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SECTION 5

MAGNET POWER SUPPLY

5.1. Introduction

The Nimrod magnet power supply plant comprises two 60 MW motor-alternator-flywheel sets which power the magnet via a mercury arc convertor installation of similar rating supplied from the alternators through phase splitting transformers giving 24 phase operation.

This report covers the period up to 31st December, 1962 and does not refer to details of design. These design aspects, with indications of the historical reasons for adopting the final design chosen are given in the following three papers published in Proc. I.E.E., Vol. 110, No. 3, March 1963.

Paper 1 General
Paper 2 Rotating machines
Paper 3 Mercury arc convertors

} All three papers have the main title:- 'Magnet Power Supply for the 7 GeV Proton Synchrotron Nimrod'.

The main power circuit is shown in Fig. 5.1(i).

The first 60 MVA motor-alternator-flywheel set was commissioned for open circuit running conditions during the last two months of 1961 and it was then used to carry out preliminary 'on load' commissioning using each half of the convertor installation in turn, with four of the magnet octants as load, during the first quarter of 1962. From April 1962 until the end of August 1962 one motor-alternator-flywheel set and one half of the convertor plant was used to pulse the magnet (four octants at any one time) in order that the magnetic survey could be carried out.

The second alternator was delivered at the beginning of September 1962. Installation was completed in about six weeks and the second motor alternator flywheel set ran up to speed for the first time on 21st October, 1962.

After further commissioning, and also re-alignment of the first motor-alternator-flywheel set to the recently installed second set, the final fitted bolts and bushes were installed in the flywheel to flywheel coupling and on 21st November, 1962 the complete rotary plant on its common 100 ft long solidly connected shaft system ran up to speed for the first time. On load testing and final commissioning could not be carried out immediately since the magnet was not available. Detailed final commissioning of power supplies was planned for January 1963 using four magnet octants and February 1963 using the whole of the magnet. This period will be covered in the second part of this report.

However, early experience on the plant has shown that when the plant is operating at its full thermal rating, pulse repetition rates will be at least 10% higher than those quoted in the design stages.

The following general operational information may be of interest:

Total running hours from October 1961-31st December, 1962 ..	1,600
Total pulsing hours	700
Pulsing hours at standard pulse and/or standard pulse +15%	460

Running hours during magnetic survey period	750
Pulsing hours during magnetic survey period .. .. .. (300 of these hours at standard pulse + 15%)	400
Approximate number of pulses during magnetic survey ..	132,000
Approximate number of pulses October 1961-31st December, 1962 ..	557,657

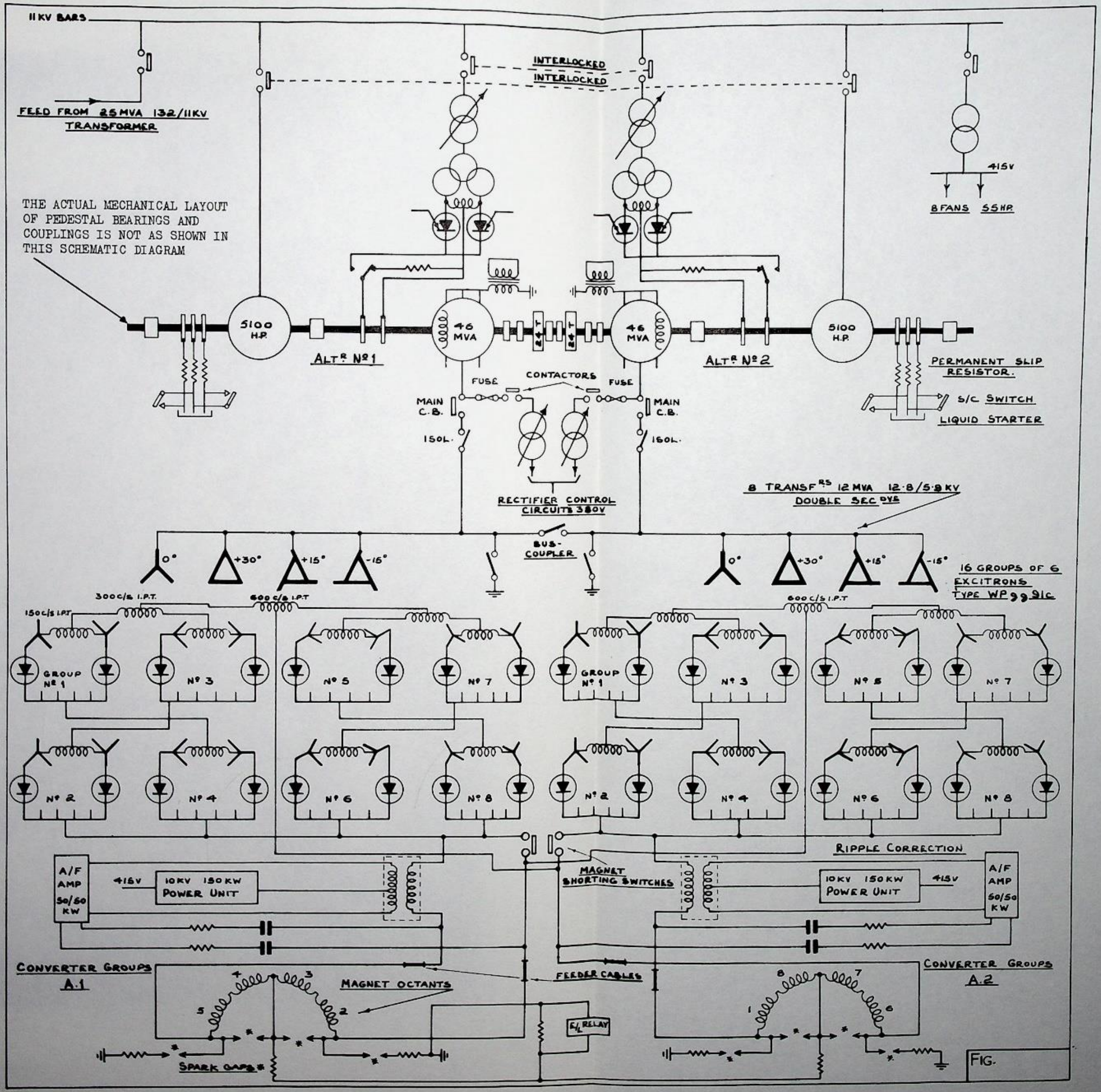
During the period September-December 1962 the power plant erection programme had to be phased so that two separate one week duration pulsing periods were available for 'magnet shakedown' purposes. During these 'shakedown' periods the opportunity was also taken to carry out such work as the determination of a variety of maximum repetition rates and ripple content of the magnet voltage. Stress values experienced on the outer vacuum vessel were also measured for the Design Group.

The two shakedown periods were 7th October-12 October, 1962 and 25th November-30th November, 1962. During these two periods the number of magnet pulses produced was about 132,000 and the period 7th October-12th October proved to be the most intensive period of pulsing to have been carried out so far. The statistics applicable to this period are as follows:

Total running hours	69½
Total pulsing hours	58 (50½ of these at standard pulse + 15%)
Total number of pulses ..	74,785 (72,270 of these at standard pulse + 15%)

Power Supplies personnel have been responsible for the operation of the plant and have also worked as a team with the staff of the power supply plant contractors during installation and subsequent early commissioning.

In the following report items of interest relative to the rotary plant and the convertor plant have been mentioned. An effort has been made to avoid repetition of the subject matter contained in the three I.E.E. papers referred to on the previous page. Nevertheless for the sake of completeness a little overlapping has occurred.



THE ACTUAL MECHANICAL LAYOUT OF PEDESTAL BEARINGS AND COUPLINGS IS NOT AS SHOWN IN THIS SCHEMATIC DIAGRAM

Fig. 5. 1(i) Nimrod Power Plant Schematic Diagram.

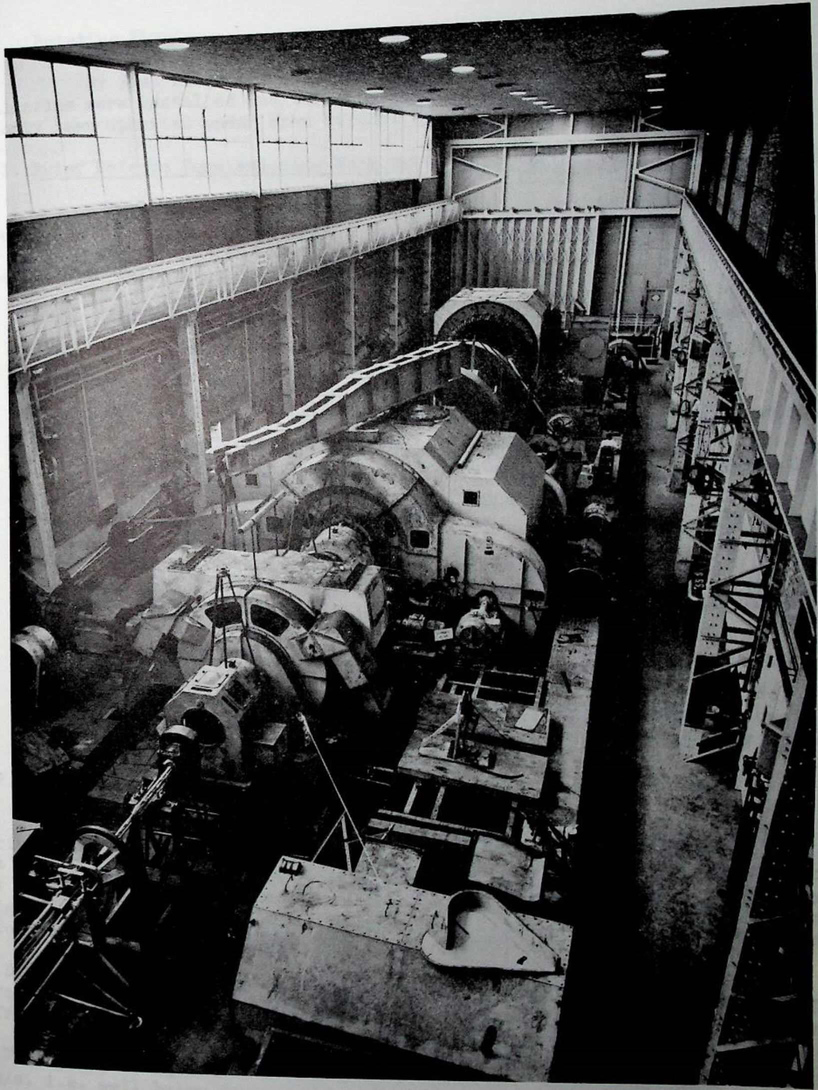


Fig. 5.1 (ii) View of Motor-Alternator-Flywheel Set during final stages of Erection. (Some of the ultrasonic equipment used for checks on the rotor forgings can be seen in the left foreground)

5.2. Rotating Plant

By 31st December, 1962 the whole of the rotating plant and its associated auxiliaries were installed and commissioned, although No. 2 motor-alternator set had only been operated under open circuit conditions.

5.2.1. Brief Note on Commissioning Work Outstanding after 31st December, 1962

There remained, however, a considerable volume of outstanding work to be completed during the first half of 1963. This will be detailed in the second part of this report but for completeness, a brief mention of a few outstanding items still to be carried out is given below:

(i) Final balancing of the twin motor-alternator-flywheel set.

(ii) Re-alignment of the set.

(iii) The grouting in of the complete set.

(iv) Determination of the behaviour of No. 2 alternator A.V.R. system.

(v) Shaft torsional oscillation frequencies with differing plant arrangements (e.g., one motor-alternator set with two flywheels) to be determined.

(vi) Investigation into the behaviour of the complete set feeding the whole of the convertor plant and a complete magnet (eight octants will not be available until February 1963).

(vii) Extensive flaw monitoring of the plant forgings from the bore by specially developed ultrasonic test equipment.

(viii) Installation of an emergency lubrication system for the set.

(ix) Examination of one of the alternator rotors (the original No. 2 rotor). This rotor had not been accepted on an ex-works basis, but had been virtually on loan to allow the magnet survey to be carried out.

5.2.2. The Foundation Block and its Behaviour

Since the rotating plant is rapidly changing from generating to motoring modes of operation with resultant torque reversals, it was decided to mount this plant on a reinforced and post-stressed concrete block. The rotary plant and its foundation block weigh about 1,600 tons and this weight is supported on eighty spring units and twelve viscous damper units. A simplified sketch of the foundation block is shown in Fig. 5.2.2(i).

Distribution of mass and stiffness in the block ensured that the range of natural frequencies of the foundation block is about 21-24 c/s, i.e. well above the frequency of the highest set running speed which is about 16.5 c/s.

The natural frequencies of the spring system are within the range 3 c/s to 4.5 c/s, i.e. well below frequencies associated with machine running speeds but sufficiently above the 2 c/s frequency applicable to the highest pulse repetition rate.

Post tensioning of the foundation block in the longitudinal direction (installed to give a compressive stress of 200 lb/in^2 in the concrete) was adopted as an insurance against the possibility of development of transverse cracks in the suspended block since such cracks would tend to lower the block natural frequency and bring it near to machine running frequencies.

The dampers serve to limit block movement during short circuit conditions and they also limit any effects of resonance while the machine is being run up or shut down.

Foundation settlement measurement equipment is installed on the block. Twelve measuring devices known as slave units are installed on the block (five along each side and one at each end). Their respective positions with respect to a master unit mounted at one end of the block can be determined to an accuracy of better than ± 0.001 in.

Having obtained a set of readings it is necessary to apply a suitable method of analysis to these to eliminate:-

(i) the effect of compression of the supporting springs due to particular loading conditions and

(ii) tilting of the whole block due to non-uniform loading conditions.

Having eliminated these effects it is possible to see just how much the block profile changes.

Effect of Block Profile Changes on Alignment

Any change in the block profile obviously means an alignment change since the machine bearing pedestals are mounted along the centre line of the foundation block.

Fig. 5.2.2(ii) shows that in as little as twenty-four hours of operation at full thermal loading the block profile can develop an increased 'hogging' characteristic of as much as 0.06 in peak to peak along its entire length. It is expected that this hogging effect can develop to a figure of 0.2 in from the original cold profile condition at which plant alignment takes place.

Reference again to Fig. 5.2.2(ii) shows that over the central 30 ft section of the block where six very critically aligned large bearing pedestals are located, although the two curves show a total peak change of 0.025 in, the relative variation between pedestals over this range is only 0.006 in.

Nevertheless it has proved necessary to misalign the machines when cold in order to achieve improved running conditions. Fig. 5.2.2(iii) shows the results achieved on No.1 motor to alternator coupling on the first occasion that this was attempted. Final alignment is always checked by strain gauge methods. When No. 1 motor to alternator coupling was first made off, the misalignment stress measured at 90° intervals as the coupling was rotated was recorded (Column A in the table). After the machine had been running, a set of readings was taken with the machine hot (Column B in the table). This shows an increase in stress of more than 1000 lb/in². As a result of these observations the drive motor was re-aligned to the alternator during a convenient shut down period but care was taken to ensure that in aligning the two couplings angularly, a gap of 0.002 in was introduced at the bottom. The corresponding strain gauge figures immediately after doing this are recorded in Column C. Note the appreciable tensile stress

