Annex D - Basic electrical systems

Why Electrics?

You could build a Europa without any electrics: use a diesel engine (no ignition circuits) with a pneumatic (compressed air) starter, mechanical fuel pump and injectors, and a flexible-drive rev counter; the essential flight instruments (altimeter and airspeed indicator) do not depend on an electrical supply, nor does a direct-reading magnetic compass; gyro instruments may be vacuum driven (turn indicator, attitude indicator, directional gyro); the pitch trim servo could be replaced by a mechanical trim, and the flaps on the tri-gear version could be manually operated. Requirements for electronics could be satisfied by hand-held communications and navigation equipment with self-contained batteries. Thus you do not need a complex electrical system, but as most builders will use an engine with an electric starter and alternator it makes sense to take advantage of having an electrical system and put it to good use.

Electrical energy can be used for ignition and starting of the engine, driving flight and engine instruments, operating electric trim and flap motors, cockpit illumination, warning and indicator lights, radios and external lights. In addition it is possible to fit an electrically-adjustable propeller, a heated pitot head and other equipment which will all need to be taken into account when designing the electrical system. Electrical systems can appear to be very complex, so we shall look at the basics first.

While there are many books and articles on electrical systems for aircraft, these sometimes give conflicting advice and our aim is to cover the options in a way that will help you decide what is best for your aircraft and the level of equipment you plan to fit.

Basic electrics

Ohm*s law

The simplest electrical circuit consists of a source of electrical energy, or Electro-Motive Force (EMF) connected to a load. Ohm*s Law tells us that the current which will flow is directly proportional to the EMF and inversely proportional to the resistance of the circuit. If the EMF is V volts and the resistance is R ohms, the current I amperes (amps) is V divided by R, thus : $I = V/R$, so that a 12 volt battery connected to a 6 ohm load would result in a current of 2 amps.

Power

The rate at which electrical energy is used is called power, measured in watts (W), and is the product of voltage and current : $W = VI$. Since $I = V/R$, $W = V^2/R$ and $W = I^2R$. In the example above, the power consumed would be 12 x 2 = 24 watts.

Practical circuits

The actual circuits in your aeroplane will obey Ohm*s Law, but there are a number of practical points to note. First, the resistance to be used is that of the whole circuit, including wiring, switch contacts and the internal resistance of the source. If these are small compared with the resistance of the load, they may be ignored for practical purposes. Second, Ohm*s Law applies to the steady state direct current (DC) and does not account for "reactive" circuit elements such as inductance (found in coils, relay control windings, motor windings) and capacitance (e.g. condensers) which can be important during transients (switching on or off) and in alternating current (AC) circuits. Third, equipment such as motors also act as generators, so that once they start turning they generate a voltage ("back EMF") which partly offsets the applied voltage so that their current consumption when running is much less than when starting. Fourth, some elements change resistance markedly with temperature (especially incandescent light bulbs, where the current at switch-on may be several times the steady state value with the filament glowing white hot to give out light).

Basic principles of aircraft wiring

To produce a safe and reliable electrical system, you need to decide what services you wish to be electrically driven, select suitable components, arrange an adequate supply of electrical power, decide on the layout and connect everything up through appropriate control and protection devices using suitable cables and terminations.

As with a motor car, the basic concept of the aircraft electrical system is to use a battery to start the engine. The engine then drives an alternator, which supplies sufficient power to run all the electrical services and recharge the battery. The battery then acts as a back-up supply in the event of an alternator failure or to cope with peak loads. An aircraft electrical system requires a high standard of control and protection. Wiring should be sized, insulated, restrained and terminated so as to give reliable service without overheating, chafing, breaking, short-circuiting or giving off toxic fumes in the event of fire.

Control

Control is exercised by a master switch (that may, depending on load, operate a solenoid contactor) between the battery and the rest of the electrical system, which consists of one or more "bus bars" which feed the positive supply to each individual circuit or group of circuits. Note that the term "bus bar" or "bus" refers to the live or positive side of a number of circuits connected together electrically; it may exist literally as a bar of metal to which connections are made, or just be a number of terminals connected to the same supply. Further control is imposed by switches on the circuits and between bus bars. All circuits are completed by being connected to "earth" (or "ground"), which on this composite aircraft normally requires a separate wire rather than connection to the frame of a metal aircraft; for convenience, these earth return wires are normally connected to an "earth bus" or "earth stud" to avoid lots of wires being run to the battery negative terminal. It is good practice to limit the number of connections to one stud to 7 - if more are needed, further studs or an earth strip should be used.

