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Honorary Editor: A. W. LINEKER, B.Sc.
Assistant Honorary Editors: H. P. ALEXANDER, B.Sc. (Eng.); W. CORMACK, D.Sc.

Volume 45 MAY 1954 Part 5

PROCEEDINGS AT THE FOUR HUNDRED AND FORTY-FOURTH GENERAL MEETING

Held at Kelvin House, corner Marshall and Hollard Streets, Johannesburg

Wednesday, 19th May 1954

PROFESSOR G. R. BOZZOLI (Vice-President) was in the Chair and declared the meeting opened at 8.5 p.m.

There were present 37 members and visitors and the Secretary.

OBITUARY

Before opening the meeting, the Chairman said he regretted to have to refer to the recent death of a member who was fairly well known to all those present, Professor John Orr, who joined the Institute on the 22nd January, 1931, and died on the 17th May, 1954.

As a mark of respect and in sympathy with the bereaved, all present rose and observed silence for a few moments.

THE PRESIDENT

THE CHAIRMAN informed members that the President of the Institute was, unfortunately, still indisposed and that was why he was not present to take the chair.

MINUTES

The minutes of the general meeting held on the 22nd April, 1954, were taken as read and were confirmed.

MEMBERSHIP

THE CHAIRMAN announced that in terms of By-Law 5.2.4, the Council had elected the undermentioned candidates to membership of the Institute in the following grades :—

Associate Members : RICHARD BYRNE BRIGHT, PERCY JOHN ELLIOTT, DAVID JOHANNES LE ROUX, RONALD MAWSON OGLESBY SIMPSON, TREVOR LLOYD WADLEY.

Graduate : BASIL RALPH HOTZ.

Associate : ARTHUR HENRY MURRAY.

Transfer from Associate Member to Member : EDWARD LEONARD BUCHANAN, GERRIT JACOBUS MULLER.

Transfer from Graduate to Associate Member : PIETER ANDRIES CHRISTIAN FAURIE, DEREK ARUNDEL ROBB, JULIAN VOLLMER.

Transfer from Associate to Associate Member: STANDISH SMYTH WOLFE.

Transfer from Associate to Graduate: WILLIAM GRAY LUMLEY.

GENERAL BUSINESS

A. W. LINEKER (Honorary Treasurer) said he did not know whether the membership were aware of the fact that Professor Bozzoli would be proceeding overseas to represent the Institute at the Conference of Commonwealth Engineering Institutions. He would take the opportunity on behalf of the members of wishing Professor Bozzoli and Mr Adams, the Institute's delegates, a very pleasant and successful visit to the Conference. Good wishes were also extended to the Presidents of the two other Institutions, the Civils and the Mechanicals, who were also going to the Conference.

PAPER AND DISCUSSION

J. A. Bosch (Associate Member) presented his paper entitled 'Electrical services in modern civil aircraft.'

The Chairman proposed a vote of thanks to the author for his paper and J. D. N. van Wyk, R. P. Channer and B. L. D. Porritt (Associate) contributed to the discussion.

GENERAL MEETING OF THE INSTITUTION OF CERTIFICATED ENGINEERS, SOUTH AFRICA

THE CHAIRMAN pointed out that Mr E. P. Reim would present his paper entitled 'Gas turbines for power generation, with reference to South African conditions' at the Institution's Monthly General Meeting to be held on the 20th May 1954 and not at the June 1954 meeting as stated at the foot of the Institute's agenda.

The Chairman declared the meeting closed at 9.30 p.m.

Institute Notes

Cape Western Local Centre

Members of the Institute visiting Cape Town are cordially invited to attend general meetings of the Cape Western Local Centre which are held in Demonstration Theatre, Electricity House, Strand Street, Cape Town, on the second Thursday of each month.

A general meeting of the Cape Western Local Centre was held in the Railway Recreation Tea Room, Railway Institute Buildings, Cape Town, on Thursday, 20th May 1954.

C. G. DOWNIE (Chairman of the Centre) was in the Chair and declared the meeting opened at 8.20 p.m.

An interesting paper entitled 'Electronic speed control of modern newspaper press,' was presented by Mr W. Van Eldick (Associate Member), supported by interesting slides and demonstrations of various items of equipment.

Contributions to the discussion on the paper were made by the Chairman, Mr C. G. Downie (Member), Dr H. D. Einhorn (Member), Messrs F. D. Opperman (Member), R. G. Canning (Associate Member), R. R. Gilmour (Associate Member), M. Benjamin (Associate Member) and J. M. Georgala (Associate Member).

Mr Van Eldick replied to a number of questions raised by members, and extended an invitation to members to visit the *Cape Argus* on Monday, 24th May 1954, at 2.30 p.m., when they would be shown over the installation during the printing of the evening paper.

There being no further business, the Chairman declared the meeting closed at 10.20 p.m.

ELECTRICAL SERVICES IN MODERN CIVIL AIRCRAFT

By J. A. BOSCH,* B.Sc.(Eng.), (Associate Member)

This paper was received on 26th March 1954

SUMMARY

This paper is a general survey of some of the more important electrical services provided in modern civil aircraft. It deals briefly with the main electrical power system and its associated equipment. The means of generating the power, controlling its voltage and the protection of the system are discussed. Included, too, are descriptions of an automatic electric propeller control circuit and two types of aircraft ignition systems.

CONTENTS

1. INTRODUCTION

The past thirty-five years have witnessed a remarkable development in the application of electrical engineering to aircraft. From the first flight of a petrol engine powered aircraft, the aircraft has been dependent on some form of electrical source for its ignition system. Originally this was operated off a magneto, but due to the lack of reliability of the old type magnetos, a change was made to an ignition coil and battery. This change can virtually be considered to be the origin of to-day's complex electrical installations in modern aircraft.

Progress in the earlier years was extremely slow and the major uses of the electrical installations were to supply power to the simple radio receivers then in use, the ignition system and the three navigational lights. The batteries were charged by means of small wind driven generators attached to the wing structure. Starting of the engines was carried out by manual swinging of the propeller or by means of a hand operated crank.

Gradually the system expanded as aircraft increased in size and passenger carrying capacity. Electric starters for the engines were introduced, cabin and cockpit lighting installed and small engine-driven generators fitted in place of the old wind-driven units. The system at this stage was comparable to that found in a modern motor bus. The system voltage was 12 volts D.C. and the generators were capable of providing 25 amperes.

During the Second World War the electrical system increased rapidly in capacity and complexity. Modern passenger aircraft have generating capacities ranging from 36 kW to 180 kW and voltages from 24-V D.C. to 120-V D.C. The system now resembles, on a miniature scale, a modern power station and its distribution system. In a modern four-engined aircraft there are four generators, one hundred electric motors, three hundred electric bulbs,

* Mr Bosch is Electrical Engineer, South African Airways.

several miles of cabling with its associated relays, circuit breakers and switches.

Electrical power is now utilised to control the pitch and speed of the propellers, raise the undercarriage, operate the throttles, control the air-conditioning system,

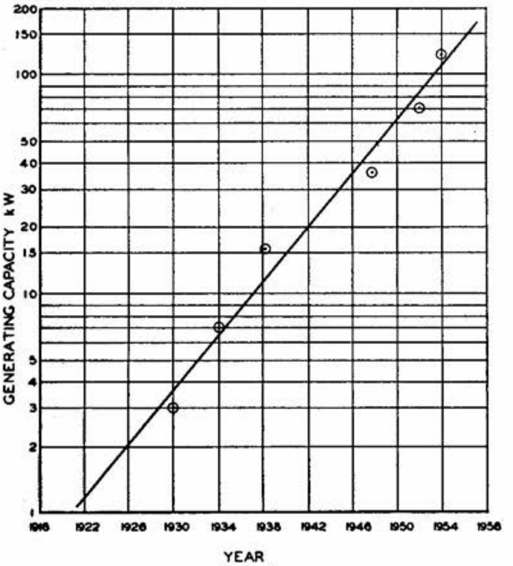

Fig. 1

energise the radio equipment and operate the instruments—in other words it has become a vital agent in the efficient and safe operation of the aircraft.

The two curves Fig. 1 and Fig. 2 give an indication of how the generating capacity of aircraft have increased (*a*) over the years since 1918 and (*b*) with the all up weight of the aircraft.

2. THE BASIC ELECTRICAL SYSTEM

The basic electrical system of an aircraft consists normally of one or more engine-driven d.c. generators coupled to a busbar distribution system through reverse-current relays and fault-sensing networks. Connected to the busbar through an isolating relay is a battery, usually of the lead-acid type, which acts as the system's reservoir at peak demand periods and also as the system's voltage stabiliser. The generator voltage is controlled by means of a carbon-pile regulator, and, by means of a second control winding on the carbon-pile regulator, the generators are cross coupled for parallel working.

