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Powering the Future with the Integrated Power System

ABSTRACT For the past four years, Advanced Surface Machinery Programs (SEA 03R2) has been developing the Integrated Power System (IPS) to reduce ship acquisition and life cycle costs while still meeting all ship performance requirements. IPS provides electrical power to ship service loads and electric propulsion for a wide range of ship applications including surface combatants, aircraft carriers, amphibious ships, auxiliary ships, sealift and high value commercial ships. IPS consists of an architecture and a family of modules from which affordable and high performance configurations can be developed for the full range of ship applications. Two years ago, the initial IPS concepts were presented at ASNE Day 1994. Since then, much has been learned through the Reduced Scale Advanced Development (RSAD) and Full Scale Advanced Development (FSAD) programs. This paper describes the fundamental IPS architecture, details the evolving "family of modules" and their interface standards, and outlines the "Mass Customization" based design process for achieving customer performance requirements with an affordable IPS configuration.

Introduction

With the end of the Cold War, affordability has become a high priority to naval architects and marine engineers designing naval ships and ship systems. For the past four years, the Advanced Surface Machinery Programs (ASMP) of the Naval Sea Systems Command (SEA 03R2) have concentrated on developing naval propulsion, electrical, and machinery control systems that enable significant reductions in the acquisition and lifecycle costs of naval warships while still meeting all performance requirements. Early on, ASMP recognized that a single technology or process was not sufficient to meet the affordability goals. Instead, ASMP has attacked cost through six affordability initiatives:

? Extend Architectural Advantage
? Promote Commonality
? Reduce Infrastructure
? Reduce Component Costs
? Reduce Manning
? Reduce Energy Costs

A major product of the ASMP efforts is the Integrated Power System (IPS). IPS consists of an architecture, family of modules, and design process from which affordable propulsion and electrical systems can be configured for a broad range of naval applications. These applications include surface combatants, aircraft carriers, amphibious ships, auxiliary ships, sealift ships and high value commercial ships.

Background

IPS has its origins in the previous Integrated Electric Drive (IED) program. The purpose of the IED program was the development of the most affordable propulsion system meeting very ambitious acoustic requirements. With the end of the Cold War, the acoustic requirements disappeared. Unfortunately, ASMP discovered through a series of studies that the IED architecture was not robust enough to produce affordable configurations meeting traditional levels of performance. These studies however, showed that an electric drive architecture based on commercial standards, commonality, and scalability could compete in cost and performance with mechanical drive options. With this realization, IPS was born. The initial IPS concepts were presented at ASNE Day 1994 [1]. A contract was awarded to Lockheed Martin in February 1995, for the IPS Full Scale Advanced Development (FSAD). ASMP has also continued investment in several technologies supporting IPS including permanent magnet motors and generators, power electronic inverters, and zonal architectures.

IPS Description

IPS consists of an architecture and a set of modules (shown generically in Figure 1), which together provide the basis for designing, procuring, and supporting marine power systems applicable over a broad range of ship types. The IPS architecture [2] integrates the generation, distribution, storage, and conversion

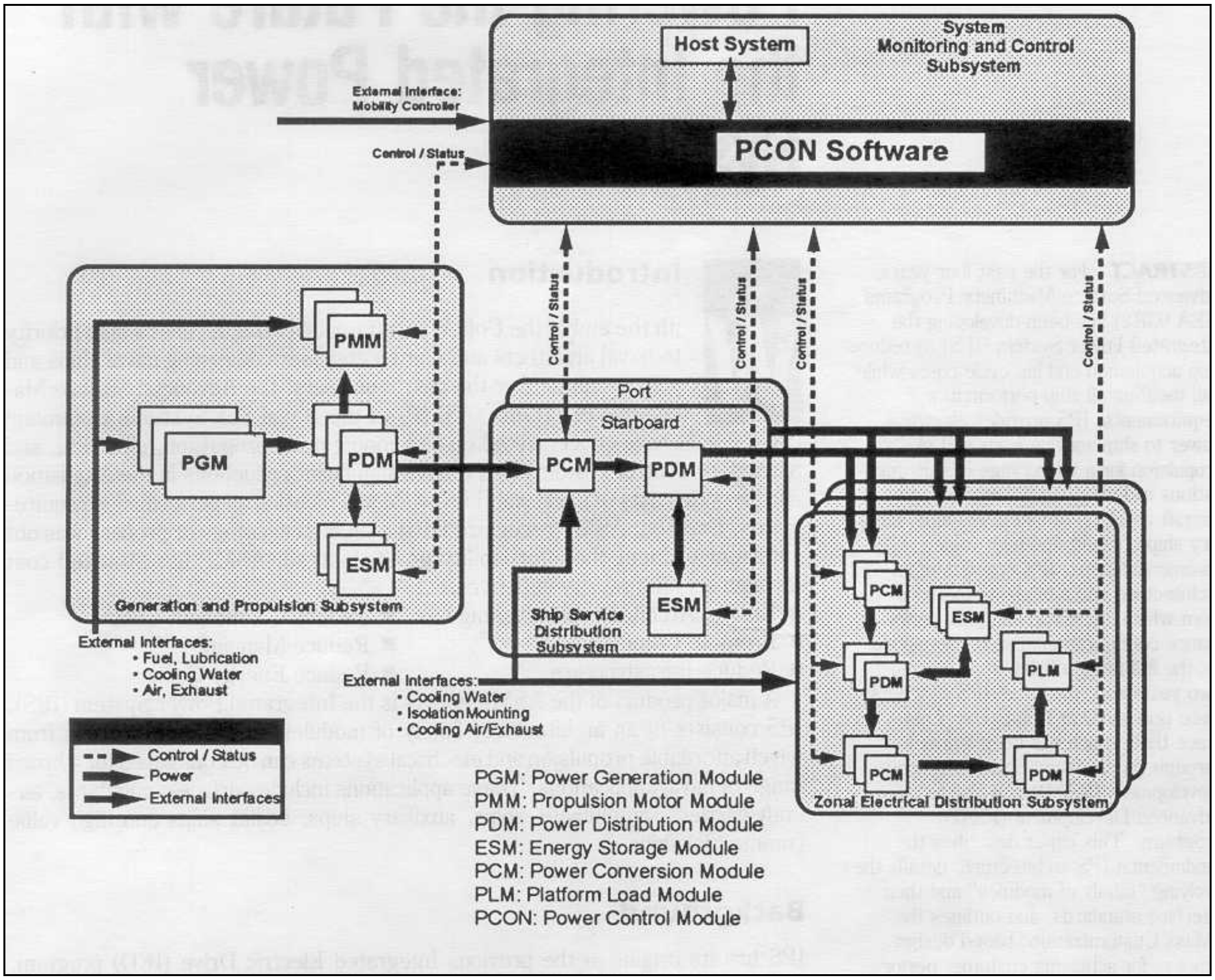

FIGURE 1. IPS Architecture and Modules

of electrical power for both ship service and electric propulsion loads. The integration process uses a methodical system for developing tailored configurations for the range of ship applications. To this end, shipboard power systems are divided into the following seven elements:

