D C SWITCHGEAR EVALUATION AT WEST DRAYTON

BY

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ABSTRACT

Circuit breakers and fuses can be tested at up to 70 000 amps at 880 volts.

SWITCHGEAR EVALUATION FACILITIES AT WEST DRAYTON

Almost every significant electrical installation contains some form of switchgear and/or fuse. Switchgear testing, therefore, is and always has been a fundamental part of any electrical system evaluation. Records of fuse tests can be traced back to the earliest days of the Admiralty Engineering Laboratory at West Drayton. At that time, however, the facilities were very limited and the rapid increase in the capacity of naval electrical systems soon necessitated the installation of a purpose-built switchgear testing facility which was installed in 1922. The d.c. power source comprised ex-submarine Edison nickel/iron cells of 1917 vintage from submarines B5 and C4. These remained in service until 1933 and were then replaced by a larger installation of lead/acid cells from an 'L' Class boat. This installation was expanded until in 1939 the Test Station capacity was 40 000A at 220V d.c.

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This capacity had been needed to develop improvements to the switchgear of H.M.S. *London* to overcome weaknesses in breaking capacity and discrimination discovered during on-board trials. Expansion of the test facilities continued to enable the switchgear for battleship d.c. power systems to be adequately tested in house, and the fault capacity was increased in stages to 70 000A (70kA) at 220 V. Even so, the requirements for switchgear testing had increased at a faster rate, and higher voltages and currents were required for testing submarine switchgear. In 1950 the main battery room was extended to its present size to accommodate nine battery banks of 106 cells each. Eight of these could be used for switchgear testing and the ninth powered a general purpose 220 V d.c. distribution system. FIG.1 is a recent photograph of this battery room which gives an impression of the enormous installed capacity. This is still one of the biggest single battery installations in the world.

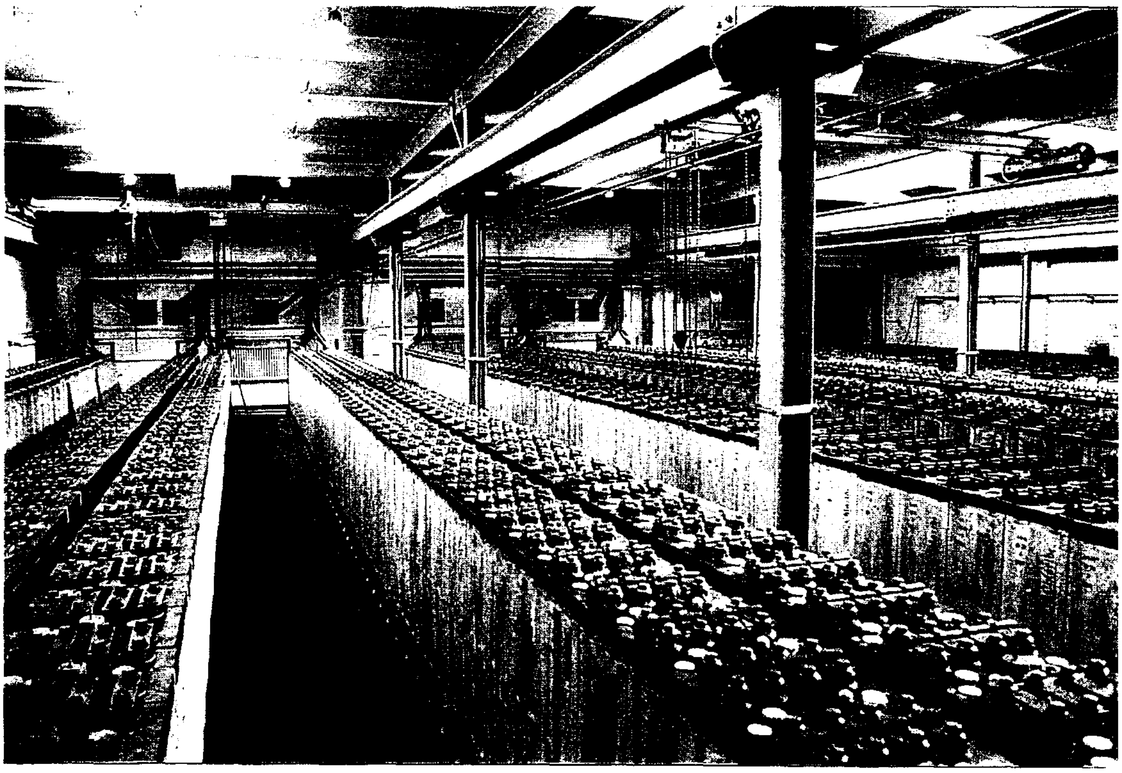

FIG. 1—THE BATTERY ROOM AT WEST DRAYTON

With the battery power of two 'P' Class submarines available, the testing capacity had now been increased to 125 kA at 220 V on 84 kA at 440 V or 52 kA at 880 V. Since then improvements in cell design have increased the fault capacity of submarine batteries, and as 'P' Class batteries were replaced by 'O' Class batteries the limit on the available test current became the test station switchgear rather than the battery capacity. New switchgear installed in 1983 has enabled the maximum levels to be increased to 150 kA at 220 V, 130 kA at 440 V and 75 kA at 880 V, but even at these levels we have not been able to meet all the requirements for testing *Vanguard* and *Upholder* switchgear.

