SINGLE GENERATOR OPERATION IN FUTURE CLASSES OF RN WARSHIPS

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ABSTRACT

The use of a common power system for both propulsion and ship's services is now standard commercial practice for the cruise market and is termed Integrated Full Electric Propulsion (IFEP). All propulsion power is provided from the electric drive. Efficient operation is obtained through the use of only as many prime movers as necessary to meet the required load, all running near their optimum efficiency, selected from a relatively large number of installed units. In order to benefit from the efficiency advantages of IFEP and to reduce Unit Purchase Cost to an acceptable level the number of prime movers in the Electric Ship (ES) concept for the Royal Navy is reduced to a minimum. Single Generator Operation (SGO), during low intensity operations, is proposed. This brings significant gains in both fuel consumption and maintenance costs due to the minimized engine running hours.

At higher powers and at Action Stations the ship will be running with more than one generator running. This article therefore addresses the issues relating to periods of operation with SGO and also discusses ride-through and fight-through. When only one generator is running a ride-through capability for essential services is considered necessary in case the prime mover trips. Limited propulsion power may also be required to maintain steerage. Classes currently in service already have a level of energy storage in weapon system Uninterruptable Power Supplies (UPS). It is perhaps the additional requirements which need to be addressed, in particular what propulsion ride-through capability is required; none, 2 minutes to start a standby generator and bring it on load, or longer, say 30 minutes.

Fight-through will also be addressed. This is the concept of providing uninterrupted power supplies to Command, Control and Indication equipment and navigation and emergency lighting. It requires an instantaneous changeover of supply (no break) which is currently provided by the UPS embedded in the parent system or more usually through the battery backed 24 volt transformer rectifier units.

The current vision of an ES power system is presented with various options for the propulsion bus and the ship's services bus. The many options for energy storage, which may be a single unit or several units distributed on one or both of the busbars, will also be described.

Finally, the article will suggest that the term SGO is inaccurate if a ride-through capability is provided as the SGO is always 'in-parallel' with one or more energy storage devices and thus this concept of operation presents less risk of loss of power than current concepts of operation.

Introduction

The use of a common power system for both propulsion and ship's services is now standard commercial practice for the cruise market and specialised shipping and is termed Integrated Full Electric Propulsion (IFEP). Partial Integrated Electric Propulsion has been employed with considerable success in the Single Role Mine-Hunters (the first of which, HMS *Sandown*, entered service in 1989) and Type 23 (HMS *Norfolk*, the first of class, was commissioned in 1990). The Auxiliary Oiler (AO) (first due to enter service in 2002) and LPD(R) (the first of class, HMS *Albion*, is due to enter service in 2003) will be the first full IFEP ships for the Royal Navy. Efficient operation is obtained through the use of the minimum number of prime movers which are necessary to meet the required load, all running near their optimum efficiency, selected from a relatively large number of smaller units. These platforms follow the accepted Royal Navy practice of maintaining a minimum of two generators running at all times.

In the Electric Ship (ES) concept fewer but more highly rated prime movers are fitted to reduce Unit Production Cost (UPC). In order to restore the fuel savings conceded by the reduced efficiency obtained from these fewer, larger prime movers operating away from their optimum operating point, it is proposed that the ES should run fuel efficient and power dense gas turbines under a regime of Single Generator Operation (SGO). This brings significant gains in both fuel consumption and maintenance costs due to the minimized engine running hours and hence Through Life Cost (TLC) reductions.

With only one generator running limited back up electrical power for some safety critical services and possibly propulsion power is considered necessary in case the prime mover trips. This is called ride-through. The level of propulsion ride-through capability required in terms of power and duration needs to be determined; i.e. none, 2 minutes to start a standby generator and bring it on load, or longer, say 30 minutes. It should be noted that the power potentially required for propulsion is generally far greater than for essential services and will be a significant factor for cost and volume of the vessel. Reference 1 considered 3 scenarios (full, partial and limited ride-through) with a 10 minute duration.

The concept of providing uninterrupted power supplies to Command, Control and Indication (CCI) equipment and navigation and emergency lighting is called fight-through. It requires an instantaneous changeover of supply (no break) which is currently provided by Uninterruptable Power Supplies (UPS) either embedded in the parent system or more usually through the battery backed 24 volt transformer rectifier units. In future power systems this could be in the form of Distributed Energy Storage (DES) in each zone providing enhanced survivability to many more key systems and equipment.

