

Chapter 8

50kVA, 400 C/S,

ENGLISH ELECTRIC CONSTANT FREQUENCY A.C. SYSTEM

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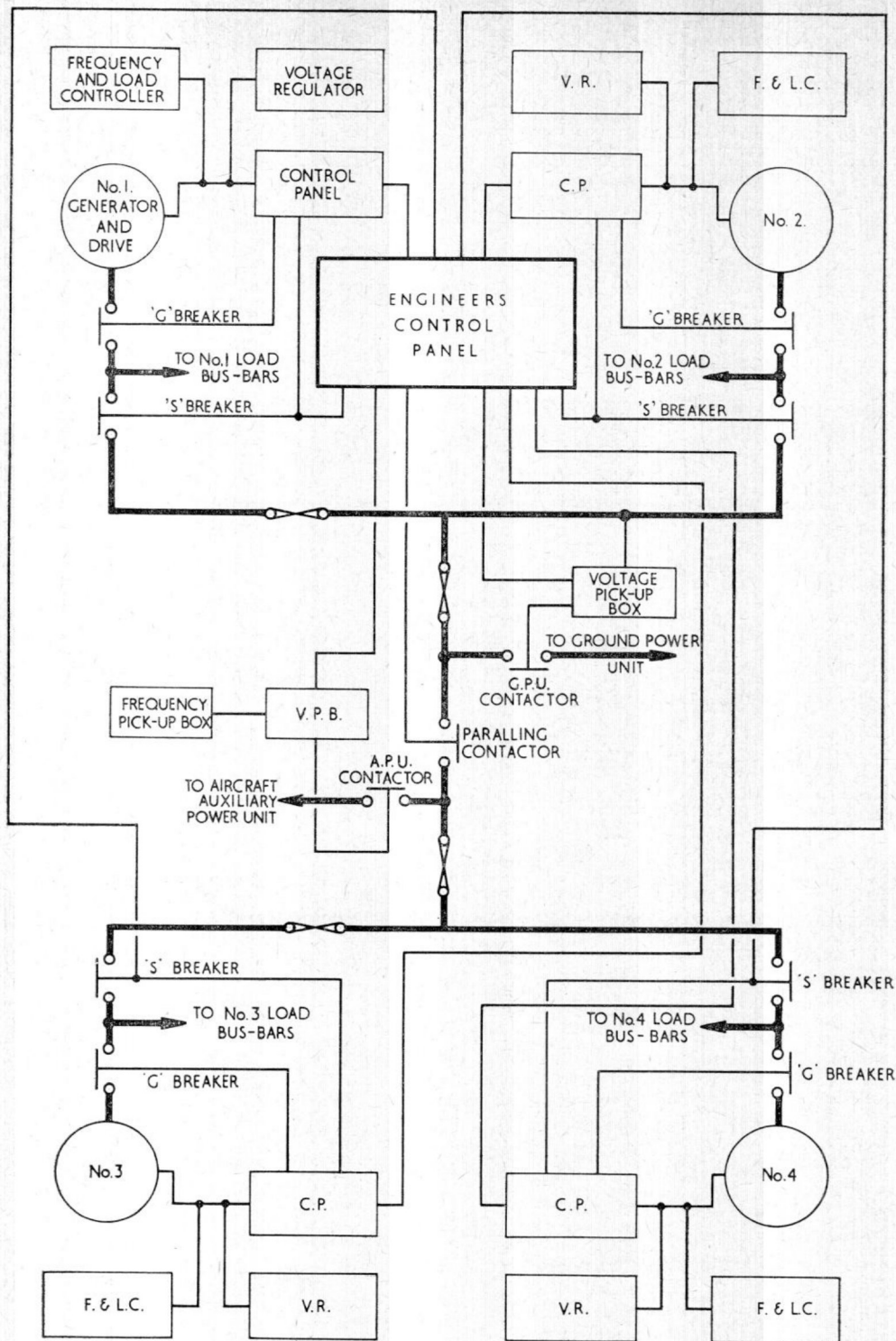


Fig. 1. Block diagram showing general system layout and typical busbar arrangement

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Introduction

1. The system provides a 3 phase, 200V, 400 c/s a.c. supply from four 50 kVA generators driven through constant speed drives by aircraft engines. The generators are normally synchronized and paralleled on synchronizing busbars, but provision is made for emergency operation, when the essential loads on the busbars must be fed by three, two or even one generator, whilst the remainder are switched off, or, when each is feeding a group of loads individually.

2. The busbars may also be supplied from a ground power unit (G.P.U.) or from the airborne auxiliary power unit (A.A.P.U.), but interlocking is provided so that only one form of supply may be switched to the busbars at one time.

3. A 28V d.c. supply for operation of relays, indicator lamps and battery charging is obtained from a transformer-rectifier unit (T.R.U.).

DESCRIPTION

General

4. Although, for convenience, the paragraphs which follow are headed by the main components of the system, the primary purpose is to describe the functioning of the system as a whole, rather than of these individual units. Diagrams are included for purposes of explanation and are therefore to some extent simplified—e.g. smoothing circuits, temperature compensating resistors, may not be shown. Note that any figures quoted are purely illustrative and should not be taken as actual working values.

Busbar arrangement

5. A block diagram showing the general layout of equipment for four generators and a typical busbar arrangement is given in fig. 1. The aircraft essential loads are split into four groups, each group being associated with one generator and connected to it by a generator ('G') circuit breaker via a feeder busbar. The generators and their respective loads are paralleled in pairs (No. 1 and No. 2 "port" and No. 3 and No. 4 "starboard") to synchronizing busbars by synchronizing ('S') circuit breakers. Provision is also made by means of a paralleling contactor so that the port and starboard synchronizing busbars may be connected together if required.

6. It will be seen from fig. 1 that various combinations of load distribution are possible. For normal operation the paralleling contactor is open. If, for example, the essential loads are to be supplied by either the G.P.U. or the A.A.P.U., the paralleling contactor is closed, the 'S' breakers are closed and the 'G' breakers are open. If the essential loads are to be supplied by one generator, the appropriate 'G' breaker is closed and the three remaining ones are open; all 'S' breakers and the paralleling contactors are closed. Other combinations are obvious.

System components

7. A simple block diagram is shown by fig. 2 of the equipment associated with one generator and Table 1 details the components.

Constant speed drive (C.S.D.)

8. The drive is of the differential hydraulic type giving a constant output speed of 6,000 rev/min for engine speeds varying between 3,600 and 8,300 rev/min. The output speed is controlled primarily by a centrifugal governor but this is trimmed by a motor-driven servo-gearbox for correction of (real) load and frequency variations.

Generator

9. The generator is an oil-cooled brushless machine with main and pilot exciters mounted on the same shaft as the generator rotor. To rectify the main exciter output silicon diodes are fitted to the rotor.

10. Cooling oil is fed from the C.S.D. oil inlet to a helical tube incorporated in the generator frame.

Voltage regulator

11. The voltage regulator circuit has four stages: the voltage reference and reactive load sensing, two magnetic amplifier stages, and a power bridge rectifier output stage.

