RAPID CYCLE TESTING OF HIGH CURRENT IGBT POWERSWITCH MODULES

BY

LIEUTENANT S. LARGE, BENG, MSC, CENG, MIMARE, RN
(Warship Support Agency – MLSIPT)
AND
MR P. WALKER, BENG, AMIEE
(Ultra Electronics (PMES Ltd))

This article is an updated version of the paper first presented at the Power Electronics and Variable Speed Drives Symposium *at the IEE on 18 September 2000*

ABSTRACT

Failure mechanisms of Insulated Gate Bipolar Transistor devices under conditions of deep thermal cycling are well documented, but available data does not apply directly to their operation within switching converters. To demonstrate acceptable reliability and performance of the IGBT powerswitch modules proposed for the ASTUTE class Submarine Main Static Converter, this application specific programme of rapid cycle testing was devised.

Introduction

The introduction of new technology into existing equipment generates the risk of long-term reliability problems.[1] The introduction of Insulated Gate Bipolar Transistor (IGBT) powerswitches into a bi-directional Main Static Converter (MSC) for application in the ASTUTE class nuclear submarine represented such a change and required risk mitigation.

The MSC directly replaces the motor generators fitted in previous classes of submarines to provide the bi-directional link between the nominal 230V DC distribution system, with its bulk energy storage, and the 440V 60Hz AC system that is normally supplied by Turbo Generators, (FIG.1).

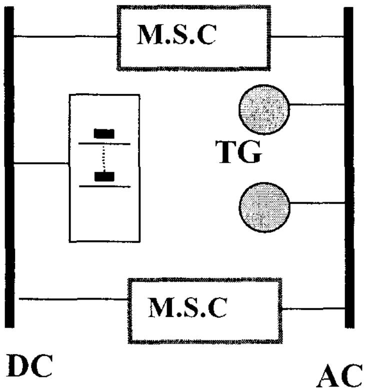

FIG.1 – BASIC SYSTEM CONFIGURATION

The static converter was originally designated as the Submarine Static Converter (SSC) and utilized Gate Turn-off Thyristor (GTO) devices. Two of these prototype converters were constructed and have been tested at DERA West Drayton, at sea in HMY *Britannia* and at the NRTE facility at Dounreay. Each of the prototypes has now been run, without failure, for a considerable period.

Early in 1998 it was decided that the SSC should be modified with IGBTs replacing the GTOs to obtain clear performance benefits. Much of the testing completed on the SSC would still be relevant to obtaining safety justification of the modified design, the MSC. However, the failure of IGBTs under conditions of deep thermal cycling is well-documented[2,3] and it was considered necessary to demonstrate the reliability of the IGBT powerswitch over the life of the submarine. To achieve this the Rapid Cycle Testing (RCT) project was devised.

IGBT powerswitches of high current capability, were developed for naval application through contracts placed on Ultra Electronics (PMES) by DERA. The IGBT powerswitch contained: laminated busbars, electrolytic and de-coupling capacitors, a current transducer and the gate drive circuitry all associated with the IGBTs themselves, (FIG.2). This module was designed with maintainability in mind as a 2-man lift.

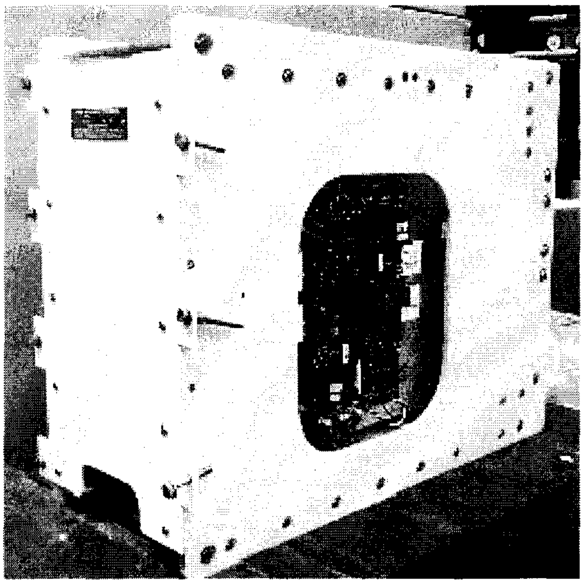

FIG.2 – THE HIGH CURRENT IGBT POWERSWITCH

Late in 1998, the MoD placed a contract for Stage One RCT on PMES. This involved the application of large cyclic load transients to these IGBT powerswitches connected in a realistic H-bridge converter configuration in order to demonstrate their suitability for long term military application. Each H-bridge was constructed from 2 identical IGBT powerswitches. These were subjected to an intensive test period, representative of every transient event predicted to occur during the total operational life of all the IGBT powerswitches in not one, but 5 submarines. The cycle profiles applied were formulated from a detailed operational analysis of the proposed application supported by corporate experience of the motor generator.

