STATIC POWER CONVERTERS FOR SUBMARINES

BY

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ABSTRACT

Since the beginning of the naval nuclear propulsion programme, the 300 kW motor generator has been used as a means of conversion and power transfer between the AC and DC electrical power systems of our nuclear submarines. The machine provides essential AC supplies in the event of a 'reactor scram', the generic term used for a reactor shutdown where nuclear heat and hence steam derived electricity ceases. The motor generator can also reverse the direction of power transfer to provide DC to charge the submarine main battery. The questionable reliability of these machines, particularly with regard to high brushwear and exciter armature problems, combined with the advance in power semi-conductors, has caused the MoD(PE) to look again at these machines. The static power converter is a machine capable of four quadrant operation using a single control strategy capable of providing smooth uninterrupted power transfer between the AC and DC systems and vice versa. This article describes the operation of this machine and some of the problems encountered in the preparation of a safety justification for installation at the shore test facility at NRTE 'Vulcan', Dounreay. The static converter is an option under consideration for the Batch 2 TRAFALGAR Class.

Introduction

Since the beginning of the naval nuclear propulsion programme, large motor generators have been used as a means of conversion and power transfer between the AC and DC electrical power systems of our nuclear submarines. The machine provides essential AC supplies in the event of a 'reactor scram', the generic term used for a reactor shutdown where nuclear heat and hence steam derived electricity ceases. The motor generator can also reverse the direction of power transfer to provide DC to charge the submarine main battery.

However, the problems with motor generator brushwear and exciter armatures meant that the Availability, Reliability and Maintainability (ARM) of these machines was poor. During the 1980s the advance in power semiconductor technology and likely future decline in the UK manufacturing base for large DC machines meant that investigation of a static alternative became increasingly attractive.

Firstly, some research into the feasibility of providing a reversible static converter with a capability for continuous transfer of power from generating AC to generating DC was required. This was carried out at DRA West Drayton in 1985/6 and proved surprisingly successful. The static converter could offer considerable advantages in terms of ARM improvement with high availability, reliability, and a more maintainable machine with a low mean time to repair. The Ministry of Defence therefore invested in a development programme which has included the following:

(*a*) Design and development of a suitable converter in accordance with appropriate DEFSTANs and Naval Engineering Standards.
(*b*) Build and Test of a 'breadboard' prototype at the factory in order to reduce the technical risk.
(*c*) Build and delivery of two prototypes to DRA West Drayton for type testing in a specially constructed submarine power system.
(*d*) Build and delivery of two units to the Naval Reactor Test Establishment (NRTE) 'Vulcan', Dounreay, to enable full integration and testing upon a live plant to take place.

At the time of writing, (*a*), (*b*) and (*c*) are all complete and installation at NRTE 'Vulcan' alongside the existing motor generator sets is now taking place. In addition to the procurement of the converters by the Directorate General Marine Engineering, Director General Submarines has been preparing the 'Vulcan' site to accept the units, providing the safety justification to prove the units conform with the latest standards applicable to a shore based Pressurised Water Reactor; this task is more onerous and expensive than many would imagine.

The Safety Case

The motor generator is mature technology with operating experience over more than a hundred years. This means that:
(*a*) The failure modes are well known and can be backed up with historical reliability data.
(*b*) Operators and plant designers are familiar with the operation and failure modes of the machine.

The safety justification for the plant must therefore be amended with the appropriate changes for the converter in place backed up with both engineering argument and failure data where appropriate. Late in the project, the spirit of DEFSTAN 00–56, the Defence Standard for the design and procurement of safety critical systems, was applied and this helped in clarifying the work required to achieve a satisfactory safety justification. Having agreed this with the independent safety assessor, the task of satisfying the requirement became less formidable. In broad terms, the following must therefore be considered for the safety case:
(*a*) Converter design philosophy. This formally explains to the safety assessor how potential hazards are minimized.
(*b*) Failure studies. These provide important information regarding the failures, their effect, and how often they are likely to happen.
(*c*) Effect of the converter's surroundings (environment) upon the converter.
(*d*) Effect of the converter upon the systems that support the reactor—in particular, on the electrical power system.
(*e*) Effect upon the operator—in particular, is the replacement to be invisible to the operator or is he to be trained in detail in the new technology?

