AN HISTORICAL OVERVIEW OF NAVY ELECTRIC DRIVE

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Abstract - Electric drives have been applied in USN applications since the early part of this century. The first installations in capital ships, however, resulted less from operational and arrangement advantages than the non-availability of high power gearing, a shortfall that was corrected between the World Wars. In conventional submarines the natural marriage of electric propulsion motors to battery energy storage more than offset the high specific weights and sizes. Mechanical drives, however, were preferred in nuclear boats with much higher submerged power requirements. In the 60's and 70's R&D programs for the first time targeted electric machinery which could provide performance and arrangement advantages without size penalties. The early successes applying superconductive technologies showed that future gas turbine DD's and nuclear submarines, in addition to being substantially smaller with equivalent payloads, would have decidedly superior maneuverability and acoustics. Commercial applications making such high technology systems affordable, however, were lacking. Considerable effort has been devoted to examining the feasibility of adapting commercially available electric drive technology to navy applications. More recent developments are focusing on advances in liquid cooling, high capacity current collectors, permanent magnet excitation and power electronics. These technologies, which may have considerable industrial and commercial marine application, promise ship drives which could simultaneously be both capable and cost effective.

Introduction

The history of electric drive in the US Navy spans nearly the entire twentieth century. The original advantages perceived for electric drive for surface ships were much as they are today - performance, reduced manning, arrangement flexibility and fuel efficiency. [1] Navy imperatives, wars, technology, and mission requirements have driven electric drive through cycles of acceptance and rejection as compared to mechanical gear reduction. Submarines, until the advent of nuclear propulsion, were entirely reliant on electric drive, and still are for emergency propulsion capability.For the period prior to 1965, this paper provides a bit of history which can be found in detail in several references.

Since 1965, a series of concerted efforts to identify and develop an electric drive system to meet the perceived Navy needs have occurred. While none of these efforts has produced an operational fleet system, a large body of knowledge has been accumulated applicable to the present interest in electric drive.

This paper provides an overview of these efforts and the rationale behind them. The emphasis is on electric propulsion for warships, rather than auxiliary and commercial ships where electric drive has enjoyed a resurgence in the last decade.

Early Applications of Electric Ship Drives

Application of electric drives for large ship propulsion in the US Navy originated with an experimental installation on the 4.1 MW per shaft

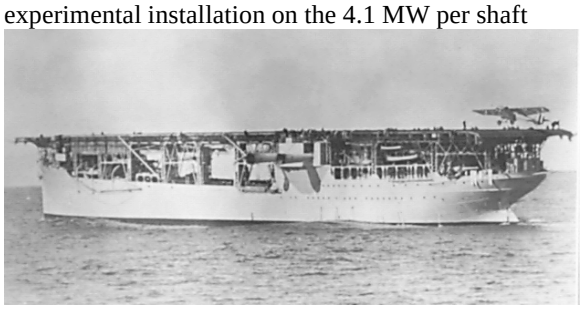

Figure 1. USS Langley

collier JUPITER (AC-3) in 1913. This steam turbo-electric ac drive employed wound rotor induction motors. The experiment was successful and the collier JUPITER was converted to the Navy's first aircraft carrier, LANGLEY (CV-1) in 1922. (Figure 1) This electric propulsion machinery remained in operation until the LANGLEY was sunk by enemy action in 1942, a testament to its durability. [2]

The early success with turbo-electric ac drives and a realization of the inherent benefits of electric drive led to major shipbuilding efforts in electric propulsion. 50 vessels were constructed with these drive systems during the interim between World Wars I and II. These included five battleships (BB-43, 44, 45, 46 and 48) with 21 MW shaft output, and two aircraft carriers (CV 2 and 3) with 135 MW output. [3] The impetus for use of electric drive in lieu of gear reduction were: the comparatively high reduction ratio achievable, elimination of reversing turbines, reduction in the number of turbines necessary, a consequent better fuel efficiency, and higher reliability. The USS New Mexico BB-40 is shown in Figure 2. It had 30 MW installed.

Figure 2. USS Mexico BB-40

Application of dc electric drives in the Navy includes its use in many diesel electric submarines. Over 160 escort vessels were built during World War II with turbo-electric or diesel electric drives ranging from about 4.5 to 9 MW. Approximately 500 small surface ships have been equipped with dc electric propulsion systems in the 225 kW to 15 MW range.

The early Navy experience with ac and dc electric drives clearly showed their advantages as compared to contemporary turbine gear drives. The number of turbo-electric propelled ships was increased by the lack of gear cutting capacity during the ship building frenzy of the World War II era. However, by the 1940's, double-reduction-gear ship drive systems had become competitive in the United States and any further large scale surface ship application of electric drives in the navy was inhibited by the higher weight, increased space requirements and comparatively lower overall transmission efficiency associated with conventional electric machinery. This reversal of choice of speed reduction and transmission was due to improvements in the metallurgy and manufacture of gears, allowing satisfactory weight, size and acoustic performance to be achieved. This situation persists to the present. However, the capability of mechanical transmission is near the limits of technology and affordability, and further improvements are more likely to be realized from investment in electric drive.

