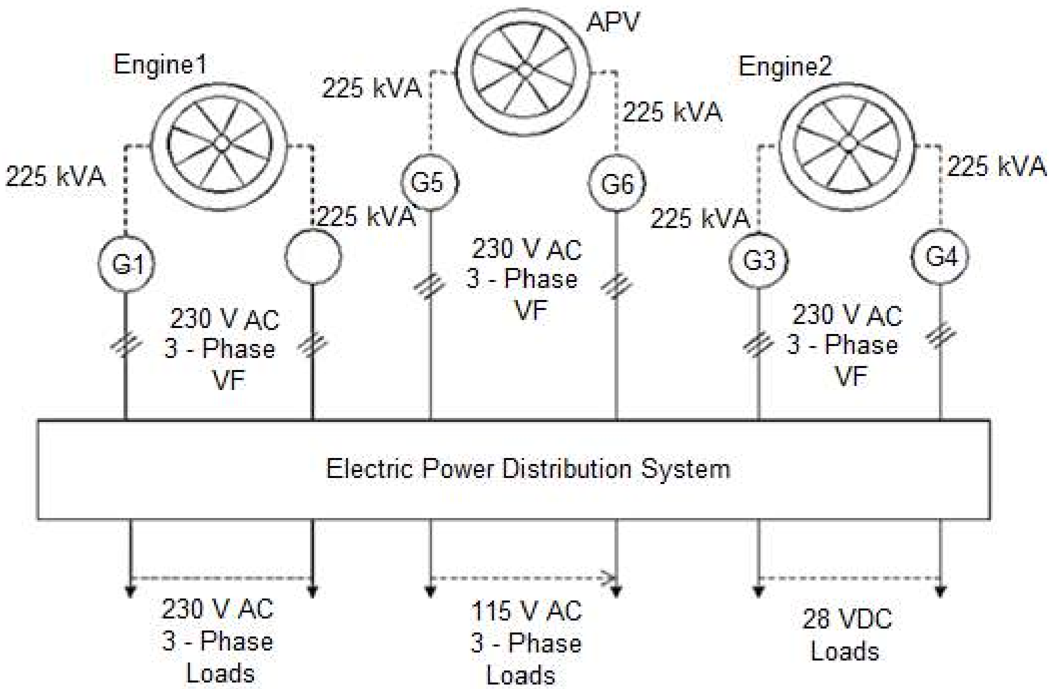

Fig. 10.6. Boeing 787 Top - level electric system

The key feature is adoption of three-phase 230 VAC electric powers compared with the conventional three-phase 115 VAC arrangement usually used. The increased voltage by a factor to 2:1 decreases feeder loses in the electrical distribution system and allows significant wiring reduction. The use higher 230 VAC phase voltage, or 400 VAC line-to-line, does require considerable care during design to avoid the possible effects of partial discharge, otherwise known as “corona”.

The salient features of the B 787 electrical power system are:

- 2 x 250 kVA starter/generators per engine resulting in 500 kVA of generated power per channel. The generator are variable frequency (VF) reflecting recent industry traits in moving away from constant frequency (CF) 400 Hz power;

- 2 x 250 kVA APU starter/generators each starter/generators drive the APU. Each main generator feeds it’s own 230 V AC main bus before being fed into the power distribution system. As well as powering 230 V AC loads, electrical power is converted into 115 VAC and 28 VDC power to feed many of the legacy subsystems that require these more conventional supplies.

A summary of the B 787 electrical loads is given in Fig 10.7.

