SUBMARINE ZONAL POWER

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ABSTRACT

Electrical distribution systems onboard nuclear submarines have remained substantially unchanged for over fifty years. Reliability is built into the system through a strategy of equipment and supply duplication. Advances in power electronics are enabling concepts such as Zonal power, incorporating a single voltage distribution bus and localised power conversion. By building reliability into the system components and supply integrity 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 Zonal concept and evaluates the major design decisions based upon comparisons with the current TRAFALGAR Class electrical distribution system.

Introduction

The electrical supply onboard a nuclear submarine is of the utmost importance to the platform's operational capability. The reliable presence of electrical power is vital for the submarine's safety, operation and war-fighting capabilities. The majority of systems are directly or indirectly dependent upon electrical power for correct operation, including many of those required for nuclear and ship safety.

Historically, nuclear submarines have used tree-based power distribution networks with split generation. Reliability is achieved through the use of multiple supplies and centralised bulk energy storage. Although there is no doubt that nuclear submarines have enjoyed highly reliable power supplies, the complexity, high maintenance requirements and additional costs brought by equipment duplication is no longer an aspect of submarine design that can (or ought) to be accommodated.

At its simplest: it is now necessary to design the required levels of reliability into the basic supply itself rather than to develop it from a complex duplication and interconnection of the functional systems. Advances in electrical power technologies have resulted in reliable, compact and efficient power converters. Such technologies offer scope for improvement and rationalisation of the current submarine electrical system.

This paper, and the study upon which it is based, proposes significant redesign of the current electrical system. A topology is described that splits the submarine into a number of distinct autonomous electrical sections or 'zones'. Each zone is fed with electrical power via a DC distribution bus, and only derives the power supplies required by the end users within that zone. A number of benefits can be observed with no significant effect on reliability and survivability.

BACKGROUND

Current System[1]

The current electrical distribution network comprises a tree structure. Electricity is generated at 440V/60Hz using two turbo-generators. It is passed to four switchboards and distributed throughout the submarine via a number of load centres[2]. 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 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.

Zonal System

It is proposed that significant improvements would be offered through the introduction of a Zonal Power Distribution System (ZPDS). In such a system the ship is divided into a number of distinct zones. Zone boundaries are chosen based upon the ship's construction and equipment layout; for example, to coincide with watertight bulkheads and, therefore, is considered a key enabler for improved modular construction and commission.

The Zonal Power Supply Unit

In general, each zone has one or more power converters known as Zonal Power Supply Units (ZPSU). These will comprise:

- Power conversion modules for supplying loads within the zone;
- Energy storage for supplying power to essential loads within the zone and back onto the main bus for auxiliary propulsion modes if required;
- Fault isolation equipment;
- Control and monitoring systems.

Power is fed to each of the ZPSUs from the main power transmission bus. This bus is the only inter-zone electrical connection. A notional zonal power system is shown in (FIG.1).

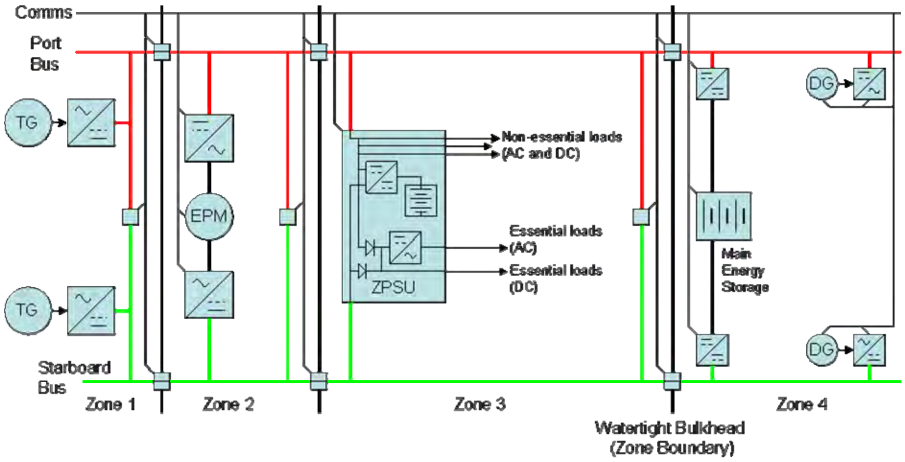


FIG.1 – NOTIONAL ZONAL POWER SYSTEM

Units would be technologically identical to provide commonality of components but would differ in volume (based on the number of pieces of equipment being supplied by each ZPSU). In a zone with more loads more converter units would need to be included in the ZPSU, making the ZPSU larger. All other aspects of the unit would remain the same from zone to zone.