It is a sobering thought that the power delivered by the batteries to the arc chutes of a piece of switchgear tested at the full 880 V level at the instant of contact separation is 66 MW. The energy stored in the circuit inductance tends to raise the total contact voltage by about 50% so the absolute peak instantaneous rate of energy dissipation could be approximately 100 MW.

Fortunately this falls very rapidly over the first millisecond. Total switchgear arcing times are typically in the order of 10–20 ms during which time a total arc energy of around 500 kJ could have been dissipated. Although expressed in joules it does not seem quite so spectacular, it still produces a very creditable bang which never ceases to jar the nerves both of operators and of staff in adjacent office accommodation.

TEST STATION HARDWARE

Power Source

Had it been required from the outset to build a d.c. short circuit test facility of adequate capacity to meet today's demands, the nature of the test station might have been quite different. Commercial test stations of similar d.c. capacity (of which there are very few) all use a medium or high voltage generator—typically 33 kV—similar to the type used in power stations. This is driven up to speed by a motor of smaller rating, and the energy for the test comes from the inertia of the combined set. The electrical power is transformed to the required voltage and rectified to d.c.

The obvious advantage of this arrangement is that the power source is also suitable for a.c. switchgear testing. For commercial test stations, of course, a.c. testing is their main business and the low demand for commercial d.c. switchgear testing has meant that few have retained or installed suitable equipment. Also, of course, batteries contain hazardous sulphuric acid, give off explosive hydrogen and require a lot of maintenance. A final advantage of the rectified a.c. system is that the master circuit breaker controlling the test needs to be of very large capacity, having to be capable of interrupting the full fault power at least once for each test without needing excessive maintainance. High voltage a.c. circuit breakers are by far the most suitable for this job.

So, why are we still using submarine batteries? Well, the historical reasons are clear from earlier paragraphs. Submarine batteries have always been available at virtually no cost to the Establishment and the cost of replacing the existing system would be prohibitive. Apart from the question of cost there are redeeming characteristics of the battery system. Almost all d.c. short circuit testing carried out at RAE West Drayton nowadays is on switchgear intended for submarine use. It is difficult to achieve a good simulation of submarine battery system faults except by using submarine batteries. The problems of the rectified a.c. schemes in this respect are the need to use a high open circuit voltage to achieve the required current, the rapid collapse of the current pulse after the initial peak, and ripple. The large battery installation is also useful as a source of power surges which might otherwise cause problems at the site power supply sub-station and increase our maximum demand charges. Various converted supplies are drawn from the battery including two 1 MW, 440 V, 60 Hz generators which provide a limited capacity a.c. switchgear testing capability. This is used mainly for investigative work rather than type testing for which the many commercial a.c. test stations provide a good service.

Test Circuit

The test circuit used for nearly all short circuit tests is that depicted diagramatically in FIG.2. The battery symbol in this diagram represents the selected battery banks connected in series/parallel combinations by grouping switches and tapped to provide the required voltage. The batteries are