Switches

Switches come in a very wide variety of shapes, sizes, ratings and functions. Whether you choose particular switches all of the same style to form a line all the way across the panel to impress everyone and ensure the captions are read, or of different styles in an ergonomically designed layout so that every function is instantly recognizable, you must use good quality DC-rated switches. Quality is vital for reliability - you cannot risk having a switch with uncertain or intermittent operation, and DC ratings are essential for the Europa system.

Every switch is a device for completing and breaking a circuit by closing and opening one or more pairs of contacts. Contacts should close with a firm action, often with a deliberate rubbing action to keep the surfaces clean for low resistance; they should open with a rapid snap action to separate the contacts quickly and extinguish any arc or sparking - this not only reduces radio interference, but gives them a longer life and minimises the chances of their welding shut. They are often made of exotic (and expensive) metals to ensure long life. AC switches are designed to cope with current which flows in both directions during every cycle, and therefore passes through zero 100 times every second (for a 50 Hz mains switch in UK, 120 for 60 Hz in USA and 800 for 400 Hz aircraft AC systems); this means that from the moment the switch is operated the current will always be zero within 10 milliseconds, extinguishing any arc starting to form and allowing the contacts to open fully without further current flowing. DC switches, in contrast, have the current flowing in one direction only, and it will be encouraged by any inductance in the circuit (motor windings, relay coils, wiring self-inductance) to keep flowing by causing a voltage to develop across the contacts - in severe cases (such as the contact breakers in car distributors) a condenser (capacitor) can be wired across the contacts to reduce sparking. Thus a 50 Hz AC switch may be rated at 30 amps, but only 2 amps DC.

Switches have one or more POLES, which refer to the number of movable contacts and hence circuits (contact pairs) operated at once, and one or more THROWS, which gives the number of circuits each pole can complete. The commonest switch is single-pole single throw (SPST) which is an ON/OFF switch controlling one circuit.

Schematic Symbols for Switches

Switches will have at least 2 positions, for example a double throw switch may have a centre OFF position, which may be spring loaded so that the toggle or rocker has to be held to make contact either way (e.g. to operate a trim circuit), it may stay in all 3 positions, or it may stay in either of 2 but be spring loaded against the third. Full details will normally be set out in a table in the catalogue so that you can select exactly what functions you want and quote the appropriate part number.

Protection

Protection is provided by circuit breakers and fuses to prevent excessive current flowing under fault conditions and causing damage. While some items of equipment (e.g. radios) may be fitted with internal fuses to protect them, the prime purpose of the circuit breaker or fuses you fit is to protect the aircraft wiring from overheating or burning out.

For example, if you decided that you wanted to use a single 10 amp circuit breaker to protect 5 circuits each taking less than 2 amps, instead of installing 5 breakers rated at 2 amps, then you should make sure that each of the 5 wires can take 10 amps continuously without overheating, even where the normal loads are very small. The earth returns must be similarly rated. The guiding principle is to assume that any piece of equipment or wire may fail in such a way as to cause a low resistance path to earth - the protection circuits should be designed to prevent a major hazard developing.

Circuit breakers

A circuit breaker is a special form of switch designed to remain closed unless the circuit it controls is overloaded. There are 2 main types - “thermal”, which takes time to trip according to the degree of overload (e.g. 20 seconds at twice the rated current) and “magnetic”, which can trip instantly the rated current is exceeded. Combinations are possible, with a higher magnetic setting to give rapid protection for large overloads but avoid “nuisance” tripping with surge currents. Note that the inrush current at switch-on may be three times the steady state running current for some equipment. More recent designs may include hydraulic damping with magnetic operation: these can provide a range of tripping delay characteristics and are little affected by ambient temperature changes. Electronic hybrid systems use a solid-state overload sensor. You should use devices without an instant trip action on small overloads, to avoid nuisance trips.