- Power Generation
- Energy Storage
- Power Conversion
- Power Distribution
- Propulsion Power
- Platform Loads
- Power Management

These elements correspond to the types of modules comprising the Family of Modules which can be thought of as a menu from which modules are selected and tailored to produce an affordable custom power system configuration meeting all the design requirements. The IPS architecture implements "Mass Customization" [3] techniques to maximize the re-use of engineering efforts between diverse applications and to maximize the commonality of components fleet wide. Modularity also promises to reduce cost by enabling the assembly and testing of modules using flexible manufacturing techniques [4]. However, a cost effective module requires careful design and a thorough understanding of the ship design, construction, and maintenance processes. If a module does not reduce the total amount of effort required to integrate its components into a ship, it will likely have little if any cost savings. Many of the challenges to modularity are discussed in [5].

In shipboard applications (Figure 2), the modules are organized into four subsystems: Generation & Propulsion, Ship Service Distribution, Zonal Electrical Distribution, and System Monitoring and Control.

The Generation & Propulsion subsystem is centered around a specific Power Distribution Module (PDM-1). PDM-1 consists of 4160 VAC 60 Hz. 3 phase electrical distribution cable and equipment. All shipboard prime movers are part of power generation modules (PGMs) that deliver power to PDM-1 and are part of the Generation & Propulsion subsystem. Other elements of this subsystem are propulsion motor modules (PMM); and potentially, energy storage modules (ESM).

The Ship Service Distribution subsystem is centered around PDM-2 which consists of 1000 VDC electrical distribution cable and equipment. Power for PDM-2 is obtained through a Power Conversion Module (PCM-4) that converts the 4160 VAC power of PDM-1 into the 1000 VDC power of PDM-2. Energy Storage Modules may also connect to PDM-2.

The Zonal Electrical Distribution System consists of several Power Distribution Modules, Energy Storage Modules, Power Conversion Modules and Power Loads. Power is obtained from PDM-2 via PCM-1 that converts the 1000 VDC of PDM-2 into 800 VDC of PDM-5. PCM-1 also performs fault isolation and current limiting functions to implement zonal survivability. Ship service loads receive power either directly from PCM-1, or from Power Conversion Modules that convert the 775 VDC into the desired form of electrical power (440 VAC 60 Hz., 440 VAC 400 Hz., 270 VDC, or 155 VDC).

Finally, the System Monitoring and Control subsystem consists of the software necessary to implement power management, fault response, and system human-computer interface. This subsystem is composed of system-level control software (PCON-1) and zonal-level control software (PCON-2). The System Monitoring and Control subsystem is assumed to reside on a computational and networking infrastructure that is external to IPS. Currently, this external infrastructure is the Standard Monitoring and Control System (SMCS). Designing the IPS control software to be independent of the host hardware as much as possible, should enable exploiting future advances in computers and networks.

Why Electric Drive?

Support for electric drive propulsion is a fundamental property of the Integrated Power System. An electric propulsion system integrated with the ship service distribution system offers the naval architect considerable flexibility, and often the choice of a more affordable ship to acquire and operate as compared to an unintegrated mechanical drive option [6-9]. Traditionally, it has been observed that replacing the reduction gear of a mechanical drive ship with a generator, switchgear, frequency changer, and motor will increase weight, volume, acquisition cost, and because of reduced efficiency, will increase operating costs. While this observation is true, it is misleading because