Due to the confined nature of submarines, it is likely that only one ZPSU would be used per zone and the largest loads (such as the main feed pumps or secondary propulsion motor) would be supplied directly from the main distribution bus from a common range of dedicated variable speed drives (VSDs).

Design of a Zonal System

Zonal Boundaries

In order to determine likely zone boundaries an analysis of major loads (>10kW) within the submarine was carried out. This, combined with the fact that it is normal to align zones to damage control boundaries[3], suggested five distinct zones within the submarine (FIG.2).

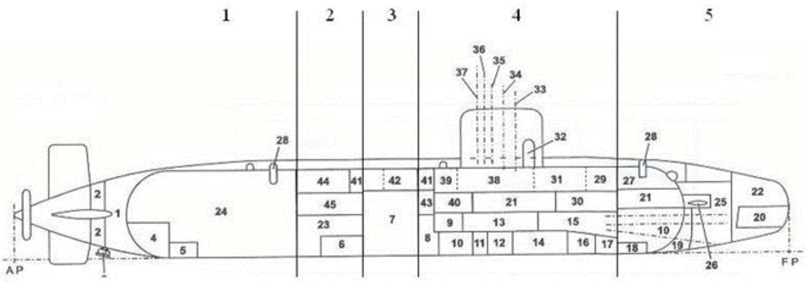


FIG.2 – PROPOSED ZONAL BOUNDARIES

In the analysis the area forward of the reactor compartment was split into two distinct zones. The intention was to provide a logical and spatial split between the accommodation/control and torpedo/weapons systems. In ASTUTE class, there is no watertight bulkhead between these zones, and the low power requirements of zone 5 may suggest merging zones 4 and 5 for electrical purposes. In such instances, and particularly in the case of ASTUTE forward compartments, it may be advantageous to use vertical zones to optimise the modular command systems layout.

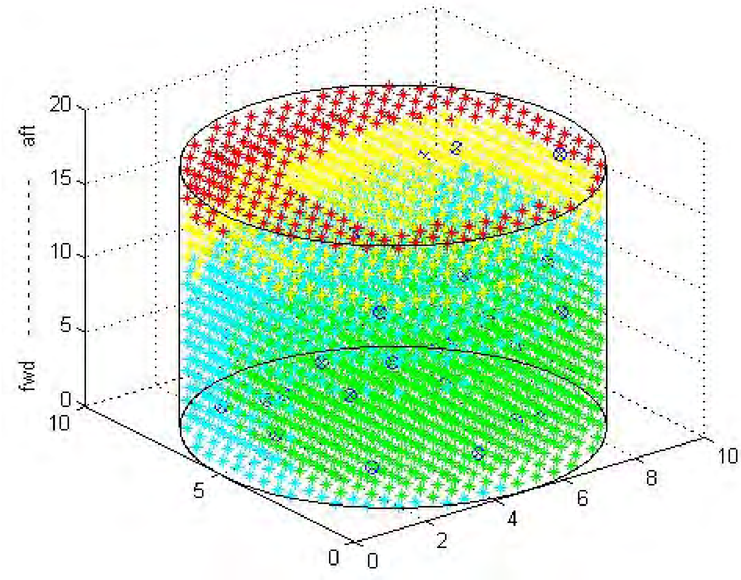
Power requirements for zone 1 were observed to be significantly higher than other zones due to loads such as the secondary and emergency propulsion motors. Large loads such as these would be supplied by dedicated power converters (in the case of the propulsion motors, variable speed drives would be used) connected directly to the main distribution bus. This approach has the advantage of reducing the space required for the ZPSU.

