ADVANCED DC POWER DISTRIBUTION ARCHITECTURE
A VISION OF THE SUBMARINE FUTURE?

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ABSTRACT

Electrical distribution systems onboard nuclear submarines have remained substantially unchanged for over fifty years. Reliability is realised in the system through a strategy of equipment and supply duplication. Advances in power electronics are enabling DC power as a viable concept, incorporating a single voltage distribution bus and localised power conversion and cleansing. By building reliability into the integrity of supply rather than relying upon duplication, the overall system reliability can be maintained or improved while simplifying the system and reducing costs. This paper examines the DC power and distribution concept and evaluates the major design decisions based upon comparisons with the current ASTUTE Class electrical distribution system.

Introduction

Integrated Full Electrical Propulsion (IFEP) vessels, require fully integrated main and auxiliary generation, distribution power and propulsion electrical systems. A key requirement for these systems will be their ability to clear electrical faults quickly with minimum disruption to the overall effectiveness of the platform, thus using technology to maximise the continuity of electrical supply even under severe fault conditions and thus optimising the ride and fight through capability. Common source technological development leads to economies of scale, when measured alongside a shrinking number of platforms; this approach is entirely consistent with the Marine Systems Development Strategy (MSDS) as endorsed by Director Equipment Capability (Above Water Effect) (DEC(AWE)) in 2006, and aligns with Director General Submarines' (DGSM) 2007/2008 Business Plan that demands 'an enhanced focus on Product and Technology Development'.

In a submarine application, there is considerable scope for DC distribution because of the following principal issues:

- **Safety**: To support the derivation of robust Safety Cases for submarine safety, propulsion availability and future Nuclear Reactor Plant (NRP);

- **Availability**: To deliver fight-through / ride-through capability (fault detection and clearing) - continuity of power for propulsion and domestic (warfighting systems) supplies with reduced reliance on the operator;

- **Cost**: To reduce Unit Purchase and Through Life Costs.

In addition, it offers the opportunity to:

- Simplify the plant, and offer flexibility of layout by exploiting the advances in power electronics;
- Support loads with energy stores where they are needed;
- Improve build processes, for example by supporting modular build and minimising hull and bulkhead penetrations;
- Support Integrated Full Electric Power, hence optimising the number of prime movers and removing the reliance on gearboxes;
- Improve plant efficiency by local conversion for consumers;
- Transmit more power with a reduced cabling mass;
- Support variable speed drives;
- Enable technology insertion.

If future submarine classes adopt Electric Propulsion, the propulsion and ship service distribution systems will be required to be "self-healing", capable of unprecedented levels of "ride-through" capability and recoverability from "black-outs". The intention is to examine the opportunity to incorporate or embed some of this technology into ASTUTE future builds, in addition to targeting longer term activity for both submarines and surface ships. The final decision on the topology for future builds, both SM and SS, will depend, amongst others, upon the balance between Unit Purchase and Through-Life costs, ease of operation and support to an enduring industrial base.

Current System as Fitted in ASTUTE

The current electrical distribution network, shown in (FIG.1) comprises a tree structure. Electricity is generated at 450V/60Hz using two turbo-generators. It is passed to four switchboards and distributed throughout the submarine via a number of load centres.