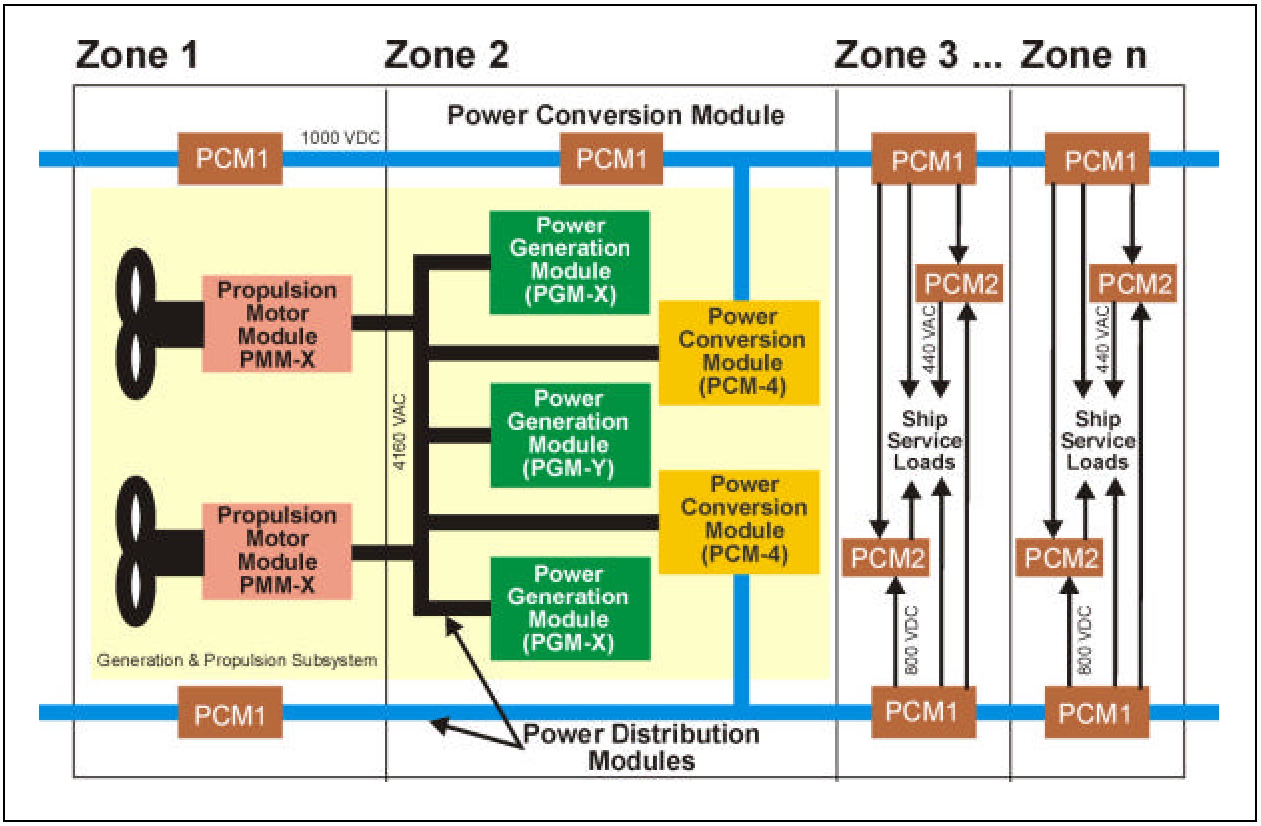

FIGURE 2. IPS Shipboard Application

a one-for-one replacement of mechanical drive components with electric drive components does not take advantage of the flexibility of electric drive that can result in improved affordability. A more balanced view would note that in the energy conversion process from the chemical energy of the fuel to the kinetic energy of the ship, the energy loss in the transmission system is very small. The dominating loss mechanisms are in the conversion of fuel into rotating mechanical energy of the prime mover (as measured by Specific Fuel Consumption or SFC), in the conversion of rotating mechanical energy into thrust (as measured by the Propulsive Coefficient or PC) and in the conversion of thrust into kinetic energy of the ship (as measured by the EHP vs. speed curve). IPS offers the ship designer flexibility in reducing these dominant loss mechanisms:

- Operate prime movers more efficiently. A mechanical drive ship typically has at least two propulsion prime movers and at least two prime movers for ship service electrical power operational at any time. Under many operational conditions, these prime movers do not operate in their most efficient speed and power range. One can operate an electric drive ship such that the most efficient combination of prime movers are on-line. Furthermore, with an IPS ship, the naval architect can select the number and ratings of the PGMs to optimize lifecycle cost without the constraint of having propulsion prime movers evenly divided among the shafts.
- Improve Propulsor Efficiency. A naval architect can use electric propulsion to improve propulsor efficiency in several ways. First, a more efficient fixed pitch propeller can be used in place of a Controllable-Reversible Pitch (CRP) propeller where gas turbines are the prime mover. Second, high efficiency Contra-Rotating (CR) propellers can be implemented without the need for complex gearing. Finally, podded propulsors can move the propulsors out of the boundary layer of the ship and into undisturbed flow.
- Improve Hull Efficiency. Electric Drive offers the naval architect considerable flexibility in locating equipment in the ship. This flexibility can be exploited by using unconventional hullforms that are difficult to implement with a mechanical drive train. Other ways of reducing hull drag include reducing propeller appendage drag by replacing CRP propellers with fixed pitch propellers, and by eliminating rudder appendage drag by replacing the rudder with steerable podded propulsors.

Reducing fuel consumption is not the only reason for implementing electric drive. An electric drive ship can be more cost effective for several other reasons as well:

- Reduced Number of Prime Movers. By combining the electric plant and the propulsion plant, the total number of prime movers on a ship can be significantly reduced. A mechanical drive destroyer for example, can be expected to have four propulsion and three ship service gas turbines. The equivalent IPS ship could have as few as three gas turbine based PGMs. Prime movers contribute significantly to initial acquisition cost, ship manning costs, maintenance costs, and training costs.
- Architectural Flexibility. In an electric drive ship, aligning prime movers with the propeller shaft is not required. This enables locating the propulsion motors in the optimal location for driving the shaft, and locating the prime movers in areas that do not interfere with ship mission equipment. In commercial cruise liners, electric drive typically results in more first-class passenger cabins in the same size ship. Similarly, more cargo can typically be carried in an electric drive cargo ship resulting in a lower required freight rate.
- Replace CRP propellers with fixed pitch propellers. CRP propellers require a complex hydraulic system and associated equipment that initially cost more and require more maintenance than fixed pitch propellers.
- Producibility. Electric drive offers several ways to improve the efficiency of the ship production process. First, the shaft lines can be much shorter, enabling the shaft alignment process to occur much earlier in the construction process. Second, the PGMs are constructed and tested in an efficient shop environment before being landed as a unit into the ship. Third, electric drive offers the potential to land expensive prime movers much later in the construction process, thereby enabling later equipment purchases and reduced finance charges. Fourth, electric drive enables modifications in the ship erection schedule that can reduce the total time needed to assemble a ship.

Why DC?

A key feature of IPS is its use of DC power in the distribution of power onboard ships. The decision to use DC instead of the more conventional AC is based on multiple investigations focused on electrical distribution system simplification and Propulsion Derived Ship Service (PDSS). The electrical distribution system simplification results were transitioned into the zonal architecture [10]. The PDSS efforts focused on combining propulsion and ship service prime movers for improved fuel efficiency to reduce ownership costs with the Integrated Electric Drive.

These PDSS studies resulted in the decision to move away from the mechanical power take-off connected to a high speed alternator and cycloconverter to a more affordable all solid state power converter using an electrical power take-off (common electrical bus). The most affordable power converter was a DC-link converter comprised of power electronic modules which were paralleled to obtain the required multi megawatt power rating. Exploiting the PDSS design attributes (power electronic modules, IGBT inverter technology) and desiring improved performance at lower ownership costs lead to distributing DC power along the port and starboard busses

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Integration of the propulsion derived ship service unit with the ship service busses provided the greatest cost, weight, volume and performance advantages with the fewest technical risks. The Ship Service Distribution System (SSDS) evolved from the conceptual PDSS studies to an integrated system taking advantage of modern semiconductor technology and load equipment design characteris tics. Each step of the SSDS design change was driven by potential ownership cost reductions.

The initial advantages from distributing DC power to dispersed invertors was in the cost saving associated with the elimination of the large electromechanical switchgear (ACB Type) used in the zonal architecture. The elimination of the switchgear was accomplish by utilizing the power electronics in conjunction with disconnect switches to perform fault protection and isolation. This can be accomplished without reducing ship performance or safety requirements by allowing the solid state source supplying the DC bus to act in a current limiting mode during casualties. In fact, the potential exists to improve performance by leveraging inherently fast switching characteristics of the solid state power semiconductors to improve shipboard power management under normal and casualty conditions.

Performance advantages provided by DC power distribution was to decouple the generator operating frequency from the narrow threshold required for ship services users load. This allows cost, size and weight optimization of the generator and rectifier. This distributed bus minimizes the number of power conversion steps between generation and users equipments. The distributed DC power can be customized to the appropriate type near the many user loads, such as 60 Hz, 400 Hz or DC power.

Utilizing zonal power conversion maintains or improves power quality requirements to many user loads, such as 60 Hz, 400 Hz or DC power. Currently, power quality continues to decrease as larger quantities of electronic power supplies are added to navy ships, the SSDS approach will eliminate this design constraint. Also, SSDS provides the opportunity to integrate user loads with a DC bus interface which eliminates two steps of power conversion, saving cost and eliminating power quality issues.

