

## Refining the Power Station Design of the All-Electric Warship

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### SYNOPSIS

The next generation of large surface combatants will feature a number of challenging hurdles with regards to performance, complexity and capability whilst being mindful of tomorrow's fiscal pressures. Over the past two decades, new warship programmes have focussed on more complex, multi-role capabilities necessitating more adaptable mission and platform systems. With tomorrow's vessels facing a service life between 35-50 years the selected power systems need to be sympathetic of today's requirements as well as through life technology insertion for tomorrow's needs.

To facilitate this, a number of tomorrow's warships are looking to adopt an all-electric architecture making use of developing energy storage technologies and more power dense prime movers. Whilst this in itself is no revelation, the impact that electric weapons and sensors have on an electrical power system, as well as the added costs incurred through provision of electrical margins, means it becomes imperative that design experience, lessons learnt, and evolving technologies are all considered during the concept design phase.

Electrification of warships has been commonplace since the early 1990s and in-service experiences on platforms with Integrated Power Systems (IPS) are now informing the requirement set for their replacement vessels. The DDG1000 Destroyer as an example, at sea since 2013, has yielded some valuable insights in areas of design optimisation and resilience that can benefit future combatant types. These experiences and the proven products on board these vessels will be augmented by new technologies and configured as part of new architectures to service the new types of loads that accompany the deployment of high energy weapons and sensors. Meeting these demands in an affordable, efficient, resilient and reliable manner will be key to ensuring the future platform's success and longevity.

This paper aims to visit the key in-service experiences of today's all electric ships whilst considering core aspects of future 'second generation' all electric ship design. This will include the need for power system 'granularity'; investigating the building blocks of power generation that make up these complex systems, whilst analysing the maturity of their constituent parts and the enabling technologies that make these systems possible.

Keywords; IPS; DDG1000; T45, QEC; All-Electric Warship

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## 1. Introduction

Generation of electrical power is a crucial aspect of naval ship design – today, more so than ever. It governs a vessel's capabilities, its longevity of service and ultimately dictates one vessel's superiority over its threats. It also governs, to a large extent, the vessel's initial acquisition cost. Increasing levels of installed electrical power is a trend that has been witnessed during successive generations of combatants and one that will continue an upward trajectory <sup>[1]</sup>.

Numerous studies into the widespread electrification of Warships have been conducted over the last 30 years – culminating with in-service examples of vessels equipped with Integrated Power Systems (IPS). Papers presented at this conference in the early 2000s<sup>[2,3]</sup> highlighted the benefits, both in operation, construction and capability of the electric warship - whilst the technologies and challenges were explored in depth.

Now in service, the UK Royal Navy's Type 45 Destroyer and the US Navy's DDG1000 class have shown that, whilst the vessels can be a technical success when operating in peacetime, the fiscal constraints of modern warship acquisition have resulted in fewer than envisaged hulls making it into service <sup>[4]</sup>, and with numerous lessons learned for future programmes relating to resilience and efficiency.

Today, requirements for global deploy-ability of multi-role naval vessels alongside the rapid advancement in sensor and weapons technologies means that many countries are considering the all-electric warship. For those navies currently fielding IPS equipped vessels, the need to supplement or eventually replace these vessels is being considered along with lessons learned from current generation IPS vessels. For those nations currently on the journey to IPS, the focus shifts to the maturation of the enabling technologies to ensure that hull numbers and capability are kept in line with the needs of the service.

In the context of maturing Directed Energy Weapons (DEW), IPS arrangements take on further importance <sup>[5]</sup> – effectively making the power generation system, the weapon's magazine. Efficient and sustainable satisfaction of pulse loads on the power system 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 realising this capability.

## 2. Review of early literature

The definition of the electric warship <sup>[2]</sup>, describes a warship featuring wholly electric propulsion, whereby prime movers generate electricity to drive electric propulsion motors, whilst simultaneously satisfying the vessel's hotel loads and mission systems.

Since the success of the Type 23 Frigate's Hybrid Electric propulsion system in the early 1990's the UK has been on a clear path to full electrification of its capital ship programmes, culminating in the Type 45 and QEC programmes. This path was outlined in successive Marine Engineering and Marine Systems Development Strategies (MEDS 1995 & MSDS 2013) as well as early papers from private companies and authors <sup>[2,3,6]</sup> throughout the late 1990's and 2000's.