The Operational Requirement

The operational requirement is to fulfil the power requirements of surface warships, submarines and in particular their weapon and sensor systems, while maximizing the system integrity and its ability to be reconfigured following action damage. Future warships will have whole ship management systems, automation, remote operation coupled to lean manning and flexibility. This grand system will be reliant on power and although discrimination will be used there will be a greater number of supplies, which require fight-through just to maintain effective operation of ship systems. It is also necessary to meet the appropriate safety and electrical standards, whether these are naval or based on Classification Society rules that accord with national policy. All this has to be achieved while reducing to a minimum initial and running costs. These overall aims translate into machinery and equipments, which offer the prospect of high integrity power supplies to all essential systems.

Single Generator Operation

Conventional Operation

Older classes of RN Warships generally operate their generators in a split system configuration. Here specific generators supply specific groups of loads with alternative supplies being available from other generators. If the generator supplying a load fails, loads supplied via Automatic Change Over Switches (ACOS) are automatically changed to the alternative supply, and loads supplied via Hand Change Over Switches (HCOS) can be manually switched if and when required. When an ACOS supply is used the break in supply can be approximately 5 seconds which currently causes sensitive systems to fail. The use of ACOS and HCOS add an associated cost and maintenance burden but more importantly impose an inefficiency on the system due to the need to run generators below their optimum operating point so as to be able to absorb the ACOS throw over load. This is particularly so in an IFEP architecture employing few prime movers. The solution is Energy Storage.

Parallel Generator Operation (PGO)

Modern merchant vessels and the Type 23 frigate operate their generators in a parallel generation configuration. Here, a number of generators, often four or five, can be operated in parallel to provide the system load. On failure of a generator, the system can be designed to shed loads so that the load demand is within the capacity of the running generators. With PGO a power management system can automatically run up and shut down generators, and start and stop loads to ensure that the generation system operates within its capacity and efficiently.

The MoD proposes to continue with PGO because:

- Available and proposed gas turbines suitable for an IFEP ship are large and the advanced cycle variants are efficient over a wide load range. This means that a small number of gas turbines will provide sufficient installed capacity for attaining maximum ship speed and efficient operation through the whole range of ship speeds. The small number of prime movers lends itself to PGO on the propulsion bus rather than split operation.
- It can take advantage of COTS based power management systems which when used with PGO can reduce manning requirements.

An extension to PGO is Minimum Generator Operation (MGO) with its extreme case being Single Generator Operation (SGO). MGO promises to reduce running hour based prime mover maintenance costs. Here the minimum number of generators required to support system demand is operated in parallel i.e. the generators share the system load rather than supply specific sections of the load. The running cost savings (in fuel and maintenance) made by operating, for example, just one rather then two prime movers for long periods using SGO will outweigh the costs of providing the energy storage to maintain the system load for the time between generator failure and bringing on line a standby generator. As already stated energy storage devices will also allow generators to be run nearer to maximum power output because starting current transients can be absorbed by these devices.

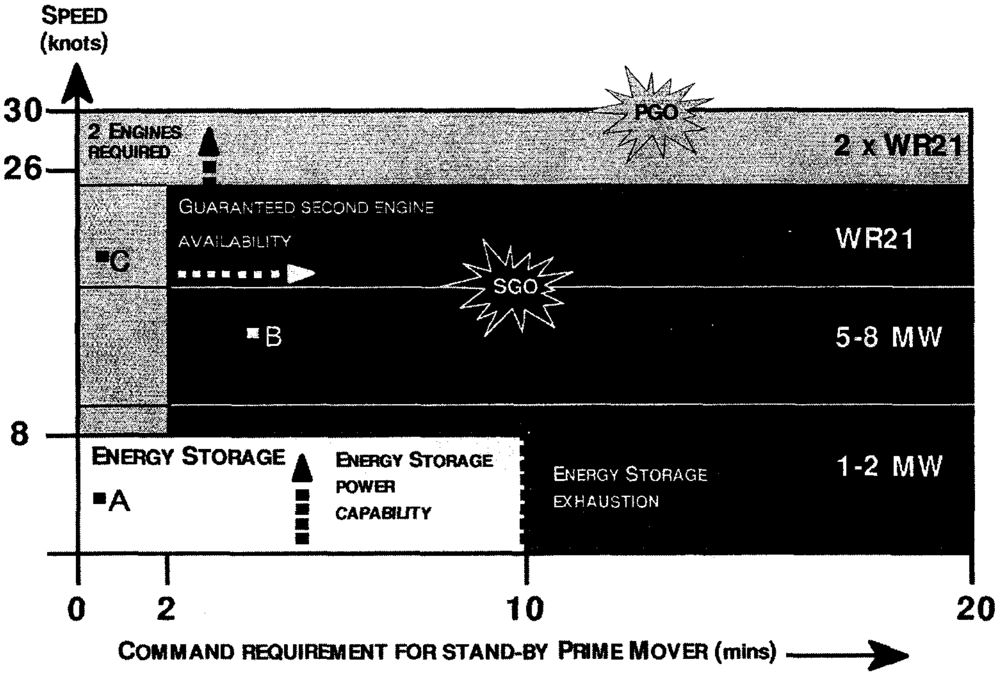
Factors supporting MGO and SGO are:

- The WR21 gas turbine alternator, when development completes in 2001, should efficiently provide between 5MW and 22MW. The use of only advanced cycle gas turbines maximizes efficiency across the power range and minimises harmful emissions.
- One or two of the prime movers can be replaced by a commercially available, efficient energy storage system (Six in a Type 23 to four in a Future Surface Combatant (FSC)). This will reduce the UPC.
- The TLC of using energy storage will be less than running a second prime mover.
- The floating energy storage device removes the need for numerous ACOS and HCOS, which are expensive to install and maintain.

Use of SGO

SGO would be used during operations in benign conditions, for example on patrol in a low threat environment and of course only applies at lower powers; once the power requirement rises beyond the output of one WR21 a second generator will be required. Depending on the final hull form and displacement of the FSC this is likely to be in the range of 26 – 28 knots.

Selection of a second generator would be determined by the Command but will include any occasion when the likely power or speed requirement exceeds the power available from the ride-through energy source and the speed of response in starting a second prime mover (2 minutes) is unacceptable. Thus Special Sea Dutymen (SSD) would not in itself be a criteria for two or more engines. This is represented graphically in (FIG.1).



OPERATING POINT A — SPEED/POWER REQUIREMENT AFTER 1ST GENERATOR TRIPS IS WITHIN CAPABILITY OF ENERGY STORAGE DEVICE, HENCE SGO ACCEPTABLE. IF ENEGY STORAGE IS NOT PROVIDED FOR PROPULSION PGO WILL BE REQUIRED IN THIS SCENARIO.

OPERATING POINT B — SPEED/POWER REQUIREMENT AFTER 1ST GENERATOR TRIPS IS OUTSIDE CAPABILITY OF ENERGY STORAGE DEVICE BUT TIME TO START NEXT PRIME MOVER IS WITHIN COMMAND REQUIREMENT, HENCE SGO ACCEPTABLE.

OPERATING POINT C — SPEED/POWER REQUIREMENT AFTER 1ST GENERATOR TRIPS IS OUTSIDE CAPABILITY OF ENERGY STORAGE DEVICE AND COMMAND REQUIRES IT BEFORE STAND-BY ENGINE CAN BE GUARANTEED, HENCE PGO IS REQUIRED IN THIS SCENARIO.

FIG.1 — SINGLE GENERATOR OPERATION

Possible instances might include RAS for breakaway, poor weather, some restricted waters or if the operational threat increased. In the Cruising State SGO would be used and probably also in Defence Watches but at Actions Stations more than one prime mover would be running. Once again speed or power available from the ride-through energy source is the decider.

The on-load generator will always be 'in-parallel' with one or more energy storage devices and their associated, highly reliable, power converters. The point is we have two sources of electrical energy but only one running generator (half the running hours with same system integrity). Thus this concept of operation will present less risk of loss of power than current systems and indeed is permitted by both NES 532 (Requirements for the design of low voltage supply and distribution systems in HM surface ships and submarines) and Classification Societies.

Ride-through for propulsion may not actually be a requirement. Current classes such as the Type 22 frigate and Type 42 Destroyer often operate just one shaft on passage with the other shaft trailing, with no ride-through capability. If the propulsion engine trips then it will take in the order of two minutes to start and select another engine. These issues will be fully investigated at the Shore Technology Demonstrator as discussed later.

