

DEMONSTRATING THE ELECTRIC SHIP

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ABSTRACT

Integrated Full Electric Propulsion (IFEP) is an everyday reality as the power system solution for naval platforms, embracing recent advances in enabling technologies to deliver cost effective, survivable, power dense solutions in a variety of applications. The MoD, in co-operation with the French government has contracted ALSTOM Power Conversion Ltd to design, build and operate an Electric Ship Technology Demonstrator (ESTD). The main objective of which is to de-risk IFEP equipment and systems to meet the requirements of future UK and French warship programmes. The key enabling technologies for ESTD are WR21 ICR Gas Turbine and the Propulsion Motor System (PM for ESTD). The ESTD is sited at the ALSTOM Power Whittle Research Centre, Whetstone near Leicester.

Key supporting objectives of ESTD are to demonstrate the practical integration of gas turbine generators, power electronics, energy storage systems and an advanced propulsion motor, analyse system performance and assess system operability and functionality.

The article will review the ESTD and PM for ESTD programmes, providing design and progress detail together with a review of the way ahead for the facility. It will be shown that ESTD is a key part of the Electric Warship concept and a 'world beating test facility'.

Introduction

In recent years a variety of papers, seminars and conferences have sought to provide detail and promote discussion on the diverse range of issues that make up the Electric Warship concept. This period has also seen a huge amount of progress in enabling technologies that have made Integrated Electric Propulsion (IEP) the system of choice for many new naval ships. A key enabler in managing the introduction of Integrated Full Electric Propulsion (IFEP) is the Electric Ship Technology Demonstrator (ESTD) and the supporting Propulsion Motor (PM) for the ESTD programme.

IEP solutions are the 'here and now' of naval marine power and propulsion systems with a range of platforms embracing the concept:

- ALBION class Landing Platform Docks (LPD) and WAVE class Auxiliary Oilers in the UK.
- The ROTTERDAM LPD class in the Netherlands.
- Mistral NTCD class in France.

All of which utilize 'turnkey' commercial solutions. Following these platforms is the UK's Type 45 Daring class destroyer, again an IEP solution but a benchmark in power dense equipment exploiting a range of technological advances – notably the United States' Integrated Power System (IPS) derived Advanced Induction Motor (AIM) development and the WR21 ICR Gas Turbine. The French Multi-Mission Frigate is another IEP candidate platform. ESTD, whilst extremely relevant to IEP solutions, looks to take the technology further with the

introduction of advanced power electronics, innovative power system architectures and energy storage.

ESTD background, aims and objectives

In early 1999, UK/France approved the funding for a joint ESTD programme and in mid-2000 a Technical Agreement to an existing UK/French Defence Research and Technology Memorandum of Understanding was signed and a contract placed with ALSTOM Power Conversion Ltd for the ESTD.

The main objectives of ESTD are:

- System integration de-risking in normal operation, and particularly system stability and protection scheme solving.
- Exploration of abnormal system operation closer to equipment limitations, including reversionary modes of operation and degraded quality of power supplies.
- Generation of Integrated Logistic Support (ILS) data, especially for the new technology inserted
- Demonstration of Single Generator Operation (SGO) supported by energy storage devices, so as to reduce equipment maintenance and Through Life Cost, whilst maintaining ride-through and fight-through capability.
- Equipment and system model validation, so that a set of validated models is available to the MoD and Délégation Générale pour l'Armement (DGA) for the assessment of future platform designs.
- Adapting COTS (Commercial Off The Shelf) solutions to meet naval requirements.

ESTD is a phased programme, the outline of the phases is as follows:

- ESTD Site Facility Construction & Installation.
- Equipment Installation and Set to Work (Notably WR21 GTA3 and PM for ESTD).
- Phase I Trials Model Validation and System Performance.
- Phase II Trials Advanced System Trials

Phase I will include model validation and inform the design for the Type 45 Destroyer and the decision making process for the Multi-Mission Frigate.

System description

The ESTD architecture is well known and discussed in many forums, with the current state of the design being shown in its simplified form at (Fig.1). The system looks to replicate one shaft line of a possible IFEP system with a:

- Range of prime movers.
- Dynamic four quadrant load.
- Concept system architecture.
- Range of representative loads.