Alongside the UK, the United States Navy also took a keen interest in all-electric warships. The US Navy required vessel's with increased range, improved control of signatures and reduced maintenance, all whilst being mindful of being able to generate increased levels of electrical power to fulfil the power requirements of in-development sensors as well as Directed Energy Weapon (DEW) and Electro-Magnetic Railgun (EMRG) programmes that were in their infancy at the time <sup>[13]</sup>. This led to increasing levels of US Department of Defence, US Navy and private investment in electrical technologies whilst various research papers <sup>[7,8]</sup> were delivered to improve technology maturation in support of these future programmes.

Given the alignment of programme drivers and their enabling technologies collaboration between UK and US Navies occurred during this period. This is a relationship that has continued via the AEP3 (Advanced Electric Power & Propulsion Project) arrangement which aims to develop the technologies required to field advanced power systems, directed energy weapons and future sensors.

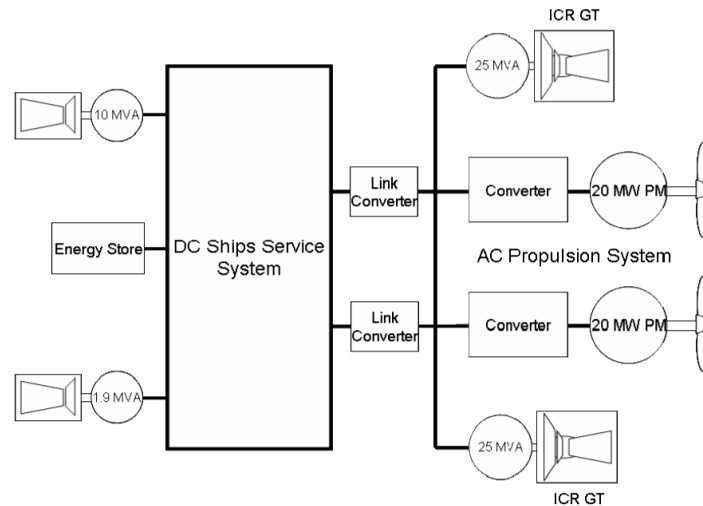


Figure 1 – ‘The Original UK Electric Warship System’ – Hodge & Mattick <sup>4</sup>

Original literature envisaged an all-electric vessel with both AC and DC power networks as shown in Figure 1 <sup>14</sup>. This would be powered by a variety of prime movers that maximised the benefits and robustness of all electric architectures. This is referred to as the power station concept – the idea being that multiple generator sizes could be configured in a way that optimally loads individual or paralleled prime movers to achieve an optimum condition with respect to economy and range, resilience to battle damage or any other condition that is desired by command. This gave the power system enough ‘granularity’ and ‘reconfigurability’ to meet various levels of demand in multiple, efficient ways.

A representation of the power station concept is highlighted in Figure 2. The concept offered ‘Minimum Generator Operations’ in peacetime which reduced through life costs – ultimately delivering the capability to run the entire vessel off a single unit; Single Generator Operation (SGO).

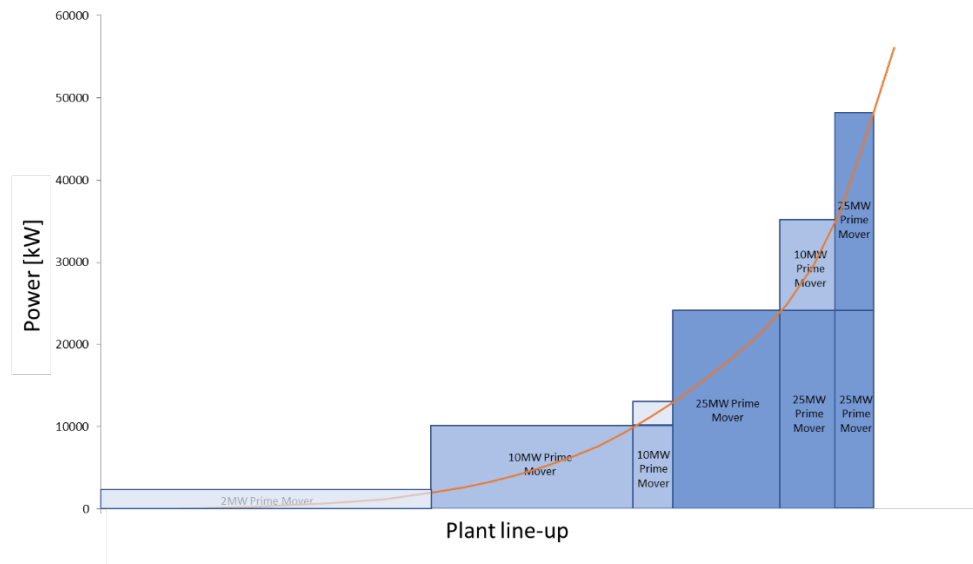


Figure 2 – The power station concept illustrating online generation components with respect to a nominal load profile