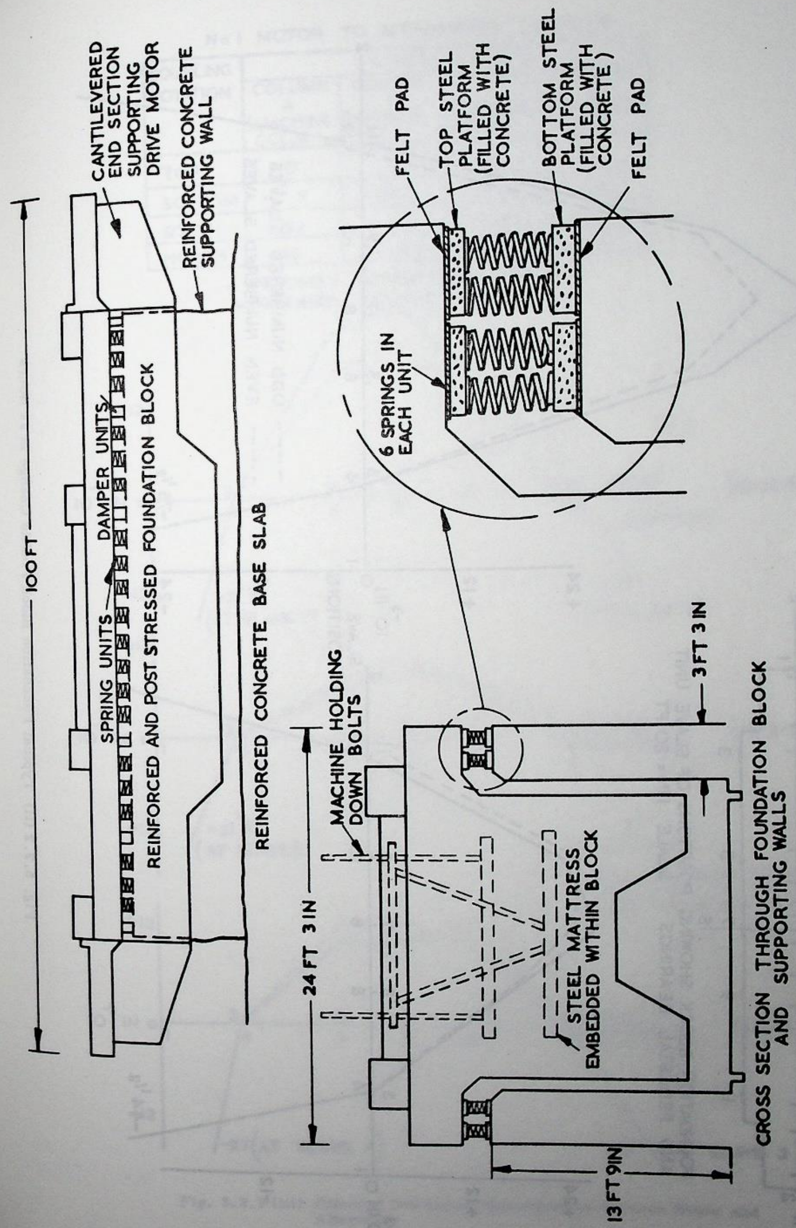


Fig. 5.2.2 (i) Simplified Sketch of Rotating Plant Foundation Arrangement

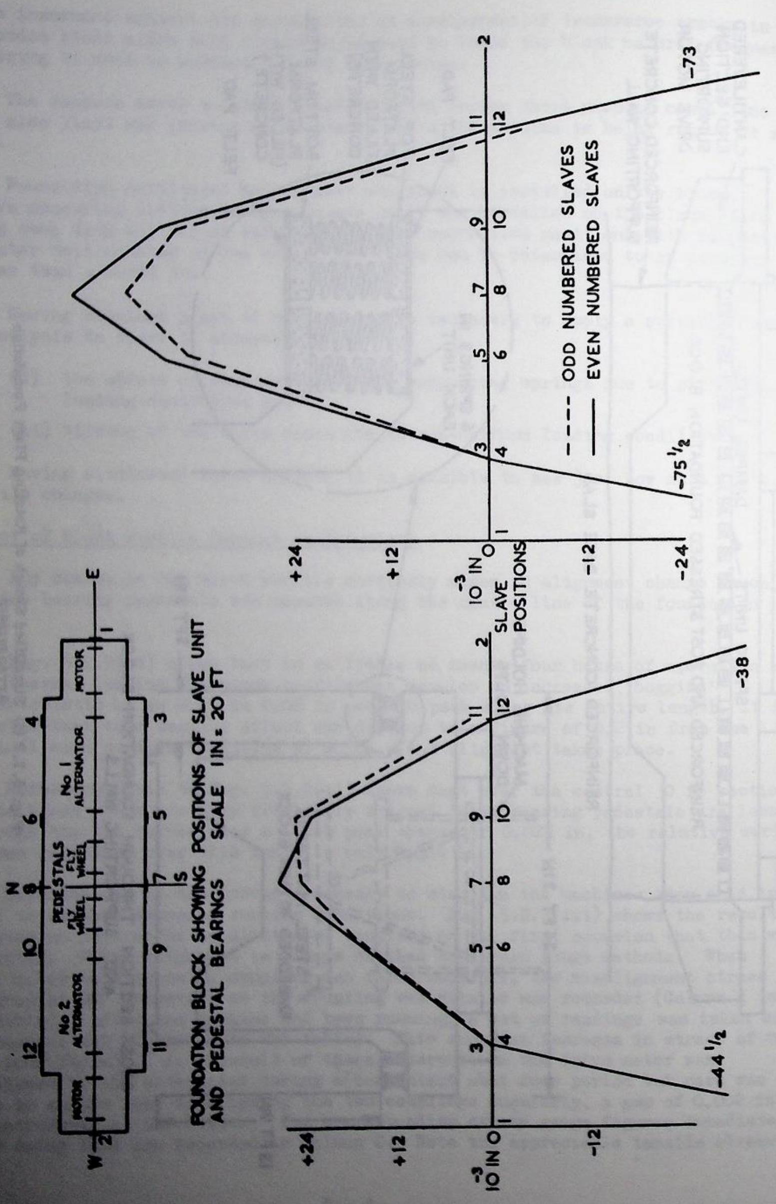


Fig. 5.2.2 (ii) Typical Foundation Block Profile Change in 24 Hours

No 1 MOTOR TO ALTERNATOR COUPLING

COUPLING ROTATION	STRESS (LB/IN²)			
	COLUMN A (MACHINE COLD)	COLUMN B (MACHINE HOT)	COLUMN C (MACHINE COLD)	COLUMN D (MACHINE HOT)
TOP	0	0	0	0
BOTTOM	−7·5	−1035	+390	−15
SOUTH	+22	−375	+240	−15
NORTH	−15	−480	+45	+7·5

− INDICATES COMPRESSIVE STRESS
+ INDICATES TENSILE STRESS

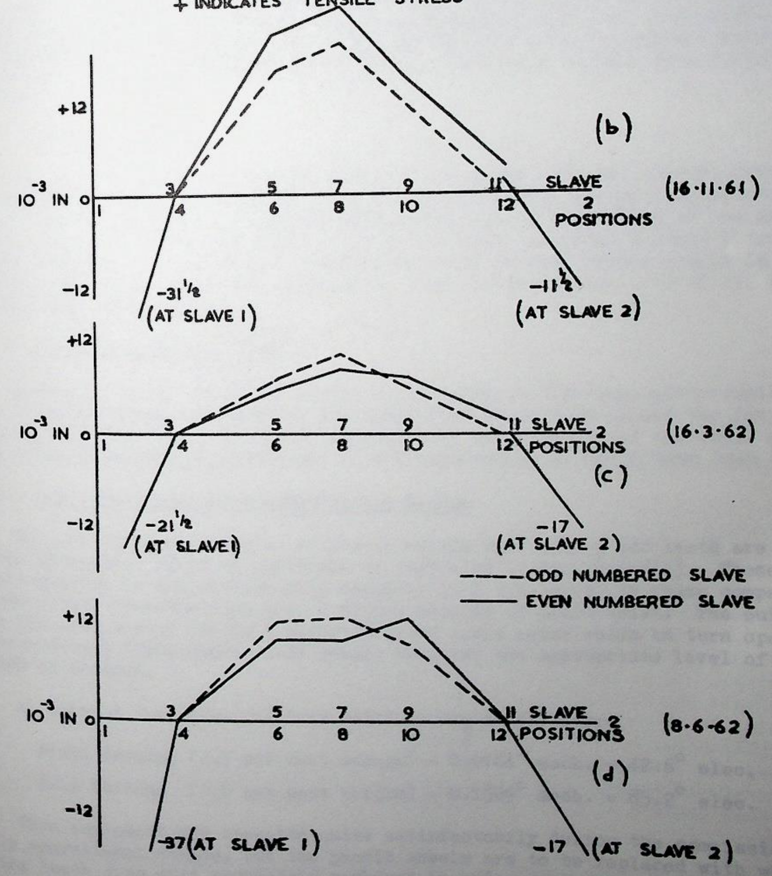


Fig. 5.2.2 (iii) Effect of Deliberate Misalignment between Motor and Alternator

introduced at the bottom of the coupling, and the appreciable degree of deliberate misalignment compared with Column A figures. Column D shows the result of an alignment check at the motor to alternator coupling with the machine hot, the indication being that the movement of the foundation block towards an increasingly hogging profile (see graphs (c) & (d) in Fig. 5.2.2(iii), had cancelled out the bending stress initially deliberately introduced to give negligible misalignment stresses with the machine hot (a reduction from 1035 lb/in^2 down to 15 lb/in^2). The corresponding foundation block profiles corresponding to the readings tabulated at B, C & D are shown in graphs (b), (c) and (d) respectively.

5.2.3. Bearing Pedestal Vibration Levels

No. 1 motor drive and bearing pedestal developed about 0.003 in peak to peak vibration before the re-alignment to which reference has just been made. This was reduced after re-alignment to 0.001 in and so far it has proved practicable to keep vibration levels down at all bearing pedestals to less than 0.001 in peak to peak.

5.2.4. Machine Bearings

Bearing temperatures are indicated in the power supplies control room and the white metal temperature does not normally exceed 65°C. During commissioning and early running one bearing has been changed because of blistering of the white metal. The bonding of the white metal to the shell has been checked ultrasonically on all bearings. Differential pressure switches across orifice plates in the oil supply pipes to the bearings, operate to trip the set if the rate of oil flow to any bearing falls too much.

5.2.5. Shaft Eccentricity Levels

Eccentricity of the shaft system is measured in the immediate vicinity of each alternator bearing pedestal and these four eccentricy values are fed to a four channel recorder. Levels of eccentricity are normally of the order of 0.001 in peak value although, on occasions, levels approaching 0.003 in have been recorded.

5.2.6. Shaft Torsional Stress Monitoring System

On each alternator a pair of phonic wheels each having 540 teeth are mounted on the alternator shaft at positions as indicated in Fig. 5.2.6(i). These phonic wheels, in conjunction with magnetic pick ups, give, by phase comparison of the output from the pick ups, a direct measure of shaft twist. The output from the pick ups is fed to a transistorised phase meter which in turn operates transistorised alarm and/or trip relays whenever the appropriate level of torsional stress is reached.

At present the alarm and trip settings are as follows:-

Alarm Setting (1.5 per unit torque) = 0.0784° mech. = 42.6° elec.

Trip Setting (3.0 per unit torque) = 0.1569° mech. = 85.2° elec.

This equipment has operated quite satisfactorily during the commissioning and early operational stages, but the phonic wheels are to be replaced with wheels having teeth even more accurately machined in order to reduce the noise level further.

Fig. 5.2.6(i) shows not only the location of the phonic wheels but illustrates generally the monitoring of the shaft system. Fig. 5.2.6(ii) shows the behaviour of the shaft system at Stations A & B (see position 4 in Fig.5.2.6(i)) monitored by the strain gauges installed at these locations. The flat top timer has incorporated in it a 1000 c/s crystal controlled oscillator, so that flat top times can be adjusted to be an odd number of half cycles of shaft torsional frequency to prevent possible build up of excessive shaft torsional stress.

5.2.7. Starting and Pre-heating of the Set

The complete set is equipped with four oil jacking pumps so that oil at 1000 lb/in^2 is introduced at the bottom of each bearing so that the shafts are lifted on a film of oil to ease starting conditions and to help avoid possible bearing damage. The selected main oil flood pump, capable of delivering 325 gal/min at a discharge pressure of 50 lb/in^2 has to be started before switching on the jacking oil system. After starting up the main flood pump and the jacking pumps the barring gear can be engaged to rotate the set at $1\frac{2}{3}$ rev/min.

The main lubrication oil tank is fitted with 30 kW of heating. In addition about 30 kW of heating is installed in each alternator stator frame. The lubricating oil is raised to a temperature of 40°C so that as the set is barring, the shaft temperature can be lifted to a minimum of 30°C before arduous pulsing commences. Stator heating can be used to assist in this process.

(a) Reason for Pre-heating

This pre-heating is carried out to ensure maximum security of the shaft system by ensuring that the transition temperature of the steel is reached or exceeded before appreciable pulsing stresses are set up. It seemed advisable to do this, particularly since extensive investigation on the Bevatron power supply had shown that it was prudent to pre-heat the Bevatron flywheel shafts to a point at which Charpy-Izod tests indicated satisfactory energy absorption levels. (2).

(b) Transition Temperatures of Chrome Molybdenum and Low Nickel Vanadium Steels

It is true to say that varying opinions are held on the subject of brittle fracture and machine failures. Nevertheless large rotors have burst and such failures have caused attention to be directed to the brittle behaviour of alloy steel forgings. It was found that if the notch toughness of the steel is evaluated over a range of temperatures by means of the Charpy-Izod impact test it becomes evident that the energy required to fracture test specimens decreases rapidly with decreasing temperature. This can be readily seen from the curves shown in Fig. 5.2.7(i) which are applicable to the steels used in Nimrod power plant forgings. If a line is drawn at, say, 15 ft lb and if the mean of the spread of results is taken for the two steels, it can be seen that the temperature corresponding to 15 ft lb fracture energy is about 20°C for the low nickel vanadium (LNV) steel and -2°C for the chrome molybdenum steel. Above these temperatures the steels will behave in an increasingly ductile way and below these temperatures in an increasingly brittle way. The temperature at which a steel specimen absorbs 15 ft lb of energy during fracture is called the transition temperature.

Again sudden failures due to extremely rapid crack propagation, will only occur if there is a sufficiently severe stress concentrator to act as a point of

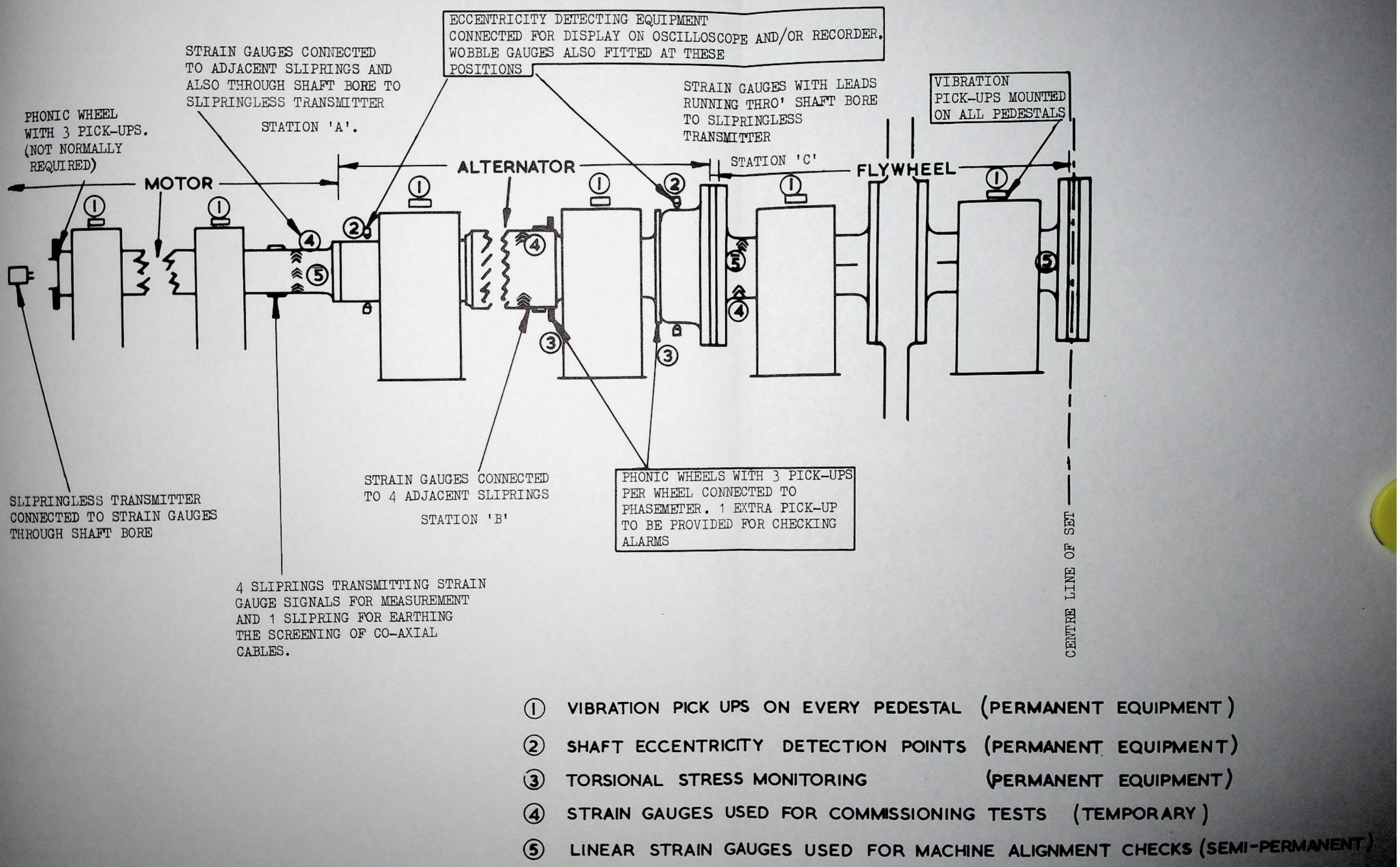


Fig. 5.2.6(i) Monitoring of the Shaft System.
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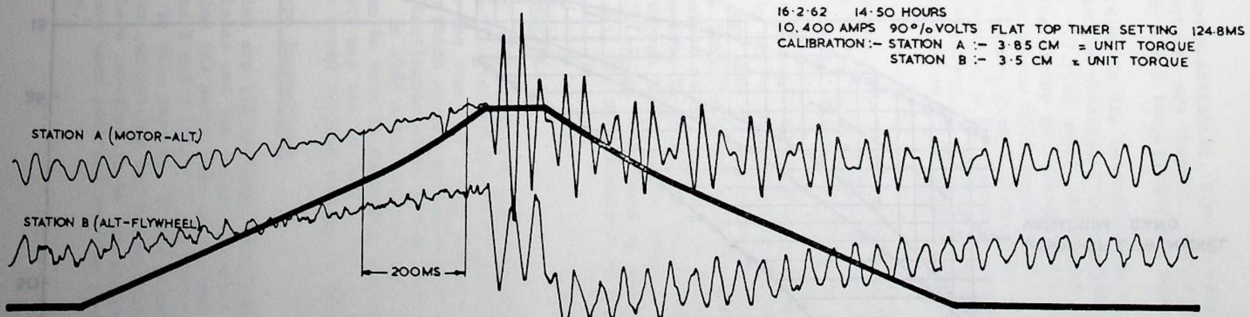