Superconductors and Related Technologies

In the late 1960's the Navy began investing in technologies designed to improve the power density and performance of electric machinery at ship propulsion power levels. Among these were stabilized superconductors. Certain materials, for example, niobium-titanium, were known to support very high electric currents (over 60,000 a/cm^2) without resistance losses when their temperature is reduced below a critical level, typically in the liquid helium range (4.2 K). Using these superconductors in field windings of electric motors and generators, it was possible to produce very intense magnetic fields with relatively small quantities of materials and very low power requirements to maintain the superconductive state. Application of superconductive field windings, along with direct water or oil cooled armature conductors and high current density brush systems, provided very compact, lightweight electric drive machinery. The reduced weight and volume of advanced motors and generators so equipped could realize the ship design and operational flexibility advantages which are inherent to electric drive systems without the penalties of conventional electric machinery. NAVSEA began to invest in such

technology in the mid-1960s, in anticipation of such advantages, and highly experimental laboratory machines were demonstrated by 1972.

Projected Benefits of Superconductive Drives

One of the more important ship design flexibility advantages of an electric drive system results from the alignment-free machinery arrangement. Prime movers can be located remotely from the motor/propeller drive to occupy less critical spaces and to minimize ducting in the case of gas-turbine-powered ships. Smaller diameter superconductive motors would permit reductions in propeller shaft rake angle and location further astern in restricted hull spaces with consequent reductions in shafting runs.

The cross-connectability of electric drives permits individual selection of turbines on a multi-turbine ship during reduced ship speed operation. This increases turbine availability by reducing the total operating time for each turbine during a ship mission.

Electric reversal capabilities eliminate the need for reversing turbines, reversing gears, or controllable reversible pitch propellers (CRP's). Dynamic braking from high speeds is achievable with energy dissipation in electric resistors and without concern for turbine overspeed.

By cross-connecting turbine-generators and propulsion motors in multi-shaft installations, simple cycle gas turbines can be operated at more favorable fuel conditions. Infinitely variable speed reduction ratio electric drives permit optimization of turbine fuel efficiency at various ship speeds. Through optimized turbine operation with a dc electric drive system, decreases in fuel consumption up to 25% may be achieved as compared to a non-cross-connected, twin-shaft turbine-gear propulsion system. (This fuel economy advantage would be reduced if advanced fuel efficient turbines, with exhaust energy recovery systems, such as recuperated units, were introduced. The significant arrangement and maneuverability benefits, however, are retained.)

Studies conducted to quantify the benefits of superconductive dc drives in destroyer type hulls projected significant size and cost savings compared to a conventional geared CRP driven ship of equivalent mission capability. [4,5] The machinery arrangement of the baseline mechanically driven DD is illustrated in (Figure 3),

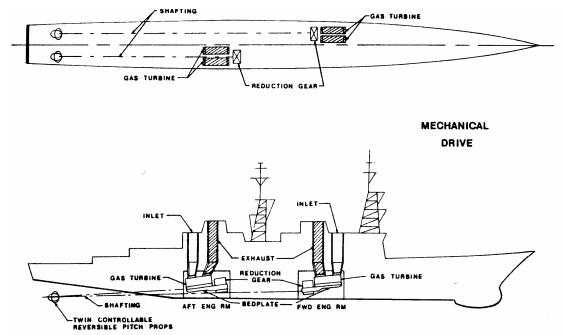

Figure 3. Mechanical Baseline DD Machinery

and one conventionally arranged electric drive machinery option is shown in (Figure 4). Results showed that reduction in required machinery weight, space and fuel tankage produced a 9% reduction in ship volume and a 25% reduction in a installed power; with no reduction in payload, speed, and range. Significant ship building and operating costs were also projected.

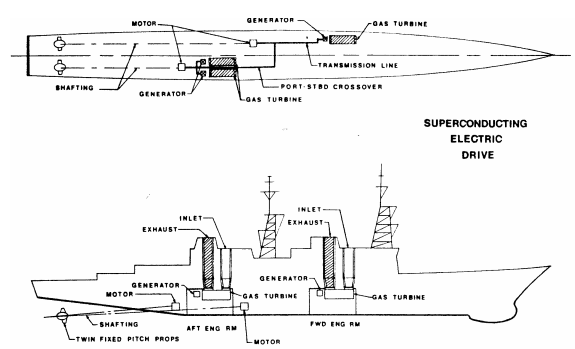

Figure 4. Electric Drive DD Machinery Arrangemnt

The availability of small diameter, high torque propulsion motors could make propulsion pods a feasible alternative to open shaft propeller arrangements for high speed combatants. Such an arrangement in a DD hull, illustrated in Figure 5, reduces machinery volume by virtually eliminating the shaftline allocation and minimize turbine ducting with aft engine location.

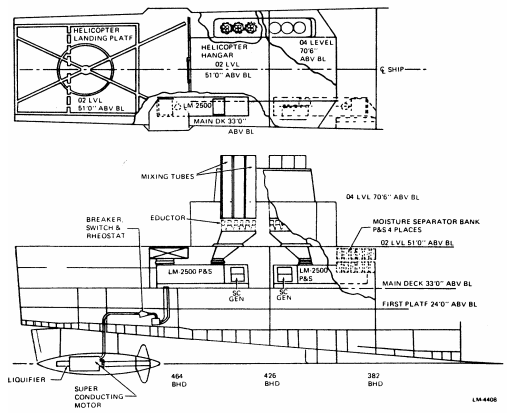

Figure 5. Pod Drive DD Arrangement

Reductions of 17% in ship displacement and 25% in fuel load were projected to compare to a mechanical baseline of equivalent payload, speed and range. A major additional benefit of the tractor pod of a system would be reduced propeller noise resulting from "clean" inflow conditions.

