POWERING THE WEAPON SYSTEM: OPTIONS ARISING FROM ESTD

D J Mattick, OBE, BScEng, CEng, MIEE, MINucE, FIMarEST
ALSTOM Power Conversion Limited, Rugby
P Deverill, B Eng (Hons), MIEE
UK Ministry of Defence, Head of Electrical Propulsion Systems

ABSTRACT

The ALSTOM Power Conversion Electric Ship Technology Demonstrator (ESTD) was the outcome of a number of years of electric ship studies which led to a contract placed by the UK MoD and the French DGA. The demonstrator makes wide use of power electronics, not only to control the propulsion motor but in particular to distribute power through Link Converters and to generate the supplies required by consumers through Zonal Power Supply Units. There is also extensive use of energy storage to support consumers in damage control zones of a ship and to support distribution and/or propulsion on loss of a prime mover. This paper reviews the technologies and systems demonstrated at ESTD and the performance achieved under arduous operation and failure scenarios. It then indicates how equipment and systems can be configured in the future to continue to supply high quality, high integrity electrical power to combat systems throughout the ship even when suffering extensive damage. It concludes that there are a number of options available to future ship designers and their application need only be limited by imagination albeit they will need to work in concert with the power system designer from the outset to realise the optimal solution for cost versus performance trade off.

Introduction

The equipment and system installation at the Electric Ship Technology Demonstrator (ESTD) has been discussed in a number of earlier papers, including References 1, 2 and 3, and only a brief overview is included here.

THE ESTD INSTALLATION

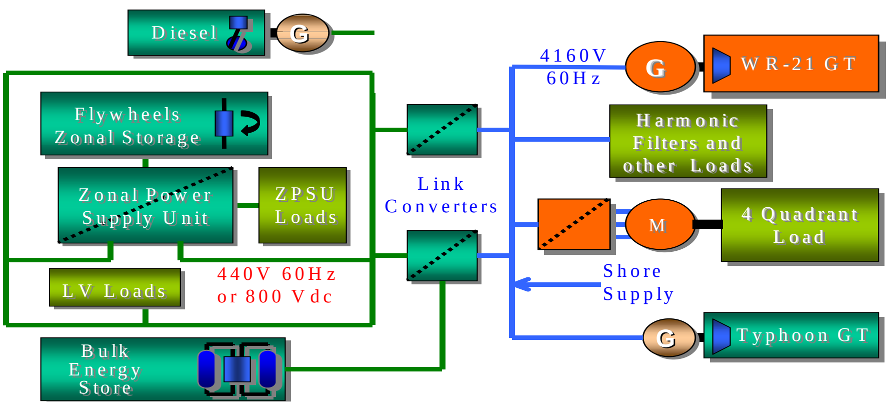

Fig. 1 ESTD Overview

Figure 1 shows a simple overview of the installation. There are two engines powering Medium Voltage (MV) generators, a 21MW WR-21 and a 4MW Typhoon Gas Turbine Alternator generating at 4.16kV. The main MV load is the 20MW 15 phase Advanced Induction Motor (AIM) and this is controlled at between 0 and 180 rpm by a pulse width modulated converter using Insulated Gate Bipolar Transistors (IGBT's) for the output inverting, or machine bridge and thyristors for the input bridge. The propulsion shaft is loaded by a Four Quadrant Load (4QL) that can replicate the 'Robinson Curves' of any hull/propeller combination within its power range as well as modelling simple ship dynamics. The converter is directly connected to the MV supply and harmonic filters are utilised to maintain MV Total Harmonic Distortion (THD) within specification. Up to 6MW of MV load can be connected using resistor banks. A 50Hz supply from the Regional Electricity Company (REC) can be connected and the motor can be run up to 10MW from this, useful for commissioning. It is also used to drive the 4QL when the propulsion system is regenerating from the windmilling shaft.