All d.c. motors, starters, relays, galley equipment etc., are fed from this main busbar through one main isolating switch. circuit-breakers. The radio equipment, too, obtains its supply from the same busbar through one main isolating switch.

In order to operate certain radio, electronic equipment and instruments an a.c. supply is necessary. This is obtained from an invertor which in turn is fed from the busbar. Fig. 3 shows a block schematic of this basic system.

In some of the latest aircraft such as the Comet Mark I the engine driven units instead of being d.c. generators are a.c. generators. These are connected to metal rectifiers which rectifies the a.c. output and feeds it into a d.c. busbar system similar to the above.

2·1 *The d.c. generator*

The d.c. generator is normally coupled to the engine through a gear-box and

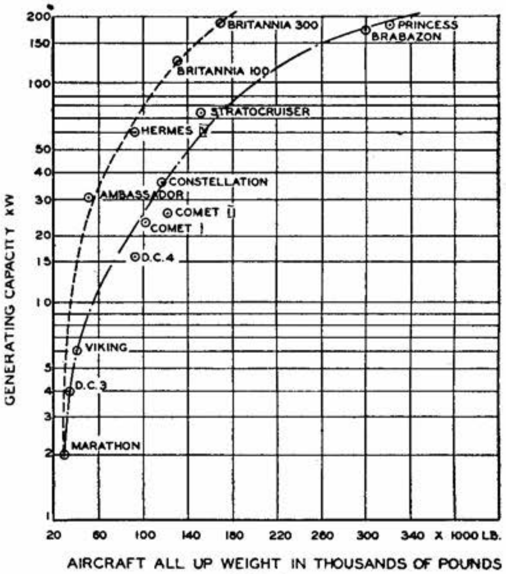

Fig. 2

operates at 2 to 3 times the engine speed. This means that at take-off the generator rotates at approximately 8 000 r.p.m. and at cruising 6 000 r.p.m. These high rotational speeds require the generator to be fitted with high quality ball bearings and that the armature be very accurately balanced dynamically. These high speeds are the result of the low weight limits enforced on all aircraft components by the necessity for obtaining maximum payload for a given maximum aircraft all-up weight. The low weight requirements mean small armature size and diameters and hence high rotational speeds for a given voltage.

Fig. 4 shows a typical aircraft generator.

Fig. 5 shows the internal wiring diagram of a 300-ampere, 4-pole generator.

The normal aircraft generator is a 4-pole shunt-wound unit with interpoles and compensating windings which enable almost sparkless commutation to be obtained throughout the speed and load range. The windings are usually protected by means of glass sleeving or tape and the generator can produce its maximum output up to yoke temperatures of 185°F. Normally, however, the generator runs at temperatures between 150° and 160°F. The cooling is taken care of by means of a blast tube, which obtains atmospheric air at a pressure of between

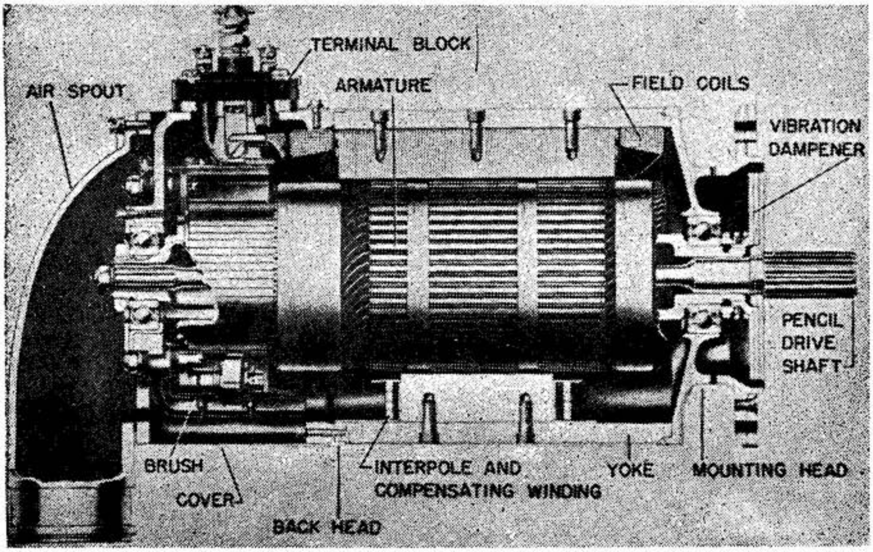

Fig. 4

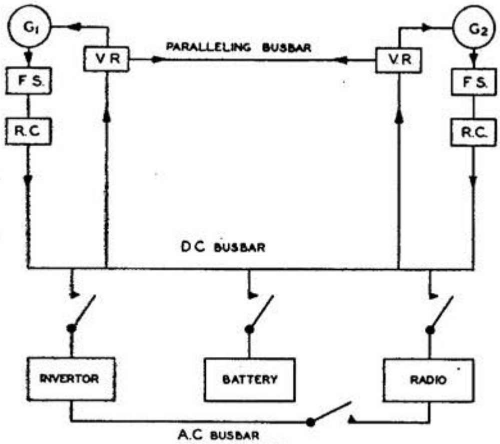

Fig. 3

6 and 8 inches of water, connected from an air scoop on the engine cowling to the generator.

The high rotational speed of the generator armature induces torsional oscillation of the armature and some manufacturers have included a slipping-clutch device in the drive system to overcome this, but this has not proved to be very successful and more modern units have discarded this device. The damping of these oscillations are now taken care of by improved drive methods and design.

The brushes fitted are both radial and trailing types—the latter is gradually replacing the radial system. The current densities range from 100 to 150 amperes per square inch. Brush pressures vary from 20 to 60 ounces, the average being around 50 ounces. At altitudes ranging from sea level to 15 000 feet brush wear is normal, that is, an average brush wears approximately $\frac{3}{8}$ inch in a thousand hours flying.

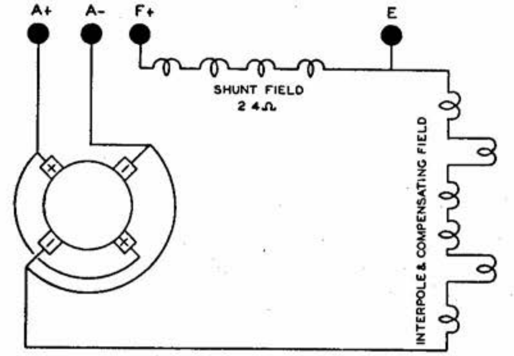

Fig. 5

However, at altitudes above 15 000 feet the standard types of brush have been known to wear $\frac{1}{2}$ inch in 25 hours at 20 000 feet and completely disappear after 30 minutes at 40 000 feet. This rapid wear at high altitudes is caused by—

i lack of moisture
ii temperature of operation and
iii lack of oxygen.

The lack of moisture is the most important cause of wear as it is suspected that it acts as a catalyst in converting the copper of the commutator to copper oxide—thus providing a thin film of copper oxide which reduces the friction between the carbon brush and the commutator considerably and consequently the wear. In special high altitude brushes lead iodide is used in small quantities—this lead iodide it is suggested combines with the copper to form an unstable cuprous iodide which oxidizes almost immediately and forms the low friction copper oxide film.

In order to maintain a high serviceability rate it has become standard practice to overhaul aircraft generators after 600 to 1 000 hours flying. This may seem a rather expensive procedure but when it is thought that the safety of the aircraft depends on the serviceability and efficient functioning of the generators the short service life is fully justified.

The voltage control is fully automatic and is carried out continuously by a carbon-pile voltage regulator. The construction of this unit is very simple. It basically consists of two controlling windings operating a spring-loaded magnetic core. This core in turn exerts pressure on a carbon column consisting of 46- to 50 $\frac{3}{8}$-inch diameter one millimetre thick carbon discs. By altering the current flowing through one or both the controlling coils the pressure exerted by the magnetic core on the carbon discs can be varied. This pressure variation varies the resistance of the carbon column. This column is connected in the shunt winding of the generator and thus acts as a field control. This field control controls the voltage output of the generator. The one control winding is connected across the generator output. The other winding is used for parallelling up two or more generators and is normally connected to what is known as the equalising busbar. The resistance range of a typical carbon pile is 1·5 to 21 ohms. For a nominal setting at, say, 27·7 volts a carbon pile

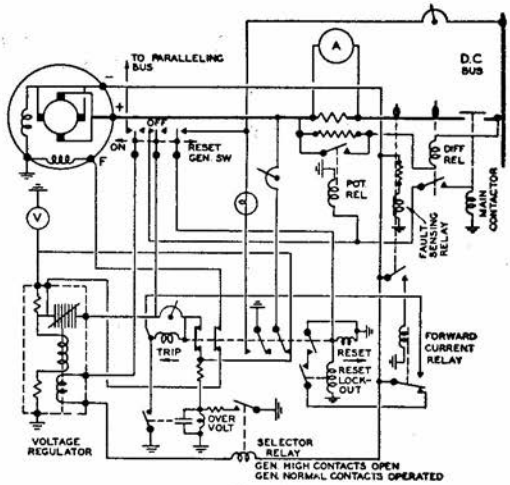

Fig. 6

can provide regulation control within plus or minus 0·8 of a volt. Small trimmer resistances plus two mechanical adjustments enable the pile to be set up to give the required voltage and regulation.