Superconducting Machinery Advanced Development

Advanced development of superconductive machinery was initiated in fiscal year 1973 under the program management of the NAVSEA Research and Technology Directorate and technical direction by DTNSRDC. The program objectives were to (a) develop the hardware engineering capability for superconductive electrical propulsion systems up to 60 MW per shaft and, (b) demonstrate capability to initiate construction of a 30 MW operational evaluation system.

At the inception of the program various machine types, design approaches, and system concepts were examined to assess their potential for a wide variety of future Navy ship propulsion applications. Superconductive dc homopolar machines were determined to best satisfy the broadest range of ship propulsion requirements. Such machines would have attractive performance and dimensional characteristics, have relatively low cryogenic requirements for the stationary non-torque superconductive magnets, be capable of delivering full torque at all speeds, and of directly varying the speed ratio between the motors and generators. The overall approach to demonstrating feasibility of building 30 MW systems with superconductive homopolar machines included the development of laboratory (proof-of-principle) systems to demonstrate technical feasibility of machine design concepts, establishing preliminary designs of full scale 30 MW systems based on validated machinery design concepts, and finally develop 2.2 MW scale models representative of the full scale system designs. Navy evaluation of these feasibility model systems in laboratory dynamometer tests and onboard a specially-constructed test craft were completed in the early 80's

<u>300 kW Superconducting Machinery:</u> One of the earliest defined tasks of the program was the design, construction and operational test of an experimental 300 kW superconductive dc system at NSWC, Annapolis. A superconductive homopolar motor began in developmental tests. [6] A superconductive dc generator, with output characteristics compatible with the laboratory motor, became operational in 1976. [7] System ancillaries controls, transmission lines and experimental lightweight switchgear for a 300 kW propulsion system were constructed and the generator matched to an LM-100 gas turbine. The completed 300 kW drive was successfully demonstrated aboard the 65 foot test craft JUPITER II in 1979, after successful laboratory testing shown in Figure 6.

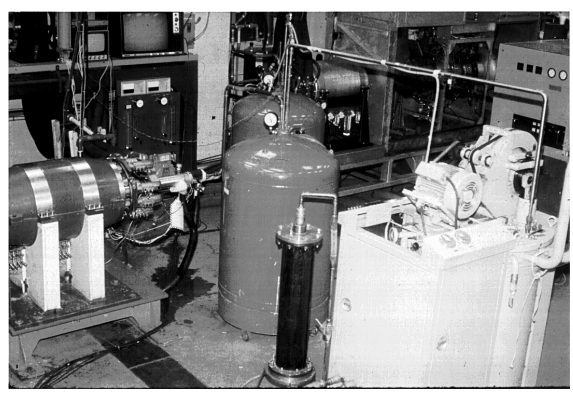

Figure 6. 300 kW Superconducting Propulsion System Laboratory Testing

<u>3000 hp Scale Model Systems</u>: Contracts were awarded in 1973 for the development of feasibility-model propulsion systems to Garret-AiResearch Manufacturing Company of California and General Electric Company, Schenectady, NY. Two system concepts were pursued through construction. One consisted of an advanced design, oil cooled, high speed alternator/ rectifier and a superconductive dc homopolar motor. A second system intended to use a superconductive dc homopolar generator with an alternate superconductive dc homopolar motor

design. A basic program requirement for these feasibility-model machinery developments that the machinery designs were not specifically optimized for 2.2 MW performance. Rather, these machines were required to be scale models which demonstrated, to the maximum extent practical, the materials, design parameters, fabrication and assembly approaches required for full size 30 MW propulsion systems.
Laboratory tests of 2.25 MW hardware were conducted over the 1980-82 period as shown in Figure 7. The successful GE motor and the rectified alternator were installed and demonstrated in JUPITER II test craft.

Figure 7. 3000 hp Superconducting Propulsion System Laboratory Tests at NSWC

Key Supporting Technology Developments

At the initiation of the advanced development program in 1973, it was recognized that there were certain component technologies critical to the development of lightweight, efficient and reliable superconductive homopolar machinery systems. The most important of these were (a) high-performance, long-life, current collectors for low speed homopolar motors and high speed generator, (b) lightweight, superconductive magnet-dewar system with low cryogenic helium refrigeration requirements and suitable for shipboard environments, (c) lightweight, high performance switchgear, and (d) reliable cryogenic refrigeration systems. Accordingly, major support technology development was undertaken at both contractor and navy laboratory sites, which successful demonstrated the feasibility of all of these key technologies.

What Happened?

The operation of 300 kW and 2.25 MW systems, taken together with results of the supporting technology work, showed conclusively that superconductive drives of the size and performance included in the cited DD studies were both feasible and buildable. Power densities, efficiencies, current densities, control characteristics, liquification rates, and magnetic field intensities appropriate to full scale equipment were demonstrated, along with very low noise levels and near field magnetic signatures. The relevant equipment, however, was clearly high tech in character and its ability to operated reliably for long periods in an difficult shipboard environment would require further confirmation. A second significant concern was the lack of a commercial market for some of the technologies ultimately included in the development hardware. Advanced liquid cooling techniques, and high current density superconducting magnet systems had application outside DOD, but liquid metal collectors, shock capable helium liquefiers, and the large high powered homopolar motors, would likely be Navy only requirements. Without a broader market, the cost to develop, buy, and support Navy unique systems might be high. There was nothing that was better in performance than the superconducting homopolars, but there was no urgency to field a full-scale system, and time was available to evaluate other alternatives.