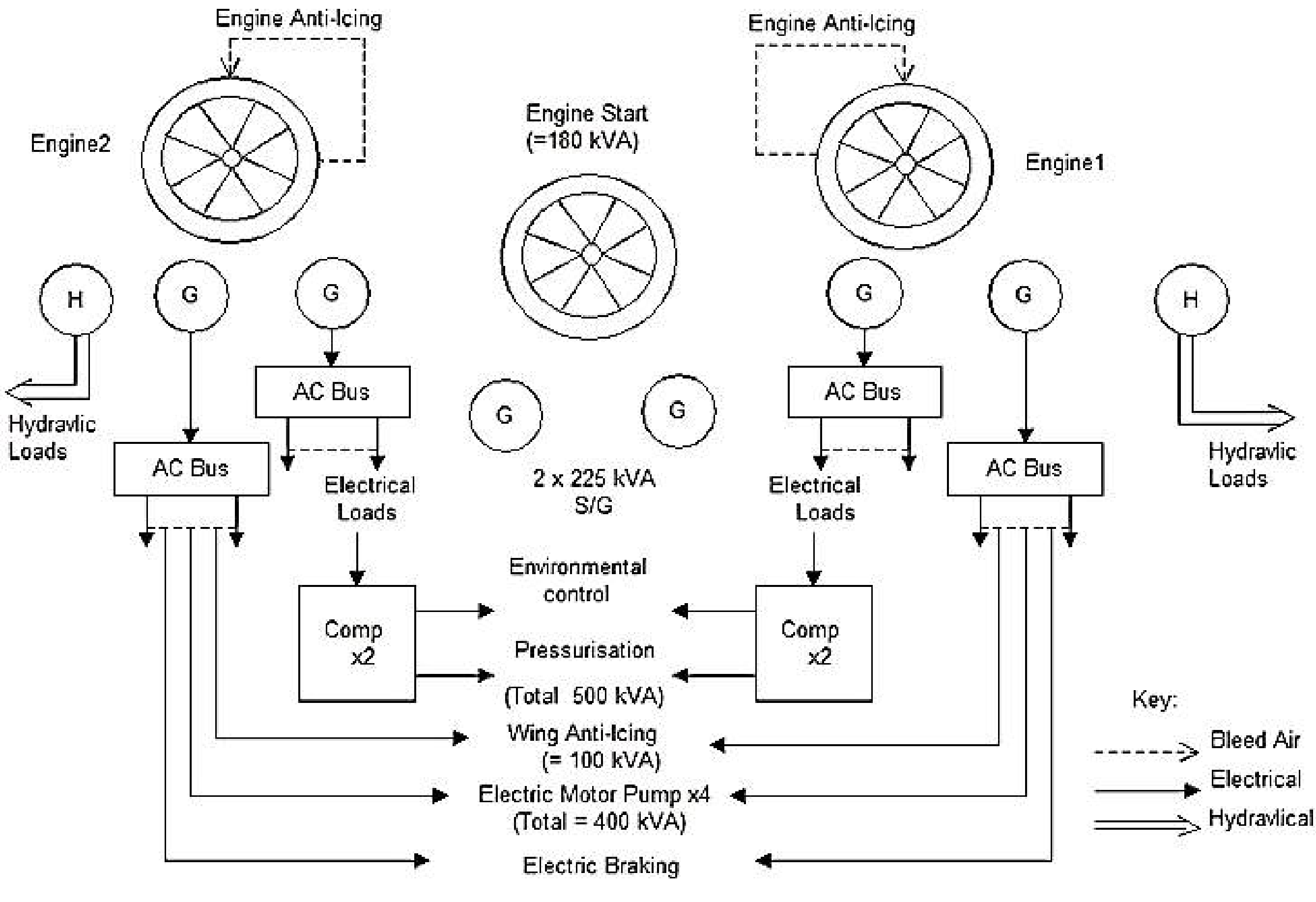

Fig 10.7. Boeing 787 electrical loads

As bleed air is no longer used within the airframe there are no air feeds to the environmental control system, cabin pressurization system, wing anti-iced system as well as other air-powered subsystems. The only bleed air taken from the engine is low-pressure fan air used to anti-ice the engine cowl. Tapping bleed air off the engine compressor is extremely wasteful, especially as engine pressure ratios and by pass ratios increase on modern engines such as the General Electric GeNex and Rolls-Royce Trent 1000. An additional saving is removal of the overhead of providing large ducts throughout the airframe to transport the air. In some part of the airframe overheat detection systems are required to warn the flight crew of hot gas leaks.

The main more-electric loads in the B 787 system are:

- **Environmental Control System (ECS) and Pressurization.** The removal of bleed air means that air for the ECS and pressurization systems needs to be pressurized by electrical means; on the B 787 four engine large electrically driven compressors are required drawing in the region of 500 kVA;

- **Wing Anti-Icing.** Non-availability of bleed air means that wing anti-icing has to be provided by electrical heating mats embedded in the wing leading edge. Wing anti-icing requires in the order of 100 kVA of electrical power;

- **Electric Motor Pumps.** Some of the aircraft hydraulic Engine Driven Pumps (EDP) are replaced by electrical driven pumps. The four new electrical motors pumps require ~ 100 kVA each giving a total load requirement of 400 kVA.

A further outcome of the adoption of the “bleedless engine” is that the aircraft engines cannot be started by the conventional means: high pressure air. The engines use the in-built starter/generators for this purpose and require ~ 180 kVA to start the engine.

The introduction of such high-powered electrical machines has a significant impact upon the aircraft electrical distribution system. Primary power electrical power distribution is undertaken by four main distribution panels, two in the forward electrical equipment bay and two others in the aft electrical equipment bay. The aft power distribution panel also contain the motor controllers of the four Electrical Motor Pumps (EMPs); two of associated pumps are located in the engine pylons and two in the aircraft center section. Also located within the aft distribution panels are the engine starter motor controllers (4) and APU starter motor controller (1). The high level of power involved and associated power distribution generate a lot of heat and the primary power distribution panels are liquid cooled. The electrically powered air conditioning packs are located in the aircraft center section. Secondary power distribution is achieved by using Remote Power Distribution Units (RPDUs) located at convenient placed around the aircraft. In all the are a total of 21 RPDUs located around the aircraft.

Conclusions

Detailed power distribution systems of conventional and advanced more electric aircrafts are explained and demonstrated. The latest aircrafts are characterized by a higher power r4ating that may reach 1 MVA per generator that the convention aircraft that has a power rating of 120 KVA per generator. The advances in power electronic switches and control devices make it possible to provide a multi – voltage distribution system inside the aircraft that have variable and fixed frequency supplies with different voltage ratings. Moving towards aircrafts than are more electric enhances the overall efficiency of the system, increases the reliability and provides flexibility and economic operations.

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СИСТЕМИ ЕЛЕКТРОПОСТАЧАННЯ ЛІТАКІВ

AIRCRAFT ELECTRICAL EQUIPMENT

Part 1

AIRCRAFT ELECTRICAL EQUIPMENT

(Англійською мовою)

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Зв.план, 2018
Підписано до видання 14.06.2018
Ум. друк арк. 11. Обл.-вид. арк. 13,38. Електронний ресурс

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Свідоцтво про внесення суб’єкта видавничої справи до Державного реєстру видавців, виготовлювачів і розповсюджувачів видавничої продукції сер. ДК № 349 від 30.03.2001