Comparison with SSN

It is perhaps worth comparing the energy sources in the Type 22 frigate or the Type 42 destroyer with those in a SSN. In the former there will be a minimum of two DGs running and one propulsion engine whereas in a SSN there is a single reactor backed up with a large lead acid battery; that is two power sources "in-parallel" (dual power source). Thus a move to SGO in surface ships with an energy storage device "in-parallel" is similar in concept to the current SSN design. The SSN design meets all nuclear safety requirements and the floating energy storage device via MG sets obviates the use of ACOS and HCOS.

The IFEP architecture

A concept IFEP system architecture based on a widely accepted medium voltage AC propulsion system and a low voltage ship service system is shown in (FIG.2).

Three GTAs are connected to the propulsion system, two WR21 GTAs and the cruise GTA. The Bulk Energy Storage (BES) system, if required, would also be connected to this system. Propulsion is provided by 20MW shaft mounted propulsion motors supplied through their associated drive converters. The ship service system is linked to the propulsion system through bi-directional static converters. Also connected to the ship service system is the 1-2MW GTA. Connection of this small GTA allows easy separation of the prime movers using the Ship's services distribution system to transfer the power without having to provide oversized cabling and protection equipment.

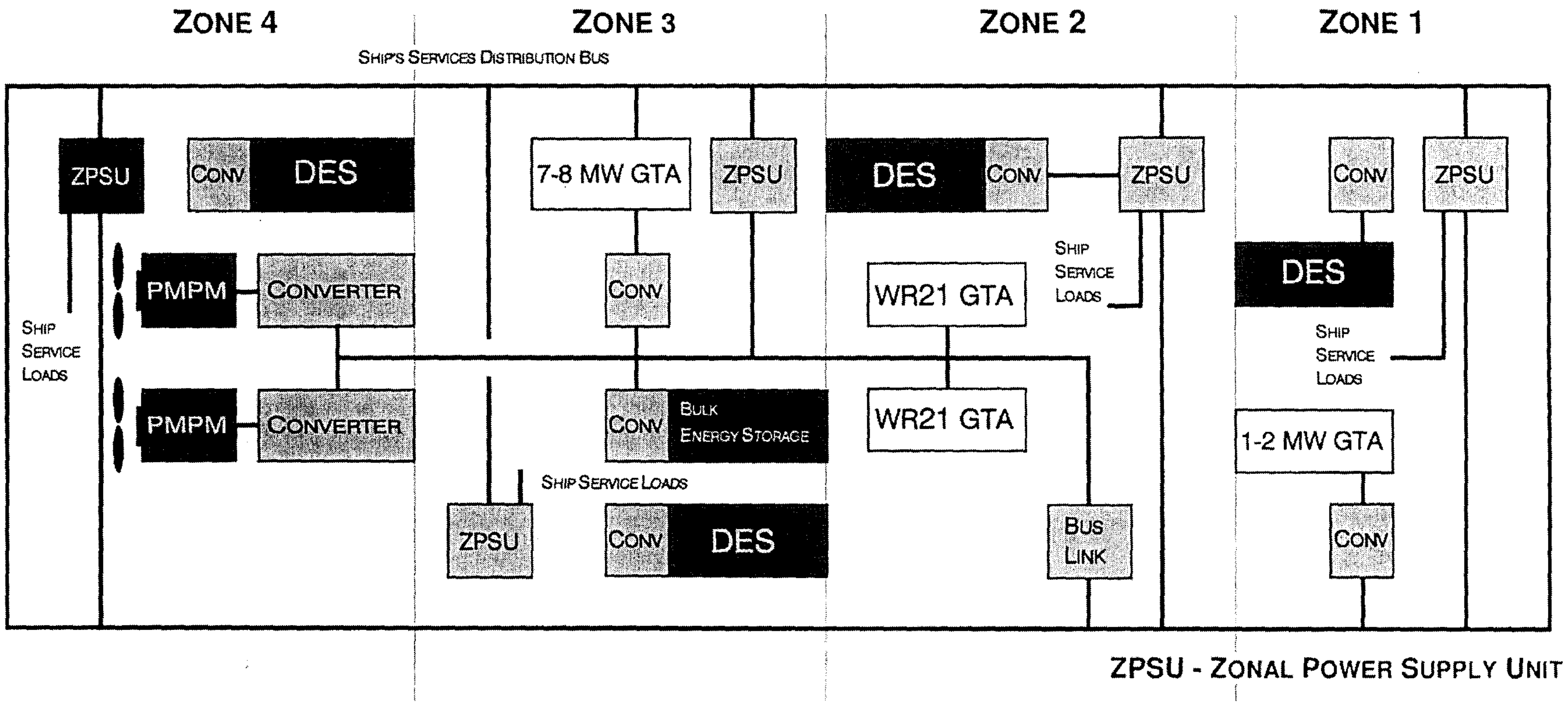


FIG. 2 — IFEP ARCHITECTURE

Energy Storage

Energy storage options

The technologies under consideration include flywheels, batteries (both conventional, advanced and high temperature), regenerative fuel cells (otherwise known as redox flow cells) and Superconducting Magnetic Energy Storage (SMES).[2] Integration of several technologies in a hybrid energy storage system may best meet the vessels requirements. This may consist of BES primarily for SGO and propulsion support and Distributed Energy Storage (DES) at a zonal level for essential services.

Conventional lead acid batteries are simple, reliable and relatively cheap but are heavy and require significant maintenance and may still be considered. Flywheel technology (FIGS 3 & 4) is fairly advanced and already in use in buses and trams but the additional motion seen by a warship needs to be catered for, probably using more robust bearings rather than gimbals. These alternative bearings may well affect the system efficiency. Containment of the rotor also needs to be considered, however tests already carried out by URENCO show that their composite Rotor fails in a totally safe manner.