A contract amendment to include Stage 2 of RCT was raised early in 2000. This involved testing the IGBT powerswitches under extreme cyclic load conditions. This stage of testing was devised to increase our confidence in the durability of the powerswitch and our knowledge of its behaviour under the most extreme operating conditions. Practical limitations of this IGBT powerswitch and hence its suitability for wider application were investigated. The authors believe that this final stage of RCT exceeded what has been attempted previously.[1]

TEST SYSTEM

RCT arrangement

The RCT system comprises of two independent Test Rigs, each of which contains 2 IGBT powerswitches configured in a single phase H-bridge inverter arrangement feeding an inductive load. The test rigs are forced air cooled in a similar manner to the MSC. A nominal 350V dc supply to the test rig is generated by a transformer and rectifier unit operating from a 415V 50Hz supply.

The test rigs were operated at a modulation frequency and a device switching frequency representative of the MSC. A bipolar switching strategy was adopted and the electrical stress imposed on each of the four IGBT powerswitches in the 2 Test Rigs was identical. (FIG.3) shows a schematic diagram of one RCT Rig.

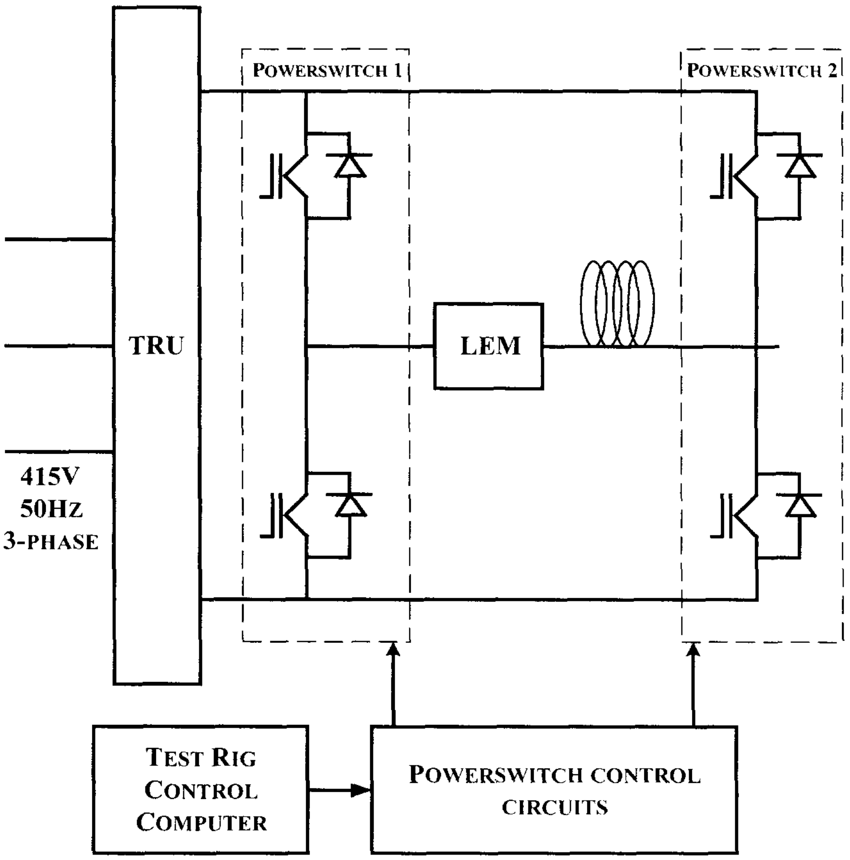

FIG.3 – RCT RIG SCHEMATIC

Test rig control computers

Dedicated computers perform the control function for each of the test rigs. Each test rig also possesses a data logger that downloads information to a single data logging computer.

The test rig control computer generates Pulse Width Modulated (PWM) control signals and performs closed loop control and protection functions. It also provides a display of test rig status and records run data, which includes elapsed time, electrical cycle parameters, thermal cycle parameters (Stage 2 RCT only) and IGBT powerswitch control temperatures.

