Don’t look back in anger: Lessons and enablers for 2nd generation Integrated Power Systems for warships.

by

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Synopsis

Future warship design will need to negotiate several emerging hurdles with regards to performance, complexity, capability, and resilience while balancing cost of ownership and environmental sustainability. Over the past two decades, most new warship programmes have fielded multi-role capability, but with rapid advancements in mission systems technology the platform systems selected need to be more adaptable now than ever to enable through life technology insertion throughout a service life of up to 50 years. To facilitate this, capital warships have and will continue to become increasingly electric, with deeper integration of ship and mission systems.

While the electrification of modern-era warships has been commonplace since the early 1990s, in-service experiences on first generation Integrated Full Electric Propulsion (IFEP) or Integrated Power Systems (IPS) must be considered alongside user requirements for a new programme. The RN Type 45 destroyer, Queen Elizabeth Class (QEC) carrier and the USN DDG-1000 destroyer programmes have yielded some interesting learning opportunities in several areas.

This paper will provide an insight into some of the learning points in the development of the power plants for these first-generation electric warships. It will then provide an insight into enabling approaches, techniques and technologies - and will specifically consider power management, prime mover type and size and associated impact on power system architecture, platform design and operability including resilience, efficiency and emissions. Some of these will provide opportunities for the discerning system designer and naval architect that were previously unavailable, and if leveraged, will ensure optimal designs giving enhanced performance and functionality in the second generation whilst simultaneously driving down platform costs and emissions.

KEYWORDS: Integrated Power Systems, full electric propulsion, collaboration, power management

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Author’s biography
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Introduction

Traditionally, warships are configured around the mission systems, with power and propulsion (P&P) viewed as a necessary supporting system and relegated to the 'back aft and down below'. However, with the proliferation of advanced high-performance (and increasingly power-hungry) mission systems we find ourselves at the dawn of the engine-as-a-weapon era, with installed power-gen now a strategic resource; generation of electrical power is a crucial aspect of modern naval ship design and sustainment. It is increasingly a vital component of vessel capability including directed energy systems required to combat hypersonic weapons which demands that power management be at the core of modern warship design. Efficient and sustainable management of pulsed power loads will be a key requirement going forward, and the arrangement, constituent parts, and level of integration of the system's design will be key in successfully realizing this capability. The rate of change of mission system technology requires unprecedented adaptability to ensure longevity of service, and ultimately the overall success as a warship programme. This paper will provide something of a stock take on our progress on the electrification journey and suggest some enablers to build upon what we have achieved in first generation systems.

A Paradigm Shift

A new capital warship programme needs to consider the power management requirements earlier, driven by the mission system and propulsion needs rather than starting from the platform then moving into the mission system and propulsion with power management being one of the last considerations. It drives one to think about the sub-systems first, remove functional boundaries during the concepting stage and explore the optimal 'insides' of the platform, then co-develop the platform design. Only by being unconstrained (or in reality, less constrained) by platform design can we field the capability needed by 21st Century war fighters. This 'inside out' approach requires us as a community to think differently to develop differentiated and adaptable solutions and realise the full benefits of both electrification and advanced mission capability.

It would require timely and much closer engagement between power system and mission system providers to understand programme requirements (e.g. physical, functional, performance) and identify risks, opportunities, constraints and limitations. Requirements are normally flowed-down to sub-system providers by the primes in a manner that can unnecessarily constrain systems, sub-systems and equipment. This approach may have been suitable for legacy programmes, but the era of hypersonic weapons and electro-magnetic railguns challenges the conventional approach. The dramatically reduced time available for identification, classification and prosecution of inbound threats – reducing time constants within automation systems and human factors, and ensuring the timely provision of correct condition of electrical power isn't best served by a traditional hierarchy of control systems or 'interfaced to' but not truly 'integrated with' adjacent systems. A radical and entirely more collaborative approach is needed that ultimately looks to tell the primes what is required for the most adaptable, efficient, resilient and capable system – that meets operational requirements that will continue to evolve and emerge over the coming decades. Inherent flexibility will be needed to support incremental acquisition and technology insertion though the life of the programme, enabling progressive re-optimisation of system architecture and performance.