The Low Voltage (LV) system can be operated at 800V DC or 440V AC and supplies some LV loads and a Zonal Power Supply Unit (ZPSU). The LV loads comprise resistive load banks, motors that can be supplied either direct online or via Variable Speed Drives (VSD), and some permanently coupled VSDs. For DC operation, all motors are fed via VSDs, with the 800V DC directly supplying its DC link. The ZPSU is a suite of power electronics that takes one of three inputs and generates all the various supplies needed by consumers in the local area. At ESTD it provides 440V 60Hz, 115V 60Hz, 115V 400Hz, 220V DC and 24V DC, chosen to be 'ship-like' supplies. The ZPSU can also generate up to 300kW of output and is supported by an adjacent Zonal Energy Store (ZES), which it automatically adopts if both the distribution system inputs fail. After a non-essential load shed, it can support 200kW of output load for up to 4 minutes. The energy store is a set of 5 flywheels rotating at 150,000 rpm, running in a vacuum and supported by magnetic bearings. However, it has been demonstrated that other energy storage devices can be harnessed as easily as flywheels. There is also a low voltage diesel generator set that can supply the 440V AC LV system but it is more normally used as a stand-alone set supporting site facilities such as cooling systems.

The LV and MV systems are interconnected by 1MW, 1.1MVA (LV rating) bi-directional power electronic Link Converters (LC) that not only transform the voltage but can isolate the LV from MV transients and vice versa. The DC link of one LC is supported by a Bulk Energy Store (BES), designed to be capable of providing 1MW for 10 minutes to act as a transitional supply while providing alternative supplies on loss of an engine, should it be the only one running.

ESTD Results

Again, the results of ESTD testing have been discussed in a variety of previous papers and, due to space limitations, only an overview can be included here to give a 'flavour' of the results.

All equipment installed at ESTD had undertaken Factory Acceptance Test or been run previously. Once installed, it was commissioned and a set of results taken to record the 'as fitted' performance. As equipment finished commissioning, it was operated with more and more other equipment until all were working in consort and the systems were fully integrated.

SCENARIO TESTS

ESTD Phase 1 completed with a suite of major scenario tests designed to demonstrate the robustness of the complete system, all of which were satisfactorily achieved. These included:

MV system and switchboard three phase bolted short circuits.

Whilst the MV system blacked out, the essential LV consumers were sustained from the ZES and ZPSU. The MV, LV or both systems could be re-energised from the BES and propulsion and LV distribution restored until another generator could be connected.

LV system three phase bolted short circuits.

A short circuit was applied on the output of the LC connected to the BES when operating in both the AC and the DC mode. The MV system saw no significant load as the LCs limited the energy transferred to the fault. The essential LV consumers were sustained from the ZES and ZPSU while the fault was cleared, at which point the non-faulted Link Converter re-energised the LV system and the ZPSU reverted to normal operation.

De-excitation of generators when operating in parallel.

Both the Typhoon and then the WR-21 were individually de-excited to simulate various types of AVR failure and mal-operation. In general the system survived these demanding faults and in all cases the LV consumers were sustained, either from the ZES and ZPSU or from HV through the link converters.

Propulsion motor crash reversal evolutions.

Full ship stopping evolutions were conducted. There was no significant variation of LV quality of supply as all HV variations were isolated by the link converters. HV quality of supply stayed within the specified Lloyds limits.

Propulsion motor trip.

Whilst operating at full power with the WR-21 and the Typhoon in parallel, the propulsion motor was tripped. Gas turbines remained running, the HV system remained energised and the LV system was unaffected.

Mal-synchronisation.

With the Typhoon at full load supporting both HV and LV systems, the WR-21 was connected 180 degrees out of phase. The HV system blacked out but the essential LV consumers were sustained from the ZES and ZPSU. The HV, LV or both systems could be re-energised from the BES and propulsion restored. However, the WR-21 was still running and this was used to restore the HV system once it was clearly safe to do so.

Illustrations.

Whilst there are many graphs that illustrate these events, the only ones of significance to this paper are the outputs from the ZPSU and these are singularly uninteresting. They are 'flat lines' where the voltage, current and quality of power supply remain in specification and unchanged throughout the major electrical transients on the supply and distribution systems.