Development of AC Electric Drive Concepts

As the superconducting electric drive effort transitioned from the proof-of-principle 400 hp system to the 3000 hp scale system development, the Navy began to look at the possibility of realizing some of the benefits of electric drive with the use of more conventional electric machinery. The Airesearch rectified alternator established liquid cooled, conventionally excited ac machines as viable generator technology. The emergence of high power solid state variable speed drives based on SCR technology for commercial industrial applications, enabled consideration of ac motors as an alternative for ship propulsion. In-house Navy assessments also included a quick look at first generation permanent magnet machines and GTO based drives, however it was determined that neither of these technologies were mature enough for serious consideration at that time.

In late 1979, NAVSEA conducted an assessment of the state-of-the-art of electric propulsion for use in Navy surface combatants. As a result, a conceptual design of an Advanced Integrated Electric Propulsion Plant (AIEPP)[8] was developed by Westinghouse Electric Corp which employed commercial derivative

generators and motors, and state-of-the-art SCR drives (Figure 8).

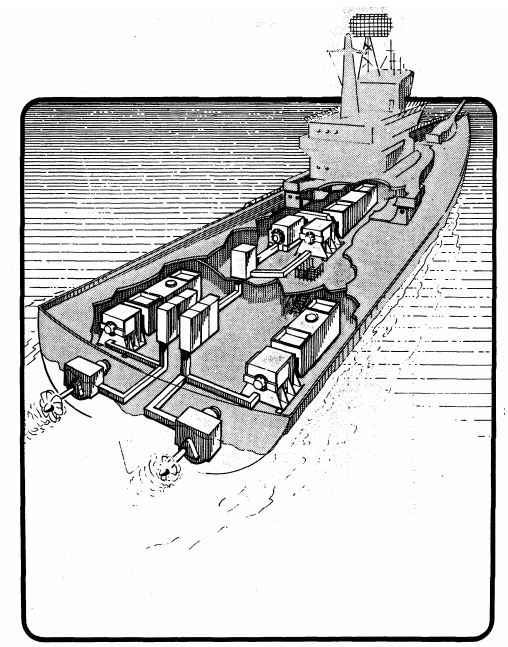

Figure 8. Advanced Integrated Electric Propulsion Plant for DDGX

This system employed 60 Hz, 3-phase synchronous generators rated at 18MW at 6300 V and 3600 rpm, with water cooled stators and air cooled rotors. Liquid cooling of the high speed rotor was found to provide marginal improvement in power density. However, the 34,500 hp, 164 rpm direct drive synchronous motor did benefit from liquid cooling of its large low speed rotor, so an all-liquid cooled design was selected. The dc-link inverters were rated at 15 MW to handle half the generator output in a single generator, two motor alignment. The synchronous link between generators and motors required a large pole number on the motor to accommodate the speed reduction between engine and propellor. The inverter also employed liquid cooling to reduce size.

The AIEPP was ultimately selected by the NAVSEA design office as the propulsion system for the DDGX (i.e. DDG 51). However, this decision was overturned by a Navy Brown Ribbon panel based on perceived risk in developing and demonstrating such a system in time to meet the ship construction schedule. As a consequence of this “near miss”, the Navy’s electric drive program was reformulated to incorporate a near term effort based on the ac machine and solid state drive system technology, in addition to the superconducting electric drive which now constituted the far term effort.

The first step in the new program was a conceptual design study in which each of the 3000 hp scale system participants were asked to provide near and far term systems for a 50 khp/shaft monohull and a 30 khp/shaft SWATH. In each case the contractors were to address potential for commonality between platforms. The near term concept for each of the notional platforms is depicted in figure 9 for one of the participants.

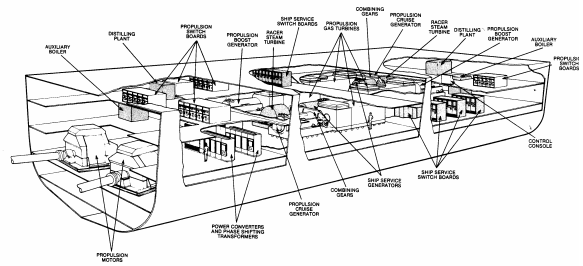

Figure 9a. Near Term Destroyer

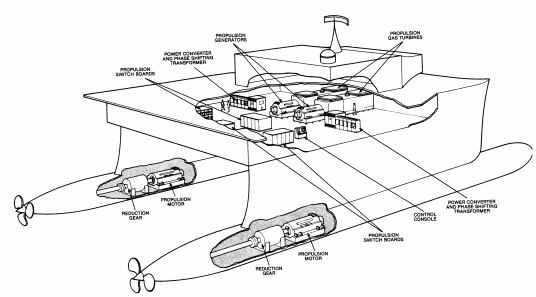

Figure 9b. Near Term SWATH

In all cases direct drive synchronous motors were used in the monohull, while higher speed, geared motors were used to meet the dimensional constraints of the SWATH lower hulls. The far term systems reflected the suprconducting homopolar motor designs and liquid cooled rectified alternators.