Finally, the dispersed DC bus can leverage the full benefit of advanced power semiconductor technology to increase the voltage and current range as industry improves device capabilities. This attribute may provide the most significant cost savings benefits for the SSDS due to the rapid improvements in power semiconductor devices to support electric automobiles and advanced power supply design technologies. Power electronics device capabilities are being exploited in flywheel energy storage devices, adjustable speed drive for motor controllers and control system interfaces between power devices and digital controllers; SSDS can leverage each of these capabilities from the industrial market.

Interface Standards

Well defined and technology-independent interface standards play a key role in achieving the IPS affordability and performance goals through Mass Customization. Interface standards must be carefully crafted to enable the creation of arbitrary system configurations with a minimum of customizing engineering effort. In an ideal world, IPS modules comprising a configuration could be specified completely independent of one another in a "plug and play" fashion. For a number of reasons, particularly in the areas of system stability and fault current capability, this is not yet achievable. Future research should enable modifications to the IPS interface standards to enable true "plug and play" compatibility of modules. IPS categorizes interfaces into a number of groups:

- Module-to-Module Power Interfaces: These Interfaces are organized by the different Power Distribution Modules and whether the interface serves as a source or a load to the Power Distribution Module.
- Module-to-Module Monitoring and Control Interfaces: The module-to-module monitoring and control interfaces are functional only. Because IPS relies on an external system for monitoring and control communication (SMCS), the physical characteristics of the interfaces (e.g. voltage levels, baud rates, pin-outs, message formats) are considered Module-to-External System Interfaces. The interfaces of concern are the actual information content exchanged between modules. These are broken down into three categories: control messages used to initiate action (type C), monitoring messages required to initiate control messages (type MC), and monitoring messages that are used for human-computer interface displays only (type M). The type C and type MC messages are standardized as much as possible for each module type. The type M messages are anticipated to be heavily tailored for the particular hardware within each module.
- Module-to-External System Interfaces: IPS modules interface to a number of other systems on a ship. These interfaces include: navigation system software interfaces, fluid system interfaces, foundation and structural interfaces, and control system interfaces. The complete interfaces are detailed in the IPS Module Interface Design Document [11].

IPS Family of Modules

The IPS Family of Modules [12] represents functional elements which formulate any IPS configurations depending on each ship's operational requirements. Each functional element of the family includes a range of standard ratings which best fit the propulsion and ship service operating profiles across a representative fleet of surface combatant ships. This best fit is determined by applying the IPS

Configuration Process to achieve the greatest commonality between IPS modules which provide the lowest ownership cost given a fleet of ships with different operational characteristics. The family of modules maintain a common module interface standard to facilitate rapid and affordable introduction of new technology as driven by industrial market forces and future war fighting requirements.

In order to initiate the development of the Family of Modules, the range of propulsion and ship service power requirements was projected as presented in Table 1. An initial set of modules was then defined to provide adequate coverage for this range of requirements. This initial family (Table 2), when applied to each of the ship types resulted in the allocation of modules as presented in Table 3.

While this first cut at the Family of Modules was largely an engineering judgment exercise, subsequent refinement will be done using a more rigorous assessment process based on overall fleet affordability.

Specific details for the Family of Modules is provided in the Module Characterization Sheet [13] and the Submodule Characterization Sheet [14]. Each of the characterization sheets will contain a summary of the machinery characteristics for the naval architect and marine engineer to utilize during the conceptual and preliminary designs of a ship. All module characterization sheets employ commercially available analysis tools.

Specific information contained within the characterizations sheets includes:

- Ship requirements affecting module selection
- Module selection guidance
- Module tailoring guidance cost attributes
- Interface criteria
- External system integration requirements
- CAD product model
- Design and analysis tools
- Simulation models
- Unique system or component support requirements

IPS Design Process

The objective of the IPS Design Process is to develop a tailored IPS configuration which meets any set of ship requirements and reduces both the ship's life cycle cost and the cost to the fleet. The ship's life cycle cost reduction is realized through the benefits already attributed to IPS. The goal of the development of the IPS Family of Modules is to find the group of modules which will minimize the fleet's life cycle cost. This reduction in fleet life cycle cost is realized through two means among others. First, the logistics burden (expense) of acquiring modules and their repair parts is minimized if the number of different modules is minimized. Second, the re-use of modules in different ship applications reduces the developmental cost of each new ship to use IPS. Once identified, the members of the Family of Modules would be developed to a degree which would comprise a complete characterization of each module and submodule [15-17]. In other words, they would already be designed and, to some degree, qualified for shipboard use.

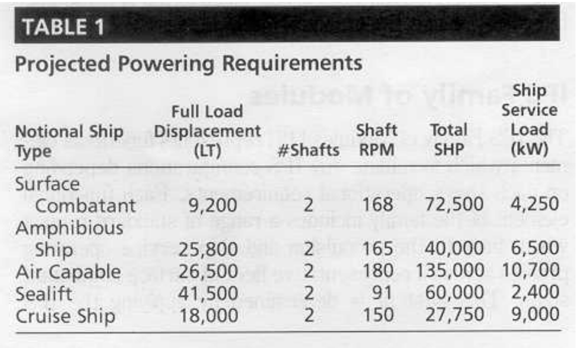
TABLE 1

Projected Powering Requirements

Notional Ship Type	Full Load Displacement (LT)	#Shafts	Shaft RPM	Total SHP	Ship Service Load (kW)
Surface Combatant	9,200	2	168	72,500	4,250
Amphibious Ship	25,800	2	165	40,000	6,500
Air Capable	26,500	2	180	135,000	10,700
Sealift	41,500	2	91	60,000	2,400
Cruise Ship	18,000	2	150	27,750	9,000

The problem confronting a ship designer of a new ship is then to discern the optimal set of modules to be included in the design. This problem is usually presented to the ship designer early in the ship design process when little specific information about the ship design is typically available. Complete information about the IPS modules will be available; although, for feasibility studies and trade-off studies only basic information contained in the characterization sheets is required. Having this information reduces risk. How to choose the optimal set of modules for a design, given a set of ship requirements, is the IPS Design Process.

The IPS Design Process is described using a Design Data Sheet (DDS) [18]. This process has seven basic steps. The entering argument is a set of ship requirements, which can include life cycle cost goals and acquisition cost goals. Input data includes the Module and Submodule Characterization Sheets. The output is an optimized IPS configuration. The seven steps of the IPS Design Process are described in Figure 3.

The first step in the IPS DDS is to articulate the ship requirements. These requirements usually include speed, payload, displacement, etc. These requirements can include cost goals. As with ship design in general, it is not always obvious what the impact of any given requirement will be on the ship. Once a design has been developed, how well it meets its requirements needs evaluation before the next design iteration.