WEAPON SYSTEM SUPPLY REQUIREMENTS

The weapon system is the warships "raison d'être" and as such must have a very high priority for electrical supply. There are many self-evident statements that can be made such as:

> The traditional 'Float, Move, Fight' priority can be 'Float, Fight, Move' in some littoral warfare roles.
>
> The quality of supply requirement must allow the weapon system to work and the applied standard is only guidance.
>
> Receiving damage from the opposition is a very good reason to keep all weapon systems operating.
>
> Few combat systems consume a standard 440V 60Hz, 115V 60Hz or 115V 400Hz without converting it.
>
> Weapon system designers are not good power supply designers and are quite likely to degrade the supply when they connect and convert it.
>
> The weapon system should be capable of operating until it suffers action damage and not be put out of action due to a hit somewhere else in the ship.

In practice, the requirement is to provide the amount of power required, to the quality required, whenever it is required.

FUTURE WEAPON SYSTEM SUPPLY REQUIREMENTS

Over recent decades the power required by weapon systems has increased although the demands on the quality of that supply have changed little. Looking to the future, the advent of weapon systems that demand high power for short duration, commonly known as 'pulsed loads', might have a dramatic impact on the methods required to 'power the weapon system'. However, there are a number of papers that have assessed this future, for example Reference 4, and they all conclude that an intermediate energy store will be required between the 'pulsed weapon' and the distribution system if the appropriate quality of power supply is to be maintained. Accordingly, this paper assumes that the impact of 'pulsed weapons' on future distribution systems will not be significantly different to any other future weapon.

WEAPON SYSTEM POWER SUPPLIES

Traditional/Legacy

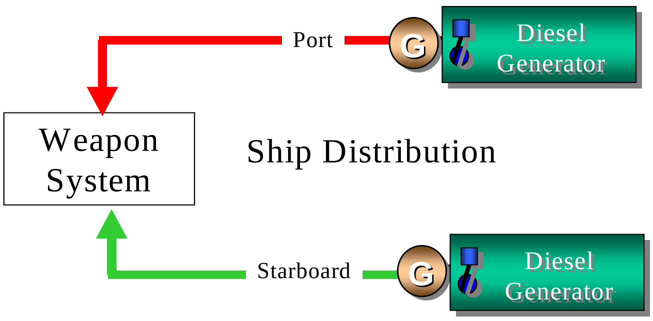

Fig. 2 Simple Legacy Distribution System

Traditional power supplies for non-electrically propelled small and medium sized warships at sea today are usually provided from two separate generator sets and distributed through a tree system that affords a discrimination capability to minimise cable sizes as the load current reduces. Whilst 450V 60Hz is normally generated, there are various conversion stages to provide the wide variety of supplies offered to the consumers, such as the weapon system. Figure 2 shows a much-simplified version of the distribution system with prime movers powering port and starboard distribution systems independently - the various stages of conversion and discrimination are not shown.

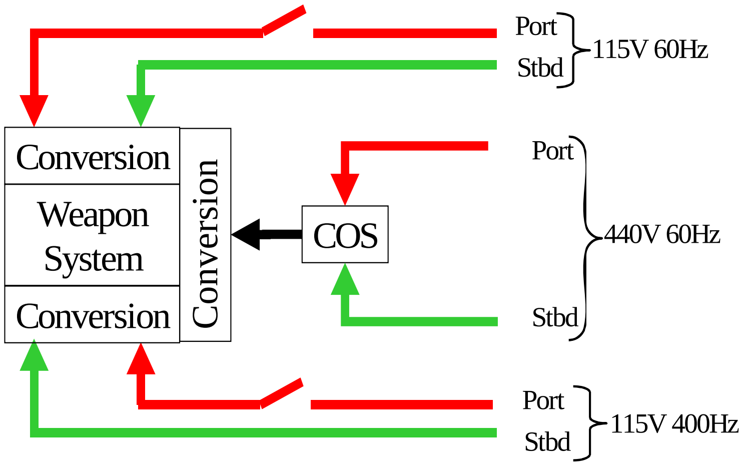

Fig. 3 Typical Current Distribution System

Typical weapon systems at sea today are supplied with a number of different voltages from a number of different sources. A typical system might be as at Figure 3. The ship distribution system will normally be run split with port and starboard supplies coming from separate generators. Either the port or the starboard 115V 60Hz and 115V 400Hz will be energised and both the 440V 60Hz supplies energised with one automatically selected by the Change Over Switch (COS). On loss of either port or starboard supplies the weapon system will see some disruption but, with good design, might ride through these. For example, 115V 60Hz may well be for 'housekeeping supplies', such as cooling or heating, where the thermal lag gives sufficient delay to allow the alternative supply to be re-energised. The 115V 400Hz may be for data transmission which is a back up to a digital system supplied from supplies converted from the 440V 60Hz system. Capacitive stored energy may be sufficient to ride through the dwell time of the 440V 60Hz Change Over Switch (COS).