Fuses

Fuses are an alternative to circuit breakers for the protection of circuits. They are normally of the cartridge type, fitted into a cylindrical holder with a screw cap allowing the fuse to be accessible by the crew. The fuse itself is simply a short length of wire sized to melt above a particular current, enclosed in a glass or ceramic tube with metal end caps. As with circuit breakers, fuses can be designed to be quick-acting or slow-blow. Anti-surge fuses, for example, may carry their nominal current continuously, twice the current for 10 seconds, and withstand a surge of 10 times the current for at least 10 milliseconds. The advantages compared with a circuit breaker are that they are cheap and compact, but they give no visible indication of having blown, replacing a fuse in flight is not nearly as quick and easy as resetting a breaker, and they are less reliable than breakers in that they can rupture without having taken an overload current. Another disadvantage is that it is easy to replace a fuse with one of the wrong rating for the circuit, even though you have carefully marked the correct rating by each fuseholder.

They can also fall into inaccessible places and become a loose article hazard. It is a good idea to have fuses for essential services within the pilot*s reach.

Cables

Current ratings of cables are dependant on so many factors that different figures are often quoted for the same size wire. This is not a question of right or wrong, but of the assumptions that are made in the calculation. It is all to do with the amount of heat generated in the wire by the current and how quickly it is dissipated. The amount of heat generated is proportional to the resistance and the square of the current (I^2R).

This heat has to flow radially outwards from the strands of wire through the insulation covering the wire and into the surroundings, which may be open air or a bunch of other equally hot cables bound tightly into a loom encased in a duct with a glassfibre / foam sandwich fuselage wall on one side and your luxury thick cockpit upholstery on the other. Manufacturers of cables will quote several current ratings e.g. 20 awg copper wire: single cable in free air 13 amps; 3 cables strapped together in air 9 amps; loom of cables in duct 7 amps; all assuming ambient temperatures not above 40°C, continuous rating.

Main bus

The busbar itself can take a variety of forms: it could be a bar of copper or brass drilled and tapped to take screws for ring-tongue terminations to feed all the services, but this all adds weight and requires extra connections. If you arrange your circuit breakers or fuses in a row, then the busbar feed can be connected directly along the row - screwed or soldered to each breaker or fuse (depending on the type of terminal fitted to the device). For screwed terminals, a strip of copper, brass or phosphor bronze 10 mm x 1 mm with holes drilled at the appropriate intervals would be suitable ; for solder terminals a length of 10 awg tinned copper wire can be used, ensuring that resin solder is applied (never use acid-based flux to solder any electrical connection).

Batteries

Batteries store electrical energy in chemical form, and are of 2 types: primary (non-rechargeable) such as for a torch (flashlight) and secondary (rechargeable). Every battery contains one or more cells, each of which has 2 electrodes in contact with an electrolyte, which may be in liquid, paste or gel form. Primary cells typically have an EMF (voltage) of 1.5V while secondary cells may be 2V or more. You may find primary cells installed in avionics equipment (e.g. to keep computer memories alive) but we will not discuss them further here, except to mention that large lithium types are not approved for aircraft use unless they have short-circuit protection.

There are two common types of secondary cell used in aircraft - lead/acid and nickel/cadmium (NICAD). Whilst the Nicad type has certain advantages in low temperature operation, capacity/weight and charge/discharge rates, they are expensive and need special precautions in aircraft to avoid overcharging; and we recommend the lead/acid type for the Europa. Lead/acid batteries are commonly used in cars, with 12 volts provided by 6 cells each having electrodes of lead and lead dioxide immersed in sulphuric acid electrolyte. When the battery is fully charged, the concentration (and hence specific gravity) of the acid is high: as it discharges, the concentration gets lower -checking the specific gravity with a hydrometer is an accurate way of measuring its state of charge. Note that purpose-built aircraft batteries may use a higher concentration of sulphuric acid than those used in cars, so that an automobile hydrometer calibration would not be correct - always consult the battery manufacturer*s specification, and always use the correct strength of acid for filling a battery received in the dry-charged state.