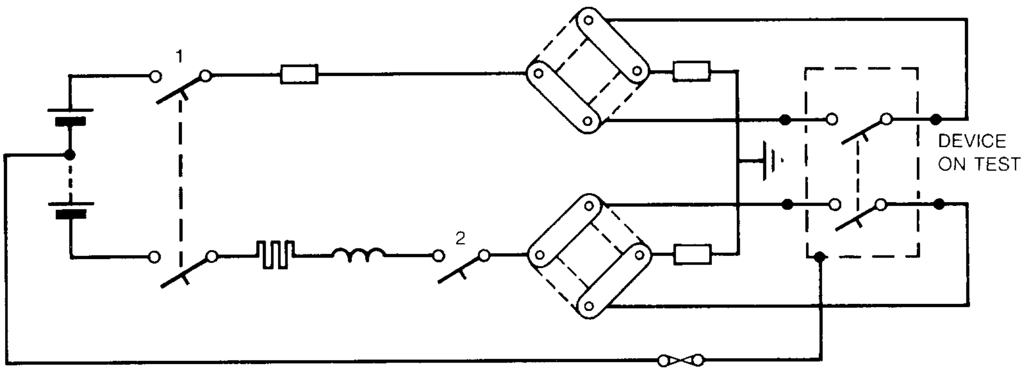

FIG. 2—TEST STATION CIRCUIT
1. MASTER CIRCUIT BREAKER
2. BREAKER THAT INITIATES TEST

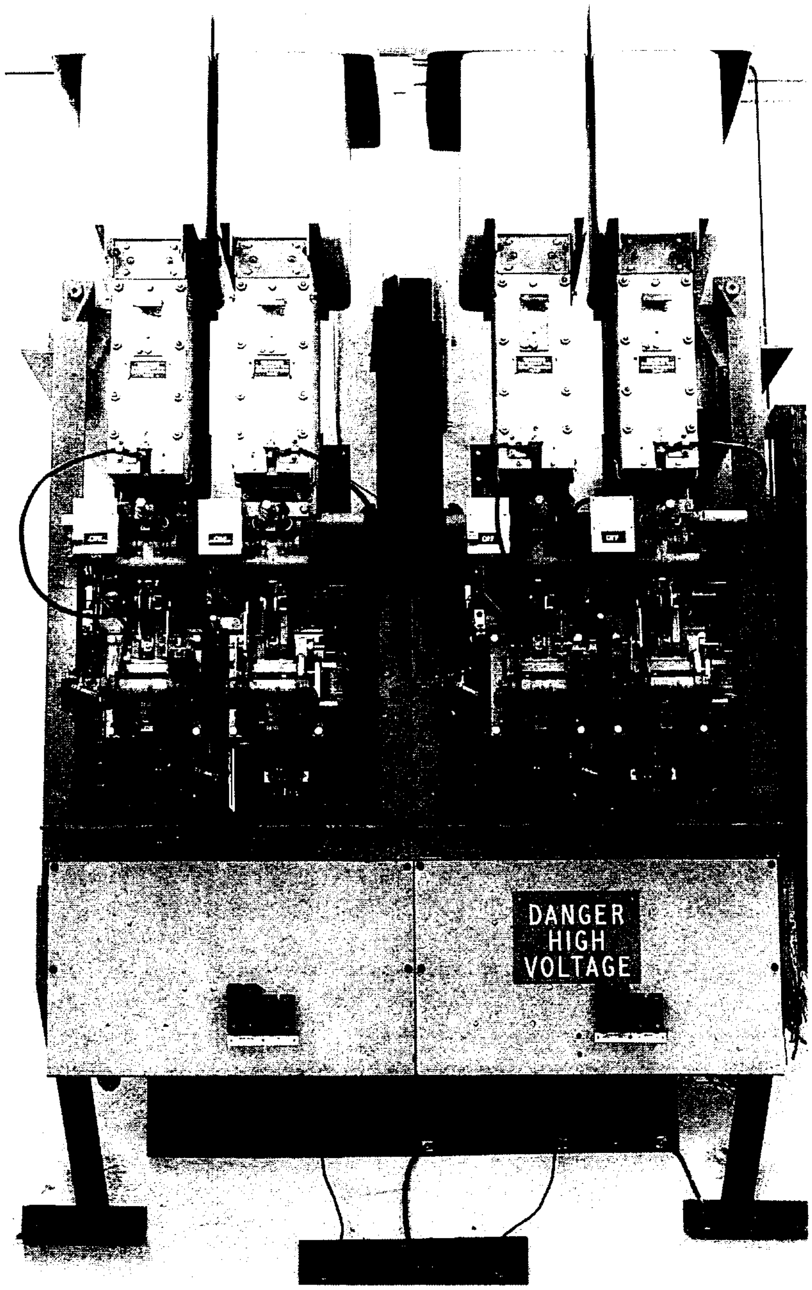

FIG. 3—MASTER CIRCUIT BREAKER

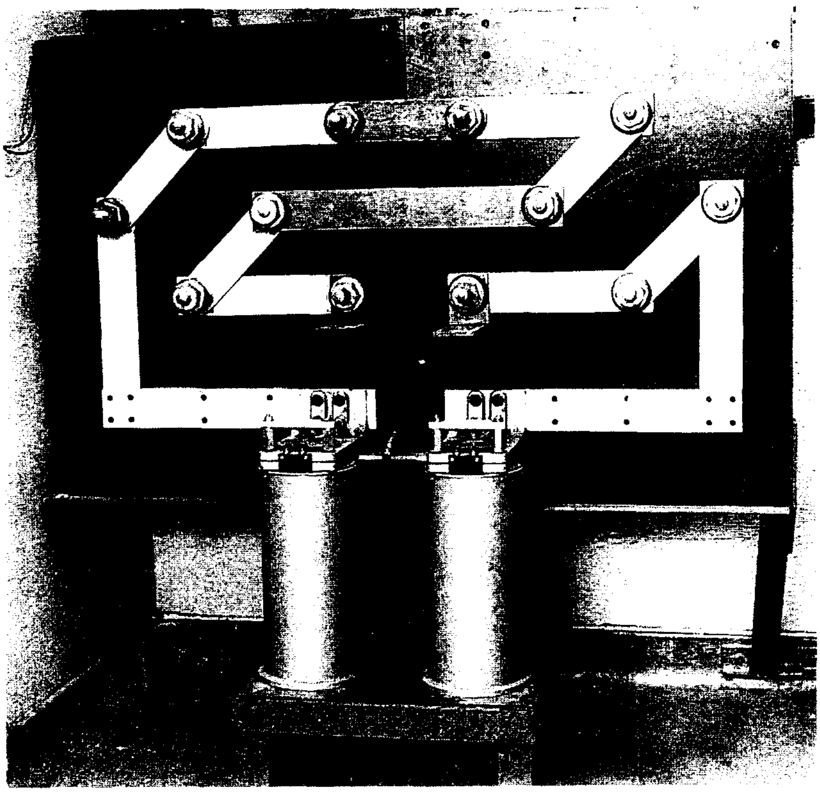

FIG. 4—THE MAIN TERMINAL AND LINK PANEL, TO WHICH THE DEVICE ON TEST IS CONNECTED

connected via the grouping switchboard (not shown) to the master circuit breaker marked as 1 on the diagram. This is situated in the first of three separate cells or bays along with the supply side current measuring shunt. The circuit breaker comprises four Whipp & Bourne type MM74, 6000A, 1500V d.c.—two per pole as shown in FIG.3. According to the manufacturer's specification one per pole would have provided adequate rupturing capacity. However these devices were designed to utilize the electromagnetic force between contacts to cause very fast initial contact separation in advance of the tripping action at high fault levels. For test station use it is essential that the contacts remain firmly closed so that the peak fault current can be demonstrated to confirm its value and so that the test station circuit breakers do not interfere with the action of the device on test. It was therefore necessary to use two breakers in parallel and to use higher than normal contact pressures. The nominal breaking capacity of these devices used normally is 200kA at 1500V d.c. Expressed in VA this is 300MVA which is comparable with the 33kV. 250MVA switchgear used in H.M.S. *Challenger* (also made by Whipp & Bourne).

Following the positive line from the supply side shunt, we come to the current direction reversing links, the low voltage side shunts, and the main test terminals to which the device on test is connected. This equipment is situated in the second of the test cells (see FIG.4). The third cell contains the circuit breaker which closes the circuit to initiate a test (labelled 2 in FIG.2) and terminals for additional resistance and inductance when required. A wide range of resisitance elements are available from relatively high value grid resistors to calibrated lengths of copper cable layed in a trough alongside the test cells. Additional inductance must normally comprise air-cored coils to avoid magnetic saturation effects of iron which would invalidate the inductive calibration of the test circuit. Modified drums of cable serve this purpose. These are situated in the third cell along with the grid resistors and the No.2 circuit breaker.

TESTING TECHNIQUES

Standards