However, such good design may not always be the case. For example, the weapon system designer may have provided an entirely adequate system for his original, target platform but it may not work in a retrofit installation. Potential problem may occur due to the volt drop associated with the extended cable runs of traditional naval tree distribution systems. Without a power source local to the Weapon System there is a good chance that action damage in adjacent damage control zones will de-energise the Weapon System. Further problems may be associated with frequency or voltage transients suffered by the generating set being seen throughout the ship. Similarly, so is harmonic distortion wherever it may be generated, and the source might be various consumers, as more and more use ever-higher power electronics as part of their conversion stages.

There is a significant risk associated with this unintended transfer of the responsibility for quality of supply to the Weapon System designer, as he has no responsibility for the distribution system.

Impact of Electric Propulsion

Electric Propulsion systems normally utilise a 'power station' approach whereby the same generators supply both propulsion and the ship service distribution. As the propulsion system is by far the biggest load, it dominates the voltage and frequency transient response of the system during normal operation with the most severe transient occurring should the propulsion system trip. Constraining the propulsion motor power ramp rates such that the generators remain within their specified performance bands can reduce this impact. However, power electronics switch the multi-megawatts required by the propulsion drives at very high speeds and as a consequence generate harmonic distortion. This can be handled in a variety of ways, including:

> Phase shifting transformers at the front end of the converter to increase the switching pulse number seen by the power system and hence reducing the harmonic burden.
>
> Active converter front end rectification.
>
> Harmonic filters tuned to reduce the harmonic distortion to acceptable limits.
>
> With Link Converters, as demonstrated at ESTD.

All of these routes add cost and volume to the installation and do not entirely relieve the harmonic burden.

Typically, transformers link the MV and LV distribution of present day, electric propulsion systems and the MV harmonic burden is reduced sufficiently to meet the specified requirement on the LV system. However, this leaves one great unknown - the amount of harmonics injected into the LV system at the point of common coupling of distorting LV systems, including Weapon Systems. Very often the total system LV harmonic burden is not known until the complete ship has been operating in all its many potential modes and geographical areas and this takes considerable periods of time.

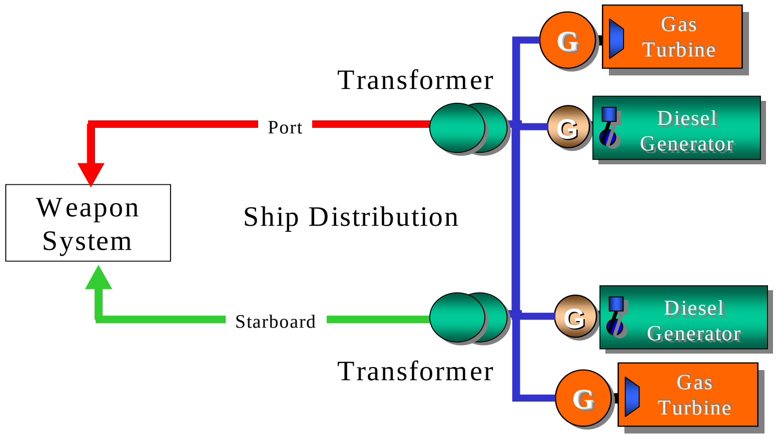

Fig. 4 Transformer Fed Distribution System

Typical Weapon System Supplies with Electric Propulsion

Since most new electric propulsion warships and auxiliaries have their main supplies fed through transformers, which replace the generator sets of traditional / legacy installations - the schematic of a typical installation is shown at Figure 4. Largely repeating above paragraph.

