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POWER SYSTEM SURVIVABILITY - HOW CAN WE DELIVER?

BY

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SYNOPSIS

Electrical power is increasingly crucial to all systems on board naval vessels, from propulsion to auxiliaries and combat systems. This electrification of warships has hardly led to significant changes to power system architectures in European naval vessels. Consequently the power system presents one of the key weaknesses in current ships. The advances of power electronics, fault protection and energy storage systems seem to provide an opportunity to achieve more robust power systems. The increased cost and risk have so far stopped these new technologies being applied to power systems. This paper will investigate how new technologies can achieve more robust power systems, at an affordable price and acceptable risk.

Authors Biography

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John Devlin is currently a Technical Manager in Frazer-Nash Consultancy, whose responsibilities include Electrical & Control system design. He has more than 20 years experience in the design of power systems for a variety of industries and has worked with the MoD on systems for both surface and sub-surface platforms.

Will Wright is a Team Leader in System Engineering for Frazer-Nash Consultancy. He has ten years experience of providing consultancy services to programme managers within the defence and aerospace sectors in the areas of technology management, options assessment and decision support.

INTRODUCTION

Over the past decade maritime platforms have become more and more dependent on electrical power: weapon system power requirements are growing due to increased radar power, introduction of high energy weapons and ultimately the electric gun; platform propulsion is moving from direct mechanical to hybrid electrical and full electrical propulsion; and auxiliaries are electrified to reduce Through Life Cost. While this increase in electrical power dependency is readily apparent in naval platforms across Europe, it has not been matched by significant changes in the fundamental architecture of power systems.

The widely-used AC tree architecture is known to significantly contribute to the overall vulnerability of power systems in the event of faults or damage. In the past the trend has been to ensure critical systems have a minimum dependency on electrical power. For (mechanical) propulsion, gearbox driven pumps have been commonplace. Hybrid and IEP propulsion systems yet have become more dependent on electrical power, also for their auxiliary systems. For combat systems, Uninterruptible Power Supplies (UPS) have become increasingly popular. However, this approach has been adversely affected by poor integration into power systems, the wide range of different UPSs in different systems and low reliability. Also the need for UPSs stem from a low survivability of the power system in particular during action damage. The real solution to the poor vulnerability of the power system is to make its architecture inherently less vulnerable.

New technologies provide a range of options to vary the power system architecture and achieve more robust power systems. The Marine Systems Development Office (MSDO) has run a number of development programmes to develop and demonstrate the future robust power system, ranging from conceptual studies with academia to full scale testing at the Electric Ship Technology Demonstrator (ESTD) [1]. The current development effort is focussed on delivering technology for a DC distribution system. However, the application of robust power system technologies in the UK and Europe has so far been inhibited by the associated risk and cost.

This paper covers the results of a study performed by Frazer-Nash Consultancy Limited (FNC) on behalf of the Ministry of Defence to look into just this issue: Is the justification to move to more robust power systems strong enough and are associated costs and risk acceptable?

First the paper identifies the shortfalls in survivability for current systems and their causes. It then determines the requirements and characteristics for more robust architectures, which are used to derive a number of options to increase the power system robustness. These options are assessed in terms of overall suitability for naval applications through a cost benefit trade-off. From the cost benefit trade-off conclusions are drawn how robust power systems can be achieved cost effectively with acceptable risk.

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[1] D Mattick, M Benatmane, N McVea and R Gerrard, “The Electric Ship Technology Demonstrator: 12 Inches To The Foot”, Proceedings AES 2005, October 2005

SHORTFALLS OF CURRENT SYSTEMS

Current naval power systems, such as illustrated in Figure 1, are generally tree architectures with local High Voltage (HV) generation and distribution. The HV loads are generally limited to the propulsion motors, bow thrusters and HV / LV transformers. The LV system is fed from two HV/LV transformers, near the HV switchboards. LV power is then distributed across the ship. It is the LV distribution architecture that is spread across the whole ship and that is essential for almost all other systems on board, including (HV) propulsion systems and combat systems. This paper therefore focuses on the LV distribution architecture.