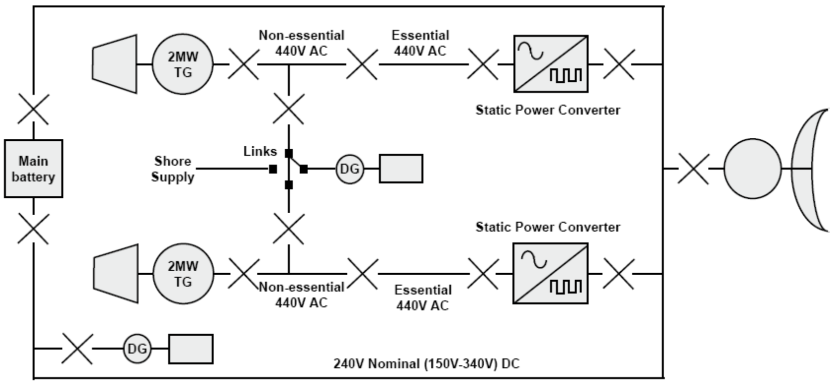

FIG.1 - CURRENT CLASS SUBMARINE (ASTUTE) ELECTRICAL DISTRIBUTION SYSTEM

Power is then either supplied directly to loads or transformed and rectified depending on load requirements. Supplies are split port and starboard and categorised according to whether loads are essential or non essential.

Bulk storage, consisting of 112 lead acid cells configured as an 8800Ah battery, provides backup power during reactor shutdown; power is transferred between the battery and loads through port and starboard static power converters (previous classes used motor generators).

Reliability and survivability are achieved through duplication of equipment and supply. Numerous transformation, rectification and inversion stages exist with cabling carrying electricity at different voltages and frequencies, back and forward, on common routes to common positions throughout the submarine. Such a structure requires multiple reactor compartment penetrations and duplicated cable runs.

This layout has not changed markedly since the first UK nuclear plants were built. Power outages are not common but are not unknown, and there is considerable scope for the plant operator to exacerbate the situation through pre-emptive (or wrong) action.

The System has a series of advantages and disadvantages for it as listed in Table 1:

TABLE 1 – *Current Class System Comparison*

Advantages	**Disadvantages**
High availability battery backed supply	Conventional discrimination with little self-healing capability
Static power converters feed essential AC supplies	Centralised, wet, battery is very vulnerable
	No zonal fight through capability
	Poor part load TG efficiency
	Mixed modes of transmission – requires more than one cable run across RC

The New Architecture

Background

This work builds upon studies carried out[1]&[2] into Submarine Secondary Systems and Zonal Distribution. It also draws upon the fact that a more power dense battery is in the marketplace. When combined with a Zonal Power System,[2] further improvements can be made in terms of overall plant reliability, which has considerable attractions in support of the NRP Safety Case. This zonal approach utilises COTS energy storage methods (for example the ZEBRA Battery system). The New Architecture - a Possible UK DC Zonal System is described later.

The adoption of such a system is viable currently and as such offers very low risk, but with the following advantages:

- Variable speed drives are easily implemented - less energy wasted;
- Number of power conversion stages reduced - improved efficiency and reduced heat burden;
- More power transmitted with same mass - cheaper;
- More power transmitted with less conductors - cheaper, simpler;
- Cabling and bulkhead penetration savings can be made, simplifying modular build;
- DC is the optimum mode for distribution; when supported by a zonally distributed battery this provides a fight-through, ride through capability for the platform.

The ZEBRA Battery, that does not gas, lends itself to distribution around the hull and a fuller development programme for use in a submarine is under discussion. This allows the current design of the AC Distribution System, (FIG.1), to be challenged with a realistic option.

Learning from Experience

The choice of propulsion plant and the Power & Distribution system is fundamentally about the architecture of the concept and the underpinning requirement. The architecture enables the flexibility and agility that the platform brings to be retained through the life of the platform. It sets the whole Concept design and the opens more options later.

Against this is an acquisition process which generally leaves propulsion options to the Assessment phase[6]. When new concepts are being programmed, either in Future Business Group (FBG) or in an Integrated Project Team (IPT), the focus is usually always on big programming issues in order to get both the project and the IPT established. So it tends to be establishing and profiling funding lines, broad order procurement strategy issues, supplier base stability, fleshing out major decision points (project / IPT launch, Initial Gate and the broad order assumption). There is some requirements activity but this is not generally constrained in that early concept phase.

The propulsion solution is mostly left to the Assessment Phase with all options open until Main Gate. That is, perhaps, not the best way to consider a decision as important as deciding upon an architecture. By setting the architecture of a through life concept much earlier in major warship procurement, it enables the MoD to pull the propulsion debate forward into the Concept phases, and in doing so perhaps constrains options by Initial Gate, rather than leaving them open until Main Gate.