Data logging computer

Each test rig contains a dedicated data logger. The information recorded by each data logger is downloaded to the data logging computer. Parameters recorded include: DC voltage, AC load current and IGBT powerswitch component temperatures.

STAGE 1 RCT

Milestones were devised to consider RCT against predicted operation of the IGBT powerswitches within the ASTUTE MSC, these are listed in Table1.

TABLE 1 – *Stage 1 RCT Milestones*

Milestone Name	Milestone Description	Number of Rig-Cycles	Comments
Equal NRTE Power Reversals	Equal the number of GTO powerswitches x power reversals achieved at NRTE.	450	450 cycles of one rig, or 225 cycles each of two rigs.
One Powerswitch-Boat Life	(Powerswitches x cycles) equals number of cycles that one powerswitch will see in 25-year boat life.	753	753 cycles of one rig, or 376 cycles each of two rigs.
One Boat Life	(Powerswitches x cycles) equals (Cycles in one boat life) x (Powerswitches involved in cycles)	22,575	22,575 cycles of one rig, or 11,288 cycles each of two rigs.
Three Boat Lives	(Powerswitches x cycles) equals (Cycles in three boats in 25 years) x (Powerswitches involved in cycles)	67,725	67,725 cycles of one rig, or 33,863 cycles each of two rigs.
Five Boat Lives	(Powerswitches x cycles) equals (Cycles in five boats in 25 years) x (Powerswitches involved in cycles)	112,875	112,875 cycles of one rig, or 56,438 cycles each of two rigs.

No failures occurred during Stage 1 for a total of 113,522 electrical cycles (60,581 cycles were completed on Test Rig 1 and 52,941 cycles on Test Rig 2). The total IGBT powerswitch operating time amassed during this period was 1,491 hours.

Test profile

During Stage 1 RCT, the IGBT powerswitches were subjected to a repetitive electrical cycle that was formulated to replicate the maximum electrical stress that can ever be expected to be imposed during its operational life. This will occur both during power reversals and under AC short circuit conditions. In these circumstances the MSC will operate according to its overload characteristic.

(FIG.4) illustrates how the RCT profile adopted replicates the MSC overload characteristic during the initial 5 seconds.

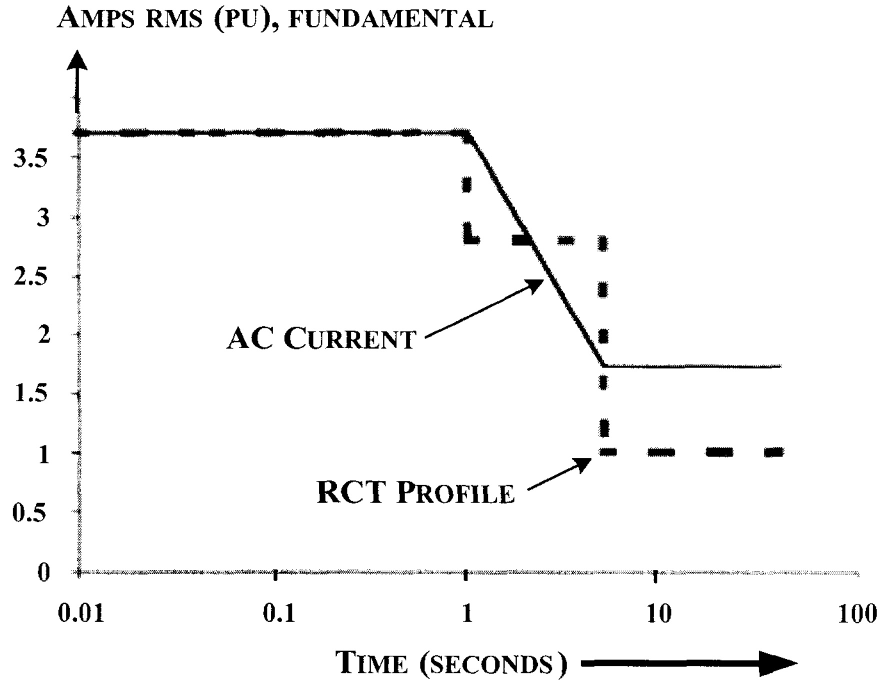

FIG.4 – PREDICTED MSC IGBT POWERSWITCH OVERLOAD PROFILE

DATA ANALYSIS

Current profile

The Stage 1 RCT current profile (45 second duration) is shown in (FIG.5) together with spot measurements recorded on Test Rig 1 data logger over one electrical cycle. The same series of measurements were recorded for every electrical cycle completed by the two test rigs during the test period.