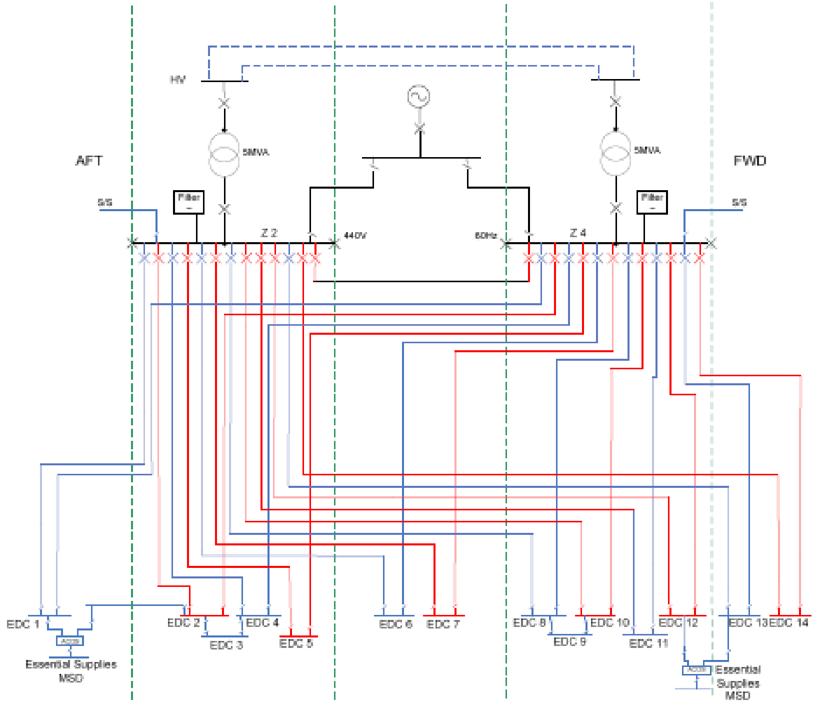

FIG.1 - SINGLE LINE DIAGRAM OF AC TREE DISTRIBUTION ARCHITECTURE

The LV distribution architecture is normally a tree architecture where the LV power is fed from two Switchboards (SWBDs), located forward and aft. The switchboards feed a number of Electrical Distribution Centres (EDCs) from where power is distributed to the loads via Distribution Panels (DPs). The fault protection system is based on current relay protection which can be very accurate due to the high fault levels of the system. In modern ships with Full Electric Propulsion, which feature a lot of power electronic loads, these systems require extensive harmonic filtering. For example in the Type 45 destroyer the harmonics generated in the system require Active Filtering equipment [2]. These Active

[2] R D Gerrard, Dr M Benatmane and Cdr S Thompson, "Type 45 – Military IEP becomes reality", AES 2007 The Vision Redrawn conference proceedings, pp. 41 – 49, September 2007

Filters consist of power electronics that compensate for the harmonic disturbances generated in the system. They are connected to the LV switchboards.

The LV architecture as described above is well proven and understood and navies around the world have extensive in-service experience. No investment in equipment or system development is required, and a good supply base for Commercial Off The Shelf (COTS) equipment exists, making these systems cost effective.

These current systems have a number of shortfalls though. These are:

- The requirement for sufficient discrimination between faults at different levels drives up the time settings due to the high number of distribution levels (SWBD, EDC and DP). It may be necessary therefore to allow faults to remain on the system for up to 0.5 s. These faults then have a negative impact on the voltage stability of the system. Because the HV and LV systems are coupled through transformers this stability challenge cascades through the whole power system, potentially causing trips on under-voltage across the system;

- Current relay protection can be very accurate for single faults. However if multiple faults occur discrimination is not guaranteed. With multiple faults the risk of trips occurring at the highest level is fairly high, potentially causing a total electrical failure;

- The Electrical Distribution Centres can be dual fed to increase the survivability. However the change over from one switchboard to the other cannot take place instantaneously which means that the loads cannot be provided with uninterrupted power and a large number of loads (in particular Induction Motor drives) need to be restarted (manually) after change-over. This Induction Motor starting then causes another QPS challenge. Power electronic Automatic Change-Over Switches can provide uninterrupted change-over, but these are expensive and only cost effective for critical loads [3].

MORE ROBUST POWER SYSTEM OPTIONS

The shortfalls mentioned above have been used to determine more robust power system architectures. The following alternative architectures will be considered in this paper:

- Zonal AC architecture with Link Converters and Bulk Energy Storage (Option 2B);

- Zonal AC architecture with Link Converter and Zonal Power Supply Units (Option 2A);

- Zonal DC architecture with Zonal Power Supply Units and power electronic fault control (Option 3A);

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[3] C Lloyd, R Simpson and G Reid, “The Type 45 Destroyer – powering to success” AES 2003 Broadening the horizons conference proceedings, pp. 198 – 207, February 2003

- Zonal DC architecture with Zonal Power Supply Units and separate variable speed drives (Option 3B).