2·2 *Generator system protection*

In order to improve the safety of the generator circuits further refinements have been included in modern aircraft circuits. These include (*i*) over-voltage controls and (*ii*) fault-sensing circuits. Circuit (*i*) consists usually of a spring-loaded polarised relay adjusted to open-circuit the generator field as soon as the output-voltage of the generator rises above 30 volts. In order to prevent transients from tripping the generator a time lag circuit of 1 to 2 seconds is incorporated in the relay operating circuit. The relay also operates a tell-tale lamp in the aircraft cockpit to indicate to the pilot that a generator has tripped off the busbar. The pilot can reset the relay and reconnect the generator, if he so wishes, by means of a switch adjacent to the light.

Circuit (*ii*) consists of a two-coil polarised relay—one coil has a few heavy conductor turns and the other a large number of fine wire. The coil of few turns is known as the current coil and is in the main feeder from the generator to the busbar. The coil of many turns is known as the shunt coil and is across the series-field of the generator—it is thus energized by the voltage developed across the series field by the normal or any fault current. The resulting magnetic fields oppose one another, the steady magnetic system aiding the shunt coil's field. On normal loads the ampere-turns of the current coil overcomes the ampere-turns of the shunt and steady magnetic system combined, and the relay remains unoperated. On an overload of 70 to 100 amperes the ampere-turns of the shunt and permanent magnet system exceeds that of the current coil and the relay operates ultimately disconnecting the generator from the busbar and warning the pilot by means of an indicator light. By means of an extra polarised relay reverse-current through the circuit does not operate the fault-sensing system.

Fig. 6 indicates the basic over-voltage and fault-sensing circuits for a two generator system.

3. AN A.C. GENERATOR-RECTIFIED SYSTEM

As mentioned above there is a system at present being used in several aircraft which consists of an engine-driven a.c. generator, and a metal-rectifier unit. The latter rectifies the generator's output and feeds it to a d.c. busbar system similar to that described above.

3·1 *General advantages and disadvantages*

The main advantages of this system over the normal d.c. one are :—

i Weight improvements with the use of an a.c. generator e.g., a 40-kW d.c. generator weighs approximately 150 lb whilst a 40-kVA a.c. generator weighs approximately 65 lb. The rectifier unit weighs less than the 85 lb difference.

The following is an indication of the comparative weights of the two systems as fitted to two modern aircraft. The Brabazon aircraft fitted with an a.c.-rectifier system has an electrical system all-up weight of 4 900 lb or 1·6 per cent of the aircraft all-up weight. This system has a capacity of 180 kVA.

The Saunders Roe Princess Flying Boat has an electrical system all-up weight of 7 250 lb or 2·33 per cent of the aircraft all-up weight. This is a d.c. system yielding 168 kW at 120 volts D.C. and 12 kW at 28 volt D.C.

ii The fault currents in a d.c. system are higher than those in the a.c.-rectifier systems. This is due to the comparatively low internal resistance of the d.c.generators, whereas in a.c. generator-powered circuits the high internal reactance of the generator limits the currents. It has been calculated that the d.c. system of the Princess Flying Boat has a fault value of 20 000 amperes; this has been restricted by connecting low value resistors between the various busbar sections. In the Brabazon with its a.c.-rectifier system the fault currents are limited to 8 000 amperes. This difference in the fault currents provides an additional weight saving by allowing smaller contactors, circuit breakers etc., to be used.

iii Due to the use of sliprings there is a slight reduction in brush wear at high altitudes.

iv Step-up and step-down transformers can be used.

v The a.c. system causes very little radio-frequency interference but unfortunately in the audio-frequency range there is a slight increase in interference.

The main disadvantages are:

i Without rectification alternators cannot be paralleled onto a common busbar system. This is due to the difficulty in synchronising the aircraft engines.

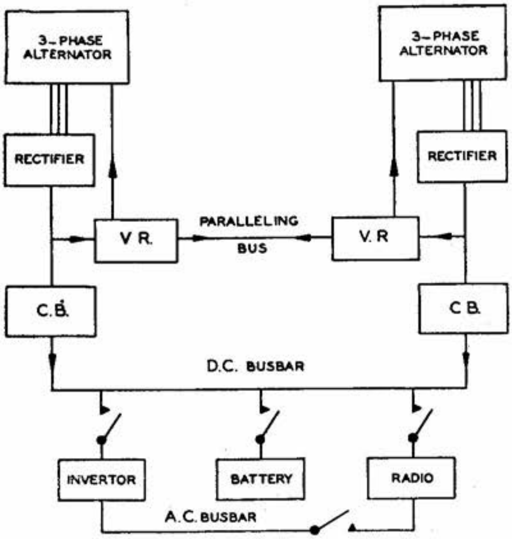

Fig. 7

ii The use of a.c. motors may lead, at the frequencies generated by the alternators, to very high rotational speeds. These high speeds mean that a.c. motors must normally be fitted with small gear boxes, whereas d.c. motors, although heavier, can be designed for high or low speeds as required.

3·2 *A typical a.c.-rectifier system*

A typical example of the a.c.-rectifier system is described below. The generating system consists of 4, 8·5-kVA, three-phase, 24-volt, 208-ampere, 6-pole, delta-connected, engined-driven a.c. generators. These rotate at speeds between 3 500 and 10 000 r.p.m. The generators in turn are each connected to a 3-phase full-wave selenium rectifier-unit which in turn is connected to a common busbar and a set of stabilising batteries. Voltage control and paralleling is effected by means of carbon-pile voltage regulators in the field circuits of the generators.

Fig. 7 shows a block schematic of the system.

Fig. 8 shows a more detailed circuit of one a.c. generator and its associated rectifier and voltage-regulator network.

Paralleling is done by means of a low resistance in the negative leg of the rectifier bridge. This resistance produces a voltage which controls the current flowing in the paralleling winding of the auxiliary carbon pile. The auxiliary carbon pile is a refinement included in the circuit to improve the range and sensitivity of the main carbon pile's control.

4. A.C. SYSTEM

No completely a.c. system is, as far as I know, being used in any civil aircraft at present, the main objection to it being the difficulties in operating the engine driven a.c. generators in parallel. Systems have been developed using auxiliary power sources such as small petrol engines or low-powered gas turbines to drive a.c. generators. These installations at present are far too heavy for civil aircraft.

5. INVERTORS

As most of the common aircraft supplies are 28-volt d.c. and as a certain amount of a.c. power is required for radio, electronic

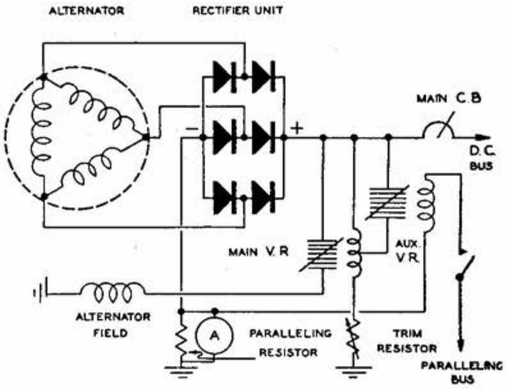

Fig. 8

and instrument equipment in the aircraft some means of generating this is provided in the aircraft. The most common method of providing this A.C. is by the use of motor-generators. These are known as invertors.

The motor is a compound-wound unit with a carbon pile connected in its shunt field acting as a speed or frequency control. This motor drives an a.c. generator on the same shaft. The field of the generator is excited from the common 28-volt busbar system through a carbon pile. The latter provides the a.c. voltage control. The control-windings of both carbon piles are connected across one phase of the a.c. circuit. The common a.c. frequency used is 400 c.p.s. and the a.c. voltage is 115 volts single-phase or three-phase.

The following are details of output and tolerances of a modern aircraft invertor.

Input (direct current)

Voltage	27·5 V
Current	126 A

Output (alternating current)

Voltage	115 V ± 5 V
Current	10 A (3-phase star-connected)
Volt-amperes ...	2 000
Power factor	0·95
Frequency	400 ± 20 c.p.s.