One key issue with this concept was the lack of a power generation component that filled the mid power ranges. The naval market had an abundance of options for low power prime movers in the 2MWe class, as well as at least 2 competing options in the 20MWe class however, no options existed for the key generation component – the ‘power dense’ 8-10MWe range <sup>14</sup>. This range of powers would be key as the majority of vessel operating hours would reside within this power band. This issue will be visited at length when considering the lessons learned on in-service power systems.

In addition to this missing generation component, pre-Type 45/DDG1000 work centred around hybrid AC-DC networks in both radial and ring configurations with generation components on either side of a AC-DC link converter. This offered Fight Through Power capability in the event of main AC grid failure as a result of battle damage, trip or short circuit fault. This can again be highlighted in Figure 1. In this configuration, a central energy storage solution also existed in order to maintain power to the DC Grid during transient operations, reversionary modes or emergencies.

### 3. Lessons learned from current generation all electric ship

#### 3.1 Type 45 Destroyer

Entering service in July 2010, HMS Daring represented the first modern IPS combatant to enter naval service. The platform was novel in several respects – not least its all-electric architecture consisting of two, complex cycle Rolls-Royce WR-21 Gas Turbines. The power system architecture is highlighted in Figure 3.

The Type 45 was the latest vessel in a long line of ‘more-electric’ platforms in the Royal Navy (RN), starting with the Type23 Hybrid Electric Frigate – with technology being matured and de-risked through the Albion Class (Landing Platform Dock) LPD’s, Bay Class LSD’s (Landing Ship Dock) and Wave Class AOR’s (Replenishment Tanker). As such the RN has been considered the world leader in electric propulsion design and operation. The Type 45’s design and build effort benefitted from a shore based de-risking programme, conducted at the Electric Ship Technology Demonstrator (ESTD) in Whetstone. This was aimed at de-risking several innovations for the time such as;

- UK’s first ‘fully-navalised’ Integrated Power System in a combatant,
- High Voltage (HV), transformer-less propulsion,
- Active Filtering of the main HV system,
- Application of Dynamic Braking Resistors,
- First application of both General Electric’s Advanced Induction Motor (AIM) and the Rolls-Royce WR-21 Gas Turbine

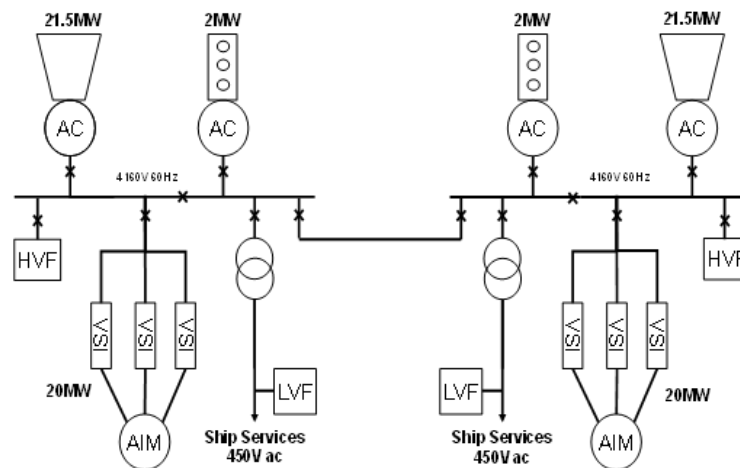


Figure 3 – A Schematic of the Type 45 Integrated Full Electric Propulsion System

The system shown above is configured around the WR-21 Gas Turbine being the main ‘at-sea’ power generation component. The small 2MW Wartsila Diesel Generators were envisaged as harbour generator sets and means of starting the main Gas Turbine Alternators (GTA) in a system that was designed with a focus on efficiency. The system was built around the concept of Single Generator Operation (SGO) whereby in peacetime, a single WR-21 GTA would deliver power at 4160V to satisfy the vessel’s hotel and propulsion power needs – leading to large fuel and maintenance savings.