There are some variants such as the Type 23 frigate where the need for a high quality of supply led to the adoption of two 950kW motor generator sets to support all ship service supplies. Military equipment in the UK Auxiliary Oiler is also fed from motor generators. In such cases, the motor-generator isolates harmonic distortion and voltage transients and much reduces frequency transients. Similar motor generator fed systems are fitted to research ships to provide clean supplies for the science packages. The volume, weight and cost of motor generator sets make them a less than preferred option for supply to Weapon Systems.

Link Converter Supplied Weapon Systems

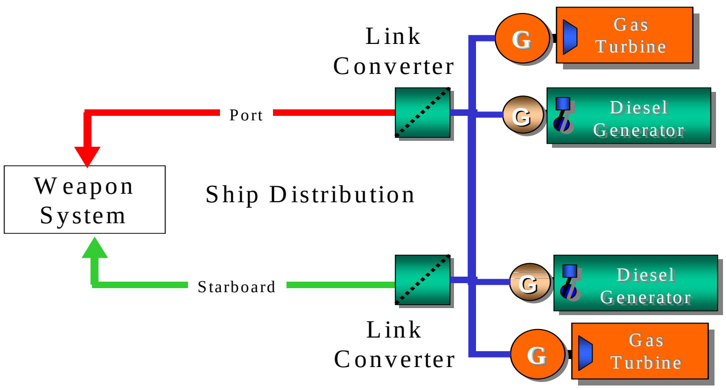

Fig. 5 Link Converter Fed Distribution System

Testing was conducted at ESTD with LV system loads representative of a weapon system and this gave the opportunity to operate a system supplied by LCs in place of transformers (Figure 5).

The ESTD experience was that LCs could provide similar supply quality to the motor generator set but with three additional functions:

1. They can isolate frequency transients as well as voltage transients;
2. They can active filter the LV side to clean up harmonics generated by the consumers;
3. They can fault current limit, reducing the fault clearance requirements of the switchgear and thus increase system fault tolerance.

These functions are illustrated below with results taken during testing at ESTD.

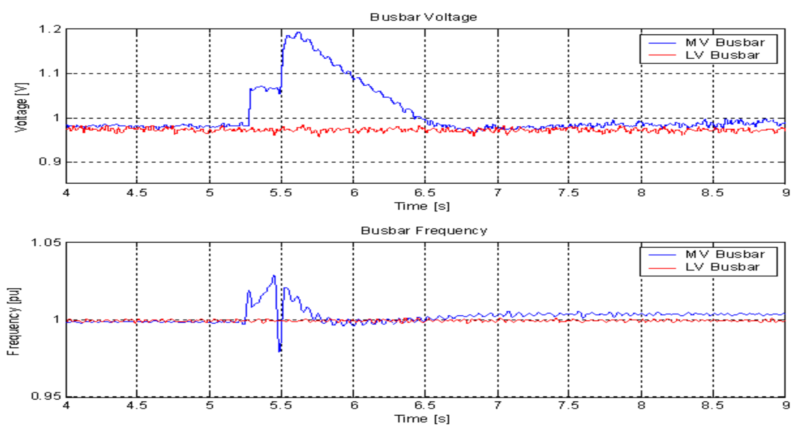

Fig. 6 MV and LV Bus Bar Voltage and Frequency

Isolate Voltage and Frequency Transients

Figure 6 shows the MV and LV bus bar voltage and frequency transients during a propulsion motor trip at ETSD. The straight line parallel to the 1 per unit axis is the LV system parameters and clearly shows the effectiveness of the LC.

The LC performs similarly when powered from distorted supplies. As long as the distortion is within the range it is designed to cope with, it will happily produce a clean 440V 60Hz or 800V DC output, as programmed.

Active Filtering the LV side

Typical results achieved by active filtering of the LV system is shown in Table I below. The results are from testing undertaken with a transformer-coupled system powered from a 2MW diesel generator with a dedicated LV active filter and not the ESTD system previously described - in this case LV distortion is dominated by the propulsion converter. However, the active filtering functionality is inherent with Link Converter and similar results could be achieved with a Link Converter filtering the LV in a coupled system.