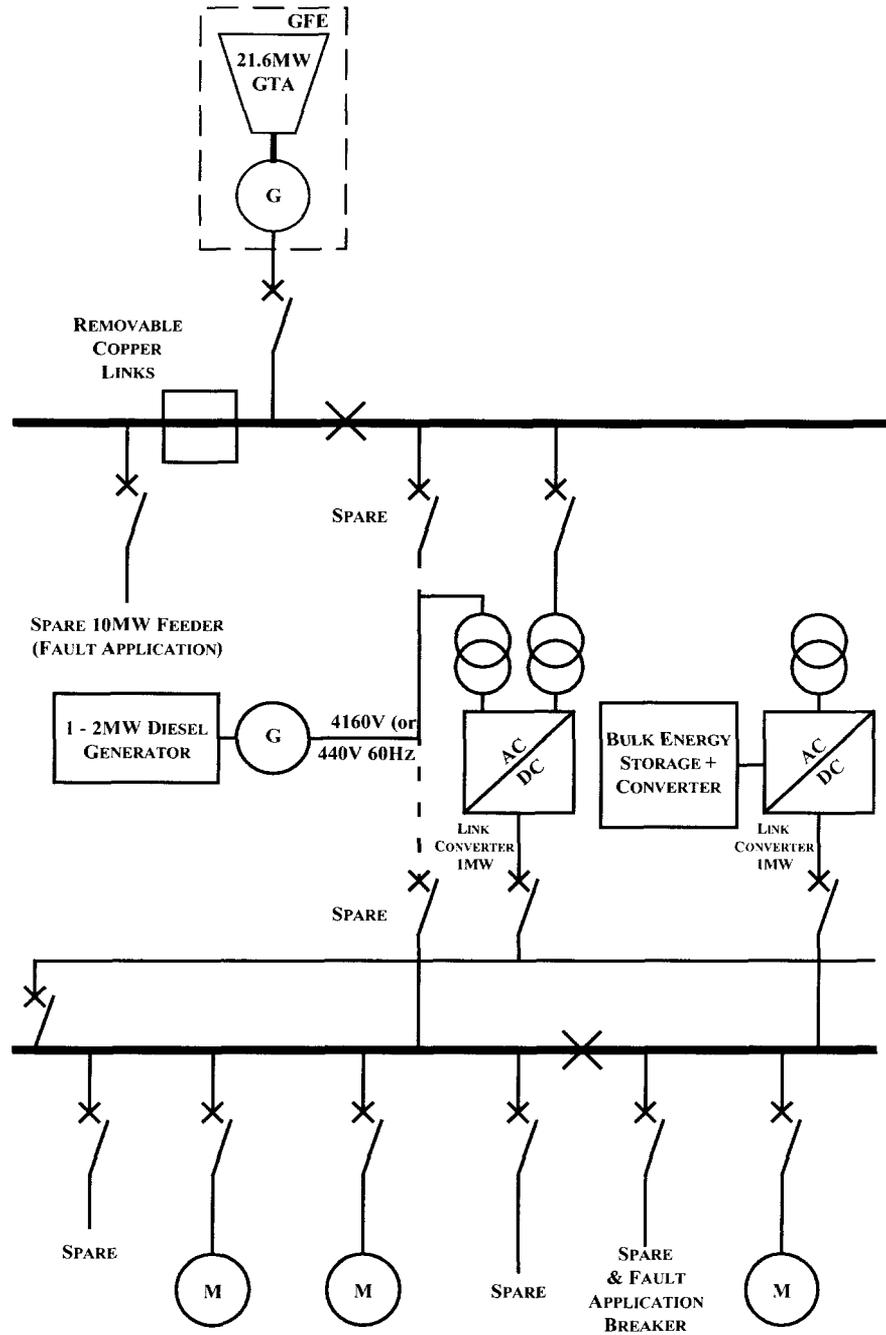


FIG.1 - ESTD SCHEMATIC

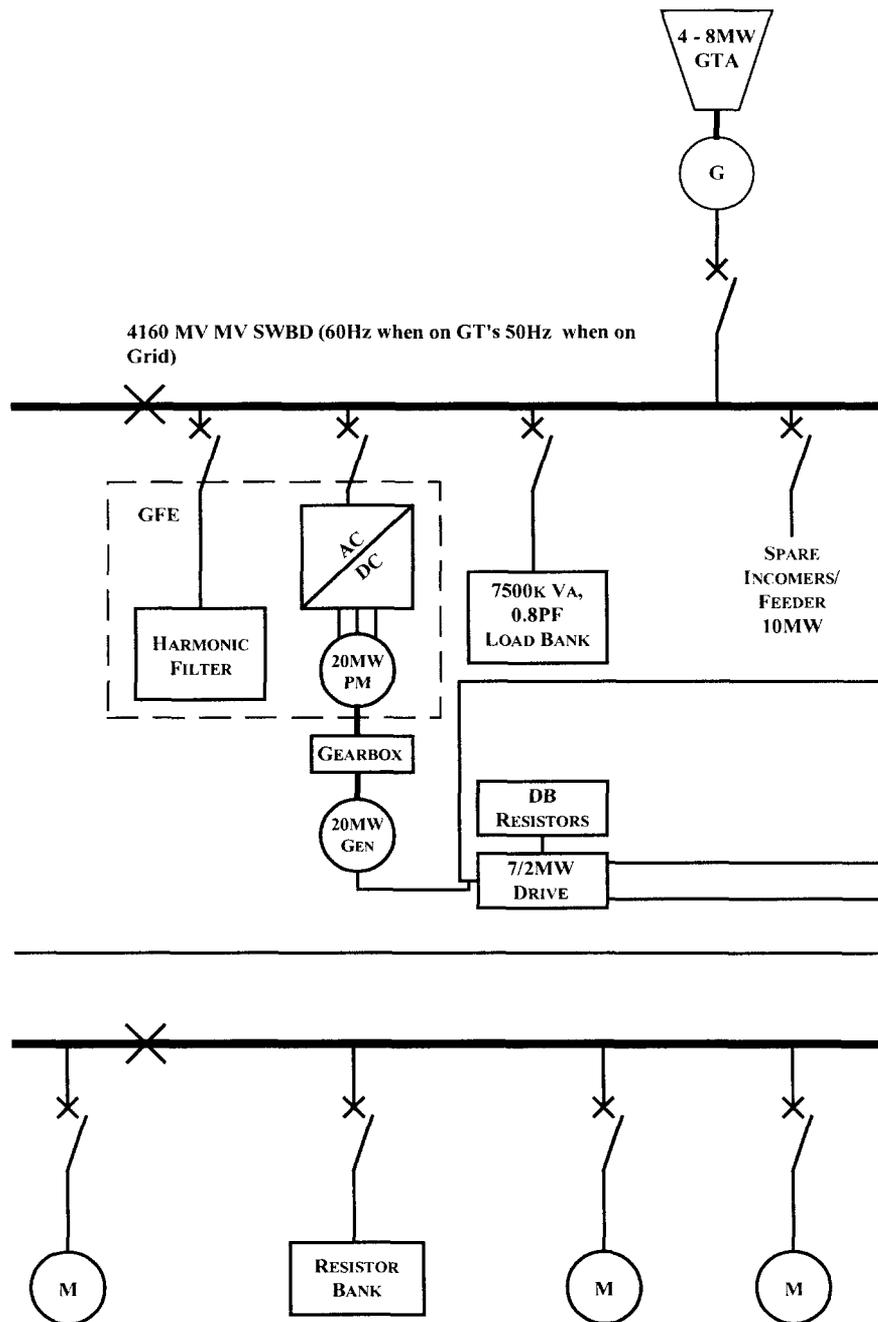


FIG.1 - ESTD SCHEMATIC

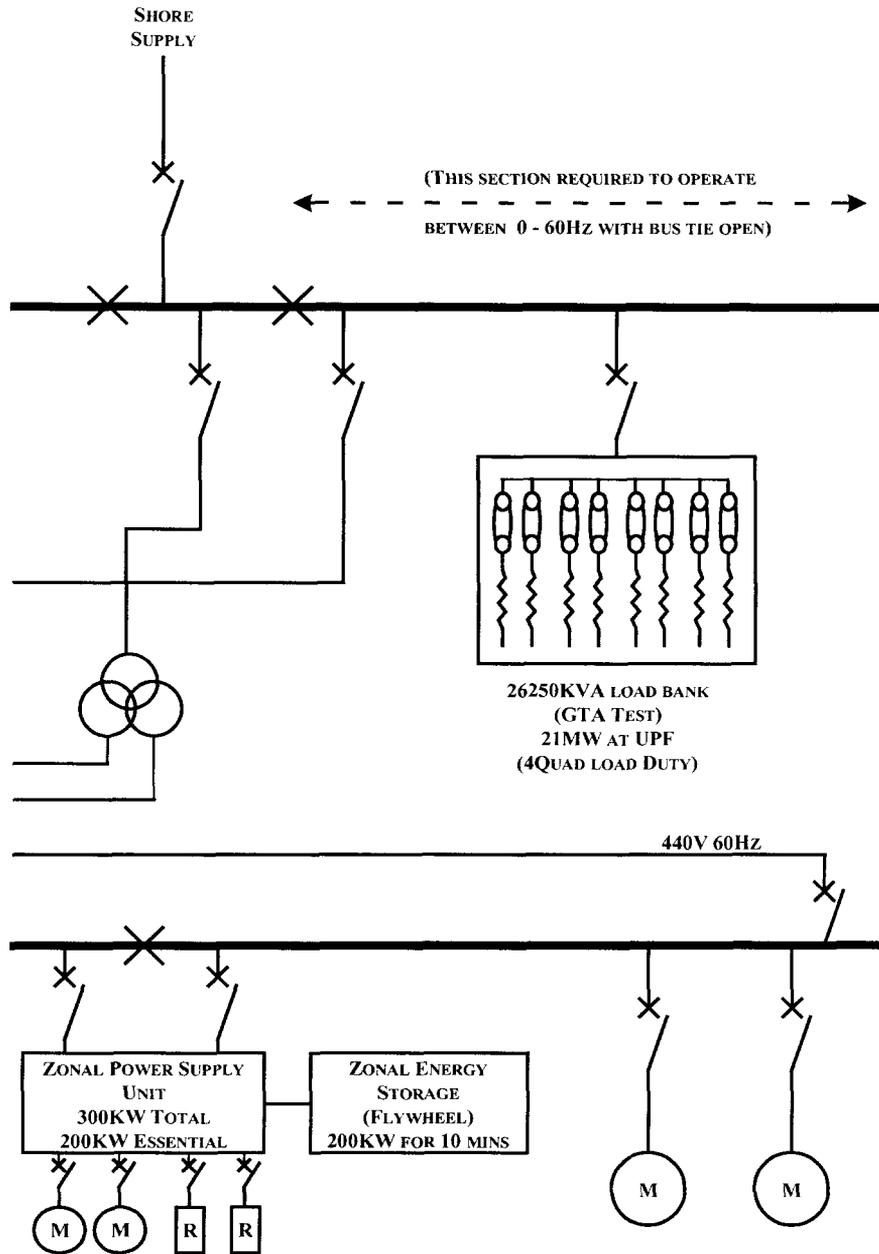


FIG.1 – ESTD SCHEMATIC

Prime Movers

The WR21 is the major Gas Turbine Alternator (GTA) prime mover providing 21MW at 0.9 Power Factor (PF) to the 60Hz 4160V system, with a Typhoon GTA set providing up to an additional 4MW at 0.8PF. The system also includes a Diesel Generator (DG) set connected directly to the 440V system, providing 1MW at 0.8PF with the ability to share load with the two link converters. Provision has been made for a second DG set to be connected directly to the High Voltage (HV) switchboard. Opportunity also exists for the system to be supplied via a shore supply connection.