Voltage reference circuit

12. The generator output feeders are tapped to feed a full wave bridge rectifier and the rectified output is applied to a resistance trigger tube bridge. The signal to the bridge is preset by a potentiometer, and voltage across the trigger tubes is virtually constant irrespective of current flow, after about three minutes warming up period. This is the

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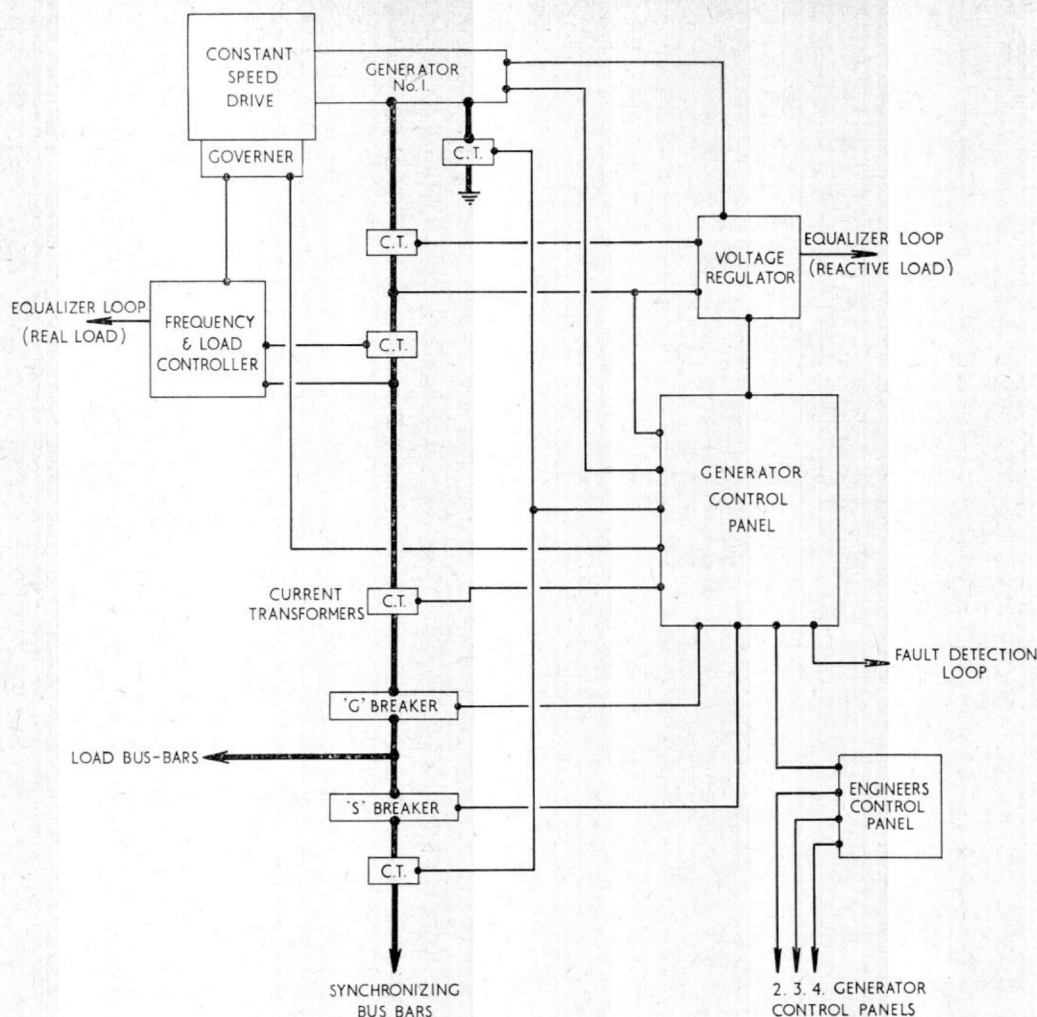


Fig. 2. Block diagram of equipment associated with one generator

voltage reference stage and determines the magnitude and direction of current flow in one d.c. control winding of the first stage magnetic amplifier.

Reactive load sensing circuit

13. When a generator is working into busbars whose voltage is kept sensibly constant, a rise or fall in its excitation will result in the machine increasing or decreasing its reactive loading. Since the generated voltage is also dependent upon excitation it will be seen that the voltage regulator controls both the output voltage and the reactive loading of the generator.

14. Consider the operation of two generators in parallel. Their respective voltage regulators cannot be adjusted to have exactly the same

response under all loading conditions. Thus when the machines are paralleled the busbars assume a voltage which depends on the mean of the two characteristics.

15. The regulator which is set to the higher level senses an under-volting condition and will try to correct by increasing excitation of its associated generator. At the same time the other regulator, sensing over-volts, will do the reverse. Therefore, whilst the mean busbar voltage remains approximately constant, the generator voltages progressively diverge and the over-volting machine takes over more and more of the total reactive load.

16. If it can be so arranged that the regulators, instead of sensing the busbar volts, sense a voltage which increases as a machine

takes on more than its share of reactive load, and vice versa, the out of balance can be kept within reasonable limits. This is the function of the reactive load sharing circuit.

17. The reactive load sensing circuit operates in conjunction with an external current transformer network which senses any change in reactive load within the system.

18. The circuit, fig. 3, consists of a trans-

former whose primary is connected across generator feeder lines A and B. Its secondary winding is connected via two blocking rectifiers to a potential divider. The electrical centre of the potential divider is connected through a load resistor to the centre tapping of the transformer. The current transformer (in phase 'C') is connected across the load resistor. This sensing circuit feeds two capacitors which in turn feed the other control winding of the first stage magnetic amplifier.

TABLE 1

Major components of system

Item	Component	Description and Function
1	Constant speed drive (C.S.D.)	66 h.p. rated differential hydraulic drive giving a constant output speed of 6,000 rev/min.
2	Generator	200V, 3 phase a.c. 400 c/s, brushless generator giving an output of 50kVA.
3	Voltage regulator	Providing generator voltage output control within 200V, r.m.s. $\pm 2\frac{1}{2}\%$, with reactive load change sensing circuit.
4	Frequency and load controller	Providing frequency control within 400 c/s $\pm 1\%$ and load sharing within 3kW of the average load of the system.
5	Generator control panel	Providing generator control including: exciter control, over voltage protection, differential current protection, underspeed detection.
6	Generator circuit breaker ('G' breaker)	Magnetic switch for connecting generator to load busbars.
7	Synchronizing circuit breaker ('S' breaker)	Magnetic switch for connecting generator and load to synchronizing busbars.
8	A.C. voltage pick-up box (2)	Prevents G.P.U. or A.A.P.U. connection to sync. busbars when main generators are on line.
9	Engineers control panel	Generator control, on/off; generator isolation and resetting; synchronization control; generator selector switch; indicators; volt and frequency meters.
10	Current transformers	Used in conjunction with various control and protection circuits.
11	Transformer rectifier unit (2)	Provide 28V d.c. supply for d.c. busbars.