This should emulate some of the principles of the UK-MoD's Tempest programme which is a collaboration between the U.K. Ministry of Defence, BAE Systems, Rolls-Royce, Leonardo S.p.A., MBDA UK and Saab, and aims to field the RAF's next generation combat aircraft, coming into service from 2035 to replace the Typhoon. The Tempest platform will be fundamentally adaptable both to the mission as well as enabling mission-system upgrades during its lifetime. It will incorporate artificial intelligence and deep learning and carry directed-energy weapons. The platform will feature an integrated power and propulsion system with intelligent power and thermal management[1].

Modern Era Electric Warships

The modern era of warship electric propulsion effectively began in the mid-1980s with the selection of a hybrid (electro-mechanical) combined diesel electric and gas (CODLAG) turbine arrangement for the UK Royal Navy (RN) Type 23 anti-submarine warfare Frigate. Based on the success of this program, an IFEP architecture was selected for a number of subsequent programs. Numerous studies into the widespread electrification of warships were conducted in the mid- to late-1990s. Papers presented at naval engineering conferences around that time highlighted the benefits[2] in operation, construction, and capability, of the electric warship while the technologies and challenges were explored in depth. These papers often cited the following;

- Lower cost of ownership by virtue of lower fuel consumption & lower on-board maintenance load via fewer installed engines providing opportunities for reduced manning
- More layout flexibility (avoiding the 'tyranny of the shaft line') enabling better platform design – de-cluttering the superstructure
- Easier to install and align

- Enhanced redundancy
- More adaptable and future-proof

The United States Navy took a different path to electric propulsion than the UK. Around the same time as the Type 23, the US Navy was beginning to base its surface fleet on the DDG-51 destroyer class which features a mechanical, all-gas turbine power plant. The power plant utilizes four GE LM2500 gas turbines for propulsion in a twin-shaft, COGAG arrangement and three Rolls-Royce gas turbine generators for electrical generation. This plant was quite ground-breaking when it was first introduced in the mid-1970's on the DD-963 destroyer class and was subsequently very mature by the time DDG-51 was launched. The success of this mechanical plant, and of the DDG-51 class, likely influenced a later move to electric propulsion in the US than the UK. The first major class USN ships with electric propulsion was the LHD8 amphibious ship featuring hybrid/CODLAG architecture in 2008 - almost 20 years after Type 23. This was followed by the fully-electric (IPS) DDG-1000 which, after a lengthy period of design and development, first entered service in 2016 - about 6 years after the Type 45 debuted.

Despite the fiscal constraints of modern warship acquisition, which have resulted in fewer than envisaged Type 45 and DDG 1000 vessels making it into service, requirements for globally agile multi-mission warships in parallel with the rapid advancement in sensor and weapons technologies means many countries are now considering the all-electric warship. For those navies currently fielding IPS vessels, the need to supplement or eventually replace these and other vessels is being considered along with experiences gain from implementing and operating first-generation IPS vessels. For those nations currently on the journey to IPS, such as Japan and Korea, the focus will naturally be on maturing enabling technologies to ensure risks are understood and mitigated, costs are managed, and hull numbers and capability are kept in line with the needs of the service.

The successes of 1st generation IFEP-powered warships do include <u>some</u> of the aforementioned but are often marginalised by the teething troubles experienced, which received (and continue to receive) widespread coverage in media although often based on speculation not fact. Route cause(s) are complex, often non-technical and not socialised. Within the last ten years, the RN Type 45 Destroyer, QEC Carrier, and USN DDG 1000 Destroyer programs have yielded valuable learning opportunities in areas of design optimization, operational aspects, and resilience of IPS that can benefit future ship programs. Continuous improvement is incumbent on all members of the naval engineering community, so in-service experience with integrated electric propulsion should be considered alongside user requirements for the new program.

Some Lessons Learned from First Generation Electric Warships

Following the success of the hybrid electromechanical arrangement in the Type 23 frigate in the early 1990s, with direct-drive electric motor mode available up to 15 knots, the all-electric Type 45 was the logical progression of technology from hybrid to IFEP insofar as it extended the significant benefits of electrification across the entire ship speed range. Entering service in 2010, HMS Daring represented the first modern IFEP-powered combatant to enter naval service. The platform was novel in several respects.

Criticality of the Electrical Power Management System

Early operational experience of integrated power systems in the cruise ship industry[3] highlighted differences in functional and performance characteristics of Gas Turbine Generators (GTGs) and (where installed) diesel generators (DGs), not in the least with respect to performance variation when considering external ambient air temperatures.