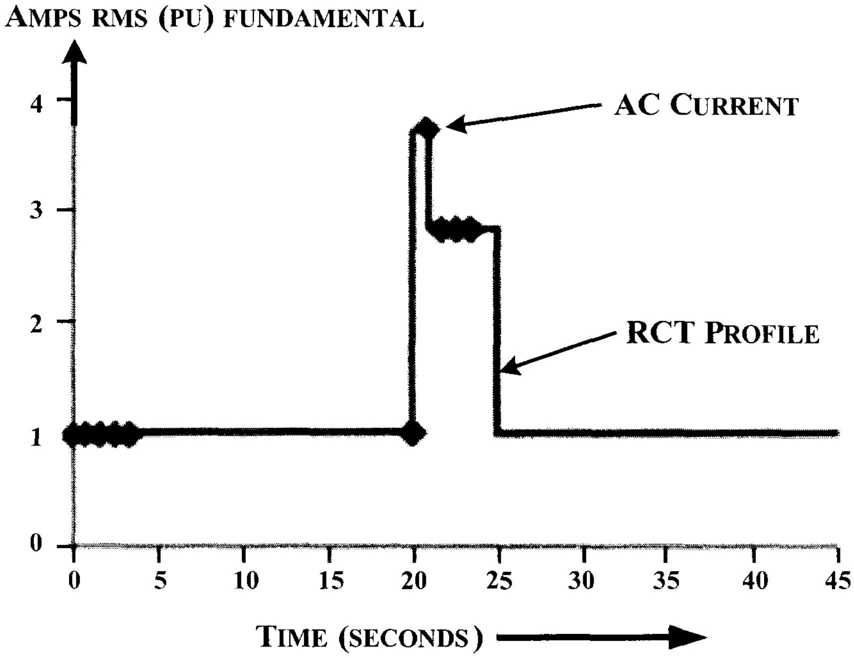

FIG.5 – CURRENT PROFILE – TEST RIG ONE

Calculated thermal performance.

The calculated device losses for the three constituent steps of the Stage 1 test profile are shown in Table 2. The loss calculations assume typical data sheet derived values for the IGBT and Diode on-state voltages and switching losses.

TABLE 2 – *Calculated Device losses*

Step	Duration (sec)	Current (pu rms)	Device Loses (W)
1	1	3.7	4224
2	4	2.8	2840
3	40	1	787
Total	45		

From the device losses and the thermal impedance of the cooling circuit, the heat sink to cooling air temperature rise is calculated at 30.3°C. In practice, a temperature deviation exists across the heat sink surface and some heat is radiated in other directions, therefore this figure is only approximate.

The device losses do not correspond directly with those for the MSC powerswitch, because of different load power factors. For the RCT arrangement, the load is highly inductive and a greater proportion of the load current (i.e. almost half) is handled by the diodes.

The device losses for the MSC were calculated at 787W at full load (i.e. step 3) and 4,224W for the one second overload duration (i.e. step 1). These are very similar to the RCT device losses, and hence the thermal performance of the IGBT powerswitch during Stage 1 RCT is directly relevant to the MSC.

The junction to heat sink temperature change for both IGBTs and diodes were calculated using the maximum thermal impedance figures provided in the manufacturer's device data sheets:

Module R_{thCK} = 0.008°C/W
IGBT R_{thJC} = 0.0125°C/W
Diode R_{thJC} = 0.021°C/W).

Assuming similar temperature rises for the MSC and a cooling air temperature of 65°C, the junction temperature was predicted to reach 105.9°C for the IGBT and 105.2°C for the diode during the overload condition. This assumed that the heat sink temperature would remain constant throughout the short duration of the overload.

The maximum permissible junction temperature for the devices is stated as 150°C, but common practice to apply a working limit of 125°C was applied. Consequently, the predicted junction temperatures were well within the capability of the devices.

Measured thermal performance

The internal component temperatures were recorded for each IGBT powerswitch under test over the duration of Stage 1 RCT.

The IGBT heat sink to cooling air temperature rise for each IGBT powerswitch was measured on the surface of the heat sink and the air temperature was approximated to the mean of inlet and outlet temperatures.

The operating temperatures measured on Test Rig 2 were several degrees higher than those on Test Rig 1, which was attributed to a variation in ventilation across the test cell area.