All these aspects will be explained in more detail but, in order to address these, a basic explanation of how the converter works is given.

Converter Operation

The most difficult conceptual aspect of the converter is how a bridge containing Gate Turn Off (GTO) thyristors and diodes can act as a rectifier and then as an inverter without a fundamental change in the control strategy.

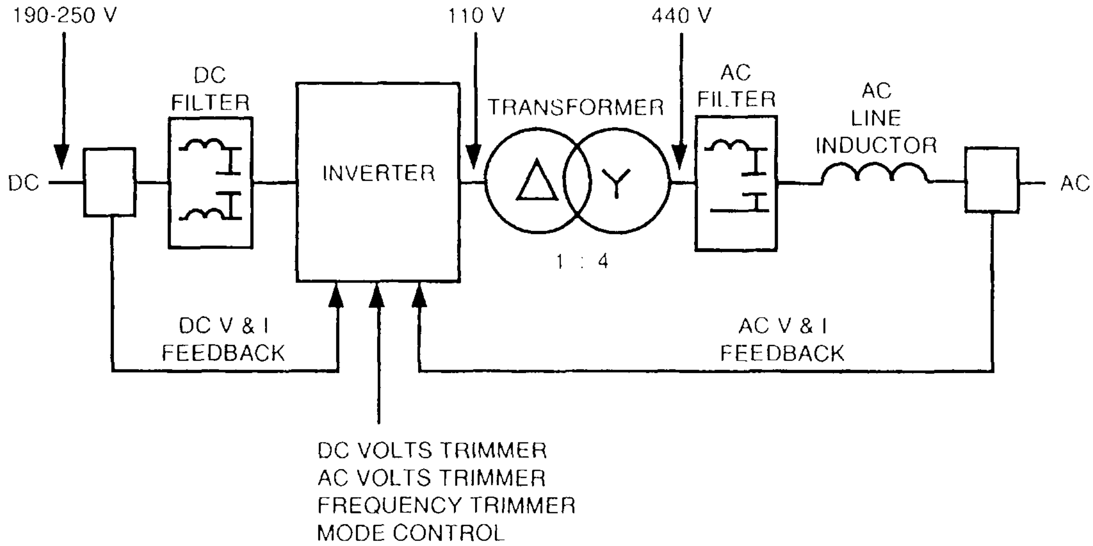

FIG 1—SCHEMATIC DIAGRAM OF A STATIC CONVERTER

It is clear from (FIG. 1) that the converter is configured as an inverter and therefore AC generation is easily obtained using pulse width modulation. When considering conversion from AC to DC, the operation of the bridge is more difficult to appreciate, particularly since the DC voltage (190–250 V) is higher than the AC due to the reduction in the voltage due to the transformer (110 V), and hence the GTOs are inherently reverse biased. The inverter bridge is therefore considered as a series of step-up converters and (FIG. 2) demonstrates the machine operating as a step-up converter. As the AC voltage is lower than the DC voltage, the current entering the battery must overcome the difference in potential. The heavy lines show the current flow during one firing pulse. In order to simplify the explanation this circuit is now redrawn in (FIG. 3) showing just one section of the bridge. If thyristor T_1 is switched on, current passes from the red to the yellow phase with none passing to the DC system. When T_1 is switched off, current must contine to flow due to the energy stored in the line inductance and the only route possible is through the battery, diode D_2 and back to the yellow phase. This current will only flow while energy is released from the inductor, when another GTO will be fired to permit current to flow between phases and the cycle is then repeated. A simulation of this carried out by Rolls-Royce and Associates, the delegated Design Authority for the naval nuclear propulsion programme, using a computer circuit modelling package (pSPICE), demonstrates the current flow to the main battery which can be seen in (FIG. 4). This shows an irregular waveform superimposed upon a DC level which, after filtering, provides a constant DC current to the battery.