Short circuit testing methods are not specified by any of the Naval Engineering Standards. In order to achieve compatibility with commercial test station results the methods laid down in the appropriate British Standard Specifications are applied wherever possible. The relevant standards are BS 4752 for circuit breakers and BS 88 for fuses. The test circuit was designed basically to comply with BS 4752 but also meets the requirements of BS 88 for fuses and can be adapted to meet the requirements of most other testing specifications.

Circuit Breaker Testing

When a circuit breaker operates, interrupting a load current, an arc is drawn between the contacts. The resistance of this arc is rapidly increased by magnetically expanding it within the arc chute until the arc is extinguished. Circuit inductance causes a voltage to be induced proportional to the rate of change of the current which adds to the supply voltage. At this stage, therefore, there are high voltages and hot ionized gas, spiked with metal vapour and particles, in close proximity within the circuit breaker. These conditions produce a danger of flash-over between live parts and the frame or enclosure of the device. If this happens the device is judged to have failed the test because either the clearances are not adequate for the induced voltages and/or the arc products have not been properly contained.

Under such transient conditions there is bound to be some current flow to earth, if only capacitive, because of the high rates of change of voltage. The difference between this and a flash-over is in the magnitude and duration of the current. A crude but effective test is used to check for flash-over. When the device is mounted in the test station its frame or enclosure is isolated from earth. The frame is then connected to the mid-point of the supply via a fine wire fuse consisting of approximately 100 mm of 0·1 mm diameter fuse wire. The load terminals of the circuit breaker are earthed via the load side current shunts so that the supply side terminals are equally stressed to earth. If sufficient current flows from either pole via the frame to blow the fuse wire fuse this is judged to be a flash over.

This is one of the most common modes of failure of circuit breakers. It is, therefore, very important that the circuit breaker is tested in a representative enclosure. If both poles flash over there is then a short circuit between the live terminals, a condition which may not be all that obvious in a short duration short circuit test. Records of the system voltages will indicate such an abnormal condition but comparison of the supply side shunt voltage record with the load side shunt voltage record is the only way of confirming this. Similarly, insulation breakdown within the test station circuit or batteries which would invalidate a test could be detected by careful comparison of the two load side shunt records.