Slight variations in operating temperatures were also noted between the IGBT powerswitches in each test rig. Subsequent measurements revealed that this was due to small differences in airflow. This was attributed to manufacturing tolerances. Despite these differences, the heat sink to ambient temperature rise for each IGBT powerswitch was consistent at approximately 20.5°C. Factors contributing to this deviation from the calculated temperature rise of 30.3°C are likely to be a high estimate of device losses, the assumption that 100% heat transfer occurs through the heat sink circuit and a variation between actual and specified thermal performance of the heat sink.

The heat sink to ambient temperature rise for all four IGBT powerswitches was observed to fall with time, before stabilizing after 4 weeks. This trend was confirmed by measurements taken from the data logger thermocouples and a platinum resistance sensor, which provided inputs to the control computer. This effect enabled cycle time to be reduced (i.e. an increase in device losses) without significantly increasing the actual heat sink temperature. This change in thermal performance was attributed to the 'forming' of thermal paste between the device module base and surface of the heat sink.

The electrolytic capacitor case temperatures were also monitored over the duration of Stage 1 RCT.

The capacitor bases were themselves mounted on heat sinks whose fins were subjected to the main cooling air stream through the IGBT powerswitch. Additionally, the capacitor cases were cooled by air that was bled through the remainder of the IGBT powerswitch.

Assuming similar temperature rises for MSC and a cooling air temperature of 65°C, the capacitor case temperature was predicted to reach 80°C. This assumed that the case temperature remained constant during the very short duration of the overload.

The maximum allowable case temperature is stated as 85°C and, although higher than the predicted maximum operating temperature, the design was considered marginal. In order to increase the margin, the capacitors used for the IGBT powerswitches were supplied without plastic casing to improve heat transfer.

The step application of an overload (3.7pu rms) from full load (1 pu rms) resulted in an IGBT junction temperature rise of $\Delta T_J=7$°C.

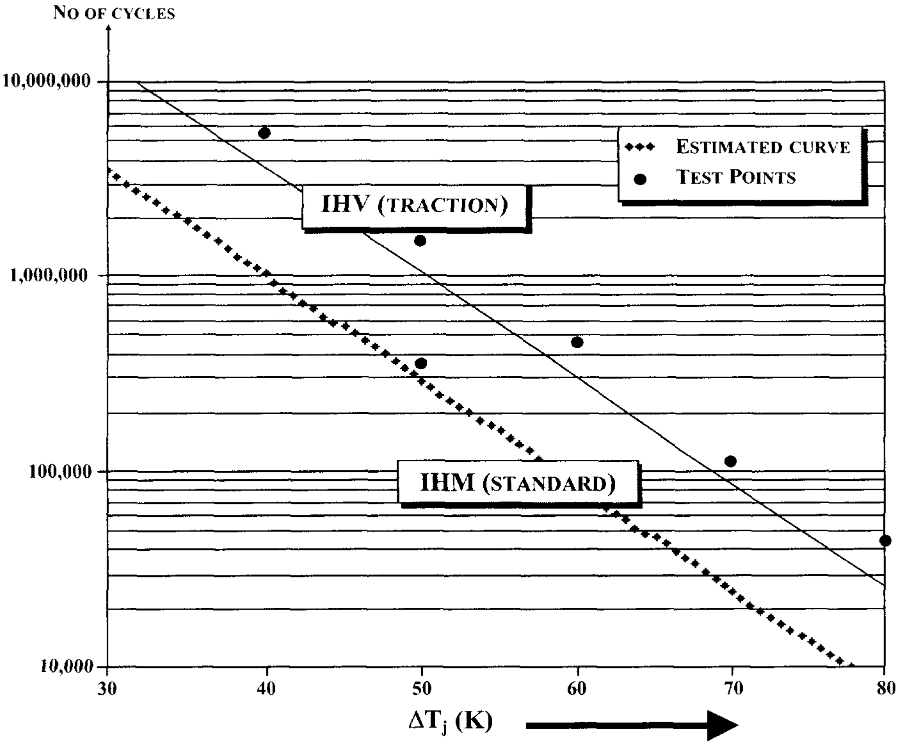

FIG.6 – MANUFACTURER'S TEMPERATURE CUCLING DATA[3]

The temperature cycling capability (Coffin-Manson Lines) for the flat packed IGBT module used is shown in (FIG.6).

It shows that the IHM module is capable of over 3 million cycles at $\Delta T_J=30$°C before any device degradation occurs. It is clear therefore that the $\Delta T_J=7$°C imposed during the Stage 1 RCT could not be expected to have any noticeable effect on the performance of the device.