Next Steps

Building on the success of these initial studies, and coincident with the first joint UK-US workshop on submarine Electrical Generation and Distribution (EG&D), new tasks were placed with CONVERTEAM to examine a future architecture, future motor technologies and Zonal Power Sources.

DC Power Systems

Why DC

The attractiveness of DC as a distribution medium for electrical power has been reported many times not least in work conducted for the Ministry of Defence[1]&[2] but also in the proceedings of Learned Societies such as the IMarEST, the IEEE and the IEE of which[3]&[4] are good examples. The following is a summary of the principal considerations that underpin the net benefit of adopting this medium.

DC distribution system is significantly more effective than the AC, transmitting at least 23.5% more power for the same mass of copper. In addition the DC systems will be more flexible, more easily controlled and re-configured than the AC system.

It is also unavoidable that naval platforms will make ever more increasing use of power electronics to condition and control the flow of power through the ship. From this perspective - the need to optimise the systems to its use - DC is more attractive than AC removing many stages of conversion and offering more compact and efficient systems.

The DC system will not suffer from the transient stability issues of an AC system. However the problem of constant power loads is important as will be addressed later in this article.

On balance it is considered that DC power systems should be examined fully as soon as practicable.

The DC Challenge

The dominant issue needing to be overcome in order to change to a DC power system is protection and fault clearance. At the power and voltage levels that will be needed by future submarine platforms (particularly with electrical propulsion systems) there is no suitable DC switchgear. What exists is too large, too bulky and too expensive for consideration.

However, there are low risk alternatives which require further development of which the concept of embedding the fault protection function within the power electronic converters is the most promising.

The technology of DC distribution is one of great promise and if the enabling developments associated with its protection are satisfactorily concluded, as looks extremely likely, then it will become the natural choice of distribution medium for an IFEP system.

The MoD Strategy

The challenge, as outlined above, is significant. There are many varieties of systems topology, style and operating mode that could meet the challenge in an operationally effective manner. However not all these square the circle between low cost and high performance as a result the MoD has adopted the following set of actions and development head-marks to ensure that the opportunities to reduce costs and improve performance are not missed:

- The UK should examine a DC EG&D system as a matter of priority;
- A Balance of Investment Study for DC and Zonal Power Distribution Systems should be conducted as soon as possible;
- The following Technology Demonstration Programmes should be set in place:
    - Selection of a new electrical energy store;
    - Development of a Zonal Energy Store;

- Development of a Zonal Power Supply Unit;
- Development of embedded power electronic DC circuit protection;
- Full Scale Reduced Scope Systems and Technology Proving.

Perhaps more importantly, the study firmly recommended that the following design principles should be adopted for the future UK Putative Power Systems.

- Minimise the use of power electronics - less conversion stages;
- Minimise the variety of distribution mediums;
- Design for stability;
- Adopt the optimum architecture.

Electric Ship Technology Demonstrator

Much of the technology necessary to enable the vision of the power system outlined in this paper has already been assessed and at a concept level proven in the Electrical Ship Technology Demonstrator (ESTD) at Whetstone, a facility managed for the French and UK Defence Ministries by Converteam. Whilst the system tested at the ESTD was notionally based around a surface ship requirement the technology and indeed the systems involved were equally applicable to submarines. The extremely wide range of technologies involved at the ESTD have been reported elsewhere but the following are particularly important to the type of system being proposed here:

DC Distribution

The ESTD was used as a test bed for the concept of DC power transmission. The ESTD systems broadly split into three elements, HV propulsion at 4,160 V, LV distribution and LV consumption. The LV distribution system was designed to be able to transmit both AC at 450 V and DC at 800 V. A direct comparison was made and - against many initial expectations - the final recommendation of the ESTD report strongly favoured DC as the transmission medium.