These options will be discussed subsequently.

Zonal AC Architecture Link Converters and Bulk Energy Storage

The Zonal AC architecture with Link Converters (LCs) and Bulk Energy Storage (BES) is illustrated in Figure 2. It consists of a zonal architecture with two separated distribution buses running from forward to aft. The EDCs can be fed from both buses. This architecture reduces the complexity and amount of cabling of the system. Alternative protection schemes such as current differential fault protection can be utilised to reduce the response time to faults.

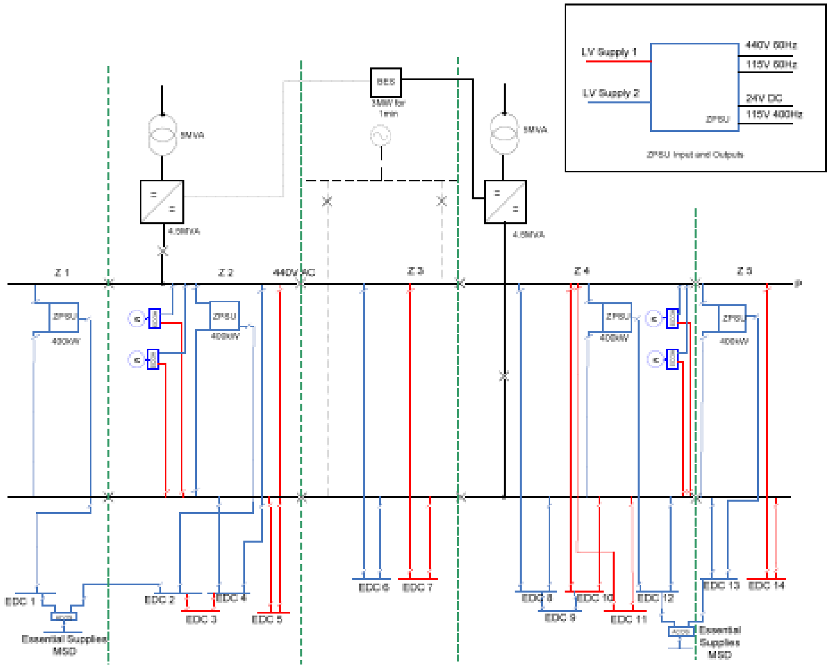

FIG.2 - SINGLE LINE DIAGRAM OF ZONAL AC ARCHITECTURE WITH LCS AND BES

This option has the added capability of the Link Converter (LC). These LCs are power electronic converters that decouple the voltage and frequency of the HV system from the voltage and frequency of the LV system. This means that disturbances do not promulgate from the LV system to the HV system and back, reducing the impact of the first shortfall of current systems. The LCs have been extensively derisked and tested at the Electric Ship Technology Demonstrator (ESTD) at the start of this century. It also allows connection of Bulk Energy Storage (BES) to the DC link of the Link Converter. The cost and size of the LC is of a similar magnitude as Active Filters, required to compensate harmonics generated in a modern IEP ship such as the RN Type 45 destroyers [2]. The BES can provide power to the LV system to ride through electrical failures. The BES in this study has been sized to ride through the time required to start alternative generator capacity (1 minute) in case of generator failure.

In conclusion, this zonal AC architecture has the potential to address the first two identified shortfalls by the application of more advanced fault protection schemes and the use of LCs with BES.

Zonal AC Architecture with Zonal Power Supply Units

In the second AC architecture option, all power is supplied to the zones via power electronic Zonal Power Supply Units (ZPSUs). The ZPSU rectifies the input voltage, which can enter from two distribution buses, to DC and subsequently inverts DC to the required voltages and frequencies. The ZPSU can provide instantaneous switchover from one distribution bus to the other. The ZPSU can also utilise distributed Zonal Energy Storage (ZES), connected to the DC link. This ZES can supply the zone with power when neither bus can supply sufficient power or during generator failure. In this option the ZES is not included but its impact will be considered in the discussion of the results.

A single line diagram of the Zonal AC architecture with ZPSU's is illustrated in Figure 3.