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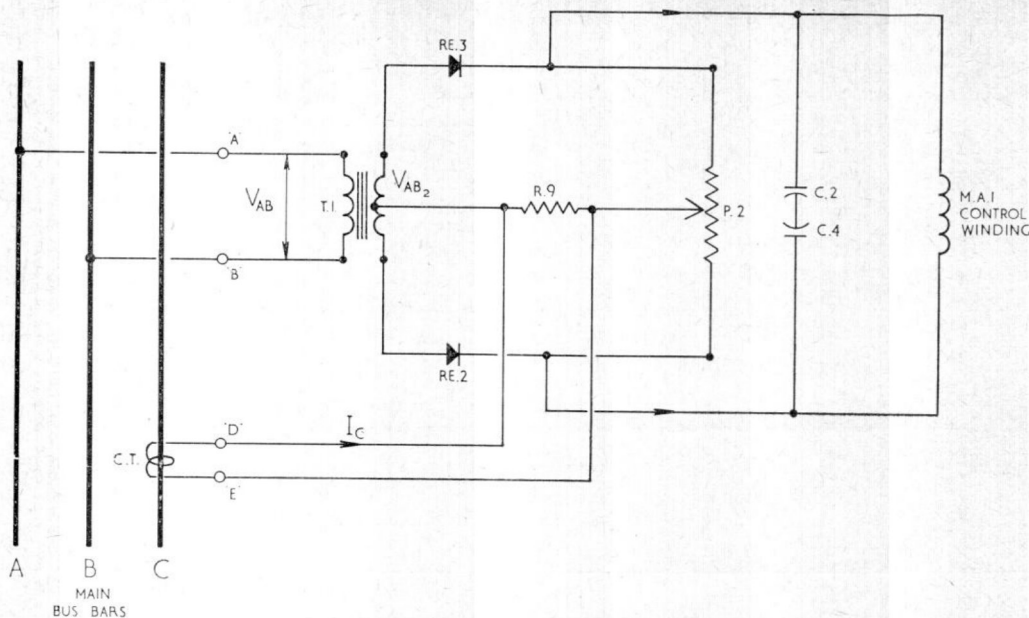


Fig. 3. Reactive load sensing circuit in voltage regulator

19. With no signal from the current transformer connected in line C, the potentials produced across each half of the divider resistor for each cycle is equal and opposite, owing to the blocking rectifiers. Thus the net voltage appearing across the capacitor is zero and no current flows in the control winding of the magnetic amplifier.

20. If a signal is obtained across the load resistor from the current transformer the voltage produced will be in phase with that produced by the transformer. Thus reactive load only is sensed by the circuit whereas real load has virtually no effect.

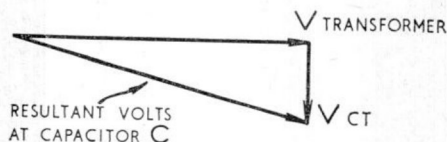


Fig. 4. Effect of reactive load

21. Suppose 3 volts is produced across the load resistor. Depending upon which direction the current is flowing the 3 volts is added to the voltage of one loop of the sensing circuit and subtracted from the other. For a complete cycle, a voltage appears across the capacitor approximately equal to $\sqrt{2}$ x the difference between loop voltages. For 30 volt potentials produced across each half of the divider resistor: $\sqrt{2} (33-27)=$

8.5V will be applied to the magnetic amplifier causing an increase or decrease in the magnetic amplifier output.

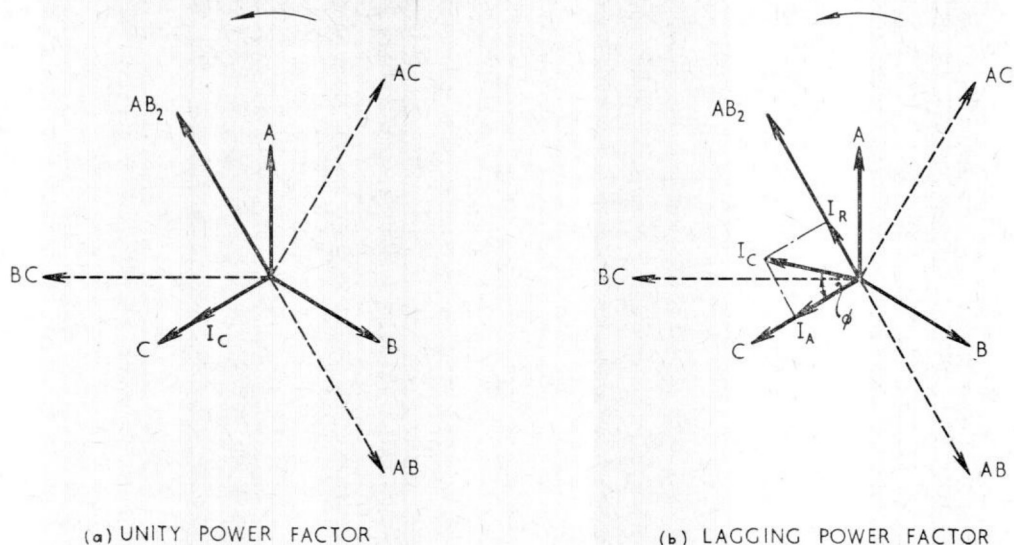
Magnetic amplifiers

22. There are two magnetic amplifiers, the main windings of which are supplied by the generator pilot exciter at a frequency of 1600 c/s. This supply is rectified first. The amplifiers are connected in cascade and coupled through an interstage filter circuit.

23. As has been stated before the two control windings of the first stage magnetic amplifier receive their signals from the voltage reference and reactive load sensing circuits. The second control winding is also supplied by the secondary winding of a stabilizing transformer. The primary winding of this transformer is supplied from the main pilot exciter, thus the transformer senses any change in main exciter field current and induces a secondary signal proportionate to the rate of this change. This signal is applied to the first stage magnetic amplifier second control winding and, as it is in the opposite sense to the signal effecting the change, damping is applied to the action of the magnetic amplifier.

24. One control winding of the second stage magnetic amplifier is supplied from the pilot exciter via a full wave bridge rectifier. The

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AT UNITY POWER FACTOR $\cos \phi = 1$ AND CURRENT I_C IS IN PHASE WITH PHASE VOLTAGE C. THERE BEING NO REACTIVE COMPONENT, NO POWER IS PRODUCED WITH TRANSFORMER SECONDARY VOLTAGE AB_2 .

AT A POWER FACTOR OF, SAY, .75 LAG CURRENT I_C HAS ACTIVE AND REACTIVE COMPONENTS I_A AND I_R . I_R IS IN PHASE WITH AB_2 WHEREAS I_A IS IN QUADRATURE. THUS ONLY THE REACTIVE COMPONENT OF I_C PRODUCES POWER WHICH CAN BE APPLIED TO THE MAGNETIC AMPLIFIER.