Integrated Electric Drive

In 1984, during this electric drive full scale update effort, NAVSEA initiated exploratory design studies on a 1052 class frigate replacement. The FFX study also carried monohull and SWATH variants, in this case 25 khp/shaft, and dictated that a common

baseline machinery plant be used in both platforms. An electric propulsion system which more or less represented a composite of the best features of the near term systems produced under the full scale update was adopted for this purpose (figure 10). Again the SWATH lower hull space limitations dictated use of a high speed ac motor and gear. Subsequent to a series of technology tradeoff studies, propulsion derived ship service (PDSS) was added to form an integrated electric system. Also, a much more stringent acoustic requirement was placed on this propulsion system than had been encountered in any of the previous surface ship electric drive efforts.

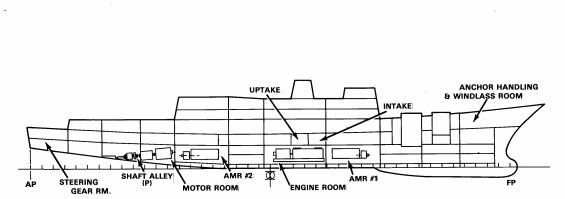

Figure 10a. Monohull

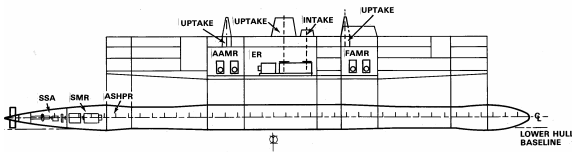

Figure 10b. SWATH

The FFX effort was eventually canceled (the combination of requirements resulted in excessively large ship designs), but not before it substantially influenced the technical requirements and procurement specifications for the advanced development of an Integrated Electric Drive (IED) system. The IED contract, which was awarded to General Electric Co. in November,1988, was directed at the 25 khp/shaft SWATH platform complete with acoustic requirements. A single machine (figure 11) was to serve as both generator and high speed, geared motor for the SWATH and as generator for a monohull application., while an option was included for development of a direct drive 50 khp motor as the need arose. The generator/motor was a four-pole, dual 3-phase, synchronous machine with direct liquid-cooled stator and air-cooled rotor. The generator application drove the machine rating of 22.187 MVA at 3600 rpm. The solid state" multi-mode" frequency converter (MMFC) was only rated for single engine cruise condition. At full power the generator and motor could be operated synchronously. The MMFC was a load commutated dc-link converter with SCR based rectifier and inverter bridges. An alternative soft switched pulse width modulated inverter was also designed and partially built, but not completed due to funding and program re-direction. The integrated electric aspect was provided via a PDSS generator system driven from a power-take-off gear. Details on the GE IED system can be found in [9].

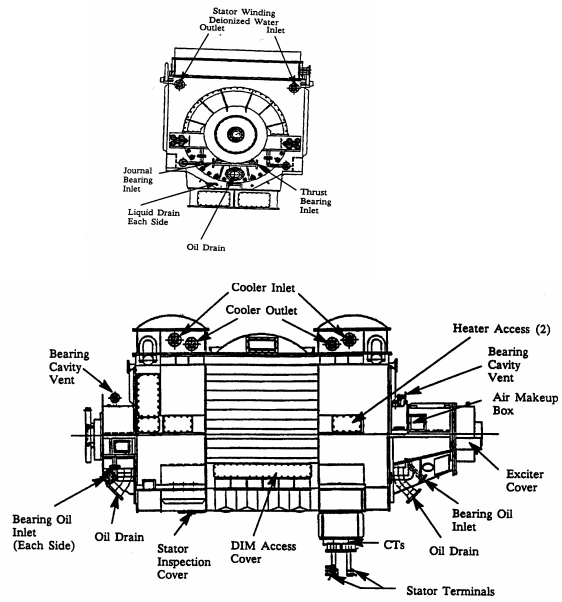

Figure 11. Integrated Electric Drive Nominal 25 khp/ 3600 RPM Machine

Cluster "A" and IED

Following FFX, the NAVSEA CONFORM program supported the Revolution at Sea initiative with a series of studies (1986-89) culminating in the Battle Force Combatant (BFC) which was characterized by substantial increases in warfighting capability as compared to the DDG 51. From the HM&E technology assessments conducted as part of these studies evolved the integrated machinery system concept which came to be known as "Cluster A", shown in figure 12 as configured for the BFC.

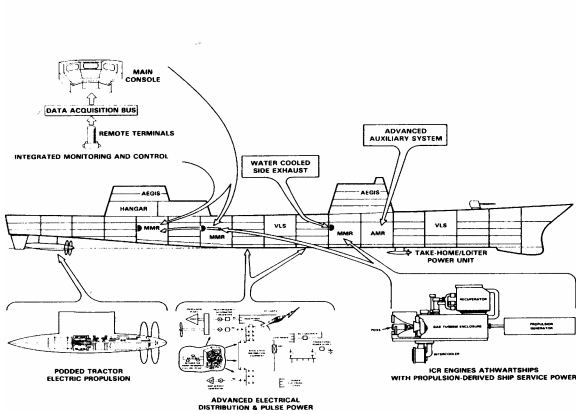

Figure 12. Cluster "A" Technologies

This concept, which originated at NSWCCD, Annapolis, added Intercooled Recuperated (ICR) gas turbines, contra-rotating tractor podded propulsors and advanced machinery control and electrical distribution systems to the basic IED system. The near term variant used high speed synchronous motors with contra-rotating epicyclic gears, while the far term variant used contra-rotating superconducting homopolar motors direct coupled to the propellors. Development began in 1987 under the Integrated Warship Systems Demonstration Program (IWSDP) with the planned initial phase including full scale system design and analysis and associated propulsor model testing (figure 13) leading to a planned intermediate scale demonstration on a PG-100 class patrol boat.