The second step in the IPS DDS is to develop an initial power requirement. Given the ship requirements, how much propulsion power and ship service power must be provided through IPS must be estimated. At least initially, this can be done parametrically. As a ship design becomes more detailed, though, this needs to be done for specific hull forms, equipment lists, et cetera.

The third step in the IPS DDS is to select an initial IPS Configuration. This initial configuration must provide the required propulsion and ship service power and focus on the IPS Modules which will have a first order impact on

TABLE 2

IPS Family of Modules

Module Type	Module Designation	Description
Power Generation	PGM-1	21MW, 4160Vac, 3phase, 60Hz ICR gas turbine driven generator
	PGM-2	3.75MW, 4160Vac, 3phase, 60Hz diesel driven generator
	PGM-3	3MW, 4160Vac, 3phase, 60Hz 501-K34 gas turbine driven generator
	PGM-4	8MW, 4160Vac, 3phase, 60Hz diesel driven generator
	PGM-5	12MW, 4160Vac, 3phase, 60Hz diesel driven generator
Propulsion Motor	PMM-1	19MW, 150rpm, cage induction motor with power converter
	PMM-2	38MW, 150rpm, cage induction motor with power converter
	PMM-3	38MW, +/-150rpm, tandem cage induction motors with power converters
	PMM-4	800kW, 360rpm, auxiliary propulsion , retractable and azimuthing
	PMM-5	52MW, 150rpm, cage induction motor with power converter
	PMM-6	12MW, 150rpm, cage induction motor with power converter
	PMM-7	28MW, 150rpm, cage induction motor with power converter
	PMM-8	1400kW, 360rpm, auxiliary propulsion , retractable and azimuthing
Power Distribution	PDM-1	4160Vac, 3phase, 60Hz switchgear & cable
	PDM-2	1000 Vdc ship service cable
Power Conversion	PCM-1	Multi-Ship Service Converter Modules, 1000Vdc to 775Vdc
	PCM-2	Multi-Ship Service Inverter Modules 775Vdc to 450Vac, 3phase, 60 or 400 Hz
	PCM-3	Multi-Ship Service Converter Modules 775Vdc to 155Vdc or 270Vdc
	PCM-4	Ship Service Converter Module 4160Vac, 3phase, 60Hz to 1000Vdc
Power Control	PCON-1	IPS system level supervisory control software
	PCON-2	Zonal level supervisory control software
Energy Storage	ESM-1	Ship Service, 1000Vdc
	ESM-2	Ship Service, 775Vdc
Platform Load	PLM-1	Uncontrolled 450Vac ship service loads
	PLM-2	Controlled 450Vac ship service loads
	PLM-3	Uncontrolled 155Vdc or 270Vdc ship service loads
	PLM-4	Controlled 155Vdc or 270Vdc ship service loads

TABLE 3

IPS Modules Allocated by Ship Type

Notional Ship Type	Power Generation	Propulsion Motor	Power Distribution	Power Conversion
Surface Combatant	(3)PGM-1 (1)PGM-3	(2)PMM-7 (2)PMM-4	(4)PDM-1 (3)PDM-2	(TBD) PCM-1 (TBD) PCM-2 (3) PCM-4
Amphibious Ship	(1)PGM-2 (5)PGM-4	(2)PMM-1 (2)PMM-8	(6)PDM-1 (4)PDM-2	(TBD) PCM-1 (TBD) PCM-2 (4) PCM-4
Air Capable	(6)PGM-1 (2)PGM-3	(2)PMM-5 (2)PMM-8	(8)PDM-1 (5)PDM-2	(TBD) PCM-1 (TBD) PCM-2 (5) PCM-4
Sealift	(1)PGM-2 (4)PGM-5	(2)PMM-1	(2)PDM-1 (1)PDM-2	(TBD) PCM-1 (TBD) PCM-2 (1) PCM-4
Cruise Ship	(4)PGM-4	(2)PMM-6	(2)PDM-1 (2)PDM-2	(TBD) PCM-1 (TBD) PCM-2 (2) PCM-4

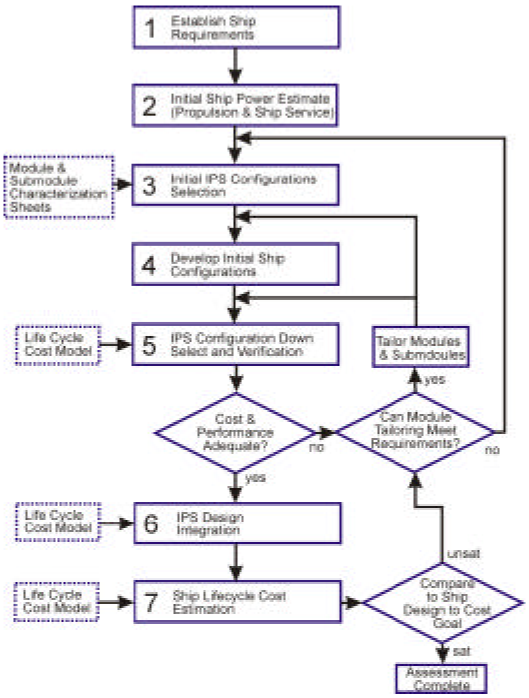

FIGURE 3. IPS Conceptual Design Proces

the ship design, such as PGMs, PMMs and the ship-level PDMs. The description of the selected modules must include size, weight, CG, cost and other top level information. This information is contained in the Module and Submodule Characterization Sheets.

The fourth step in the IPS DDS is to develop an initial ship configuration from the initial IPS Configuration. The modules selected in the preceding step must be placed within a ship hull design. The effect of these modules on machinery box size and, consequently, hull form, displacement and CG, among other characteristics, must be assessed.

The fifth step of the IPS DDS is to take the results of the fourth step and ensure that the initial IPS Configuration fulfills the ship requirements. Once the hull form is described in the fourth step, the power estimate developed in the second step of the IPS DDS can be refined. If the hull form requires more power than the selected IPS Configuration can provide, then either modules must be tailored or different modules must be selected. It is in this step that the first cost estimates are developed.

The sixth step is to develop a detailed IPS Configuration from the IPS Configuration which successfully emerges from the fifth step. Whereas higher-level trade-offs would be accomplished in the fifth step, lower-level trade offs are performed in the sixth step. These would include zonal configurations for SSDS and the like.

The seventh and final step is to develop a life cycle cost estimate for the ship. A discussion of the major elements of the life cycle cost calculation follows. An acceptable cost estimate signals completion of the design, whereas an excessive cost estimate indicates a need for design iteration.