These experiences indicated there is a need to accommodate the variable performance attributes of each type of prime mover within a more sophisticated electrical power management system (EPMS). If fitted, a closed-loop control system would have monitored available capacity within the power system line-up based on prevalent operational and environmental conditions, with active and intelligent management and matching of the generating capacity to the variable load demand while maintaining adequate spinning reserve in accordance with the extant threat state, ensuring all equipment within the system remain within their respective performance envelopes

Resilience and Granularity: The Napier Program

A lack of resilience in the T45 power and propulsion system ultimately undermined operational effectiveness[4]. In 2011, an independent study commissioned by the UK MOD suggested there was "no single root cause underlying the low reliability", but rather a "large group of unconnected individual causes"[5]. The Napier program was initiated by the UK MOD in 2014 to urgently address the issues and restore command confidence in the class. The Napier program is comprised of two discrete but highly integrated projects:

1. The Equipment Improvement Plan (EIP), which seeks to improve equipment reliability by targeting individual failure modes observed since EIS.

2. The Power Improvement Project (PIP), which seeks to improve system resilience and redundancy by replacing and installing additional diesel power generation sources to more than double the existing capacity.

The program is charged with delivering a reliable power and propulsion (P&P) system architecture with redundancy matching the resilience demands of the RN and ultimately restoring command confidence and enabling the Type 45 Destroyer to reach its full potential.

Although this paper will not detail the specifics of the DDG1000 architecture or development process[6], it is worth highlighting here as a comparison to the Type 45 and other RN ships featuring electric propulsion. As the US Navy's first true IPS warship, the DDG-1000 began development around the same time that Type 45 was being designed and built, with initial conceptual planning occurring in the late 1990's. The DDG-1000 power plant is based on four gas turbine generators delivering around 80MWe of power to a hybrid 4160VAC IPS system featuring an Integrated Fight-Through Power (IFTP) system consisting of a zonal 1kVDC grid. Interestingly, this is the same voltage rating as the Type 45 Destroyer despite featuring almost twice as much installed power. The four generators are configured as pairs of Main Turbine Generators (MTG), using the Rolls-Royce MT30 (35.4MWe), and Auxiliary Turbine Generators (ATG), using the Rolls-Royce RR4500 (3.9MWe). Given the respective ratings, the power generation system features a large ratio between MTG and ATG outputs, similar in that respect to Type 45 Destroyer. For both classes, this meant the MTGs were required for most operating conditions which results in reduced resilience due to excessive dependence on two engines. The Type 45, however, utilizes a complex-cycle gas turbine (WR-21) as the MTG, which remains relatively efficient across a wide throttle range, especially when compared to simple-cycle gas turbines. The DDG-1000, on the other hand, must operate its large simple-cycle gas turbines (MT30) at well below design point, thereby resulting in sub-optimal system efficiency.

It is clear that not all benefits of IFEP were realised in T45 or DDG1000 (layout, Resilience, Economy/range) and these have been comprehensively covered in previous papers[7].

Looking back, the RN has been on an interesting journey in the last sixty years in terms of propulsion system technology. Steam turbine-powered mechanical propulsion was displaced with gas turbine mechanical throughout the 1960's and 1970's, which was then progressively replaced by gas turbine hybrid electric drive through the 1990's, and based on the success of the electric drive, was followed by GT-powered integrated full electric propulsion in the late 2000's. It seemed logical to assume that the RN Type 26 guided missile frigate programme would adopt IFEP in the early 2010's, but actually a GT-hybrid arrangement was selected based on the requirements and constraints of the programme. More recently, a Diesel-Mechanical (CODAD) arrangement was configured in the RN Type 31 frigate, albeit pulled-through from the Danish design.

What about next-generation capital warships? Should we abandon the pursuit of IFEP?