Large civil aircraft carry two invertors, one for normal operation and the other for emergency use in the event of the failure of the normal unit. An automatic change-over system senses the failure of one and switches

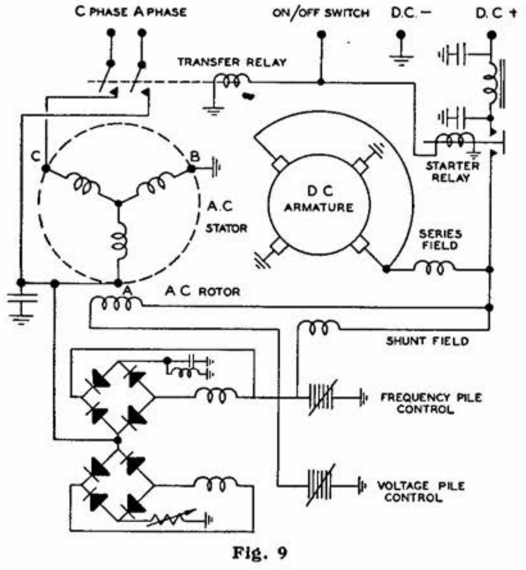

Fig. 9

the stand-by in, at the same time by means of a light warns the pilot that this has occurred.

Fig. 9 shows a typical invertor installation.

6. ELECTRICAL MOTORS IN AIRCRAFT

6·1 *D.C. motors*

A large number of d.c. motors are used in the modern civil aircraft. These operate various systems such as the hydraulic, control, etc. They range in power from 1/100th h.p. to 5 h.p. These motors are used for engine starting, propeller pitch control, fuel booster pumps, auxiliary hydraulic pumps, cowl flap actuators, fans and blowers, light flasher drive, under-carriage and landing gear actuators, landing light retraction, pumps, motor-driven valves, voltage boosters, etc.

Aircraft d.c. motors differ from normal d.c. motors in one main characteristic, viz., weight. The weight bogey is always present in all aircraft accessories and in the aircraft d.c. motor it is reduced by :—

i The use of greater armature speeds
ii The use of insulating materials capable of withstanding higher temperatures, thus allowing higher operating temperatures.
iii The use of lightweight alloys for structural parts such as end housings, etc.

The motors used for engine starting are series-wound direct-cranking, i.e., no flywheel is incorporated in the starter. The motor, through gearing and a torque-limiting clutch, engages the engine crankshaft direct. It is normally energized from the busbar system by means of a solenoid, which, in turn is remotely controlled by the pilot from the cockpit. A typical starter develops 4 h.p., draws a peak current of 400 amperes and produces a torque of 800 lb.ft. The efficiency is between 65 and 70 per cent.

In certain mechanisms operated by d.c. motors the operating limiting points must be held within close tolerances. This is the case in all actuators, operating valves, flaps, cowls, etc. In these units, spring-loaded electric clutches are used. The latter are energized whilst power is supplied to the motor, but immediately act as a brake when the power is removed.

Both series- and shunt-wound motors are used; the former are normally used with small gear boxes on actuators, valves, pump motors, etc. The latter are employed on fans and motor-driven switches, and de-icing equipment. Shunt-wound motors are in use for long periods at a time whilst the series-wound machines are used for short periods only. Thus the latter have a much shorter time rating than an equivalent shunt-wound machine. Where reversible motors are required either the connections of the field or armature are reversed if the loading is the same in either direction. When the loading varies, as it does with a flap motor, two different field windings are employed.

6·2 *A.C. motors*

These are not normally employed on civil aircraft mainly because of the high rotational speeds. The latter is occasioned by the 400-c.p.s. a.c. supply available, e.g., a two-pole motor on 400 c.p.s. has a synchronous speed of 24 000 r.p.m. and an 8-pole motor on 400 c.p.s. a speed of 6 000 r.p.m. These high speeds with the small torques available are difficult to use and consequently gear boxes are necessary. This additional weight and lack of speed variation has kept the use of a.c. motors in aircraft to a very small number.

7. IGNITION SYSTEMS

There are two types of ignition systems in common use at present. They are known as the high-tension and low-tension systems respectively. Both, ultimately produce a high voltage at the spark plug and it will be seen that the name really indicates the system of distribution from the magneto to the spark plug and does not describe the system as a whole.

7·1 *The high-tension ignition system*

In the high-tension system the main elements are (*i*) the high-tension magneto and contact-breaker, (*ii*) the distributor, (*iii*) the high-voltage distributing harness and (*iv*) the spark plugs. Item (*i*) consists of a rotating magnet rotating between the soft iron poles carrying the primary and secondary windings of the magneto. This construction enables higher voltages to be obtained due to the fact that more and heavier insulation can be used between the two windings. This rotating magnet also operates a cam which in turn operates the contact breaking points. The output from a typical magneto of this type is between 10 000 and 12 000 volts.

Item (*ii*) consists of a rotary arm synchronised to the magneto and engine crank shaft. This arm distributes the magneto's high voltage to the correct spark plugs by means of a ring of contacts and item (*iii*).

Item (*iii*) the high-voltage harness is made up of a number of heavily neoprene insulated steel conductors enclosed in a cast duralumin jacket. These conductors feed the high voltage from the distributor to the spark plugs. The heavy insulation prevents short circuits and reduces the corona effects. The jacket acts as screening and reduces radio interference. Where the leads come out of the jacket they are encased in flexible conduits which help in turn to reduce radio interference. This screening fortunately gives the ignition circuit a high capacity and it is found that once a spark plug ignites this high capacity causes large discharge currents to flow. The latter have been estimated to be between 30 and 150 amperes. These high currents in turn lead to rapid spark-electrode erosion and thus short spark plug life.

At high altitudes this high-tension system suffers from excessive corona and tracking troubles and thus has gradually been replaced by the so called low-tension system in aircraft flying above 20 000 ft.

Item (*iv*) the spark plug. This is a more robust and needless to say more expensive version of the ordinary car plug. Various metals are used for the electrodes, platinum-iridium being amongst the best. The heavy capacity discharge-currents normally cause rapid electrode erosion and this has partially been overcome by the fitting of a 1 000-ohm resistor in series with the spark gap. The average life of spark plugs between overhauls is about 500 hours. Plugs are usually discarded after 1 000- to 1 500-hours flying. Lead deposits from the fuel are another bugbear as far as spark plug life is concerned.

7·2 *The low-tension ignition system*

This system differs very little from the above high-voltage system. The main components are essentially the same in number and function. In the low-tension system, however, there is one additional element, namely, the step-up transformer. The latter is required as a low-tension system magneto generates a voltage whose peak value lies between 250 and 300 volts. This low voltage is fed through a slightly modified distributor and neoprene insulated harness to the step-up transformers situated very close to the spark plugs. There is a separate transformer for every plug. These step the 250 to 300 volts up to 10 000 to 12 000 volts enough to provide adequate sparking voltage and energy for the plug.

The main advantages of this system are :

- *i* no or very little corona and tracking troubles as most of the system operates at a comparatively low voltage
- *ii* reduction in the storage capacity current and hence a reduction in the electrode erosion
- *iii* longer life of distributor rotor and contacts
- *iv* less radio interference as the high voltage radiating leads are kept very short.

8. ELECTRICAL PROPELLER SPEED CONTROL AND REVERSING

The power developed by an aircraft engine is absorbed by the propeller. The power the propeller absorbs in turn is determined by its speed and its pitch. Thus for a given power the pitch determines the propeller speed. Normally the engine powers are set by the pilot and the propellers automatically change their pitch to keep the engine speeds in the desired range.

Further in order to improve passenger comfort and also to prevent over speeding of the engines when engine power is changed some means of automatic propeller speed control is necessary. This originally was done by means of a hydraulic system in which the only electrical unit present was a motor-driven feathering pump. This system had various drawbacks, the main of which were (*i*) no automatic synchronising of propeller speeds and (*ii*) time lag in taking control. To overcome these a fully electric speed control unit was developed. This electric unit provides (*i*) fully automatic synchronising and speed control, (*ii*) rapid and accurate control (*iii*) propeller reversing and (*iv*) propeller feathering. The latter has been made fully automatic on some aircraft and operates immediately the engine torque drops below a certain level. This is very useful in the case of an engine failing on take-off as it automatically reduces the drag of the unserviceable engine by feathering the propeller.

The basic elements of a typical electrical system are :

- *i* the master control unit which determines the propeller speed
- *ii* the contactor unit which senses and corrects any variation in speed between the propeller and the master unit
- *iii* the pitch control motor which is fitted to the propeller hub and controls the pitch of the propeller through gearing
- *iv* The a.c. generator on the engine which checks the propeller speeds and transmits it to the contactor.

The master control unit consists basically of a stable variable-speed d.c. motor of the 'amplidyne' type driving either two or more contactors, one for each propeller, mechanically through a system of gears. The pilot of the aircraft can alter the speed of the master unit by means of a simple lever.

Each contactor consists of a rotor wound with a 3-phase winding which is energised from a 3-phase a.c. generator fitted to the engine. The electro-magnetic field produced by the winding rotates in a direction opposite to that of the mechanical rotation of the rotor. Thus any difference in rotational speeds between the master unit and the propeller will produce a magnetic field rotating either in one or the other direction depending on whether the propeller or the master unit is the faster. This resultant rotation of the field is sensed by a hysteresis cup fitted concentric with the rotor and which operates an interrupter and switch. This interrupter and switch in turn energise, through various relays and slip rings, the series-wound pitch control motor causing it to rotate in such a direction that the propeller speed is brought into exact synchronisation with the master control. This operation goes on continuously whilst the unit is in circuit. Exact synchronisation is obtained all the time.