It is important to realize the relationship of the IPS DDS to the greater ship design effort. IPS will not be the sole driver in the selection of a hull form, for example. The IPS DDS is meant to be used in addition to and complementary to all of the other design steps presently used for U.S. Naval ships. It provides good information about the propulsion and electric distribution systems early in the ship design process. The IPS DDS is compatible with the ship design process now practiced by the U.S. Navy and represents an improvement in the characterization of propulsion and electric distribution plants.

Life Cycle Cost Analysis

The motivation behind IPS is to reduce the fleet's life cycle cost. No design pursuit is more fraught with controversy than an attempt at a detailed cost estimate or cost comparison. Nonetheless, IPS is developing a life cycle cost analysis which will provide the principal yardstick for the selection of the IPS Family of Modules and the tool by which a specific IPS configuration can be optimized for a given ship application. While the preeminent concern of IPS is *life cycle* cost, of which acquisition cost is an important element, it is recognized that budget realities sometimes place a value on acquisition cost over and above its numerical effect in a calculation of life cycle cost. IPS will attempt to address this dilemma by providing a means to quantify any life cycle cost penalty which occurs by making decisions based on minimum acquisition cost.

There are many attributes of life cycle cost. Figure 4 shows how the components of life cycle cost have been organized for use in analysis.

Synthesizing an analysis which contains a complete characterization of all of these cost components is a daunting task. Not all of the cost components need be available, though, for conducting trade-offs of portions of a ship design. A brief discussion of the life cycle cost components of immediate interest is warranted.

The major non-recurring cost elements are ship acquisition and fleet introduction. These are the up-front costs that are of particular concern to the ship program manager. In addition to the delivered cost of the components, information generally held by the equipment manufacturers, their installation cost must be included, which is the shipbuilder's input. It is here that any ship producibility benefits due to modularity will accrue. Since much of the advantage of electric drive lies in its operational and arrangement flexibility, the ship impact cost of these features

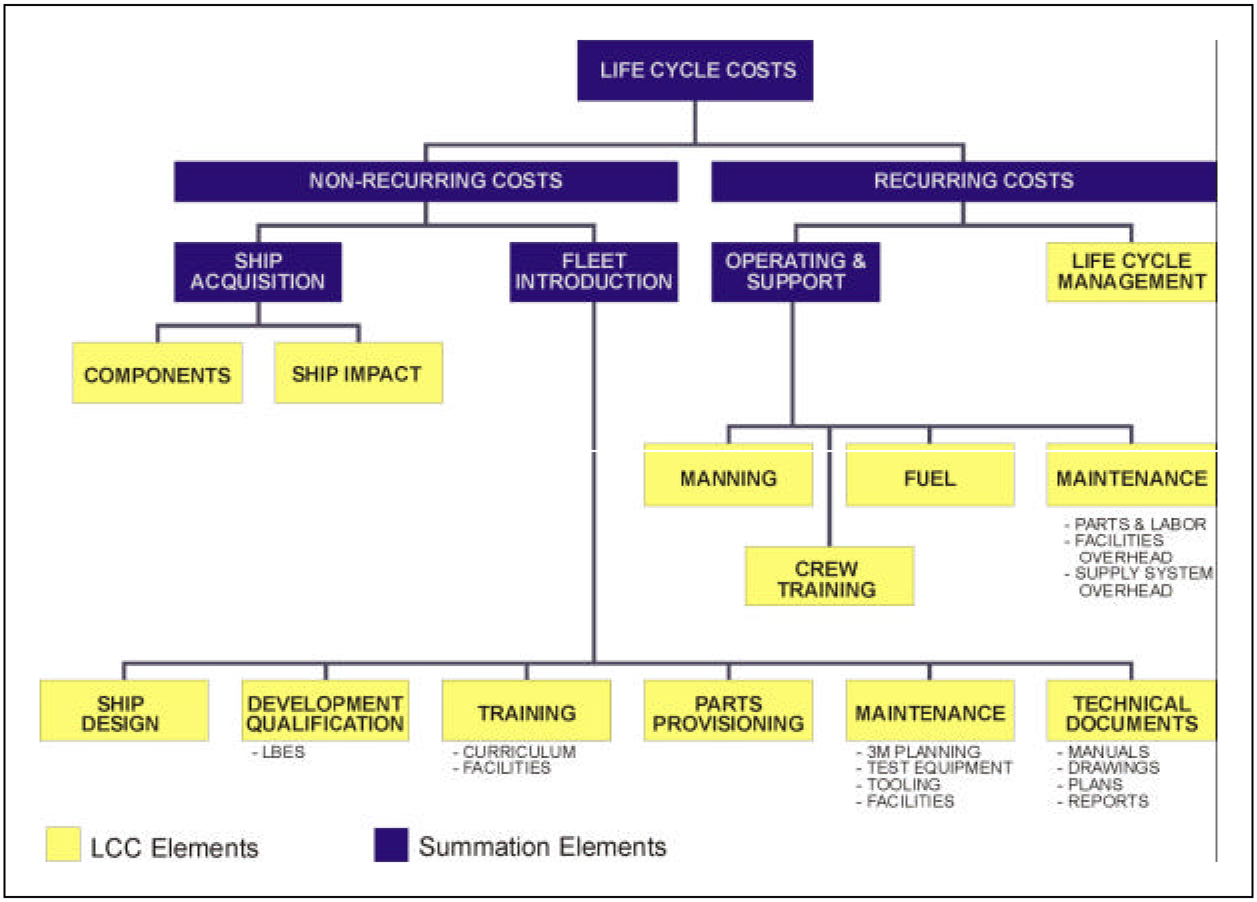

FIGURE 4. Life Cycle Cost Model

is included. This also allows tradeoffs of machinery size and weight against delivered cost. The Fleet Introduction element is a catchall for those items associated with getting the equipment ready and preparing the Navy's support infrastructure for introduction of new machinery. At present, much of this cost is captured in the lead ship of each class since each machinery plant is largely a custom design. For purposes of IPS costing, it is assumed that IPS will be the machinery system for all of the ship variants incorporated in the notional fleet, and therefore these introduction costs will be captured at the fleet level and not assigned to any one ship class. Impacts of commonality and interface standardization will likely be felt in these areas.

At the Fleet level, recurring costs will be of significance with operating and support as the primary element. Perhaps the three most salient components of this cost are fuel, manning and maintenance. Enough has been said about how IPS seeks to improve fuel consumption by operating prime movers at more efficient loadings. Computing fuel consumption and applying projected fuel costs is well understood. Performing a definitive analysis for manning costs requires knowing the number of personnel required and the cost per person which is related to their ratings and skills. Maintenance costs are complex to assess since they are affected by manning, component design characteristics and class maintenance philosophy.