IT MAY BE ARGUED THAT, OWING TO THE ACTION OF THE CURRENT TRANSFORMER, I_C SHOULD BE SHOWN IN THE OPPOSITE DIRECTION I.E. 180° OUT OF PHASE. HOWEVER, THE CONDITIONS SHOWN CAN BE ARRANGED BY MERELY CHANGING OVER CONNECTIONS 'D' AND 'E,' IF NECESSARY.

Fig. 5. Vector diagrams showing real and reactive loads

other control winding is supplied with a signal from the first stage magnetic amplifier. This varies the impedance and the output owing to the gain of the two stages. The final output stage is connected across a bridge rectifier whose output provides the necessary excitation for the generator main exciter.

Frequency and load controller

25. When generators are operated in parallel it is necessary that they run at the same speed. Any tendency of a controller to try to increase its associated generator's speed (i.e. frequency) will result in the generator advancing its voltage vector, with respect to the others, and taking on more real load, and vice versa.

26. Since all the controllers cannot be set to control at exactly the same level it will be apparent that, by a similar reasoning to that applied to the reactive load sharing system, the real load sharing circuit must apply a correcting signal to the controller, propor-

tional to the generator's out-of-balance loading.

27. The load sharing system consists of a current transformer in one phase of each generator, which, in conjunction with a transformer-rectifier circuit, operates one control winding of a magnetic amplifier. The magnetic amplifier in turn controls a speed trim servo motor on the hydraulic drive governor.

28. The magnetic amplifier control windings are connected in an equalizing loop so that under steady-state no current flows through them, but under unbalanced conditions current in them is proportional to the out of balance.

29. The frequency control circuit supplies a second control winding on the magnetic-amplifier, so that, whilst both this and the real load sharing circuit ultimately affect the speed trim motor, they function independently of each other.

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Real load sharing circuit

30. A simplified diagram of the real load sharing circuit is shown in fig. 6. The potential divider P is connected via D.1 and D.2 to the secondary of the single-phase transformer, whose primary is between phase A and earth. The electrical centre of P is connected to the transformer centre tap through resistor R, and the current transformer C.T. which is used to sense any out of balance load on the line output from each generator, is connected across the resistor.

31. Ignoring any effect by the current transformer for each half-cycle, current may flow in one rectifier loop but will be blocked by the rectifier in the other loop. The voltages (say 10V) produced across P for each half-cycle will be equal and opposite, and the net voltage appearing across capacitor C will be zero for a complete cycle.

32. Considering now the effect of the current transformer, current flowing from it will produce a voltage across R (say 3V) which will add to the voltage for one half-cycle but subtract from the total voltage for the other half-cycle. For a complete cycle a d.c. voltage will appear across the capacitor equal to $\sqrt{2}x$ the difference between the

half-cycle voltages; i.e. $\sqrt{2}(13-7)=8.5V$. After smoothing, this d.c. signal is applied to the magnetic amplifier control windings which ultimately operate the two-phase speed trim motor on the hydraulic drive.

33. It will be seen from the diagram that the magnitude and direction of the current flowing through the magnetic amplifier control windings will be dependent upon the magnitude and direction of the real load current.

34. The control windings of the magnetic amplifiers for all four machines are connected by a loop (para. 28). Under balanced-load conditions the voltages across all the control windings balance out and no current flows through them. If one machine tends to take on real load, the voltage across its magnetic amplifier will increase proportionally and the voltage across the other magnetic amplifiers will be decreased by one-third of this value. Current will circulate round the loop through the magnetic amplifier control windings to correct the change.

35. As can be seen from the vector diagram (fig. 4), an increase in reactive load will not materially affect the output voltage of the single-phase transformer and hence will not operate the magnetic amplifier.

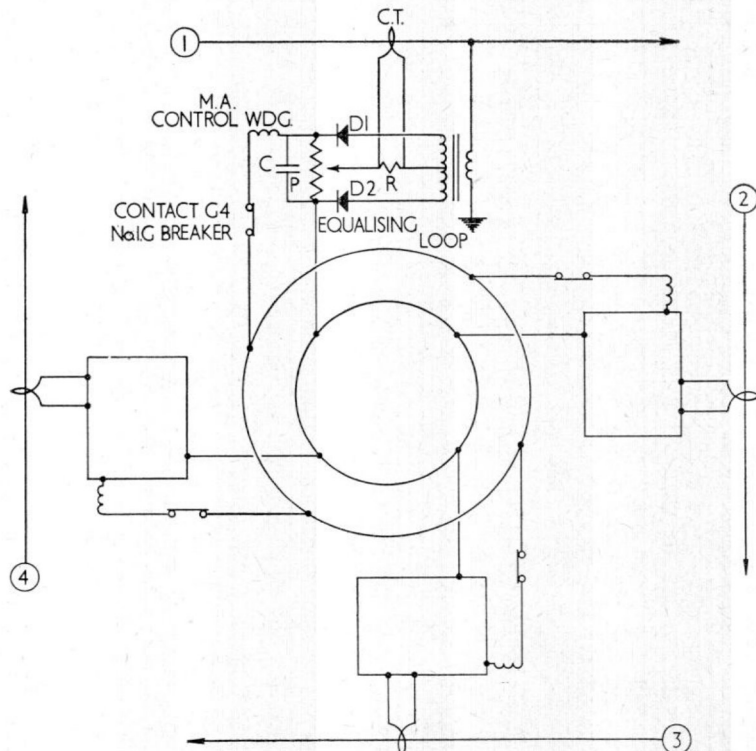


Fig. 6. Real load sharing circuit

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Operation of magnetic amplifier

36. The magnetic amplifier control winding is in two sections, each of which controls a transducer as shown in fig. 7. The transducers act as variable impedances sensitive to the magnitude and direction of current through the magnetic amplifier control winding. Thus, if at some instant the control signal makes T.1 a high impedance and T.2 a low impedance, the instantaneous current through the control phase will be in the direction shown by the arrows. If the control signal is reversed the relative values of impedance of T.1 and T.2 will also be reversed, current will flow in the opposite sense, and the governor control motor will change direction.

Frequency control circuit

37. The frequency discriminator is shown in fig. 8. The choke-capacitance circuits L.1, C.1 and L.2, C.2 are tuned for resonance at the upper and lower frequency limits of 450 and 350 c/s respectively.

38. Assuming similar response characteristics for each L.C. circuit, at 400 c/s the voltage across each choke and hence across

C.3 and C.4 will also be equal and opposite and no current will flow through the magnetic amplifier control winding. If the frequency tends towards the resonant frequency of L.1-C.1, the voltage across L.1 will be greater than that across L.2 and current will flow through the magnetic amplifier. Similarly, if the frequency tends towards the lower limit, current flow will be in the opposite direction.