16·2·62 14·50 HOURS
10,400 AMPS 90°/o VOLTS FLAT TOP TIMER SETTING 124·8MS
CALIBRATION :- STATION A :- 3·85 CM = UNIT TORQUE
STATION B :- 3·5 CM = UNIT TORQUE

Fig. 5.2.6 (ii) Behaviour of the Shaft System

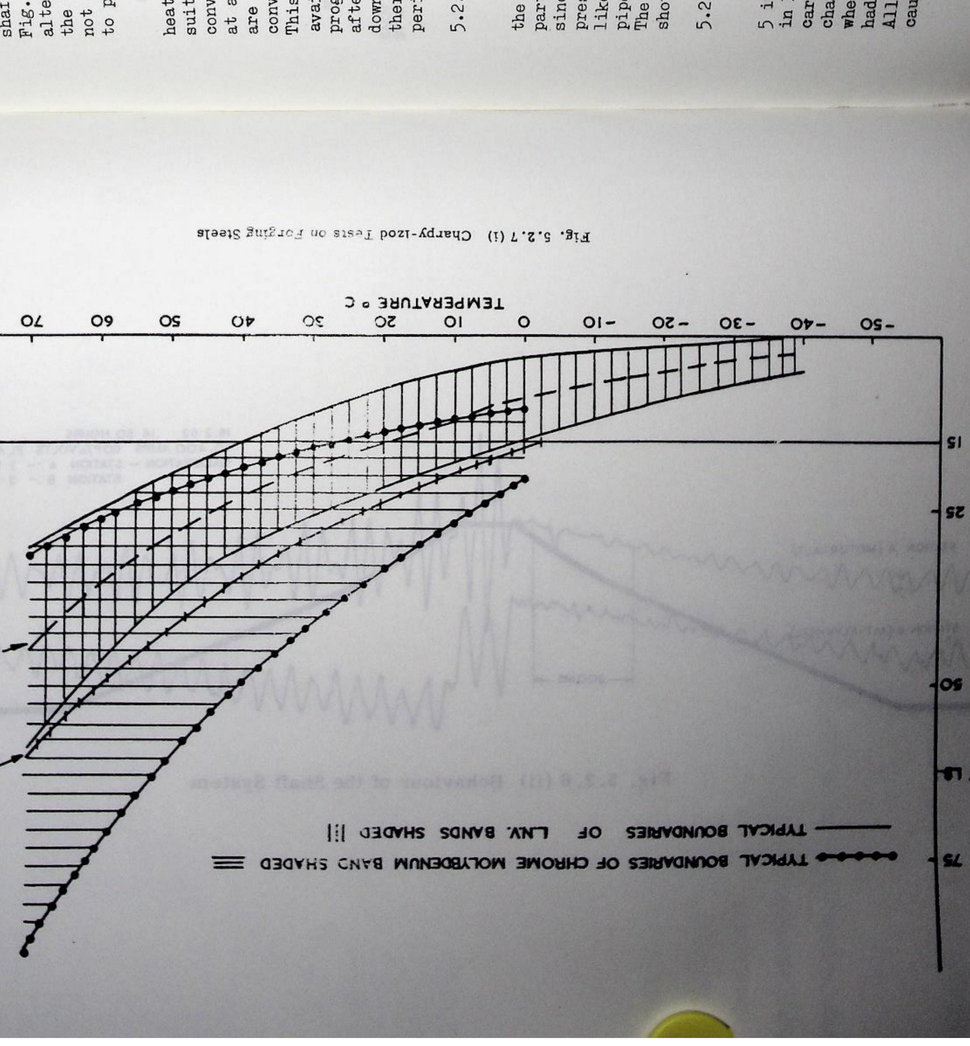


Fig. 5.2.7 (i) Charpy-izod Tests on Forging Steels

origin. However it is not practicable, even in very high quality forgings, to be certain that no flaws whatever are present. Where failures have occurred, most have taken place when the steel temperature has been below the transition temperature.

One of the difficulties in the determination of the transition temperature is the wide spread of results obtained from specimens taken from various parts of the same forging. Fig. 5.2.7(i) shows the spread of results for the alternator LNV rotor forgings and the chrome molybdenum motor forgings. The flywheel half shafts are also made from chrome molybdenum steel. It can be seen from Fig. 5.2.7(i) that in our case, from a transition temperature viewpoint, the alternator forgings are more of a problem than the motor or flywheel shafts. If the mean curve of the LNV spread of results is taken, a figure of 15 ft lb is not achieved until a temperature of 20°C is reached. It seems prudent therefore to pre-heat to at least 30°C.

In practice this temperature is achieved by alternator and lubricating oil heating as far as is practicable, followed by a pulsing programme specifically suited to mercury arc convertor ageing requirements. Since this mercury arc convertor ageing programme is carried out with long flat top times (typically 8 s) at a magnet current of 5 kA and only 30% of peak voltage, the shaft torque levels are low so that this duty can be carried out not only to effect the necessary convertor plant ageing, but also to assist in raising machine and shaft temperatures. This does mean, however, that the power supplies and the magnet load have to be available for 2 hours before normal pulsing is required. At the end of the pulsing programme 20 min are required to bring the set to rest with the brakes fully on after which the set is barred for a further hour or so, so that the rotors cool down evenly and possibilities of shaft bending are avoided. Power supplies plant has therefore to be operational for approximately $3\frac{1}{2}$ hours in excess of the pulsing period required.

5.2.8. <u>Lubrication Oil System</u>

A certain amount of difficulty has been experienced with air entrainment in the oil system with resultant difficulties of pump priming. This could be particularly serious in the event of a pump failure or a site electrical failure since the stand by pump which should automatically cut in, could fail to build up pressure. A temporary continuous bleed system was installed to greatly reduce the likelihood of failure. In 1963 modifications will be carried out to the existing pipework and in addition to this an emergency gravity fed system will be installed. The head of oil available may not be sufficient to prevent some bearing wipe but should be sufficient to avoid serious damage to the journal and bearing system.

5.2.9. <u>Routine Intrascope Inspections</u>

The alternator poles are 115 in long. The laminations are clamped between 5 in thick steel end plates and the poles are keyed to the rotor body as shown in Fig. 5.2.9(i). During the early life of the set intrascope inspections were carried out at locations X and Y (Fig.5.2.9(i))in order to ascertain whether changes were occurring in this region. It was possible to ascertain, for example, whether any gaps between laminations (or between laminations and end plates) had changed, whether there appeared to be any significant key movement, etc. All changes observed have been recorded and the changes noted so far do not give cause for undue concern.

5.2.10. Flywheels

Tests have been carried out to determine the temperature rise of the flywheel when either the eddy current braking system or the mechanical band braking system is applied. The rise in rim temperature is somewhat similar in the two cases and temperatures of up to 140°C at the rim are reached. The running temperature of the flywheel is normally not less than about 60°C, thus the temperature rise does not exceed 80°C. It is important that this rise should not be significantly exceeded otherwise the compressive stress in the rim approaches the yield point of the steel very closely. For this reason eddy current braking and mechanical braking cannot be used simultaneously for a more rapid shut down. Furthermore one mechanical brake or one eddy current brake must not be used to stop the complete twin set.

An ultrasonic survey has been carried out on both flywheels and it was found that in the case of No. 1 flywheel there were 132 significant defect echoes distributed in about a 270° arc of the flywheel disc whereas No. 2 flywheel had only about 28 flaws distributed within about a 90° arc. It would appear that No. 1 flywheel disc is peppered with slag inclusions. It is reasonable that the two flywheel discs should not give similar results when ultrasonically scanned, since they were separately made and not from the same melt.

The flywheels will be ultrasonically scanned at intervals to try to ensure that no significant change occurs in the known flaw patterns. It must be emphasised that these remarks apply only to the flywheel discs which are made from quite an ordinary steel having a minimum yield point of 20 ton/in^2.

The chemical composition is:-

Carbon	0.28/0.34%	Silicon	0.1/0.3%
Manganese	0.8/1.1%	Sulphur and Phosphorous	0.05%

The half shafts are made from a chrome molybdenum steel having a minimum yield point of 40 ton/in^2. The chemical composition is:-

Carbon	0.25-0.35%	Chromium	2.5-3.5%
Silicon	0.1 -0.35%	Molybdenum	0.3-0.7%
Manganese	0.65% max.	Sulphur	0.05% max.
Nickel	0.4% max.	Phosphorous	0.05% max.

These half shafts will also be scanned ultrasonically at bearing journal locations during the final commissioning stages in 1963 (see section 5.2.13 on ultrasonics).

5.2.11 Alternator Automatic Voltage Regulation System

Fig.5.2.11(i) shows a block schematic of this system. The basic reference voltage is generated by reference neons fed from a stabilised supply. The output of the reference circuit is fed to a potential divider chain so that any selected value in the range 20% to 100% can be obtained to within a fraction of 1%. The transient voltage characteristic of the alternator is curved and if the excitation is controlled to follow a similarly shaped characteristic, the A.V.R. duty is less arduous and therefore more accurate than would be the case if the excitation followed a linear characteristic. This shaped characteristic is

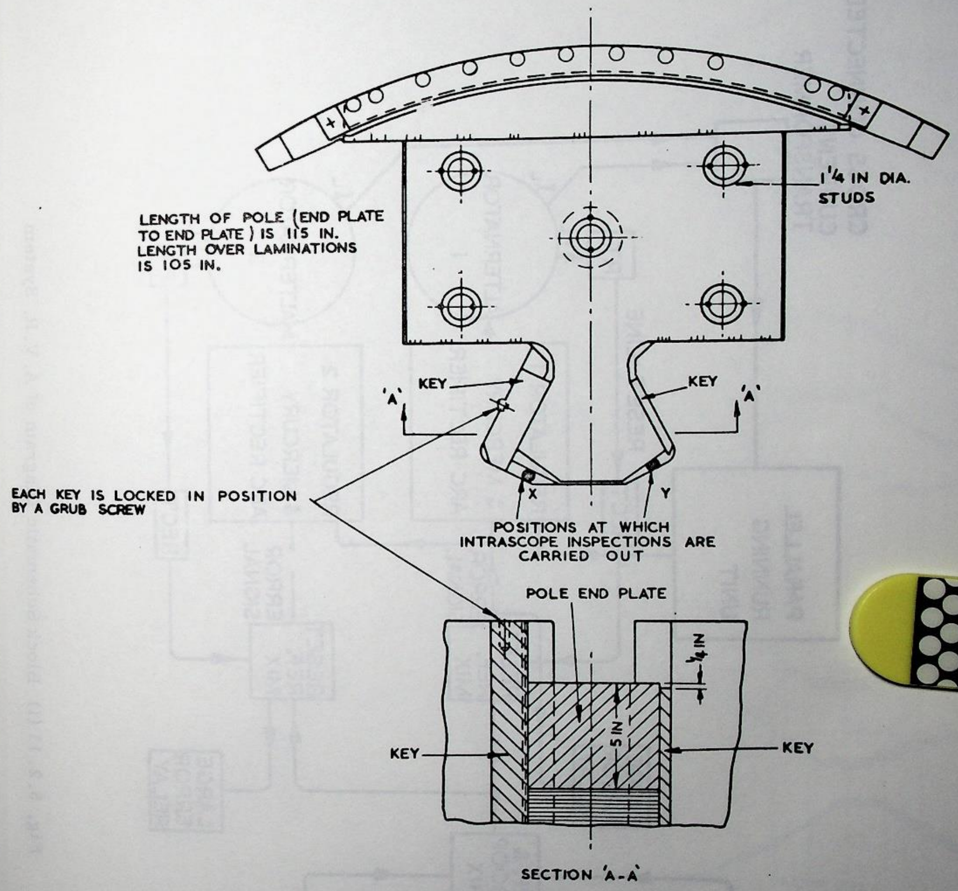


Fig. 5.2.9 (i) Pole/Rotor Dovetail Assembly

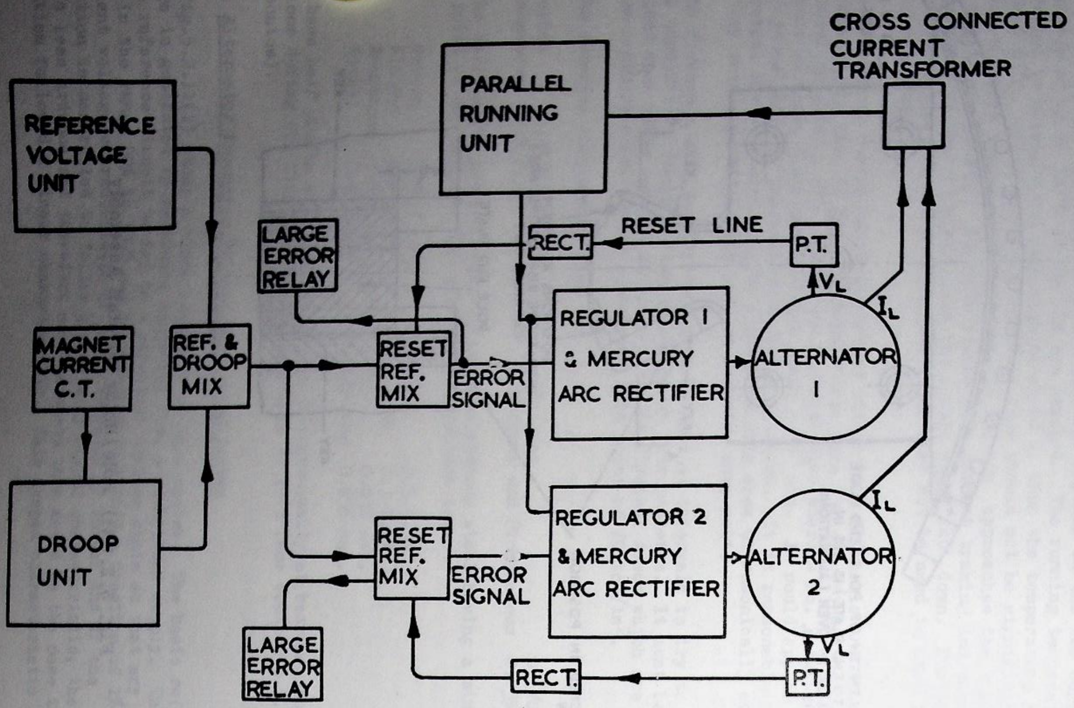


Fig. 5.2.11 (i) Block Schematic Diagram of A.V.R. System

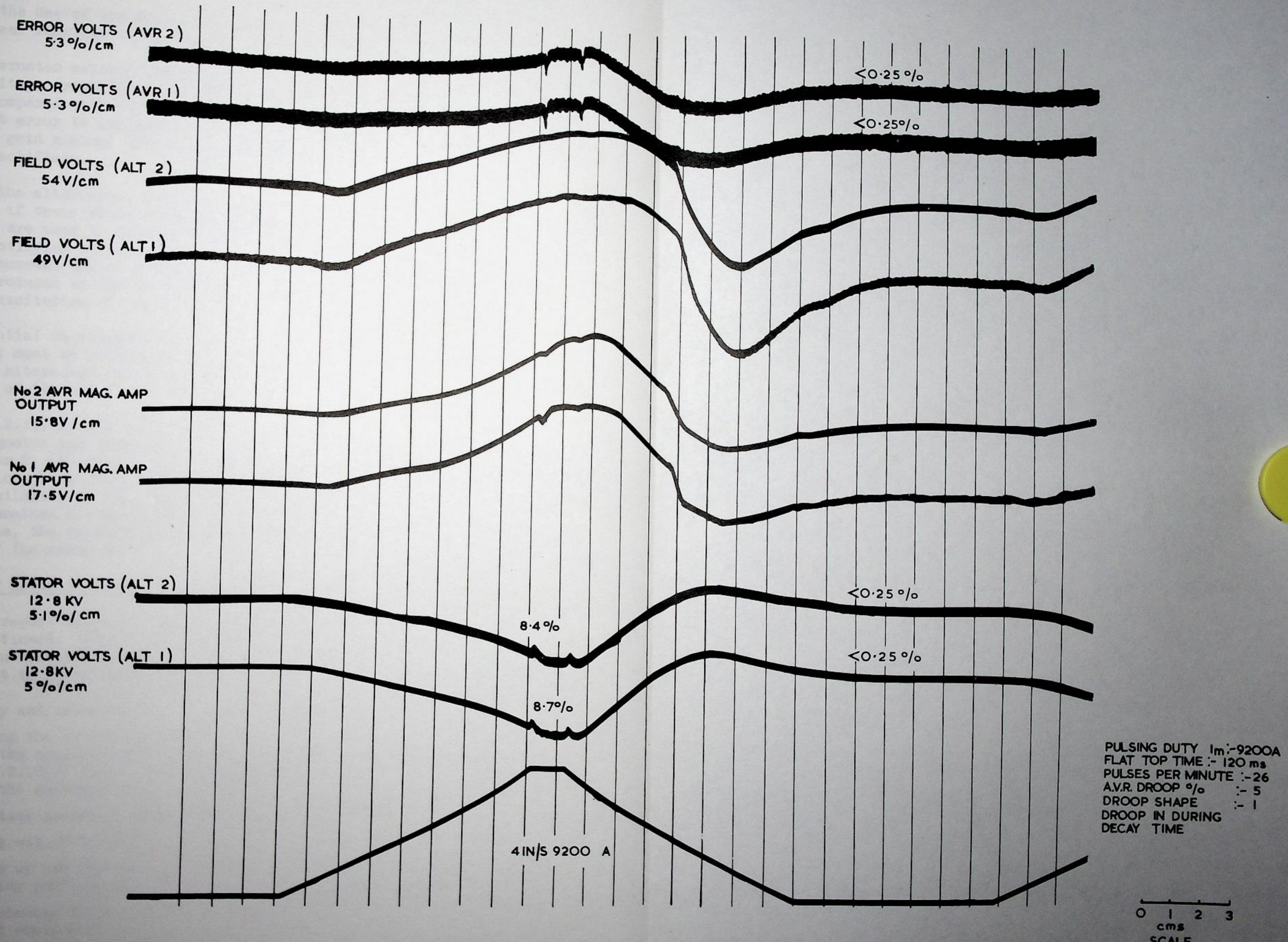


Fig. 5.2.11(iii) Aspects of A.V.R. Performance (End of 12 hour run).

achieved by the use of the droop unit which provides a controlling voltage (which is a non-linear function of the magnet current) to modify the reference voltage.