At the outset of the IPS effort of analyzing life cycle cost, component cost, ship impact cost, producibility cost, and fuel costs are being addressed first. They are first order cost drivers. The second set of cost components to be characterized are ship design cost, development and qualification cost, manning cost and technical documentation cost. These components are associated with getting IPS into the fleet. The other cost components are being treated subsequently.

IPS Development Process

In developing IPS, ASMP has pursued a strategy of using three overlapping development phases: Reduced Scale Advanced Development (RSAD), Full Scale Advanced Development (FSAD), and Full Scale Engineered Development (FSED). Currently, RSAD is in its last year, FSAD has completed the first year of a three year program, and advanced work has started on FSED.

The purpose of RSAD is the development of test hardware, systems and component technologies at or less than full scale in conjunction with computer simulation and physical modeling. After extensive technology surveys, consideration of different systems architectures and cost/benefit systems analysis, the following concepts were selected for development as part of RSAD:

- **Permanent Magnet Motors and Generators.** The Navy tested a 2 MW scaled propulsion motor built by Kaman Electromagnetics Corporation (KEC) and Newport News Shipbuilding (NNS). As discussed in the following section, permanent magnet technology offers considerable promise in reducing the size and cost of propulsion motors.
- **Permanent magnet motor and generator drive system.** The Navy is currently outfitting a patrol boat with a gas turbine driven permanent magnet generator and permanent magnet motors to study the system issues associated with PM drive technology. The testing of this system should be completed in FY96.
- **Electrical Bus Duct.** The Navy funded producibility studies and conceptual designs of electrical bus duct for shipboard applications. The studies showed that although the bus duct potentially had life cycle cost savings over cable, the savings were not large enough to warrant diverting precious R&D dollars to develop the concept further. The Navy intends to use cable in IPS for the foreseeable future. The key technical risk area continues to be the performance of the bus duct under shock.
- **Ship Service Inverter Modules (SSIM).** The Navy contracted for the construction of two types of 750 VDC to 450 Vac inverters to test the concepts of DC zonal electrical distribution. One inverter type is water cooled while the other is air cooled. The test results associated with these inverters are playing an important role in determining the characteristics of PCM-2.
- **Zonal Electrical Distribution System test facility**. The Navy constructed a three electrical zone facility at the Annapolis Detachment of the Naval Surface Warfare Center (NSWC) for testing the characteristics of the ZEDS equipment and to develop control algorithms. This facility is also being used to test FSAD components and control strategies.

The Navy began Full Scale Advanced Development (FSAD) with the award of a contract to Lockheed Martin in February 1995. FSAD consists of two parallel efforts: A systems engineering effort to define the IPS family of modules, design process, and module interface standards, and a machinery development effort leading to the manufacture and test of full scale prototype components and systems at a land based engineering site (LBES) at the Philadelphia Detachment of NSWC. Much of the content of this paper is a result of the system engineering efforts. The principle components being developed by Lockheed Martin for the LBES site include:

- A 25, 000 SHP 150 RPM, 15 phase squirrel cage induction propulsion motor
- A series Insulated Gate Bipolar Transistor (IGBT) converter for the propulsion motor
- A 21 MW 4160 Vac generator for use with an ICR gas turbine
- A 200 kW Ship Service Inverter Module
- A 100 kW Ship Service Converter Module
- Supervisory and Zonal control software

Full Scale Engineered Development (FSED) will complete the engineering of a ship ready system consisting of machinery modules for fleet introduction with all required support in place. The modules chosen for FSED will most likely be those of the first application of IPS to a naval platform. FSED is currently scheduled to start with the award of module development contracts in FY98 and the completion of testing in FY01. The current FSAD contract with Lockheed Martin will directly support FSED with preliminary module designs and with the development of Supervisory and Zonal control software (PCON-1 and PCON-2).

Technology Insertion

One advantage of IPS is the potential to affordably introduce new technologies. By establishing interface standards between modules that are technology independent to the greatest extent possible, improvements to modules can be implemented with a minimum of impact to other modules. Currently, IPS is designed using proven technologies. However, a number of new technologies offer the potential to significantly improve the performance and affordability of IPS. The flexible and scalable IPS architecture should minimize the cost of inserting these technologies into existing and new IPS modules. Recognizing that the insertion of new components into the IPS family of modules will increase certain elements of life cycle cost while decreasing others, the decision to use a new technology should be based on a complete life cycle cost analysis. Of particular interest to ASMP are Permanent Magnet Machines and Power Electronic Building Blocks which were the cornerstones of the original IPS concept presented two years ago.

Permanent magnet (PM) motor technology is presently competing with the commercial induction motor for lower power level adjustable speed drive applications based on higher efficiency or greater power density depending on the needs of the application. The potential for increased power without significant increase in cost makes PM motors attractive for Navy ship applications where there may be some size constraints such as SWATH or Trimaran hullforms or podded propulsors. Even in-hull arrangements can benefit from reduced size for smaller displacement ships as indicated by the projected acquisition cost savings for substituting the PM motor for the induction motor in the ASMP surface combatant studies. The Navy anticipates a growing infrastructure of commercial PM motor manufactures that can support both commercial and military needs. To accelerate the development of this infrastructure, the Navy is continuing development of a PM motor module in the power range suitable for ship propulsion and conforming to the IPS PMM interface specifications.

The Power Electronic Building Block (PEBB) is a new device that integrates within a single unit, all the elements required for generalized power processing. It will replace many single application multi-component power control circuits with a single device that delivers digitally synthesized power under device level control as well as system level control. PEBBs are a standard set of snap together parts that start at the semiconductor chip level and build up to the system level while integrating intelligence at various levels for custom performance — a power electronic analogy of a microprocessor. The Office of Naval Research (ONR) in cooperation with the Department of Energy (DOE), Advanced Research Projects Agency (ARPA), United States Air Force, and the Electric Power Research Institute (EPRI) is developing the PEBB and its supporting technologies. ASMP is contributing to the effort by participating in the concurrent engineering of applications using PEBBs. When available, PEBBs offer the potential to significantly reduce the cost, size, and weight of most of the power conversion components in IPS.

Other technologies with potential for enhancing IPS are summarized in Table 4.