Generator control panel

39. The control panel fulfils various fault detection and control functions: generator control, single or parallel operation; phase sequence protection; undervoltage protection below 167V; over voltage protection above 222V; under-speed protection in conjunction with a hydraulic under-speed switch; under-excitation with unbalance of reactive load exceeding 35 kVAR; over-excitation with unbalance of reactive load exceeding 25 kVAR; line/line and line/earth fault protection, fault current exceeding 40A; field flashing in conjunction with "re-set" push; anti-cycling during all fault conditions. Table 2 summarizes the function of components on the panel and fig. 11 shows a typical layout.

TABLE 2
Main components of generator control panel and their major functions

Component	Function
Master relay (M.R.)	Generator main control. Control of 'G' and 'S' breakers.
Exciter control relay (E.C.R.)	Exciter field breaking during fault conditions. Master relay control during fault conditions.
Lock-out relay (L.O.R.)	Prevents "cycling" of E.C.R. if reset button is pressed before a fault is cleared.
Paralleling relay (P.R.)	Closes 'S' breaker for parallel operation in conjunction with generator selector switch.
Over-voltage unit (O.V.U.)	Trips E.C.R. during overvoltage conditions in conjunction with mutual reactor and voltage sensing circuit.
Under-voltage and reverse phase sequence unit (U.V. & R.P.S.)	Detects correct phase sequence of generator conditions and trips E.C.R. when voltage falls below specified value.
Time delay units	Prevents "nuisance" tripping of E.C.R. during transients.
Differential protection unit (D.P.U.)	Trips E.C.R. when fault current exceeds specified value, in conjunction with current transformer network.
Mutual reactor	Detects excitation faults which may occur during parallel operation and load switching.

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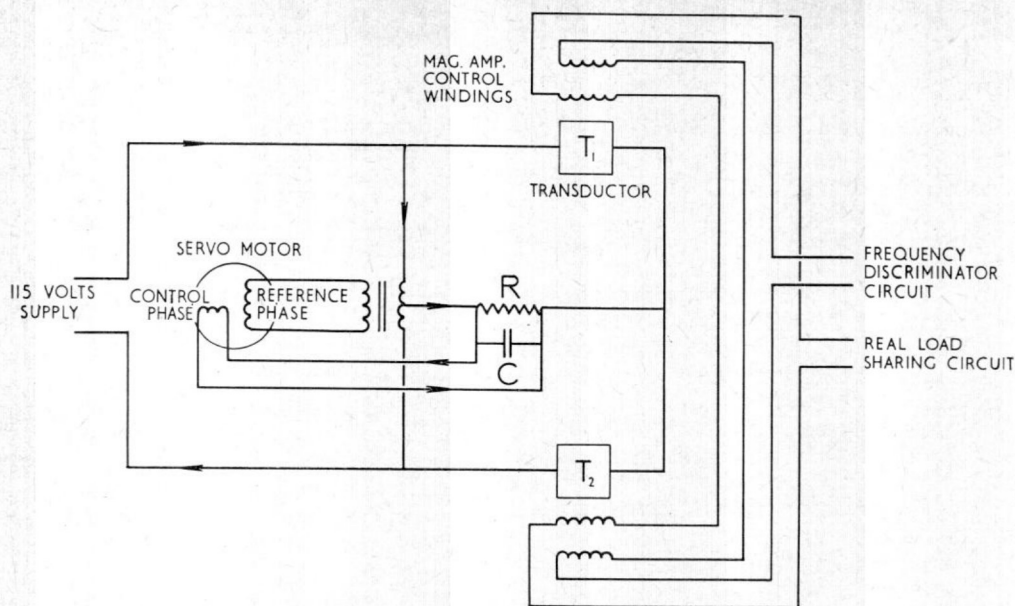


Fig. 7. Magnetic amplifier servo motor circuit

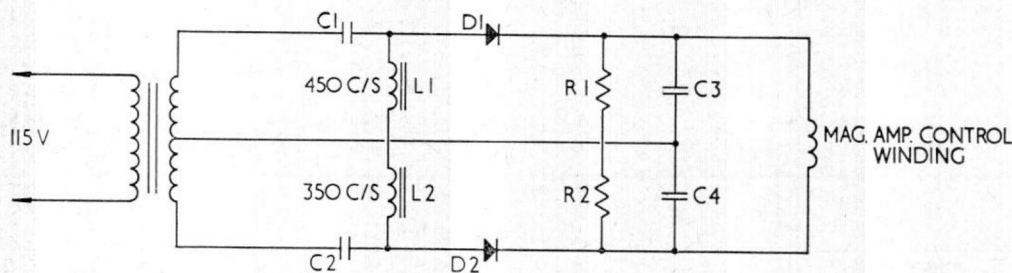


Fig. 8. Frequency discriminator circuit

Over voltage protection

40. When a generator is running singly the protection unit can be arranged to operate on the generated voltage. This is not possible however, when generators are running in parallel since an over-voltage in one of them will increase the busbar volts and affect all the protection units equally. The circuit must therefore be modified to select and close down the faulty generator. This is done by a looped current transformer/mutual reactor network and the overvoltage protection unit.

41. A typical arrangement of a sensing network for a two generator system is shown in fig. 9. If, under normal operating conditions each machine is supplying 125A reactive load and the current transformers (C.T.) ratios are 125/1, then 1A will circulate around the loop. Compared with the current transformer the mutual reactor primary windings are of

high impedance and therefore little or no current will flow in them.

42. Suppose No. 1 machine "overvolts" and takes on 188A, reactive load, then the current supplied by No. 2 machine will be reduced to 62A. It follows then that more current will be induced in the secondary of C.T.1 and less in the secondary of C.T.2. Since only one value of current may flow in the loop, balance is attained by diverting the "spill current" through the mutual reactor primaries. Therefore, both mutual reactors receive a signal according to the unbalance, each in the opposite sense, and pass it to the overvoltage and undervoltage circuits.

43. Assume that No. 1 generator overvolts to 220V and No. 2 generator remains at 200V then the busbar voltage will become the mean of these two voltages, 210V. The mutual

reactor associated with No. 1 generator sends a boost signal to its overvoltage unit such that it senses a greater voltage than the busbar voltage, i.e. approximately 220V. No. 1 generator is tripped off line via the E.C.R., the M/5 relay and the "G" magnetic switch. At the same time the mutual reactor associated with No. 2 generator sends a buck signal of the same magnitude to its overvoltage unit such that the latter senses a lower voltage than the busbar voltage, 200V. This, therefore, has no effect on the sound generator circuits.

44. With No. 1 generator tripped off line, No. 2 generator takes on all the load. No. 2 mutual reactor is short circuited via interlock contacts on No. 1 "G" magnetic switch to ensure that no false overvoltage or undervoltage signals are supplied direct to No. 2 generator circuits from the feeders, no boost or buck signals being required.