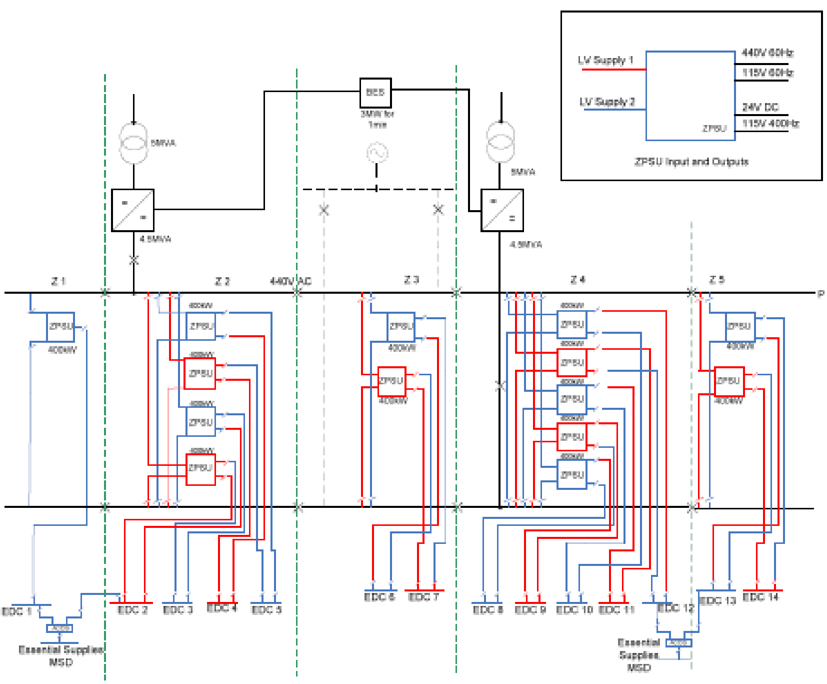

FIG.3 - SINGLE LINE DIAGRAM OF ZONAL AC ARCHITECTURE WITH ZPSUS

The capability of the ZPSU to switch over instantaneously from one distribution bus to another allows it to address all three shortfalls of current systems, but at the penalty of a high amount of power electronics in the system.

Zonal DC Architecture with Zonal Power Supply Units

The zonal AC architecture with ZPSUs converts the power from AC to DC and to AC again twice. This causes significant losses and requires extensive hardware. In the zonal DC architecture as represented in Figure 4 the link converter converts the power from HV to DC. The power is then distributed across the ship at DC, to be converted to AC again in the ZPSUs. This arrangement was also tested at ESTD. The unavailability of (shock-rated) breakers for DC systems has previously made DC systems unattainable. Advances in switchgear and power electronic control schemes have made this architecture technically feasible. The presence of power electronics at both ends of the distribution bus can be utilised to limit faults and protect the system. Power electronic control can also be used to ensure system stability. The use of the power electronics to control system faults and ensure DC power system stability will be tested over the current year at the ESTD.

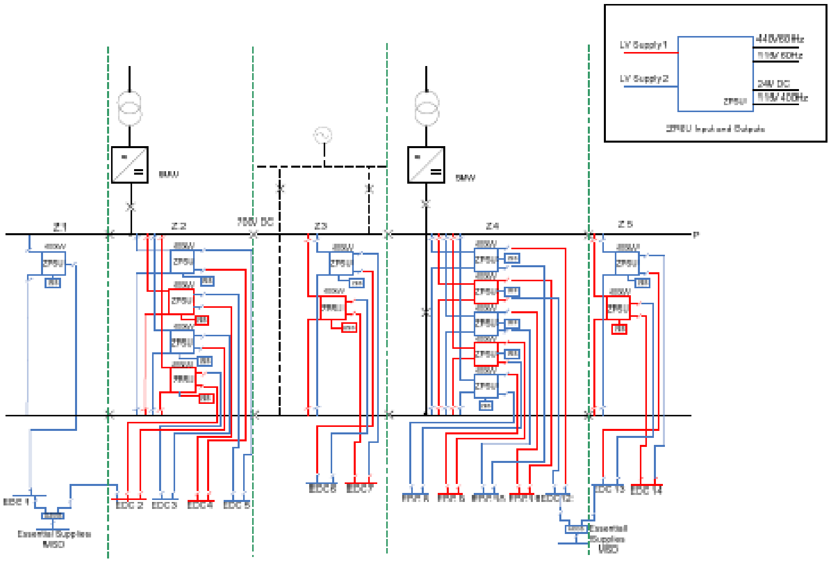

FIG.4 - SINGLE LINE DIAGRAM OF ZONAL DC ARCHITECTURE WITH ZPSUS

As with the zonal AC architecture with ZPSUs, this option addresses all three shortfalls. It is envisaged that this option can do this with a lower penalty on additional equipment and losses as both the Link converter and ZPSU comprise of only one conversion stage compared to two for the AC system.