For aircraft applications wet lead-acid batteries are giving way to absorbed-electrolyte types such as ‘Dryfit*.

The chemical reactions in batteries are beyond the scope of this chapter, but you should know that hydrogen gas may be given off at the positive electrode: this gas is highly flammable, which is why battery installations should allow ventilation to avoid build-up of flammable gases, and why you are recommended always to disconnect the negative side of a battery first and reconnect it last; this reduces the chance of a spark on the positive terminal igniting any hydrogen. A further chemical point is that lead sulphate will form on electrodes not covered by electrolyte, which reduces the effective area of the plates and hence the battery capacity - it is therefore important to keep the electrolyte level topped up so that it covers the plates, using distilled water (unless electrolyte was lost by spillage, in which case it should be replaced with acid of the same concentration as that remaining). All batteries will have a means of allowing the cells to “breathe” and avoid pressure build up - purpose built aircraft batteries may have special caps to prevent spillage under negative ‘g* conditions.

The capacity of a battery is its ability to deliver electrical energy between the fully-charged state (e.g. 2.3 volts/cell) and the point at which its output voltage is too low to be useful (e.g. 1.8 volts/cell), measured in ampere-hours (AH). It should be noted that a 12 volt battery provides twice the energy of a 6 volt and half the energy of a 24 volt battery of the same AH rating (remember power in watts is volts x amps, energy is power x time). The capacity is normally quoted over a particular time period for discharge, typically 10 hours or 20 hours. A so-called “24 AH” battery may deliver 1.2 amps for 20 hours, but only 2.2 amps for 10 hours - equivalent to 22 AH. The capacity will reduce much further at a rapid discharge rate, perhaps to 13 AH over 1 hour, and to only 12 AH over 30 minutes. Do not assume therefore, that in the event of alternator failure, your fully-charged 24 AH battery would supply 24 amps for 1 hour - it would be wise to shed all non-essential loads to reduce consumption of electricity or to land well before the hour. A further point is the temperature: most battery ratings are quoted for 25°C ambient, and extremes of temperatures can make a big difference: you may get very little out of a lead/acid battery at temperatures well below freezing; a common solution in cold climates is to remove the battery and keep it warm indoors until you are ready to go out to the aeroplane, refit it and start. Clearly, also, prolonged cranking of an engine will discharge a higher proportion of battery capacity at say 150 to 200 amps than these currents might suggest.

Battery capacity deteriorates with age and abuse. Abuse includes frequent rapid discharges, leaving the battery in a discharged state, charging at too rapid a rate, and physical damage (do not drop!). Battery manufacturers will quote a recommended maximum charge rate (e.g. 0.25 amps per AH capacity for a 24 AH battery would mean not going above 6 amps) - this applies both to off-aircraft charging (some chargers designed for car batteries can seriously damage your aircraft battery) and to on-aircraft charging from the alternator - a powerful alternator may deliver a high current to a battery in a low state of charge after a problem start.

Self-discharge can be a problem: do not leave a battery for long periods without the occasional recharge, but do not leave it on permanent trickle-charge or gassing may occur - a maximum of 20 hours charging period is recommended. Be particularly careful if you have a wet-charged battery during build to keep it maintained until it is required for use; a dry-charged battery should not be prepared for use until you need it, but can be very useful in the workshop for checking its mountings and preparing the layout of cables and terminations.

A battery saver, a device which keeps a battery fully charged when left unused over long periods, could safely be left connected permanently instead. An appropriate product is available through Europa Aviation.

The internal resistance of a battery varies inversely with capacity: this is normally only important when you draw a high current for starting, when the reduction in terminal voltage is directly proportional to this resistance.

Alternators

An EMF (voltage) is generated whenever the magnetic flux through a coil is changed - either by rotating coils in a magnetic field or by rotating magnets past fixed coils. If the output from the coils is connected directly to a load, alternating current (AC) would flow, at a frequency dependant on the rate of rotation. Such a device would be called a “frequency-wild” alternator; to make it work with a 12 volt direct current system, as on the Europa, it needs a rectifier to allow the current through the circuit to flow only one way, and a regulator to control the voltage output to about 14 volts - this level is set so that it can recharge the 12 volt battery without being high enough to damage 12 volt equipment.