STAGE 2 RCT

Stage 2 RCT was designed to subject the IGBT powerswitch to a higher thermal stress than that expected in the MSC. The purpose of Stage 2 RCT was to examine the failure modes of the IGBT powerswitch components under conditions of deep thermal cycling. In particular, the tests subject devices to a defined junction temperature rise and enable published failure modes to be investigated under representative operating conditions. A further aim was to quantify the operational life of the IGBT powerswitch and to ascertain the practical limitations to its future application.

Using both of the test rigs previously described it was possible to execute two distinct thermal cycles simultaneously.

The IGBT devices selected for the MSC were housed in IHM (standard) packages and have a temperature cycling capability predicted by the manufacturer as shown in Figure 6. In order to meet the constraints of the project and complete Stage 2 RCT to schedule it was necessary to subject the IGBT powerswitch to higher values of ΔT_J than that normally designed.

Failure Modes

Flat-pack IGBTs are characterized by a large number of wire contacts. A typical high power IGBT module contains 450 wires together with 900 wedge bonds.[3] Thermal cycling has been identified as the cause of 2 distinct primary failure modes, which depend upon the value of ΔT_J.

> *Junction Thermal Cycling Fatigue*
>
> In cases of highly cyclic load duties, with $50°C < \Delta T_J < 65°C$, the repetitive heating and cooling of the soldered wire bonds has been shown to be a major cause of failure. The weakness of the bonding technology has, historically been responsible for IGBT reliability shortcoming.[3]
>
> *Tile Thermal Cycling Fatigue*
>
> In cases with extreme junction temperature excursions, $\Delta T_J > 75°C$, failure of the device tile solder bond has been reported. A mismatch between coefficients of thermal expansion generates high stresses within the solder layer, between the copper base-plate and the ceramic substrate, which induce crack propagation and delamination.[3]

Test profile

The test rig cooling system was disabled and a load of 600A rms 60Hz fundamental, with ripple components, was applied. In this condition, the rig was natural air cooled until the heat sink temperature reached an upper limit. The test rig cooling system was then enabled and the load removed. In this condition, the rig was forced air cooled until the heat sink temperature fell below a lower limit. (A lower limit of 5°C above ambient and an upper limit of 107°C were applied for both test rigs.)

A typical temperature profile is shown in (FIG.7). This shows an almost constant temperature rise followed by an exponential cooling to near ambient. The temperature cycle (axis not indicated) was approximately 47 minutes.

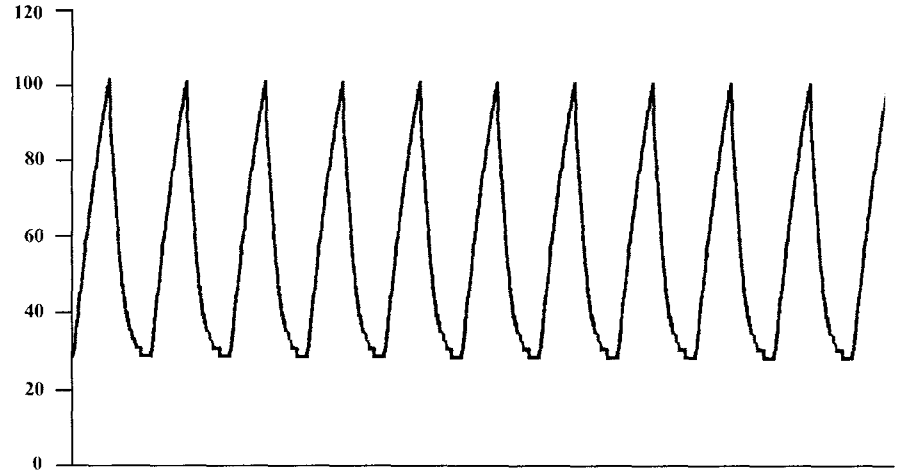

FIG.7 – TEMPERATURE PROFILE FOR TEST RIG 2 ($\Delta T_J = 75°C$)

A calibration check was carried out on the devices at weekly intervals.

STAGE 2 TEST RESULTS

Completed Cycles

The predicted capability of the IGBT modules and the actual test profiles achieved during Stage 2 RCT are indicated in Table 3.