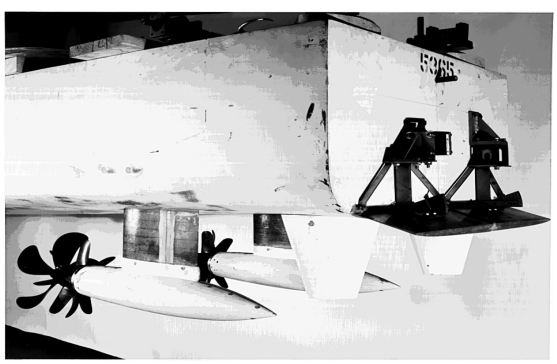

Figure 13. Integrated Warship Demonstration Program - Podded Propulsion Model Testing

Briefing of Cluster A for the BFC to then CNO ADM Trost, led in September 1988, to his designating "Integrated Electric Drive (IED) & Associated Cluster of Technologies" as the "method of propulsion for the next class of surface battle force combatants", and to the establishment of the NAVSEA IED Program Office for coordinated development of the Cluster A integrated machinery system. The integrated machinery concept presented to ADM Trost was driven by the requirements resulting from the OPNAV Revolution at Sea studies. The SCFR Study provided ship functional requirements in the form of the Battle Force Combatant (BFC) and Mission Essential Unit (MEU). The Ship Operational Characteristics Study (SOCS) incorporated operator input into thirteen Imperative Characteristics for future surface ships. Clearly the BFC Cluster A variant was a performance driven design responding to the need for improved warfighting capability. While the target timeframe for the BFC was 2010 operational capability, Congress stated an interest in an earlier introduction of the "IED" technologies. This was interpreted by the program manager at the time as an edict to put IED on the earliest new construction opportunity which in this case were the DDG-51 Flight III or a follow-on variant of the AOE-6 class. Coincident with the analysis of earlier introduction of IED was a request by OPNAV for validation of the performance attributes presented in the IED CNO Executive Board as input to development of an IED Operational Requirement (OR). After considerable effort it was concluded that within the constraints of a "mod-repeat" ship design and with no premium on enhanced performance, IED was not affordable relative to the existing machinery systems. Also, with the near term introduction focus, the more advanced features of the Cluster A concept such as podded propulsors and the superconducting motor alternative were dropped from the overall program as originally proposed.

While this exercise answered the early introduction issue, it did not resolve the OR validation. Since it was in the context of a performance driven ship design that IED was originally sold, an analysis of DDG variants with enhanced acoustics performance was conducted which included podded propulsor and superconducting motor alternatives. The results of this study confirmed the original BFC conclusion that IED was the best alternative for achieving enhanced performance. From this evolved the IED five cornerstone requirements which served as a basis for the initial version of the IED Operational Requirements -

- combat systems support
- sustainability
- passive protection

- signatures
- affordablity.

Submarine Electric Drive Development

In the late 1980s, a congressionally directed ARPA submarine technology program included the development of electric drive concepts for future submarines. Candidate systems identified included superconducting electric drives very similar to those discussed earlier in this paper. A substantial additional investment in motor, superconducting magnet, and current collector technology resulted, which is discussed elsewhere in these conference proceedings. In addition, this study stimulated the proposal of a permanent magnet ac motor with solid state speed control as an alternative approach with significant power density benefits. As there was no commitment to a ship application, navy interest slowly diminished in this application.

Integrated Power System Evolution

As the Cold War came to a close the diminished threat resulted in reduced defense budgets and elimination of any near term new design/new construction opportunities (i.e. DDG 51 Flt III, AOE(V)). Without a firm ship commitment the IED program elements could not be justified as acquisition programs and thus a non-acquisition program status was proposed. A Non-Acquisition Program Definition Document (NAPDD) replaced the OR as the requirements document and program focus shifted from enhanced performance to improved affordability at existing performance levels. Studies were conducted to establish the affordability of the program elements, individually and in various combinations. A partial life cycle cost (R&D, acquisition, fuel & manning) comparison was made between the alternatives and the baseline DDG 51. The conclusions drawn from the study were that Intercooled Recuperated Engine (ICR), Standard Monitoring and Control Systems (SMCS) and AC Zonal Electrical Drive System (AC ZEDS) were affordable, but IED and PDSS as originally defined, were not, compared to mechanical drive. The NAPDD was redrafted to reflect these findings and IED was relegated to completion of the existing contract and shelving the equipment designs for possible future use should a change in requirements occur.