Zonal Power Supply Units

A major element of the vision for the future power system is that unnecessary intermediate modes of power are avoided in the path between the source and the final end user. This is seen as being satisfied by the use of Zonal Power Supply Units (ZPSUs) and these were tested successfully at the ESTD where a simulated zone had its power transmitted by the main power systems and then conditioned by the ZPSU to user requirements by individual power electronic modules. A most important advantage of ZPSUs in this context is that when designed with some dedicated “zonal” energy storage they provide excellent security of supply to the users, isolating them from system transients and failures that would overwhelm traditional systems.

Link Converters

The inter-connection between the HV Propulsion System and the LV Distribution System is clearly crucial and is one that not only underpins the efficiency gains of power system integration but also enables much of the overall system's fault resilience and continuity of power. As implemented at the ESTD, the link converters could utilise bulk energy storage (the submarine battery) but whether energy storage is better implemented as a distributed system within zones or through a combination of both distributed and centralised storage is a debate that has yet to be fully formed.

Nevertheless as implemented at the ESTD the link converters proved both the feasibility of the technology but also the huge benefits to be gained for their use in terms of fault containment. Faults on the propulsion system or within a zone were not seen elsewhere on the overall system.

DC Stability

It is a common misconception that DC systems are inherently stable. They may avoid the issue of transient stability but there is one circumstance when stability is far from assured. It is simply when more current is drawn as voltage falls - as occurs when supplying a constant power load. Constant power loads are common in naval practice; every constant frequency constant speed fluid pump exhibits constant power and their impact on any system - including DC needs to be understood.

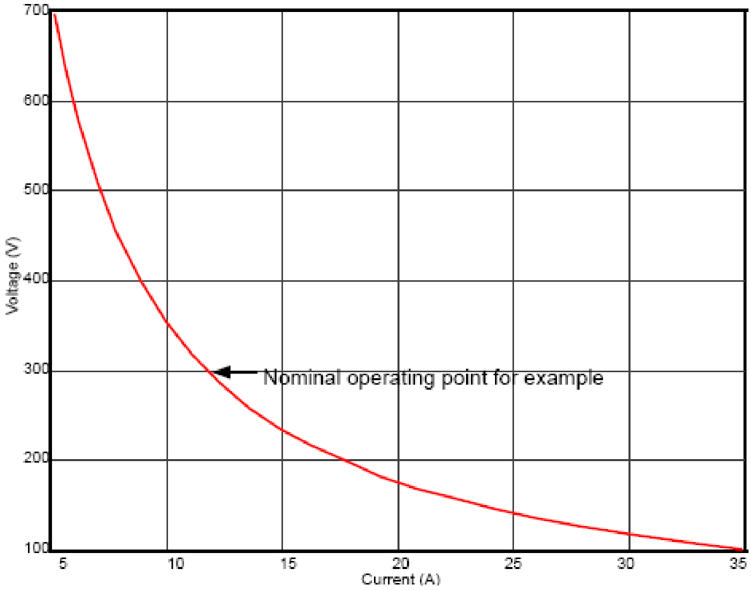

FIG.2 - CONSTANT POWER V-I CHARACTERISTIC

A constant power system is one in which the product of current with voltage is constant. When drawn as a graph this is simply a rectangular hyperbola as is shown in (FIG.2).

The relationship between voltage and current shown in (FIG.2) is clearly non-linear and because the relation between these quantities appears in any circuit analysis the assessment of the system dynamics becomes complicated. One answer lies in the brute force non-linear analysis of[3] however there is a simpler - more traditional - technique fully covered at[4] known as linearisation around a set point. The key to this method is to move from actual circuit levels of voltage and current to their changes (perturbational quantities). When this is done the non-linear curve of (FIG.2) is reduced to its tangent at any operating point of interest. This still enables precise identification of the boundaries of stability although any time domain simulation of the true response will be suspect once the circuit values depart significantly form their set points.