ZPSU Location

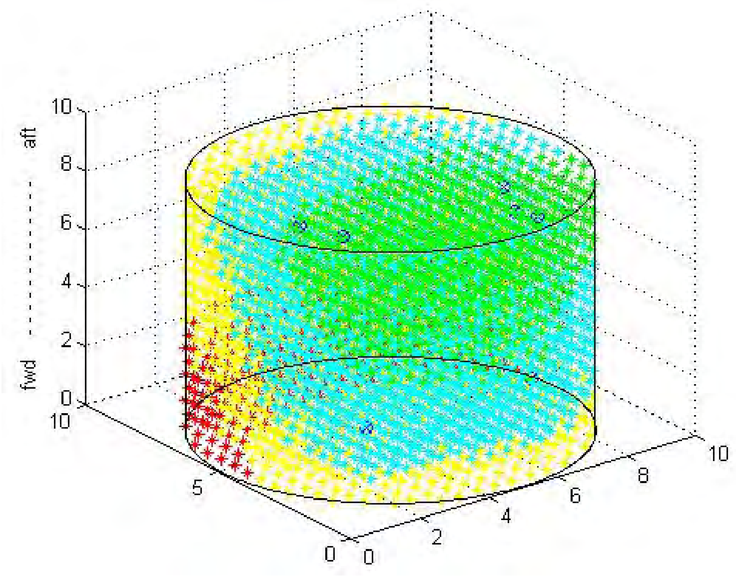
The location of a ZPSU within each zone will have an impact on the benefits realised. Factors such as space requirements and the layout of other submarine equipment, in addition to considerations such as fire and flood, will dictate the location of the unit.

An analysis of cabling costs for each zone was carried out to demonstrate the impact of ZPSU location. Zones were spatially divided into regular intervals, resulting in a 3 dimensional map of sites to be analysed. Cabling lengths for a ZPSU located at each site were calculated.

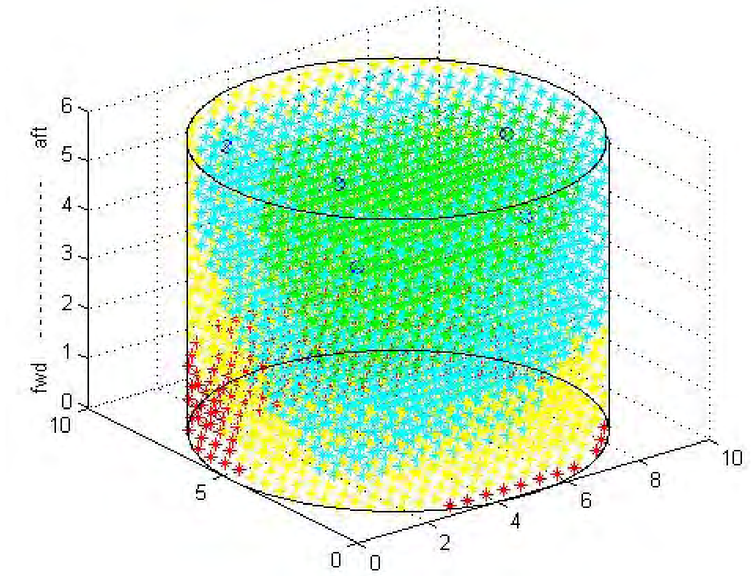
A colour coded diagram illustrating the resulting cable lengths was generated for ease of understanding (FIG.3) Graphical representation allowed a contoured view to be developed showing the optimal position for a ZPSU in a given zone. The colour of the marker at each site indicates the cable length required (shortest – green, blue, yellow, red – longest). Each ⊗ symbol represents the position of a load, and each coloured marker represents a potential ZPSU site. Note that the analysis was carried out for loads greater than 10kW, and none were located in zone 5, therefore no graph has been produced.