Upon entry into service the class realised a number of shortcomings relating to system design, equipment specification and operational concepts. This paper will address the system design aspects only in light of application of these lessons to a second generation of all-electric warships.

### 3.1.1 Type 45 System Design

As referenced above, most studies at the time were conducted around the aforementioned power station concept – employing multiple generators configured in a way to economically match load to demand. However, questions remained whether this concept was feasible from an integration perspective. The question being would the multiple prime movers, of various sizes feasibly fit in the hull form of a 7000-tonne warship.

During the derivation of the T45 system the MEDP had a focus towards all electric technologies and economy to reduce fuel consumption from both a cost but also security of supply perspective. 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 whilst being deliverable within the timescales of T45 Entry Into Service (EIS). The design shown in Figure 3, is a departure from the original literature which formed the underpinnings of a robust all electric warship power system design. The concept of operation can be shown below in Figure 4.

In its capacity as the main generation component of the IPS, the WR-21's design intent supposedly removed part of the requirement for power station concept that was used in Hodge and Mattick's original vision of the all-electric warship. The WR-21 unit delivers high efficiency at a variety of powers however this addressed only part of the rationale for the inclusion of other generator components – such as the 2MVA and 10MVA units in Figure 1.

Whilst the consideration of efficiency and power density had been maintained as part of the T45 system design, the aspect of redundancy and power system resilience was lost via the deletion of the mid-sized generation component – an equally important consideration which resulted in an over-arching reliance on the WR-21 gas turbine. This is supported by assessing WR-21 annual operating hours which have been exceeded by 25% compared to original estimates, every year since first of class in service.

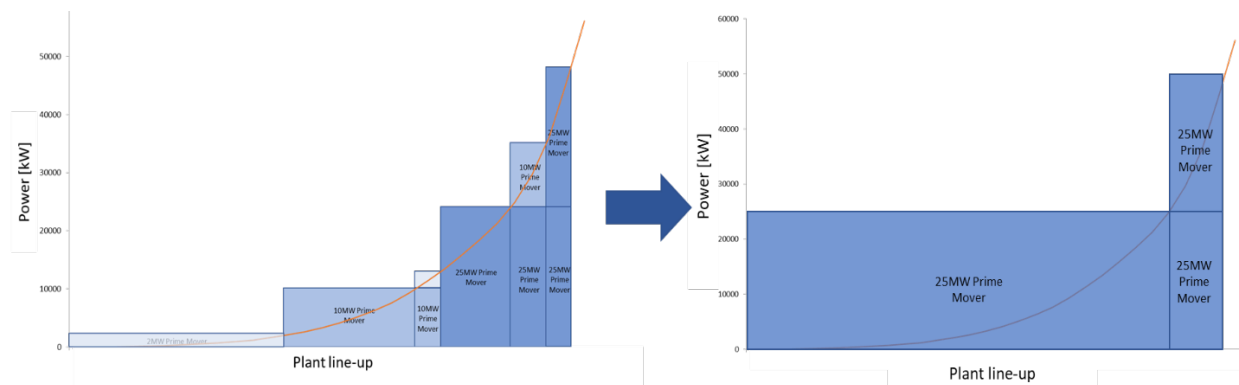


Figure 4 – The Power Station Concept compared to the original ‘sea-going’ Concept of Operation (right) of the T45 power system

Had it been fitted; the mid-sized generator would have provided adequate redundancy in the event of WR-21 unavailability and would have handled a large part of the vessel's eventual sea going operational profile – resulting in lower WR-21 running hours, which would have been run in a more favourable power range. The addition of this mid-sized generator would have also added more survivability to the system and would have meant the WR-21 would have operated in a much more favourable part of its operational envelope – offering a potential increase in the product's robustness.

Ultimately, this increase in granularity is now being achieved via an increase in the number and rating of the Diesel Generators onboard through Power Improvement Plan under the Project Napier programme.

### 3.1.2 ESTD & T45 Shore Integration De-risking Programme

In terms of system verification and de-risking of integration and operation, the Type 45 power system underwent testing at the T45 Shore Integration Facility at ESTD Whetstone. Other examples of such a facility

exist in Philadelphia, USA and are widely considered as examples of best practice in the discipline of proving and de-risking complex IPS systems. The work conducted at Whetstone provided the opportunity for the <sup>[9]</sup>;

- Validation of complex electrical system models,
- Proving load shedding schedules during failure events, whilst maintaining QPS
- Translation of land-based power system protection to the more demanding naval environment
- Testing the fault tolerance and robustness of the various electrical systems on board
- Derivation of the logic behind load sharing between various power generation components.