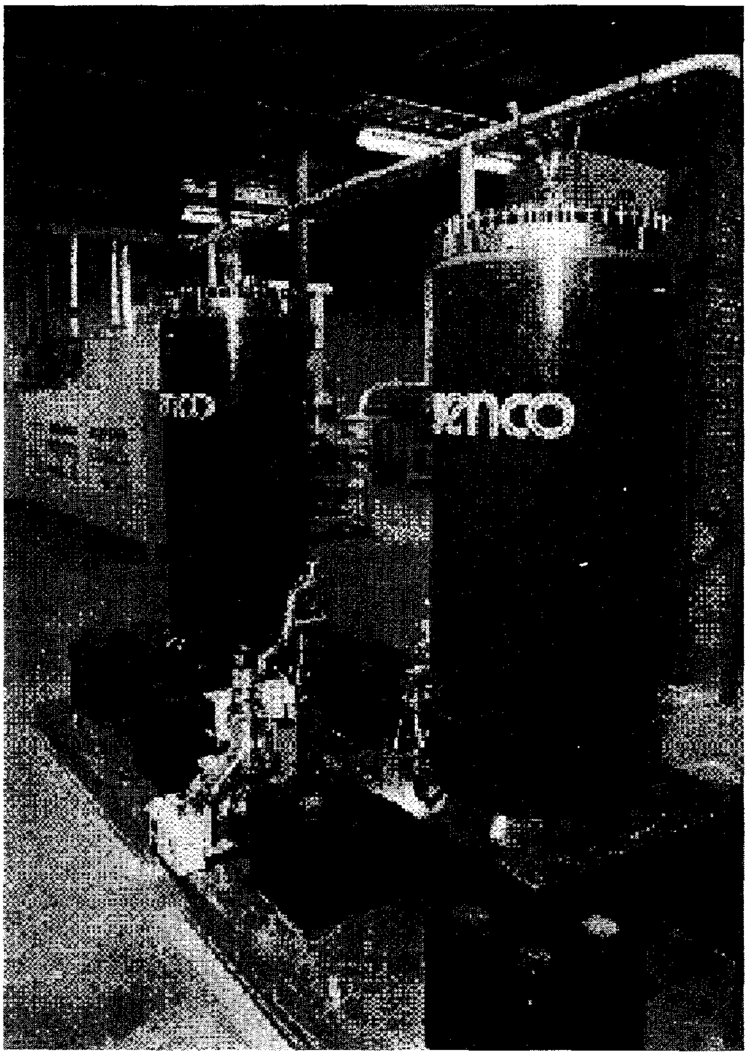


FIG.3. — URENCO FLYWHEELS

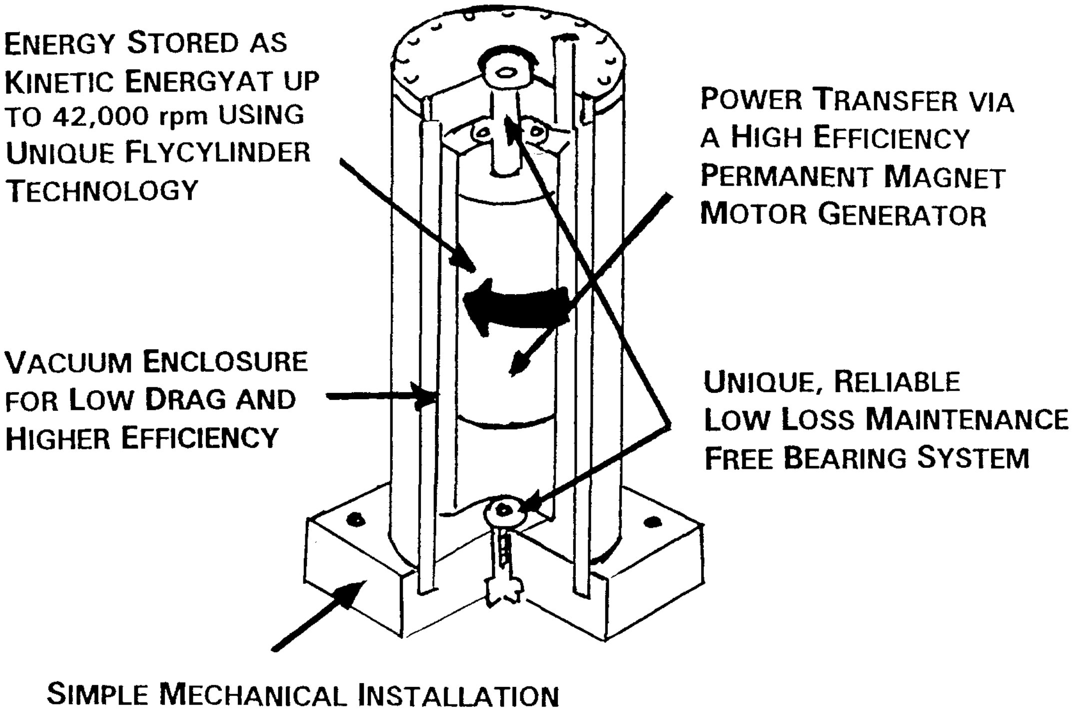


FIG.4. — URENCO FLYWHEEL DESIGN

Regenerative fuel cells (Redox) (FIG.5) are being developed by National Power to store power generated in excess of requirements until required during periods of peak demand. They store or release electrical energy by means of a reversible electrochemical reaction between two salt solutions (the electrolytes). The reaction occurs within an electrochemical cell. The cell has two compartments, one for each electrolyte, physically separated by an ion-exchange membrane. In contrast to most types of battery system, the electrolytes flow into and out of the cells and are transformed electrochemically inside the cells. Thus the power output of the battery is determined by the size of the cell but the endurance is governed by the size of the two tanks containing the electrolytes. Ideally a Redox system in a naval environment would use higher strength electrolytes to maximize the power density of the system and the plastic pipework and tanks, which are used by National Power, replaced to cater for the naval environment.