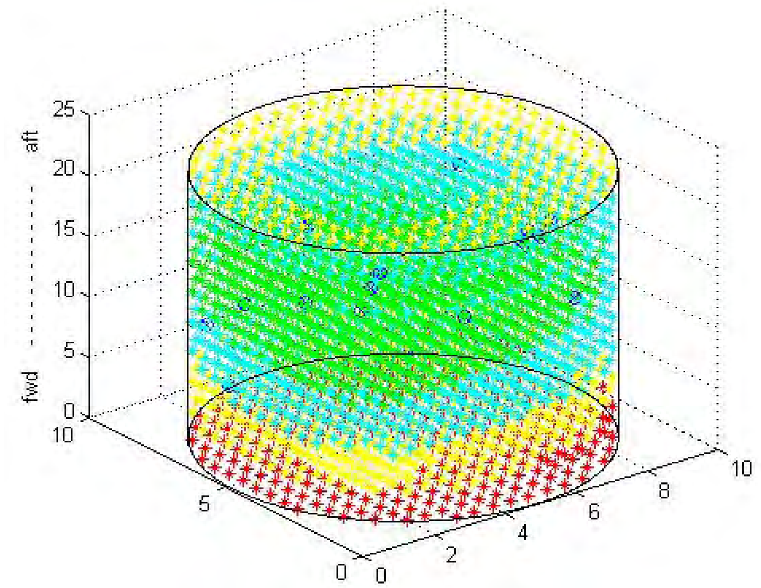
[A] ZONE 1



[B] ZONE 2



[C] ZONE 3



[D] ZONE 4

FIG.3 – ZPSU LOCATION ANALYSIS

Comparison, based on an approximation allowing simplification of cable runs, revealed that if placed in the optimal position in each zone, the zonal system will allow cabling savings of approximately 55% over the existing tree distribution system. Average savings are approximately 30%.

DC Distribution

In addition to proposing a Zonal topology the study suggested introduction of a DC distribution system.

Implementation of the existing AC transmission system, although entirely feasible for a zonal configuration, would not gain the full advantages offered by such a step change in electrical power system topology. The overall system integration would be more difficult and quality of power supply would remain as a key issue demanding extensive harmonic current filtration. In addition the overall system in terms of its use of copper would be larger, heavier, and less efficient. Moreover, the current AC tree distribution requires the whole system to be designed to the required Quality of Power Supplies (QPS). On the other hand, a DC zonal distribution topology easily lends itself to the local management of QPS as dictated by the end user equipment requirements.

The majority of large loads require an AC supply, which suggests advantages for AC distribution. However, the majority of these loads are motors which will benefit from variable speed drives. DC distribution will allow simpler, more flexible control of such loads. A complete discussion of DC power transmission is provided at[4].

Transmission of power using DC has a number of advantages for a zonal power scheme within a submarine:

- Higher power transmission for a given cable mass;
- Simple parallel operation and load transfer - no synchronisation required;
- Energy storage is DC;
- Efficient, variable speed motor drives are easily implemented;
- Better electromagnetic signature than an AC system;
- Improved system power density via reduction in the number of power conversion stages;
- Converter technology is now mature;
- Protection equipment could be built into the ZPSUs utilising the embedded power electronics.

A possible disadvantage of adopting a DC transmission system is the immaturity of the application area. Also, little analysis and development has been done on the control schemes for such a system, although the use of embedded power electronics for fault clearance has been demonstrated using a link converter during the Electric Ship Technology Demonstration (ESTD) programme.

The quantity of power electronics used in a DC zonal system will be greater than that used on the current class. However, the ASTUTE electrical system already uses significant amounts of power electronics which have replaced older, high maintenance equipment such as motor-generators. Assuming that the large loads would be supplied by their own dedicated VSD, this would result in similar quantities of power electronics in zonal distribution, but the overall design would produce a more rational system.

Distribution Bus Topology

The current system uses a tree structure to distribute power throughout the submarine. This structure results in multiple reactor compartment penetrations and duplicated cable runs. An alternative design may offer improved performance and reliability.

A wide variety of bus configurations are possible, including single, dual, hybrid, ring, and tree types. In general, tree configurations will be similar to the current system (the benchmark of comparison), and a ring-main topology is a dual bus with the ends joined (identical installation issues for a dual bus system). Thus, neither needs further specific consideration; rather, a brief assessment of the other topologies is presented.

Single Bus

A single bus transmission system consists of one main bus running longitudinally between the zones. A single bus topology is only worthy of consideration if the bus can be made robust enough to withstand any foreseeable threat that results in the continued need for prolonged electrical power distribution. However, if this can be achieved, then the advantages of such a system are significant.