However, due to pressures on maintaining T45 in service date, and subsequent programme build schedules, the vast amount of testing work was conducted in parallel to equipment and vessel build, meaning that some of the lessons learned during testing could not be rectified in the as built system. Indeed, the equipment used during system testing at Whetstone was fitted to HMS Duncan, the final vessel of the class – meaning the test equipment used represented its final, as delivered configuration.

A fundamental lesson is that undertaking complex de-risking work on an innovative IPS system, in parallel to a tight build programme which necessitated production hardware to be installed early in the vessel build programme offered insufficient time to identify and rectify problems. This added significant pressures to; not only the build programme, but also the vessel's test and commissioning programme. In addition, the ESTD configuration differed somewhat in terms of power sources and layout compared to the eventual T45 installation.

These issues, amongst other well documented equipment issues, manifested itself during early vessel service life in the form of reduced power system availability. As such, incorporation of all lessons learned during both ESTD and T45 Shore Integration Testing has proved a significant challenge and has only been rectified via extensive re-engineering efforts post entry into service.

One point to note is that, whilst land based test facilities are a useful tool in proving the functional integration of the IPS system – it is difficult to completely mimic sea frame integration; resulting in lack of identification of the physical integration issues that may cause issues on all-electric warships. Cooling arrangements using on-board sea water systems are not always adequately simulated in a testing environment whereas issues relating to prolonged in-service transversals such as ambient air temperature, pitch and roll or equipment thermal fatigue as part of a naval installation cannot be established. These considerations should not be underestimated during a robust design stage.

### *3.1.3 The criticality of the Electrical Power Management System (EPMS)*

Early operational experience of integrated power systems in the cruise ship industry highlighted differences in functional and performance characteristics of GTAs and (where installed) Diesel generators, not least with respect to performance variation when considering higher ambient temperatures. These experiences indicated that there is a need to accommodate the variable performance attributes of each type of prime mover within a more sophisticated EPMS utilising a Closed Loop control methodology.

Such Closed-Loop systems have enabled identification of available spinning-reserve within the power system based on prevalent operational and environmental conditions, with active and intelligent management and matching of the generating capacity to the variable load demand.

Unfortunately, these experiences and lessons were not reflected in the specification of EPMS in the Type 45 Destroyer programme, resulting in an less than seamless introduction of IPS into service in a front-line combatant.

### *3.1.4 Type 45 - lessons learned summary*

Negating the omission of DC technologies [which were the result of a lack of available and mature solutions that met the naval requirement], there were a number of architectural issues that resulted in the issues experienced during early T45 service being more critical than they may have been. Key to this was the issue of integrating the power station concept into a 7,000-tonne class vessel. The omission of 'primary', and power dense power generation components at mid and lower powers, coupled with an over reliance on a single prime mover type resulted in sub-optimal power system resilience.

In addition, a compressed testing schedule which overlapped production timescales meant that proper analysis of lessons learned could not then be embodied in the production equipment that would eventually be supplied to the vessels. This can be summarised with the following 3 lessons learned;

#### *3.1.4.1 Power System Resilience / Granularity*

Project Napier has gone some way to restoring power system granularity – the mid-sized GT would have helped alleviate in service issues via a more robust system which would have degraded gracefully in the event of equipment trip/failure whilst still meeting the economy targets of the MOD. This mid-sized GT could have also been supplemented by Energy Storage Devices in order to offer a redundant back up of supplies.

#### *3.1.4.2 Adequate Testing Prior to Production of Deliver Spec Items*

Early testing of design and equipment prior to product equipment manufacture would have led to lessons learned being embodied in a revised equipment and systems design. This would have eased pressure on early in-service experiences on the platform but may have resulted in a delayed EIS.

In conclusion, it is the author's view that due to; the build schedule, programme cost and constraints around EIS - certain systems and equipment were designed, manufactured and installed without all systems being fully tested in a representative arrangement and environment, validated and integrated with respect to system reliability. This resulted in residual design issues being carried into the production standard equipment – resulting in platform reliability issues.

#### *3.1.4.3 Specification of an active Closed-Loop Control System*

Use power and propulsion CONOPS derived from comprehensive Operational Analysis (OA) to match the power system to the mission across all operating scenarios (machinery states, generator line-ups, threat states, climates, etc.), adequately translating the required platform operational capability into physical, functional and performance requirements at an executive-controls, system and equipment level. Modelling and simulation should be used to derive the requirements and algorithms for the sophisticated closed-loop control system to achieve a more fully-integrated power system and meet ship performance and life-cycle cost targets.