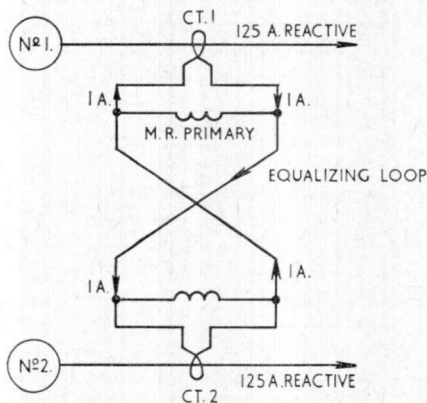
Over voltage unit

45. The unit consists of two step-down transformers connected in open delta, the primary windings of which are supplied from the generator busbars A.B.C., two (A and C) direct and one (B) through the secondary of the mutual reactor. The secondary winding output is fed through a full wave bridge rectifier to a time delay and temperature

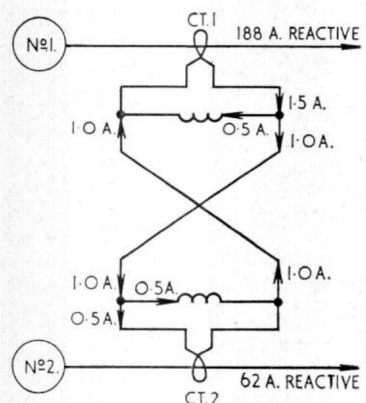
compensating network which controls the operation of three transistors, which in turn control a relay OVSR/2. Under normal conditions the circuit is non-conducting and therefore the relay contacts remain open. When an overvoltage condition occurs the circuit conducts, the relay coil becomes energized and the contacts close bringing the generator off line through the E.C.R.

Under voltage protection

46. The same current transformer/mutual reactor network is used in conjunction with an undervoltage protection unit. The action during an undervoltage fault is the opposite of the foregoing. Assume No. 1 generator undervolts to 175V and No. 2 generator remains at 200V. The busbar voltage becomes the mean of these two voltages, i.e. 188V. The mutual reactor associated with No. 1 generator sends a buck signal to the undervoltage signal circuit such that it senses a lower voltage than the busbar voltage, i.e. 175V and No. 1 generator is tripped off line via the E.C.R., the M/5 relay, and the "G" magnetic switch. At the same time the mutual reactor associated with No. 2 generator sends a boost signal to its undervoltage circuit such that it senses a higher voltage than the busbar voltage, i.e. 200V. This has no effect on the sound generator circuits.



BALANCED LOAD CONDITION



GENERATOR OVER EXCITED

Fig. 9. Current transformer loop circuit

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Under voltage and reverse phase sequence unit

47. The unit consists of two step-down transformers connected in open delta, the primary windings of which are supplied from the generator busbars A.B.C., two (A and C) direct and one (B) through the secondary of the mutual reactor. The secondary winding output is fed through a full wave bridge rectifier to a voltage and phase sensing circuit which controls the operation of a transistorized amplifier circuit. This in turn operates a relay UVRS/1. Under normal conditions the circuit is non-conducting and the relay contacts remain open. If an undervoltage or incorrect phase sequence condition occurs, the circuit conducts, the relay contacts close bringing the generator off the line through the E.C.R.

Time delay units

48. There are two time delay units fitted: the undervoltage time delay (U.V.T.D.) and the underspeed time delay (U.S.T.D.). The U.V.T.D. prevents "nuisance" tripping during transients caused by heavy load switching. The U.S.T.D. prevents tripping during momentary oil starvation in the C.S.D. caused by negative g conditions; oil starvation is unlikely as the C.S.D. is fitted with an aerobatic oil tank, and the time delay unit, although fitted, is usually short circuited. The time delay is long enough to prevent nuisance tripping but short enough to prevent a generator, which has lost its excitation, from remaining on line long enough to overheat the other generator.

Differential protection circuit

49. The circuit detects line-to-line and line-to-earth faults in the generator and on the feeders up to the 'G' breakers, and provides differential current protection of the generator output when the fault exceeds a predetermined value. The circuit operates in conjunction with a current transformer network on a "Merz-Price" system.

50. If the C.T. network becomes unbalanced owing to a line-to-line or line-to-earth fault a signal is sensed by the differential protection unit (D.P.U.). When the fault current exceeds, say, 42A a relay in the D.P.U. operates causing the E.C.R. to trip, hence the generator is brought off the line. The supply to the D.P.U. is, of course, 3-phase but the unit still operates satisfactorily if the supply is effectively single phased owing to a line-to-line fault.

51. A time delay circuit is incorporated in the D.P.U. to avoid "nuisance" tripping when momentary high surge currents are sensed during synchronization of two generators.

Generator circuit breaker ('G' breaker)

52. This is a mechanically latched-in type magnetic switch. It has close and trip coils which are energized only momentarily during operation of the switch. In addition to the main contacts five auxiliary contacts are provided for use in the external circuit.

53. The 'G' breaker connects the generator to the load busbars.

Synchronizing circuit breakers ('S' breaker)

54. The 'S' breaker is identical in construction and operation to the 'G' breaker and is used to connect the generator to the synchronizing busbars.

Auxiliary, ground supply and paralleling circuit breakers

55. These three units are identical in construction to the 'G' and 'S' breakers. Their particular applications in the circuit are described later under "Operation."

Voltage pick-up box

56. The voltage pick-up box prevents connection of the G.P.U. or A.A.P.U. to the synchronizing busbars when the main aircraft generators are on line. Alternatively if either the G.P.U. or A.A.P.U. is on line the unit prevents the other two supply sources being connected to the synchronizing busbars.

57. The box contains two transformers whose primary windings are connected respectively to phase A and phase B of the synchronizing busbars. The stepped down output of the transformers is rectified and applied to the coils of two relays. The relays each have three contacts, two normally closed, and one normally open. The normally closed contacts are connected to the G.P.U. and A.A.P.U. contactors and thus if any generator is on line the potential applied to the transformers opens the contacts and isolates the ground or auxiliary supplies. Alternatively if all generators are off the line no potential is applied to the transformers, the contacts remain closed and either the ground or auxiliary supplies may be switched on line.

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Transformer rectifier unit

58. The T.R.U. provides the d.c. power required to operate and control the aircraft services. Two units are incorporated each having an input of 200 volts, 400 c/s.3 phase obtained from the main busbars. This is transformed and rectified to provide a nominal 28 volts d.c. unregulated output.

59. Provision is made whereby one unit can be fed, if necessary, by an alternative supply from a ram air turbine alternator. Thus, should a main generating system failure occur owing to engine flame out, the essential d.c. loads can still be supplied from this alternative supply.

Engineers control panel

60. This contains all the switches, indicators, meters etc. necessary for the control of the main operating system and standby electrical supplies.

OPERATION

61. Fig. 11 is a schematic diagram showing the port channels of a typical four channel system and its associated control gear. This diagram should be referred to when reading the following description.

62. Before the aircraft engines can be started or any supplies switched on, the battery isolating switch must be closed. If this is not done damage to the system may result.

63. If 28 volts d.c. is now applied to the generator control panel via circuit breaker 1V1 and the engineers generator control switches are in the OFF position, any 'G' breakers which may be closed are tripped, and the 'S' breakers are closed. Thus all 'G' breakers are open, all 'S' breakers are closed, and the ground power unit may be plugged in and switched to the synchronizing busbars for engine starting.