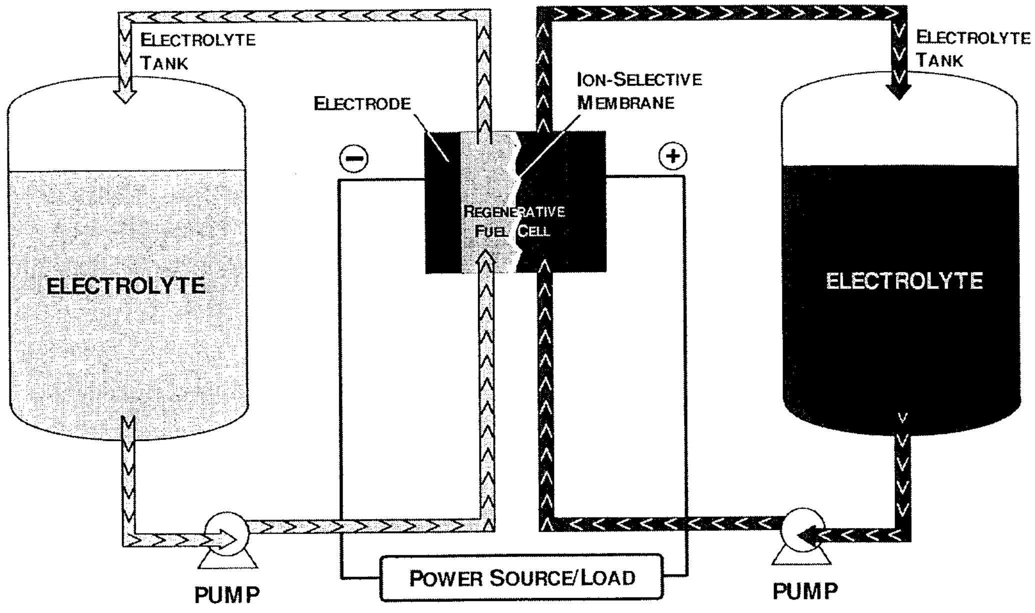


FIG.5 — REDOX SYSTEM

The Zonal Concept

The concept of dividing future classes of ship into zones to enhance survivability also extends to the power system. At least two supplies would be provided for all essential loads. Current classes, using split generation and distribution, rely on the provision of normal and alternative supplies via ACOSs to essential services to ensure a suitable level of survivability. Future systems could be supported by energy storage embedded in each zone providing UPS, not only to weapon systems and sensors, but to all essential services until power is restored to the zonal distribution point. The duration of this fight-through could be as little as 100ms, the time to clear a fault on the distribution system, or longer, say 10 minutes.

The continuous supply of electrical power is likely to be essential for the post-damage sustainability of all operationally essential and critical functions. To minimize vulnerability and to maximize recoverability of these functions, the electrical power system should make optimum use of the zonal sub-division of the platform. The system is likely to have to satisfy the following requirements:

- Primary sources of electrical power should ideally be in separate zones (preferably those containing the systems with the most critical operational functions), though not every zone need necessarily have its own generator.
- Each zone must contain at least one Zonal Power Supply Unit (ZPSU).
- Each ZPSU must be supplied with electrical power from at least two sources.
- Each zone must contain at least one energy storage device capable of supplying the power necessary to maintain operationally essential and critical functions within that zone while the reversionary supply to the ZPSU is selected or until another generator can be brought on load. Although 2 min may be adequate, it may prove necessary to rely on this stored power for up to 10 min.

- There is to be the facility to isolate power at each inter-zone boundary, from either side.
- There is to be a comprehensive supply protection and discrimination system which, if centrally controlled, is to continue to function on loss of central control.
- An emergency source of electrical power is required to supply all those services that are essential for safety in an emergency for a period of 18 hours, satisfying the Provisional Rules for the Classification of Naval Ships.[3]

Energy Storage Requirements for FSC and CVF

Potential energy storage requirements to replace power supplies to most essential services and to allow SGO were determined in Reference 1 and are tabulated below. The requirements for pulsed weapons, load levelling and accumulator/air bottle replacement have not been quantified, nor do the figures below include pulsed loads for aircraft starting or electric motor starting.

Three scenarios have been proposed for the operation of ships under SGO. They are:

- Full Scenario
  RAS breakaway propulsion (18 knots) + Full ships services load.
- Partial Scenario
  Safe propulsion (8 knots) + Partial ships services load
- Limited Scenario
  Zero propulsion + Limited ships services load

TABLE 1 — *Energy Storage Requirements for FSC*

Scenario	**Ride-through duration (secs)**	**Propulsion System Continuous Load (MW)**	**Ships Services System Continuous Load (MW)**	**Total Energy Requirement (MJ)**
Full	600	5.1	1.73	4098
Partial	600	0.53	0.726	754
Limited	600	Zero	0.453	272

TABLE 2 — *Energy Storage Requirements for CVF*

Scenario	**Ride-through duration (secs)**	**Propulsion System Continuous Load (MW)**	**Ships Services System Continuous Load (MW)**	**Total Energy Requirement (MJ)**
Full	600	13.8	7.87	13002
Partial	600	3.2	3.99	4314
Limited	600	Zero	1.9	1140

It is interesting to look at the power available from a SSN lead acid battery which provides in the region of 745 MJ and a seven flywheel system from URENCO which provides 84 MJ and compare these figures to the power requirements of both the FSC and the CVF in each scenario. In the case of the FSC, one flywheel system per zone (assuming four zones) could provide the power for the limited scenario with an additional four flywheel systems, with one more in each of the zones or all four connected to the propulsion bus, used to satisfy the power requirements in the partial scenario. Alternatively a single SSN battery could satisfy the partial scenario but would not be distributed in the zones. For the CVF a SSN battery as BES and flywheels distributed in the various zones could provide power in the limited scenario, however power demands for limited propulsion are high. Note that a SSK battery has 4 times the capacity of a SSN battery but weighs approximately 1700 tonnes.