The use of this linearisation leads to an often misunderstood term: negative impedance (or resistance). The term arises because for a positive change in one parameter (voltage or current) there is a negative change in the other (current or voltage). Their ratio in terms of perturbational quantities is therefore always negative. This is as would be expected from (FIG.2) as the curve always has a negative slope. Since the ratio of changes in voltage to changes in current has units of resistance (Ohms) and since the circuit diagram drawn in terms of perturbational quantities is identical to that for real circuit values the term negative resistance (or impedance) is commonly used. This also leads to the use of the term negative resistance (or impedance) instability. But neither should be taken to mean a negative resistance appears in the real circuit; it does not, it only arises in the linearised circuit using perturbational quantities.

The analysis of a constant power DC circuit using the method of linearisation around a set point (as at[4]) is far simpler than tacking the full non-linear analysis and produces precise indications of stability margins and boundaries (which the full non-linear analysis is incapable of doing).

Making the Advanced DC Zonal Architecture Possible

As has been explained in[5] the relation of the load to source impedance is of crucial importance in determining system stability. Interestingly the relative values depend on whether a stabilising capacitance is present. Without the capacitance the load impedance has to be smaller than the source impedance for stability. This is clearly unacceptable as it would imply a power source that consumed more energy than it delivered. With a capacitor the load impedance has to be greater than the source impedance for stability. This is also satisfactory for efficiency as it implies an efficient energy source, but importantly it also shows that a reduction in the capacitance present in the system would make it tend towards instability.

This situation can be improved by dynamic control of source impedance which can ensure that the source impedance, as seen by the load, is always low enough for stability. Under fault conditions when the load impedance drops dramatically the source impedance has to follow and this is achieved by a control regime termed Fold-Back and is illustrated in (FIG.3).

Fold-Back is envisaged as being implemented in a form of distributed intelligence such that communication between devices and equipment is not essential though it would be used in normal operation. Fold-Back produces a form of load related voltage droop and this would also improve parallel generator load sharing and would, even more importantly, automatically limit overload conditions. Its system stabilising characteristics therefore extend beyond simple stabilisation of constant power systems, the following characteristics are improved:

- Overloads are current limited;
- Foldback interrupts sustained faults;
- Positive Feedback and latching occurs;
- Fault level independent of generator impedance;
- Switchgear opens off-load;
- Bus Voltage recovers automatically.