There are virtually no applications in ships and submarines where short circuit current could not flow in either direction according to the location of the fault, e.g. interconnector circuit breakers. This means that both sides of the device should be capable of being 'supply side' terminals during a fault and the current reversing links are used to enable circuit breakers to be tested in both modes. Inevitably the terminals on one side are physically nearer to the pivots of the operating mechanism and more difficult to insulate. (Hence the convention that the pivoted side of the main poles should be connected as the output or load side of the circuit breaker in normal circumstances.)

The magnitude of the problem for the circuit breakers depends on the total arc energy (∫i.V.dt). Unlike for a fuse, this is usually highest at the maximum fault current, so making and breaking tests are carried out at this level. However the actual arc energy depends on the time at which the contacts open. It is sometimes necessary, even under short circuit conditions, to delay tripping to allow time for circuit breakers further 'downstream' to clear the fault to limit the extent of loss of supply (discrimination). In such cases the tripping of the device on test is controlled by a test station timer so that the contacts part as the current reaches its maximum value. Nuclear submarine main switchgear is tested like this whereas SSK main switchgear can be permitted to trip 'instantaneously' and has integral tripping devices to achieve this. In testing such switchgear tripping is not controlled by the test station. The integral tripping device, set to maximum level, is allowed to do its job, usually cutting off the current before the maximum level is achieved.

It is vital that a circuit breaker can not only break but also make a circuit under fault conditions without welding. The make/break test sequence normally used assumes a pessimistic scenario where a closed circuit breaker trips clearing a short circuit fault but the operator or watchkeeper does not realize the severity of the problem and makes two attempts to reclose the circuit breaker with the fault still present (i.e. one break and two make/break operations). Although this is very unlikely, particularly in a submarine, it demonstrates a healthy safety margin necessary when basing type approval on a single test sample. However if space and weight constraints are such that this would be considered over-engineering, e.g. for a conventional submarine, the testing requirement may be cut to one break followed by one make/break operation.

Currents in the normal operating range of a d.c. circuit breaker can also cause problems and it is usually a current between 3% and 10% of the rated current at which the arc energy peaks because the arc chute magnetic field is now too weak to push the arc plasma up into the arc chute. This is termed the critical current and a second series of tests are normally carried out to check operation at this level also. This often causes more problems than the main test.

Finally, for time-delayed circuit breakers a thorough fault test must be carried out to demonstrate that the device can actually carry the full current for the maximum specified period. For this test the device is closed before the test and does not trip until after the test is over. The maximum capacity of the equipment provides a 1 second test at 150 kA with the maximum duration increasing at reduced test currents with the inverse of the current squared. There are two possible modes of failure. The most likely is contact separation caused by the very high electromagnetic forces and the second is overheating of some component such as a shunt or a connector.

Fuse Testing

Fuse testing techniques are somewhat similar to those of circuit breaker testing but there are significant differences. Firstly, a fuse is normally regarded as a single pole interrupting device, so fuses are tested one at a time with one set of test station test terminals shorted out. This means that one end of the fuse is earthed and the other experiences the full transient peak voltage. Also, because of the symmetry of the fuse, there is no difference between supply and load side so the tests do not have to be repeated in both directions of current flow.

The arc is normally completely contained within the cartridge so there is less chance of a flash-over spoiling an otherwise satisfactory interruption of current. If arc products do escape it is normally through a hole burned through one or both end caps. When this occurs the fuse is considered to have failed the test. Even without such a hole appearing the voltage alone could cause flash-over. Therefore for a formal fuse test the fuse link or cartridge is contained within a metal enclosure with specified clearances. This is connected to the earthed side of the supply via a fine wire fuse to detect flash over as already described for circuit breaker tests.

Because fuses are very compact and rely on the exclusion of ionized air from the cartridge, arcing times are usually very short and the rate of change of current is very high. This can lead to excessive arc voltages which might cause secondary damage possibly of a far more serious nature than the original fault. The limit on arc voltage during a test is a variable parameter but is usually in the range 2 to 2·5 kV for system voltages of 220 to 440V d.c.

The time/current characteristics of a fuse are fixed by its design, construction and, to some extent, its installation (the longer fusing times being dependent on heat conduction form the fuse link). Also for a fuse there is a marked tendency for the total arc energy dissipation to increase as the fusing current decreases. Therefore fuses are tested at a number of different current levels, from the maximum rupturing capacity down to 1·25 times the rated minimum fusing current (usually five different levels) and are more inclined to fail at the lower levels at which the fuse body temperature rise is at its highest.