The alternator voltage transformer (12.8 kV/180 V) output is rectified, to produce a voltage proportional to the average of the three line voltages, and fed back to be compared with the combined outputs of the reference and droop circuits. The resultant error is applied to the regulator magnetic amplifier, which in turn controls the grid control unit supplying the grid impulses to the mercury arc excitation rectifiers.

Should the alternators ever run in parallel, a circulating current will flow between them if their excitations are unequal so a pair of cross connected current transformers are used to measure this current. Their outputs are fed to a phase sensitive rectifying circuit to produce a direct voltage proportional to the circulating current and of polarity dependent on the phase of the current. The voltage so produced is fed in opposing senses to each regulator amplifier to correct the excitation of the alternators.

An essential requirement of A.V.R. performance is that pulse to pulse repeatability must be maintained and one of the closest tolerances specified was that the alternator voltage should have recovered to within ±0.25% of 12.8 kV within 0.2 s of the end of the decay period.

Figs. 5.2.11(ii) and 5.2.11(iii) show traces of (a) error volts AVR1 and AVR2, (b) magnetic amplifier outputs AVR1 and AVR2, (c) field volts alternator 1 and alternator 2, (d) stator volts alternator 1 and alternator 2 under standard pulse conditions both at the beginning and end of a twelve hour pulsing period. The close similarity of the stator voltage traces may be noted; similarly, error volts have remained virtually the same over this period. On both alternator voltage traces, the voltage has recovered to within ±0.25% of 12.8 kV within 0.2 s of the end of the decay period.

5.2.12. Brief notes on General Routine Commissioning

In this report certain items which it is hoped will be of general interest have been mentioned. Much time was inevitably spent in the period under review in carrying out routine work associated with plant of this nature. The following list is by no means complete but serves as an example of such work:-

(i) Primary and/or secondary injection testing of all plant protection.

(ii) Checking the extensive sequence interlocking system on the plant - also the complete alarm and tripping system.
Fig. 5.2.12(i) lists the main protective devices on the plant together with the switches, etc., with which they are associated.

(iii) Electrical pressure testing of plant and cables.

(iv) Phasing out of transformers.

(v) Setting up and adjusting switchgear and ensuring that closing and tripping performances are in accordance with those laid down in B.S.S.

(vi) Commissioning tests on all auxiliaries: e.g., motors, cyclic resistors, liquid controllers, batteries, oil purifiers, etc.

(vii) Checking excitation and ignition circuits of the excitation rectifiers, grid-anode phasing, etc.

(viii) Dry out runs on alternators and static dry out procedures on the motors.

(ix) Pressure testing of oil and water circuits and the calibration of orifice plates in these circuits.

5.2.13. Ultrasonic Scanning of the Rotary Plant

Reference has been made in sections 5.2.4 and 5.2.10 to flaw detection by ultrasonic methods on the flywheel discs, and the checking of the bonding between the white metal and the steel shell of machine bearings. Conventional ultrasonic test equipment is, of course, freely available to carry out such examinations and also examinations from the exterior surface of bearing journal locations. It was by this means that the East generator shaft of the Bevatron magnet power supply was found to have serious flaw patterns in the vicinity of a bearing journal. Flaws were also found on the West generator shaft but these were not so serious. However in a Bevatron Engineering Note (3) a comment is made that in the case of the East generator shaft the ultrasonic observations were sufficient to reject the shaft on current inspection standards for installation in new equipment. Ultrasonic survey programmes were set up on a three shift basis for both machines.

In the case of the Nimrod machines, the locations at which ultrasonic examination can be carried out is limited to the bearing journal positions. In the case of the alternators this amounts to about 13% of the shaft length.

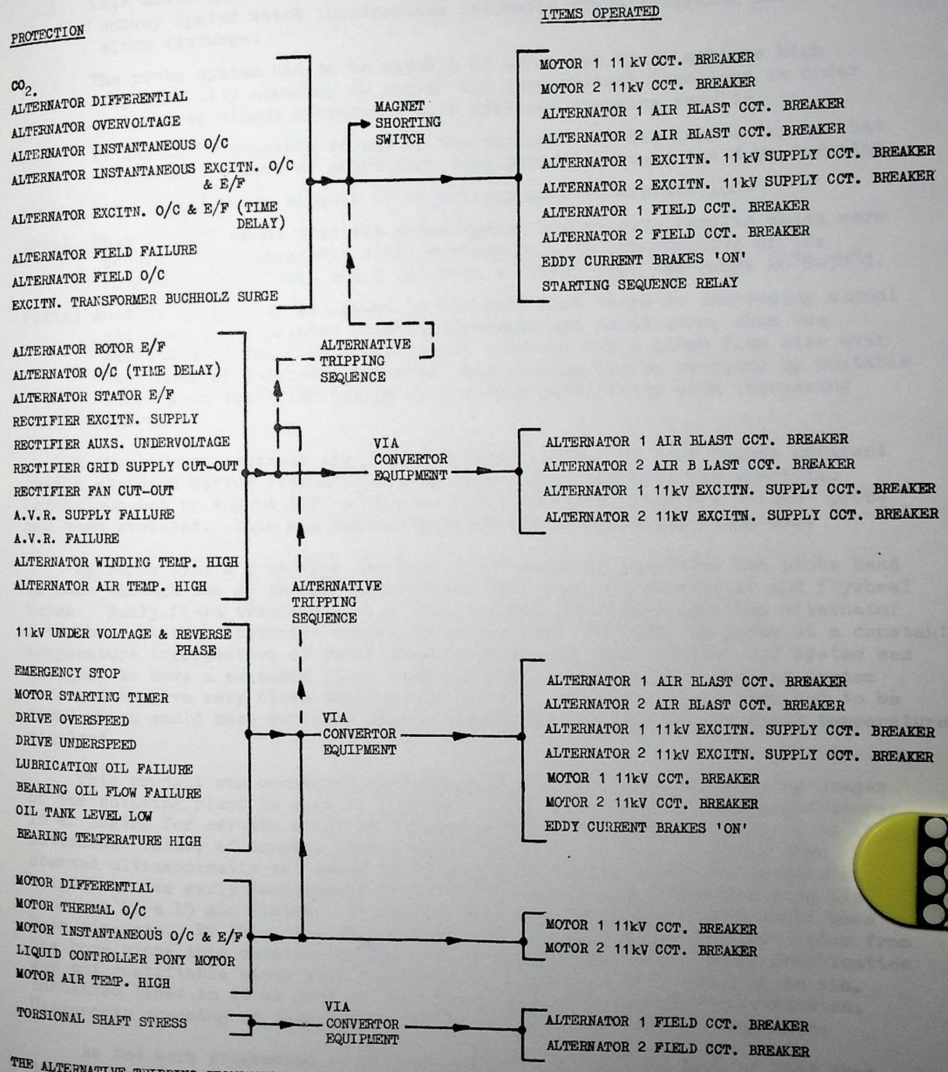
However, the Nimrod motor-alternator-flywheel set has central boreholes throughout the shaft system. In the 14 ft 6 in long motor rotor forging the borehole is 2¾ in dia., in the 25 ft long alternator rotor forging it is 4½ in dia. and in the 4 ft 6 in long flywheel half shaft it is also 4½ in dia.

Since ultrasonic techniques have been accepted for many years as a means of evaluating the soundness of parts of rotary plant (e.g., end bells of turbo-alternator rotors) and in view of the American experience, it appeared prudent for ultrasonic inspection to be carried out on Nimrod. The practicability of scanning from the bore was considered. This had the obvious advantages that no machine dismantling need take place and very much more of the forgings could be examined.

There was no commercially available equipment to carry out this work and various firms were approached to see whether a reasonable development contract could be arranged to investigate this problem. There were obvious difficulties to be overcome some of which are now mentioned:-

(i) The ultrasonic probe head would be out of the sight of the operator and up to 45 ft away from him, yet acoustic coupling conditions between the probe and the bore surface had to be constant throughout a survey. Furthermore the probe head had to pass through the 2¾ in dia. motor rotor bore before entering the 4½ in dia. bores.

(ii) Time of inspection had to be as short as possible. In this connection it is interesting to note that to examine the alternator rotor forging alone for bore surface flaws, and also flaws from the bore surface radially into the forging up to a distance of 10.5 in from the bore (to the base of the pole dovetails), requires results to be obtained at about 60,000 probe locations.



THE ALTERNATIVE TRIPPING SEQUENCES, SHOWN – – – – OCCUR ONLY IN THE EVENT OF A FAILURE IN THE MAIN LINE TRIPPING SEQUENCE, SHOWN ———

Fig. 5.2.12 (i) Rotating Plant Protection (Simplified)

(iii) This means that it was necessary to devise, in effect, a continuous survey system which incorporates automatic trace recording and alarm features.

(iv) The probe system had to be capable of being set up to achieve high repeatability accuracy in radial and longitudinal locations in order to achieve direct comparison with previous scanning results.

(v) It had to be possible to set up the equipment within half a day so that use could be made of short shut down periods of say, two days duration.

(vi) Results had to be capable of relatively easy interpretation.

(vii) This in turn meant that the probe system had to give results which were accurate and comparable with previous results irrespective of the forging temperature, which can vary at least over the range 20°C-70°C.

(viii) Another difficulty is caused by the fact that there is increasing signal attenuation as greater steel thicknesses are penetrated; thus the amplitude of the flaw trace is not constant for a given flaw size over the range of interest. However this problem can be overcome by suitable swept gain amplifier design to increase sensitivity with increasing range.

A development contract was placed in April 1960. It soon became apparent that a standard barium titanate/perspex probe could not meet the specified conditions but by August 1960 a much more satisfactory "free oil column" probe had been produced. This was basically an immersion technique using oil.

By March 1961 a prototype had been produced which permitted the probe head to pass through the $2\frac{3}{4}$ in dia. motor rotor bore into the alternator and flywheel bores. Early field trials had also been carried out direct into the alternator rotor bore at the alternator manufacturer's works. To keep the probe at a constant temperature irrespective of rotor steel temperature, the couplant oil system was designed to have a suitable flow, combined with a couplant oil heating system arranged to give very close temperature control. A couplant oil then had to be found which would have suitably stable characteristics at the operating temperature required.

This project was commenced sufficiently early in the manufacturing stages of the rotating plant to make it possible to enlist the aid of the manufacturer in arranging for certain holes in various parts of the rotor forging to be flat bottomed. These, of course, give a vastly different signal response when scanned ultrasonically and acted as 'navigation' marks, which was particularly helpful in the early development trials. The bore surface finishes were also improved to a 15 µin finish. It would appear that a 50 µin finish would have been adequate. By this time it had also been decided not to scan the motor from the bore since this complicated probe head design even more. Extra complication was not justifiable since half the length of the motor bore has a $2\frac{3}{4}$ in dia. insulated liner in it as part of this particular type of motor construction. Ultrasonic scanning in this region is therefore not possible in any case.

As the work progressed it became apparent in the first half of 1962 that it would be helpful to attempt to improve the probe design further. The oil columns incorporated in the probe design attenuated longitudinal ultrasonic waves only to a small degree, thus considerable reverberation signals existed which tended to mask the useful flaw signals. The oil column probe was finally replaced by a Nylatron G.S. column probe incorporating suitable couplant oil channels. This proved to be a major improvement and early results showed that interpretation of the results obtained was very much simpler.

The final probes which will be supplied are as follows:-

(i) A circumferential surface wave probe. The range of detection to be over a 90° arc of the bore surface. The sensitivity to be such that a V scratch 0.25 in in length, having an included angle of 3-5° and a depth of 0.005 in, will be clearly and unmistakably indicated. Frequency 2.5 Mc/s.

(ii) A longitudinal surface wave probe. Minimum range of detection to be 3.5 in ahead of the probe. Sensitivity as defined in (i) above. Frequency 2.5 Mc/s.

(iii) A longitudinal wave (V.L.O.) probe. The sensitivity requirement to be such that the probe is capable of detecting $\frac{1}{8}$in dia. flat bottomed holes drilled radially over a range from 0.1 in below the bore surface to 10.5 in from the bore surface. Frequency 2.5 Mc/s.

(iv) Suitable standard type probes for scanning the four 11in dia. journals and the eight 20 in dia. shaft journals from the exterior.

The development phase of this contract was virtually completed by December 1962. The commissioning of the final equipment and the initial and very detailed ultrasonic surveys of the rotary plant will take place during the first half of 1963 and will be described in the second part of this report. Before then a paper will be published on this project.

This introduction has been given at some length since no information is at present available elsewhere on the general background and considerations which led to the development of this special equipment. As far as is known this is the first time that such a comprehensive equipment has ever been produced for monitoring forgings in service from a central bore hole.

5.3. Convertor Plant

In this section some of the more interesting problems which arose during the commissioning of the convertor plant are discussed. As an introduction, a general description is given of the main power circuit of the convertors and the essential control items. As already mentioned in section 5.1 a more detailed description, together with early design considerations, will be found in the three papers published in the proceedings of the I.E.E. (1).

5.3.1. General Description of Power Circuit

The basic circuit is shown in Fig.5.1(i). It will be seen that the convertor installation is in two identical parts and that each half is made up of eight groups of convertors. Each group itself comprises six single anode convertors, and these are of the water cooled, continuously evacuated, excitron type.

For each half of the plant there are four main rectifier transformers having a primary rating of 11.93 MVA and supplied at 12.8 kV from the alternators via an air blast circuit breaker. Each transformer has two secondary windings connected double star with an interphase transformer, the no load secondary voltage being 3,400 V phase to neutral. The primary windings of the transformers are connected star, delta, extended delta + 15° and extended delta -15° respectively, and this has been arranged so that each half of the convertor plant operates as a 24 phase installation. The secondary windings of the transformer having the star connected primary, are associated with convertor groups 1 and 2; the delta connected transformer with groups 3 and 4 and so on. The groups are connected in a series parallel arrangement shown in Fig.5.1(i) and the manner in which they operate to give a 24 phase output, and the function of the interphase transformers, will be explained by reference to Figs.5.3.1(ii), 5.3.1(iii), 5.3.1(iv).

The magnet current pulse is such that it demands three distinct modes of operation of the convertor plant.

(i) A period of approximately 0.7 s during which time all convertors are operating as free firing rectifiers and current is increasing in the magnet. The actual time of current rise is variable depending on the value of magnet field required.

(ii) A short period which is adjustable in 1 ms increments during which time the magnet current is held approximately constant.
This condition is obtained by arranging that only one group of convertors in each series pair operates as a rectifier, whilst the second group functions as an invertor. The degree of inversion is such that there is just sufficient forward voltage as a resultant output across the series pair to overcome the resistive drop in the load and its connections.

(iii) A period of time similar in magnitude to the current rise time (i) during which the magnet current decays to zero.
During this time all convertors function as invertors to transfer the energy stored in the magnet to the power supply system.

A typical magnet current pulse waveform is given in Fig. 5.3.1(v) while Fig.5.3.1(ii) shows the build up of the d.c. voltage waveform across one series pair of convertor groups. It has been assumed that the angle of overlap for the condition considered is 37½° and that the safety angle during inversion is 22½°.