Propeller reversing is obtained by switching out the master control and energising the pitch control motor in such a way as to reverse the pitch to a pre-

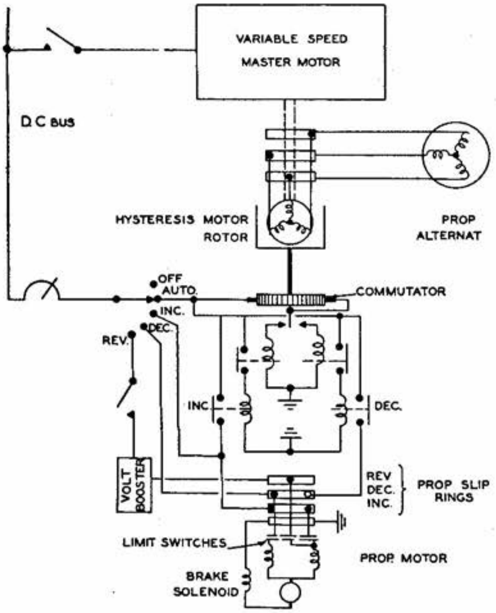

Fig. 10

determined stop. This reversing process can only be used when the aircraft is on the ground and provides an efficient braking system for stopping the aircraft on landing.

Fig. 10 shows the basic elements of the above system.

9. MISCELLANEOUS ELECTRICAL COMPONENTS

In addition to the above there are the following miscellaneous items fitted to all civil multi-engined aircraft.

9·1 *Relays*

These are mainly employed in the aircraft to provide remote switching of heavy currents, save weight in reducing heavy cable runs and performing automatic switching functions.

The relays are designed to function correctly with voltages between 75 and 125 per cent of the nominal system voltage. They are made to operate in any position regardless of vibration and low acceleration forces. The contacts have a wiping motion when making or breaking and thus keep the contact resistance to low values. The contact points are usually made of silver alloy which gives a reasonable life at high altitudes and does not tend to weld when passing heavy currents. The majority of relays have open contacts and only when used in compartments where explosive gases are present are the contacts enclosed in explosion proof containers. There are polarized and non-polarized relays and in circuits employing a.c. laminated pole-pieces are used.

The following are typical characteristics of heavy current relays:

	Voltage	*Rated amperes*	*Holding coil current amperes*	*Weight lbs*
	12	35	0·50	0·50
American	12	200	1·00	2·35
	24	50	0·30	0·70
	24	200	0·50	2·10
British	24	200	?	3·8

9·2 *Heaters*

Electric heaters are an essential item in most aircraft. As seen from the following description, they perform many functions.

(*i*) In the galley they operate ovens, urns, hot water containers, etc., which provide the necessary cooking, tea-making and food-warming facilities which contribute much to passenger comfort.

The average electrical load for a large four-engined fifty-seater aircraft galley is approximately 7·5 kW, i.e., 250 amperes on the 30-volt supply. It can thus be seen that the galley load is an important portion of the main electrical load.

The ovens used have circulating fans built in which ensure an even distribution of the hot air in the oven. Time switches fitted to these ovens control the period during which the elements are energized, and an automatic alarm notifies the steward when the food placed in the oven is ready.

Most of the food used in an aircraft is pre-cooked and frozen. Consequently the ovens must provide sufficient heat to de-freeze and warm the food.

(*ii*) In the cockpit the wind shields are kept free of ice and moisture by means of heaters built in between the layers of glass. The cockpit itself is heated by means of a hot air blower which consists of a small electric fan and an electrical heater.

(*iii*) Wherever required by the air crew, de-fogger heaters which supply hot air for de-fogging purposes are provided. These are normally found in astradomes and drift sights and thus enables the navigator to take clear navigational sights.

(*iv*) Pitot tubes are fitted with heaters to ensure that ice accumulations do not interfere with correct readings of the air speed. These heaters normally take between 5 and 15 amperes.

(*v*) Heaters for de-icing systems. These heaters are fitted to both the leading edges of propellers and wings to prevent the accumulation of ice which would cause a deterioration in the aero dynamic efficiency of the surfaces. For this purpose the heater wires are enclosed in a tough rubber sheath, the rubber being specially treated to with-stand high temperatures.

9·3 *Thermo-switches*

Thermo switches are used in systems which provide automatic protection and automatic control. Typical of these are :—

i Oil, water, etc., temperature control

ii Fire-warning circuits. These fire-warning circuits are fitted in all the essential passenger and baggage and engine compartments. By means of bells and lights the thermo-switches warn the pilot of excessive temperature rises in the various compartments. He is thus able to determine where a fire is developing and take the necessary extinguishing action.

The majority of the thermo-switches used are of bi-metallic construction. These are mechanically robust and possess the facility for automatically re-setting them-selves after a decrease in temperature.

In this category are found thermo-couples. These provide indications of cylinder temperature, oil temperature, etc., to the pilot.

(*iii*) The cabin temperature is con-trolled by means of a mixture of thermo-switches and Wheatstone bridges. The temperature can be controlled within close tolerances and over a considerable range.

9·4 *Lights*

Approximately 300 lights ranging from tiny instrument lights of 0·72 watts to motorized landing lamps of 600-watt rating are fitted to the average four-engined aircraft. These lights are used for warning systems, lighting of cabin and cockpit, navigational lights, etc.

In the cockpit there are fluorescent lamps used for night flying. These cause the instrument dials to glow whilst the cockpit ambient lighting is kept at a very low level.

The majority of the lamps used are specially selected as they are subjected to varying voltages and continuous vibration. This tends to lower the average life of the lamps considerably, 200 to 300 hours being considered normal.

9·5 *Switches and circuit-breakers*

The switches in common use are smaller and more robust versions of the normal tumbler-switches. These are usually fitted to switch panels in neat rows and are all clearly labelled. When this type of tumbler-switch is used in a circuit a fuse is also included. This in an aircraft means extra weight. In order to cut down the weight a switch type of circuit-breaker was developed and is now commonly used. These circuit-breakers are of two basic types, thermo-statically operated and magnetically operated.

The thermostatic breakers have a con-siderable time lag and are usually used in circuits where the protection is not critical and where they are seldom used to perform switching functions. The magnetic circuit breakers on the other hand can be set to operate almost instantaneously and can be re-set often without harming or damaging the internal operating mechanism. These are employed, as a result of the above, in circuits requiring critical protection and which have to be switched on and off fairly frequently.

The average life of a switch in an aircraft ranges between 8 000 and 12 000 hours. The circuit-breakers used have capacities which range from 1 ampere to 250 amperes.

9·6 *Wire and cabling*

In view of the weight difficulties that exist in aircraft a maximum effort is made to keep down the weight of any wire and cabling installed. This is achieved by using the minimum possible amount of insulation and by utilising current densities almost double that used in normal practice. A further complication is the extreme vibration to which the cabling and cable harnesses are subjected. This problem is partially overcome by using multi-stranded conductors. Moisture in its turn, too, causes unnecessary difficulties in the form of corrosion. This is cut down to the minimum by having each individual strand tinned.

Aircraft cable thus consists of a multistranded, tinned-copper conductor covered with a thin neoprene or plastic layer which in turn is encased in a varnished braided cotton outer. The insulation can withstand an average voltage between 250 and 300 volts. In locations where the cabling is subjected to high temperatures the outer covering usually consists of thin asbestos tape enclosed in fibre-glass sleeving. This latter cable unfortunately breaks down mechanically when subjected to chafing and thus rigid clamping to the air frame is usually necessary.

To prevent moisture, oil, hydraulic fluid, etc., from damaging the insulation in certain sections of the wiring, polyvinyl or some type of plastic sleeving is used to encase it.

The busbar system, to be as light as possible, is made from solid aluminium rod. It normally runs inside the wing structure and extends to the two outboard engines. The centre of this section is in turn connected to a further busbar, much heavier in cross section, running down towards the tail of the aircraft. These sections are bolted together and all minor feeders are in turn bolted to the busbar.

Where necessary cable ends are fitted with lugs. These are both soldered and crimped to the wire. Crimping is gradually replacing soldering, the main reason being the numerous fractures that occur at the point where the soldered and unsoldered part of the wiring meet in soldered joints.

9·7 *Accumulators*

The accumulators used in aircraft are commonly of the lead-acid type encased in hard rubber containers. Again due to the weight limitations the capacity and size of the accumulator is kept as low as possible. The main function of the accumulator is to provide the system with a reference and stabilizing voltage. The average capacity is 60 to 80 ampere-hours. It can thus be seen that in the event of an emergency it can only be used to operate minor components such as instruments and emergency lights.