Switchboards

Three main switchboards are provided at ESTD, a single 4160V HV switchboard split into five zones, and two LV switchboards, one AC (440V, 60Hz) and one DC (800V), these are connected in an either or configuration to the HV switchboard via the link converters. The switchboards contain advanced microprocessor based directional and zonal protection relays with the ability for their settings to automatically change to suit the current configuration. The HV and LV switchboards are at (FIGS 2 & 3).

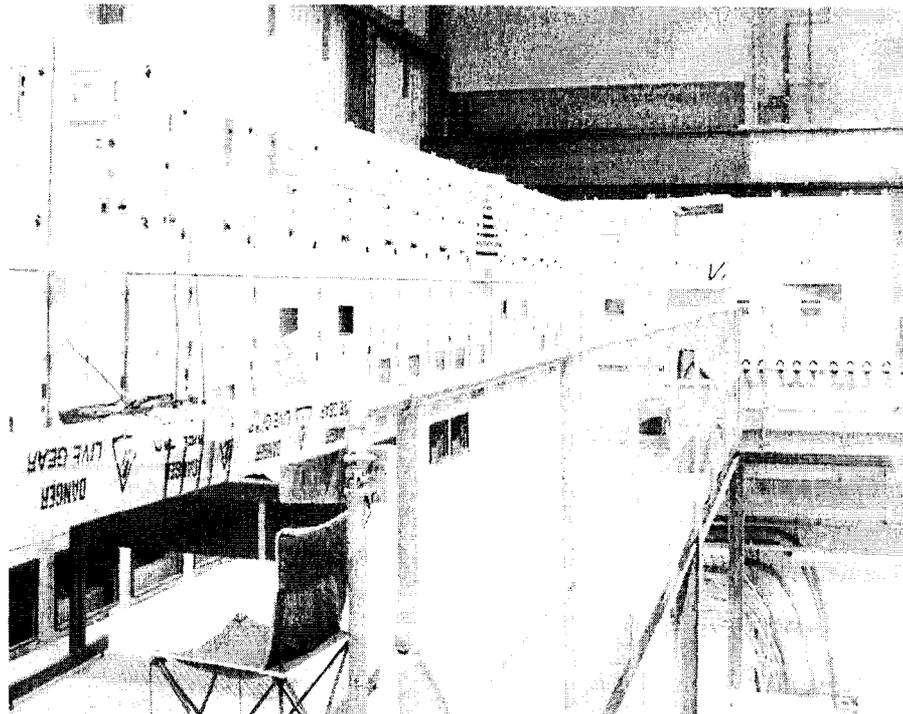


Fig.2.– HV SWITCHBOARD

- The HV switchboard is a COTS design and is not optimized for naval use due to cost constraints. It does however contain a blend of standard electromagnetic operating mechanisms and more novel magnetically latched breakers in order to compare their suitability for naval marine use. The circuit breakers are rated for the ESTD system at up to 4000A with a fault capacity of 31.5kA.

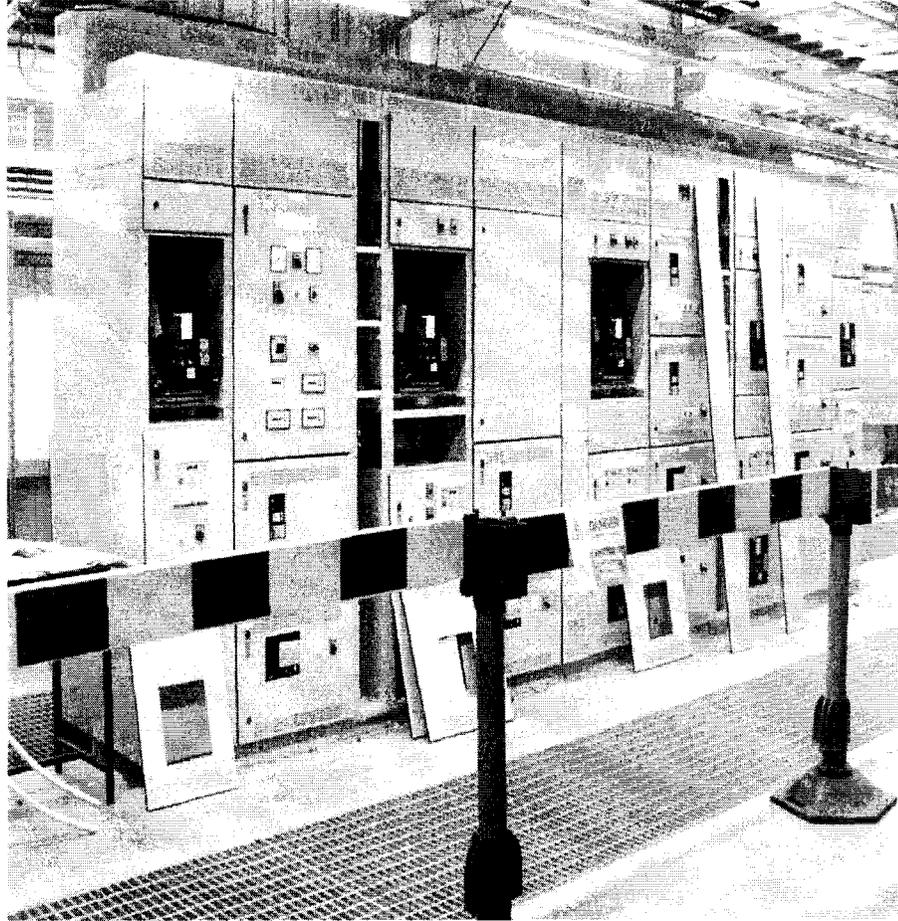


FIG.3 – LV SWITCHBOARD

- The LV Switchboards are split into 4 zones with a cable tie providing the ability for the system to operate as a ring main. The two different LV switchboards are provided to allow comparisons between DC and AC systems to be made during testing. Only one of the LV Switchboards will be connected to the HV System at any one time, either the AC or the DC, but not both simultaneously. The DC switchboard makes use of AC circuit breakers with a DC capability. It also take advantage of the fact that the switchboard is always convertor fed, with no directly connected DG set, and therefore has a considerably lower fault level requirement than the AC switchboard, which could be convertor, transformer and/or DG set supplied. The DC protection available as COTS equipment is also considerably more limited than that available for AC, so some of the advanced features of the AC relays are not fitted.