Zonal DC Architecture with Variable Speed Drives

In industry motor drives have moved from direct online and soft start arrangement to Variable Speed Drives (VSDs). VSDs can deliver efficiency savings that pay back the required investment within a few years. They also provide a number of other benefits such as reduced noise characteristics and improved voltage stability. Naval systems have not yet followed that trend, because naval systems have a low utilisation due to system redundancy, and because naval build programmes have a strong UPC focus. The benefits are equally valid though and the authors expect future classes will slowly move towards increased use of VSDs, if only to satisfy the requirement to reduce the environmental impact of naval vessels.

DC architectures provide an opportunity to connect the inverters of VSDs directly to the DC distribution bus. The method of connection to the DC bus, directly or through a DC-DC converter and the impact the drives will have on the DC system stability, due to their constant power nature, need to be further addressed. This work is ongoing in the DC architecture development programme being undertaken by the MSDO.

The second DC architecture option, as illustrated in Figure 5, utilises VSDs for large motor loads, connected directly to the DC distribution bus. This means the number of Zonal Power Supply Units comes down, considerably reducing system size and cost.

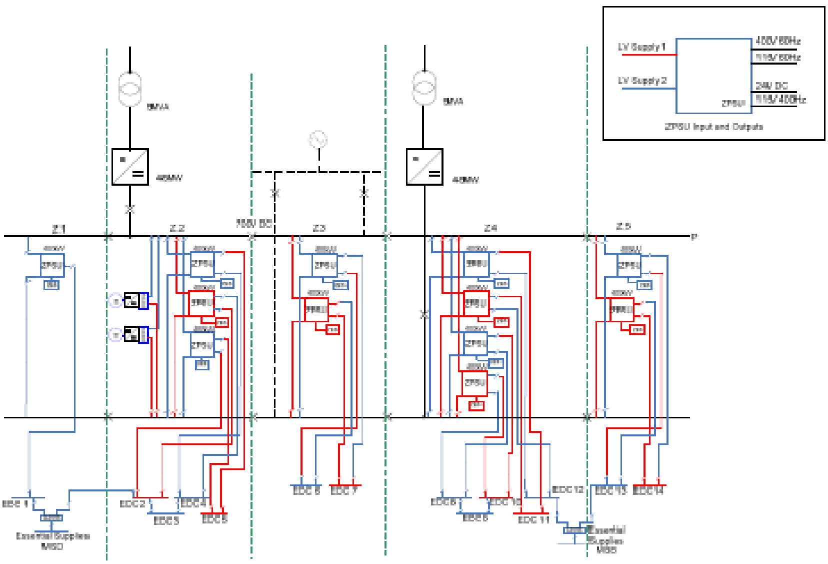

FIG.5 - SINGLE LINE DIAGRAM OF ZONAL DC ARCHITECTURE WITH VSDS

The power system architecture options described in the previous paragraphs were compared with each other through a cost benefit analysis using a multi-criteria decision analysis tool. Through two stakeholder workshops the criteria were defined and the options were scored against the criteria. Subsequently the criteria were weighted. The overall approach is schematically summarised in Figure 6.