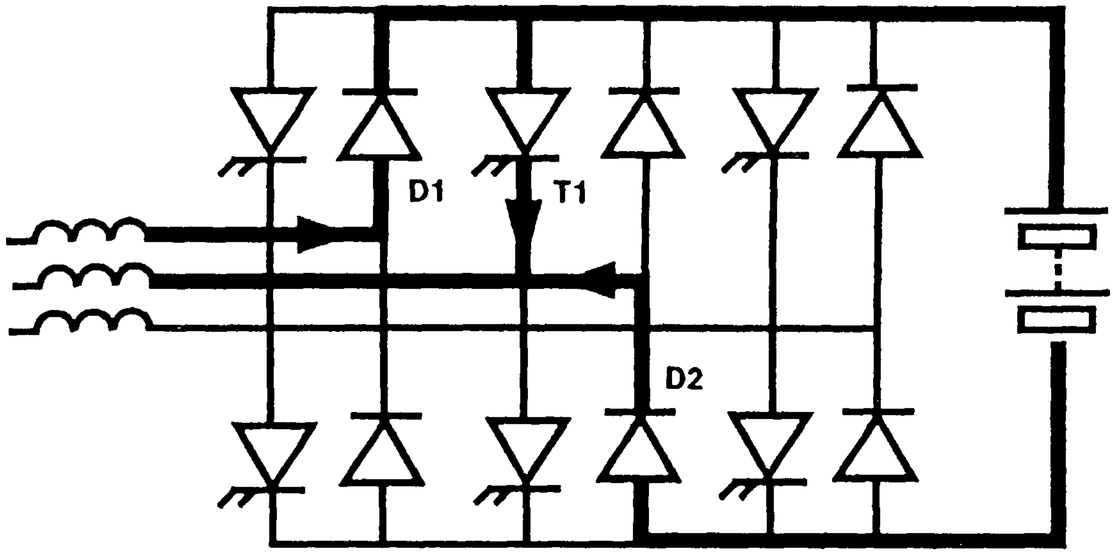

FIG. 2—THE CONVERTER CONFIGURED AS A STEP-UP CONVERTER

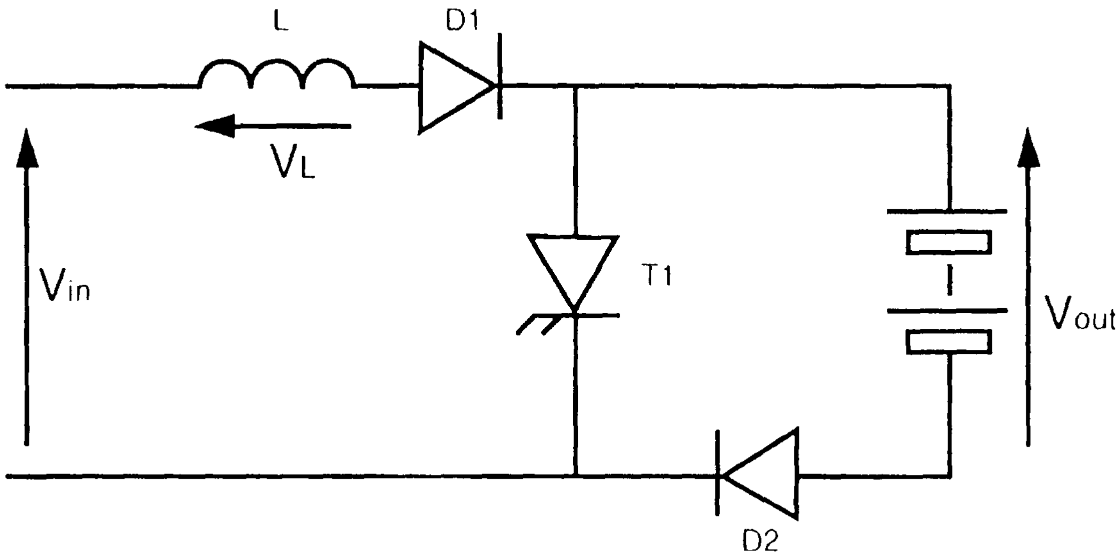

FIG. 3—SIMPLIFIED REPRESENTATION OF THE STATIC CONVERTER

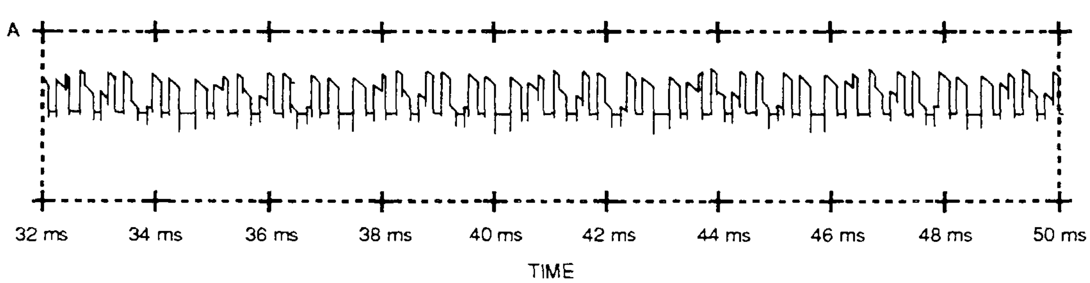

FIG. 4—UNFILTERED DC CURRENT TO MAIN BATTERY OVER ONE AC CYCLE

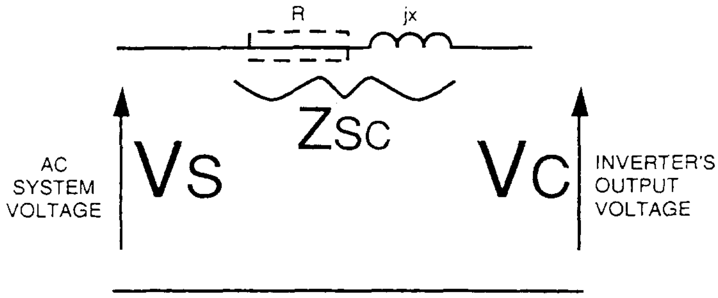

FIG. 5—SIMPLIFIED SINGLE PHASE REPRESENTATION OF THE STATIC CONVERTER

Converter Control

The most elegant aspect of the converter is the way in which it controls power flow in both directions under one common control strategy. If the converter is considered as a simple single phase machine as illustrated in (FIG. 5) where Z_{sc} is the converter line inductor, V_s the system AC voltage and V_c the converter output voltage, then if $\underline{V_c}$, $\underline{V_s}$ and $\underline{I}$ are expressed in phasor terms:

$$\underline{I} = \frac{V_c - V_s}{R + jX}$$

If V_c can be controlled such that the phase and magnitude can be held constant with respect to V_s for a given operating condition, then:

$$V_c = k\ (\mathrm{Cos}\ \delta + j.\mathrm{Sin}\ \delta).V_s$$

where k is a scalar and δ the phase shift.

Therefore, by substitution:

$$\underline{I} = \frac{V_s\ (k.\ \mathrm{Cos}\ \delta - 1 + j.k.\mathrm{Sin}\ \delta)}{R + j.X}$$

hence:

$$\underline{I} = \frac{V_s\ R(k\ \cos\ \delta - 1) + V\ X.k.\mathrm{Sin}\ \delta)}{R^2 + X^2} + \frac{j.V_s\ Rk.\mathrm{Sin}\ \delta - V_s\ X\ (k.\mathrm{Cos}\ \delta - 1)}{R^2 + X^2}$$

As X>>R, then:

$$\underline{I} = \underbrace{\frac{V_s.k.\mathrm{Sin}\ \delta}{X}}_{\text{Real Component}} - \underbrace{\frac{j.V_s.(k.\mathrm{Cos}\ \delta - 1)}{X}}_{\text{Reactive Component}} \qquad \ldots(1)$$

This demonstrates how real and reactive components of current may be controlled by K (the ratio between the peak amplitude of the inverters fundamental output voltage and the AC system voltage) and δ (the phase difference between the AC system voltage and the converters output voltage (the load angle)). (FIG. 6) shows the converter quadrant diagram which graphically plots Equation 1. This equation also demonstrates that to a first approximation, although not completely decoupled, control of current can be achieved by:

(*a*) Varying the RMS inverter output voltage to control reactive current.

(*b*) Varying the phase of the inverter voltage with respect to the AC system voltage to control real current (variation of load angle).

It also demonstrates the importance of the line inductor which substitutes for the synchronous reactance of an AC synchronous machine. Detail of the converter design will be dealt with later.