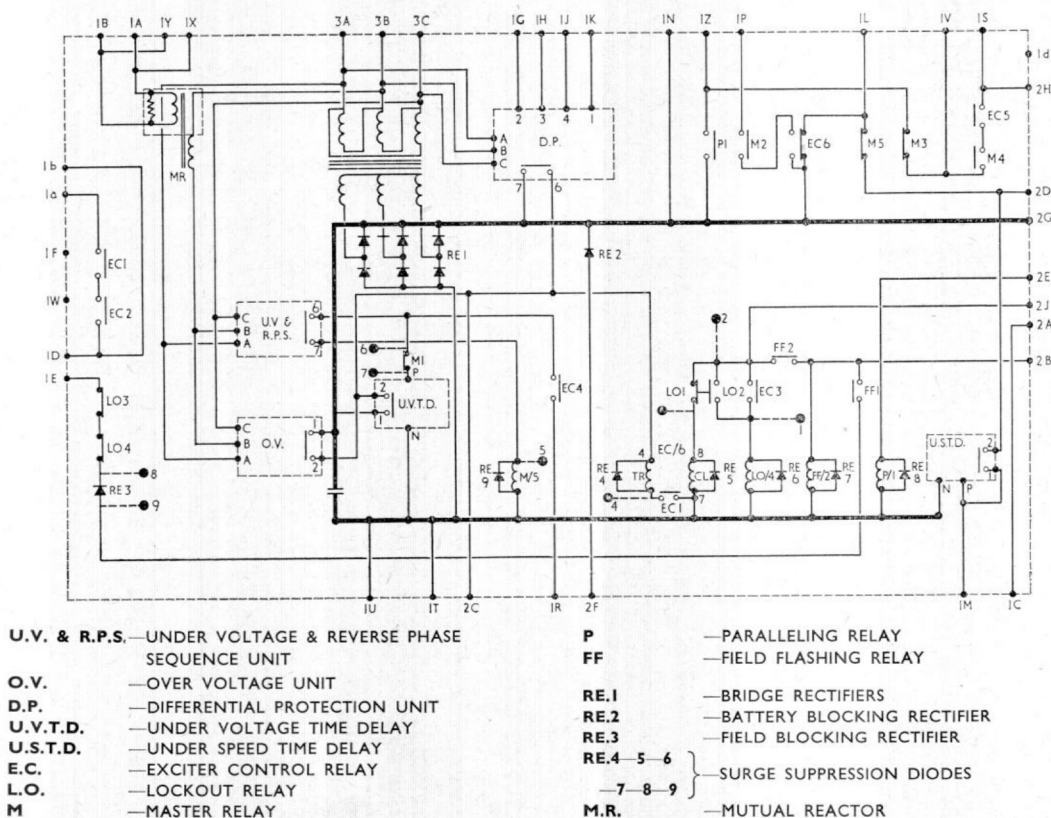


Fig. 10. Typical layout of generator control panel

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Normal starting

64. Note that the exciter control relay is normally in the 'set' position and contact EC4 is closed unless some fault occurred on the system previously, and the relay has not been reset.

65. The generator control switches are placed in the ON position and each engine is started in turn. On each channel, when the voltage reaches, say, 178V the U.V. & R.P.S. unit contacts close; then, when the frequency reaches, approximately 360 c/s, the C.S.D. underspeed switch (an oil pressure operated switch) closes.

66. Thus a circuit is completed to the master relay coil M/5 which becomes energized. Contacts M.5 and M.3 open breaking the circuit to the trip coil of the 'G' breaker and to the close coil of the 'S' breaker via auxiliary contacts on the 'G' breaker. Contacts M2 close and, via auxiliary contacts on the 'S' breaker, complete the circuit to the close coil on the 'G' breaker. Contacts M1 open-circuit the under voltage time delay unit.

67. The 'G' breaker is now closed and the 'S' breaker is now open; thus the generator is connected to its main busbars and the loads associated with the generator are transferred from the synchronizing bars to the machine.

68. The generator control switch may be left in the OFF position for testing, if desired, and transfer of the loads will then occur when the switch is placed in the ON position. There is a time delay of about 0.1 sec. during this change-over. When all engines are running, each generator is supplying its own loads individually and the G.P.U. can be switched off the synchronizing bars preparatory to paralleling the generators.

Paralleling

69. There should now be no voltage on the synchronizing busbars and the G.P.U. and A.A.P.U. contactors should be in the tripped position. Thus 28 volts d.c. is supplied from feeder IP8 through auxiliary contacts on the G.P.U. and A.A.P.U. contactors to one side of each of the port and starboard synchronizing light and push switches.

70. Consider the two port side channels only as shown in fig. 11. The synchronizing light is connected across phase 'B' of the

synchronizing bars and phase 'B' of each generator via a synchronizing selector switch on the engineers control panel. The voltage across this lamp depends upon the phase difference, frequency and voltage between the synchronizing busbars and the generator, and therefore when the two are of the same voltage and frequency and are in phase the voltage across the lamp is zero.

71. The first generator to be connected, say No. 1, is selected on the engineers selector switch; the synchronizing push switch is depressed momentarily and the coil of relay P/1 is energized via terminal 2E on the control panel. Contacts P1 close, energizing the close coil of the 'S' breaker thus connecting the generator to the synchronizing busbars.

72. If generator No. 2 is now selected the synchronizing light glows bright and dark at a rate dependent upon the phase relationship between the incoming machine and the busbars. If the lamp remains bright for a lengthy period, indicating that the generator and busbar are at the same frequency but 180° out of phase, a resistive load should be switched on. This will upset the system sufficiently to cause the necessary frequency difference. The synchronizing push switch is operated momentarily during a dark period and the second generator is paralleled by the closing of its associated paralleling relay contacts and 'S' breaker. This same procedure is followed for each starboard generator.

73. So that the port and starboard synchronizing busbars may be connected together a further paralleling circuit breaker is incorporated in the system (see fig. 1). Before this is done, however, it must be ensured that the outputs of any generator connected to these busbars are in phase and their voltages approximately equal. The values of the outputs can be compared by reference to the two sets of meters, and the phase relationship can be checked by pressing the busbar paralleling synchronizing light push switch. When this is operated the light is connected across the two sets of busbars and by the same method used for paralleling the generators it can be deduced when the outputs of both sides are the same. At this point the Busbar Paralleling Switch should be selected from NORMAL to PARALLEL. This supplies 28 volts d.c. to three relays, one of which operates the close coil of the paralleling breaker. The other two complete the load

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sharing loops between port and starboard channels.

74. To separate the busbars it is only necessary to select back to NORMAL on the busbar paralleling switch.

Shutting down

75. As each engine shuts down, its generator is automatically taken off load and the only action necessary by the operator is to open the battery isolating switch when all engines have stopped.