50Hz Operation

The HV Switchboard will normally be operated at 60Hz from the two GTAs but it can also be operated at 50Hz from the 12MVA shore supply connection. The whole HV busbar can be supplied at 50Hz from the shore supply, it can or course not be paralleled with either of the Gas Turbines during this time. The 50Hz can be used to supply the Link Convertors, or the PM, it is not envisaged that the load banks will be connected to the HV system at 50Hz, as this is wasteful of power to no benefit. The four quadrant load convertor, is always supplied at 50Hz, this can occur when the whole HV bus is at 50Hz, or when the first three zones are at 60Hz on the GTA supplies, with the bus-coupler Open. During 50Hz operation, the limit on the system is the incoming 12MVA supply - the PM, or Link Convertors, can be operated independently or collectively up to this power limit. The four quadrant load convertor also draws 50Hz, but is unlikely to draw significant power when the PM Convertor is powering, due to the nature of the 4QL system. The right hand section of HV board is arranged to operate from 0-60Hz, depending on the speed of the 4 Quadrant load generator.

HV to LV Power conversion

During GTA3 testing, a 1MVA transformer provides power from the HV to the LV bus in the normal manner, however for Phase I and II testing, power is provided to the LV boards via two 1MW @ Unity Power Factor (UPF) link convertors. These are bi-directional power convertors that, in conjunction with a Link Transformer pass power between the HV and LV systems. The Link Convertors have COTS IGBT direct water cooled power modules, with filtering on both the input and output bridges. Unlike transformers, they isolate the frequency, voltage and harmonic distortion of the HV system from the LV system, negating a requirement for active filters.

Energy storage

Energy storage is provided at ESTD to asses technology solutions for bulk energy storage, similar power requirements to that required for Propulsion Ride Through and zonal energy storage, rated for Uninterruptible Power Supplies (UPS).

Bulk Energy Storage (BES) (FIG.4)

BES is a large Electrochemical Storage Device that provides 1MW of power for 10 minutes. The device consists of 10 Cells, connected in 5 parallel paths of 2 series modules. The technology within the cells is Regensys® by Innogy, in its proposed marine form called Marigenix™. The BES is connected to the link convertor via the Bulk Energy Storage Convertor (BESC). This convertor ensures that the voltage from the cells during charging or discharging is compatible with the DC link voltage on the link convertor and controls the charging and discharging of the BES under all modes.

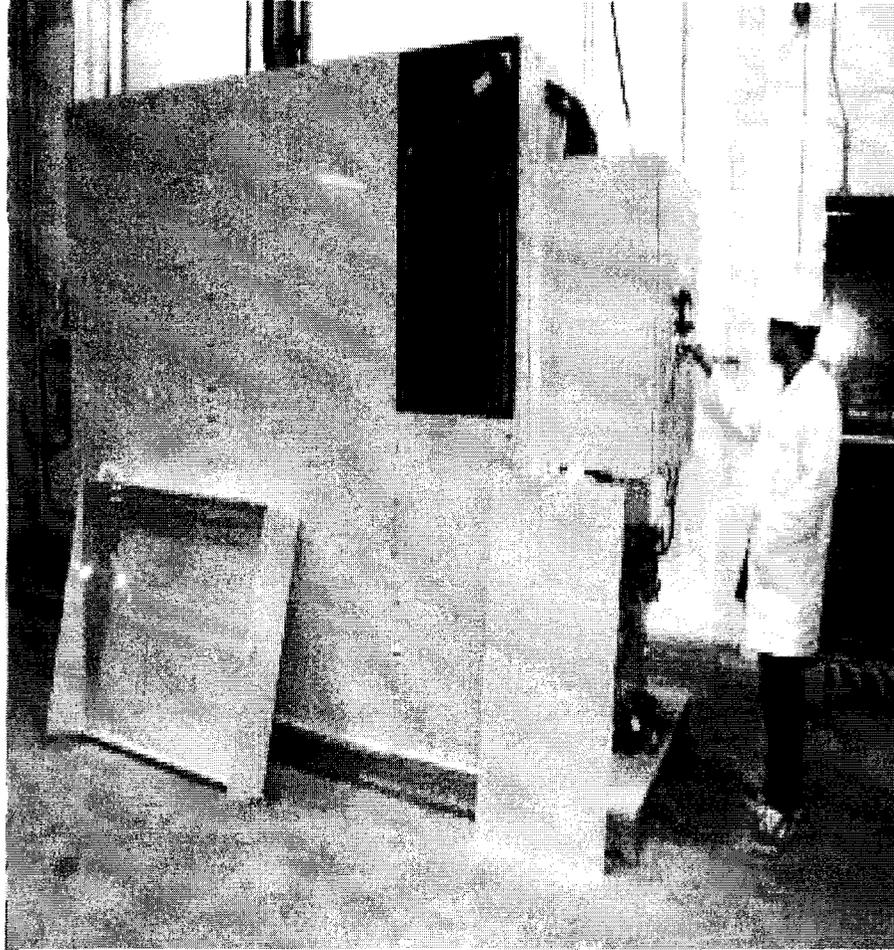


FIG.4 – BULK ENERGY STORAGE

Zonal Power Supply Unit and Energy Storage (ZPSU)

Connected to the LV System is the ZPSU and its associated Energy Storage. The ZPSU has two inputs, from different sections of the LV board, so if one section blacks out, the other input automatically takes over. The ZPSU provides 300kW of LV Power supplies, with a flywheel backup Zonal Energy Storage (ZES) (FIG.5). The ZES is provided by multiple flywheels connected in parallel to provide 200kW of power for 4 minutes in the event that both inputs to the ZPSU become de-energized. Each flywheel incorporates an inverter in order to maintain the volts during discharging/charging to a level that is required by the ZPSU. The Urenco flywheels provide energy to the essential loads on the ZPSU only and do not provide power back into the main LV system.