Table 1 Results achieved by Active Filtering

DIESEL GENERATOR SUPPLY, PROPULSION MOTOR AT 30% SPEED AND 700KW LV LOAD		
Without Active Filtering	LV Voltage total harmonic distortion	18%
With Active Filtering	LV Voltage total harmonic distortion	3.8%
DIESEL GENERATOR SUPPLY, PROPULSION MOTOR STOPPED AND 450KW NON-LINEAR LV LOAD		
Without Active Filtering	LV Voltage total harmonic distortion	4.4%
With Active Filtering	LV Voltage total harmonic distortion	1.5%

Fault Current Limiting

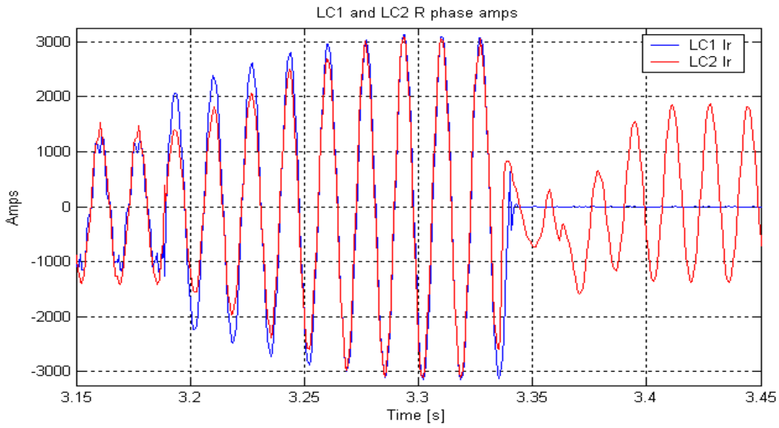

Fig. 7 LC current outputs in short circuit conditions

Figure 7 shows the Link Converter current outputs with a short circuit applied to the output of one of them. The current rises to its limit of some 170% full load and remains there until the protection system discriminates and clears the fault. The healthy link converter then recovers and re-supplies the remaining load.

It is important to note that this does not provide a continuity of supply to the consumers as the voltage must fall close to zero at the short circuit site. Nor does it provide a faster recovery than a traditional system, as the recovery time is dependent on the protection system. However, it does provide much-reduced fault current and therefore much reduced electromagnetic forces are imposed on the current carrying equipment.

One unusual aspect of this arrangement is that the discrimination fault currents are much reduced compared to classic systems and thus the traditional methodologies need modification. However, there are no emergent problems as modern protection devices can be set sufficiently accurately and are sufficiently stable to support reduced discrimination settings.

At ESTD a further functionality was added to one LC, the ability to take power from the BES and supply an output. At ESTD the original concept was to be able to supply MV from the BES should a single running generator fail. However, the ability to support the LV system from the BES was also implemented and demonstrated - and indeed to supply both the LV and HV in parallel - and such functionality is available should it be needed to support single generator operation.

Zonal Power Supply Unit Supplied Weapon Systems

There are some significant drawbacks to the weapon power supply systems discussed above. Firstly, the weapon system is at the end of an extended distribution system that can be interrupted by remote faults or action damage. Secondly, whilst many of the converted supplies are vital to the functioning of the weapon system, their generation and distribution systems can also be interrupted by remote faults or action damage. The combination is that the weapon system can be severely affected by many and various actions that are frequently only realised by experience.

A third drawback is that much of the power taken by the weapon system is converted internally to the supplies required by the weapon system. Weapon system designers use a variety of means to generate their required voltages and frequencies and this conversion process can severely degrade the quality of supply provided by the ship distribution system and, in extreme cases, cause failures on other connected loads.

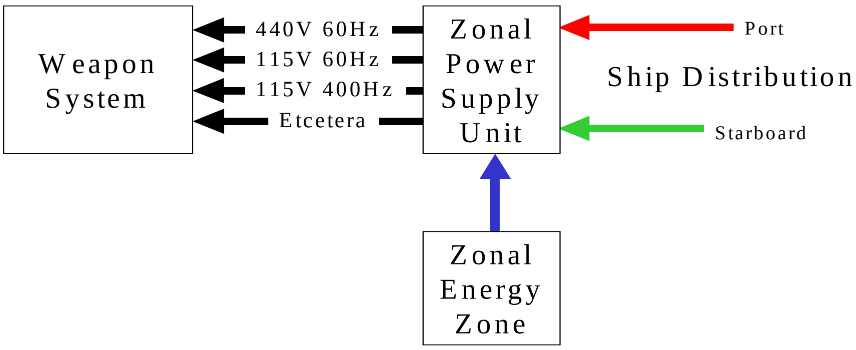

Fig. 8 ZPSU Supplied Weapon System

By using a ZPSU arrangement such as that of Figure 8 these drawbacks can be overcome. The port and starboard ship distribution supplies are used by the ZPSU power electronics to generate the supplies required by the weapon system.