TABLE 3 – *Stage 2 progress*

Test Rig	ΔT_J (°C)	Predicted No. of Cycles	Cycles Achieved	Average Cycle Time (mins)
1	65	>45,000	4,954	41.4
2	75	>15,000	3,385	47.1

The duration of the test period was approximately 24 weeks. To achieve the predicted number of cycles that were indicated in Table 3 would have required extensive modifications to the test arrangement. This could not be accommodated within the budget of the project. The cycles achieved therefore represent the best attempt, but clearly do not approach the total required to invoke the two identified modes of failure.

Calibration tests

At regular intervals, a calibration check was carried out on the IGBTs. The objective of this test was to detect any change in the Saturation Voltage (V_{CE} Sat) of the IGBT over time.

Observations

An unexpected occurrence was observed for one IGBT module within each of the powerswitches of Test Rig 1. This was detected during the calibration tests at week 20. At this time over two and a half thousand thermal cycles had been completed, each cycle covering a range of 65°C. During these tests the value of V_{CE} Sat at a constant current of 200A has been recorded weekly for each of the IGBTs in the Powerswitch. At week 20 the V_{CE} Sat measured across two IGBTs decreased markedly. V_{CE} Sat should be 1 volt, but the reading was seen to fall as low as 700mV for one of the IGBTs and was seen to fall intermittently on the other. (FIG.8) shows the drop in saturation voltage (in millivolts) over the test period (in weeks).

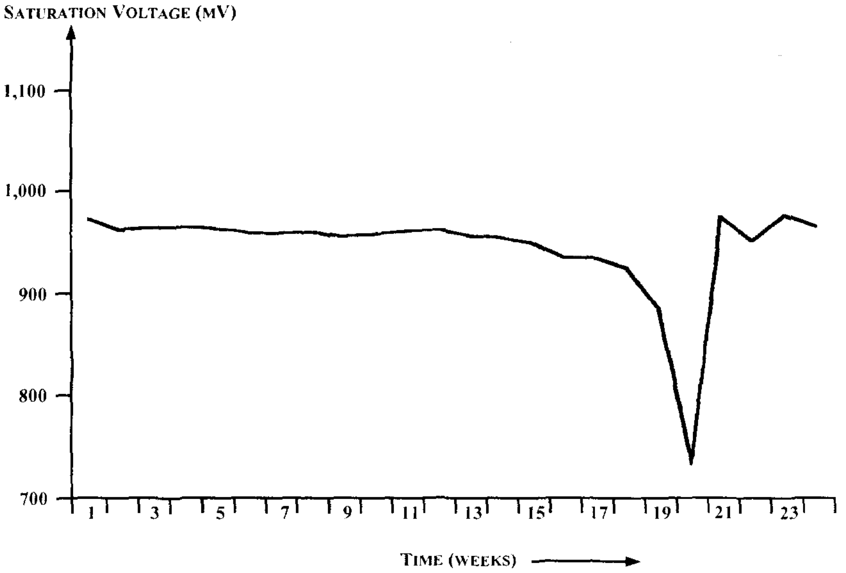

FIG. 8 RECORDED SATURATION VOLTAGE (MV)

It was suspected that the auxiliary contacts, from where V_{CE} SAT were measured, had failed and on fitting bypass connections V_{CE} SAT was seen to recover. Auxiliary collector and emitter contacts are labelled in small case in (FIG.9).

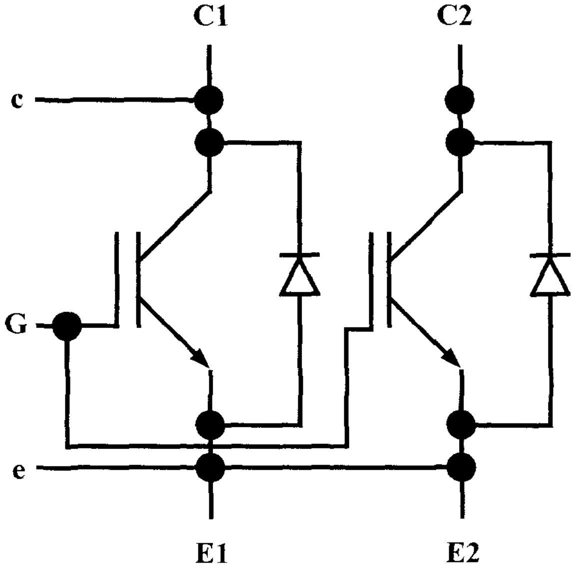

FIG.9 – CIRCUIT DIAGRAM FOR A SINGLE IGBT

The IGBT powerswitch continued to operate normally despite this unexpected occurrence, but the suspected failure introduced some uncertainty over protection philosophy and its effectiveness, as normal practice is to monitor for a sharp rise in V_{CE} SAT that indicates device failure. Consequently, the suspect devices were removed and returned to the manufacturer for laboratory examination.