Curve 1 shows the anode voltage of one star group of say convertor group No.1; curve 2 shows an anode voltage associated with the other star of the same transformer secondary. Because of the action of the 150 c/s interphase transformer, each anode conducts for 1/3rd of a cycle and the d.c. current is shared equally between the two star windings. Since anodes associated with each star group are conducting simultaneously, the effective d.c. voltage due to the convertor group is the mean of curves 1 and 2 and is drawn as curve 3. The voltage across the 150 c/s interphase transformer will be the difference between curves 1 and 2.

Curve 4 is similar in waveform to curve 3 but is displaced in phase by 30° to represent the d.c. voltage of the series convertor group, say group 4.

When changing into flat top condition the d.c. voltage waveform of group 1 convertors moves into the negative invertor region as shown by curve 3 whilst curve 4 remains in the positive rectifier region until the end of flat top.

The nett d.c. voltage across the series pair of convertors is the algebraic sum of the voltages due to the individual groups and is indicated by the heavy full line on the Fig. 5.3.1(ii).

The nett d.c. voltage due to series convertor groups 3 and 2 will be similar in waveform to that due to groups 1 and 4 already considered, but since group 3 is 30° out of phase with group 1, then switching into flat top cannot occur at the same instant. On Fig. 5.3.1(iii) the waveforms for groups 1-4 and 3-2 are shown dotted and the effect of the 300 c/s interphase transformer is that the nett d.c. voltage output across the four groups is the average of the two curves, and is shown by the full heavy line. The voltage across the 300 c/s interphase transformer is the difference between the two dotted curves, and it can be seen that during full rectification and full inversion this should be zero.

Convertor groups 5, 6, 7 and 8 are all phase displaced by 15° relative to groups 1, 2, 3 and 4 already discussed, and perform in precisely the same manner.

It follows that the output voltage waveform of these two parts of the plant will be similar in shape but displaced in phase by 15°. This is shown on the dotted curves of Fig. 5.3.1(iv) and the effect of the 600 c/s interphase transformer is that the nett d.c. voltage output from each half of the convertor installation is as shown by the full heavy line. The voltage across the 600 c/s interphase transformer is the difference between the two dotted curves as indicated.

5.3.2. Commissioning Experience

No attempt will be made here to cover all the commissioning tests which have been carried out. Many of these were of a routine nature of limited general interest, and a complete record is available in the form of test schedules which were completed as the various tests were carried out. It is considered preferable to describe some of the more interesting aspects of the plant, and tests which were carried out to establish the plant performance.

(a) Main Rectifier Transformers

One of the tests carried out on the main transformers was a pressure test at 30 kV d.c. During this test one of the transformers broke down at approximately 12 kV d.c. and it was necessary to remove the transformer from its tank to find

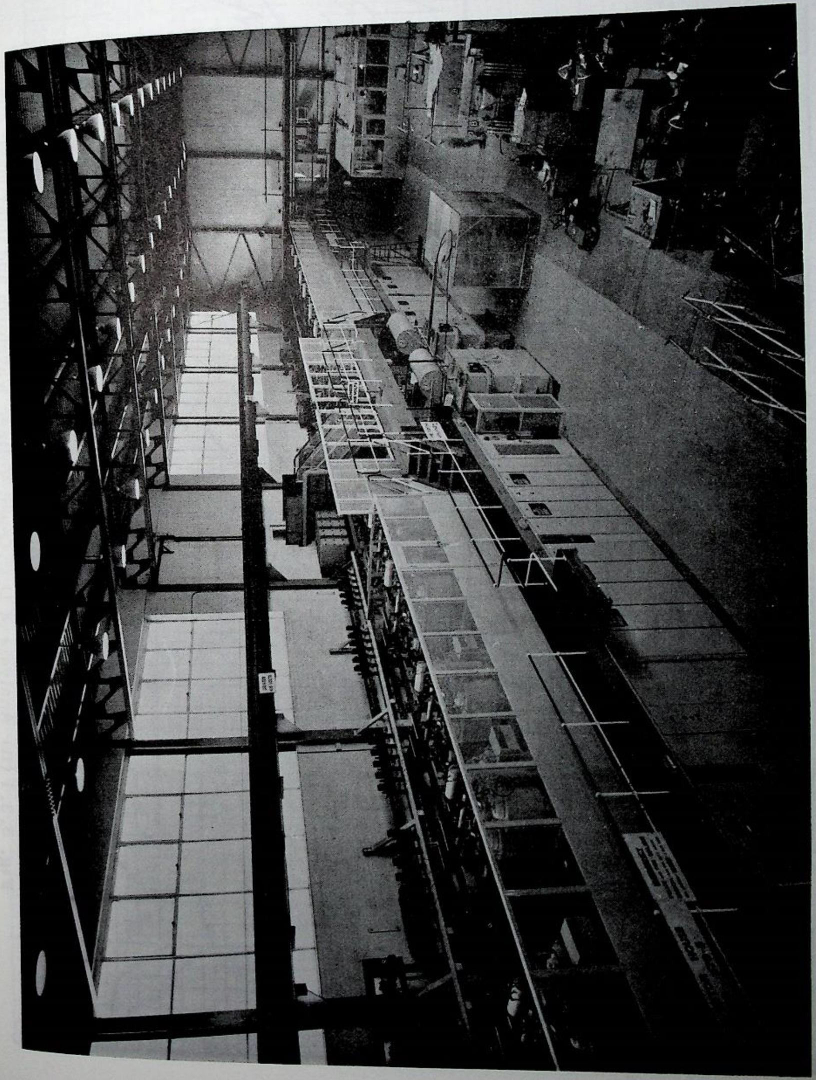


Fig. 5.3.1 (i) View of Convertor House showing the rectifier gallery with control gear underneath. The two primary ripple filter chokes can be seen in the centre of the picture and to the right the Brentford regulating transformers.

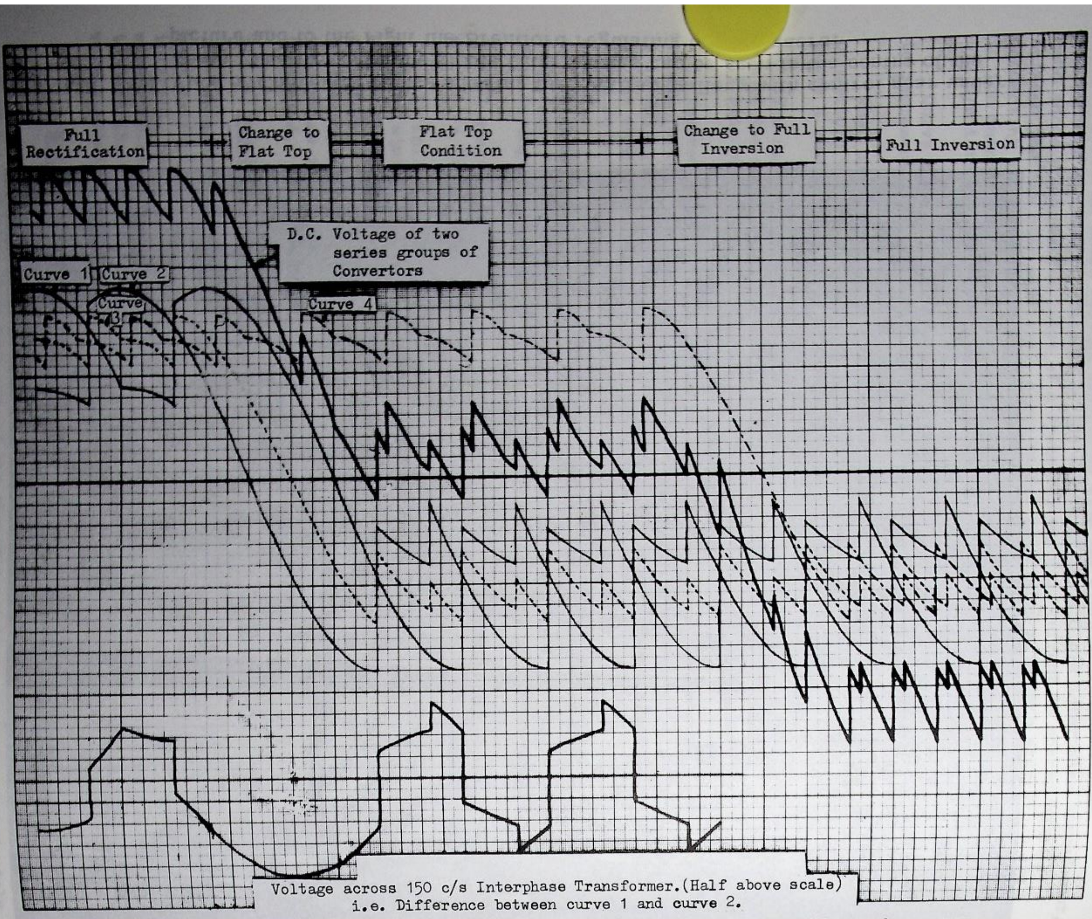


Fig. 5.3.1 (ii) Analysis of D.C. Ouput Voltage Waveform and Interphase Transformer Waveforms (Part 1)

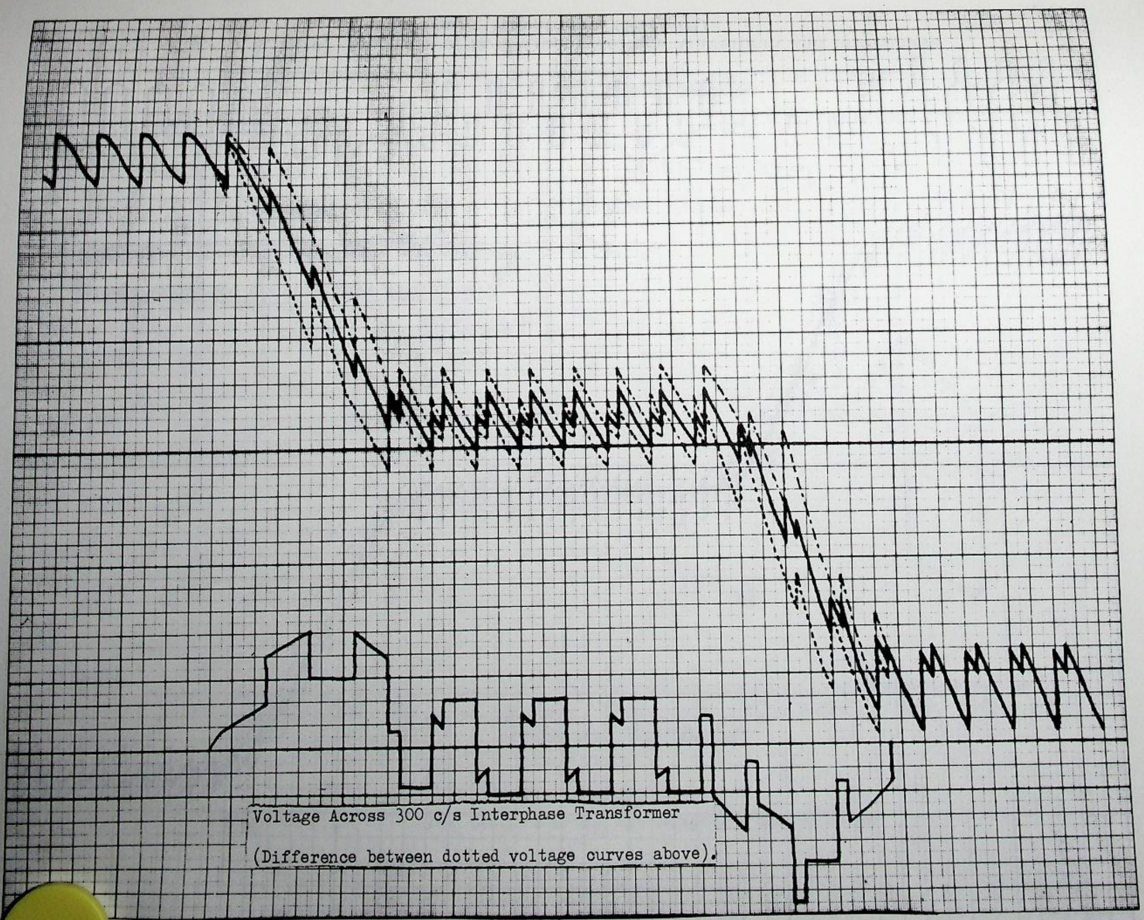


Fig. 5.3.1 (iii) Analysis of D.C. Ouput Voltage Waveform and Interphase Transformer Waveforms (Part II)

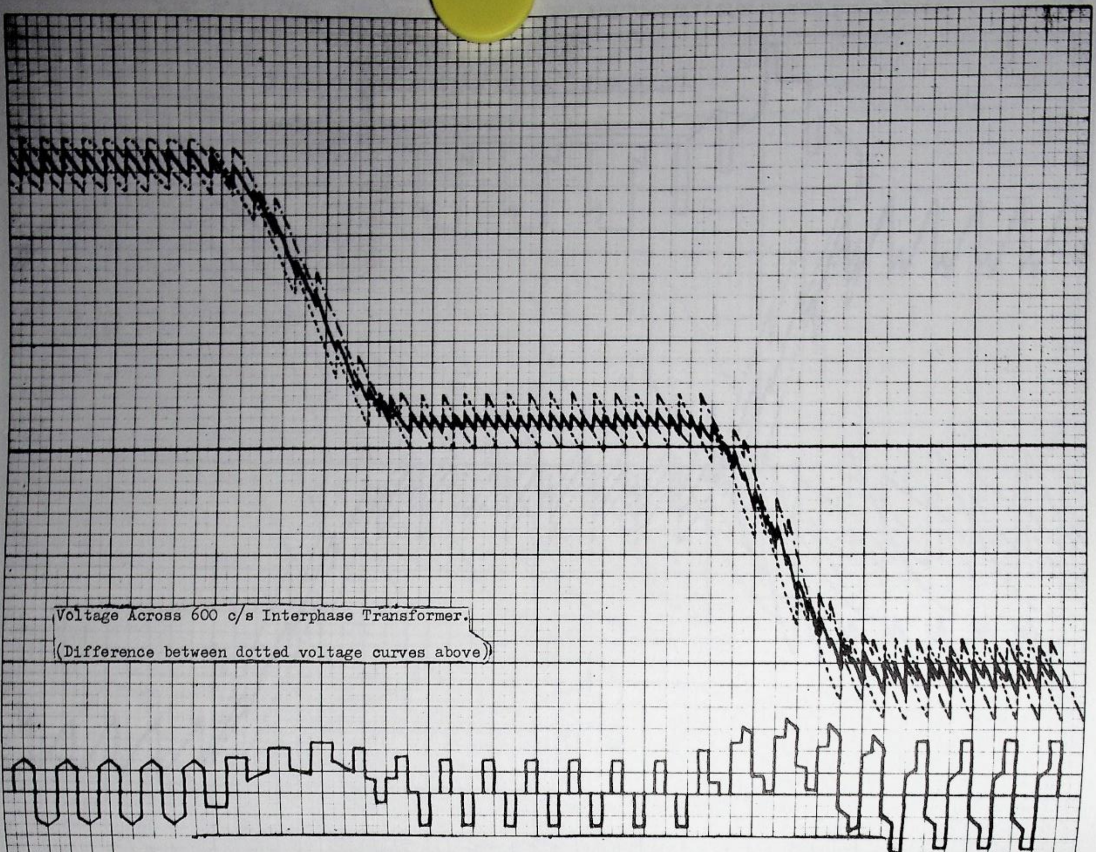


Fig. 5.3.1 (iv) Analysis of D.C.Ouput Voltage Waveform and Interphase Transformer Waveforms (Part III)

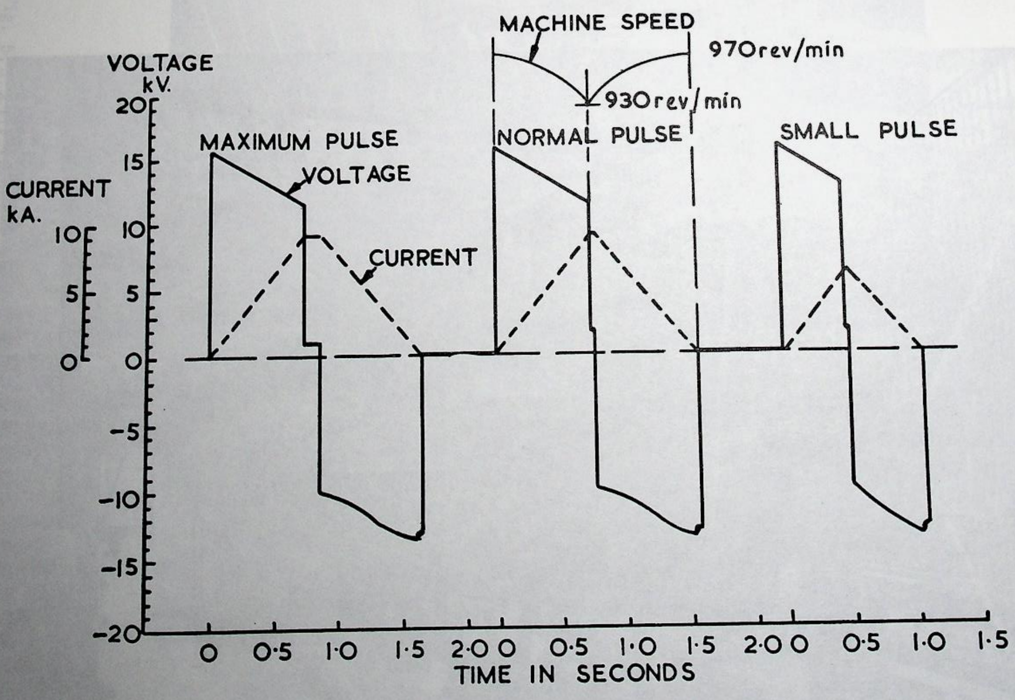


Fig. 5.3.1 (v) Pulse Shapes from the Magnet Power Plant

Fig. 5.3.1 (vi) View of Transformer Yard
(The building in the centre of the yard, with open doors, contains the air blast switchgear).