At intermediate levels, especially for larger fuses, the combination of load and fusing time means that the test circuit can be overloaded, particularly the inductance drums of which only a limited range is available because of space constraints. This is a common test station problem generally and in these circumstances it is allowable to derive the test current for the initial period of the test from an alternative source to preheat the fuse link to near operating temperature so long as the open circuit voltage and circuit inductance are correct at the time the fuse blows. To achieve this the usual technique is to connect a low voltage variable source of current (single phase a.c. normally) directly across the fuse via a two pole circuit breaker. The RMS value of the current is regulated to equal the required d.c. test current until the fuse is about to blow; then the preheating circuit breaker is opened and the test station No.2 circuit breaker closed in rapid succession (gap not exceeding 0·2s) to apply the correct test conditions. This is a nerve-racking task for the operator. He must judge the condition of the fuse by monitoring the volt drop across the fuse which is increasing as the fuse resistance increases with temperature. If he leaves it too late the test is not valid; if too early the test has to be aborted to avoid damaging the test station loads. The consequences of problems with this change-over itself are fairly self-evident.

Other Types of Test

Although the main test types are described above, the test station is very flexible in application and many different types of test can be undertaken. Examples of these are equipment through-fault testing, temperature rise testing and life testing.

An equipment through-fault test checks that components such as switches and contactors and wiring are adequately protected by built in or specified external fuses or circuit breakers. Following such a test some damage is allowed providing the equipment still functions. In the case of contactors, contact welding is normally allowed if the contacts can be readily replaced but in some cases this is not permitted.

A notable example of temperature rise testing was the UPHOLDER Class propulsion control switchboard motor starting resistor testing. For this test three 600 kW switchable load banks were adapted to represent the propulsion motor load. These were controlled in synchronism with the switchboard cam contactors to provide transient loads representative of starting and normal and emergency manoeuvring cycles of the propulsion motor (one armature only).

CONTROL AND INSTRUMENTATION

Synchronization of events is a fundamental aspect of short circuit testing. A breaking capacity test on a circuit breaker provides a good example.

In preparation for the test the instrumentation will have been checked and calibrated and at least one dummy run will have been carried out to check control sequences. Just before the test the No.1 circuit breaker (FIG.2) and the device on test are closed. When the automatic sequence is initiated a bank of electronic timers send out accurately timed control signals. The first stage is to start any non-automatic instruments or cameras (if required). Then the current is applied by closure of the No.2 cicuit breaker. As mentioned already, some devices then trip automatically and others require an external trip signal from the timer. For preliminary tests the No.1 circuit breaker is usually tripped within 50 ms of the opening of the device on test to limit any damage resulting from failure of the device on test. However for the formal acceptance test there must be a delay of at least 100 ms between arc extinction and opening the No.1 circuit breaker. For economy the No.2 circuit breaker is not designed to be able to interrupt the test current and so must always open after the No.1.

If the test is successful it is then necessary to conduct a make/break test. This is very similar to the break test except that the roles of the device on test and the test station No.2 circuit breakers are reversed so that the device on test both makes and breaks the circuit. The final tripping of the No.1 circuit breaker is the most important event in the sequence to ensure that the test current is not allowed to flow too long for the sake of both device on test and test station. Therefore this event is controlled by two independent tripping circuits and timers. This function of circuit breaker operation timing, was not trusted to electronic timers until 1983. Before that the pendulum timer shown in FIG.5, was used. The origins of this device are obscure. It is thought to be of German origin and pre-1914 in date and it may have been bought second-hand.

Since a circuit breaker is assessed in a single series of tests it is important to glean as much information as possible from the test about the operation of the device. Also, if the device fails, comprehensive test records can often help to determine the cause of the failure. A typical circuit breaker test may involve transient measurement of the following :

(*a*) input current;
(*b*) output current;
(*c*) supply voltage;
(*d*) left hand pole arc voltage;
(*e*) right hand pole arc voltage;
(*f*) contact travel recorder;
(*g*) closing circuit current;
(*h*) tripping circuit current.