The Original UK Electric Ship Vision

The RN vision of the electric warship describes a warship featuring wholly-electric propulsion, whereby prime movers generate electricity to drive electric propulsion motors, while simultaneously satisfying the electrical loads from hotel and mission system

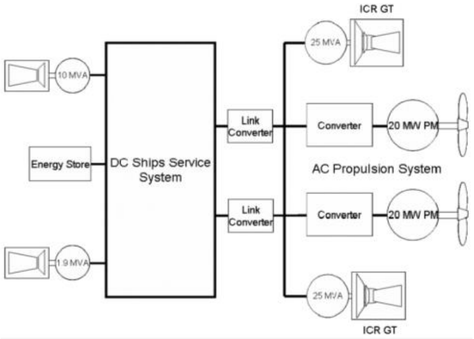

Figure 1 – the original UK electric ship concept

Since the success of the Type 23 Frigate's hybrid electric propulsion system in the early 1990s, the UK has been on a clear path to full electrification of its capital warships, culminating in the Type 45 and QEC programs. This path was supported by successive Marine Engineering and Marine Systems Development Strategies (MEDS 1995 and MSDS 2013).

Original literature[2] envisaged an all-electric vessel with both alternating current (ac) and direct current (dc) power networks as shown in Figure 1 (from Ref 2). This would be powered by a mix of prime movers and, along with energy storage, would maximize the benefits and robustness of all-electric architectures and satisfying the requirements of individual programs. This is referred to as the 'power station' concept in which multiple generator sizes can be configured in a way that allows prime movers to be optimally loaded with respect to economy and range, redundancy against equipment defects, and resilience to battle damage. This gives the power system enough 'granularity' and 'reconfigurability' to efficiently meet various levels of demand in multiple ways.

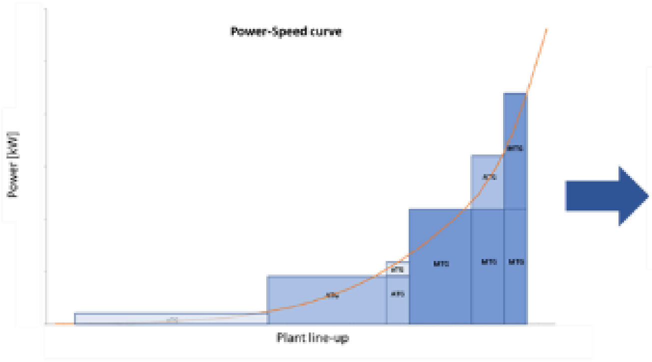

Figure 2 – electric ship vision generator modes

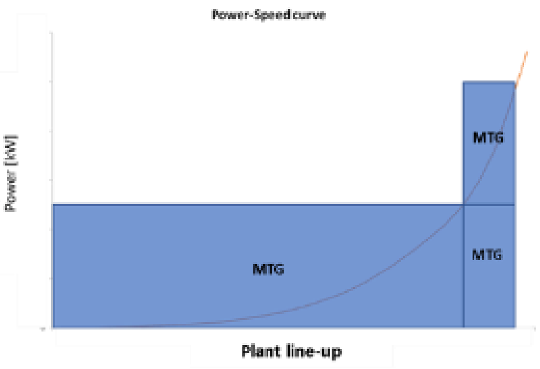

Figure 3 – de facto Type 45 sea-going generator modes

Online generation components are demonstrated in Figure 2 with respect to a nominal load profile, where aTG = small auxiliary Turbine Generator, ATG = Auxiliary Turbine Generator, MTG = Main Turbine Generator. The concept offered 'Minimum Generator Operations' in peacetime, which reduced through-life costs, thereby ultimately delivering the capability to run the entire vessel off a single unit for single generator operation (SGO) in benign / low threat cruising conditions.