#### *3.1.4.4 Key Output for Next Generation Vessels*

The challenge is on all stakeholders to converge on a power system architecture that meets efficiency, availability and resilience targets. This system should be more optimally matched to the military mission across all operating scenarios and constraints.

In addition, confidence in single generator operations may only be gained via adequate back up of power – in many cases this would be satisfied via the inclusion of an energy storage system which may or may not reside on the DC link of the main propulsion converter – such a device would maintain critical supplies in event of generator trip during SGO.

The remainder of lesson captured above may be rectified via early planning, robust design practices and an early, pre-planned de-risking strategy.

### **3.2 DDG1000 Destroyer**

The United States, at a similar time to the UK's Type 45 programme, were also converging on all-electric propulsion for the DD(X) programme. The US Navy was predominantly a service built around mechanical propulsion systems with a bias towards power dense gas turbines. At this time, it was recognised that the US Navy were on a different path to that of the Royal Navy. The DDG1000 programme, borne from the DD(X) programme, settled on an all gas turbine solution with; 2 Rolls-Royce RR4500 Gas Turbine Generators [rated at 4.4MWe and 2 Rolls-Royce MT30 Gas Turbine Generators [rated at 35.4MWe]. These GTG's delivered up to 80MWe of power at 4160V to a Hybrid AC-DC IPS system featuring an Integrated Fight Through Power system consisting of a zonal DC Grid<sup>[7]</sup>.

### 3.2.1 System Design

Noteworthy is the decision to operate the main AC system at 4160V <sup>[10]</sup>. This being the same voltage as the Type 45 Destroyer – whilst featuring almost twice as much installed power. In order to manage short circuit fault current levels a number of restrictions are placed on the main AC generation system. The Type 45 features 2 main 4160V High Voltage switchboards which have an interconnecting bus tie joining the two – meaning the switch board configuration and plant line up can be reconfigured to facilitate single or twin island modes, satisfying a number of operational scenarios.

The power system architecture and system voltage on the DDG1000 IPS however, makes this configuration impossible. The inability to parallel all 4 prime movers across two interconnected switch boards limits reconfigurability and handling of reversionary or economic modes. This would have been avoided with a higher system voltage much in the same way that the QEC carrier programme selected a 11kV system.

### 3.2.2 Complication of a 'gap in the power station

Similar to Type 45, the DDG1000 has 2 Auxiliary Generators (ATG) and 2 Main Generators (MTG). Given the ATG and MTG ratings, this, as per T45 offers a large 9:1 ratio between the economic power outputs of the main and auxiliary units. The Concept of Operation (CONOPS) for DDG1000 however did not 'benefit' from a complex cycle Gas Turbine – meaning the Auxiliary Generators were still regarded as a fundamental part of the power system.

Using an idealised CONOPs this would offer some level of 'compliance' to the original power station concept – offering economic use of the power station at various power levels. Using the ATG's at powers up to 8.8MWe, whilst employing MTG's at powers above. Figure 5 below however, illustrates that a platform such as DDG1000 is configured around an economic escort cruise speed of around 16 knots or 18-20knots when on escort operation. The vessel spends the majority of its sea-going operational profile in this 16-20 knot speed range whilst also requiring power for hotel and service loads. The combined power requirement of propulsion and these other services means the vessel spends the majority of its service life demanding between 8-18MWe from the power system. Given the current power station fit and it's economically addressable power output, it can be concluded that the vessel is more often than not placed in a poor part of its operating window from both a fuel burn perspective, but also redundancy.

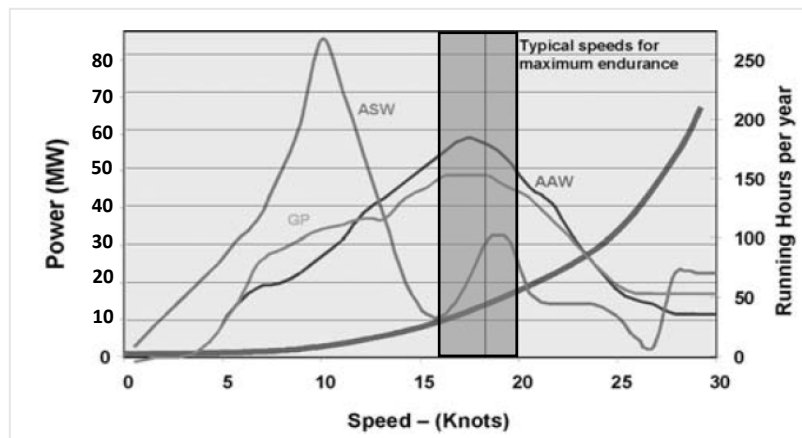


Figure 5 – A nominal AAW Destroyer Operational Profile overlaid with an estimated DDG1000 P-S Curve