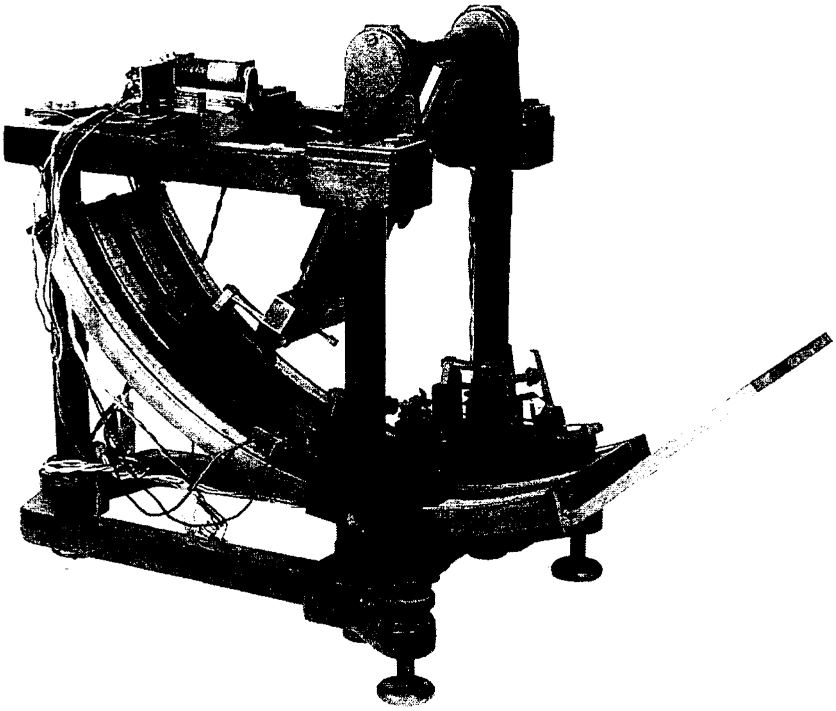

FIG. 5—PENDULUM TIMER

From test we can determine the maximum current, the time delay between closing signal and contact closure, the time delay between tripping signal (if any) and contact separation, the arcing time, the arc energy and the maximum arc voltage. Such records also enable the operation of the test station equipment and the device on test to be checked. For example the circuit breaker mechanism may stick during closure or, because of the high electomagnetic forces, on opening the velocity of the mechanism may be so high that the moving contact bounces reclosed momentarily. The contact travel recorder trace enables such faults to be detected. The supply voltage trace is required to prove that the device was stressed at the specified open circuit voltage for the minimum period of 100 ms after arc extinction.

A parameter not mentioned above is circuit inductance. Before each test series a preliminary test is carried out with the terminals of the device on test shorted by heavy copper links. The main purpose of this test is to show that the test current will actually reach the specified value, called the Prospective Current, but the trace of the current transient can also be used to determine the total circuit inductance.

The smooth rise in current can be mathematically modelled as:

$$i = I_M (i - e^{-t/T})$$

$$T = t \text{ when } i = 0{\cdot}632\, I_M$$

$$T = \frac{L}{R}$$

$$R = \frac{V_o}{I_M}$$

where i = instantaneous current at time t

I_M = maximum current

T = circuit time constant

L = total circuit inductance

R = total circuit resistance

V_o = open circuit voltage

Since I_M and V_o are specified parameters, R is automatically defined; so, for simplicity, inductance is defined by specifying a circuit time constant which is measured directly from the prospective current trace and is usually of the order of 10–15 ms.

This is a very important parameter since the stored magnetic energy which must be dissipated in the arc or arcs is given by $\frac{1}{2}Li^2$. For most fast-acting conventional submarine circuit breakers an increase in L slows down the rate of rise of current and therefore reduces the peak current achieved. This can have the beneficial effect of reducing arc energy. For a nuclear submarine breaker where tripping is delayed to provide discrimination the current always achieves its prospective value. Therefore an increase in L increases arc energy. Unfortunately, in accordance with a well known law of engineering, time constants on conventional submarines (3–5 ms) are much lower than those of nuclear submarines (7–10 ms).

The current pulse measuring shunts have to be of special design so that they have negligible inductance. Conventional shunts produce erroneous output signals while the rate of change of current is high (values of the order of 10 000 000 A/s are not uncommon). Another problem is that the supply side shunt and the supply voltage signals can both carry high voltages to earth during the test and therefore need interposing isolating amplifiers between the test circuit and the recording instrument.

In the past this recording instrument has been either the ubiquitous ultraviolet oscillograph or before that a similar but more cumbersome optical device needing dark-room facilities. Recently it has been possible to replace the analogue ultraviolet oscillograph with an eight-channel digital transient recording system, supplied by Data Laboratories Ltd., which provides better accuracy and frequency response. The frequency response of the analogue device was particularly inadequate for measuring the very fast transient arc voltages from fuses. In contrast the transient recorder can take readings into its memory at up to 2 μs per sample. Transients which cannot be captured at the sample rate are not usually considered significant because of their short duration. Each sample is measured using a 12 bit analogue to digital converter which allows a measurement resolution of 1 in 4096.

Once captured, the transient data is transferred into the memory of a Hewlett-Packard type 9816 computer which enables it to be analysed, processed, stored on disc and plotted on a digital x-y plotter. The computer is programmed to work out the required derived parameters such as time constant, arc energy, etc. This system has improved the quality of the results obtained and the 9 cm discs, which can each store one complete breaking capacity test sequence with eight channels of data, provide a much more durable and useful record of the test than the old ultraviolet traces.