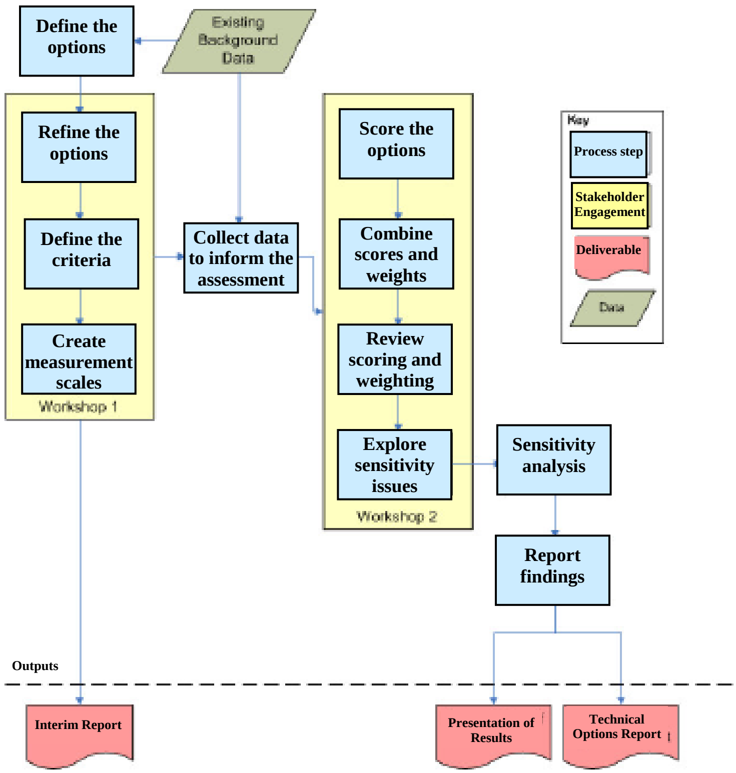

FIG.6 - APPROACH FOR COMPARISON OF THE OPTIONS

This paper covers the criteria that were considered most important and were found to drive the decision making. These criteria are:

- Vulnerability: The vulnerability of each option to damage resulting in loss of supply of vital and essential services. The assessment is subjective;
- Graceful degradation: The ability to maintain vital and essential services in the event of failure of or damage to key parts of the system. The assessment is subjective;
- Signature: The impact on overall ship signature of each option. The assessment is subjective;
- Growth potential: The ability to accommodate future increases in load beyond the design and growth margins. A possible scenario is the future addition of a 1 MW high energy weapon system. The assessment is subjective;
- Technical maturity: The Technology Readiness Level (TRL) of the system objectively based on the TRL scale definitions used by MOD UK which range from 1 to 9;

- Weight: The overall mass (in kg) of equipment for each option. This criterion is a measure of the impact the power system has on the overall ship size and therefore cost.

The benefits as described above were then weighed against the costs associated with each option. The cost of the options is mainly driven by the following three cost drivers:

- The Unit Purchase Cost (UPC): The one-off procurement cost per vessel estimated for each option;

- System efficiency: An estimate of the system efficiency (in terms of losses) associated with the architecture, converted into a monetary value, related to the cost of fuel;

- Maintenance: The maintenance burden associated with each of the options is estimated in terms of consumables and manpower over the lifetime of a ship (25 years).

DISCUSSION OF RESULTS OF THE ANALYSIS

The weights attributed to the criteria by the stakeholders are presented in Table 1. These weights represent the relative importance the stakeholders have assigned to the criteria. The scores of the options are illustrated in Figure 7.

TABLE 1 - *Weights Attributed to the Criteria*

Criteria	**Weight**
Graceful degradation	100
Recoverability	10
Vulnerability	50
Signature	25
No. of Disc Compartments	0
Number of Components	0
Weight	5
Volume	1
Growth Potential	25
Reliability	5
Technical Maturity	10
Bulkhead Penetration	0
Length of Cabling	5

The outcome of the multi criteria decision analysis is discussed in this paragraph. First the assessment of the benefits will be discussed, then the cost of the options and how this relates to the benefits and finally the cost-benefit trade off will be considered.

Benefits of the Power System Options

Figure 7 illustrates the contributions from each of the benefit criteria to the overall preference of the options. Higher values represent a stronger preference from the stakeholders. It should be noted that all scores are relative scores. For example the AC tree system has no score for graceful degradation and vulnerability. Significant investment has been made in these systems to increase their vulnerability, for example by implementing ACOS to change over from one EDC to another in case of failure at EDC level or in its feed. The score for vulnerability means that the AC tree system has been given relatively the lowest score by the stakeholders and therefore gets no preference from the stakeholders for this criterion.