76. Considering one channel only, as the engine speed falls the C.S.D. underspeed switch drops out and the master relay is de-energized; contacts M5 close and trip the 'G' breaker. The 'S' breaker remains closed so that this particular generator's loads are now fed from the synchronizing busbars by the other generator(s).

77. This sequence of operation will also occur if one engine fails or its speed falls below the normal limit. If, however, the generator selector switch is left in the ON position the generator will automatically take over its load again from the synchronizing busbars (as with normal starting) when the fault is cleared. The generator must, of course, be re-synchronized on to the busbars.

78. If more than one engine is closed down so that the total load on the synchronizing bars is approaching the maximum capacity of the remaining generators, the A.A.P.U. should be started. The generators still running may be isolated by moving their control switches from ON to ISOLATE; this trips the appropriate 'S' breakers and allows each generator to supply its load individually.

79. As there is now no a.c. on the synchronizing busbars the contacts in the voltage pick-up boxes close. Closure of the starboard pick-up box contacts connects the close coil of the A.A.P.U. contactor to the normally open contacts of a relay. The operating coil of this relay is supplied from a frequency pick-up box, which is fed from the A.A.P.U. generator busbars. The frequency pick-up unit contacts close only when the frequency of the A.A.P.U. generator is within prescribed limits and under these conditions will supply 28 volts d.c. to the

relay coil. The relay contacts close and connect 28 volts d.c. to the close coil of the A.A.P.U. contacts, thus connecting the A.A.P.U. to the starboard synchronizing busbars. A further set of normally closed contacts on the relay feeds 28 volts d.c. to the trip coil of the A.A.P.U. contactor when the A.A.P.U. frequency rises above or falls below the specified value or when the A.A.P.U. is shut down.

80. A set of auxiliary contacts on the A.A.P.U. contactor open and break the supply to the starboard synchronizing push switch thus preventing connection of No. 3 and No. 4 generators to the synchronizing busbars.

81. If it is required to connect the A.A.P.U. to the port synchronizing busbars the busbar paralleling switch should be operated to PARALLEL.

Operation under fault conditions

82. The fault-detecting circuits have already been described and their operation in conjunction with the various control relays will now be considered.

Line-to-line and line-to-earth faults

83. A line or earth fault in one of the phases energizes a relay in the differential protection unit (D.P.U.) closing the contacts and thus energizing the trip coil of the E.C.R. Contacts EC.2 open breaking the exciter field and EC.6 closes tripping the 'G' breaker. EC.4 opens de-energizing the master relay and contact M.4 opens preventing tripping of the 'S' breaker. Auxiliary contacts on the tripped 'G' breaker complete the supply to the close coil of the 'S' breaker. The 'G' breaker indicator light now shows a fault and the generator control switch should be moved to the OFF position for resetting.

Over voltage fault

84. The over voltage unit (O.V.U.) relay coil is energized and contacts OVSR/2 close; this energizes the trip coil of the E.C.R. bringing the generator off line as in para. 83.

Under voltage fault

85. The under voltage and reverse phase sequence unit (U.V. & R.P.S.) contacts close and shortly afterwards so do those of the time delay unit (U.V.T.D.). This de-energizes the master relay coil and trips the E.C.R.

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Incorrect phase sequence

86. Protection against incorrect phase sequence is provided by the under voltage unit which has sensing circuits that fail to function if such a fault is apparent, and the generator fails to come on to line when starting.

Resetting

87. When the generator control switch is moved to the OFF position the 28 volts d.c. supply to the M.R. coil is broken and contact M.5 closes; the supply is applied to M.5 directly, instead of via the C.S.D. underspeed switch, and the 'G' breaker trips. If the switch is now moved to RESET the supply energizes the field flashing relay FF/2 closing contacts FF.1, which supply field flashing through contacts LO.4 and LO.3, and FF.2 which energize the close (CL.) coil of the E.C.R. via lock-out relay contacts LO.1.

88. Energization of the E.C.R. close coil closes contacts EC.1, EC.2, EC.3, EC.4 and

EC.5 and opens EC.6. Closure of EC.3 energizes lock-out relay coil LOR/4; contact LO.4 and LO.3 open to break the field flashing circuit.

89. If the fault on the system persists the E.C.R. trips again, but the circuit to its set coil is broken by open contacts LO.1, and the L.O. relay is still energized through closed contacts LO.2 so that further attempts to reset the E.C.R. cannot be made until the control switch is turned from RESET to OFF and back to RESET again.

90. If the fault clears and the control switch is turned to OFF the field flashing and lock-out relays are de-energized, contacts FF.1, FF.2 and LO.2 open and contacts LO.1, LO.3 and LO.4 close. The control switch may now be returned to the ON position so that the master relay is energized, contacts M.4 and M.2 close tripping the 'S' breaker and closing the 'G' breaker. The generators loads are transferred back from the synchronizing busbars and the generator must be re-paralleled.

TABLE 3

Summary of operational sequence of control and protective devices

Normal operation

STARTING

Battery isolating switch closed.

Ground power supply connected.

28 volts d.c. applied to control panels.

 'G' breakers trip.

 'S' breakers close.

G.P.U. switched to synchronizing busbars.

Generator control switches ON.

Engines started in turn.

 'G' breakers close.

 'S' breakers trip.

 Load transferred to generator as each engine comes up to speed.

G.P.U. Disconnected from synchronizing busbars and plug removed.
 All loads supplied individually by generators.

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Table 3—continued

PARALLELING

Check for no voltage on synchronizing busbars.

Synchronizing selector switch set to BUSBAR, observe voltmeter.

Synchronizing selector switch set to No. 1.

Synchronizing push switch pressed momentarily.

No. 1. 'S' breaker closes.

Selector switch set to No. 2.

Synchronizing lamp glows and extinguishes periodically.

Synchronizing push pressed momentarily during dark period.

No. 2. 'S' breaker closes.

Repeat for generator No. 3 and No. 4.

CLOSING DOWN A GENERATOR

Generator control switch to OFF.

'G' breaker opens.

'S' breaker remains closed.

Generator's loads supplied from synchronizing busbars.

RUNNING A GENERATOR SINGLY

Generator control switch to ISOLATE.

'S' breaker opens.

'G' breaker remains closed.

Generator supplies its own loads only.

CLOSING DOWN SYSTEM

Engines shut off.

'G' breakers open as speed of each engine falls.

'S' breakers remain closed.

Battery isolating switch opened.

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Table 3—continued

Operation under fault conditions

Fault protection circuit trips E.C.R. breaking exciter field circuit and tripping 'G' breaker.

Generator control switch OFF.

Synchronizing selector switch set to faulty generator.

Control switch put to RESET momentarily then put back to OFF.

Exciter field flashed.

Generator output shown on voltmeter.

Control switch put to ON.

If fault has cleared:

'S' breaker opens.

'G' breaker closes.

Re-synchronize generator.

If fault persists:

'S' breaker opens.

'G' breaker closes then re-opens.

'S' breaker recloses.

Re-setting attempted again and if fault has still not cleared generator left closed down.

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