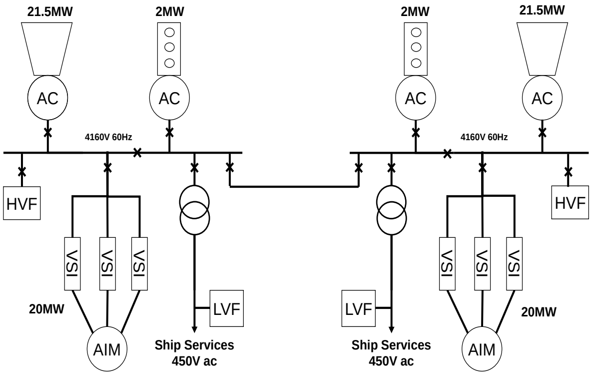

Figure 4 – Type 45 destroyer electrical power system

As previously mentioned, most IPS studies in the 1990s were conducted around the original IFEP power station concept (illustrated in Figure 1 & 2) employing multiple generator ratings configured to economically match capacity to demand. During the derivation of the T45 system, the MEDP had a focus toward all-electric technologies and efficiency to reduce fuel consumption for reasons of both cost and security of supply. Running parallel to the T45 design endeavour and the MEDP was the development of the WR-21 complex cycle gas turbine, which promised to fulfil the objectives of low fuel burn across the operating range while being deliverable within the timescales of T45 Entry into Service (EIS). The power system design that was shown in Figure 4 (with concept of operation shown in Figure 3) is a departure from the original IFEP concept (Figure 1), which formed the underpinnings of a robust all-electric warship power system design. Negating the omission of dc technologies, which was the result of a lack of mature naval solutions, there were several architectural factors that resulted in the issues experienced during early Type 45 service being more critical than they may actually have been. Key to this was the issue of integrating the original power station concept into a 7400-tonne displacement class vessel. The omission of 'primary' mid-sized power generation components coupled with an overreliance on a single prime mover type, resulted in sub-optimal power system resilience.

That was then – but this is now, where more resilient power systems are required in second generation IFEP arrangements. Moreover, with advanced mission systems required to counter or neutralise the threat posed by hypersonic weapons there will be far less tolerance to less than completely integrated and optimised systems supported by robust and intelligent power system and platform automation systems. Indeed, integration should be more than just ensuring all components within a system remain within their respective performance envelopes across all operational scenarios. Of course, we need to define the problem before developing solutions, but there are limits on the achievable height above sea level of RADAR (and the associated increase in beam to satisfy ship stability) so inevitably the new warship programme will look to the ship systems for solutions. These are likely to include more intelligent proactive integration of ME, WE and platform management systems and sub-systems, for example EPMS directly communicating to Combat Management System (CMS) e.g. feed forward signals to demand spooling-up (or down) of generators to meet the anticipated military need (augmented by Artificial Intelligence and machine learning), and active management or 'spinning-reserve' of online power generators.

The unique approach adopted by the RN QEC programme

Benefits that were realised on QEC included enhanced adaptability, survivability and resilience - partly because of a large ship, but also due to an early decision on P&P system architecture and also the radically different procurement strategy and partnership approach with industry[8]. This included early (pre-alliance) decisions on system architecture and design optimization, leveraging expertise from industry. A partnership approach between UK MoD and industry via a formal commercial alliance (Main Alliance, and Power & Propulsion Sub-Alliance) was used covering detailed design, risk and opportunity management, integration and delivery. This principle could be extended to CMS and mission systems suppliers in increasing complex new warships.

'Back-aft and Down-below'

In legacy/simple warships, space is usually allocated 'back-aft and down-below' due to the need to configure mechanical arrangements requiring alignment to the shaft line, as shown in Figure 5. Modest levels of vertical separation were achieved on T23 and T26 insofar as locating two of the four DG sets above tank top level to slightly enhance survivability/resilience.

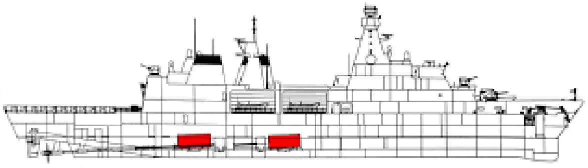

Figure 5 - Type 31 indicative arrangement[9]

Substantially more survivability was achieved in QEC carrier by virtue of power-density of MT30 GTG by virtue of the size and layout flexibility of the platform design. Figure 6 shows the two MT30 GT Gensets can be seen located in the sponsons of the carrier (outboard of the hangar) providing approximately two-thirds of the installed power generating capacity of the platform with very substantial vertical as well as longitudinally separation.

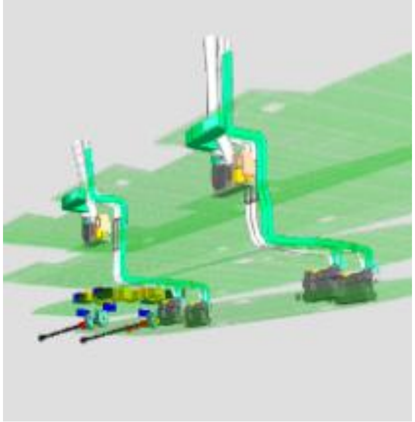

Figure 6 – QEC carrier engine arrangement (courtesy of Thales)

We need to access similar features in smaller more affordable warships, achieving better dispersal of assets and hence survivability and resilience. This could include a degree of modularity e.g. power system components such as generators or Energy Storage Devices in ISO containers as shared fleet-wide assets deployed as needed to support the mission**.**

A more collaborative approach
A whole-platform approach – with an early decision on system architecture is needed to unlock the full potential of IFEP, with power, data and cooling at the centre of ship design.