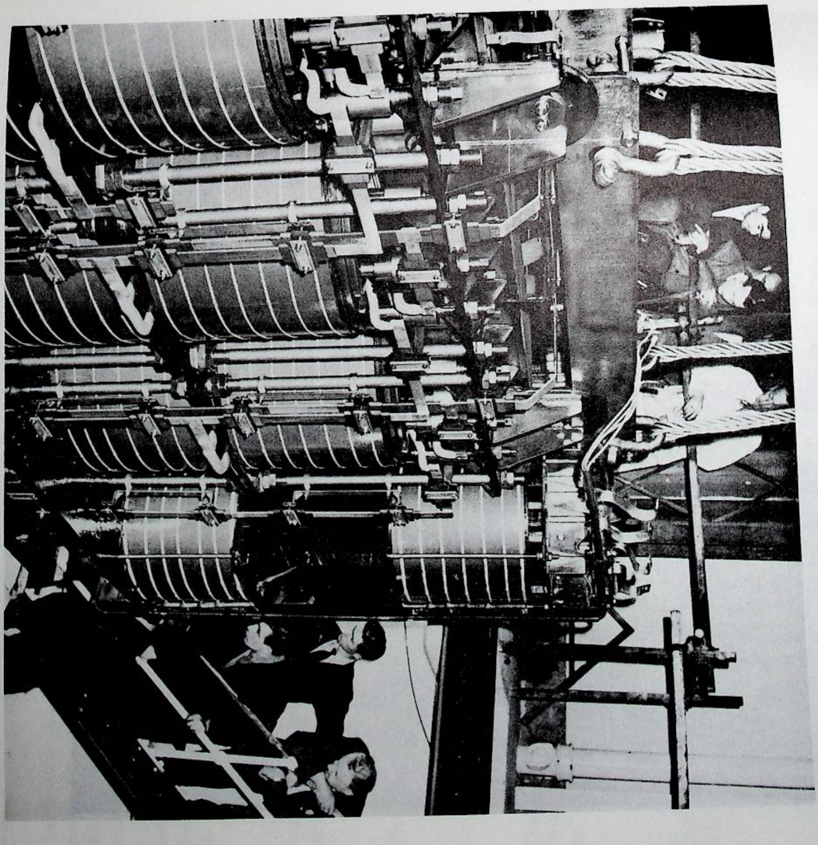


Fig. 5.3.2 (i) General View of Rectifier Transformer Removed from its Tank

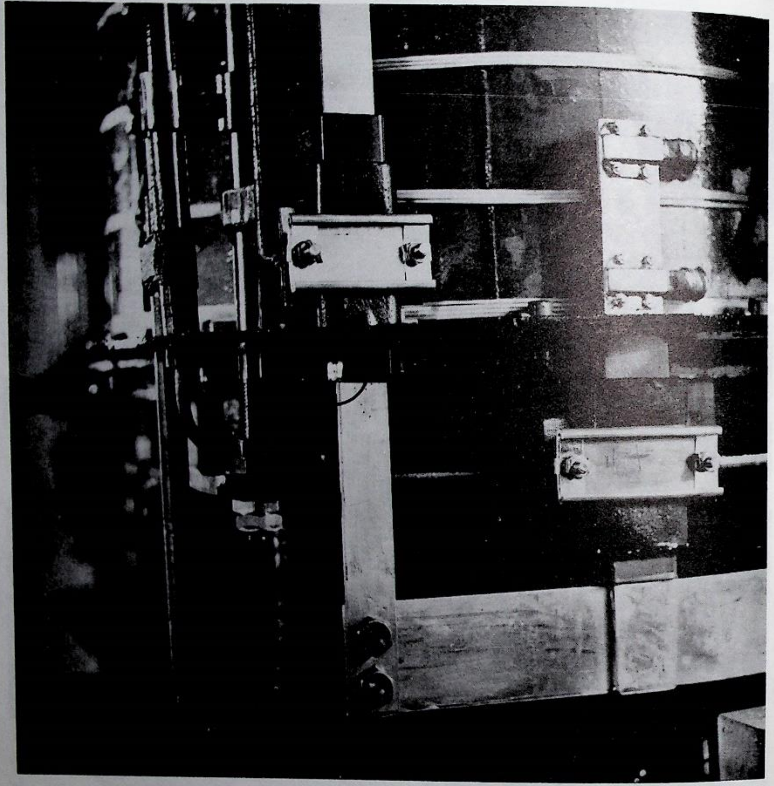


Fig. 5.3.2 (ii) View of Rectifier Transformer Neutral Connection Showing Damaged Insulation

the cause of the trouble. It was found that at one point there had been insufficient clearance between a neutral connection and a web on the side of the tank. It was concluded also that the method of locating the transformers in their tanks was not positive, and that movement had occurred in transit.

Photographs are included of the transformer being removed from its tank, and a close up of the neutral connection showing the damaged insulation where chafing had occurred, resulting in breakdown on pressure test (Figs. 5.3.2(i) and 5.3.2(ii)).

As a result of these findings it was necessary to examine each of the eight transformers and to modify the method of locating the transformers in their tanks. Fortunately it was possible to do this by draining down the oil and working through inspection covers in the sides of the tanks.

(b) Convertor Load Sharing

By far the largest part of the commissioning time has been spent in carrying out adjustments to the plant to obtain reasonable load sharing between the paralleled convertor units. The causes of poor load sharing have in general been due to one of the following:-

(i) Current compensation influence on grid phasing.

(ii) Incorrect operation of the interphase transformers.

(iii) Unsymmetrical capacity to earth of the d.c. connections to the magnet.

(iv) Faults in the grid impulse generating circuits.

The last item is of little general interest and will not be dealt with further. The first three items will be treated under their separate headings.

(i) Current Compensation Influence on Grid Phasing

In order that the synchrotron as a whole may operate at its maximum repetition rate, it is necessary that at the end of the flat top period the magnet current is reduced to zero as quickly as possible. This is done by so phasing the convertor grid impulses that the anodes can only conduct during the time when their voltages are negative relative to the transformer neutral. Thus the convertors are operating as invertors. This is possible due to the high inductance of the magnet, which produces a back e.m.f. to force the current through the convertors from anode to cathode, against the direction of the applied anode voltage.

It is desirable to operate with the maximum degree of inversion possible, and this involves continually altering the phasing of the convertor grid impulses as a fuction of load current. Fig. 5.3.2(iii) explains the reason for this. At (a) is shown one of the double star main transformer connections and the anode voltage waveforms produced by this transformer are shown at (b) and (c) with the convertors operating as invertors. At (b) anode 1 is shown commutating to anode 2 at an angle δ before the anode voltage waveforms cross each other. Commutation can only occur from one anode to another which is more positive and therefore would be impossible if the grid impulse of anode 2 were retarded beyond the cross over point. In fact commutation must be complete well before this cross over point to allow sufficient time for de-ionisation of the space surrounding the extinguished anode which would otherwise re-ignite. The minimum time in which commutation must be completed before the cross over point, is called the safety angle and is shown as the angle δ on Fig. 5.3.2(iii). This diagram has been drawn neglecting commutation time, i.e. angle of overlap μ which is shown in (c). Since we must maintain the safety angle δ after commutation, it is necessary that the grid impulses must be advanced by an angle μ giving $\beta = \delta + \mu$. The overlap angle is a function of load current and commutating voltage and Fig. 5.3.2(iv) shows the amount of grid advance applicable for given currents at the various operating voltages. This control is known as 'current compensation'.

The circuit which initiates the generation of convertor grid impulses relies on an a.c. waveform of alternator frequency being cut by a d.c. voltage. By varying the level of the d.c. voltage input, the point at which this cuts the a.c. waveform and hence the phase position of the grid impulses, is changed. Each group of convertors has its own current compensation control, which is obtained by connecting in series with the d.c. input to the grid control units a component which is a function of d.c. current fed via d.c. current transformers (see Fig. 5.3.2(v)). The original scheme was such that the d.c. current for each group supplied its own current compensation control. This scheme was unstable and various forms of cross connection were tried to provide some current compounding control to give even load sharing between the convertor paths. The scheme finally adopted is shown in Fig. 5.3.2(vi) which indicates, for example, that the d.c. current in group 1 influences the grid phasing of groups 3 and 7, whilst the currents in groups 3 and 7 also influence the grid phasing of group 1. Current compensation is only effective during inversion and does not influence impulse phasing during rectification. During flat top the cross compounding of groups 1, 3, 5 and 7 will be operative to assist load sharing and during current decay groups 4, 2, 8 and 6 will behave similarly.

It will be clear that the primary function of the current compensation control is to provide an adequate safety angle. The current sharing feature is a secondary aspect and is not a closed loop control in the normal sense, in that there is no controlling influence operating directly as a function of current unbalance. Load sharing will only be correct if the current compensation controls are precisely set up and any differences in the settings between one convertor group and another will in fact enforce current unbalance.

(ii) Incorrect Operation of Interphase Transformers

The function of the interphase transformers (I.P.T's) has been explained in section 5.3.1. It will have been seen that the largest voltage/time areas across the I.P.T's, and hence the maximum flux conditions, occur when switching from rectification to inversion or from inversion into rectification. The latter condition applies at the end of an injection platform which is produced at the beginning of the current pulse at approximately 170 A. The injection platform is produced in the same way as flat top is produced at peak current. At the end of the platform period the odd numbered groups of convertors are switched from invertor to rectifier duty to continue the current rise period. Fig. 5.3.2(vii) shows the I.P.T. waveform obtained on a programme with injection platform and a very small peak d.c. current. It is included to show the voltage/time areas to which the I.P.T's are subjected when changing from rectification to inversion and vice-versa.

The control of convertor switching from rectification to inversion and vice-versa is from a master timing unit which is set up to provide the required periods for current rise, injection platform, flat top and repetition rate. The timer

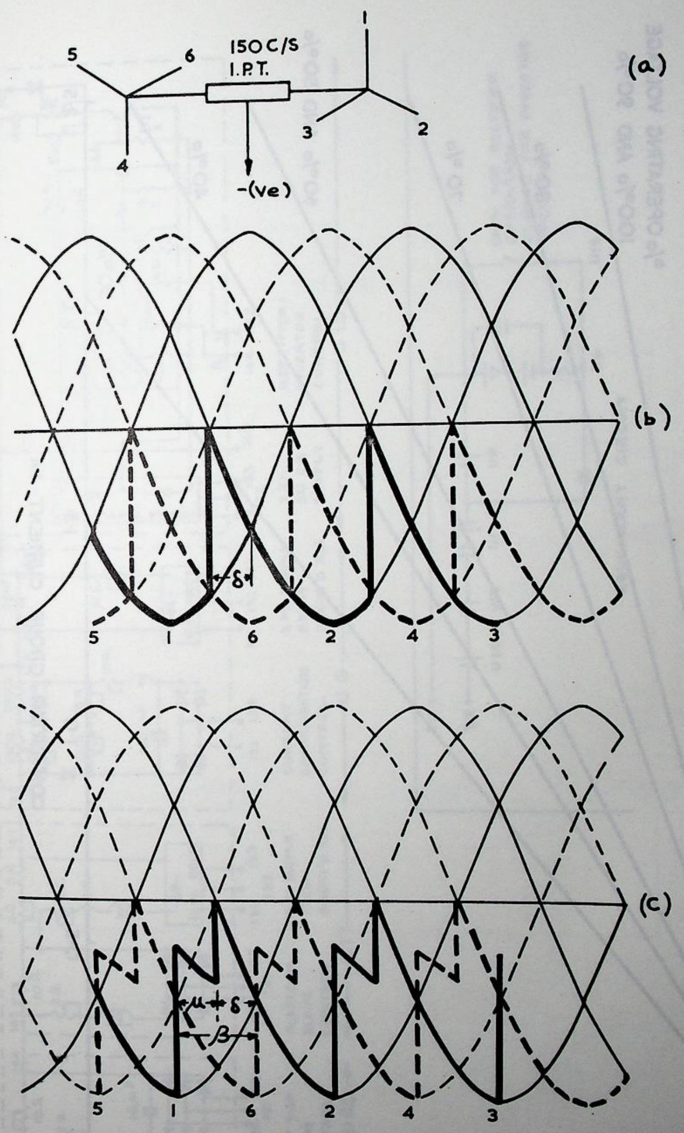


Fig. 5.3.2 (iii) Effect of Current Compensation Control on Invertor Operation

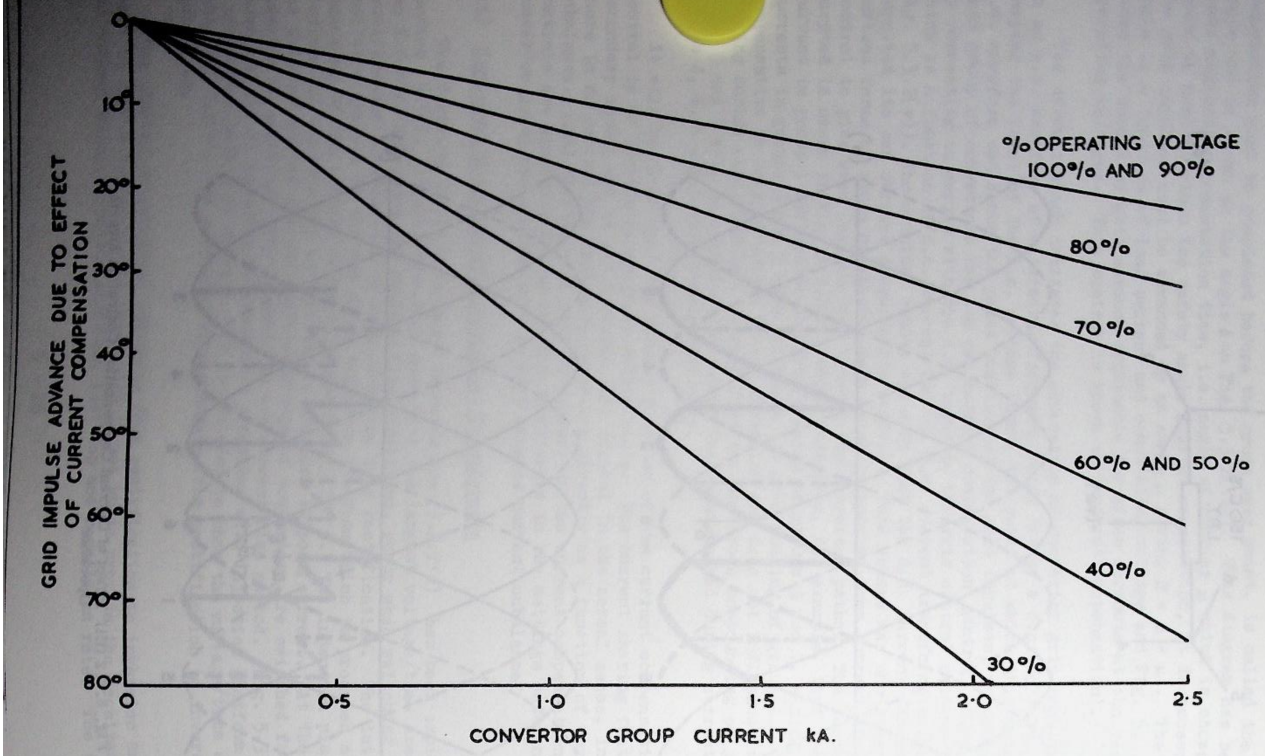


Fig. 5.3.2 (iv) Degree of Phase Advance due to Current Compensation

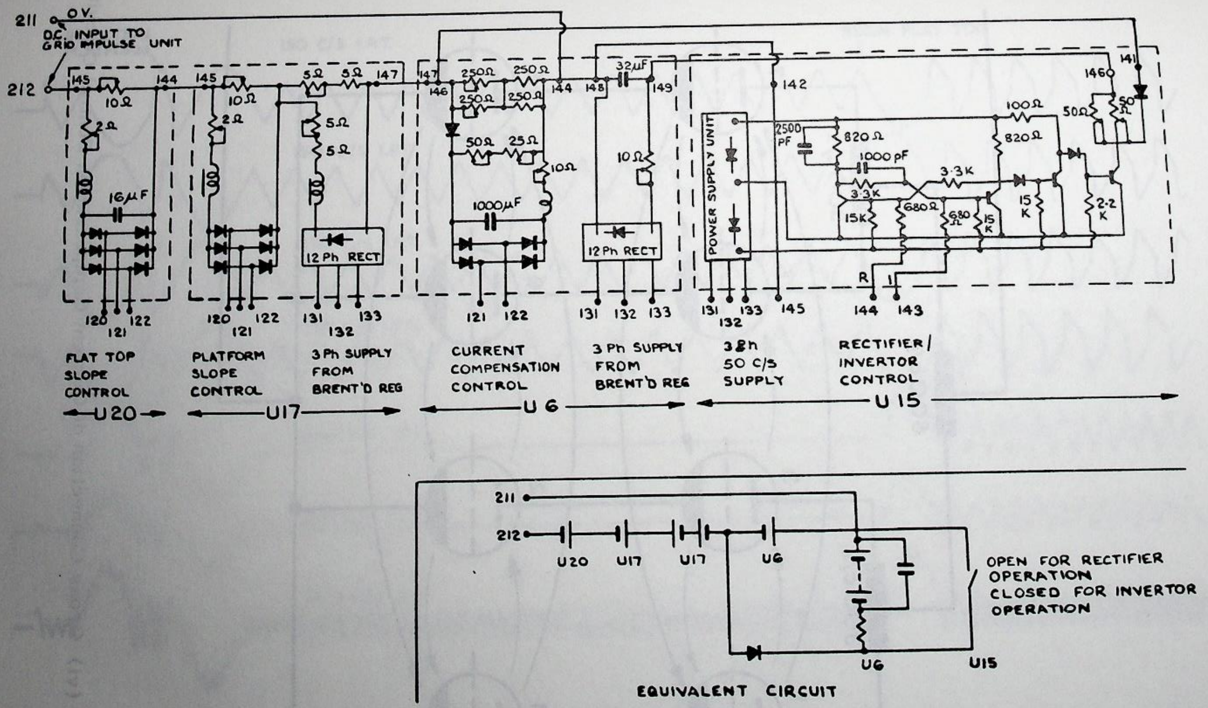


Fig. 5.3.2 (v) Circuit Diagram Showing Components Contributing to the D.C. Input Voltage of Grid Control Units