In a large surface vessel, a multiple bus system can protect against single weapon hits because of the spatial separation between the buses. In a submarine, where space is limited, it is highly likely that any design threat that results in damage to one of the buses will also damage another in the same part of the submarine. It may also be possible to by-pass a breach in a distribution bus using temporary damage control cables similar to those used in the surface flotilla. The advantages of multiple bus systems in submarines are therefore not as clear, and a detailed survivability assessment is required to assess the feasibility of each solution.

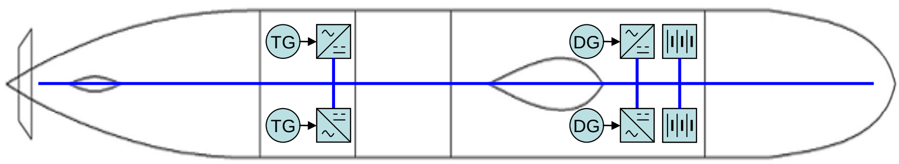


FIG.4 – SINGLE TRANSMISSION BUS TOPOLOGY

Compared to other Zonal transmission systems, a single bus system offers the following advantages:

- Reduced bulkhead penetrations;
- Minimised transmission cable length;
- Reduced installation and through life costs;
- Simplified control strategy and equipment.

In the event of damage resulting in a bus failure at any single point, essential supplies must still be maintained. In order to accomplish this, distributed generation and energy storage (fore and aft) with enough capacity to supply the essential loads is required. This will place limitations on the placement of generators and energy storage. Energy storage and control of power to essential loads are discussed later.

Dual Bus

A dual transmission bus system would consist of two separate buses running longitudinally along either port and starboard or top and bottom of the vessel.

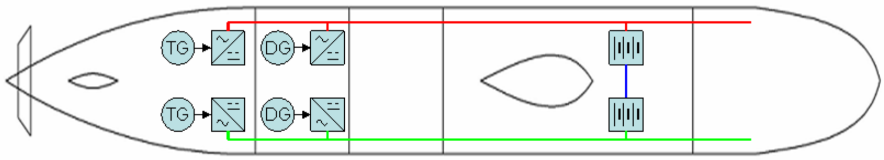


FIG.5 – DUAL TRANSMISSION BUS TOPOLOGY

Compared to other zonal transmission systems, a dual bus topology would offer:

- Dual redundancy;
- Ability to route power around bus faults;
- More equipment location flexibility than a single bus;
- Ability to use an energy storage configuration similar to the current system.

Disadvantages are:

- Longer (and hence heavier) distribution bus-bars required;
- Control equipment required is more complicated;
- More bulkhead penetrations than a single bus;

- More expensive than single bus.

A dual bus system also suggests using more than one ZPSU in a zone to increase survivability. However, this approach will lead to a system which uses large amounts of power electronics and cabling, which would increase installation and maintenance costs; thus negating one of the primary objectives of installing a Zonal power system.

Hybrid Bus

A vast number of different topologies fall into the hybrid category. An example is given below:

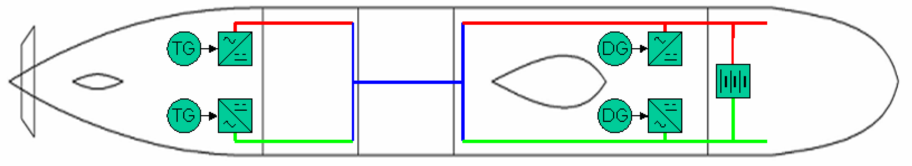


FIG.6 – HYBRID TRANSMISSION BUS TOPOLOGY

Hybrid systems have advantages over a dual bus system in terms of bulkhead penetrations and cabling length. However, they must still employ distributed generation and energy storage to maintain fore and aft essential equipment in case the single section of bus fails.

It is considered that hybrid systems offer little merit over a single bus system. A possible exception to this is in zones with a very high power requirement, such as the aft propulsion zone.

Comparison of Bus Topologies

A comparison of current and zonal bus topologies was conducted according to various metrics. It was determined that the single bus system is worthy of consideration as a main distribution topology. A detailed survivability analysis is required to confirm the feasibility of a single bus system.

Energy storage

The current T-class system utilises a single main battery to ensure essential supply integrity. An ideal energy storage solution for a Zonal power system would be to distribute the storage between the zones. Local storage such as this is of particular importance in a single bus system where no dedicated alternative supply route is possible in the case of temporary bus failure.