This approach should also include the weapons engineering and combat management systems community to socialise the services needed for all equipment, controls systems and sub-systems in terms of voltages, frequencies, power consumption, power factors and efficiency characteristics using the concept of employment to identify the opportunities for integrating and optimising whilst avoiding unintended dependencies.

Ratios and power-density.
As discussed, the power generation systems in first-generation IFEP-powered destroyers have no mid-size generator and furthermore feature a large ratio between the MTG and ATG rating. Whilst it is imperative to minimise the number of engines installed, ratios of nine- or ten-to-one will not facilitate the required granularity and resilience, and although system modelling against programme-specific requirements will inform the optimum ratio, it is postulated that the ideal is within the range three- or four-to-one. The QEC power system achieved this albeit via the adoption of medium-speed diesels in a design requiring substantially less power-density from the generators in the main machinery spaces than a destroyer.

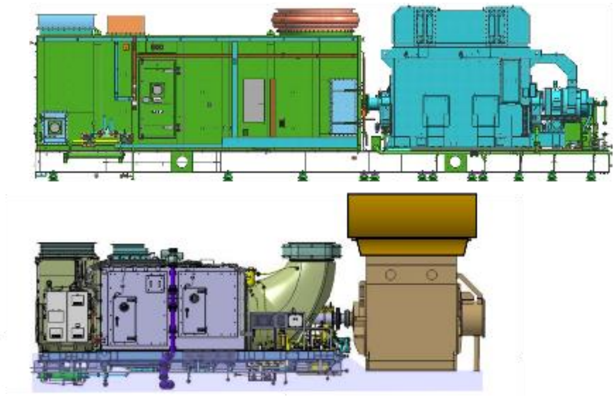

Figure 7 – indicative designs of MT30-GTG

Given the need to adhere to naval damage stability criteria, one of the keys to accessing IFEP in more affordable platforms i.e. sub-10,000te displacement destroyers and frigates is the availability of shorter gas turbine generators[10]. In response to continued interest in the electrification of surface warships, the compact package used in the mechanical drive variant has been applied to the MT30 in genset configuration, resulting in a significantly shorter more power-dense unit compared to the QEC and DDG-1000 configuration, as illustrated in Figure 7.

Figure 8 - the AG9160 GT Genset

This will enable the adoption of IFEP in smaller warships whilst adhering to naval damage stability criteria. The 3000kWe-rated AG9140 has had substantial success, but with the demand for high installed electrical power from the DDG51-Flight 3 programme, the AG9160 GTG has been developed, delivering 4000kWe in a relatively power-dense package, as illustrated in Figure 8.

Utilising dc (or variable-frequency) micro-grids to unlock of the power-density of DGs is worthy of deeper evaluation. The 3000kWe-rated S4000M53 engine performance map shown in Figure 9 demonstrates the potential to be released from operating at a constant 1800rpm for 60Hz in terms of delivering the engine's full potential (4300kWb @ 2170rpm) in conjunction with appropriately rated generator and power electronics.

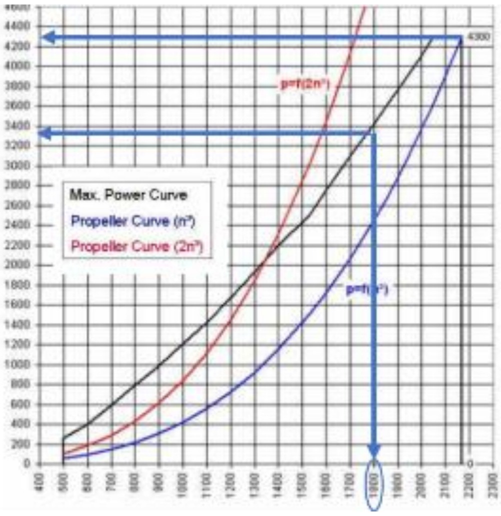

Figure 9 - 20V 4000 M93L - performance diagram[12]

In addition to higher power density (and system-level benefits from a slightly reduced ratio between generator ratings) there would also be a modest reduction in fuel consumption even with power conversion losses factored-in. Another advantage of the variable speed unit is that the reduced speed enables the maintenance / time between overhauls (TBO) to be extended by up to approximately 20 percent, which may result in lower cost of ownership[11].