This has contributed to US Navy abandoning the concept of single generator operation <sup>[11]</sup> – instead prioritising robustness. The result, in contrast to Type 45, is a highly resilient system that is often operated in a sub-optimal way from an efficiency perspective. Using the rationale above it can be deduced that a more realistic CONOPs of the vessel will mean the vessel typically operates on a single RR4500 and a single MT30 gas turbine the majority of the time. Meaning the combined 40MW plant operates at around 20-40% capacity – resulting in system inefficiencies and potentially greater than anticipated fuel burn.

Combining this plant line up with the limitations stated around system voltage it could be assumed that the R4500 operates on one switchboard – providing domestic loads only, whilst the MT30 operates in isolation, on



the second switchboard satisfying propulsion demand only. This results in a less than perfectly integrated power system – satisfying propulsion and services demand separately across two prime movers and two “islands”.

### 3.2.3 DDG1000 - Lessons Learned Summary

Literature review and in-service experiences point to a number of lessons learned from DDG1000 Entry into Service. Once again, as per Type 45 an increase in granularity of the power system is required to economically and resiliently match generation capacity to demand. Due to the increased platform size of the DDG1000 platform the author recommends this could be achieved either via the provision of further 4+MWe class ATGs, or ATG's with a higher power output dependant on market availability. This would result in greater power system efficiency during the mainstay of vessel operation – yielding benefits in vessel range and through life operating costs.

This prime mover configuration should be reviewed in conjunction with an increase in system voltage to around 11kV to allow more plant configurations – placing less restrictions on bus and generator states. This would have drastically improved the flexibility, efficiency and operational effectiveness of the DDG1000 power system.

## 4. Distribution topologies for next generation IPS vessels

In addition to ratings of power generation components there are also various distribution topologies that should be considered for future all-electric ship power station design. Previous literature <sup>[2,3,7,8,10]</sup> highlights the options of ring, radial, zonal and hybrid architectures.

Type 45 employs a radial power system, in which the supply is cascaded down from the generators via switchboards to supply various consumers at various voltages such as propulsion and service loads. Amongst other reasons, the radial system was selected for Type 45 due to readily available equipment and reduced protection complexity – HV AC circuit breakers offering overcurrent protection were mature and ready to deploy at sea in a front-line combatant whereas other technologies were seen as higher risk or immature.

Radial distribution systems are also favoured in other UK applications of the electric warships however, DDG1000 features a hybrid arrangement consisting of a 1000V DC Zonal Integrated Fight Through Power system alongside a more conventional Ring AC arrangement <sup>[10]</sup>. Future demands for DC power may change this current posture and drive solutions to either more DC focussed hybrid systems or full DC networks.

Looking forward, wholly zonal power systems may be more favoured in naval applications due to their increased redundancy <sup>[7]</sup>. Such systems split the vessel into transverse power zones which typically align with watertight bulkheads – offering the ability to isolate faults or battle damage. Each zone can be configured to contain a power source; either in the form of a generator or energy storage. Via Power Conversion Modules, power can be conditioned to supply a variety of propulsion and service loads within each zone either in isolation or as an integrated system. This offers a wide range of reconfigurable plant line ups – helping power system resilience, efficiency and contributing to the vessels overall survivability policy.

Despite many of the world's all-electric ships adopting AC power systems the potential advantages of Direct Current (DC) mean it is attracting much attention in the offshore and naval markets <sup>[12]</sup>. Indeed, ease of energy storage integration, the possibility of variable speed generation and potential mass and volume savings make DC an attractive proposition – without wish to duplicate work, further benefits to DC systems have also been identified. This would yield savings in both the initial procurement of a second generation of all-electric warship but also reduce fuel consumption – addressing one of the original drivers for increased electrification and reducing whole life costs.