Since the charging current can vary between 10 and possibly 75 amperes due to changes in the generator loads the accumulator must be constructed to withstand fairly high temperatures and be able to rid itself of fair quantities of gas. In order to prevent this moist gas from attacking the aluminium skin of the aircraft a special venting system is fitted.

10. CONCLUSION

From the above rather brief survey it can be appreciated that the modern aircraft is a complex device from the electrical point of view, the problem unfortunately becomes more complicated with each new aircraft produced. This necessitates continual training of maintenance personnel, the purchasing and use of new and expensive test equipment, and the tracing and clearing of obscure and complicated electrical faults.

If the trend in military aircraft is any indication of what is to happen in civil aircraft, and this has proved to be the case in the past, the majority of functions at present performed by means of hydraulic and compressed air systems will be done by means of electric motors.

This will mean a great increase in the capacity of the generating system, which most likely will consist of steam-cooled a.c. generators working into metal rectifier units. The control and system protection will be on the a.c. side of the circuit. It seems probable that the d.c. voltage used will be around 120 volts as this will mean a considerable saving in wire weight, size of motors, etc., compared with a 24-volt system of the same capacity.

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DISCUSSION

J. D. N. van Wyk: We must credit the author with the courage to tackle such a diverse and hence difficult subject. If he had all the time necessary at his disposal, we feel sure that he would have been able to give a most comprehensive and excellent article on this subject. Abbreviating this to a paper to be read in a limited time, however, has complicated matters and a few points need illuminating.

The author maintains that the troublesome magneto, in its early stages, was the origin of the present complex electrical systems as we know them to-day, but fails to tell us when the magneto was so improved as to be almost exclusively used on modern aero-engines.

The battery-coil ignition system has two main disadvantages which almost prohibit its use on aero-engines viz :

a reduced performance with increased sparking frequencies, and
b performance dependent on the battery condition and voltage.

To make the coil ignition system independent of these variables, additional equipment has to be added, which makes the system so cumbersome and complex as to be virtually impossible to apply it to engines having more than 6 cylinders.

The author compares the weight factor of a.c. and d.c. systems and mentions that a 40-kW d.c. generator weighs about 150 lb whilst for a 40-kVA a.c. generator the weight is about 65 lb

This yields the following figures for weight in lb per kW :

D.C. about 3·75 lb/kW
A.C. about 1·63 lb/kVA

In his description of typical aircraft systems viz. the Brabazon (a.c. rectifier system) and the Sounder Roe Princess Flying Boats (d.c. system) we get the following figures :

D.C. system about 40 lb/kW
A.C. system about 27 lb/kVA

The difference between these sets of figures comparing d.c. and a.c., appears particularly large, roughly a factor of 10.

In F. G. Spreadbury's book, *Aircraft Electrical Engineering*, published in 1943, he mentions a figure of 10 lb/kVA as typical for aircraft a.c. generators. Some figures available on systems in Japanese aircraft used during World War II gives about 13·3 lb/kW for d.c. generators.

The figures 3·75 and 1·65 lb/kW and lb/kVA respectively indicates some phenomenal advances in design and construction in recent years. It would be extremely interesting if the author could tell what these major advances in design were.

During the war many types of military aircraft e.g. Lincolns and Lancasters were forced to adopt the system of an auxiliary power supply. This had the advantage of using higher voltages and reduced the importance of the batteries. The higher voltages reduced cable sizes and thus their weight which must form a fair proportion of the electrical systems weight at low voltages.

In military aircraft it had two main disadvantages viz.

a the system was more vulnerable, being concentrated in one spot instead of being spread over four engines, and
b in high flying aircraft the engine for the auxiliary supply had to be supercharged making it heavy or otherwise the operating ceiling of the aircraft was reduced.

Since none of these factors seem to be present in modern pressurized civil aircraft and although the author dismisses the subject by stating that these units are at present too heavy, a few weight figures would have been very interesting as the rapid expansion of demands on the electrical system of modern four-engined aircraft may force the use of these units in future.

The author mentioned carbon-pile regulators being used almost exclusively on aircraft systems. As we know these have to be carefully designed and intelligently maintained otherwise a changing voltage or load condition may bring them within a range where hunting occurs. These factors make one wonder whether other systems of regulators have been extensively tried. The Tirrel-type of regulator was used at one stage and it would be interesting to have the author's view on why this or other types were not used more extensively.

The author describes the automatic propeller speed- and synchronization-control on modern aircraft. According to the author's brief description, the pilot sets the speed of the propeller by adjusting the speed of the master controller i.e. the amplidyne motor. Now for a given throttle setting the motor will have a certain speed range between the coarse and fine pitch setting limits of the propeller. The limits of the speed range will vary for different throttle i.e. engine power settings. Could the author enlighten us how it is ensured that the master speed control setting, set by the pilot, does not exceed the limits set to the speed by the actual engine power? In other words, how do we ensure co-ordination between power setting by means of the throttles and speed setting by means of the master controller?

R. P. Channer: I think I may safely say that Mr Bosch is perhaps one of the few persons in the Union who, due to his personal and direct contact with modern high speed aircraft, is qualified to describe as he has done, the unusual and peculiar snags associated with modern aviation.

He has, as he explained, only touched on the fringe of the various subjects concerned with airborne aviation electrics, nevertheless very little has been left to the imagination. However, referring back for a while you will remember that at an altitude of 40 000 feet generator brushes wear so quickly that they may completely disappear after 30 minutes of operation, well—if any of you good people had ideas of owning your own private aircraft—please do not be put off by Mr Bosch's remarks, for, although this is true at high altitudes, the small aircraft is normally not permitted to fly higher than 10 000 feet, at which altitude generator brushes behave normally.

This reminds me of two other important items mentioned by Mr Bosch.

a The improbability of a complete alternating current system, and
b the reference made to steam cooling of generators.

I do not believe that alternating current will completely replace the direct current system as used to-day. A.C. generators coupled with rectifier units and supplying power to a bank of batteries are being used to-day in preference to d.c. generators, mainly I believe, because of commutator and brush problems at high altitude, nevertheless, the difficulty of paralleling or synchronizing two or more alternators, as well as maintaining a tolerable frequency standard by automatic means, presents a major problem, especially since the main function of the prime movers (reciprocating engines or jets) is to propel the aircraft, and secondly to drive the generators. Incidentally, it was suggested some years ago that once the generators on multi-engined aircraft were correctly synchronized they would in turn keep the engines synchronized electrically, but, as the generators are only a mere fraction of the horse power developed by the engines, this seems improbable.

Independent operation of a.c. generators, that is, say four separate alternating current supplies, coupled to an aircraft electrical system or load divided into four sections, one section to each generator, thereby eliminating the need for parallel operation of generators, would not be permissible without elaborate automatic change-over switchgear which could transfer a section of the load from one supply to another in the event of the failure of any one generator.

It must be appreciated also, that electrical services on an aircraft, whilst varying in degree of importance, are all essential and no ornaments are tolerated.

In addition to frequency variation and synchronizing problems, alternating current motors also present their problem. To eliminate starting difficulties, commutator and brush troubles, all motors would need to be of the 3-phase variety, each requiring three insulated leads, a 3-phase circuit-breaker and, for heavy current remotely operated motors, a 3-phase relay and a pair of relay-coil leads (a total of five conductors in all) as compared with one lead, one single-phase switch or relay with one coil energizing lead and an earth return (a total of two conductors) in the present d.c. system.

Individual fusing of 3-phase legs would not be permissible, 3-phase overcurrent trip switches would have to replace dozens of the simple glass enclosed fuses of the d.c. system, thus adding weight and complicated mechanism.

Many d.c. motors used on aircraft, once energized, run until automatically switched off by means of a limit-switch when the apparatus being driven has reached the required position. These limit-switches being single phase can be adjusted to extremely fine tolerances, but whether or not a 3-phase limit-switch could be adjusted to the same degree of accuracy, I do not know.

I am not an aircraft designer nor am I trying to belittle the introduction of alternating systems on aircraft, but simply from a practical point of view expressing my idea of the problems which I imagine are facing the present day aircraft electrical engineer.

In conclusion, the latest technical information from the U.S.A. is to the effect that new high altitude d.c. generators have been designed and manufactured (this bears out with Mr Bosch's proposals for the futuristic application of generators).

One of these generators whilst still a blast cooled unit is not affected by altitude, since it uses air bled from the pressurized cabin of the aircraft. A second type incorporates a cooling system utilizing the vaporization of water (steam), and the third is cooled with a chemical coolant, circulating in a closed recirculating system.

All three types are designed with improved insulation, larger commutators and staggered brushes resulting in decreased brush temperature and greater air flow over the commutator. Normal operation at altitudes far in excess of 40 000 feet is claimed.