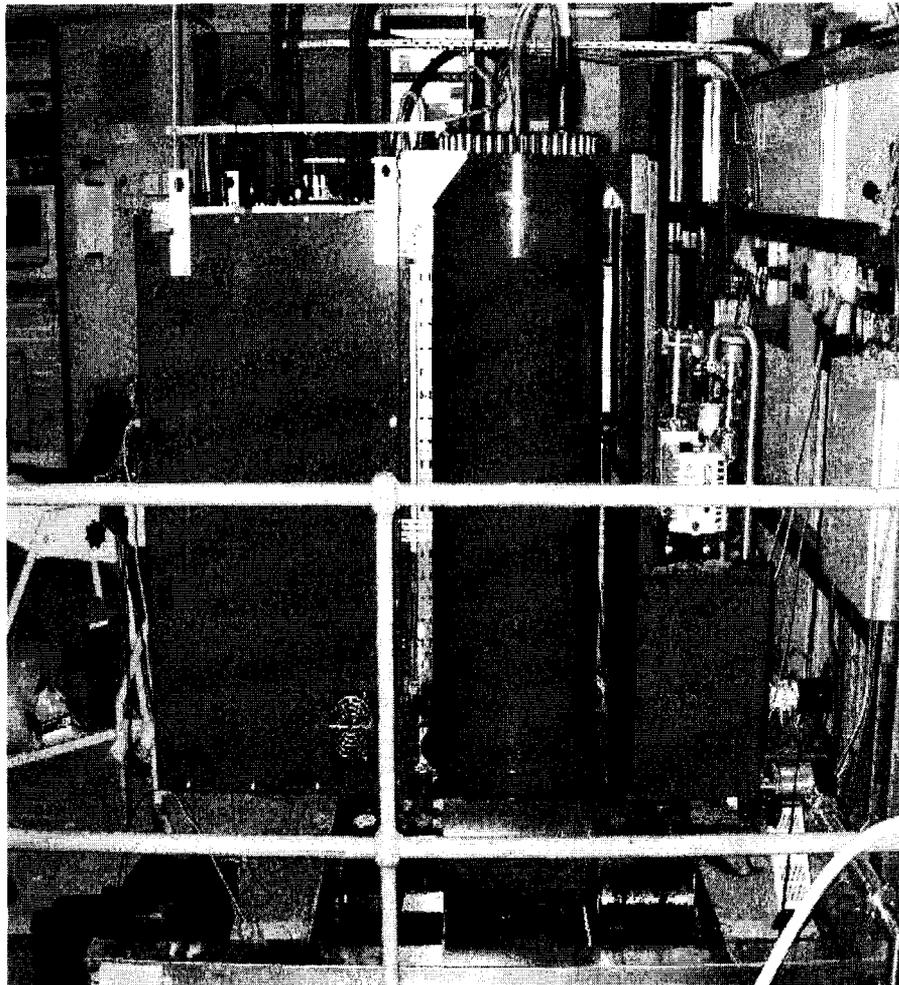


FIG.5 -- ZONAL ENERGY STORAGE

Load Banks

Two load banks are provided arranged for 60Hz operation, one rated 7.5MVA @0.8PF and one at 23.3MVA @0.9 PF. The smaller load bank has eight parallel contactors, four, which connect resistive elements at 10, 20, 30 and 40%, and four which connect reactive elements of 10,20,30 and 40% of the total load bank capacity. The larger load bank is connected to the HV system via a contactor panel, that performs two duties, Star Point Shorting and On Load Switching depending if the system is being used for GTA Testing (25% step resistive, reactive or combined load) or Four Quadrant Load (purely resistive) testing. For the later, the centre point of each resistor is shorted into a star point to allow full torque(amps) to be developed astern at half speed (volts), compared with full speed in the ahead direction.

Government Furnished Equipment (GFE) PM system

The Propulsion Motor System is provided under a separate MoD Contract to the main facility and will be covered in detail in this article. It uses ALSTOM's 15 Phase AIM in conjunction with three off 5 phase VDM 25000 convertor channels to provide 20MW of propulsion power at 180RPM.

Four Quadrant Load (4QL)

The GFE PM is connected to a load generator via a gearbox. The gearbox forms part of the system so that a more cost effective higher speed generator can be used as the load machine. The load generator gives 60Hz at a shaft speed of 514 RPM. As well as producing a classical square law for torque in both the ahead and astern directions, it is capable of providing motoring torque in both directions in order to simulate the torque generated on a propeller during manoeuvring due to the speed of the vessel. Since it can motor and brake in both ahead and astern directions it operates in all four quadrants.

Motoring Quadrants

The larger load bank is configured effectively as one large resistor. This resistor is placed across the 4QL generator windings via two breakers and electrically loads the generator. The voltage on the output terminals of the generator is controlled by the slipring fed DC field. It is controlled to provide the required torque at any speed to simulate a ship's propeller. Where generator V/F limits are reached the Convertor Dynamic Breaking (DB) will be used. It is therefore the control of the voltage of the generator terminals, and not the load bank resistance that is varied to simulate a propeller torque curve.

Astern Motoring Quadrant

There is a requirement to achieve full torque on the PM in reverse at half the speed of ahead running, this means that during the reversal of the PM, the resistor bank resistance is halved. With half speed and therefore half volts, then half the resistance will still result in rated current, and therefore full propeller torque. This resistor halving takes place using circuit breakers on the resistor bank.

Regenerating Quadrants

During the regenerating quadrants, the 4QL requires some external energy in order to simulate the propeller 'windmilling' through the water due to ships motion. This tests the PM's ability to regenerate and dissipate its energy into dynamic braking resistors fitted to the propulsion convertors. The 'windmilling' energy would normally be provided by the kinetic energy of the ship, but the 4QL System provides this into the PM by motoring the four quadrant generator, this is operated at variable frequency using an ALSTOM VDM5000 PWM convertor 4QLC fed from the 50Hz shore supply.

4QL Convertor Rating

The 4QL Convertor provides 2MW of power into the 4QL Generator at speeds of 25% or greater. The convertor/generator (motor) provides a maximum torque, which when multiplied by 25% speed gives 2MW power, therefore in reality it can produce considerably more regenerating power into the system when related to full speed, but this is not required for regeneration testing.

4QL operation

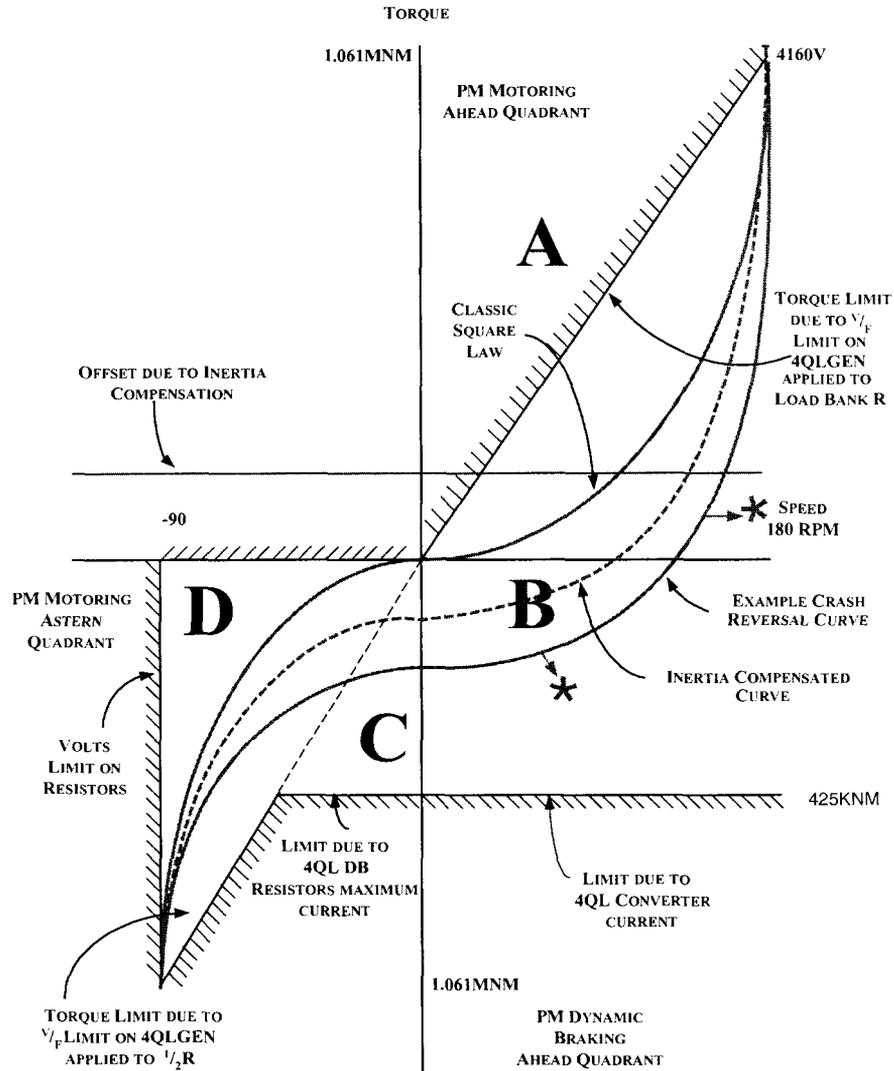


FIG.6 - 4QLS EXPLAINED

(FIG.6) 4 shows a typical Robinson Curve and the limits of the system fitted to ESTD. A crash reversal from full speed is one of the most arduous manoeuvres that can be performed, when this is undertaken, the propeller torque begins on the 100% curve, but rapidly crosses the other curves as the ship speed decays. By the time the ship has stopped, the propeller torque will finish at a point on the 0% speed curve. From start to finish of the manoeuvre, it will follow a characteristic that approximates to the curve shown in FIG.6. The exact shape and magnitude of the curve depends on many factors, the propeller, the ship's hull characteristics and the ramp rate of the propeller shaft. On ESTD the requirement is not to test specific ship curves, but to test the propulsion motor on a realistic generic curve.