Results of laboratory examination

Following electron microscopy the IGBT device manufacturer revealed that all three main power terminals had delaminated at their solder joints. This was reported as commensurate with devices having been operated for more than 20,000 thermal cycles of 5 minute duration and $\Delta T_J = 80°C$.[4] This is a tertiary failure mode only induced by static laboratory testing and it is surmized that this was induced by the combination of the high impulse current cycling of stage 1 testing and the thermal cycling of stage 2 testing. This failure mode was purely a function of RCT and the replacement of IGBT devices on completion of stage 1 RCT would have prevented its occurrence.

The manufacturer also stated that wire bonds were in good condition and that the solder layer between device baseplate and substrate showed normal delamination levels commensurate with 2,000 cycles of 5 minute duration and $\Delta T_J = 80°C$.[4] This presents good correlation between the practical results of this RCT and the manufacturer's laboratory testing and data extrapolation techniques, providing enhanced confidence in their predictions for device life for future applications.

CONCLUSIONS

Stage 1

The IGBT powerswitches were subjected to a repetitive electrical cycle that was representative of the worst case stress likely to be imposed during operation in the MSC.

Between 25 October and 3 December 1999, a total of 113,522 electrical cycles were imposed on 2 test rigs, each containing two IGBT powerswitches. This exceeded the estimated total number of events predicted to occur in all of the IGBT powerswitches in all 5 submarines during a 25year life. (An event being defined as any type of significant switching transient). During Stage 1 RCT, no powerswitch failures occurred.

The overload repeated during Stage 1 RCT is representative of the worst case event that is ever likely to be experienced by an IGBT powerswitch in the MSC. The total number of events that one IGBT powerswitch will see in a boat life is estimated at 753. This was clearly far less than the number imposed during Stage 1 RCT.

The device heatsink temperatures recorded during the tests were commensurate with predicted values. Consequently, Stage 1 RCT has provided confidence that, even under extreme conditions, the IGBT and diode junction temperatures will remain well within the working limit of 125°C during the duty likely to be experienced in the MSC.

The electrical cycle imposed on the IGBT module represents a junction temperature rise of only ΔT_J=7°C. The IGBT selected is capable of over 3 million cycles at ΔT_J=30°C before any degradation occurs. Hence, the ΔT_J=7°C imposed during the Stage 1 RCT will have had very little effect on the performance of the device.

A high degree of confidence can be taken that the in service thermal cycling duty will not cause any degradation in the performance characteristics of the IGBT powerswitches.

Stage 2

During Stage 2testing, four powerswitch modules were subjected to deep thermal cycling, far in excess of any operational condition likely to be imposed during application in the ASTUTE MSC.

Due to limitations with the existing test rig arrangement, which was developed specifically for Stage 1 tests, it was not possible to carry out the necessary number of thermal cycles required to thoroughly investigate published modes of failure for the IGBT modules.

A significant number of thermal cycles were carried out and a tertiary failure mode was identified after electron microscopy conducted by the manufacturer. None of the other powerswitch components were affected and this failure was attributed to the combination of stage 1and 2 testing and thus would not be encountered in a real application.

The accuracy and integrity of this particular manufacturer's life and reliability predictions for its power semiconductor devices has inadvertently been demonstrated through a period of rapid cycle testing in an application specific project.

References

1. Colin OATES. 'Accelerated Life Testing of a Traction Inverter.' *Power Engineering Journal* October 1999. Volume13 No 5.
2. Y. SHAKWEH. 'Power Devices For Medium Voltage PWM Converters.' *Power Engineering Journal* December 1999.
3. T. SCHUTZE,; H. BERG.; M. HIERHOLZER. 'Further Improvements in the Reliability of IGBT Modules.'
4. DR STACHE. *EUPEC Product Analysis Report EF2166* dated 27 October 2000.

Bibliography

1. 'Rapid Cycle Testing of High Current IGBT Powerswitch Modules, Stage One Test Report.' *Ultra Electronics (PMES) 1999*, Unpublished.
2. 'Evaluation of an IGBT powerswitch for application in a prototype converter.' *Ultra Electronics (PMES) 1998*, Unpublished.