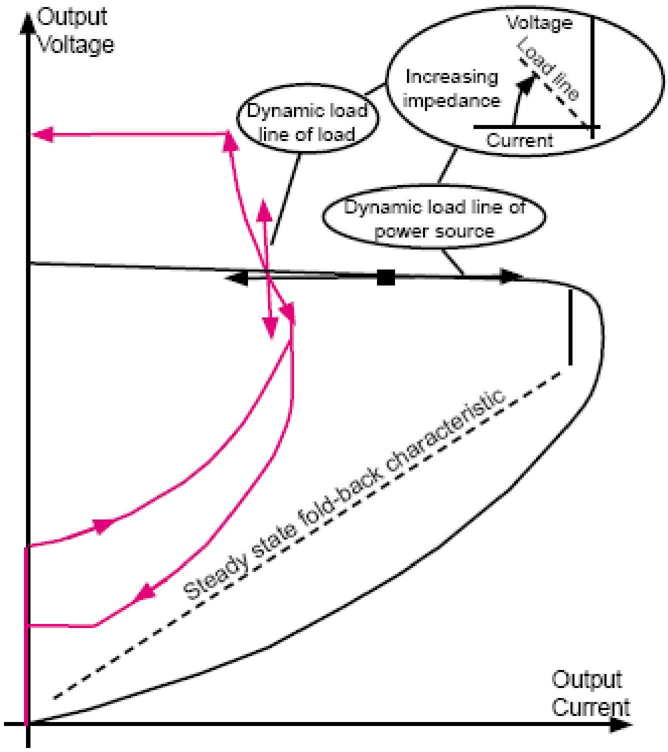

FIG.3 - FOLD-BACK IMPEDANCE CHARACTERISTIC

As has been mentioned above the main tenet for stability in this proposed system is that the maximum combined dynamic source impedance must be less than the minimum combined dynamic load impedance. The power source droop is regulated to be frequency-dependent and can accept data from the Platform Management System; with the load impedance regulated to also be frequency-dependent. In effect the dynamic load resistance is constrained to be always positive and so the system is inherently stable. Filtering harmonics in the system will be important and the diagram shown in (FIG.4) illustrates the proposed arrangement. (FIG.4) illustrates two generators and one load, in this case a motor. Each item has a DC filter; the DC bus has stray inductance and the filters resonate through this stray inductance - passive damping is the vertical line and the active damping is shown horizontally. The diodes limit inrush and backfeed.

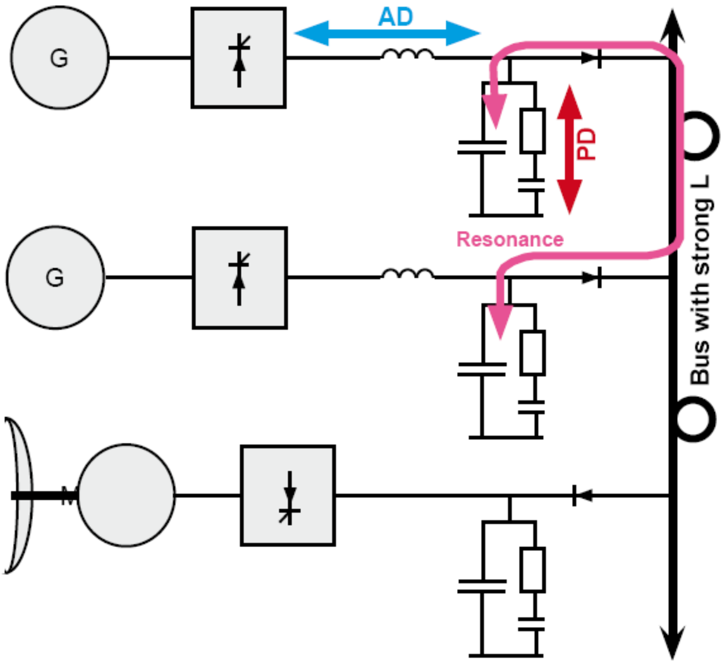

FIG.4 - DAMPING AND FILTRATION ARRANGEMENTS

To realise the advantages of this system, more power dense busbars are a necessity. Those proposed are derived from VDM 25000 laminated busbar experience, which will need some further development on termination and inter-connections, they are illustrated at inherently stable. Filtering harmonics in the system will be important and the diagram shown in (FIG.4) illustrates the proposed arrangement. (FIG.4) illustrates two generators and one load, in this case a motor. Each item has a DC filter; the DC bus has stray inductance and the filters resonate through this stray inductance - passive damping is the vertical line and the active damping is shown horizontally. The diodes limit inrush and backfeed.

Possible UK DC Zonal System

DC Distribution has natural synergies with zonal distribution that would bring benefits of reduced costs beyond that possible from each on their own. Some thought as to the architecture of a DC based zonal distribution has been undertaken by Converteam.

This work follows on from a brainstorming session arranged by MoD FBG and engaging several other stakeholders including Rolls-Royce and BAE SYSTEMS. The resulting putative system, including a high voltage propulsion segment, is at (FIG.6) (provided by Converteam).