Advanced Surface Machinery Programs

The change in requirements was accompanied by a change in the program office title to Advanced Surface Machinery Programs (ASMP) and restructuring of the programs towards affordability. Early on, ASMP recognized that a single technology or process was not sufficient to meet the affordability goals. Instead, ASMP attacked cost through six affordability initiatives:

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

The search for a more affordable electric propulsion system took two paths. First, the emergence of commercial marine electric drives in ice breakers and cruise liners (Figure 14) [10,11] stimulated a look at the differences between the IED machinery and its affordable commercial counterparts. A look beyond the Navy procurement process, known to be a major cost factor, revealed Navy requirements which dictated use of non-standard design/fabrication practices. An assessment was made on the IED generator to determine what could be done to minimize the non-standard practices and thus reduce cost. Also, Direct Drive Motor design studies were done to determine if cost effective propulsion motors could be developed which met surface combatant space constraints, using commercial design and manufacturing processes. Various cooling schemes were addressed and full range power converters were used which allowed optimization of the motor independent of generation frequency.

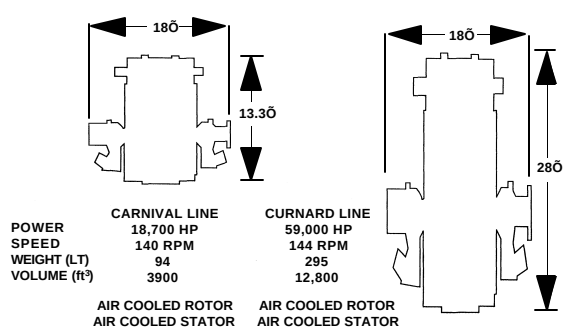

Figure 14. Commercial Marine Electric Drive

Secondly, new permanent magnet material and advanced power electronics technology provided the potential for increased commonality between commercial and military equipments. The aforementioned ASED study effort spawned a look by Newport News Shipbuilding (NNS) for alternative technology. In conjunction with Kaman Electric Corporation (KEC), NNS developed a permanent magnet elctric drive (PMED) system concept which they proposed for both submarine and surface ship applications[12], and began development of a 3000 hp scale pm motor under their IRAD program. The Navy decided to pursue parallel efforts in superconducting and PM machines, with the submarine community supporting superconducting, and ASMP supporting PM - in this case Navy agreed to fund testing of the NNS/KEC motor and development of a PM generator for system test and evaluation. The NNS/KEC concept (figure 15) employed a low voltage dc distribution system which enabled use of the latest IGBT/PWM based power converter technology vice the line commutated SCR's. It was in fact the availability of such advanced solid state motor control along with the new PM materials and machine fabrication techniques which enabled the PM motor development.

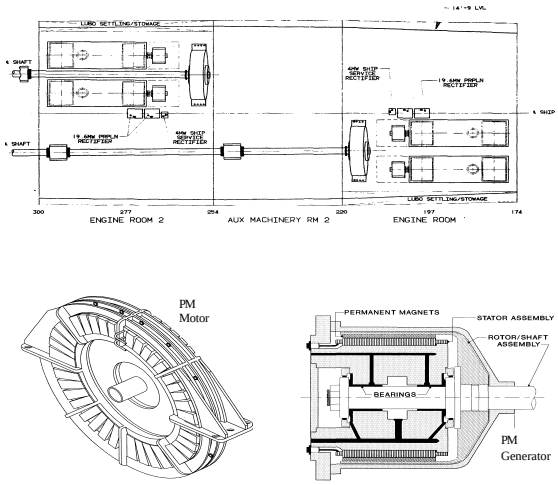

Figure 15. NNS/Kec Permanent Magnet Electric Drive System Concept

From these efforts evolved the initial Integrated Power System (IPS) concept based on the commercial marine electric power architecture and incorporating PM machines and IGBT/PWM power electronics. In mid 1992, the Navy initiated the 21st Century Destroyer Study with the objectives to 1) establish the feasibility of providing a viable strike/AAW capability within a smaller hull than the DDG-51 at a follow ship cost in the neighborhood of $500M ($FY94), and 2) develop the technology road map for incorporating any new technologies required to meet the first objective. In support of this ASMP provided machinery characterization of a PMED based IPS configuration which resulted a reduction in ship acquisition cost of $10M relative to the mechanical drive alternative. From this and follow-on DD21 studies, IPS became a leading candidate technology for the Surface Combatant 21 (SC 21) leading to formalization of the R&D program.

The IPS program [13] was established with the objectives of 1) defining the power system architecture for electrical power generation, distribution, conversion, storage and control for supplying propulsion motors and other electrical loads; and 2) developing a family of modules which will serve as the building blocks for designing, procuring and supporting marine power systems applicable across a broad range of ship types. This was to include establishing module interface standards which would be technology independent to the maximum extent possible.

In keeping with the affordability theme, the IPS development was structured in three overlapping phases in order to reduce risk and minimize financial exposure. The PM machine and power electronics technology assessments and the power system architecture studies constituted the Reduced Scale Advanced Development (RSAD)phase. In the Full Scale Advanced Development(FSAD) phase, for which a contract was awarded to Lockheed Martin Ocean, Radar and Sensor Systems in February 1995, components are being developed for land based testing to validate the system architecture and interface specifications. Designs for incorporating these components into modules will also be developed with the modules being procured and qualified in the Full Scale Engineered Development (FSED) phase.

The Lockheed Martin system incorporates a commercial marine approach to electric power generation and propulsion distribution in combination with a zonal dc electrical distribution system for ship service power. The generator (figure 16) is a conventional two-pole, 60 Hz machine produced by Brush Electric that produces the required 22 MW output power at 4160 Vac.