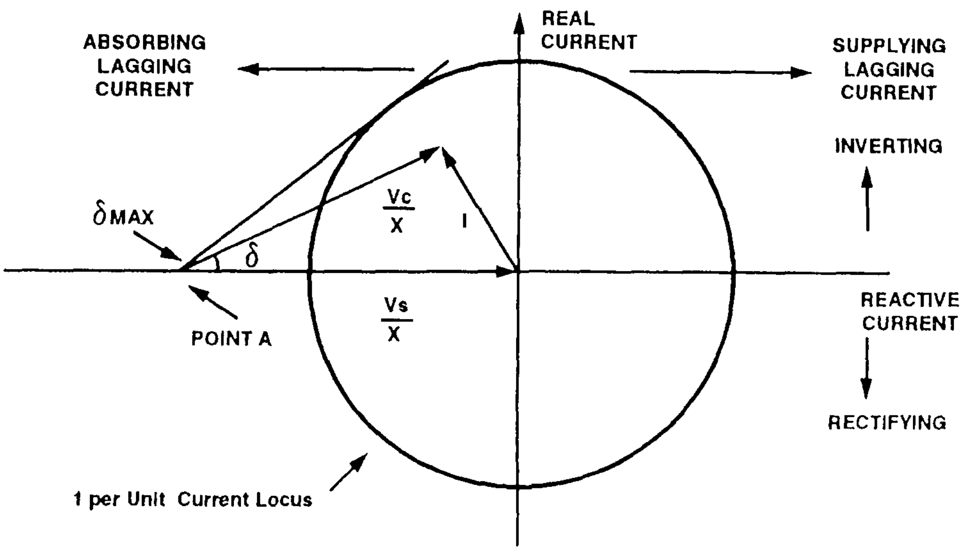

FIG. 6—QUADRANT DIAGRAM OF THE STATIC CONVERTER

Failure Studies

The safety justification for the shore test facility at NRTE 'Vulcan' is probabilistic in nature. This means that failures of all components within the overall plant design are considered numerically. This, when combined with a fault tree type of analysis, gives the overall probability of failure. This in turn leads to a realistic assessment of the type and probability of failures, the risk, and hence the consequence of installing this type of device upon the general public in terms of fission product release per millenium. Replacing the motor generator directly with the static power converter is a major modification to a key element of the power system and this aspect of the safety case needed considerable amendment. Early in the programme, the strategy for amending the justification was agreed which removed some of the project risk in this area.

The major subjects examined in the justification were:

(*a*) Re-issue of current power system documentation where it was felt that updating was required.

(*b*) A Failure Modes Effects and Criticality Analysis (FMECA) of the converter and its effect upon the power system. This contains failure data of all sub-systems and components where applicable. In addition, the effect of the power system upon the converter was considered.

(*c*) Environmental hazards of the surroundings upon the converter.

The justification work is now complete and is undergoing assessment by the Safety and Reliability Directorate of AEA Technology, the MOD's independent safety assessors.

Effect of the Converter's Surroundings upon the Converter

The converter is a step-change in technology from the motor generators and there may be hazards within the facility which may have a detrimental effect upon the converter to which the motor generator, because of its robust nature, is immune. There are two aspects to this work:

(*a*) Proving that internal hazards within the plant are acceptable as either the converter is immune or protected.

(*b*) Zonal analysis. This identifies hazards due to physical placement of the converter.

Examples of internal hazards within the plant are other failure modes within the power system to which the converter may react in a different manner. This may not be unacceptable, but the effect upon the system and hence on plant safety must be examined and overcome if necessary. Zonal analysis looks at the physical positioning of the converter and an example may be the likely damage caused by the missiles which emanate from an exploding pressure vessel, such as a hydrogen bottle. If the converter can show it is sufficiently protected electrically, if not physically, then the unlikely event of an explosion would not lead to a hazardous situation due to the response of the converter alone. If there is a concern regarding the converter's response, then this must be overcome, perhaps by re-siting the bottle. Another method of overcoming this type of failure is to prove that the likelihood of occurrence is so small that the potential risk to the plant is negligible.