Whilst the decision has yet to be made, much of the current thinking within the MoD is aligned to a DC power system. The system shown here is a further development of an initial outline concept during a joint MoD and Industry think tank. The system generates at 750V DC to enable efficient Pulse Width Modulation inversion with optimised switching intervals. It is worthy of note that

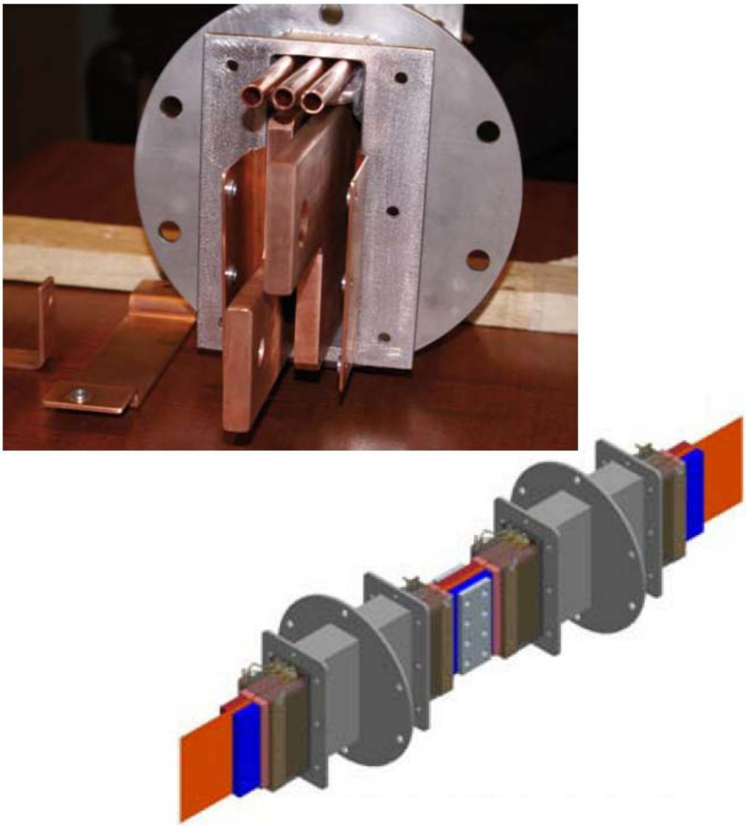

FIG.5 - LAMINATED BUSBAR CONFIGURATION

Hybrid and IFEP propulsion solutions are equally applicable to this baseline topology, albeit that a dual voltage system would be required for IFEP.

Power is generated by two TGs and two DGs; the rectified power is distributed through a zonal-configured distribution system. In each zone the Port and Starboard DC rails provide power to local distribution centres (switchboards). Consumer power is provided by Zonal Energy Stores (ZES) and Zonal Power Supply Units fed via DC-DC Converters from each set of Port and Starboard switchboards. The local switchboards in the main machinery space also supply power for hybrid drive (if required) to the two propulsion motors and integrate the power inputs from the DGs and TGs.

Two main switchboards are present in each zone of the boat and are located port and starboard to aid survivability. Cross links are optional for each zone but if present will also be used for shore supply connections. Each ZES has an energy store (most likely a modern battery); this is included for two purposes, each of which is equally important, to supply the zone loads during system interruption and also to feed back via the DC-DC converter into the distribution system to provide the platform-wide back up similar to current batteries.

The protection for this system does not rely on costly DC switchgear; it is proposed to merge protection and power conversion functions within the power electronic converters.