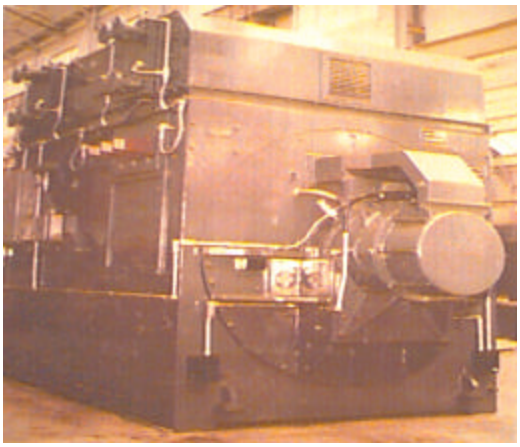

Figure 16. Brush Generator

The power is distributed in this form via conventional medium voltage cable and switchgear to the propulsion converter which produces the voltage and frequency required by the propulsion motor. The converter consists of a diode rectifier front end and multiple Pulse Width Modulated (PWM) inverter sections paralleled to achieve the desired power levels. The inverter section development extends the state-of-the-art in Insulated Gate Bipolar Transistor (IGBT) based PWM technology to the medium voltage range. The direct drive motor is a squirrel cage induction motor based on severe duty commercial marine and industrial designs by GEC (Figure 17). In parallel with the induction motor design effort under the FSAD contract, development of a PM propulsion motor module was initiated, but has been interrupted due to funding shortfalls. The ship service dc power is produced by a conventional transformer/rectifier, and distributed via dc cable and converted by Ship Service Inverter Modules (SSIM's) to 60 or 400 Hz, or variable frequency/voltage as required.

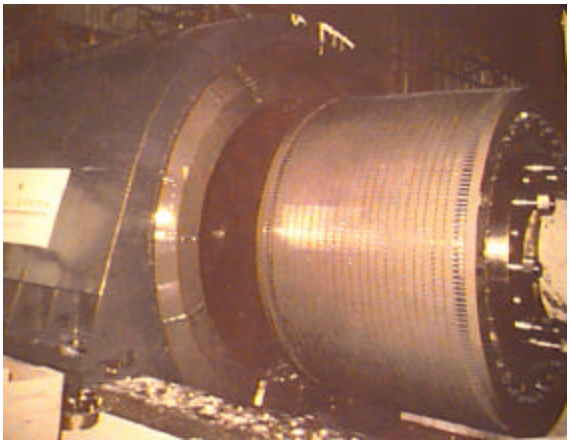

Figure 17. Induction Motor

While the focus of the Navy's present FSAD effort is on system integration with maximum use of commercial technology, the IPS architecture will allow incorporation of developing technologies such as the permanent magnet electric machines, fuel cells and the Power Electronic Building Block (PEBB) into future ship designs as programmed, pre-planned replacements for the "core" technology in the first generation IPS modules. Use of technology independent module interface standards will facilitate technology insertion with minimum impact on the more efficient and streamlined ship design and construction process.

Summary and Conclusions

The foregoing discussion only highlights what is a rich and successful history of the application of electric drive to navy ships, and the more recent attempts to meet new requirements through the use of "Integrated Electric Drive" concepts and new technology. In reviewing various accounts of fleet experience with electric drive, the vast majority are found to be very positive. This is true also for ship application/impact analyses over the past two decades. Electric drive, integrated with the ship service power system, with the proper selection of technology and system/ship propulsor arrangements, invariably results in benefits beyond these available with mechanical drive systems. It should be emphasized that electric drive rarely, if ever, is attractive as a backfit, due to the inability to take full advantage of the operating and arrangement flexibility electric drive provides. A singular exception was the retrofit of diesel electric drive onto the QEII which had

a payback period of only a few years. The inherent attractiveness of electric drive, including its use in podded propulsor arrangements, is also evidenced by it growing pervasiveness in the high end commercial and support ship designs. [14] More than once, electric drive has been endorsed as the way of the future at the highest levels of the navy, because proponents were able to calculate and articulate its advantages. Unfortunately, each of these commitments has been followed by a change in requirements, driven by world events, new technology, budgets, etc. It is a tribute to the robustness of the concept of integrated electric propulsion that it has been resurrected and adapted to these changes, and still appears to be the leading propulsion transmission candidate for future ships.

A summary of the past 30 years of electric drive experience might be:

- Superconducting Electric Drive was successfully demonstrated but perceived as costly and very risky, so it was put on the “back burner” in about 1985.

- The Advanced Integrated Electric Propulsion Plant proposed for the DDGX (DDG-51) was adapted from commercial technology but ran afoul of a conservative evaluation board in about 1983.

- The Integrated Electric Drive program was nearly complete in delivering advanced ac electric drive to meet increased performance goals when the cold war ended and the system was deemed unaffordable.

- The Integrated Power System electric drive based again largely on commercially available machinery technology has answered the affordability and performance goals of the next generation surface navy and full-scale hardware will be tested in FY98 -- unless a new round of changes in requirements occurs to obsolete this approach.

- Research and Development programs are actively developing the next generation of machinery technology including superconducting/homopolar technology, permanent magnet technology integration of electric transmission and propulsor, and all electric ship concepts.

It would appear that we have run out of reasons for not including electric drive in the next generation of combatant ships. It is now up to the technical community to assure that the lessons of the past are combined with the best that affordable technology has to offer to provide the future navy with superior power and propulsion systems.

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