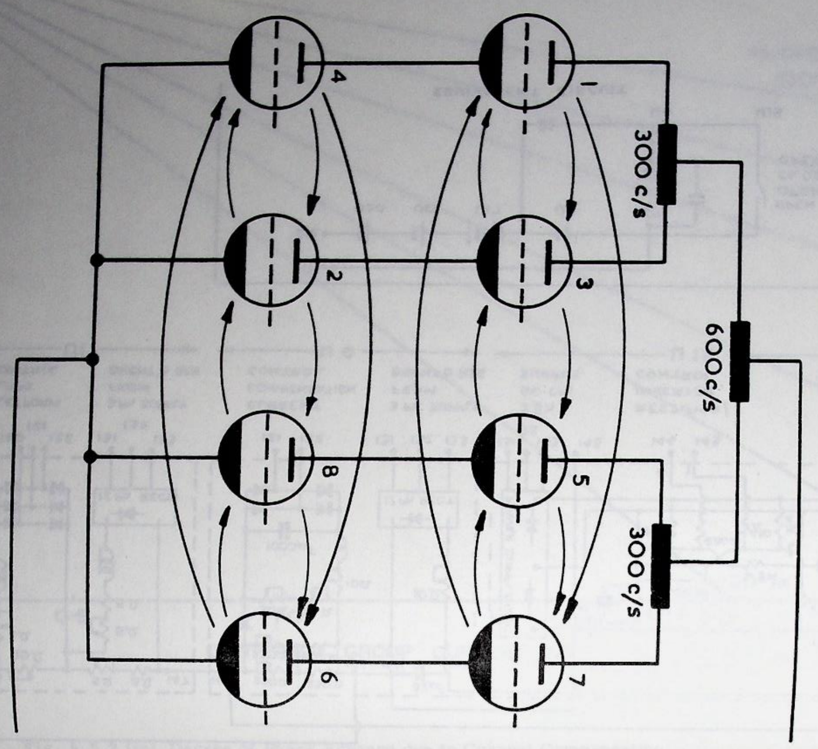


Fig. 5.3.2 (vi) Cross Connection of Current Compensation Control Circuits

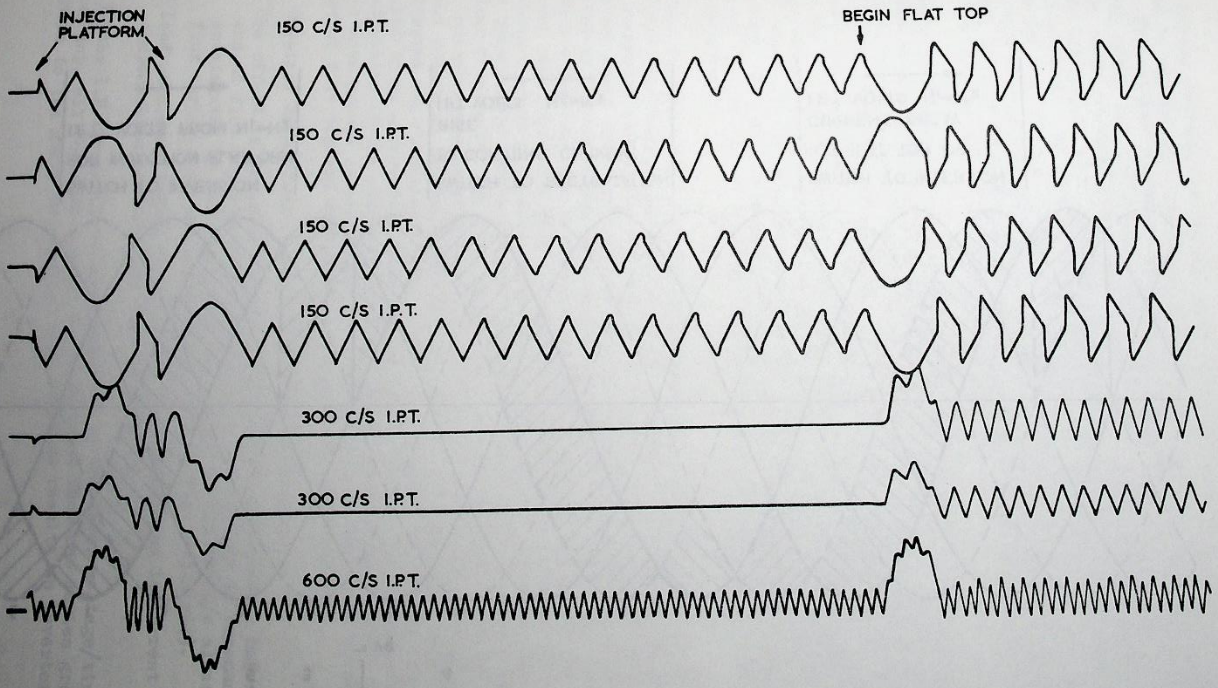


Fig. 5.3.2 (vii) Interphase Transformer Waveforms with Premagnetisation

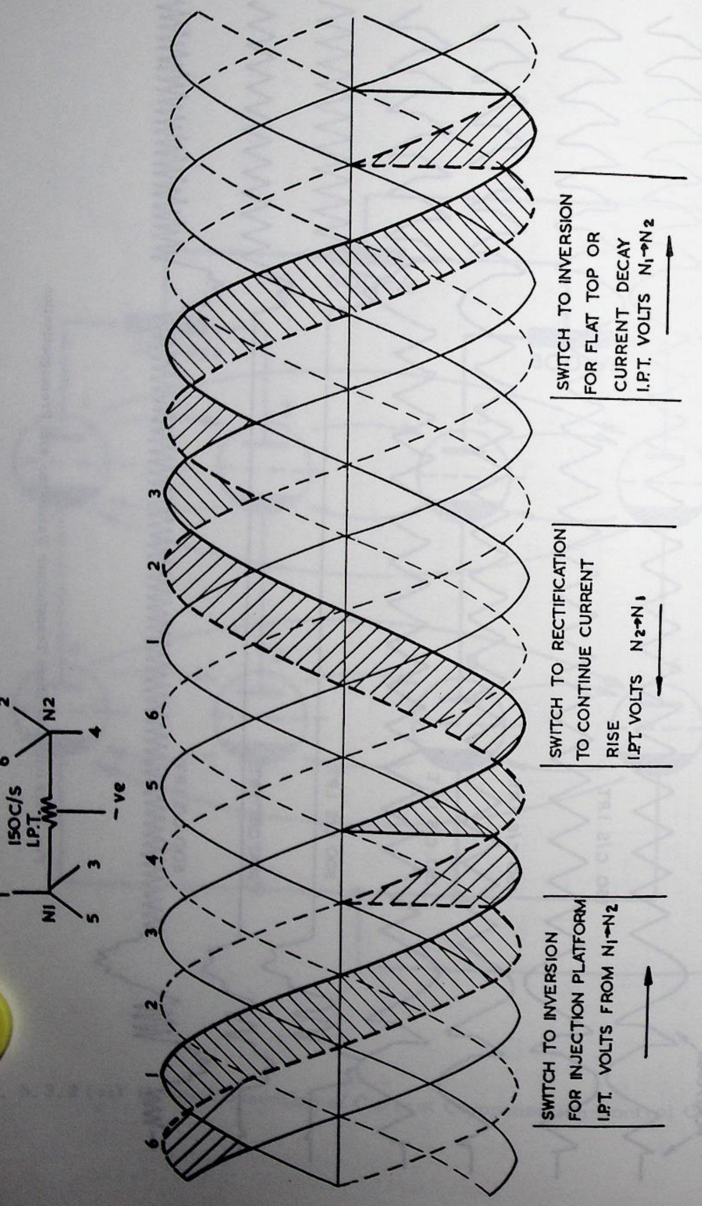


Fig. 5.3.2 (viii) Polarity of 150c/s I.P.T. Voltage Waveforms

output pulses operate via impulse amplifiers and transformers, and multivibrator switches to change the d.c. input level to the grid control units as explained above. This alters the phase position of the grid impulses and gives the required operating mode, i.e. rectification or inversion. The design of the timer is such that the large voltage/time areas to which the I.P.T's are subjected occur in opposite directions each time the convertor operating mode is changed. Fig. 5.3.2(viii) indicates how this occurs for the 150 c/s I.P.T. and the same applies for the 300 c/s I.P.T. This can be seen by reference to Fig. 5.3.2(vii). In the case of the 600 c/s I.P.T. the same condition applies for injection platform, but the flux change at the beginning and the end of flat top are in the same direction and it is not possible to avoid this.

Early operating experience showed that the design of the interphase transformers was such that precise setting up of the grid circuits and current compensation circuits was essential if I.P.T. saturation at the end of flat top was to be avoided, particularly so in the case of the 300 c/s I.P.T's. Fig. 5.3.2(ix) has been drawn to show the effect of current compensation errors on the 300 c/s I.P.T's during flat top. At (c) is shown the I.P.T. waveform when current compensation settings are precise. At (b) the case is shown where there is a 3° error in current compensation and at (a) a $7\frac{1}{2}^\circ$ error is shown. At (c) it is clear that alternate positive and negative voltage/time areas are equal whilst at (a) and (b) this is not so and the d.c. component of flux will quickly cause saturation.

Test results confirmed that the dimensions of the I.P.T's were such that they would not function properly without pre-magnetisation of the core. If the plant commenced operation with the I.P.T. cores fluxed at remanance level, saturation would occur on the first large voltage/time area to which they are subjected at the beginning of injection platform. Fig. 5.3.2(x) is included to show this effect and can be compared with Fig. 5.3.2(vii) which was taken under identical conditions but with pre-magnetisation. Pre-magnetisation is obtained by passing a pulse of d.c. current through the I.P.T. windings from an external source immediately before the commencement of each magnet current pulse. The idealised fluctuation of flux in the core of the I.P.T's is shown in Fig.5.3.2(xi) which indicates the reversals of flux in the 300 c/s I.P.T. In practice the flux does not remain at the pre-magnetising level as indicated but tends always to move towards the remanance level. This is particularly so when the I.P.T's are subjected to an alternating flux change which, due to the hysteresis characteristic of the material, produces a de-magnetising effect. The 300 c/s I.P.T's have proved particularly troublesome in that they tend to saturate at the end of flat top and the probable reasons for this are:-

(i) Physical dimensions of the I.P.T's are inadequate.

(ii) The effect of pre-magnetisation has reduced considerably before the end of flat top time and the core flux has reduced to remanance value, accelerated by the de-magnetising effect of the 300 c/s alternating flux during flat top, which can be seen in Fig. 5.3.2(vii).

(iii) Load unbalance during flat top due to inaccuracies in current compensation control (see Fig. 5.3.2(ix)).

If the I.P.T's saturate when subjected to the large voltage/time area at the end of flat top, all the load current is transferred from one series group of invertors to the group in parallel with it, which results in invertor arc through and a shut down of the plant.

The problem has been overcome by deliberately causing an out of balance of current to exist in the series groups of convertors on each side of the 300 c/s interphase transformers. This produces a d.c. flux in the I.P.T. core in the opposite direction to that to which it is subjected at the end of flat top. This effect has been obtained by introducing small phase shifts in the convertor grid circuits.

(iii) Unsymmetrical Capacity to Earth of the D.C. Connections to the Magnet

During the commissioning stages it was not always possible to use the eight magnet octants as a load and various connections were made to octants as available, in groups of four. Some connections were such that the lengths of cable were dissimilar from the positive and negative terminals of the power plant, and it was observed that under this condition load sharing between the convertor groups was poor. This was due to the unbalanced capacity condition which existed with different cable lengths. Experiments were carried out to simulate the condition under symmetrical cabling arrangements and it was found that although up to 20 μF could be connected between the positive connection and earth with no ill effect on load sharing, a 1.16 μF capacitor connected from the negative terminal to earth could make the plant inoperative.

Investigation showed that on the odd numbered groups of convertors a small step appeared on the leading edge of the grid impulses (see Fig. 5.3.2(xii)) when the 1.16 μF capacitor was connected from the negative terminal of the plant to earth. This step caused premature firing of the anodes and bad load sharing between groups. It was noted that this effect only occurred during full inversion (i.e. magnet current decay period) and that the grid voltage step corresponded with a disturbance in the d.c. input to the grid control units.

The cause of this trouble is not yet clearly understood but it was cured by connecting a 1 μF capacitor across the terminals of the grid control units.

(c) Power Supply Harmonics

The harmonic voltages present in the power supply d.c. output were measured. To do this, an amplifier with tuned negative feed-back was constructed and the results for the case of 10,500 A peak magnet current having a 844 ms flat top with no slope control are given below (Table 5.3.2(I)). All voltages are peak to peak. The harmonics are expressed relative to the fundamental frequency of the alternators, the actual frequency depending on the pulse dimensions and repetition rate. The values given are those at the power supply terminals and take no account of the ripple filter equipment which has not yet been commissioned.