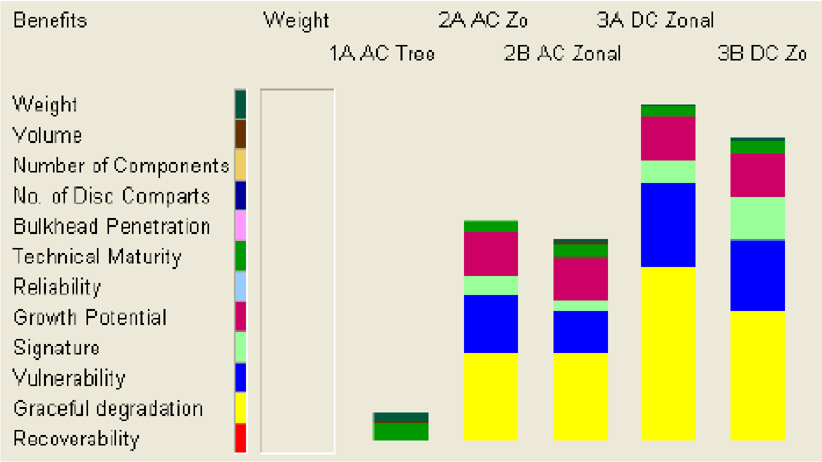

FIG.7 - CONTRIBUTIONS OF CRITERIA TO OVERALL PREFERENCE

We can derive a number of conclusions from this figure.

Firstly the AC tree option has low scores compared to the other options. This low score is primarily caused by the three shortfalls current systems encompass. The AC tree scores strongly on Technical Maturity and Weight, which generally are criteria considered important by the shipbuilder (who was not directly represented in the stakeholder group). This probably explains why current naval vessels have not adopted more advanced power system architectures yet.

Secondly, the benefits of the alternative architectures are dominated by four criteria: Graceful degradation, Vulnerability, Signature and Growth Potential. These criteria attracted the heaviest weightings as attributed by the stakeholder group.

Thirdly the DC architectures appear to be the more attractive than their AC counterparts, largely due to their perceived advantages under Graceful degradation and Vulnerability. This was partly attributed to the distributed energy stores, which could be applied to the AC zonal architecture with ZPSUs as well.

Cost of the Power System Options

The breakdown of the relative estimates of the cost of the options is presented in Figure 8.

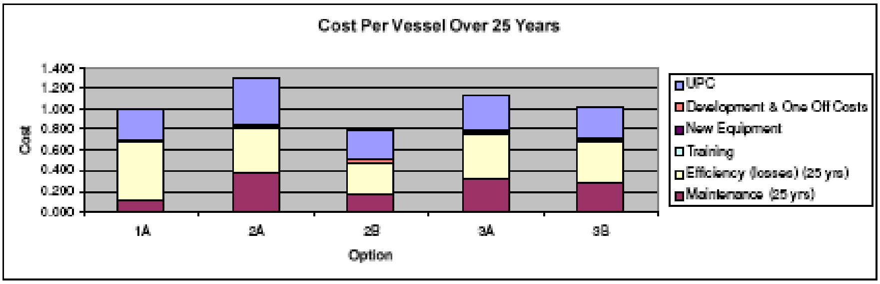

FIG.8 - RELATIVE COST BREAKDOWN OF POWER SYSTEM OPTIONS

A number of conclusions can be derived from this data.

The zonal architecture with Link Converters and BES seems to provide an opportunity to reduce the cost of power systems relative to tree architectures. This is partly driven by the lower installation cost of cabling due to the reduced system complexity of a zonal architecture. Furthermore the Link Converter operates at an increased system efficiency compared to the Active Filter. Whether the increased efficiency will be actually achieved will depend on the utilisation profile of the Active Filter compared to the Link Converter. The utilisation profiles have not been considered in this study. It would seem reasonable however to conclude that the introduction of a Link Converter does not increase the losses relative to an Active Filter arrangement, but does provide significant benefit in decoupling HV and LV voltage and frequency.

The cost of the procurement and maintenance of the additional power electronics for the AC architecture with ZPSUs adds 50% to the procurement cost and 250% to the maintenance cost. This cost penalty would be further exacerbated by using BES to achieve the ultimate benefit of this architecture.

The procurement cost of a DC architecture with ZPSUs that utilises VSDs is only marginally higher than current power systems. The figures show that the additional maintenance of the power electronics in the ZPSU would make this option more expensive through life. Experience in industry with VSD however demonstrates that these extra maintenance costs are more than offset by the system efficiency savings, which have not been included in the figures above.

Cost-Benefit Trade-off

Figure 9 plots the benefit scores against the estimated cost through the life of the vessel of each of the options.