It is unlikely that local storage would be possible for all loads within a given zone. Moreover, this would result in a large number of dedicated Uninterruptible Power Supplies (UPS) with the consequential cost and maintenance burden. A more feasible approach is to consider just the supply requirements for just the essential loads. Using advanced battery technology and the associated improvements in power density greatly increases the probability that each zone's essential supply battery can be located within the zone[5].

In addition to the distributed essential batteries, a large battery would also be required to maintain the requirements for submerged propulsion when the primary means of propulsion and power generation is not available. Part of this requirement could be met by increasing the size of each zonal battery as space and weight restrictions allow. This could result in a design problem with regard to trim and weight distribution, however, this could be off set by locating the DGs forward in the volume vacated by the main battery. This would result in a system with increased survivability over the current class.

It is unlikely that local storage for both large and all essential loads within a zone would be possible. Local storage would be used for loads supplied by the ZPSU; large loads would need to use remote bulk storage or draw power from a combination of batteries in other zones. Furthermore load shedding strategies would need to be employed to ensure that the generation system does not become overloaded, and the available power continues to be distributed to the most important loads within the submarine.

Control

The current electrical system relies upon a manual system for contingency management. Protection systems are implemented in the form of automatic circuit breakers, but manual control is required to reconfigure the system to restore supplies to equipment when faults occur. As the amount of electrical equipment within the submarine grows, this strategy will become infeasible in terms of the demands placed upon human operators to deal with faults in a fast, reliable manner. More importantly, as the level of power electronics increases, the ability to use the devices as the primary means of fault limitation and clearance becomes attractive.

There are two main types of control system architecture, namely distributed and centralised. The current class uses a centralised system, with the control and monitoring equipment located in a manned control room. A distributed control system offers greater survivability than a centralised system, assuming that each distributed section has the ability to operate with a degree of autonomy. If any zone within the submarine becomes damaged, and inter-zone communication is lost, the other zones are designed to continue to operate as close to normal as is possible until remedial action is taken. In Platform Management Systems (PMS) this is often referred to as a 'master' and 'slave' configuration.

Distributed control promises many advantages over centralised control systems. However, in order to ensure system reliability, these control systems will need to demonstrate a high level of robustness and the ability to deal with any faults which may occur.

Summary

The previous investigation and discussion has demonstrated that the concept of zonal distribution of electrical power within a nuclear submarine has significant advantages. These advantages accrue further if DC is the chosen medium for power transmission. Benefits include:

- Up to 55% saving in cabling costs alone dependent on the position of the ZPSUs;
- Enhanced simplicity of a modular submarine build and system commissioning;
- Distributed energy storage, even if only partial;
- The need for duplicate power supplies will be avoided;
- Improved system integration and flexibility of operation and inter-connection;
- Improved power quality;
- Reduced harmonic distortion burden on input AC power system (for a DC transmission system this translates to reduced harmonic currents flowing in the generator windings).

However, some concerns still exist. Having only one ZPSU per zone offers limited reliability: a lack of redundancy means a single point of failure for all electrical equipment within that zone. While this is an important issue for a surface ship, in a submarine the significance is less clear. A submarine is subject to different, primarily internal, design threats and different operating conditions to a surface vessel.

In a submarine the size of zones would mean that significant damage to a ZPSU would also mean significant damage to the electrical equipment it was designed to supply. In addition, redundancy through duplication of the ZPSU would not necessarily improve reliability, if a second unit was included, it would likely be damaged by the same incident. Furthermore, the decreased complexity offered by the simplest Zonal system would be reduced by any duplication, with the revised system partially reverting to the current design.

It is recognised that there is concern in relation to survivability and reliability for a system employing a single ZPSU. However, there is a performance/benefit trade-off associated with increasing reliability through duplication. Further work is required to determine whether a single ZPSU will satisfy reliability and survivability criteria, and to what extent the inclusion of a second ZPSU will adversely affect cost and performance.

References

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4. “Submarine Secondary Systems Options Study Report”, Report Number R4265, BMT Defence Services Ltd., 2006.

5. “Energy Study Report”, Annex E, Submarine Secondary Systems Options Study Report, Report Number R4265, BMT Defence Services Ltd., 2006.