TABLE 5.3.2(I). HARMONIC VOLTAGES

Harmonic	1st (Fundamental)	2nd	3rd	6th	12th	24th	48th	72nd
A1 Power Supply	25	65	30	50	60	250	130	85
A2 Power Supply	30	60	30	50	60	250	125	100

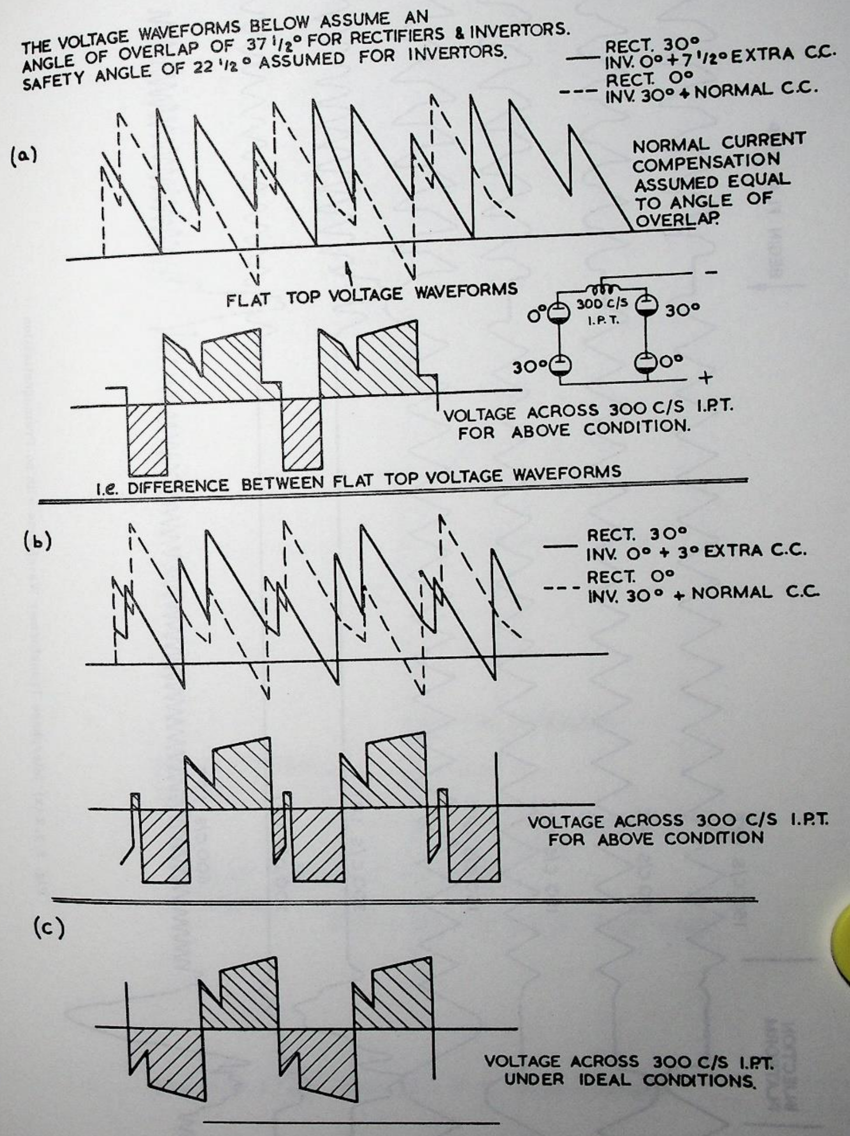


Fig. 5.3.2 (ix) 300c/s I.P.T. Waveforms Showing Effect of Incorrect Grid Phasing

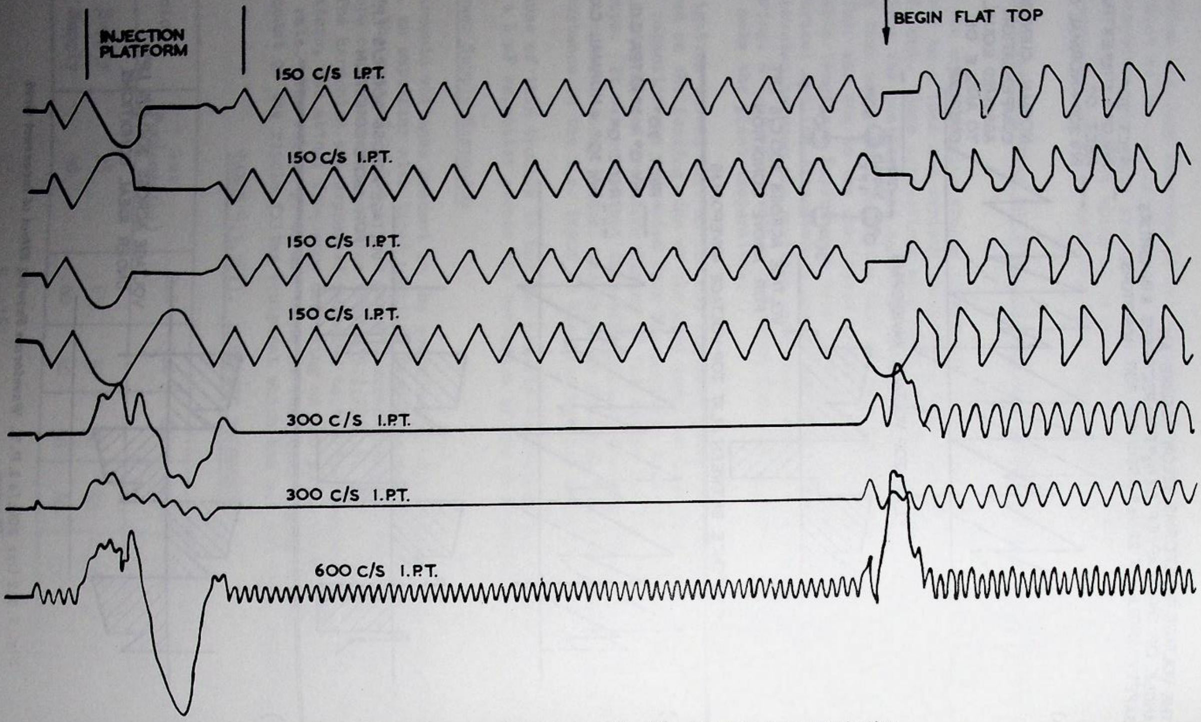


Fig. 5.3.2 (x) Interphase Transformer Waveforms with no Premagnetisation

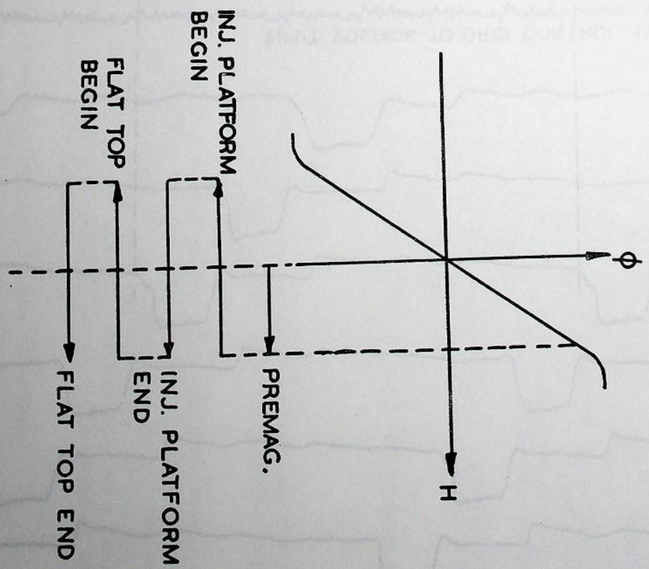


Fig. 5.3.2 (xi) 300 c/s I.P.T. Flux Changes.

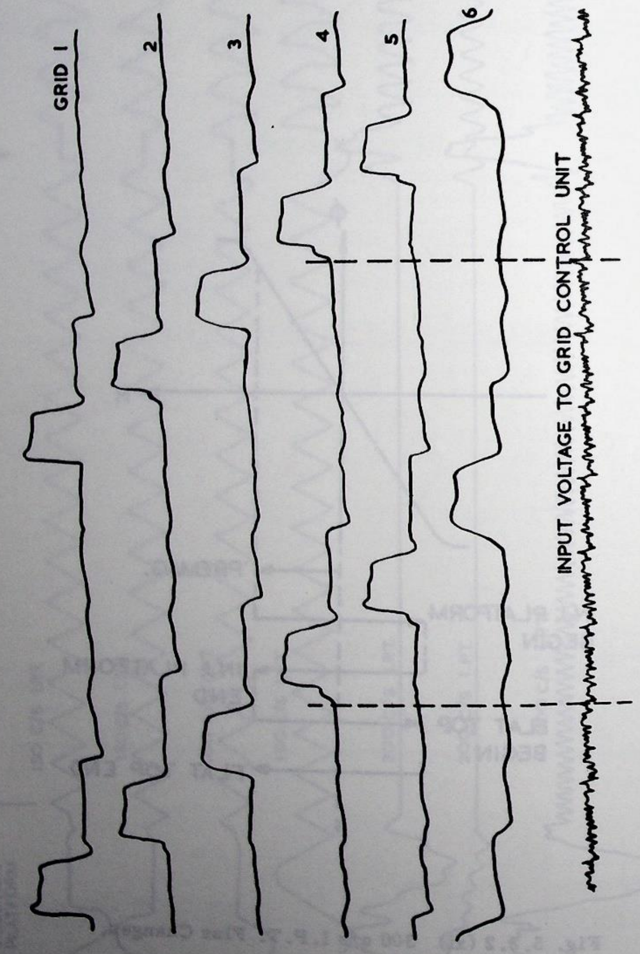


Fig. 5.3.2 (xii) Step on Grid Impulses with Capacitor Connected to Power Supply Negative Terminal

The second harmonic (approximately 100 c/s) was reduced to the value of 65 V peak to peak from a value of approximately 230 V peak to peak. Tests carried out to investigate the cause of the large 2nd harmonic, showed that this was due to a presence of this harmonic in the d.c. input voltage of the grid control units. It was found that this was being generated in the current compensation circuit (see Fig.5.3.2(v)) due to the action of the d.c. current transformers supplying this circuit. By connecting a 1,000 μF capacitor across the circuit the reduction in ripple in the power supply output voltage was obtained. It is felt that inherent inaccuracies of approximately 2° between the impulses of the grid control units largely account for the remaining low frequency harmonics.

(d) Flat Top Slope Control

To enable experiments to be carried out in the beam path of the synchrotron, it is necessary to control the rate of change of the flux during flat top to move the beam radially inwards, or outwards, on to targets. This involves being able to control the slope of magnet current during flat top, and is achieved by a preset variable component in the input voltage to the grid impulse generating units associated with the odd numbered groups of invertors. See Fig. 5.3.2(v). By this means the degree of inversion of these groups is controlled, so that the nett d.c. voltage applied to the magnet is either just sufficient to overcome the circuit IR drop (true flat top), or is more negative or more positive than this value to give negative or positive flat top slopes as required.

A similar control to that explained above is included to control the slope of the injection platform, so as to obtain the precise magnet field level required for injection of protons into the synchrotron.

The flat top slopes possible for 100%, 90% and 80% voltage operation are given in Table 5.3.2(II).

(e) Protection Circuits

For the sake of completeness a summary of the main protection devices on the convertor plant is given, although the detailed commissioning tests carried out on these devices will not be included.

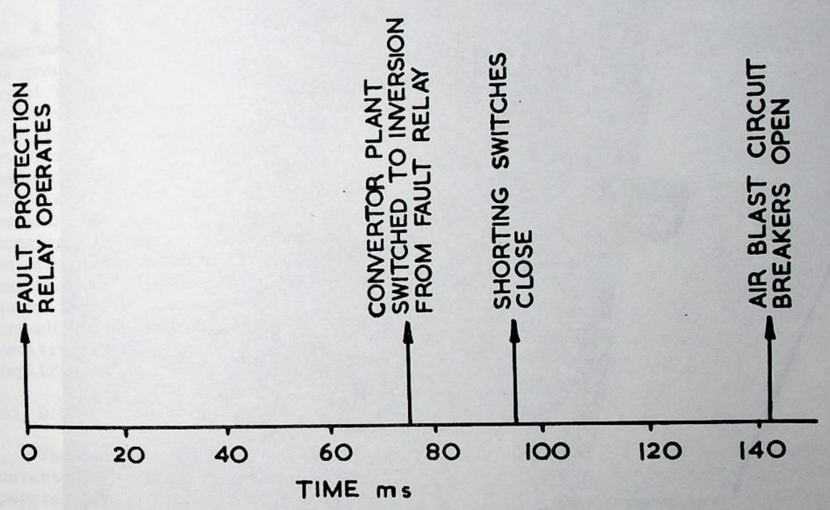
The primary protection on the plant, which operates in the event of a serious fault or overload, comprises two air blast circuit breakers which isolate the convertor plant from the source of a.c. power, and two air operated high speed magnet shorting switches. These items and their position in the power circuit are indicated in Fig.5.1(i). In addition, in the event of a fault, all the convertor groups are switched to full inversion. The order of operation of the primary protection is as follows:-

(i) All convertors switched to full inversion.
(ii) Magnet short circuiting switches close.
(iii) Air blast circuit breakers open.

The times between the inception of a fault and operation of the protection have been measured from an oscillograph and are as indicated on Fig. 5.3.2(xiii).

TABLE 5.3.2(II) MAGNET CURRENT FLAT TOP SLOPES

Alternator Voltage	Magnet Current At Start of Flat Top	Slope Control Regulator Setting	Slope (amps/second)
100%	10,000 A	0	-650
"	"	20	0
"	"	45	+610
"	9,180 A	0	-500
"	"	25	0
"	"	45	+680
"	7,500 A	0	-330
"	"	20	0
"	"	30	+200
"	"	40	+400
"	5,000 A	0	-110
"	"	13	0
"	"	20	+110
"	"	25	+140
"	"	30	+225
"	3,000 A	0	-70
"	"	3	0
"	"	10	+70
"	"	15	+140
"	"	17	+170
"	"	20	+200
90%	9,700 A	0	-820
"	"	37	0
"	"	50	+280
"	9,100 A	0	-800
"	"	20	-140
"	"	37	0
"	7,500 A	0	-440
"	"	32	0
"	"	50	+210
"	5,000 A	0	-240
"	"	20	0
"	"	35	+150
"	"	40	+180
"	3,000 A	0	-90
"	"	10	0
"	"	20	+90
"	"	25	+120
80%	9,150 A	0	0
"	"	20	+380
"	"	25	+530
"	7,300 A	0	-90
"	"	8	0
"	"	30	+380
"	5,100 A	0	-80
"	"	5	0
"	"	30	+225
"	3,000 A	0	-45
"	"	15	+70
"	"	20	+125



Note: It is important that the convertors are switched into inversion before the shorting switches close. Switch into inversion normally takes place via an electronic circuit within a few milliseconds of a protective relay operating. But in the event of failure of this circuit, back up protection is provided via an impulse choke connected across the shorting switch operating coils. The oscillogram from which the times indicated above were taken was a case where switching into inversion was from the back up circuit to prove that this was satisfactory.

Fig. 5. 3. 2. (xiii) Sequence of Operation of Primary Protection

Fig. 5.3.3 (i) Power Supply Control Room

The main protection devices are:-

(i) Back Fire Protection:

In the event of reversal of current a biased off impulse choke in each anode connection provides an impulse which operates a multivibrator to operate the primary protection.

(ii) Arc Through Protection:

A transformer connected from cathode to neutral of each convertor group responds to the large voltage swing in the event of an arc through of any anode of the group. The secondary voltage is connected to a half wave rectifier and the output is applied to a multivibrator circuit, to operate the primary protection. Half wave rectification of the transformer voltage makes the circuit direction sensitive, and it only responds to an arc through from inversion to rectification - not from rectification to inversion. This is a modification incorporated during commissioning. The protection is automatically suppressed below approximately 1000 A and is switched in at this level of magnet current by an impulse choke in the main d.c. busbar. This suppression is required to prevent operation when changing from inversion to rectification at the end of the injection platform. The original arc through protection circuit was not direction sensitive and each time the master timer sent out an impulse to switch the plant to inversion a second impulse was required to operate an electronic circuit to suppress the arc through protection circuit. By modifying the circuit to make it direction sensitive it was possible to delete the protection suppression feature and to simplify the overall circuit.

(iii) D.C. Overcurrent Protection:

The output from d.c. current transformers in each of the series groups of convertors is fed to a biased off multivibrator circuit which can be adjusted to operate at different input levels. There is one multivibrator circuit for each half of the plant and the circuit is so arranged that an overload in any series group will cause the protection to operate.

(iv) Transformer Protection:

A conventional relay in the primary supply to each transformer gives protection against short circuit and overload faults. There is an element in each phase of the supply with time delay and instantaneous settings.

(v) Magnet Overvoltage:

Spark gaps are connected across magnet octants and to earth as indicated in Fig. 5.1(i). In the event of a gap breakdown the fault current causes an output pulse from bi-directional impulse chokes to operate a multivibrator circuit, which in turn operates the primary protection.

(vi) Magnet Earth Leakage:

In the event of an earth fault, a conventional relay operates the primary protection (see Fig. 5.1(i)).

5.3.3. Further Work

Although the initial commissioning tests on the convertor plant had been completed by the end of 1962 there remained a considerable amount of work to be done. Some of the more interesting work then outstanding is summarised here:-

(a) Reduction of Backfire Rate

The backfire rate on the plant was excessive and unacceptable. It was thought that the cause of the backfires was known and further tests were to be carried out by the manufacturers to overcome this trouble. It was considered preferable to delay issuing further details until investigations were completed. The extent of this problem was not fully appreciated until early 1963 after prolonged pulsing periods became available.

(b) Platform and Flat Top Slope Controls

At that time the controls for flat top slope and injection platform slope were to some extent interdependent. Work was proceeding to separate these two controls.

(c) Grid Control Units

The grid control units are standard items of equipment as used on normal industrial installations. For this particular plant extremely precise grid units are desirable, as will be appreciated from what has already been said relative to the problems of load sharing during flat top, saturation of interphase transformers, and low frequency ripple in the d.c. output voltage. Further work was programmed to improve the accuracy of the grid units.

The existing grid control units were not satisfactory from the point of view of access to component parts. Also it was very desirable that the grid control circuits generally should be at earth potential to allow adjustments and checks to be made during plant operation. The possibility of modifying the grid control arrangements to enable this improvement to be incorporated was under consideration.

(d) Modification to Flat Top Voltage Characteristic

It had been found that at the commencement of flat top a re-distribution of the magnet flux takes place which reduces the flux level over the effective part of the magnet octants. This problem is dealt with in more detail in section 4.7.2. Thus at the start of flat top the magnet flux drops to a lower level, and consideration is being given to a modification to the grid control circuits of the convertor plant to produce a d.c. voltage transient to counteract this effect.

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