Since most of these records are classed as commercial-in-confidence, a simple fuse test was carried out to provide an example test record for this article. A typical 60A a.c. fuse was chosen to illustrate also the unsuitability in d.c. circuits of fuses designed for a.c. only. A modest but quite typical prospective current level of 35 kA was used at an open circuit voltage of 440 V d.c. with a circuit time constant of 4–5 ms. The time delay between closure of No.2 and tripping of No.1 circuit breakers was set to 200 ms to give the fuse plenty of time to clear. FIG.6 is a tracing of the current record of this test and shows that this fuse was completely incapable of interrupting such a fault. The arc current was in fact increasing as more and more metal melted until it was extinguished by opening No.1 circuit breaker. This test was filmed on a high speed ciné camera and FIG.7 is a print from a frame taken as the arc was decaying. FIG.8 shows the condition of the fuse link after the test.

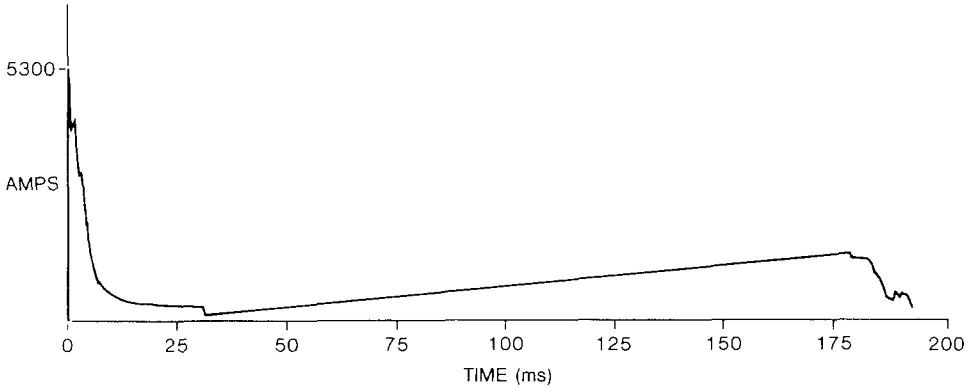

FIG. 6—TYPICAL FUSE TEST CURRENT RECORD

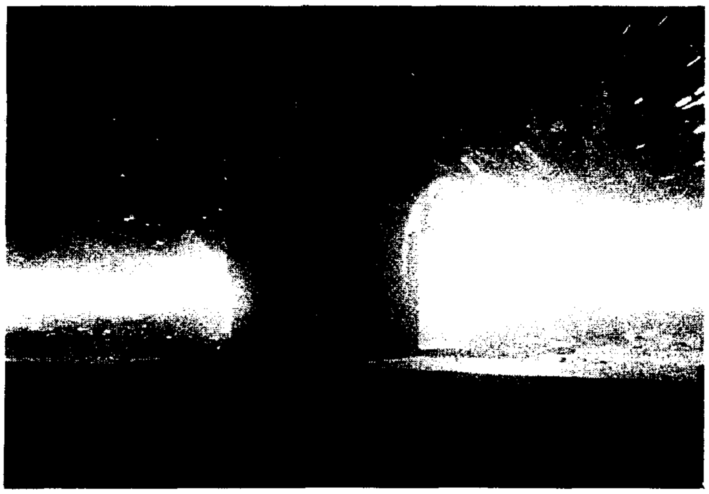

FIG. 7—ARC EFFLUX FROM FUSE UNDER TEST

FIG. 8—FAILED FUSE AFTER TEST

The main difference between this test failure and a fuse failing in an equipment in service is that in tightly packed practical equipment the arc would probably have spread to adjacent conductors causing flash-over between poles and consequent extensive damage and loss of supply.

THE FUTURE

The basic requirements and the techniques used for switchgear testing have not really changed throughout the history of the Establishment. Since they are based on the funamental principles of electrical engineering there is little scope for change. However the scale and frequency of testing requirements have changed and will continue to do so. Already VANGUARD and UPHOLDER Class submarine projects have produced testing requirements beyond the capacity of the existing equipment. Fortunately these have been met by other testing stations, namely the Brown-Boveri Electrical Testing Laboratory in the U.S.A. and that of Switchgear Testing Company Ltd, at Manchester. Only the American test station could meet the highest level VANGUARD d.c. switchgear testing requirement.

The RAE Naval Engineering Department's test station at West Drayton was, however, able to meet most of the testing requirements for these projects and is currently undertaking work for SSN 20. Essential in-service submarine fleet support requirements, together with possible future submarine projects and the increasing interest in electric propulsion systems for surface ships provide definite pointers to a continuing need for such facilities in the foreseeable future.

In today's climate of change with increasing emphasis on value for money, the long-term future of all the test facilities at RAE West Drayton is under continual review. Much depends on the availability of suitable alternative facilities, and in this respect it should be noted that the trend in the commercial field is away from large d.c. systems and the naval requirement is becoming increasingly unique. A possible way ahead may be indicated by the Defence Research Agency proposals for some form of commercial status for the Establishment. This would present a formidable challenge but, with the knowledge that the Establishment meets a real and continuing need, the future, whatever it may hold, can be faced with a justifiable degree of confidence.