B. L. D. Porritt (Associate): Firstly I would like to congratulate Mr Bosch on his paper. Secondly, with regard to the electrical starting equipment for piston engines which he briefly mentioned, I had hoped he would have included in that section some mention of the special equipment for starting jet engines. I believe this electrical equipment is non-conventional and has to withstand astronomical currents for quite considerable periods and I wonder if Mr Bosch would give us a few details on that equipment ?

SOME NOTES ON POWER FACTOR CORRECTION ECONOMICS

By F. G. HEYMANN (Associate Member)

The discussion which follows will apply only where a charge per kVA of maximum demand is made by an electrical power supply authority. An attempt is made to show that calculations of saving effected by power-factor correction may easily be in error if the various annual charges involved are not estimated accurately and if certain small effects are neglected when synchronous condensers are employed.

STATIC CONDENSERS

When the power factor of a consumer is corrected by means of static condensers, the losses in the condensers are so small that they may be neglected altogether. The vector diagram in Fig. 1 may therefore be used :—

P = power input during the maximum demand period

D_o = kVA maximum demand before correction

$\cos\phi_o$ = power factor before correction

D = kVA maximum demand after correction

$\cos\phi$ = power factor after correction

Q = kVA capacity of correcting equipment.

It can be shown[1] that maximum saving occurs at a corrected power factor which is determined only by the following factors :—

k = annual charge per kVA of maximum demand

c = cost per kVA of correcting equipment

r = annual per-unit rate of interest, depreciation and maintenance referred to capital expenditure for correcting equipment.

If ϕ_m is the optimum phase angle, then :

$$\sin\phi_m = cr/k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 1$$

Bolton[1] has shown that the maximum saving may be written as follows :—(see also Equation 8 of this paper).

$$S_m = kD_o\{1 - \cos(\phi_o - \phi_m)\} \quad \ldots\ldots 2$$

It is important to estimate ϕ_m correctly, otherwise the calculated saving may be appreciably in error, especially if ϕ_o is small.

If ϕ_m is under-estimated, the saving calculated by Equation *2* may be considerably greater than the actual saving, whilst too high a value of ϕ_m has the opposite effect.

Assume that the optimum phase angle is under-estimated so that it appears to be $\phi_m - \delta$ (where δ is small)

$\therefore$ Calculated maximum saving

$$= kD_o\{1 - \cos(\phi_o - \phi_m + \delta)\}$$

$$= kD_o\{1 - \cos(\phi_o - \phi_m)\cos\delta + \sin(\phi_o - \phi_m)\sin\delta\}$$

If δ is small, then $\cos\delta \doteqdot 1$ and $\sin\delta \doteqdot \delta$

$\therefore$ Calculated maximum saving $\doteqdot$

$$kD_o\{1 - \cos(\phi_o - \phi_m) + \delta\sin(\phi_o - \phi_m)\}$$

$$\therefore \text{Error} \doteqdot kD_o\delta\sin(\phi_o - \phi_m) \quad \ldots\ldots\ldots\ldots \; 3$$

Percentage error

$$= \frac{\delta\sin(\phi_o - \phi_m)}{1 - \cos(\phi_o - \phi_m)} \times 100 \text{ per cent}$$

$$= \frac{2\,\delta\sin\tfrac{1}{2}(\phi_o - \phi_m)\cos\tfrac{1}{2}(\phi_o - \phi_m)}{2\sin^2\tfrac{1}{2}(\phi_o - \phi_m)} \times 100 \text{ per cent}$$

$$= \delta\cot\tfrac{1}{2}(\phi_o - \phi_m) \times 100 \text{ per cent} \ldots\ldots \; 4$$

This error may be large since the cotangent of a small angle is large.

The actual saving which results from correcting to a final phase angle which is slightly different from the optimum, is not much less than the maximum saving, since $\dfrac{\delta S}{\delta\phi} = 0$ at $\phi = \phi_m$ (see later)

Equation *4* for percentage error may be simplified by assuming ϕ_m to be small compared with ϕ_o, which is usually the case.

$$\therefore \text{ Percentage error} \doteqdot \delta \cot\left(\frac{\phi_o}{2}\right) \times 100 \text{ per cent} \qquad 5$$

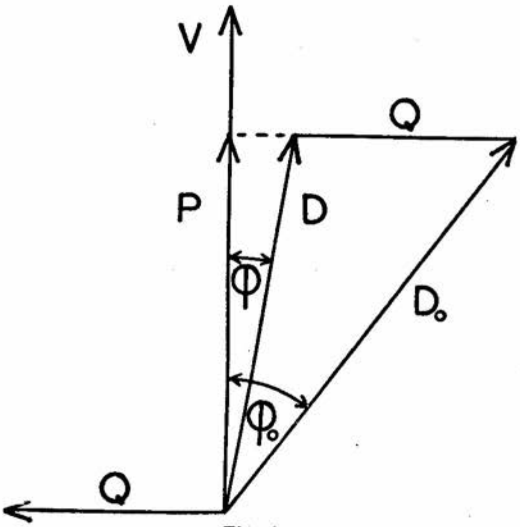

Fig. 1

Table I will indicate the approximate error if $\delta = 0{\cdot}02$ radian ($\delta = 1{\cdot}15°$)

TABLE I

$\cos\phi_o$	0·866	0·707	0·5
ϕ_o	30°	45°	60°
Percentage error	7·5	4·8	3·5

It is evident that an error in ϕ_m of several degrees may be important. (The percentage error is really somewhat greater than indicated by the simple relation. If $\phi_m = 0{\cdot}1$ radian, closer approximations in the three cases are 9·3, 5·6 and 3·9 per cent error respectively.)

SYNCHRONOUS CONDENSERS

The loss in a synchronous condenser may not normally be neglected since it amounts to several per cent of the kVA rating.

The effect of loss in correcting equipment is two-fold :—

i The input power is increased
ii The maximum demand is affected.

i In order to determine the increased charge due to the increase in energy consumption, it becomes necessary to estimate the total energy lost in the correcting equipment per annum.

In the case of a synchronous condenser the losses will vary if the amount of correction kVAr is varied with changes in load. However, it is probable that the correction kVAr will not vary greatly if load fluctuation is due to variation in mechanical load on machines and not so much due to switching on and off. The machines are usually induction motors so that their reactive current components do not vary greatly between no-load and full load.

It is therefore simplest to assume that the loss is practically constant, or possibly a loss factor can be introduced to account for variation in loss during operation.

Let the annual charge for loss per kVA of installed correcting equipment be denoted by u

Then : $u =$ (Cost per kWh $\times$ operating time $\times$ loss factor) $\times \cos\phi_c = p\cos\phi_c$

where $\cos\phi_c =$ power factor of correcting equipment at full rating.

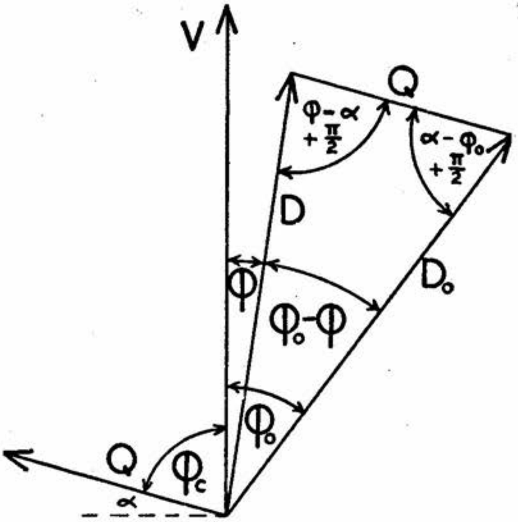

Fig. 2

The loss factor will be less than unity since in general the correcting equipment will not run at full rating continuously.

The optimum corrected power factor will now be at a phase angle given by

$$\sin \phi_m = \frac{cr + u}{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 6$$

since u merely adds to the annual charge per kVA of correcting equipment

ii The above relation does not, however, include the effect of losses on maximum demand.

When losses are appreciable, the vector diagram will appear as in Fig. 2.