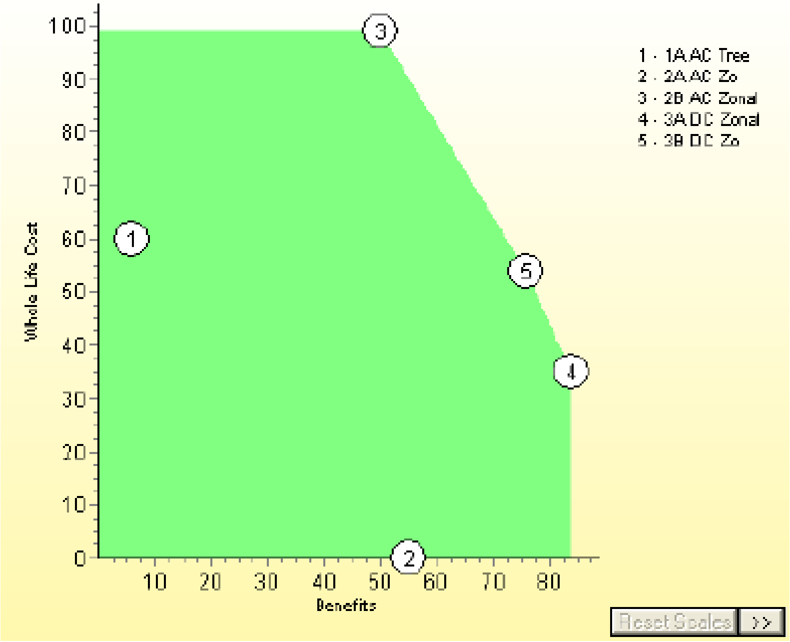

FIG.9 - COST-BENEFIT COMPARISON BETWEEN OPTIONS

On each axis higher numbers are better so that the DC architecture with ZPSUs has most benefit and the zonal AC architecture with LCs and BES is the least costly. In reading the plot the most favourable options lie on the boundary of the shaded region, namely the zonal AC architecture with ZPSUs, zonal DC architecture with ZPSUs and zonal DC architecture with ZPSUs and VSDs (in order of increasing expense).

This cost benefit map clearly demonstrates the increased performance in terms of Graceful degradation, Vulnerability, Signature and Growth potential for the zonal AC architecture with LCs and BES. Moreover this architecture demonstrates an opportunity to reduce UPC and TLC. If further weight is given to Survivability, DC architectures with ZPSUs, with or without VSDs, will begin to represent the best trade-off between benefit and cost.

It should be noted that the cost data used in the study was difficult to derive with high confidence and consequently the figures tend to be somewhat conservative. The results were subjected to sensitivity tests on account of this. These revealed that if the cost of power electronic devices were to reduce with time and/or the cost of fuel were to significantly increase, both of which are eminently feasible, then the advanced zonal architectures considered by the study would become even more cost competitive compared with the conventional AC tree option.

CONCLUSIONS

1. The introduction of Link Converters for HV to LV conversion increases system robustness and efficiency at no extra cost or risk.

2. The introduction of zonal architectures provides an opportunity to achieve UPC reductions due to the reduced cabling. Additionally it allows for more advanced fault protection schemes. In combination with Link Converters the basic AC zonal architecture reduces two of the three identified shortfalls of current systems: the slow response to faults and the poor performance during multiple faults. The remaining shortfall is the inability to provide uninterrupted power in the event of faults or damage to all loads. The basic AC zonal architecture additionally reduces UPC and TLC with minimal additional risk.

3. To achieve uninterrupted power supply and make use of Zonal Energy stores, architectures with distributed power electronic conversions are required. The best performing and most cost effective means of achieving this is through DC architectures as this minimises the conversion stages and thus equipment and losses.

4. Industry has demonstrated that the introduction of variable speed drives for large motor loads provides an opportunity to achieve significant efficiency saving and improved signature and Quality of Power Supply performance. These benefits have not been quantified by this paper. However if variable speed drives are introduced to DC architectures and connected directly to the DC distribution bus, the cost penalty associated with the increased use of power electronics in DC architectures can be minimised.

FINALLY

The increasing dependence on electrical power for all systems onboard naval vessels, be they propulsion, auxiliary or combat systems, cries out for more robust power system architectures. This paper demonstrates that the first improvement in robustness through zonal AC architectures does not actually require additional investment but rather shows the potential for cost savings. Further improvements in survivability can also be achieved with more advanced DC architectures at only slightly higher cost and risk. Investment to achieve increased naval platform survivability in any other area without tackling the power system survivability would be difficult to justify in these financially challenging times.