Intelligent application of Energy Storage Devices (ESD)
The type or types of ESD within the system should be influenced by the known and anticipated electrical load demand characteristics such that they minimise installed power via peak-lopping of pulse-loads, to smooth fluctuating loads across the system and/or enhance the performance of other components of the power system in specific scenarios, for example to increase surge margin of engines during sudden transient operation. ESD could also be used to provide ride-through capability during occasional events to retain quality of power supply within tolerance thereby increasing system resilience.

Environmental sustainability: reducing platform CO2 emissions is only possible at scale via a truly integrated approach and optimised systems across the platform. This includes avoiding unnecessary power conversion losses in sub-optimal system architectures and the inefficiencies of prolonged engine running at part load. Also, by leveraging the potential efficiency benefits of variable-speed engine operation

More robust approach to design and growth margins.
There is a natural creative tension between the programme manager and the technical community around margins, due to the additional acquisition costs. However, unless the new warship has a design life of a mere ten or fifteen years, the rate of change of mission system technology demands closer inspection of margin policy, especially around predictable future mission system load demand. As stated by Admiral John Richardson, USN "*Buy as much power as you can afford because it's like RAM on your computer, you're going to need more as soon as you buy it*"[13].

Conclusions
Since embarking on the electrification journey in 1984, the Royal Navy and UK industry have had many learning opportunities along the way, spanning a number of classes of ship, arrangements and technology. This recently culminated in the QEC programme, where the approach taken on the design, development, integration and delivery of QEC capability is unique and the outcome has demonstrated the clear benefits of a partnership approach compared to other programmes, perhaps most notably Type 45 destroyer.

Project Napier will address the residual issues to some extent on Type 45, and the feasibility of implementing the changes associated with this project demonstrate the inherent adaptability in IPS compared to mechanical arrangements. It is clear that confidence in single generator operations may only be gained via adequate equipment reliability and system resilience – in second generation IPS this may also be satisfied by a more granular power system architecture and via the inclusion of a carefully-configured energy storage system.

The remainder of lessons articulated in this paper may be implemented by a robust systems-approach and design practices. Also by using a risk-based approach to verification and delivery, and an early, pre-planned (and costed) de-risking strategy. Where required, physical testing and system integration/validation, with all systems being fully tested in as representative an arrangement and environment as possible should be completed before design freeze of the IPS architecture and certainly well ahead of the first-of-class ship build schedule, leaving adequate headroom for iteration. The challenge for new programs and their stakeholders is to leverage lessons from the first generation and converge on a power system architecture that meets whole-life cost, efficiency, availability and resilience targets and adheres to layout constraints, and has identified, acceptable and manageable risks. For increasingly complex power and propulsion arrangements in the new 'Engine as a Weapon' era, the approach used on the RN QEC program should be emulated given the inherent difficulty in specifying the required platform capability (and implied functionality within sub-systems) by the user community and extended to include the CMS and weapons engineering community. Indeed, one of the key learning points from 1st generation IFEP is that no single individual or even organisation is able to adequately specify the required operational capability – a partnership approach gives the best outcome. Next generation complex warships would be prudent to adopt a naval equivalent of the RAF's Tempest programme. Integration ensures all components in a system remain within performance envelopes across all operational scenarios whilst simultaneously meeting required outcomes. But integration also needs to include proactive identification of opportunities to optimise the system or system of systems, supported by Modelling & Simulation – and hardware in the loop testing at the required scale to prove capability de-risk the programme.

So don't look back in anger – but do look back … to understand the lessons learned from the journey, and use them to continuously improve outcomes in the next generation. This is incumbent on us in order to identify and throw-off unnecessary constraints and unlock the full potential of electric warships thereby retaining military advantage in the face of significant threats from highly advanced and capable weapons, both now and over the coming decades.

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