Conclusion

When fully developed the Integrated Power System will provide ship designers with an architecture and family of modules from which affordable shipboard electric power

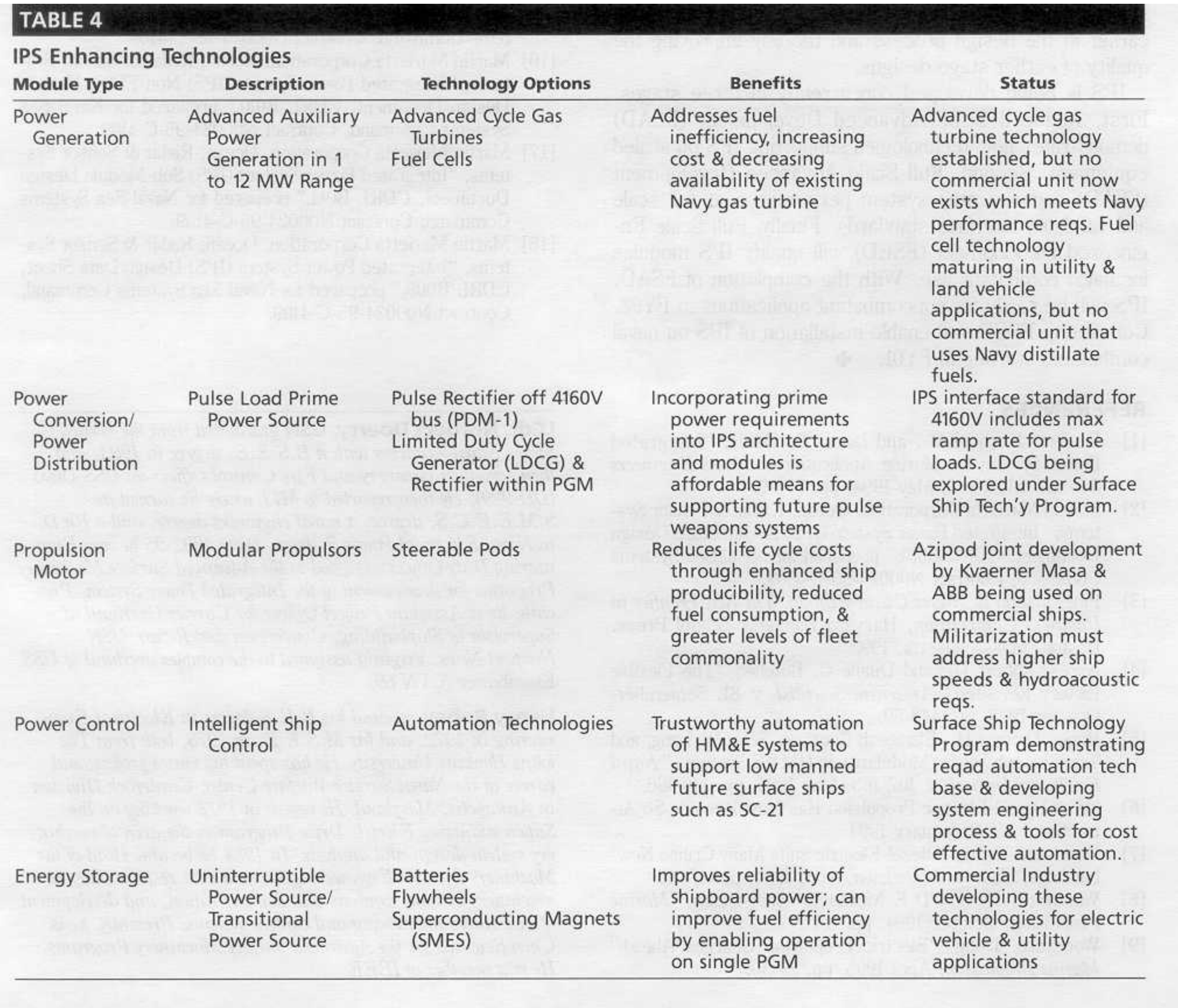

TABLE 4

IPS Enhancing Technologies

Module Type	Description	Technology Options	Benefits	Status
Power Generation	Advanced Auxiliary Power Generation in 1 to 12 MW Range	Advanced Cycle Gas Turbines Fuel Cells	Addresses fuel inefficiency, increasing cost & decreasing availability of existing Navy gas turbine	Advanced cycle gas turbine technology established, but no commercial unit now exists which meets Navy performance reqs. Fuel cell technology maturing in utility & land vehicle applications, but no commercial unit that uses Navy distillate fuels.
Power Conversion/ Power Distribution	Pulse Load Prime Power Source	Pulse Rectifier off 4160V bus (PDM-1) Limited Duty Cycle Generator (LDCG) & Rectifier within PGM	Incorporating prime power requirements into IPS architecture and modules is affordable means for supporting future pulse weapons systems	IPS interface standard for 4160V includes max ramp rate for pulse loads. LDCG being explored under Surface Ship Tech'y Program.
Propulsion Motor	Modular Propulsors	Steerable Pods	Reduces life cycle costs through enhanced ship producibility, reduced fuel consumption, & greater levels of fleet commonality	Azipod joint development by Kvaerner Masa & ABB being used on commercial ships. Militarization must address higher ship speeds & hydroacoustic reqs.
Power Control	Intelligent Ship Control	Automation Technologies	Trustworthy automation of HM&E systems to support low manned future surface ships such as SC-21	Surface Ship Technology Program demonstrating reqad automation tech base & developing system engineering process & tools for cost effective automation.
Energy Storage	Uninterruptible Power Source/ Transitional Power Source	Batteries Flywheels Superconducting Magnets (SMES)	Improves reliability of shipboard power; can improve fuel efficiency by enabling operation on single PGM	Commercial Industry developing these technologies for electric vehicle & utility applications

systems for both ship service and propulsion loads can be developed for a broad range of ship requirements. Additionally, IPS provides a ready mechanism, through its use of modules and standard interfaces, to insert advanced technologies when they mature. Furthermore, the Life Cycle Cost model developed to determine the initial IPS family of modules also can serve as a tool for determining when the insertion of new technologies is affordable.

The IPS family of modules are organized into six categories: Power Generation Modules (PGM), Power Distribution Modules (PDM), Energy Storage Modules (ESM), Power Conversion Module (PCM), Power Load Modules (PLM and PMM), and Power Control Modules (PCON). For the ship designer, modules are described with Module Characterization Sheets that include 2-D and 3-D electronic drawings and a CAD product model description. The process for integrating modules into an IPS configuration for concept and preliminary design is detailed in the IPS Design Data Sheet. This process aids the ship designer by providing considerable detail of equipment much earlier in the design process and thereby improving the quality of earlier stage designs.

IPS is being developed concurrently in three stages. First, Reduced Scale Advanced Development (RSAD) demonstrates new technologies supporting IPS on scaled equipment. Second, Full Scale Advanced Development (FSAD) demonstrates system performance at full scale and validates interface standards. Finally, Full Scale Engineered Development (FSED) will qualify IPS modules for naval combatant use. With the completion of FSAD, IPS will be ready for noncombatant applications in FY98. Completing FSED will enable installation of IPS on naval combatants starting in FY01.

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