Whilst Figure 8 shows typical output supplies for legacy systems, it is possible to make the appropriate ZPSU module produce any particular supply required by weapon system, selectable through software. Adopting such an approach can return the responsibility for the quality of supply from the weapon system designer to the power system designer.

The other key feature of the ZPSU type system is the ZES. This stores the energy required to provide a transitional power supply to the ZPSU if both inputs from the ship distribution system are interrupted. The rating of the ZES can be selected depending on the load requirement from the ZPSU. At ESTD the ZPSU output was 300kW total; if both distribution inputs were lost the ZES supported a load shed to 200kW and then a further 4 minutes of essential load operation. This was sufficient for faults to be cleared by discrimination devices and power supplies to be restored to the ZPSU and could be sufficient time to start, connect and load an alternative prime mover.

Whilst the ESTD ZPSU was conceived to be capable of providing power throughout a damage control zone, it could as easily be harnessed to provide power to a single weapon system.

With a ZPSU any particular quality of output power supply can be achieved and this will be sustained in all conditions as long as there is an input power source to the ZPSU. At ESTD the output was retained during LV and HV short circuits, HV mal-synchronisation and generator de-excitation as well as all 'normal' evolutions such as crash reversal of the ship.

Finally, if this form of local conversion is adopted the quality of supply of the distribution system becomes less onerous. As long as the ZPSU is correctly specified it does not matter if the distribution system is DC or AC, varying voltage and/or frequency and/or high harmonic distortion since the weapon system can be supplied with the quality of supply it requires, generated locally. In practice, this means that the distribution system quality of supply is no longer dominated by the standards that currently act as the interface between distribution system and consumers but by environmental conditions surrounding the system - for example electric and magnetic fields, noise and vibration and cooling systems.

Conclusions

With the advent of power electronics there are a number of emerging ways of providing power to the weapon system that overcome drawbacks in legacy distribution systems. The main ways demonstrated at ESTD were:

1. Link Converter supplied LV Distribution Systems: Link Converters can isolate disturbances and transients on the generation system from the LV distribution system. Such disturbances include frequency and voltage transients and high harmonic distortion. By using a BES, the Link Converter can also support the LV distribution system on loss of a running generator.

2. Zonal Power Supply Unit supplied Weapon Systems: A ZPSU can provide all supplies required in a damage control zone, or by a particular weapon system, by local conversion from the distribution system. When supplemented by an appropriately sized ZES, transitional power can be provided to support the essential output while the system is reconfigured after fault or action damage on the distribution system.

There are many other ways that power electronics can be harnessed to support future distribution systems. However, what ESTD has shown is that conceptual systems can be turned into reality and provide high quality, high integrity supplies to weapon systems that allow them to continue operation despite considerable damage to the electrical distribution system.

Acknowledgements

The support of colleagues both in the Ministry of Defence, ALSTOM Power Conversion and throughout industry is gratefully acknowledged.

Any views expressed in this paper are those of the authors and do not necessarily represent those of the Ministry of Defence or HM Government.

References

1. A Weston, F Danan, N Smith, M Butcher, D Mattick 'The Electric Ship Technology Demonstrator: Results and Lessons from the first full year of System Testing', INEC, Amsterdam, Holland, 2004.

2. ALSTOM Power Conversion, 'Electric Ship Technology Demonstrator Presentation Day', City Conference Centre, London, December 2004.

3. D Mattick, M Benatmane, N McVea, R Gerrard, 'The Electric Ship Technology Demonstrator: 12 inches to the foot', AES, Paris, France, 2005.

4. E Lewis, S Cheong, M Butcher, 'Predicting pulsed loads on electrical power systems by means of the electric ship technology demonstrator' AES, Paris, France, 2005.