The symbols have the same significance as before, with the addition of —

$\cos\phi_c$ = power factor of correcting equipment

$= \sin \alpha$

From the diagram it follows that —

$$\frac{D_o}{\sin\left(\frac{\pi}{2}+\phi-\alpha\right)} = \frac{D}{\sin\left(\frac{\pi}{2}-\phi_o+\alpha\right)} = \frac{Q}{\sin(\phi_o-\phi)}$$

i.e. $$\frac{D_o}{\cos(\phi-\alpha)} = \frac{D}{\cos(\phi_o-\alpha)} = \frac{Q}{\sin(\phi_o-\phi)}$$

$$\therefore \quad D = D_o \frac{\cos(\phi_o-\alpha)}{\cos(\phi-\alpha)}$$

and $$Q = D_o \frac{\sin(\phi_o-\phi)}{\cos(\phi-\alpha)}$$

The annual charge for maximum demand before correction is kD_o

The annual charge for maximum demand and correcting equipment is $kD + (cr+u)Q$ after correction

$\therefore$ Annual saving: $S = kD_o - kD - (cr+u)Q$

Substituting for D and Q :—

$$S = kD_o - kD_o \frac{\cos(\phi_o-\alpha)}{\cos(\phi-\alpha)} - (cr+u)\, D_o \frac{\sin(\phi_o-\phi)}{\cos(\phi-\alpha)}$$

$$= kD_o \left\{1 - \frac{\cos(\phi_o-\alpha)}{\cos(\phi-\alpha)} - x\frac{\sin(\phi_o-\phi)}{\cos(\phi-\alpha)}\right\}$$

$$= kD_o \left\{1 - \frac{\cos(\phi_o-\alpha) + x\sin(\phi_o-\phi)}{\cos(\phi-\alpha)}\right\} \ldots \quad 7$$

$$\left(\text{where } x = \frac{cr+u}{k}\right)$$

Differentiating with respect to ϕ :—

$$\frac{\delta S}{\delta\phi} = kD_o \frac{x\cos(\phi_o-\phi)\cos(\phi-\alpha) - \sin(\phi-\alpha)\{\cos(\phi_o-\alpha) + x\sin(\phi_o-\phi)\}}{\cos^2(\phi-\alpha)}$$

$$= \frac{kD_o}{\cos^2(\phi-\alpha)}\Big[x\{\cos(\phi_o-\phi)\cos(\phi-\alpha) - \sin(\phi_o-\phi)\sin(\phi-\alpha)\} - \sin(\phi-\alpha)\cos(\phi_o-\alpha)\Big]$$

$$= \frac{kD_o \,.\, \cos(\phi_o-\alpha)}{\cos^2(\phi-\alpha)}\left\{x - \sin(\phi-\alpha)\right\}$$

The maximum saving will occur when $\frac{\delta S}{\delta\phi} = 0$

If the optimum phase angle is ϕ_m, then $\sin(\phi_m-\alpha) = x$

$\therefore$ Maximum saving is given by :—

$$S_m = kD_o\left\{1 - \frac{\cos(\phi_o-\alpha) + \sin(\phi_m-\alpha)\sin(\phi_o-\phi_m)}{\cos(\phi_m-\alpha)}\right\}$$

$$= kD_o\left\{1 - \frac{\cos(\phi_o-\phi_m+\phi_m-\alpha) + \sin(\phi_m-\alpha)\sin(\phi_o-\phi_m)}{\cos(\phi_m-\alpha)}\right\}$$

$$= kD_o\left\{1 - \frac{\cos(\phi_o-\phi_m)\cos(\phi_m-\alpha) - \sin(\phi_m-\alpha)\sin(\phi_o-\phi_m) + \sin(\phi_m-\alpha)\sin(\phi_o-\phi_m)}{\cos(\phi_m-\alpha)}\right\}$$

$$= kD_o\left\{1 - \cos(\phi_o-\phi_m)\right\} \ldots \quad 8$$

This means that here the calculation of maximum saving again involves the correct estimation of ϕ_m

Since ϕ_m and a are usually small

$$x = \sin(\phi_m - a) \doteqdot \phi_m - a$$

$$\therefore \quad \phi_m \doteqdot x + a$$

and $a \doteqdot \sin a = \cos\phi_c$

Thus the maximum saving may be calculated from a value of ϕ_m given by —

$$\left.\begin{aligned}\phi_m &= \frac{cr + u}{k} + \cos \phi_c \text{ radian} \\ &= \frac{c\,r}{k} + \left(\frac{p}{k} + 1\right)\cos \phi_c \text{ radian}\end{aligned}\right\} \ldots\ldots 9$$

In the case of static condensers the losses are so small (about 0·5 per cent) that $\cos\phi_c$ is negligible.

When synchronous condensers are employed, the losses may not be negligible.

If the effect of losses on maximum demand is neglected, then the approximate error, expressed as a percentage of maximum saving, becomes —

$$\text{Percentage error} \doteqdot \cos \phi_c \,.\, \cot \left(\frac{\phi_o}{2}\right) \times 100 \text{ per cent} \ldots\ldots 10$$

If losses are neglected altogether :—

Percentage error

$$\left.\begin{aligned}&\doteqdot \left(\frac{u}{k} + \cos \phi_c\right) . \cot \left(\frac{\phi_o}{2}\right) \times 100 \text{ per cent} \\ &= \left(\frac{p}{k} + 1\right) \cos \phi_c \,.\, \cot \left(\frac{\phi_o}{2}\right) \times 100 \text{ per cent}\end{aligned}\right\} \ldots\ldots 11$$

PROBABLE VALUES OF OPTIMUM PHASE ANGLE

Bolton[2] states that the ratio $\frac{cr}{k}$ will normally lie between 0·1 and 0·2 with probable extremes of 0·05 and 0·3, the lower values being more probable than the higher ones.

The factor $\frac{u}{k} = \frac{p}{k} \cos \phi_c$ depends on the cost of energy, running time and loss in correcting equipment.

Assume : *i* Loss factor = 1

ii Cost/kWh = 0·5 penny

iii Running time = 2 000 hrs per annum

$$\therefore \quad p = \frac{£2\,000 \times 0{\cdot}5}{240} \doteqdot £4$$

The order of k is roughly £4 per kVA of maximum demand p.a.

$$\therefore \quad \frac{p}{k} \doteqdot 1$$

The power factor, $\cos\phi_c$, of correcting equipment will vary with the size of synchronous condenser.

In a machine rated at about 250 kVA the power factor will be 0·05 approximately. Larger machines will in general have lower power factors, and smaller machines, higher power factors.

Taking the case of a 250-kVA machine, Table II will give an indication of the errors to be expected.

TABLE II

$\cos\phi_o$	0·866	0·707	0·5
ϕ_o	30°	45°	60°
Percentage error	18·7	12·1	8·7

The above figures assume that only the effect of losses on maximum demand has been neglected.

If losses are neglected altogether, the error will be approximately doubled.

As has been indicated before, the error is underestimated in the simple relation so that the actual error is greater than shown above.

EXAMPLE

Original maximum demand is 250 kVA at a power factor of 0·7. Let cost of correcting equipment be £3 per kVA and r = 10 per cent p.a. Let p be £3 p.a., and k = £4 p.a. per kVA of maximum demand. Also let $\cos\phi_c$ be 0·05.

$$\phi_m = \frac{3 \times 0{\cdot}1}{4} + \left(\frac{3}{4} + 1\right) \times 0{\cdot}05 = 0{\cdot}162\,5 \text{ radian}$$

$$\phi_o = \text{arc cos } 0{\cdot}7 = 0{\cdot}795 \text{ radian}$$

a $\therefore$ Maximum saving $S_m =$

$$\begin{aligned} &£4 \times 250\ (1 - \cos 0{\cdot}632\ 5) \\ &= £1\ 000 \times (1 - 0{\cdot}806\ 5) \\ &= £193{\cdot}5 \end{aligned}$$

$D = 185$ kVA

$Q = 149$ kVA

b If the effect of losses on maximum demand is neglected, it follows—

Estimated $\phi_m = 0{\cdot}112\ 5$

$$\begin{aligned} \text{Calculated saving} &= £1\ 000\ (1 - \cos 0{\cdot}682\ 5) \\ &= £1\ 000\ (1 - 0{\cdot}776) \\ &= £224 \end{aligned}$$

$(D = 184$ kVA)

$(Q = 159$ kVA)

$$\begin{aligned} \text{Actual saving} &= £193{\cdot}5 - 0{\cdot}9 \\ &= £192{\cdot}6 \end{aligned}$$

Percentage error $= \dfrac{31{\cdot}4 \times 100}{192{\cdot}6} = 16{\cdot}3$ per cent (12 per cent by approximate relation)

c If losses are neglected altogether, the figures are—

Estimated $\phi_m = 0{\cdot}075$

$$\begin{aligned} \text{Calculated saving} &= £1\ 000\ (1 - \cos 0{\cdot}72) \\ &= £1\ 000\ (1 - 0{\cdot}752) \\ &= £248 \end{aligned}$$

$(D = 184$ kVA)

$(Q = 165$ kVA)

Actual saving $= £193{\cdot}5 - 2{\cdot}7 = £190{\cdot}8$

Percentage error $= \dfrac{57{\cdot}2 \times 100}{190{\cdot}8} = 30$ per cent (21 per cent by approximate relation).

The error is greater if the original power factor is higher. It is therefore evident that it is important to include the effects of losses in the calculation of saving effected by power-factor correction, otherwise the calculated saving will be much greater than the actual saving, resulting in too optimistic a view.

REFERENCE

1. BOLTON, D. J. *Electrical Engineering Economics*. Chapman and Hall (1936). pp. 254, 258.
2. *op. cit.*, p. 257.