Effect of the Converter upon the Systems which Support the Reactor

The use of any semiconductor converter as opposed to a rotating machine, for all its potential advantages, will inevitably introduce discontinuities in the generated waveform. The converter has been designed to meet the appropriate engineering standards for Electromagnetic Compatability and quality of generated waveform (DEFSTAN 59–41 and NES 501). The largest problem regarding the quality of waveform is in the generated DC voltage which is due to the nature of the step-up converter. The filter on the DC side of the converter removes the majority of this and does not therefore pose a problem for the DC power systems or main battery. Another concern is the harmonics generated on the AC side; however, both the system total harmonic distortion and individual harmonic levels are well within the permitted maximum.

The other main area of risk is the control system and its performance under transient conditions. This has been tested under severe conditions upon the power system mock-up at West Drayton. Although minor adjustments have had to be made, the converter has again performed surprisingly well for such a novel application, with only minor changes to control algorithms.

Effect upon the Operator

At the very outset of the static converter project, a decision had to be made regarding the philosophy of control as seen by the operator and implemented on the electrical power system operating panel. Although the operators at the 'Vulcan' shore test facility, and in the nuclear submarine to which this equipment will eventually be fitted, are trained to the high standards expected, does the electrical panel operator need to change his philosophy of operating? It was decided that this was not in the interest of plant safety and training and therefore the adjusting trimmers and controls on the panel will have exactly the same effect as with the existing motor generator. This is made easier by fact that, as previously mentioned, varying the inverter RMS output voltage controls reactive current while varying the phase of the inverter voltage with respect to the AC system voltage controls real current. This philosophy must not be confused with the maintainer's need to understand the equipment for which he is responsible; however, there is not a requirement for a detailed knowledge of power semiconductor technology for the majority of operators.

Converter Design

One of the design constraints placed upon the manufacturers was that the converter must not exceed the space envelope currently occupied by the motor generator for the same power output. This has been achieved with a weight saving of some 30%. The converter to be installed at 'Vulcan' is rated at 450 kW and consists of six modules, each of identical size and construction. Each module is constructed around the transformer and inverter bridge and is completely independent of the other five. The control circuitry is linked for synchronism only but does not require any inputs from another module as sensing of voltages, currents and frequencies is within each module. Although the modules are identical, there is an allowance for error which means that there will be a certain amount of power transfer between modules; however this is negligible.

Each module has its own diagnostic circuitry which tells the maintainer which circuit has failed in the event of an unplanned shutdown. Whilst one module is off-line, the converter can still handle the full design load. Repair by replacement *in situ* is the repair philosophy with access possible to all modules; all components can be replaced at sea with the exception of the transformer assembly. It may be possible within future designs to spread the location of modules which will enhance the redundancy argument, particularly in a damage control situation. The disadvantage of this will be the need to bring the AC and DC power systems together at several points, which may make this an impractical suggestion.

Testing Programme

The testing programme was devised some two years ago to support the procurement process and safety justification. Defence Research Establishment West Drayton, part of the new Defence Research Agency, which possesses the largest DC test facility in Europe, provides an approximation to a submarine power system such that full type testing can be carried out to identify any shortcomings during transient conditions. This has proved to be successful due to a combination of high quality equipment, the facilities and the quality of the personnel at West Drayton. The third prototype will shortly be delivered to NRTE 'Vulcan' and should be in use on a live reactor plant in 1993.

Summary

The static converter offers considerable ARM advantages over the motor generator. The equipment will be comparatively easy to support and will reduce the weight and increase the flexibility of this type of conversion machinery. Unit production cost should be comparable with the motor generator; recent information seems to predict that with a suitable production run, this may be the case. There may also be whole-life cost savings which, combined with the advantages outlined above, will make the converter a strong contender for the Batch 2 TRAFLAGAR class.

It is appreciated that judgement on the UK's ability to design and build large DC machines at an acceptable price is somewhat subjective and possibly controversial, as it involves making an assessment of the future of individual companies. Conversely, the ability to support power semiconductor machines such as the static converter is likely to exist well into the next century.

The static converter project is an example of a successful step forward in technology within a mature project. Perhaps more importantly, it is an example of how to install a major yet novel piece of electrical engineering into a mature plant with an acceptable safety justification. It has also demonstrated the benefits of applying DEFSTAN 00–56, even at a late stage in a safety critical project.