System proving with the Shore Technology Demonstrator (STD)

For IFEP and SGO to be accepted by future platform projects requires generic demonstration to be undertaken in time to inform their respective equipment selection milestones. The aim of the STD is to reduce the risk of specifying IFEP with SGO for future warships using emerging technologies not found in commercial systems to a level acceptable to Platform Prime Contractors (who may not be shipbuilders). The work will include setting design parameters, identifying specific equipment developments and performing a wide range of testing upon a representative power system to prove the integration of the various novel technologies and prove system integrity.

In the past major changes to propulsion systems in particular were preceded by extensive shore trials with the aim of ensuring that in-service problems were obviated so that platform availability and reliability requirements were not prejudiced. With the current procurement strategy the onus rests with the Platform Prime Contractor to underwrite the performance of the platform and its systems, including propulsion. With the emergence of new technology, in this case IFEP, it can be anticipated that prospective Primes would seek to impose a risk premium to cover what they might regard as unproven aspects of the design, equipment and operation of the propulsion system. With the move towards implementing SGO in future warships, it is in the MoD's interest to commission a shore demonstration of the generic IFEP technology. This will prove and de-risk the technology and operation to the extent that a Propulsion Prime will be able to offer an affordable IFEP system without an undue risk premium, and without the need for the MoD to mandate a solution.

There is now a funded requirement for an affordable and comprehensive STD that will convincingly de-risk and prove the operation of a generic IFEP system, and its principal components. The STD Programme will permit the main operating modes to be investigated, particularly the integrity issues associated with SGO, as well as fault and transient conditions. It should also permit demonstration and testing of individual components, and sub systems, and allow alternative components to be compared.

The main equipment to be integrated into the STD includes:

- Advanced GTAs of various powers.
- Switchgear.
- Solid state power conversion devices.
- Various energy storage devices together with their associated power conversion devices and a propulsion motor.

Conclusion

The article has sought to indicate the potential for a significant change in marine engineering technology with a move to IFEP and SGO that will improve operational capability while at the same time driving down the UPC and TLC, utilizing modern technology and meeting anticipated future legislative requirements. This step change in marine engineering philosophy is needed now so that the advantages can be taken forward into the imminent design of three classes of ship and submarine that will form the backbone of the Royal Navy until the middle of the 21st Century. LPD(R) has taken its lead from the commercial sector's approach to IFEP; the ES's aim is to improve upon this and utilize the technological developments, which are beneficial in enabling the most cost effective means of achieving the platform's power system requirements.

The SGO concept incorporates energy storage devices, potentially batteries or flywheels, or a combination of several technologies. The energy storage device can be distributed through the zones and provides sufficient power to ship services and limited propulsion power for 2 to 30 minutes, depending on the requirement, whilst a standby GTA is started. The opportunity to implement SGO will provide very significant benefits in operating costs. The availability of zoned energy storage devices gives a power integrity which will be significantly better than a Type 23 running on 2 or more generators, whilst minimizing generator running hours and operating them near their peak efficiency. Replacement of ACOSs (with finite time delay) with UPS will be a significant enhancement. In this respect the prime mover and the Energy Storage Device can be considered as two power sources permanently in parallel rather than an on-line prime mover with a back-up power supply.

The STD is considered to be an essential tool for de-risking IFEP and proving system integrity using SGO and proving the ability to integrate these technologies together. It will provide the opportunity to instil confidence in an IFEP architecture employing SGO; a vital step if the fallback option of 6 or more prime movers proves unaffordable in both UPC and TLC.

Acknowledgements

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2. Mr N. Yeaman from the future surface combatant project.
3. Lieutenant Commander P.D. Gilbert RN from the Future Surface Combatant project.

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