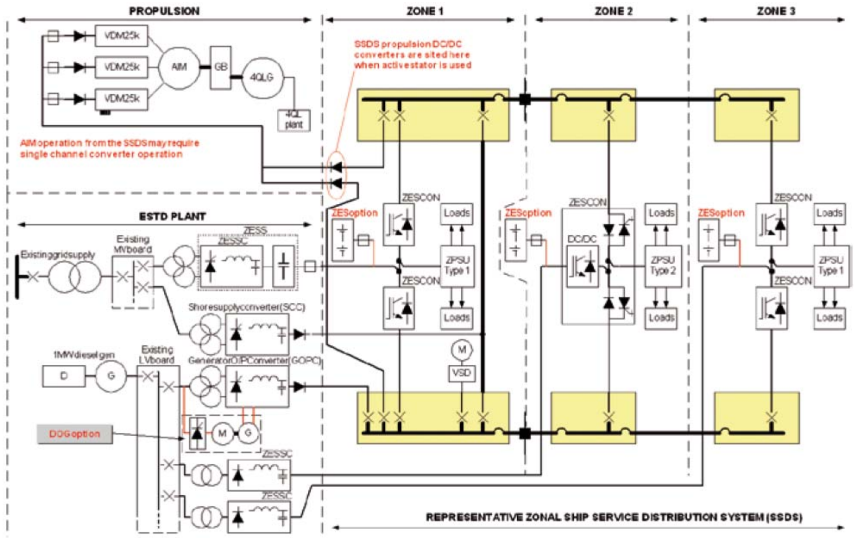

FIG.6 - PROPOSED UK ADVANCED DC ZONAL DISTRIBUTION ARCHITECTURE

The Choice of DC Voltage

(FIG.7) below articulates why DC systems to date have been between 750 and 800v. The limiting factor remains the rating of the load machines and as such 750v DC, the voltage proposed throughout the UK studies and that used by the USA, is ideal for ships services.

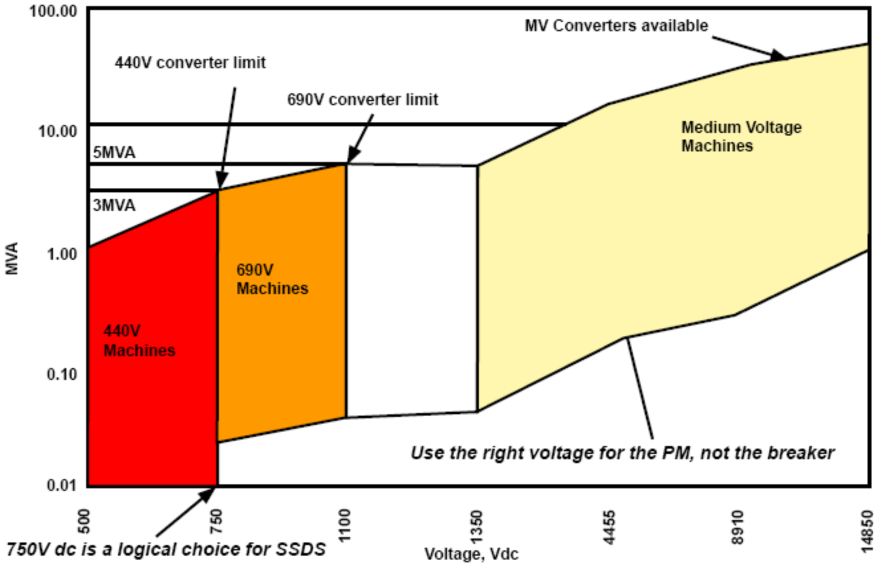

FIG.7 - VOLTAGE CHOICE FOR A DC ARCHITECTURE
(COURTESY MR ALLAN CRANE, CONVERTEAM)

Conclusion

An advanced DC power distribution architecture has been proposed that uses equipment available in the current marketplace and satisfies the key naval requirements of:

- Safety
  - Supports the derivation of robust Safety Cases.
- Availability
  - Survivability and graceful degradation with low operator input;
  - Very high transmission efficiency and power density;
  - Simple conversion equipment;
  - Prime movers operate under ideal conditions.
- Cost
  - Made affordable as a result of its simplicity.

An opportunity now exists for a step change to be taken in naval electrical power generation and distribution to great future benefit for the Royal Navy; it is argued that with new submarine and surface ship projects in train there has never been a better time to exploit this new technology.

Finally and perhaps more importantly, the industrial lead in renewable energy is moving towards DC distribution; with technology on the shelf that has potential to reduce costs at the same time as increasing operational effectiveness, the UK MoD has the opportunity to move with the times and invest in its own enduring industrial base.

References

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6. Acquisition broken down into 6 phases - Concept, Assessment, Design, Manufacture, In-Service and Disposal.