With reference to FIG.6:

- In Area A the 4QL Generator is generating and dissipating energy into the large load bank. The level of torque is set by the current flowing into the load bank, and is varied by altering the DC slipping fed generator field. The generator must not be overfluxed and therefore it must keep a constant V/F ratio, which effectively means that it is limited by a line from the origin to the max torque that is proportional to speed. Figures below this torque limit can be set and varied simply by field control. In this region the maximum torque is 1.06 MNm and at max RPM this gives the 20MW rating point.
- In Area B, the 4QL Generator no longer acts as a generator, as the torque has changed polarity. The machine becomes a motor driven by the 4QL variable speed drive. This drive draws power from the mains supply and motors the load train, requiring the PM to generate and dissipate energy into its Dynamic Braking Resistors. The limits of this area are due to the current rating of the drive, giving 425kNm, which at speeds of >25% satisfy the contractual requirement of 2MW in this quadrant.
- In Area C, the 4QL is not yet into the astern generating region since the machine would be overfluxed. In this small area, until the curve crosses the constant V/F line, the astern braking is provided by a set of dynamic braking resistors on the 4QL (Not the PM) convertor. As well as a torque limit in this area, there is an energy limit, since the energy is dissipated in a resistor of a short term rating.
- Area D is back into the generator/load bank dissipation mode. This area can be set up to mirror Area A, where the system provides maximum torque at maximum speed in order to produce 20MW, or it can be set up as shown to produce maximum torque at half astern speed to give 10MW. In order to produce the maximum torque at half speed, the load bank resistance is halved by contactors, giving maximum current using only half speed (volts).

Facility equipment

The ESTD also comprises facility equipment such as cooling, auxiliary 50Hz sources, fuel distribution and lubrication systems.

PM FOR THE ESTD

Requirements

The PM for the ESTD system, comprising a motor and convertor, is required to provide up to full load torque (1.061MNm) at all speeds up to 180 rpm ahead and 90 rpm astern, operating in all 4 quadrants as a representative PM system with no barred speed ranges or operating restrictions.

Design of the PM for the ESTD System

An electrical overview of the system is shown in (FIG.7).

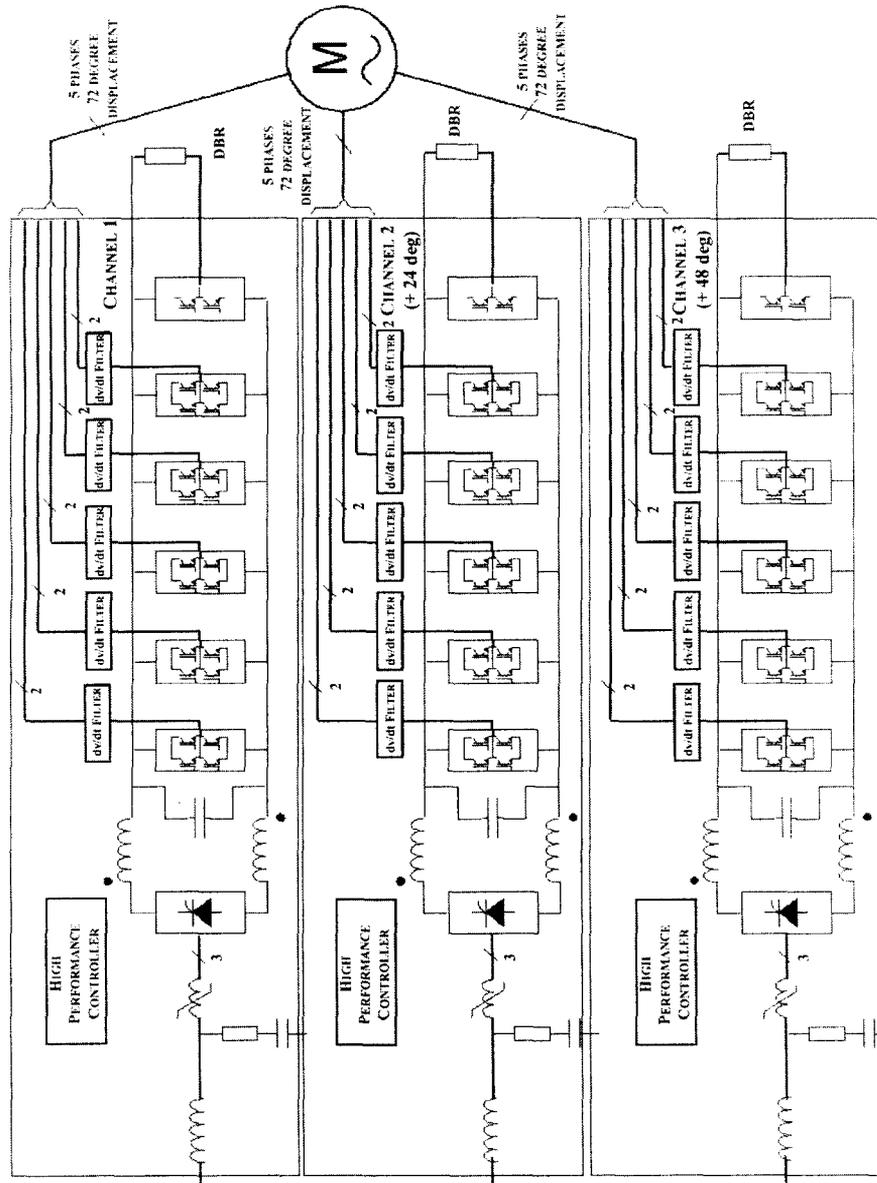


FIG.7 – AN ELECTRICAL OVERVIEW OF THE SYSTEM (EXCLUDING HARMONIC FILTER)

The decision on motor internal electrical design such as the number of phases needs to be taken with full cognisance of the effect it has on the converter design. Despite a review of the converter topologies possible for this system a PWM H-bridge design was again chosen. This made the design for this system an evolution of the one for the US IPS programme and many of the broad parameters are the same such as converter supply voltage and number of motor phases.

However the detail in a number of areas was revised based on the feedback of actual system results which allowed a validation and revision of the design tools and models.

Also a number of changes were made as a direct result of the IPS programme which take the system from the demonstrator to ship ready hardware for production. For the motor the IPS testing showed that the insulation was being stressed by the high rate of change of voltages and as a result of this an extensive insulation upgrade programme was undertaken. The latest insulation system now has a design life of 40 years service. The testing also showed that there was excessive cooling in certain areas and at all powers below full speed – this has led to an optimized cooling system, with variable speed drive fans and a higher power density results. The final major change for the motor is the inclusion of an integral lubrication system rather than the separate lubricating oil skid that was supplied to IPS.

The major changes for the converter result primarily from the lessons of achieving the very high power density in the IPS installation. The IPS converter had all 15 phases in one cubicle but for the 20MW PM System it has been divided into 3 cubicles (channels) each of 5 phases. Each channel is identical with improve cubicle layout on a more modular basis with the largest module sizes and weights reduced. An increase in IGBT device ratings from 1.6kV to 3.3kV has been made – the 3.3kV is widely used in the transportation industry and has multiple sources. This device rating increase could have been used to greatly increase power density but in order to improve access and maintainability some of this new space has been utilized.

System lessons from Philadelphia such as operation on a reduced number of phases for higher efficiency at lower powers have been implemented along with updated software to increase stability margins on a wide range of driving generator powers and combinations. Also lessons on the heating effects of the harmonic currents have enabled an improvement in the design of the harmonic filter to complete the system for use in ESTD. The motor is at (FIG.8) with the converter at (FIG.9).