One clear disadvantage of DC power systems is managing protection. DC current does not benefit from the natural zero crossing point that occurs in AC current, making faults more difficult to interrupt and clear. However, as DC technology matures; leveraging advances in both offshore marine markets but also automotive and aerospace markets, technologies are becoming available to counter this – albeit cost effectively meeting naval transversals such as shock remain a challenge.

With a requirement for increased levels of energy storage being integrated into warships in the future, DC will be the preferred distribution technology for electric warships in the medium and long term. This will be of benefit to platforms in the 2030 timeframe <sup>[13]</sup>.

However, for the most part, many near term all-electric warship programmes [Next generation] can be satisfied by the adoption of zonal, High Voltage AC systems. The zonal system offers increased redundancy over radial system architectures. The inclusion of common AC generation, distribution and consumers also lowers the amount of power conversion stages required for essential loads which helps to reduce the power system's susceptibility – again further increasing the vessel's survivability.

HV AC technology is mature and cost-effective – as such, equipment items such as Power Conversion Modules can offer equal capability to near term DC systems in facilitating energy storage insertion on tomorrow's vessels. Despite a future shift towards DC, HV AC zonal systems will still enable the use of high energy weapons and sensors for next generation IPS vessels without the need for developing potentially expensive MVDC equipment and their associated protection components.

## 5. Conclusion for future, next generation IPS

After review of the system designs and in-service experiences of the UK RNs Type 45 platform and the US Navy's DDG1000 programme various conclusions can be made. The T45 system placed an overwhelming priority on engineering the most efficient solution; yielding a design that is not optimal in providing distributed power generation in the event of a machinery casualty. In contrast, the DDG1000 system can be assumed to operate in a manner that prioritises spare electrical generation capacity and robustness – potentially compromising efficiency and subsequently vessel range. Next generation IPS vessels will need to blend these two key drivers in order to achieve a more balanced power system.

A good example of where this requirement has been successfully embodied is the Royal Navy's Queen Elizabeth Class Aircraft Carriers. With an 11kV Integrated Power System powered by a range of high-power Gas Turbines, alongside a range of mid-power diesel generators, the system is well balanced, widely reconfigurable and offers a range of efficient cruise modes. This benefitted from several, well established Systems Engineering toolsets such as Multi-Criteria Decision-Making techniques for generation component selection <sup>[14]</sup> as well as a novel commercial construct which incentivised coherent and cost-effective integration from several industry partners. Given that there was no single entity capable of providing a turn-key IPS solution in the UK, the commercial alliance adopted by the Aircraft Carrier Alliance was key in delivering a design that was well tailored to the requirements, with low risk, and integrated from both a physical and functional perspective.

Whilst extensive operational service experience has not yet been gained, early signs point to a well configured system that benefits extensively from the lessons learnt across the UK's T45, LPD and AOR programmes. The challenge is now on all IPS stakeholders; from procurement agencies to Industry to take this success and make the technology scalable in order to facilitate integration into next generation combatant IPS platforms. A number of the technologies discussed in this paper could enable this goal.

Going forward, IPS architectures will remain a consideration for most upcoming capital warship programmes in modern Navies. This paper has re-visited the original power station concept whilst touching on advances in modern topologies and calls on industry to develop the necessary power components to facilitate tomorrow's requirements. It can be concluded that key to this is selecting a power system architecture, supported by various methods of power generation at various power ratings combined with; an adequate power system voltage, intelligent closed loop control, energy storage systems and configured in an HV AC Zonal system <sup>[7,8,13]</sup>. This should be considered in the context of holistic programme requirements and an agreed CONOPS.

Secondly, as with all novel equipment and systems – a rigorous de-risking plan should be incorporated prior to production equipment manufacture – a good example of this is the use of Land Based Test Site (LBTS), Philadelphia, USA. This will offer an opportunity for equipment manufacturers, and the ministries that specify the equipment to learn the lessons of this testing programme and iterate a more robust set of requirements.

The author has concluded that, given the drivers of cost, economy, flexibility and survivability, power station granularity should be a primary consideration during the robust design phase of tomorrow's IPS ships. Such a

system is built around a large generation component of around 30MWe where options exist in both the Rolls-Royce AND GE portfolios. This should be supplemented by adequately sized, power dense Auxiliary Generation components.

Such power system architectures will restore the original power station concept in a cost-effective way; making the efficient and robust generation of power at all key powers feasible in a destroyer sized platform. This design solution, along with adequate commercial practices, are vital in satisfying the diverse needs of tomorrow's warships whilst being mindful of the budget constraints that have seen hull numbers diminish in previous IPS classes.

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