Alternators can have integral diodes for rectification and voltage regulators mounted directly on them, as with most car systems, or they may have a separate rectifier / regulator as fitted to the Rotax 912. The Rotax system employs a special device called a silicon-controlled rectifier (SCR or Thyristor) which allows the rectifier output voltage to be regulated.

Some alternators have their magnetic field produced by passing an electric current through coils known as “field windings”, which can be controlled by a separate alternator field switch. This enables the output of the alternator to be turned on and off: in the “off” state there is negligible current absorbed as a reverse flow from the battery because the diodes act as electrical non-return valves.

Ignition systems

Ignition systems provide electrical energy in the form of a spark across the electrodes of sparking plugs to ignite the fuel-air mixture inside the cylinders at the correct timing for the power stroke. To do this, the system needs a source of power, a means of converting it into the high-voltage (“high tension”) current necessary to jump the points gap, and a trigger to control the timing.

When describing the action of the alternator, we noted how an EMF was generated by changing the magnetic flux through a coil by using the mechanical energy from rotating coils or magnets. If 2 coils are wound on the same magnetisable core, then an EMF can be induced in one coil by changing the current in the other coil: this is the principle of the transformer, where high current and low voltage is transformed into low current and high voltage. The ignition coil is simply a form of transformer, which generates a high voltage output for the spark because of a rapid change in magnetic flux caused by switching the input current.

Because of the inductance of the coil, a much higher rate of change takes place when switching off the low-voltage current than when switching on - hence the use of a “circuit-breaker”, operated by a cam geared to the crankshaft with an advance/retard mechanism to get the timing right, and a rotor arm to direct the high voltage output to the plug in the appropriate cylinder (this is the “distributor”).

An alternative to storing energy in the coil and then generating a spark by interrupting the low-voltage current is to use a capacitor to store the energy, then use a high-speed semi-conductor (transistor) switch to discharge it through a coil. This is known as capacitative discharge ignition (CDI) and has a number of advantages over the traditional circuit breaker. The coils used can be smaller and lighter, so that several are employed (to avoid the need for a distributor) with the outputs directly connected to the sparking plugs; also the timing can be triggered from a magnetic pick-up coil on the engine to allow electronic control (e.g. to retard the spark for starting). CDI systems can operate up to high RPM, when powerful sparks are needed and contact breakers are having difficulty keeping up mechanically (there is not time for the full current to establish in the coil before it is broken for the next spark). CDI systems have ample spark energy - in dual-plug per cylinder engines it is common to have a “wasted spark” fed to the cylinder which is not on the power stroke.

Certified aero-engines require 2 independent means of ignition, so that all cylinders can work even if one system fails. The commonest way of achieving this is to use 2 magnetos (permanent magnet generators driven by the engine, which are independent of the main alternator or generator) each feeding separate ignition systems, with 2 plugs per cylinder. In the Rotax 912, the 2 magnetos are integral with the alternators but each is electrically entirely separate.

If dual ignition is required, for other types of engine without using magnetos, then it should be possible to supply electrical power to the systems from 2 independent sources so that a single failure cannot cause total ignition failure. Thus, if you wish to treat aircraft battery and alternator as separate power sources, you should not arrange for both supplies to come through one master switch!

Flight instruments

Flight instruments come in 3 main categories: pitot-static, gyro and compass. Apart from lighting, which can apply to all instruments if you need it, the usual candidates for an electrical supply are the gyro instruments (attitude indicator, directional gyro and turn indicator). The choice between driving them electrically or from a vacuum system depends on:-

cost: electrically driven gyros are very much more expensive;

weight: vacuum driven gyros are usually lighter, even allowing for the weight of the pump;

complexity: connecting electrical gyros is simpler than fitting a vacuum pump, connecting tubing, regulator, pressure gauge and filter(s);

redundancy: having a mix of electrical and vacuum instruments avoids losing all gyros in the event of either supply system failing;

speed: electrical gyros are usually quicker to run up to speed.