FIG.8 – MODEL OF ESTD 20 MW AIM

The motor will be 3m high, 3.6m wide at the feet, 3.3m frame length and weigh 89 tonnes. The converter parameters are shown compared to the IPS design in FIG.9.

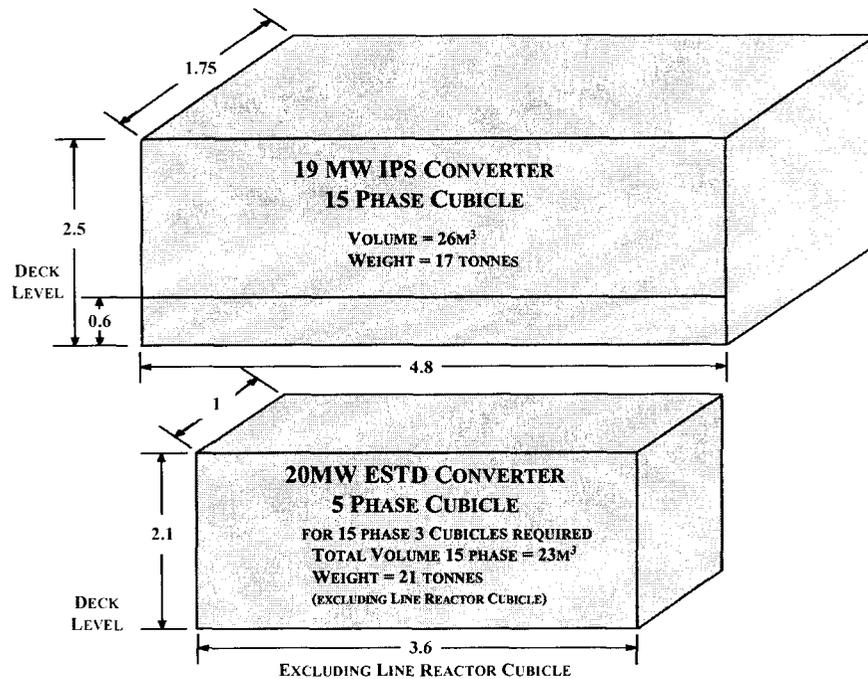


FIG.9 – IPS AND ESTD 20MW SYSTEM CONVERTER COMPARISON

Future advancements

Further improvements are being considered for the AIM system, particularly with respect to system efficiency, signature, power density and weight. New devices based on Silicon Carbide are becoming available and could be utilized as they achieve the required ratings. The implication of efficiency on Through Life Costs can be significant and design efforts can result in improved component as well as system efficiency. Snubber Energy Recovery (SER) can be incorporated within the converter, which would utilise the wasted energy within the snubber circuits. This is projected to improve the efficiency by 5% at low powers and 0.5% at full power. Low power efficiency gains are significant due to warship's operating profiles involving substantive periods at low speeds for cruise and littoral operations.

At present the AIM system cannot be operated with an input voltage of higher than 4.2kV without the use of transformers. Transformers increase the system volume and weight and reduce system efficiency and therefore their inclusion is not desired. Utilizing technology of the near future a direct input 6.6kV converter could be produced but this requires further insulation development.

A further improvement could be the use of advanced materials to enable increased flux density concentrations to be developed and hence greater power developed for a given frame size. However the high cost of such changes mean they would only be employed where absolutely necessary from a space constraint perspective. Additionally composite materials could be used for the motor construction that would significantly reduce the weight of the motor.

Facility detail

The ESTD Facility is housed in a purpose built new building at the ALSTOM Whittle Research Centre at Whetstone near Leicester. (Fig.10) shows the internal layout of the building.

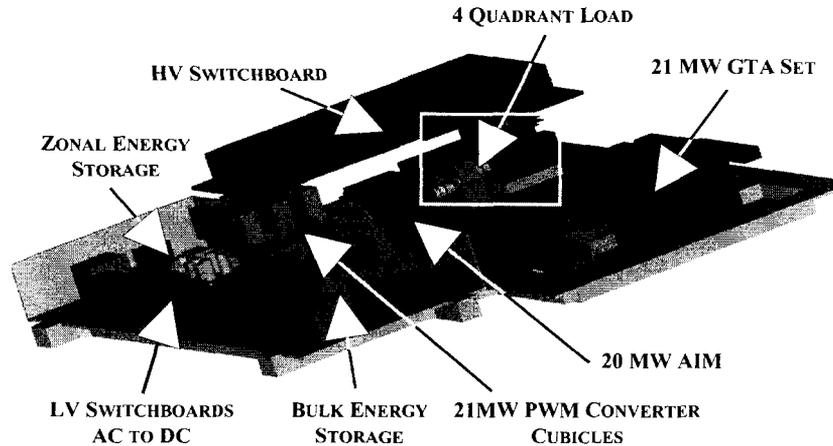


FIG.10 – ESTD LAYOUT

Progress

The end of the construction phase is approaching with the building and civil works complete and a range of equipment either installed or being assembled. Efforts now are focussed on installation and commissioning.

TESTING

The WR21 and the PM for ESTD will undergo specific equipment tests on site to allow acceptance of their delivery, installation.

PM for ESTD

In addition to the basic motor and converter checks, which includes insulation and converter bridge tests, the main Propulsion Motor system tests can be summarized as follows:

- Uncoupled tests to run the machine on 5, 10, then 15 phases:
 - Define ramp rates.
 - Machine control tests to check the converter-motor system stability.
 - Local and remote control operation.
 - Protection tests and earth current measurement.
- Coupled tests:
 - Reach full power at full speed at forward and astern.
 - Demonstrate reversionary mode of operation on 5 and 10 phases.
 - Heat run of the PM system at full power.

- ❑ Demonstrate control strategy robustness at starting/stopping slave channels and picking up spinning machine control tests to check the convertor-motor system stability.
- ❑ Local and remote control operation.
- ❑ Protection tests and earth current measurement.

WR21

The 21MW WR21 gas turbine is refurbished from its previous development, re-configured to a GTA by the addition of an alternator and an appropriate engine controller. The gas turbine itself, although a prototype, has been designed to meet Naval Standards and a sister engine set has already completed more than 1,500 endurance hours at DCN Indret in France.

The equipment nevertheless requires further testing to support its use in a GTA configuration for the Type 45 and the ESTD projects. GTA1 and 2 tests were successfully implemented at Pyestock in the second quarter of 2001 to prove the engine ability to operate at constant speed against a water brake throughout its full power range.

This series of tests now gives the MoD confidence that the equipment will fit its purpose at the ESTD. The ESTD GTA3 tests are scheduled to round off the acceptance of the GTA delivery and installation into the ESTD, while completing the last phase of GTA tests by driving a real alternator.

Apart from basic installation and safety checks, the main WR21 GTA3 tests are summarized as:

- Steady state operation.
- Overload test.
- Correct operation without and with load.
- Automatic Voltage Regulator (AVR) testing including transient voltage response using reactive load.
- Governor testing including transient frequency response.
- Synchronising and load transfer.
- Parallel operation with the TYPHOON generator.
- Open circuit.

The last part of the WR21 GTA3 tests will include combined PM for ESTD/WR21 performance trials. These will provide the opportunity to check the stability of both equipment working together, as well as checking for the absence of heating effects that could be induced by the high harmonic currents drawn by the propulsion motor system through the alternator and various filters' inductances.

Phase 1 trials

The purpose of the Phase 1 trials is to perform typical ship like operation and apply major faults that future platforms will potentially face during their life. Phase 1 trials will also provide valuable Electromagnetic Compatibility (EMC) and acoustic measurements on equipment such as the WR21 GTA and PM for the ESTD.

The following list outlines and describes the fault scenarios that have been developed for Phase 1:

- *WR21 GTA Trip*
WR21GTA/4.5MW GTA operating in parallel with the HV system loaded to 25MW.
This scenario will demonstrate the ability of the other power sources to increase their power to their maximum, while the PM output is reduced to within the system capacity. The HV/LV link convertors are to maintain no-break supply to the LV system.
- *Crash Stop with the HV System at Full System Load*
WR21GTA/4.5MW GTA operating in parallel with the HV system loaded to 25MW.
This scenario tests the regenerative braking of the PM and the system behaviour of reversing the PM.
- *De-excitation of one Alternator with two Alternators in Parallel*
WR21GTA/4.5MW GTA operating in parallel.
This scenario tests the excitation protection on the GTAs whilst the ESTD system will maintain as much propulsive power as possible and no-break supply to the LV system.
- *Short-circuit on Ship Service Busbar on Supply to HV/LV Link Convertors*
A short circuit is applied at one link convertor terminal when it is working in parallel with the other one.
This scenario will test the fault current discrimination of the LV system in the event of a short circuit, and will show the capacity of the second link convertor to cope with overpower demand and maintain power to some of the LV loads, others being rejected.
- *Failure of Auto-Synchronisation with a GTA being Paralleled onto the system with another GTA*
This test consists of paralleling GTAs onto each other 180 degrees out of phase.
This scenario will test system discrimination.
- *Short Circuit on the HV System with WR21 operating as the only generator*
The short circuit will be applied close to the WR21 GTA feeder.
This scenario tests the behaviour of the system on failure of the WR21 GTA while in single generator operation.
- *Short Circuit on the HV System when Fully Powered and Loaded*
This scenario will show the discrimination of the HV system, when a short circuit is applied at one of its major consumer terminals, in this case the 7.5MVA load bank. The load bank should be rejected whilst the WR21 and the 4.5MW TYPHOON GTAs should remain on line operating in parallel.

Phase 2 Trials Database

The aim of the Phase 2 trials is to perform additional trials to build on the information gained from Phase 1. The trials have yet to be defined and a database of potential trials is being maintained, extracts of the database are at Table 1.

TABLE 1 – Possible ESTD Phase 2 trials

Test summary	Purpose
Additional trials for modelling validation following Phase 1 results.	Complete validation of models.
Reduced ship service voltage on DC LV System down from 800VDC.	Explore 750V/700V for optimizing equipment procurement.
Reduced ship service voltage on AC LV System down from 440V/60Hz.	Know the limit voltage to ensure a correct operation.
Reduced HV bus frequency in transient and steady state.	Prove flexibility of link converters in transient and steady state.
Reduce HV and LV QPS requirements.	Prove possibility to operate with high THD, and to determine minimum acceptable standard of quality of power supply for AC and DC system. Watch behaviour of equipment with voltage THD up to 26% to reduce requirements for new projects.
Reduced HV switchboard frequency and voltage with complementary HV loads (pumps, fans, etc.).	Know the limit of frequency to ensure the correct operation of HV equipment.
Disable some circuit breakers and apply faults on either HV or LV switchboard.	Reduce risk associated with the safety of equipment and personnel. Prove the correct operation of the 2nd order protections.
Optimization of control logic for PM to improve: efficiency, QPS and THD, acoustic signature.	To establish best efficiency at various operating conditions.
Investigation of the effect of pulse power loads on the LV distribution (EMCATS, new type of weapons etc.).	Know behaviour of system with pulses to simulate impact of new weapons on system in transient state.
Trip of PM system with 2 groups in parallel.	Watch behaviour of HV system with total loss of PM.
Loss of speed regulator of GTA2.	Watch behaviour of protection system in the case of loss of speed regulator and reduce risk associated of the safety of equipment.
Test allowing the full run down for the flywheel.	Establish the minimum flywheel speed that is practical (max kWh).
Exceed environmental specification. (noise, vibration).	Explore environmental performance margin of equipment.
EMC measurement for ESTD system.	Identify and define EMC maps. Identify magnetic fields to support designs. Define decreasing laws and propagation modes depending on equipment type and operating state/load.
EMC measurement for HV cable.	Measure EMC fields near HV cable (IEC cable) according to the distance from it.
Test with non linear loads.	To be sure that LV load on ESTD system is really representative of LV loads on an electric ship.
Failure of auto-synchronization with GTA1 already on line.	To test survivability during failure of the auto-synchronization of GTA2 when WR21 is already on line.

Test summary	Purpose
Urgent change of configuration for the ship – Peace cruise to war cruise.	To test behaviour of system and measure time to reach the final configuration.
Use system without Machinery Control & Automation (MCAS).	Test possibility to keep the control of electrical system if MCAS is not available (reversionary/local control test).
Investigate rejection of the braking power to the bulk energy storage rather than resistors.	Watch if the link convertor and the bulk energy storage are able to absorb regenerated power.
Compare different types of HV/LV conversion (link convertor versus transformer, etc.).	To determine convenient and inconvenient for each system
Investigation for using and integration of alternative energy storage (Li Ion batteries), for both ZPSU and BES.	To find an alternative energy storage solution.
Additional tests to improve some equipment signature.	Check improvements of some equipment signature after modifications.
Investigate operation, maintenance procedure and safety procedures for main equipment.	Check that operation, maintenance and safety procedures are easily applicable.
Optimize PM ramp rates.	To find the best ramp rates with regard to electrical performances, environmental performances and mechanical performances.

Current and future programmes

Originally conceived to de-risk future platform concepts, the French DGA and UK MoD focus on the Multi-Mission Frigate and Type 45 respectively have increased the importance of the ESTD timescales greatly. The DGA require Phase 1 results on time in order to put forward electric propulsion as a contender to their next platform. The Phase 1 results are also extremely important to the Type 45 de-risking process as its IEP, as a subset of the IFEP architecture at ESTD. In support of which a period of bespoke Type 45 Shore Integration Testing has been programmed into the ESTD facility. This will bring the other items of Type 45 ship fit equipment, the DG set, the harmonic filters and the ship services transformer to the site in order to test a half ship set of equipment.

The future of ESTD post Phase 2 trials is already under discussion. It is not necessarily limited to the UK or French MoD programmes, there is also an open opportunity for industry to take advantage of the significant investment made in the site as is the potential for foreign government involvement.

Modelling - ESTD and beyond

Modelling, in support of the ESTD, is a key output of the programme in terms of validated system and equipment models; a library of models which can support the design, integration, performance and operability analysis of future naval systems. The modelling efforts in support of the ESTD will provide an assessment of the ESTD scenarios at all stages of ESTD testing to assist with trial predication, model validation and performance improvements. The functionality of the models for ESTD will allow assessment of dynamic performance, system transients, external impacts and bounds of operation. System modelling is a key enabler in power system design and the ESTD models will integrate into the MoD/DGA power system model libraries – enabling a ‘fuel to thrust’ approach. Key issues however with modelling are how to manage the proprietary nature of models, validation

techniques and fidelity of modelling, these issues are attracting significant focus and need 'buy in' from the broader stakeholding community – notably equipment suppliers and system integrators.

Summary

The article has shown that the ESTD and PM for the ESTD are key enablers for the Electric Warship programme with the potential to inform a wide range of platforms. ESTD is an advanced technology demonstrator which represents the most power dense Naval Marine Power System and includes a range of novel and advanced technologies with the capacity to be enhanced to include future systems.

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